An Innovative Fan Control Strategy Aimed at Responding to Human Physiological Characteristics for Comfort Sleeping

Wei Yu [a,b]*, Yan Zhang [a,b], Chenqiu Du [a,b], Baizhan Li [a,b], Hong Liu [a,b], Yue Zhang [a,b], Shen Wei[c]

[a] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing, China
[b] National Centre for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing, China
[c] The Bartlett School of Construction and Project Management, University College London, London WC1E 7HB, UK

*Corresponding author
E-mail: yuweixscq@126.com (WY)

Abstract:

A comfortable sleeping environment can improve sleep quality. Electric fans are widely accepted as an effective method in South China to improve the thermal environment in summer when people are sleeping. To determine the proper fan control strategy under the all-night blowing mode, pre-sleep and during-sleep experiments were performed in a climate room. Under 6 operating conditions (28/30/32 °C, 50%/80% RH), subjective sensations (thermal sensation votes and sleep quality indexes) were recorded and objective physiological parameters (brain waves and skin temperature) were monitored. The results showed that the comfortable air speed interval before sleep was 0.15–1.44 m/s. The skin temperature showed a clear trend of first rising, then falling, stabilising, rising again, and finally rising with fluctuations throughout the night. Based on the characteristics of physiological parameters in different sleep periods, the sleeping time was divided into 5 stages to perform linear regression, and a dynamic air supply control strategy for fans that imitated the circadian rhythm of sleep was proposed. Compared with steady-state blowing, the sleep efficiency and proportion of deep sleep under this optimisation control strategy increased by 3.24% and 3.59%, respectively. This study provides a reference for fan control in a sleep environment.

Keywords: Sleep quality, Fan control, Thermal comfort, Skin temperature

1. Introduction

Sleep occupies almost one-third of the human lifetime [1]. Sleep is essential for the body to recover from both physical and psychological fatigue suffered throughout the day and to restore energy to maintain bodily functions [2]. Studies have shown that poor sleep quality can impair the cognitive ability of the elderly [3] and influence the learning and working efficiency of young people during the day [4]. The indoor thermal environment is a major factor influencing sleep quality, among others [5]. Furthermore, a comfortable indoor thermal environment is more important during sleep at night than during the day because of the reduced metabolic rate and limited thermoregulatory function at night [6]. As sleep thermal environments are closely related to sleep quality, a well-maintained indoor thermal environment during sleep helps to reduce the number of wake-ups [7]. In contrast, an uncomfortable thermal environment will activate the thermoregulatory defence mechanisms and disrupt sleep [8]. A study in Hong Kong reported that approximately 60% of respondents woke up because of thermal discomfort during sleep [9]. In the Hot Summer and Cold Winter region of China, 60% to 90% of people complained of insomnia during summer nights [10]. Therefore, it is vital to explore the maintenance of an indoor thermal environment during sleep to provide good sleep quality.

Sleep quality is influenced by many indoor environmental factors, such as temperature[6, 10, 11], relative humidity [11], and airflow [12-17]. Airflow can improve the thermal comfort and sleep quality of humans in a hot environment. One study [18] showed that under the operating conditions of 23°C, 50% RH, and 3.27 clo, 75% of the subjects believed that ventilation during sleep was more beneficial than no ventilation. In a warm and humid environment, airflow increases the convective heat loss, which helps to reduce arousal and improve sleep quality by reducing the rectal temperature, skin temperature, and sweating rate [19]. Studies have shown that when a person was awake, an increase in the air speed within a certain range can be used to compensate for the increase in temperature [12, 16]. One study found that the recirculation of indoor air generated by ceiling fans could increase the maximum allowable indoor temperature to 32.5 °C [15]. When a person was asleep, increasing the airflow has the same effect. For the elderly, supplying air of 0.80 m/s allowed them to maintain sleep quality and thermal comfort at a temperature of 3 K higher than neutral temperature (30°C) [13]. For university students, increasing the fan speed to 1.17 m/s at 30 °C /60-80% RH also enabled subjects to achieve thermal neutrality while lying down [20]. Common measures to improve the overheated environment by an increase in airflow during sleep include natural ventilation (mainly open windows) [21], air conditioners [22], bedside personalised ventilation systems [18], and electric fans [23]. Air conditioning is one of the easiest ways to adjust the unsuitable indoor thermal environment for sleeping [22]. At the same time, it poses tremendous pressure on building energy consumption, especially in China, nearly one-third [24]. Alternatively, many studies have verified the thermal preferences of people to improve thermal environment through changes in air speed rather than just temperature [25, 26]. In such cases, increasing airflow through the electric fans is less energy consuming and enable to improve the thermal comfort of human in moderate thermal environments. Researchers have proved in an environment of 28–32 °C, electric fans can be used as an effective cooling method [23]. Especially at night, the decrease of solar radiation and air temperature further promotes the application potential of fans. Given that the electric fan is widely used to increase heat loss both in China [27] and other countries worldwide [28], it is a tool worth promoting to create a comfortable sleeping environment in summer.

The human body has different physiological and biochemical characteristics at different stages of the sleep-cycle [16]. Because of the circadian rhythm of humans, the thermophysiological parameters during sleep, such as skin temperature, core body temperature, and metabolic rate, all follow the general rule of first rising, then falling, and then rising again [29-33]. Because of the dynamic trends in physiological parameters and the dynamic thermal demands of humans[6,37,38], it is inappropriate to set a constant air speed during sleep. However, previous studies have only focused on steady-state blowing throughout the night, whether it is a bedside personalised ventilation system (v=0.15 m/s)[18] to control the micro-environment of the bed, or the ceiling fan (v=0.7 m/s), task fan (v=0.6 m/s)[13], and fan box (v=1.7 m/s)[19] to control the local airflow environment around the bed. One study focused on the dynamic changes in temperature showed that the Fall-Rise condition was more conducive to the body preparing for waking up [10]. However, to our knowledge, there are no studies on dynamic air speeds throughout the night.

The variation in the circadian rhythm of the human body reveals that people need a dynamic thermal environment during sleep. Electric fans are such applicable tools to improve the local thermal environment. Therefore, the main objectives of this study are as follows:

(1) Obtain a comfortable air speed interval for using the fan during sleep.
(2) Propose a dynamic air supply control strategy for fans.
(3) Verify that the optimisation control strategy can help improve sleep quality.

2. Methods

We conducted 3 experiments. First, through the pre-sleep experiment under 6 operating conditions, the comfortable air speed interval of the subjects was determined. The second part was the during-sleep experiment under 4 suitable operating conditions. Sleep quality was evaluated using subjective questionnaires and physiological parameters. Based on the physiological characteristics of people during sleep, a dynamic air supply control strategy for fans was proposed and proven to be effective in the third verification experiment.

2.1 Experimental design

2.1.1 Pre-sleep experiment

The pre-sleep experiment selected three temperature levels of 28 °C, 30 °C, and 32 °C, with two relative humidity levels of 50% and 80%, which were combined into 6 operating conditions, covering a wide range of neutral to hot conditions. Each operating condition corresponded to 4 different fan gears, selected from the range of the lowest to the highest acceptable fan gears as fed back by the subjects in the preliminary experiment, according to the equal difference principle. The corresponding air speed values at various fan gears were measured then. The specific operating conditions and air speed values are listed in Table 1. Six subjects were selected randomly from the recruited ones, and a within-subject design was performed for the pre-sleep experiment.

Table 1 Operating conditions in the pre-sleep experiment

operating condition	temperature （°C）	humidity （%）	air speed （m/s）			
1	28	50	1 gear- 0.44	4 gear- 0.64	10 gear- 0.82	16 gear- 1.14
2	28	80	1 gear- 0.44	4 gear- 0.64	10 gear- 0.82	16 gear- 1.14
3	30	50	1 gear- 0.44	10 gear- 0.82	16 gear- 1.14	20 gear- 1.31
4	30	80	4 gear- 0.64	16 gear- 1.14	20 gear- 1.31	23 gear- 1.47
5	32	50	1 gear- 0.44	10 gear- 0.82	20 gear- 1.31	23 gear- 1.47
6	32	80	10 gear- 0.82	20 gear- 1.31	23 gear- 1.47	26 gear- 1.56

The pre-sleep state refers to the period when people are reclining and ready to fall asleep, but are still conscious. Physiological parameters, such as the human metabolic rate at this time (0.8 met), are the closest to them during sleep (0.7 met) [34].

The pre-sleep experiment required the subjects not to exercise vigorously within 24 h before the experiment. On the day of the experiment, the subjects needed to arrive at the laboratory 30 min in advance, change into their sleepwear, and remain quiet to minimise the impact of the external environment. Subsequently, the subjects entered the climate room and lay on the bed to start the formal experiment. First, subjects needed to lie down for 20 min under no wind to get accustomed to the situation, and then fill in the thermal sensation votes (TSV) immediately. Second, the fan was turned on and blew at the first air speed for 20 min; the subjects were asked to fill in the questionnaire immediately after this blowing. Third, the fan was turned off, at which point one type of air speed test was completed. The subjects underwent a 20-min recovery period to eliminate the cognitive effects of the air speed in the previous condition. These recovery periods can offset the major influence of the exposure sequence. The specific experimental process is shown in Fig.1.

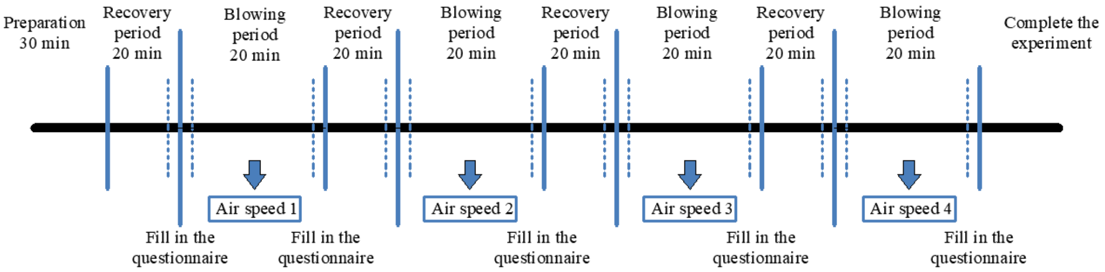


Fig. 1. Flow chart of the thermal comfort experiment before sleep

2.1.2 During-sleep experiment

Four operating conditions were tested in the during-sleep experiment. Two extreme conditions of 28 °C /50% RH and 32 °C /80% RH were excluded according to the thermal comfort feedback of the subjects in the pre-sleep experiment. The air speed of each operating condition was based on the regression results of the air speed and TSV in the pre-sleep experiment.

The order of the experiment was designed in the standard Latin square (Table 2) to minimise the possible discomfort of the subjects on the first night and the psychological factors that may interfere with the sleep quality of the subjects on different experiment nights. All information related to the operating condition was kept confidential to the subjects. Twelve subjects participated into the during-sleep experiment and were randomly divided into 4 groups. Only one subject entered the climate room for the experiment each night, and each subject was asked to sleep on 4 consecutive nights; thus, the experiment lasted 48 days.

According to a previous investigation on the sleep habits of subjects, the sleep time was set from 00:00 to 08:00. The experiment started at 0.00, and the experimenter turned off the lights and turned on the fan. The subjects fell asleep with a slight delay (within 15 min) from the start of the experiment. The subjects needed to arrive at the laboratory in advance to change into sleepwear and wear the physiological parameter probes. The subjects were asked to cover themselves with the quilts for sleep. The subjects' TSV was recorded during the pre-sleep and post-sleep periods, and the evaluation of the sleep quality was recorded after waking up. Physiological parameters, including Electroencephalography (EEG) and skin temperature, were monitored overnight. The specific experimental process is shown in Fig. 2.

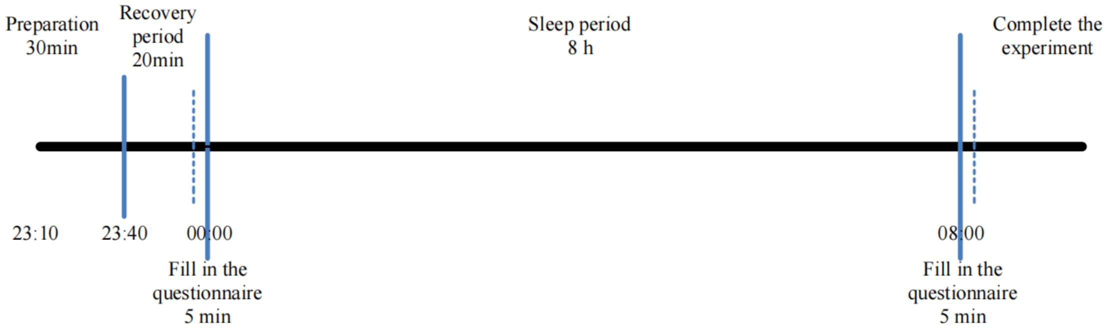


Fig. 2. The flow chart of the during-sleep experiment

2.1.3 Verification experiment

The verification experiment of the optimisation blowing strategy used steady blowing as a control. The background operating condition was set to 30 °C /50% RH. Before the verification experiment, engineers modified the control system of the fan and added the dynamic air supply control strategy into the program.

The experimental order is listed in Table 2. The 12 subjects were randomly divided into 2 groups, and everyone needed to sleep on 2 consecutive nights; thus, the experiment lasted 24 days. The experimental process was the same as that in the during-sleep experiment. The subjects filled in the subjective questionnaires about sleep quality after waking up, and the sleep duration and skin temperature were monitored overnight.

Table 2 Operating conditions in the during-sleep experiment

During-sleep experiment				
Subject	Experiment order			
	First night	Second night	Third night	Fourth night
Group1 (3 subjects)	A	B	C	D
Group2 (3 subjects)	B	C	D	A
Group3 (3 subjects)	C	D	A	B
Group4 (3 subjects)	D	A	B	C

Verification experiment		
Subject	Experiment order	
	First night	Second night
Group1 (6 subjects)	B	E
Group2 (6 subjects)	E	B

A：28°C;80% RH;0.44m/s; steady-state blowing

B：30°C;50% RH;0.78m/s; steady-state blowing

C：30°C;80% RH;1.31m/s; steady-state blowing

D：32°C;50% RH;1.31m/s; steady-state blowing

E：30°C;50% RH; Variable air speed; optimisation strategy blowing

2.2 Experimental platform

The experiments were conducted in a climate room at Chongqing University (Fig.

3). The dimensions of the room were 4 m (length) × 3 m (width) × 3 m (height). The temperature and humidity parameters were automatically controlled using refrigeration units, air handlers, heaters, and humidifiers. The air speed was controlled using a frequency converter. The dry-bulb temperature control range of the working area in the climate room was -5 °C–40 °C, the control accuracy was ±0.3 °C (<10 °C, ±0.5 °C); the relative humidity control range was 10%–90% RH, and the control accuracy was ±5%. To avoid other significant airflow in the climate room, the background air speed was controlled to be less than 0.10 m/s through the top orifice. The bedding included a straw mat and a summer cool quilt, the thermal resistance of which can be estimated to be 1.64 clo (containing subjects' short-sleeve sleepwear) [35]. The fan used in the research was a 9b household floor fan with 26 gears, air volume ≥54 m³/min, and 70% speed regulation ratio, which could achieve step-less speed regulation. It was placed at a distance of 1 m from the end of the bed. The blowing direction was from the subjects' feet to the head.

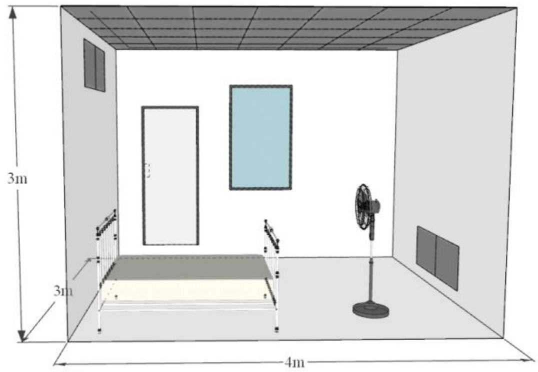


Fig. 3. The climate room

2.3 Data collection

2.3.1 Subjects

Considering the experimental period and operating conditions comprehensively, twelve college students were selected, including 6 males (age: 23.7±0.9; height: 174.2±6.0 cm; weight: 63.3±5.9 kg) and 6 females (age: 23.7±0.7; height: 162.2±1.3 cm; weight: 49.8±4.6 kg). Set α err= 0.05, sample size=12, power=0.8, the effect size f can be calculated to be 0.5 (a large effect is 0.4) [36]. Therefore, this sample size was considered representative, and the experimental results of 12 subjects can effectively reflect the overall situation. Recruited subjects had no sleep disorders or diseases affecting sleep and absence of smoking and alcohol abuse. The Pittsburgh Sleep Quality Index was used for those who met the requirements to investigate the sleep quality in recent months. The higher the cumulative score, the worse the sleep quality. Subjects with a total score ＞5 were excluded [37]. During the experiment, the subjects wore short-sleeved sleepwear uniformly.

2.3.2 Objective measurements

All measuring instruments used in the experiments were calibrated. The air speed of the fan was measured using the AirDistSys 5000 universal breeze speed monitoring system. Its measurement range was 0.05–5 m/s, and its reading accuracy was ±0.02 m/s ±1%. Eight gears of the 9b fan were measured. Considering the person's posture when lying down, eight measuring points were placed on the central axis of the bed (1.9 m long and 0.9 m wide) at the height of 0.9 m from the floor, flush with the fan axis. The first measuring point A was 0.2 m away from the end of the bed, and the last measuring point H was 0.3 m away from the head of the bed, with measurement points at intervals of 0.2 m. The distribution of the measurement points is shown in Fig. 4. For the constant air speed values in the pre-sleep and during-sleep experiments, the sampling time was 5 min and the sampling frequency was 8 Hz. For the dynamic air speed values in the verification experiment, the sampling time was 8 h and the data was recorded every 10 sec. The mean, standard deviation and range of air speeds for each fan gear are shown in Table 3. In this study, the average air speed at 8 measurement points was used as the mean value of the various fan gears.

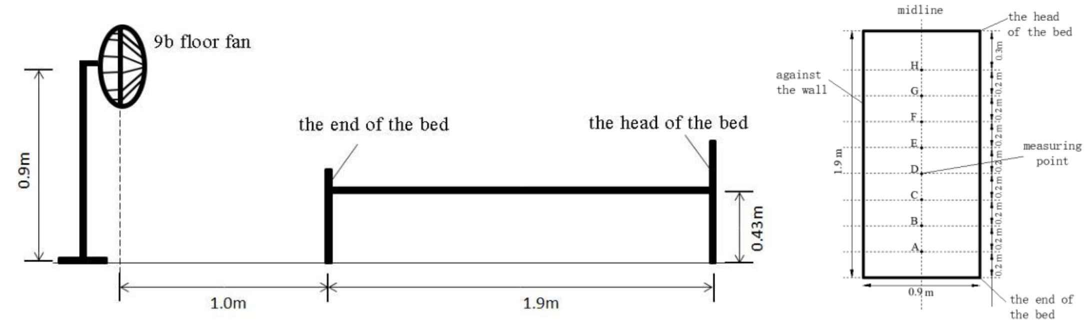


Fig. 4. Experimental layout

Table 3 Mean, standard deviation and range of air speeds for each fan gear (m/s)

Fan gear	1	4	8	10	16	20	23	26
Mean	0.44	0.64	0.78	0.82	1.14	1.31	1.47	1.56
Standard deviation	0.06	0.10	0.10	0.14	0.22	0.29	0.38	0.41
Range	0.30-0.48	0.48-0.72	0.55-0.87	0.53-0.93	0.73-1.33	0.77-1.55	0.79-1.82	0.83-1.93

The skin temperature of the subjects during sleep was collected using temperature probes connected to the SKT100C skin temperature signal amplification module (Biopac, Goleta, CA, USA) (Fig. 5). The gain multiple of SKT100C was 5,2,1,0.5 F/V, and the resolution was 0.0001 °C. This device automatically collected data with a sampling interval of 1 sec. In the experiment, the 7-point method was used to collect the local skin temperature of each body part and calculate the mean skin temperature using the following formula [38]:

$$MST = 0.07t_A + 0.35t_B + 0.14t_C + 0.05t_D + 0.19t_E + 0.13t_F + 0.07t_G \tag{1}$$

where $t_{A,B,C\cdots}$ is the local skin temperature of various parts of the body (°C); A: head; B: trunk; C: arm; D: hand; E: thigh; F: leg; and G: foot.

EEG is one of the most reliable indexes for the evaluation of sleep quality at various periods and can also reflect the effect of the thermal environment during sleep [6, 16, 39]. The subjects' brain waves were collected using a CAP100C EEG cap (Biopac, Goleta, CA, USA) (Fig. 5). This cap held 19 embedded tin electrodes close to the subject's head, and its electrodes were pre-positioned in the international 10/20 montage. After the subject wore the electrode cap, the EEG recording gel was injected into each electrode (via a central gel access hole) with a blunt-tipped syringe. The

EEG electrodes were plugged into the data acquisition and analysis software (Acq knowledge) through the MP150 mainframe and EEG100C signal amplification module. The results of EEG bands were interpreted in 2 steps. First, a digital filter was applied to decompose the EEG signal into 4 frequency bands, 0.5-4Hz is the δ band, 4-8Hz is the θ band, 8-12Hz is the α band, and 12-30Hz is the β band [40]. Second, Fast Fourier Transform [41] was used to perform EEG spectrum analysis and obtain each EEG band spectral power, as Fast Fourier Transform can convert the time domain waveform into a series of individual sine wave components in the frequency domain. Finally, the relative spectral power (%) of EEG was calculated to normalize the absolute EEG power of each subject.

The sleep quality of the subjects was monitored using a FitbitCharge3 bracelet in the verification experiment because the subjects reported that the EEG cap influenced sleep quality in the during-sleep experiment. This bracelet is almost as reliable as PSG [40] and can visually provide the specific duration of wake after sleep onset (WASO), REM, light sleep (N1 + N2), and deep sleep (N3). Based on these data, the total sleep time (TST), sleep efficiency (SE), sleep onset latency (SOL), the proportion of REM sleep, and the proportion of N3 can be calculated. A higher value of SE, a higher proportion of REM, and a higher proportion of N3 mean better sleep quality [21]. On the contrary, the higher the SOL, the worse the sleep quality [21]. The calculation formulae are as follows:

$$TST = WASO + REM + N1 + N2 + N3 \tag{2}$$

$$SE = (REM + N1 + N2 + N3) / TST \tag{3}$$

$$SOL = \text{the length of time from full wakefulness to sleep} \tag{4}$$

$$\text{The proportion of } REM = REM / TST \tag{5}$$

$$\text{The proportion of } N3 = N3 / TST \tag{6}$$

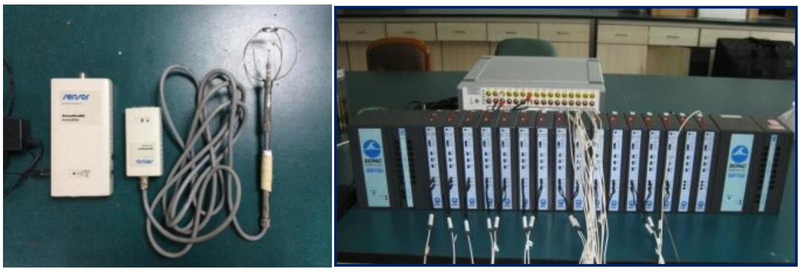


Fig. 5. Experimental apparatus

2.3.3 Subjective measurements

The thermal sensations of the subjects were assessed on a 7-point scale (-3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, and 3: hot) [42]. Sleep quality was assessed using 4 indexes (ease of falling asleep, ease of awakening, calmness of sleep, and satisfaction with sleep). The content of the sleep quality questionnaire (Table 4) was partially modified [43]. The higher the score, the better the sleep quality.

Table 4 Sleep Quality Questionnaire

score question	1	2	3	4	5

1. Ease of falling asleep	very difficult	quite difficult	neither easy nor difficult	fairly easy	very easy
2. Ease of awakening	not at all	not much	moderately	fairly	fully
3. Calmness of sleep	very restless	quite restless	neither calm nor restless	fairly calm	very calm
4. Satisfaction with sleep	not at all	not much	moderately	fairly	fully

2.4 Data analysis

The statistical analyses were performed using SPSS (version 21.0; IBM Ltd., USA) and R (version 4.1.0). Regression analysis was used to reveal the relationship of the TSV with the air speed value and the trend of the circadian rhythm during sleep. The coefficient of determination R^2 was used to evaluate the effect of the regression model. The value of R^2 ranges from 0 to 1, and the larger the value, the better the fit of the model.

Normality and homogeneity of variance tests were performed on TSV, sleep quality questionnaire evaluation, skin temperature, and sleep duration. These measured data conformed to the normal distribution by the Shapiro-Wilk test. The Mann-Kendall trend test was performed on the variation trend of skin temperature. Analysis of variance was used to determine whether different operating conditions had a significant impact on the measurement results and test whether the regression coefficient was statistically significant. Statistical significance was set at $p < 0.05$.

3. Experimental results

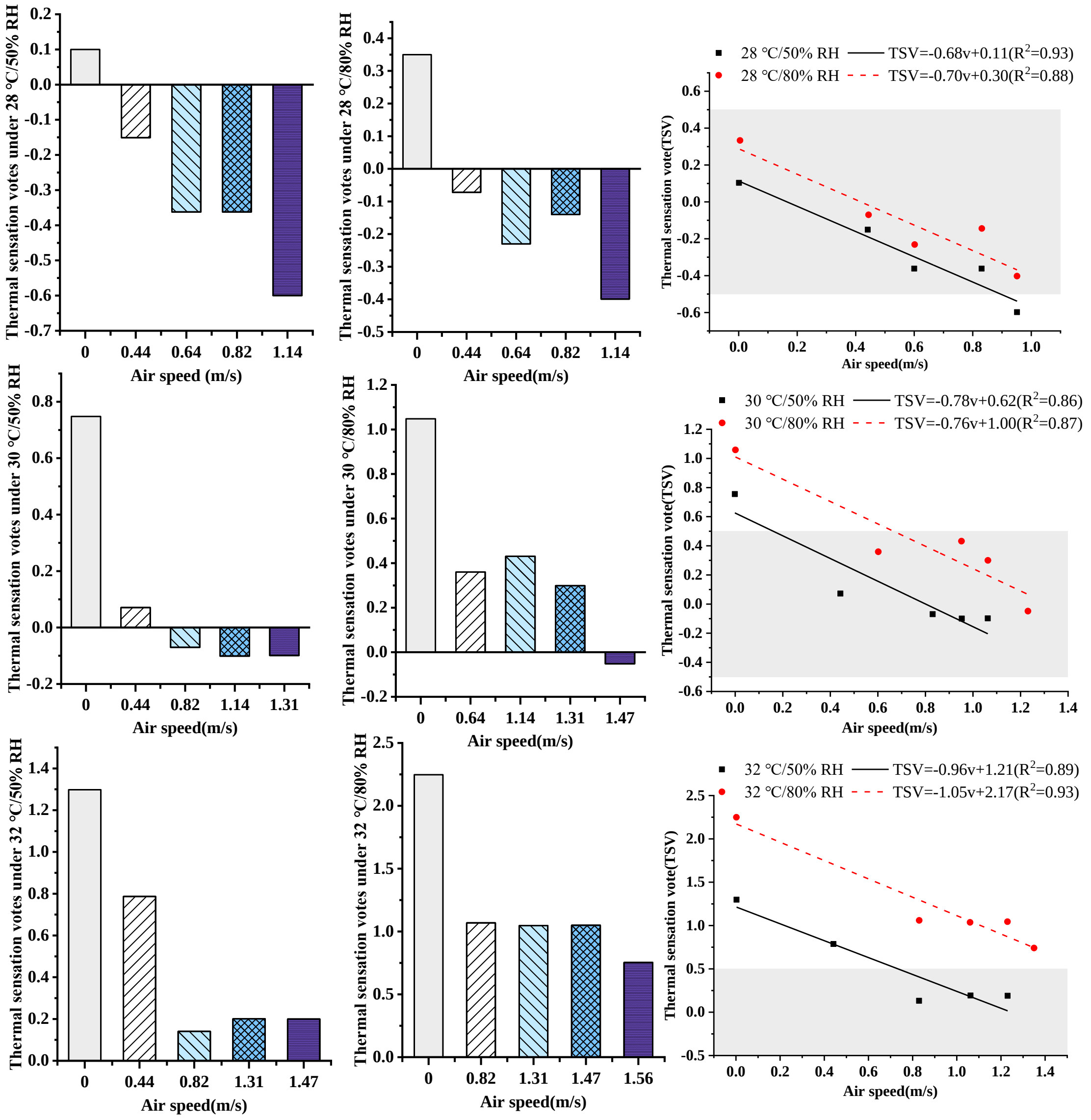
3.1 Comfortable air speed interval in the pre-sleep experiment

Fig. 6(a) shows the variation of the subjects' TSV with air speed under different operating conditions in the pre-sleep experiment. Under the same operating conditions, the TSV of the subjects decreased significantly with an increase in air speed. Increased air speed speeds up the evaporation of sweat from the surface of the human skin, which removes heat from the body and stimulates cold receptors of the skin to produce cold sensations [44]. It is worth noting that at 28 °C /50% RH, the subjects' TSV was closest to 0 (thermoneutral state) with no wind, representing the subjects' thermal sensation was the best at this time. Turning on the fan caused the TSV to deviate from the optimal state and drop below -0.5. Thus, the subjects did not need to regulate their thermal environment. At 32 °C /80% RH, even if the air speed was adjusted to the maximum value of 1.56m/s, using fans alone can no longer reduce the thermal sensation of the subjects to the acceptable range, indicating that this operating condition has exceeded the upper limit for air speed that can improve thermal comfort. Therefore, these 2 operating conditions were excluded from the subsequent experiments. In the other 4 operating conditions, the air supply all made the TSV of the subjects closer to the thermal neutrality. In particular, under 2 operating conditions of 30 °C /80% RH and 32 °C /50% RH, the subjects' TSV decreased from 1.05/1.30 under the no-wind condition to -0.05/0.14 under the fan-on condition.

The regression results of TSV and air speed showed that the speed of the change of thermal sensation with air speed was positively correlated with the ambient temperature. Temperature mainly affected the slope of the regression line, while humidity affected the intercept of it. According to the acceptable thermal comfort interval TSV$\in$(-0.5, 0.5) [35] (as shown in the shaded part in Fig. 6(b)), the comfortable air speed interval before sleep was obtained. As the temperature and humidity increased, the comfortable air speed interval widened and then narrowed: from 0.90m/s at 28 °C /50% RH to 1.31m/s at 30 °C /80% RH and then to 0.95m/s at 32 °C /80% RH. The air speed had more possibility for improvement at 30 °C /50% RH and 30 °C /80% RH, but it can be adjusted less for 28 °C and 32 °C. Furthermore, with an increase in temperature and humidity, the minimum value of the comfortable air speed interval increased from 0.00 m/s at 28 °C /50% RH to 1.59 m/s at 32 °C /80% RH, and the maximum value of the interval increased from 0.90 m/s at 28 °C /50% RH to 2.54 m/s at 32 °C /80% RH, which indicated that the higher the temperature and humidity, the greater the air speed required to improve the thermal comfort. Taking the 30 °C /50% RH as an example, the regression equation was as follows:

$$TSV = -0.78v + 0.62\left(R^2 = 0.86, p = 0.022 < 0.05\right) \tag{7}$$

Based on the calculation of this regression equation, the corresponding air speed v=0.15 m/s when TSV=0.5, v=1.44 m/s when TSV=-0.5, and v= 0.79 m/s when thermal neutrality was attained. Therefore, the air speed interval that met the thermal comfort zone of the subjects at 30 °C /50% RH was (0.15, 1.44) m/s.



(a) TSV (b) Linear regression of TSV and air speed

Fig. 6. The relationship between the subject's TSV and air speed under different operating conditions

3.2 During-sleep experiment

3.2.1 Subjective sensations

Fig. 7 shows the subjects' TSV in the during-sleep experiment. When the subjects' TSV distribution was considered in 3 different periods comprehensively, the thermal sensation of the subjects was closer to the thermal neutral state at 30 °C /50% RH and 30 °C /80% RH, followed by 28 °C /80% RH, and it was the furthest at 32 °C /50% RH. The subjects' TSV in each period differed significantly between 4 operating conditions ($p<0.05$). Except at 32 °C /50% RH, the subjects' TSV under constant air speed decreased during sleep. The thermal sensation of subjects was closer to the thermal neutral state at 28 °C /80% RH in the pre-sleep period, in contrast to 30 °C /50% RH during sleep and the post-sleep period. The subjects' TSV varied dynamically before, during and after sleep, suggesting that maintaining constant thermal environment parameters throughout the night is inappropriate.

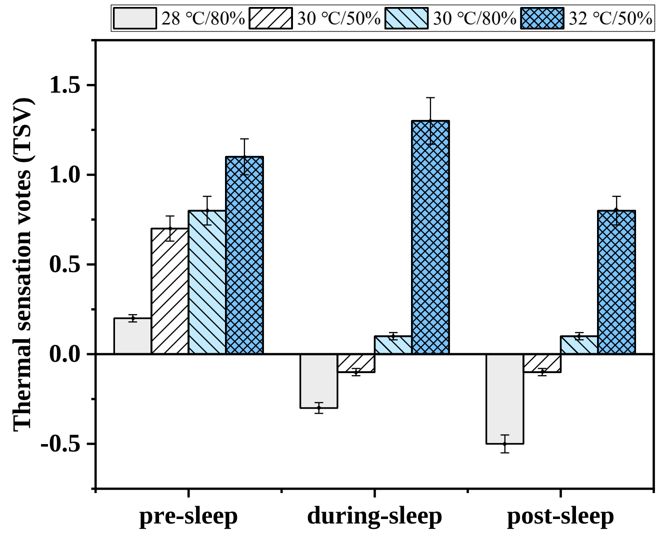


Fig. 7. The subjects' TSV under different operating conditions in the during-sleep experiment

Fig. 8 shows the subjects' evaluation of their sleep quality in the during-sleep experiment. The score for the ease of falling asleep, ease of awaking, and satisfaction with sleep at 30 °C /50% RH were higher than those under any other conditions. Furthermore, the change in the ease of falling asleep ($p=0.031$) and satisfaction with sleep ($p=0.043$) with the operating conditions were significant. Comprehensively, the subjects self-evaluated that they had better sleep quality at 30 °C /50% RH.

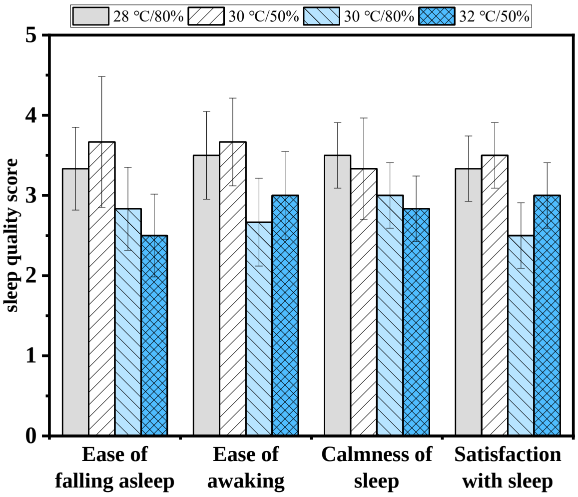


Fig. 8. The evaluation of subjects' sleep quality under different operating conditions in the during-sleep experiment

3.2.2 Objective physiological index

Fig. 9 shows the variation of the mean skin temperature of the subjects under different operating conditions. The mean skin temperature generally increased as temperature and humidity increased; however, the opposite was observed between 30 °C /50% RH and 30 °C /80% RH. This difference was because the air speed at 30 °C /80% RH was 1.31 m/s, which was much higher than that at 30 °C /50% RH, and the high relative humidity of 80% also made the surface of the human skin more humid. Therefore, the higher air speed accelerates the evaporation of water from the surface of the skin and takes away heat. The mean skin temperature changed significantly with operating conditions ($p<0.001$). However, the mean skin temperature reflected roughly similar trends under different conditions. By the Mann-Kendall trend test, the skin temperature rose significantly when the experiment started soon. After the turning point at 1:00, the skin temperature showed a significant downward trend and increased significantly except 30 °C /80% RH. Nearly awaking, the skin temperature rose slightly, except 32 °C /50% RH did not meet a significant upward trend. The above trends objectively reflected the dynamic variability of physiological parameters of humans during sleep. The trends for the other 3 conditions were not as significant as that of 28 °C /80% RH, which may be because the difference of environmental conditions obscures the influence of endogenous circadian rhythm [45].

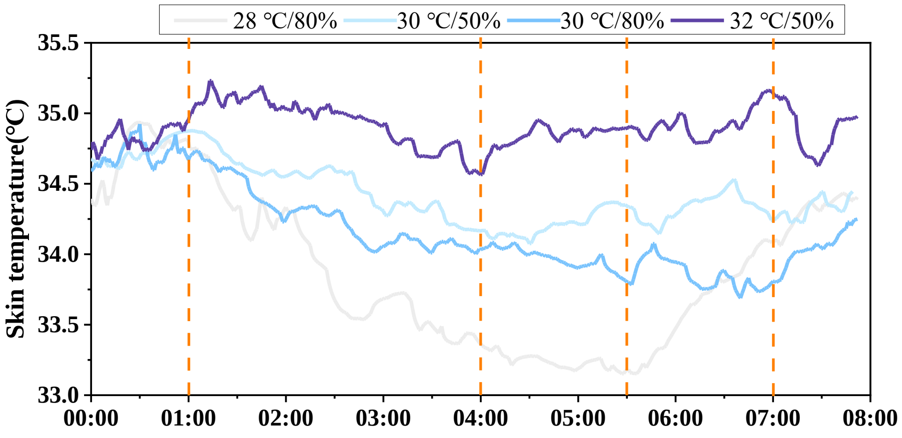


Fig. 9. The mean skin temperature of the subjects under different operating conditions in the during-sleep experiment

4. Optimisation strategy

The during-sleep experiment concluded that the subjects had the optimal thermal comfort and the best sleep quality at 30 °C /50% RH among 4 operating conditions. Since this study aims to improve sleep quality, the development and verification of the fan optimisation strategy were only conducted at 30 °C /50% RH, an optimal operating condition.

4.1 Optimisation strategy development

With constant air supply throughout the night, the changes in thermal requirements and fluctuations in physiological parameters of people indicated that they may require a dynamic thermal environment during sleep. Therefore, this research proposed a dynamic air supply control strategy for fans that imitated the circadian rhythm of sleep. First, the circadian rhythm based on skin temperature needed to be summarised [45, 46]. The skin temperature under 4 operating conditions was averaged and then smoothened by using a moving interval average with a 25 min time step. According to the position of the extreme point of the curve, the 8-hour sleep time was divided into 5 stages (00:00–01:00, 01:00–04:00, 04:00–05:30, 05:30–07:00, 07:00–08:00). As regards the traditional multiple regression model for the prediction of the circadian rhythm [46], linear regression was performed on the skin temperature at each stage. The regression equations and R^2 at each stage are shown in Table 5; each of them was statistically significant, tested by the analysis of variance. Among them, the linear regression results of the second stage (R^2=0.98) and the fourth stage (R^2=0.99) were well fitted. From 4:00 to 5:30, the goodness of fit was not very high (R^2=0.42); however, the slope of the curve was one order of magnitude less than that of the adjacent curve; thus, it was still considered as a horizontal straight line. Fig. 10(a) shows that the circadian rhythm has 5 trends: rising, falling, stabilising, rising again, and finally rising with fluctuation.

In the dynamic air supply control strategy for the fan, the air speed values of 3 stable stages (high, medium, and low) were determined based on the regression results of TSV and air speed in the pre-sleep experiment and were within the comfortable air speed interval at 30 °C /50% RH. Among them, the highest air speed value was still lower than the upper limit of 0.80 m/s recommended by ASHRAE [17]. Because the skin temperature can reflect the thermal sensation of people [47, 48], when the skin temperature is higher, people feel hotter, and they need a higher air speed to achieve a thermal neutral state. Based on such correspondence between skin temperature and air speed, the air speed variation curve of the optimisation blowing strategy was finally attained (Fig. 10(b)).

1) From 00:00 to 01:00, owing to the significantly increased blood flow of human skin [8], the human heat release increases correspondingly, and the mean skin temperature increases. However, because the skin temperature at this stage is mainly influenced by physiological factors [49], an adjustment of the air speed has little effect on the skin temperature. At 30 °C /50% RH, the skin temperature difference was only 0.09 °C from 00:00 to 01:00. Owing to the slight skin temperature difference, this stage was assumed to be stable. Since subjects were in the process of falling

asleep, their thermal sensation did not differ much from that before sleep. Therefore, the air speed at this stage corresponded to the thermal neutral state before sleep. According to the regression result of TSV and air speed at 30 °C /50% RH (Formula 7), the air speed was selected as v=0.79 m/s when TSV=0, which was the maximum air speed during sleep.

2) From 01:00 to 04:00, the skin temperature showed a downward trend. At this stage, the thermal demand of the subjects increased; thus, the air speed showed a linear decrease from v= 0.79 m/s to v= 0.15 m/s.

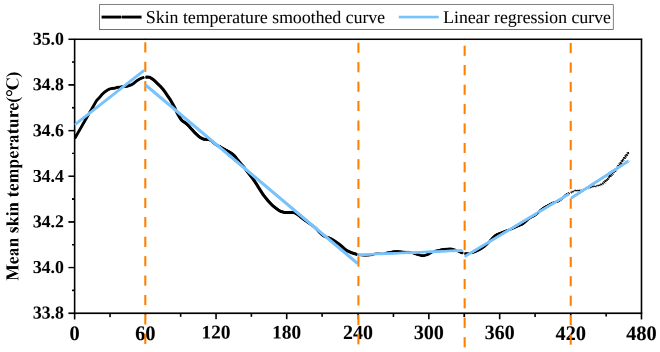
3) From 04:00 to 05:30, the mean skin temperature of the subjects was relatively stable, and the air speed at this stage could also be maintained at a stable and low value. As the human body temperature and metabolic rate decrease during sleep [6], the amount of heat released decreases accordingly. However, the convective effect caused by the surrounding air speed accelerates the evaporation of human sweat and increases the heat release of the human body [50]. Therefore, an appropriate decrease in air speed is an effective way to reduce heat loss and meet the thermal comfort requirements of people. In summary, the air speed at this stage was designed to be less than the maximum air speed but not lower than the comfortable air speed interval corresponding to TSV ∈ (-0.5, 0.5). Therefore, according to Formula 7, the air speed of v= 0.15 m/s when TSV=0.5 was selected as the minimum during sleep.

4) From 05:30 to 07:00, the mean skin temperature of the subjects showed an upward trend; thus, the air speed increased linearly from v= 0.15 m/s to v= 0.47 m/s.

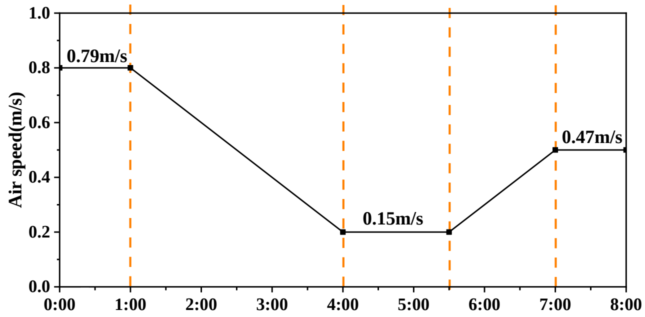
5) From 07:00 to 08:00, the mean skin temperature increased with fluctuation. Similar to the state when falling asleep, the skin temperature near waking up is also mainly influenced by endogenous physiological factors [51], which have little effect on the skin temperature even though changing the thermal environment. Therefore, the air speed value was designed to be stable. As the mean skin temperature was an intermediate value at this stage, the average of the maximum and minimum selected air speed was 0.47 m/s.

Table 5 Linear regression equation of skin temperature at each stage of sleep

Time	0:00-1:00	1:00-4:00	4:00-5:30	5:30-7:00	7:00-8:00
Equation			$y = ax + b$		
Slope	0.0041	-0.0044	0.0002	0.0031	0.0034
Intercept	34.625	35.062	34.004	33.025	32.897
R^2	0.862	0.984	0.421	0.995	0.878
P-value			<0.01		



(a) The circadian rhythm



(b) Optimisation blowing strategy

Fig. 10. Design diagram of optimisation blowing strategy

Pulse width modulation (PWM) control was applied to realise the dynamic air supply of the fan. According to the previous fan speed measurement, the air speed feedback value can be obtained at different gears, which corresponded to different duty ratios in the PWM control. Therefore, according to the air speed variable curve proposed in the optimisation control strategy, corresponding to the PWM-air speed table, the change in the air speed can be realised by adjusting the pulse width. Finally, the dynamic air supply operation of the fan can be completed by driving the motor. Fig. 11 shows the schematic diagram of the fan speed modification.

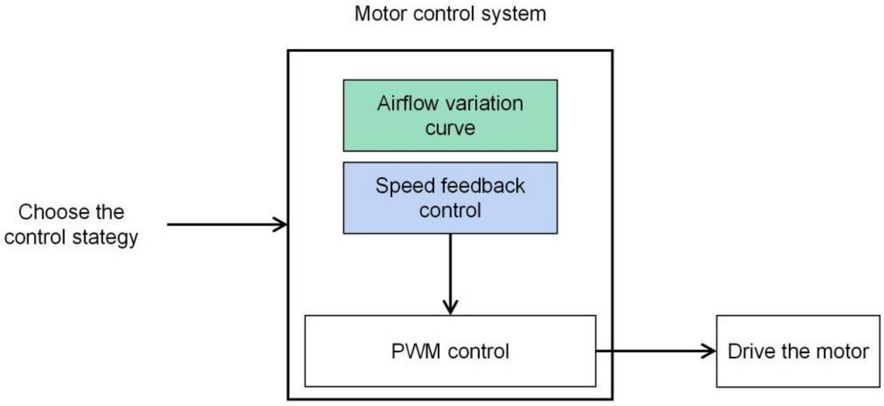


Fig. 11. schematic diagram of the fan speed modification

4.2 Optimisation strategy verification

The subjective evaluation of sleep quality revealed a significant difference between 2 blowing strategies (Fig. 12). Four indexes, ease of falling asleep, ease of awaking, calmness of sleep and satisfaction with sleep, all showed that at 30 °C /50% RH, the subjective evaluation of subjects under the optimisation strategy blowing was higher than that under steady-state blowing. Among 4 indexes, ease of falling asleep, calmness of sleep and satisfaction with sleep significantly improved ($p<0.05$), which partly verified the effectiveness of the optimisation strategy.

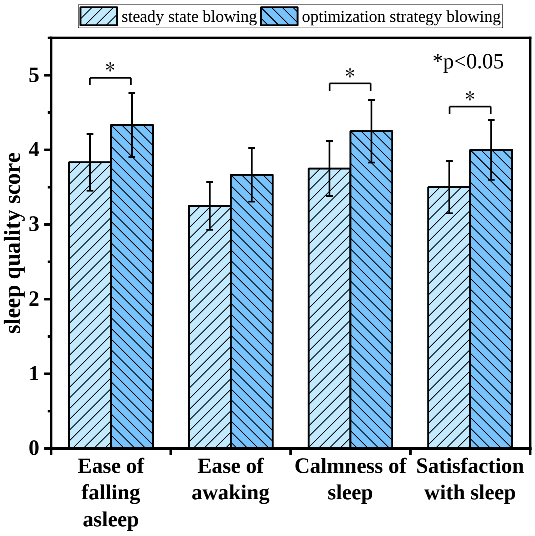


Fig. 12. Subjective evaluation of sleep quality under 2 blowing strategies in the verification experiment

Fig. 13 shows the comparison of the skin temperature between 2 blowing strategies. The values were very close at the initial stage and the last stage. However, during the middle sleep stage of 1:00–6:30, the skin temperature of the subjects under optimisation strategy blowing was significantly higher than that under the steady-state blowing ($p<0.001$), which corresponded to the decrease in air speed at this stage. Because a mild increase in skin temperature indicates that the neurons in the brain area move towards a more sleep-like firing pattern [33], the sleep quality of the subjects improved under optimisation strategy blowing. Due to the small thermal resistance of summer clothing and mattresses, the human skin is directly exposed to the outside environment. The skin temperature, which determines people's heat exchange and thermal comfort, will change more sensitively with the change in the environment. Therefore, changes in skin temperature can better reflect whether the optimisation blowing strategy is effective.

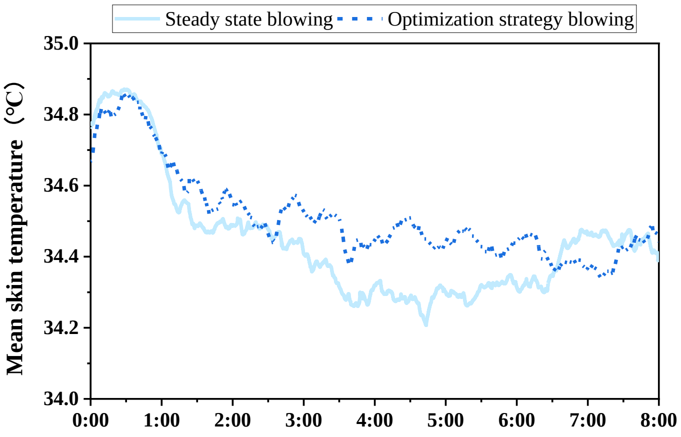


Fig. 13. Skin temperature of the subjects under 2 blowing strategies in the verification experiment

The physiological indexes in Table 6 also show that optimisation strategy blowing significantly improved the sleep quality of the subjects, which was consistent with the questionnaire feedback. The subjects took a longer time to fall asleep under steady-state blowing. Between 2 blowing strategies, there was a significant difference in sleep efficiency and the proportion of N3 ($p<0.01$); the sleep efficiency of subjects under optimisation strategy blowing was significantly increased by 3.24%, and the proportion of N3 was significantly increased by 3.59%.

Table 6 Bracelet data and sleep quality of subjects under 2 blowing strategies in the verification experiment

	Steady-state blowing	**Optimisation strategy blowing**
Sleep duration		
Wake after sleep onset (WASO)	815	627
Rapid Eye Movement (REM)	1001	1061
Light sleep (N1+N2)	2917	2800
Deep sleep (N3)	960	1171
Actual sleep time	4878	5032
Total sleep time (TST)	5693	5659
Sleep quality evaluation index		
Sleep efficiency (SE)	85.68%	88.92%**
sleep onset latency (SOL)	11.58	9.17
Proportion of REM	20.52%	21.09%
Proportion of N3	19.68%	23.27%**

** indicates $p<0.01$ tested by analysis of variance

5. Discussion

Our study demonstrated that the local airflow of fans could compensate for the discomfort caused by temperature and humidity in a hot environment, as shown in Fig. 6. Under the operating condition of 30 °C /50% RH, when the fan turned from the no-wind state into the first speed, the TSV of the subjects dropped from 0.75 to 0.08 (Fig.6(a)), which satisfied the thermal comfort range proposed by Fanger [52]. ASHRAE Standard 55–2017 [17] regulates an extension of the summer comfort zone by increasing air speed to 0.80 m/s (without occupant control) when operating temperature up to 30.3 °C, which is similar to the regulations in Chinese standard GB/T50785-2012 [53]. EN 15251 [54] specifies that the air speed can be increased to 0.80 m/s, which would compensate for an operative temperature increase by 2.8 °C above comfort temperature at still air. These standards extend the acceptable range of air speed, allowing increased airflow to compensate for temperature increases at the boundary of the comfort zone. Chen [20] carried out a blowing experiment on the human body in the recycling state and found that under the environmental condition of 27-30 °C and 40%-80% RH, the thermoneutral air speed interval was 0.25-1.17 m/s. This is slightly narrower than the comfortable air speed interval of this study (0.16-1.31 m/s), which may be due to the difference in bedding thermal resistance and the thermal history of subjects in the different places. Although the increase of air speed has a certain improvement effect on the thermal sensation in a hot environment, it is only applicable to a specific environment. This study found that at 32 °C/80% RH, the fan alone could not satisfy the thermal comfort of subjects. The cooling effect of airflow is affected by temperature. An increase in the air speed in an environment ≤ 32 °C can improve the TSV, while it failed in a hot environment at 34 °C [56].

This study reflected the subjects' thermal comfort and sleep quality from both subjective questionnaires and objective physiological parameters measurements. Through spectrum analysis of EEG in the during-sleep experiment, the relative EEG power of each frequency band of the subjects under 4 operating conditions was obtained (Fig. 14). The power of the δ band far exceeded the other three bands. Studies [57, 58] have shown that the δ band is related to slow-wave sleep and the β band is often related to agitated, nervous, and activated neurons. Therefore, a higher δ-band and lower β-band indicate a deeper and calmer sleep. Among 4 operating conditions, the relative power of the δ band was higher, and the β band power was lower at 30 °C /50% RH, indicating that the subjects' sleep quality under this condition was better. Moreover, EEG measurements can indirectly reflect the impact of the thermal environment on sleep [58, 59]. In this study, as subjects had the best sleep quality at 30 °C /50% RH, this can partly explain the thermal comfort of the subjects was better under this condition.

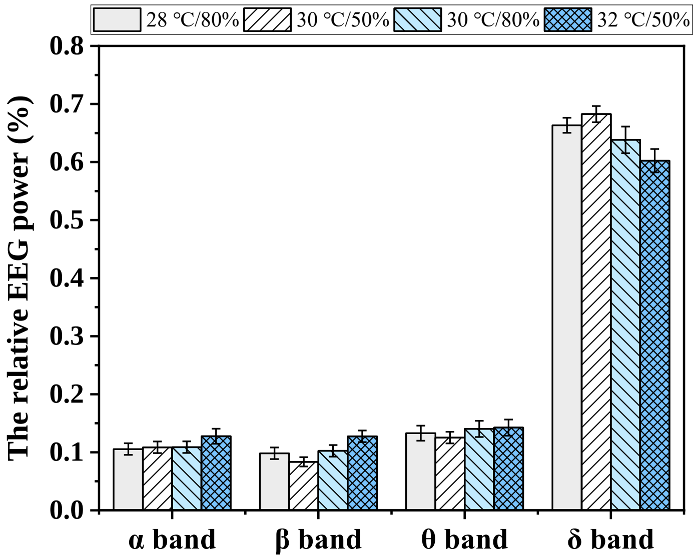


Fig. 14. The relative EEG power of each frequency band under different operating conditions in the during-sleep experiment

This study divided sleep stages mainly based on the trend of skin temperature. Many studies on thermal comfort in the sleep state have measured skin temperature, of which the trend is similar to our finding [5, 6, 10, 18, 49, 58, 60, 61], especially during the first 4 hours of 8-hour sleep. After the lights were turned off, the skin temperature rose rapidly and reached a peak value within 1 h due to the increase in skin blood flow [8]. Subsequently, skin temperature began to drop and reached the minimum value in the sleep state due to reduced metabolism and skin blood flow [10, 58, 60, 61]. Lan et al. also found that skin temperature value was lowest near the midpoint of sleep time [61]. In the last 4 hours of 8-hour sleep, our study's skin temperature trend closely resembled Tsuzuki's study [60], which also showed that after the skin temperature dropped to the lowest point, it remained at the lowest value for nearly 2 h and then rose. Most studies also found that the skin temperature would rise in the last 4 hours [50, 58] due to hypothalamic secretin promoting thermogenesis before awakening [62, 63]. However, some studies did not find an evident change trend but only fluctuating [6, 10], which may be attributed to the inconsistencies such as the operating conditions, the accuracy of the measuring instruments, and the subjects themselves. Overall, the trend of skin temperature is similar in most studies, which justifies it as a general rule. Therefore, it is reasonable to divide the sleep stages over the whole night and design the control strategy based on the skin temperature. Furthermore, the human skin temperature is also an effective physiological indicator that reflects the thermal comfort of an individual in the sleep environment [59]. As skin temperature is positively correlated with thermal sensation [6, 47, 48, 59], a decrease in the skin temperature from 1:00 to 4:00 represents a decrease in the thermal sensation of the subjects (Fig. 9). Therefore, at that time, the fan speed slowed down in the optimisation control strategy to reduce the cold feeling of the subjects brought by the blowing.

In the generalisation of the optimisation control strategy, researchers should note that this control strategy is primarily applicable to young and middle-aged people. This optimisation control strategy can still be used as a reference when applied to the elderly or people whose sleep time is not from 0.00 to 8.00. Because the different stages of sleep activity are causally associated with heat redistribution in the periphery of the body [64], the variation trend in skin temperature for sleeping people is a general rule, and the trend in the optimisation control strategy is essentially the same, the findings of this study can be applied directly. Researchers only need to re-test the comfortable airspeed intervals before sleep for different populations and appropriately modify the air speed for each stage. We are also collecting the sleep time preferences of different people and their feedback on the comfortable air speed to refine the control strategy for further comparative studies.

There are some limitations in this study. Only one type of optimisation strategy was explored, whereas other control strategies, such as sinusoidal and natural airflow, have also been proven to be effective [65, 66]. In analysing EEG spectral power, there are inherent limitations, such as noise in EEG signals, which is more difficult to recognise in the power spectrum than in the raw signal [41]. In addition to skin temperature, biomarkers such as melatonin and plasma cortisol have also been proven to assess circadian rhythm overnight [45]. In the future, these biomarkers could be used to quantitatively design the air speed to modify the fan control strategy.

6. Conclusions

This study proposed a dynamic air supply control strategy for fans that imitated the circadian rhythm of sleep. The main findings of this study are as follows.

1. Under the environmental conditions of 28 °C /80% RH, 30 °C /50% RH, 30 °C /80% RH, and 32 °C /50% RH, fan blowing made the thermal sensation of the subjects closer to the thermal neutral state. With fans used throughout the night, better sleep quality was experienced at 30 °C /50% RH, and its corresponding comfortable air speed interval was (0.15,1.44) m/s.

2. According to the different physiological characteristics of each stage of sleep, the air speed should change dynamically. A dynamic air supply control strategy for fans was proposed based on the physiological characteristics of humans during sleep. The trend of the fan control strategy can be summarised as stabilising, then falling, stabilising, rising again, and finally stabilising. It has been verified that this optimisation control strategy can improve sleep quality. Compared with steady-state

blowing, the sleep efficiency and the proportion of deep sleep significantly increased by 3.24% and 3.59%, respectively, under this dynamic air supply control strategy.

The effect of a fan with a sinusoidal airflow on the improvement of sleep quality can be studied in the future. The quantitative design of the air speed from other objective physiological parameters reflecting the circadian rhythm would help to establish a more accurate fan control strategy mode.

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