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Sex-based thermal comfort zones and energy savings in spaces with joint operation of air conditioner and fan

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ABSTRACT

Fan and air conditioner combined systems (FACS) have been demonstrated as a viable alternative to conventional air conditioning systems, providing thermal comfort to occupants while consuming less energy. However, few studies have quantitatively established occupant comfort zones for FACS operation and analyzed its energy saving effects. An experiment was conducted first to develop thermal comfort zone in spaces with FACS operation. As the indoor temperature rises, the upper limit of air speed accepted by occupants increases. Females exhibit an upper comfort range parameter of 29.8 °C and 1.4 m/s, while males demonstrate 29.3 °C and 1.5 m/s. There are noticeable differences in comfort ranges between males and females, especially in cooler conditions. Based on the established comfort zone, energy simulation studies were conducted for most regions of China to investigate the potential energy savings resulting from the implementation of FACS in ASHRAE standard office building. Buildings incorporating FACS demonstrate a reduction in HVAC system energy consumption by more than 16 % when compared to indoor temperature set at 26 °C. In hot summer and warm winter climates, HVAC system energy savings of over 100 GJ/year can be achieved using FACS for the standard building. Considering sex differences in FACS operation leads to additional energy savings.

1. Introduction

In buildings, heating, ventilation, and air conditioning (HVAC) systems account for 40–50 % of energy consumption [1]. However, a study assessing occupant thermal comfort in buildings revealed that only 11 % of the surveyed buildings were able to meet the ASHRAE-55 standard to the satisfaction of at least 80 % of users [2]. The inadequate satisfaction of occupants with regards to thermal comfort can be attributed to the one-size-fits-all control approach of HVAC systems, which fails to consider individual differences, such as sex [3]. Considering the close relationship between thermal comfort and building energy consumption, it becomes imperative to explore energy-saving methods while ensuring the maintenance of thermal comfort for building occupants.

In contrast to adjusting the entire space and creating a uniform indoor environment using only common split-type air conditioners or central air conditioning (Scenario 1 in Fig. 1), the Fan and Air Conditioning Combined System (FACS) creates a non-uniform thermal environment by simultaneously operating air conditioning and fans. Because fans can be placed in areas where people are active or working, it allows the created airflow temperature to be close to the indoor air temperature (Scenarios 2–4 in Fig. 1). In comparison to increasing the air conditioning supply air speed, this approach avoids sending low-temperature airflow into the occupied zone while increasing the air speed to compensate for the cooling effect, further allowing a higher setpoint for the air conditioning. This localized system has been proven effective in enhancing the thermal comfort of occupants, as supported by established studies (refer to Table 1). The range of comfortable operating temperatures and mean air speeds is specified in the standard ASHRAE-55 [4]. However, it is important to note that this range is determined based on standard effective temperature (SET) calculations. In the building environment where FACS is implemented, the higher convective heat transfer often leads to differences in human skin heat dissipation and skin wetness compared to the standard environment. Consequently, there could potentially be inaccuracies in calculating the SET for this specific type of environment. Moreover, the standard ASHRAE-55 does not provide an upper limit for air speed in terms of comfort [5]. Existing studies have identified discrepancies when using this range to assess the comfort of FACS-operated environments [6–8]. Many of these studies discovered that the acceptable range for fixed air speed extends to 1.2–1.5 m/s when the indoor air temperature exceeds

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27 °C. Therefore, it may be necessary to reconsider the comfort ranges for occupants under FACS operation.

Several studies conducted in traditional uniform indoor environments have consistently shown that females exhibit higher sensitivity to changes in ambient temperature, often experiencing discomfort in colder environments compared to males [13–16]. Zhang et al. [17] used c corrective power (CP) to evaluate the efficacy of local air jets and observed a potential influence of sex on CP. In environments where FACS is applied, only a limited number of studies have investigated the potential sex differences in thermal comfort. Verhaart et al. [18] reported that males exhibited a preference for higher air speeds compared to females when utilizing fans for local cooling in an environment with a temperature of 27.5 °C (slightly warmer). In a study by Zhai et al. [19], it was found that females preferred lower air speeds than males in environments with temperatures of 28 °C compared to 30 °C ($p < 0.01$). Given the practical applications, the majority of current studies in this field primarily concentrate on examining the viability of FACS in both neutral and high-temperature environments (refer to Table 1). Although these studies demonstrate the potential of FACS for practical use, they may not offer a comprehensive understanding of the comfort range in different sexes during FACS operation. In the practical application of FACS, the potential difference between sexes can lead to the risk of thermal discomfort among individuals sharing the same environment. By identifying the thresholds of environmental parameters that cause hot and cold discomfort for each sex, it becomes possible to avoid inadequate system settings in practical scenarios. Therefore, considering sex differences may enhance the comprehensiveness of established comfort ranges when exploring the parameter ranges for creating a comfortable environment in FACS operations.

The application of FACS can lead to indoor air temperatures that exceed the recommended range set by current standards, resulting in energy savings. A cross-sectional comparative study on energy consumption for creating non-uniform environments highlighted that the utilization of fans for cooling purposes tends to be more energy-efficient [20]. Atthajariyakul and Lertsatittanakorn [21] demonstrated that implementing FACS can lead to a significant reduction of 1959.51 GWh/year in electricity consumption within commercial buildings in Thailand. Additionally, a field study carried out in the USA [9] estimated an annual electricity saving of 44 kWh/m^2 by raising the air conditioning set point temperature from 23 °C without fans to 26 °C with fans. However, discussions regarding the impact of FACS on building energy savings primarily focus on experimental conditions and do not thoroughly explore the energy savings within specific quantitative comfort ranges. This limitation potentially underestimates the achievable energy savings through FACS implementation in HVAC systems within buildings. Conversely, energy-saving systems that operate outside of user comfort ranges may not be practically viable. Overall, existing studies largely support the utilization of FACS to enhance occupant satisfaction and realize potential energy savings. Nevertheless, further supplementation is necessary to comprehensively analyze the combined effects of FACS operation on both occupant comfort and energy savings.

This study conducted subject experiments in indoor environments created using the FACS, which had different indoor air temperatures and air speeds. Additionally, EnergyPlus software was employed for building energy simulations based on the ASHRAE 90.1 standard building model. The study focus is illustrated in Fig. 2, with the aim of addressing the following questions: 1. What is the quantitative comfort environmental parameter range for FACS operation? 2. Does the comfort environmental parameter range for FACS operation show sex differences? 3. Based on comfort operation parameters, what is the energy-saving potential of operating this system in representative cities in different climate regions of China?

2. Methodology

2.1. Subjects experiment

Subject experiments were conducted at Shanghai Jiao Tong University during the summertime of 2022 to investigate the comfort zone for localized air distribution with fan in air-conditioned spaces. The artificial climate chamber is shown in Fig. 3. The indoor air temperature range considered to be neutral typically falls between 24 and 28 °C [31]. To obtain a wide range of thermal sensation votes, the air-conditioned room temperatures were set at 23 °C, 26 °C, 29 °C, and 32 °C. Localized air distribution achieved by placing a fan in front of the subject. By changing the distance from the subject and the power of the fan, mean air speeds of 0 m/s, 0.4 m/s, 0.8 m/s, 1.6 m/s, and 2.4 m/s can be provided to the subject area. According to ASHRAE 55–2020 and existing research, the acceptable maximum air speed increases with the rise in temperature [4,6,29]. Therefore, in high-temperature environments, lower air speeds may not effectively improve occupants' thermal sensation. Similarly, in low-temperature environments, too high air speed settings may lead to unbearable discomfort. Since this study aims to explore the range of comfortable environmental parameters for indoor environments under the operation of FACS, applying the same range of air speeds to different indoor air temperatures may not accurately determine the comfortable air speed threshold for each temperature range. Therefore, this study specifically determined three levels of air speed were specifically determined for each air temperature, with the upper limit of the designed air speed increasing as the air temperature rises. The RH is controlled between 50 and 60 %, which is considered the moderate indoor RH range for summer season [32,33]. Calculations using the CBE Thermal Comfort Tool indicate that the fluctuation of RH within this range causes a variation in thermal sensation of less than 0.2 units [34]. Therefore, it is considered that the fluctuation of RH in the experiment has a minimal impact on the experimental results. Table 2 presents the designed experimental conditions, along with the corresponding actual environmental parameters. The air temperature in the experimental environment is assumed to be equal to the operating temperature, considering that the black globe temperature closely approximates the air temperature. A random number generator was

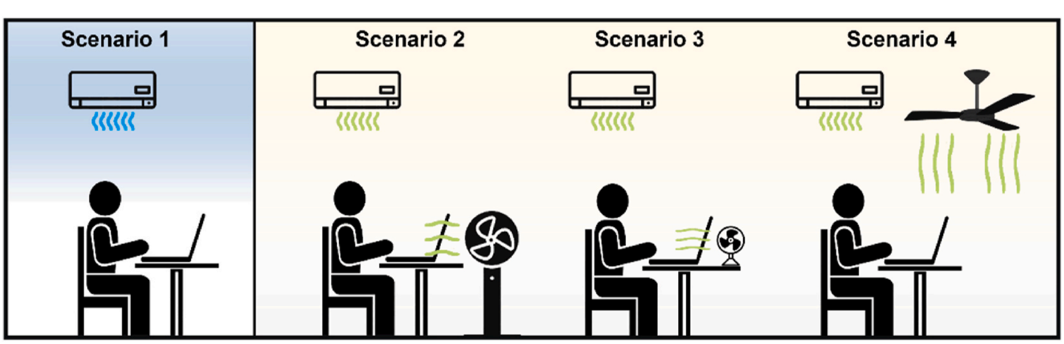

Fig. 1. Schematic diagram of FACS system operation.

employed to generate a randomized sequence for the experimental conditions [35]. The environmental parameters monitoring points were positioned 1.2 m above the ground. The instruments used for measurement are presented in Table 3. The ceiling-installed air conditioning system employed a low-speed air supply, and the angle of air supply was strategically adjusted to prevent direct airflow into the subject's area.

The subject sample size was determined using G*power software, based on the following parameters: statistical test (ANOVA), effect size (0.25), α error (0.05), 1-β (0.8), and number of groups (2) [36]. The calculated minimum sample size was 24; however, a sample size of 27 was ultimately chosen. All subjects were students and teachers from Shanghai Jiao Tong University (refer to Table 4). The female subjects' clothing thermal insulation is approximately 0.51 clo, while that of male's is about 0.45 clo. Details of clothing can be found in supplementary materials S1. Each subject was required to participate in all experimental conditions listed in Table 2, with a minimum rest period of 24 h between each condition. Prior to the experiment, subjects were instructed to refrain from consuming caffeine, alcohol, and engaging in intense physical activity. The study protocol was approved by the Science and Technology Ethics Committee of the university, and verbal and written informed consent were obtained from each subject before their participation in the experiments.

Each experimental condition lasted for 90 min, comprising a 30-min pre-experimental adaptation followed by a 60-min formal experimental period, see Fig. 4a. The experiment was conducted with four subjects participating simultaneously. During the adaptation period, subjects were provided a resting period in chamber A, maintained at an indoor temperature of 26 °C and an air speed of less than 0.1 m/s, to ensure the elimination of any prior thermal experiences. Following the adaptation, the subjects moved to chamber B for the formal experiment. At the 30th and 60th minute, the subjects were required to complete a questionnaire, as depicted in Fig. 4b. Throughout the experiment, subjects were allowed to engage in activities such as typing and using their mobile phones, which maintained an approximate metabolic rate of 1.1 MET.

2.2. Draft acceptance rate (DAR)

Draft sensation is defined as "the perceived flow of air or movement caused by air currents in an indoor environment" [4]. When subjects have a "noticeable" or "strong" draft sensation and there is a demand for "lower air speed," it is considered that the subjects cannot accept the air speed in the current environment. The draft acceptance rate (DAR) is defined as the ratio of the number of people who can accept the air speed in the environment to the total number of people, and it is calculated using Equation (1).

$$DAR = \frac{N_{Acceptable}}{N_{Total}} \times 100\% \tag{1}$$

2.3. Energy simulation model for practical application

The EnergyPlus models for various building types have been made available by the U.S. Department of Energy to facilitate standardized benchmarking studies focused on energy simulation [37]. In this study, the ASHRAE-90.1 standard model for a medium-sized office building was employed to assess the electricity consumption of the FACS operation. The building model consists of three floors, encompassing a total area of 4982 m^2 and accommodating a population of 268 individuals. Additional information can be found in the ASHRAE-90.1 [37]. Default settings were maintained for the HVAC system operation schedule, occupants' attendance schedule, and lighting operation schedule. It was assumed that each occupant's workstation was equipped with a fan, resulting in a total of 268 fans, with their operating time aligned with that of the HVAC system. The power consumption of fans operating at various speeds was determined based on Zhai et al. [19]. The hourly air conditioning set point and fan speed were kept constant.

To comprehensively assess the energy-saving potential of the system across various regions, the simulation study was conducted for the provincial capitals of all 23 Chinese provinces. All selected regions have summer cooling demands (see supplementary materials S2 for details). The cooling season periods for various regions were determined according to Huo [38], while the thermal resistance of the envelope was determined in accordance with Chinese national standards [39–41]. The electricity consumption during the cooling season for a standard building in various regions using this system can be determined through Equation (2). The weather files corresponding to each region were obtained from the EnergyPlus weather file library.

$$E_{FACS,i} = E_{ac,i} + E_{fan,i} \tag{2}$$

where $E_{FACS,i}$ is the cooling season electricity consumption (GJ/year) of FACS when the standard building is in region i; $E_{ac,i}$ is the air conditioning system operating electricity consumption (GJ/year); $E_{fan,i}$ is the fan operating electricity consumption (GJ/year).

2.4. Data processing

Using one-way repeated measures analysis of variance, the differences in thermal sensation and draft sensation among participants under the same temperature conditions but different air speeds were analyzed. Post-hoc tests were conducted using paired sample t-tests when the variances between different groups were equal, and Tamhane's post-hoc

Table 1
Existing studies on FACS.

Ref.	Sample size	V_{air} (m/s)	V_{air} fixed?	T_{air} (°C)	Relative humidity (RH) (%)	Findings/Conclusions
[5]	10 males 10 females	0.1, 0.6, 1.2	fixed	28–30	50	The increase in air speed from 0.6 m/s to 1.2 m/s resulted in a corresponding increase of 2 °C in the limit value of acceptable operating temperature.
[6]	18 males 18 females	0.2–2.5	not fixed	26, 29, 32	40-60; 70-90	The preferred air speed at high humidity was approximately 0.15–0.3 m/s higher than that at moderate humidity. With the preferred air speed, the upper acceptable temperature could be increased by 1 °C.
[8]	15 males 15 females	0.6, 1.0, 1.5, 2.0	fixed	28, 30, 32, 34	40–50	The minimum air speed necessary for temperatures of 28 °C, 30 °C, and 32 °C are 0 m/s, 1 m/s, and 2 m/s, respectively.
[9]	11 males 3 females	0.2,0.6	fixed	23, 26, 27	50–60	The thermal comfort experienced in a room with a controlled fan at 26 °C is significantly better than that in a room set at 23 °C.
[10]	13 males 13 females	0.07–1.87 (1.1 m height)	fixed	24, 27, 30	60	In situations where there is a considerable initial metabolic rate at 30 °C, enhancing the air speed from 0.07 to 1.87 m/s has shown to improve thermal comfort.
[11]	62 males 57 females	0.33–1.04	not fixed	25–30	50	It is possible to maintain comfortable conditions up to 31 °C (1.0 met) and 29 °C (1.2 met) with an air speed of 1 m/s or higher. A broader comfort range is achieved with user-controllable fan speed.
[12]	8 males 8 females	0.4–1.7	not fixed	26, 30	60, 80	In an environment where users can control the air speed, the 80 % acceptable limit implicit in comfort standards could be extended to 30 °C and 60 % RH.

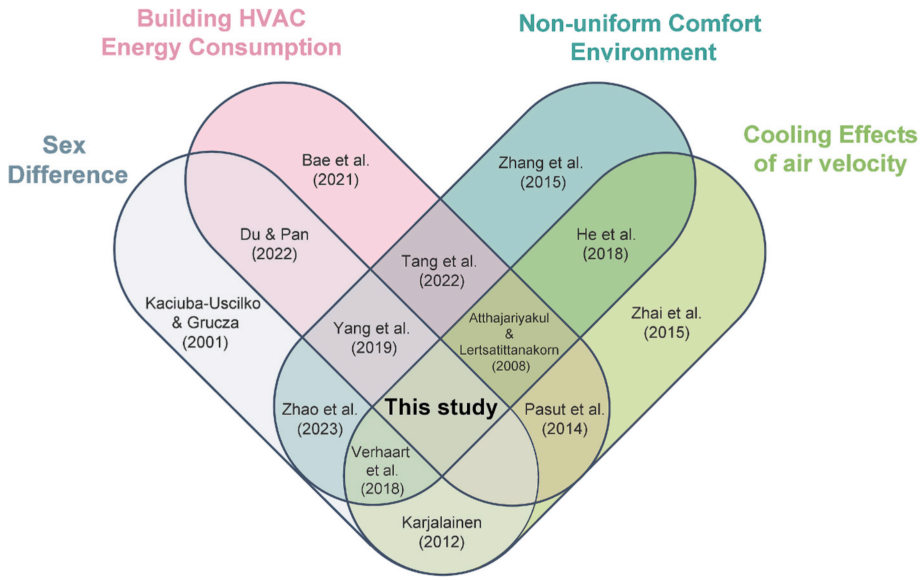

Fig. 2. Relationship between existing studies [17,18,20–30] and this study.

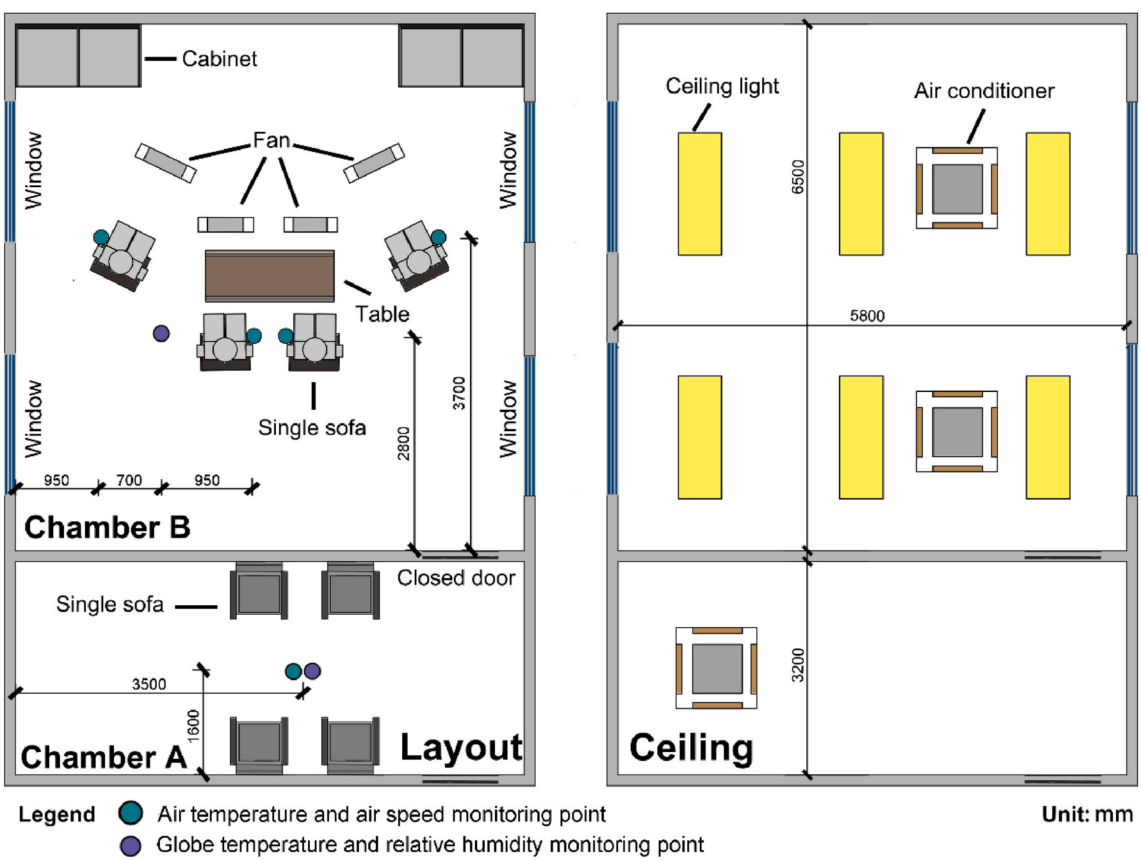

Fig. 3. The layout of climate chamber.

test was applied when the variances were unequal. To avoid reporting trivial and insignificant differences, Cohen's d was calculated for samples showing significant differences. Cohen's d values of 0.2–0.5 were considered small effect sizes, 0.5–0.8 were considered moderate effect sizes, and values greater than 0.8 were considered large effect sizes [42]. Spearman's correlation analysis was used to examine the relationship between the data variables. A Spearman's correlation coefficient greater than 0.6 indicated a strong correlation, while values between 0.4 and 0.6 indicated a moderate correlation, and values between 0.2 and 0.4 indicated a weak correlation [43]. Chi-square test was employed to test the differences between sample rates and between two categorical variables. A larger chi-square value indicated a greater difference between the variables [44]. Nonlinear regression was conducted using the Levenberg-Marquardt algorithm and global optimization algorithm [45]. Two-tailed statistical significance tests were performed. The symbol "*" indicates significant difference ($P < 0.05$), while "**"

Table 2
Experimental designed and measured parameters.

T_{air} (°C) Designed value (Measured value)	V_{air} (m/s) Designed value (Measured value)	RH (%) Measured value	Black globe temperature (°C) Measured value
23 (23.2 ± 0.3)	0.4 (0.37 ± 0.09)	56 ± 2	23.7 ± 0.3
23 (22.7 ± 0.2)	0.8 (0.75 ± 0.06)	50 ± 3	22.8 ± 0.2
23 (22.8 ± 0.2)	<0.1 (0.09 ± 0.03)	55 ± 3	23.1 ± 0.4
26 (26.1 ± 0.3)	<0.1 (0.07 ± 0.06)	60 ± 1	26.4 ± 0.2
26 (25.7 ± 0.2)	0.8 (0.78 ± 0.06)	58 ± 2	25.8 ± 0.3
26 (25.9 ± 0.2)	1.6 (1.59 ± 0.05)	64 ± 3	26.2 ± 0.3
29 (29.3 ± 0.3)	<0.1 (0.07 ± 0.04)	63 ± 2	29.5 ± 0.3
29 (28.7 ± 0.4)	0.8 (0.79 ± 0.09)	61 ± 3	29.4 ± 0.4
29 (28.9 ± 0.2)	1.6 (1.56 ± 0.04)	60 ± 1	29.0 ± 0.4
32 (32.3 ± 0.2)	<0.1 (0.06 ± 0.04)	64 ± 2	32.6 ± 0.3
32 (31.9 ± 0.3)	1.6 (1.59 ± 0.10)	65 ± 1	32.8 ± 0.3
32 (31.8 ± 0.2)	2.4 (2.35 ± 0.10)	63 ± 1	32.5 ± 0.2

Table 3
Environment parameters measuring instruments.

Parameters	Instrument	Measurement accuracy
Indoor air temperature	Swema 03+	±0.2 °C between 10 and 40 °C
Indoor air speed	Swema 03+	±0.03 m/s between 0.05 and 1.00 m/s ±3 % of reading between 1.00 and 3.00 m/s
Globe temperature	Swema 05	±0.1 °C between 0 and 50 °C
Relative humidity	TR-76Ui	±2.5%RH (at 25 °C, between 10 % and 85%RH) ±4.0%RH (at 25 °C, between 0 and 10% or between 85 % and 99%RH)

Table 4
Subjects information.

	Number	Age	Height (mm)	Weight (kg)
Male	13	23.1 ± 4.3	175.8 ± 5.4	68.9 ± 7.8
Female	14	24.4 ± 4.9	164.9 ± 6.0	54.1 ± 5.3

indicates significant difference ($P < 0.01$).

3. Results

3.1. Thermal sensation model

The thermal sensation of subjects in different experimental environments is shown in Fig. 5. For males, increasing the air speed to 0.4 m/s significantly reduces thermal sensation compared to the still air environment at 23 °C ($P < 0.01$, $d = 0.78$). In the 26 °C environment, there are significant differences in thermal sensation among the three air speed levels. At environmental temperature of 29 °C, air speed of 1.6 m/s is required to significantly improve thermal sensation. At 32 °C, air speed of 1.6 m/s effectively reduces male thermal sensation, and further increasing the air speed does not have a significant improvement effect. For females, exposure to air speed of 0.8 m/s significantly reduces thermal sensation compared to being in a still air environment at 23 °C ($P < 0.01$, $d = 0.93$). In the 29 °C and 32 °C environments, air speeds of 1.6 m/s and 2.4 m/s, respectively, are required to improve female thermal sensation. Significant sex differences in thermal sensation were observed in certain conditions. At indoor air temperature of 23 °C and air speed of 0.8 m/s, the thermal sensation experienced by males was significantly higher compared to females in the 26 °C environment, significant sex differences in thermal sensation were observed for all three air speed levels.

The regression relationship between air temperature, air speed, and thermal sensation is established as shown in Table 5. Fig. 6 presents a contour map of thermal sensation under the interaction of air temperature and air speed. The contour lines indicate thermal sensation values, with a difference of 0.5 thermal sensation units between adjacent lines. The spacing between contour lines reflects the sensitivity of thermal sensation changes. It was observed that males are less sensitive to thermal sensation changes compared to females under different environmental conditions. Additionally, females experience lower thermal sensation at lower air temperatures, while the difference in thermal sensation between males and females is smaller in higher temperature environments.

3.2. Draft sensation acceptance rate model

Fig. 7 illustrates the draft sensation experienced by participants under different conditions. As the air temperature decreases at the same air speed, occupants perceive a stronger draft sensation. In environments with air speeds of 1.6 m/s and 2.4 m/s, over 70 % of the occupants reported a "noticeable" or "strong" draft sensation. In environments where the temperature was 23 °C and the air speed was 0.8 m/s ($P < 0.05$, $d = 0.48$), 26 °C and 0.8 m/s ($P < 0.05$, $d = 0.48$), and 32 °C and 2.4 m/s ($P < 0.01$, $d = 0.44$), females reported significantly higher draft sensations compared to males. The air speed preference of subject in the environment under various experimental conditions is shown in Table 6. In still air environments at 29 °C and 32 °C, 60.8 % and 84.0 % of the subjects, respectively, expressed a desire for increasing air speed. Conversely, the need to reduce air speed was predominantly observed in conditions involving temperatures of 23 °C with moving air, 26 °C with an air speed of 1.6 m/s, and 32 °C with an air speed of 2.4 m/s. At air speeds of 0.8 m/s and 1.6 m/s, as the environmental temperature decreased, the occupants' demand for reducing air speed increased ($r = 0.383$, $p < 0.01$; $r = 0.457$, $p < 0.01$). Overall, a significant correlation was observed between the voting rate for the sensations of "obvious" and "strong" drafts and the demand for reducing air speed ($r = 0.751$, $p < 0.01$).

The calculated results of draft acceptance rates in different environments are shown in Table 7. In an environment with a temperature of 26 °C and an air speed of 1.6 m/s, the draft acceptance rate of occupants is the lowest. Keeping the air speed constant, as the environmental temperature rises to 29 °C, the draft acceptance rate significantly increases ($\chi 2 = 13.23$, $P < 0.01$). Furthermore, by further increasing the environmental temperature to 32 °C, the draft acceptance rate of females can still be significantly increased ($\chi 2 = 4.46$, $P < 0.05$). However, in an environment of 32 °C, increasing the air speed to 2.4 m/s results in a decrease in draft acceptance rate for both males and females, with females experiencing a more significant decrease ($\chi 2 = 13.80$, $P < 0.01$). In addition, even in an environment of 23 °C with a lower airspeed supplying the air, the draft acceptance rate is only 62.50 %–65.38 %.

The regression relationship between air temperature, air speed, and draft acceptance rate is established, as shown in Table 8. Fig. 8 illustrates the contour plots of draft acceptance rate considering the interaction between air temperature and air speed. The contour lines are labeled with air draft acceptance rate values, with a 10 % difference between adjacent lines. In a low-temperature environment, these contour lines become progressively denser as the air speed increases. For males, these contour lines are sparser in high-temperature environments. This indicates that in environments with lower air temperature, there is a greatly variation in draft acceptance rate when individuals are exposed to different air speeds. Conversely, males exhibit decreased sensitivity to air speed perception in higher-temperature environments.

3.3. Sex-specific comfort zone

The range of comfort parameters when FACS operates is defined by the region enclosed by the contour lines representing a 75 % draft acceptance rate and the thermal sensation scale of '-0.5′ to '+0.5′, as depicted in Fig. 9. For males, the upper limit for comfortable environmental parameters is approximately 29.3 °C and 1.5 m/s (P1 in Fig. 9),

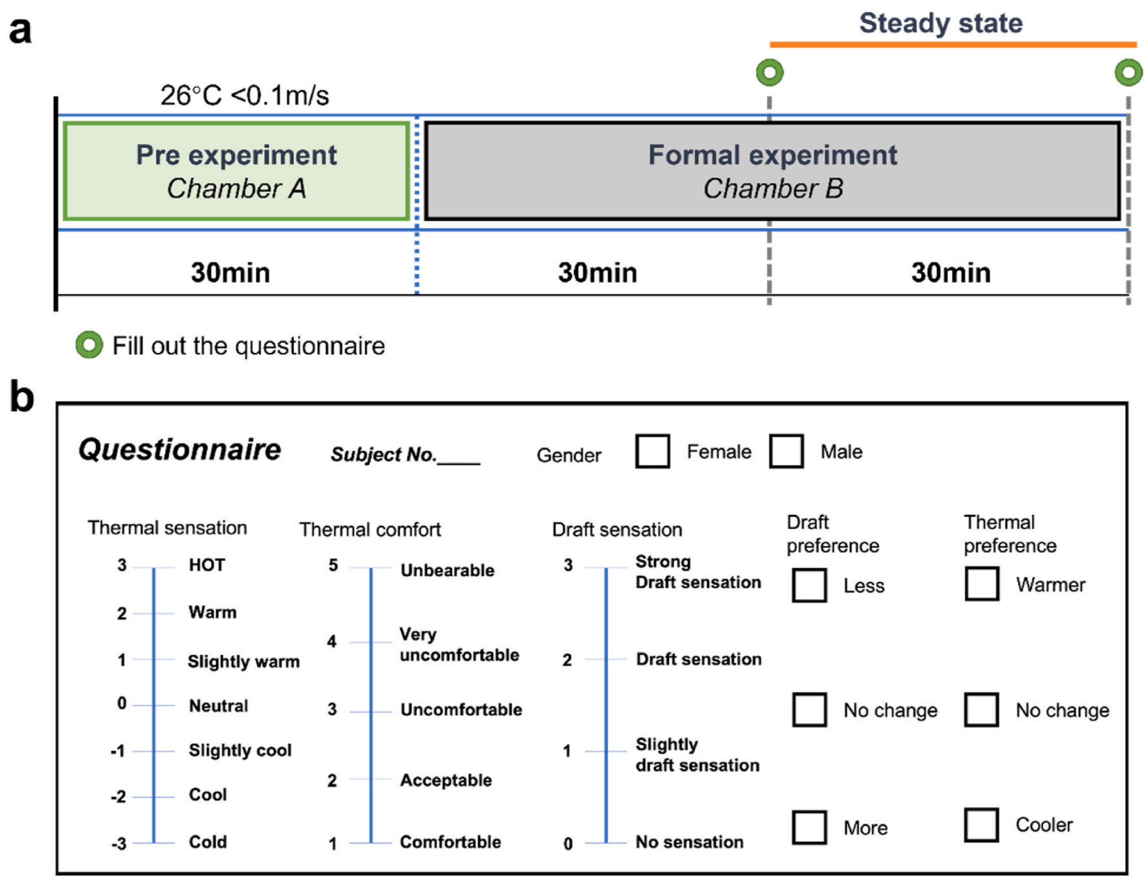

Fig. 4. Experimental procedure and questionnaire information.

while for females, it is 29.8 °C and 1.4 m/s (P2 in Fig. 9). These two parameter points also correspond to the most energy-efficient FACS operation settings for male and female comfort, respectively. It should be noted that in situations where uniform air speed and indoor air temperature are required, setting the indoor air temperature to 29.0 °C and providing an air speed of 1.3 m/s (P3 in Fig. 9) to the both sexes can achieve comfort and simultaneously reduce energy consumption.

The comfort zone established in this study differs to some extent from the comfort range given in ASHRAE-55, especially in the male population, where the differences are more noticeable. In environments below 26 °C, the comfortable range of air speed for males exceeds the ASHRAE-55 standard. In warmer environments, according to the ASHRAE-55 standard, air speed of 1 m/s can increase the indoor air temperature from 27 °C to above 30 °C, resulting in a cooling effect of over 3 °C. However, the findings of this study demonstrate a limited effective range in enhancing human thermal sensation through fan usage. The air speed of 1 m/s achieves a cooling effect of approximately 2 °C. In environments with temperatures exceeding 29 °C, the thermal sensation can be effectively improved only when the air speed exceeds 1.0 m/s. It should be noted that this study found that as the indoor air temperature increases, the highest acceptable air speed also increases. In environments above 26 °C, occupants can maintain a comfortable air speed of 1.3 m/s or higher.

3.4. Simulation of building energy consumption in practical applications

The proposed environmental control strategies were evaluated for energy consumption using the EnergyPlus software. The operating settings for energy consumption comparison and their corresponding explanations can be found in Table 9. Fig. 10 displays the results of assessing the cooling season energy consumption of the standard building across different cities, considering various setting strategies. Using Shanghai City, located in a region with hot summer and cold winter (HSCW), as a case study, when maintaining an indoor environmental temperature of 26 °C solely using air conditioning, the building's HVAC system consumes 265.8 GJ/year. However, implementing a combined system of fan and air conditioning, which results in an additional fan energy consumption, but can effectively reduce air conditioning energy usage. In comparison to air conditioning operation with a setpoint of 26 °C, this system can achieve energy savings of over 16.5 % annually. When providing the same air speed and air temperature for all occupants in the space, as applied in the CSS2 operating setting, the building's HVAC system's electricity consumption is 231.9 GJ. However, when different comfort environmental settings are provided for different sex occupants, the electricity consumption can be further reduced. Under the operating settings of CSS3 (for males) and CSS4 (for females), the annual electricity consumption is 226.8 GJ and 216.6 GJ, respectively.

It should be noted that in regions with hot summer and warm winter (HSWW), the application of this integrated system to meet user comfort requirements can achieve higher energy efficiency. Taking Haikou City as an example, energy savings can reach up to 133.5 GJ/year. However, in severe cold (SC) regions with low cooling demands during the summer, such as Harbin City, while the system can still achieve approximately 20 % energy savings, the overall reduction in energy consumption is comparatively limited.

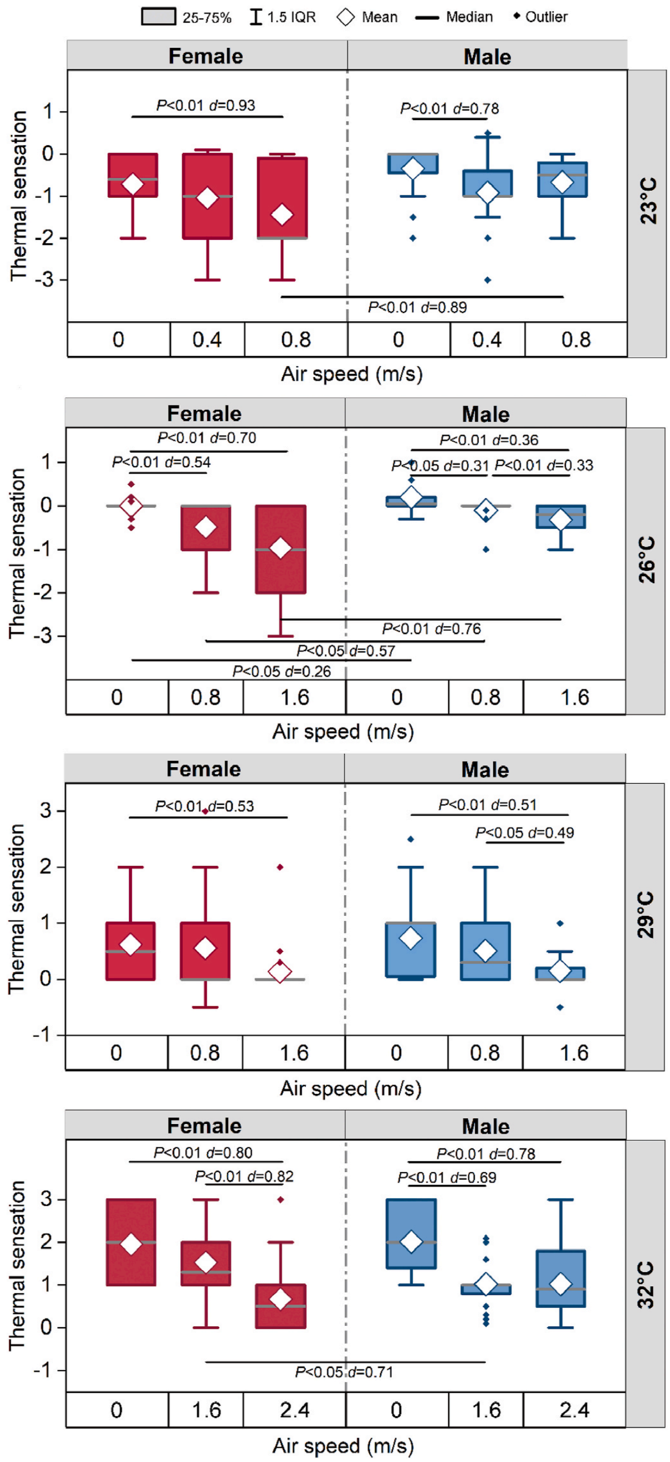

Fig. 5. Thermal sensation in different experiment conditions.

Table 5
Sex-specific regression model of thermal sensation.

Sex	Thermal sensation regression model	R^2
Male	$TSV = 0.247 \times T_{air} - 0.527 \times V_{air} + 0.006 \times T_{air} \times V_{air} - 6.233$	0.80**
Female	$TSV = 0.288 \times T_{air} - 1.7457 \times V_{air} + 0.043 \times T_{air} \times V_{air} - 7.438$	0.83**

4. Discussion

4.1. Difference between thermal comfort zone and true thermal comfort vote

Fig. 11a displays both the actual thermal comfort votes and the proposed comfort zone of this study. The colored contour map represents the actual thermal comfort votes of the subjects, and the closed blue line area represents the environmental parameter comfort range established in this study. The figure demonstrates a strong alignment between the proposed thermal comfort range and the actual thermal comfort votes. Notably, this study employed the 75 % acceptance rate contour as a boundary, which considers the acceptance level of three-quarters of occupants towards air speed. However, Fig. 11a indicates that employing the 75 % acceptance rate contour as the boundary for draft sensation may appear to be overly cautious. This suggests that despite some individuals perceiving obvious draft sensation and expressing a preference for lower air speed, a comprehensive evaluation of indoor air temperature and air speed reveals that they still find the environment comfortable. This observation further suggests that reasonably increases in air speed in real-life environmental conditions may not result in a notable decline in thermal comfort. However, it is important to acknowledge that the participants involved in this study were aged between 20 and 39 years, indicating that the proposed comfort range may be more relevant to this specific age group. In comparison to the old, younger occupants typically possess a higher metabolic rate, produce more heat, and have a thicker layer of subcutaneous fat [46]. This provides some explanation for the higher comfort ratings observed among participants in low-temperature environments (23 °C). The comfort range provided by this study is compared with several existing studies [5–8,11,12,19,27,47], as depicted in Fig. 11b. Overall, the comfort range established is relatively consistent with existing research findings.

4.2. Sex difference

The research conducted by Xiong et al. [48] revealed that the disparity in thermal sensation between sexes is relatively minor under thermal neutral conditions. At a lower temperature environment (22 °C), females experience a cooler sensation compared to males, whereas at higher temperatures (32 °C and 37 °C), females report a warmer sensation than males. These findings align with the observations of the current study. This study revealed that when considering the combined effect of air speed and indoor air temperature, females exhibited a narrower range of environmental parameters for achieving neutral thermal sensation compared to males. Females had a higher neutral environment temperature and were more susceptible to experiencing an unacceptable draft sensation. In a 26 °C environment, it was observed that individuals exposed to air speeds ranging from 0 to 1.6 m/s exhibited significant sex differences in thermal sensation, with the effect size increasing as the air speed increased. This indicates that changes in air speed within a neutral temperature environment can result in varying thermal sensations between males and females. Generally, females have a higher specific surface area compared to males and less adipose tissue around the organs [25]. These factors, combined with the influence of estrogen on blood regulation, contribute to the females dissipating more heat and generating less heat in a cool environment [49]. Consequently, females are more likely to experience uncomfortable cold sensations. In a high-temperature environment, compared to males, females have a higher thermal insulation for the upper body's underwear and the overall clothing, leading to the need for higher airflow speed for better heat dissipation. Zhai et al. [19] conducted an analysis of sex differences in an environment where fans and air conditioning were operated simultaneously. Their findings indicated that females generally exhibit a preference for significantly lower air speeds compared to males ($p < 0.01$). However, the study did not

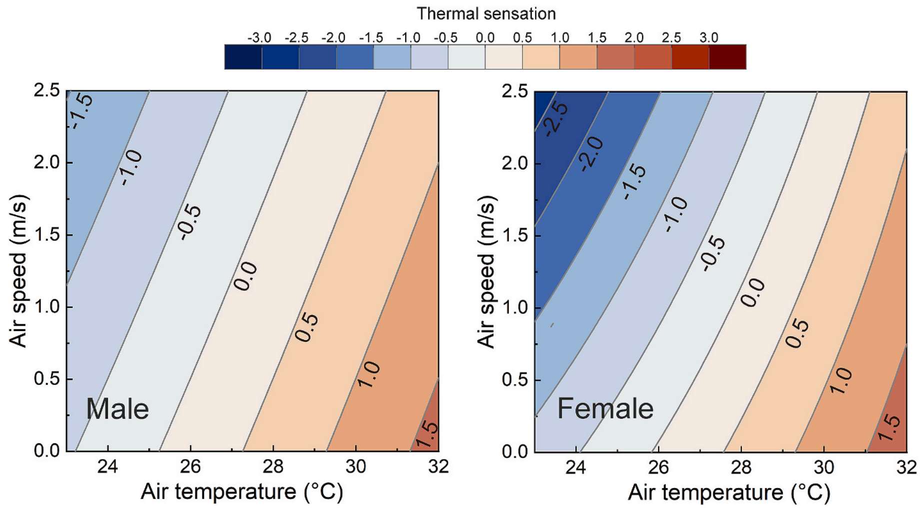

Fig. 6. Sex-specific thermal sensation in different environments. (left) male (right) female.

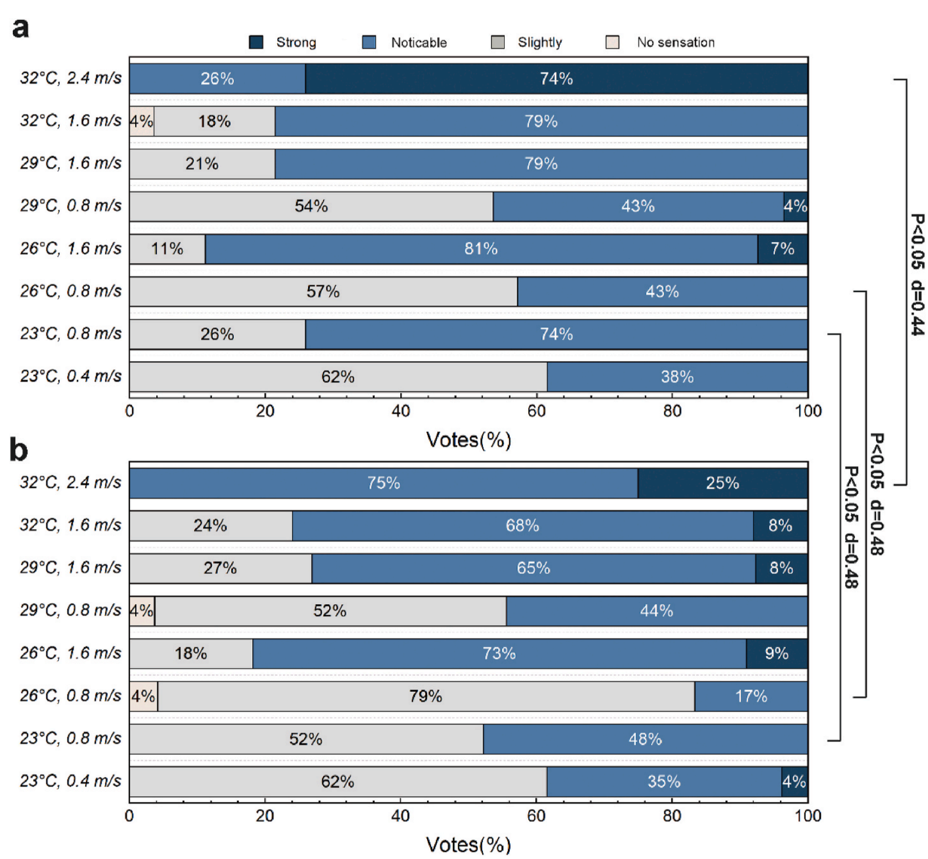

Fig. 7. Draft sensation in different experiment conditions. (a) female (b) male.

identify any significant sex differences in thermal sensation across various environments. This may be attributed to the lack of control in their study for other individual differences, including age, climate region, and culture. The absence of such controls could have contributed to the observed lack of significance in sex differences. They pointed out in their study that occupants from different countries may have a difference of 1.2 thermal sensation units in the same environment due to cultural variations.

4.3. Energy efficiency

According to this study, it is recommended to use FACS in both office and residential buildings to create a comfortable indoor environment while achieving energy savings. Based on the established comfort zone in this study, energy simulations were conducted using EnergyPlus on the standard medium-sized office building. The results showed that when achieving thermal comfort for occupants, the operation of FACS can reduce HVAC energy consumption.

The study demonstrates that maintaining the indoor temperature at

Table 6
Draft preferences in different experiment conditions.

Experiment condition		Lower	No change	Higher
T_{air} (°C)	V_{air} (m/s)			
32	2.4	54.90 %	45.10 %	0.00 %
	1.6	22.64 %	49.06 %	28.30 %
	<0.1	0.00 %	16.00 %	84.00 %
29	1.6	33.33 %	61.11 %	5.56 %
	0.8	18.18 %	67.27 %	14.55 %
	<0.1	0.00 %	39.22 %	60.78 %
26	1.6	69.39 %	30.61 %	0.00 %
	0.8	26.92 %	73.08 %	0.00 %
	<0.1	0.00 %	70.83 %	29.17 %
23 °C	0.8	64.00 %	36.00 %	0.00 %
	0.4	65.38 %	34.62 %	0.00 %
	<0.1	0.00 %	92.16 %	7.84 %

Table 7
Draft Acceptance Rate in different environments.

T_{air} (°C)	V_{air} (m/s)	DAR_{Male} (%)	DAR_{Female} (%)
32	2.4	54.17 %	37.04 %
32	1.6	76.00 %	89.29 %
32	< 0.1	100.00 %	100.00 %
29	1.6	76.92 %	60.71 %
29	0.8	85.19 %	89.29 %
29	< 0.1	100.00 %	100.00 %
26	1.6	36.36 %	29.63 %
26	0.8	100.00 %	78.57 %
26	< 0.1	100.00 %	100.00 %
23	0.8	69.57 %	51.85 %
23	0.4	62.50 %	65.38 %
23	< 0.1	100.00 %	100.00 %

29.0 °C and ensuring an air speed of 1.3 m/s can achieve thermal comfort for all occupants (both sexes) while also reducing energy consumption. However, this is a one-size-fits-all operating setting for FACS in the space. In practical terms, there are scenarios in which users can modify fan speed or adjust air supply distance to customize their local air speed. This flexibility enables individuals of both sexes sharing the same temperature environment to experience different air speeds. Compared to a one-size-fits-all control strategy, providing different comfort settings for different sexes can further increase energy savings and should not be overlooked.

Although this study focused on energy simulations in office buildings, the same combined operation strategy can be applied to residential buildings as well. Our previous research has shown that over 50 % of household air conditioners in China have setpoints below 27 °C [50]. The total completed floor area of residential buildings is approximately seven times that of office buildings for new constructions in 2021. Considering the larger building area and potentially longer usage time,

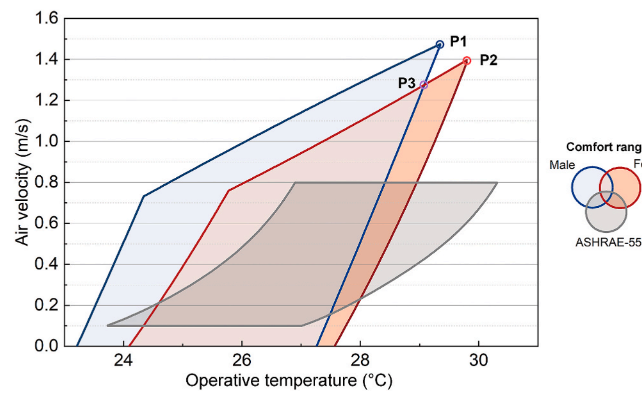

Fig. 9. Sex-specific comfort range of air temperature and air speed.

Table 8
Sex-specific regression model of draft acceptance rate.

Sex	Draft sensation acceptance rate regression model	R^2
Male	$DAR = -2.9062 + 0.2870 \times T_{air} - 0.0052 \times T_{air}^2 - 1.3672 \times V_{air} - 0.1128 \times V_{air}^2 + 0.0456 \times T_{air} \times V_{air},\ V_{air} > 0\ m/s$ $DAR = 0,\ V_{air} = 0\ m/s$	0.87**
Female	$DAR = -1.8294 + 0.1993 \times T_{air} - 0.0035 \times T_{air}^2 - 1.7747 \times V_{air} - 0.2003 \times V_{air}^2 + 0.0629 \times T_{air} \times V_{air},\ V_{air} > 0\ m/s$ $DAR = 0,\ V_{air} = 0\ m/s$	0.89**

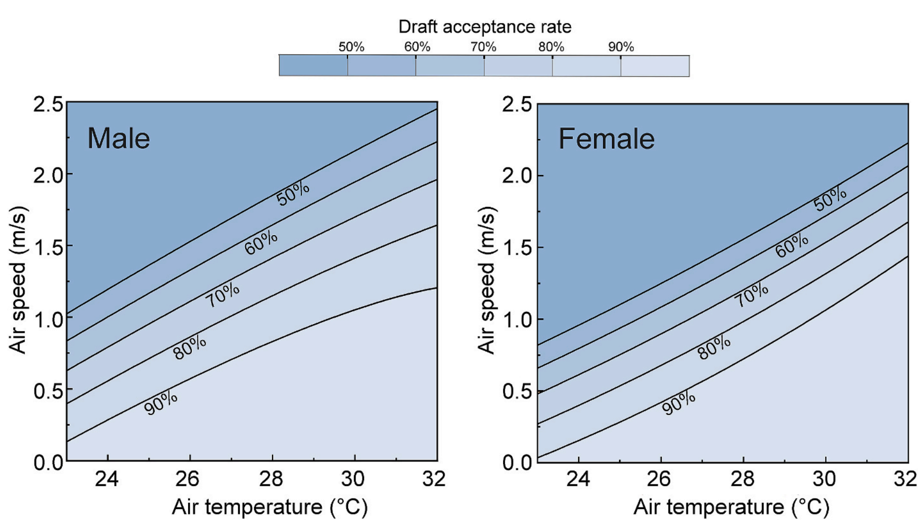

Fig. 8. Sex-specific draft acceptance rate in different environments (left) male (right) female.

Table 9
Operating settings for annual energy consumption comparison.

Operating setting	A/C setpoint (°C)	Air speed, m/s (Fan power, W)	Note
CSS1	26	0	Common air conditioning set point
CSS2	29.0	1.3 m/s (9.4W)	The most energy-efficient FACS operation settings for satisfying the thermal comfort of all occupants (both sexes).
CSS3	29.3	1.5 m/s (11W)	The most energy-efficient FACS operating setting for satisfying male thermal comfort.
CSS4	29.8	1.4 m/s (10W)	The most energy-efficient FACS operating setting for satisfying female thermal comfort.

the energy-saving achieved by implementing FACS in residential buildings need to be considered.

4.4. Practical practice

The FACS system offers practical flexibility for real-world applications. In buildings where air conditioning is already installed, optimizing indoor HVAC system energy consumption can be effectively achieved by installing low-cost fans. In buildings, air conditioning systems are used to adjust the overall indoor temperature, while additional fans are installed to provide appropriate air speed. For the FACS system, there is a wide variety of fan options, as detailed in Fig. 12. In centralized office environments, desktop fans can provide localized airflow. They are aesthetically pleasing, highly adjustable, allowing individuals to create a comfortable microenvironment in specific areas. For small independent offices, stand fans are also a good solution, offering a greater range of adjustable fan speeds. Some personalized ventilation (PV) systems deliver cooled air to occupants through vents installed at their workstations, avoiding the need to regulate the air temperature in the entire room [51–53]. However, since the air vents are directly installed in the working zone and the air supply temperature is often low, this system may cause discomfort due to draft sensation. In fact, changing the overall indoor temperature using air conditionings and then supplying clean indoor return air to the working zone by PV system could be an effective method worth evaluating. This method delivers airflow at the same temperature as the return air, avoiding discomfort caused by low-temperature airflow and providing higher air speed to effectively compensate for temperature effects. This approach can be considered an extension of FACS. For situations where there is no need to independently create indoor environments for different sex occupants, ceiling fans offer a solution. By installing a small number of ceiling fans, high airspeeds can be achieved in the working area. Existing studies found that the airflow direction of fans has an insignificant impact on thermal sensation [27,54], supporting the applicability of the comfort zone given in this study in scenarios involving ceiling fan usage.

With the increasing concern about the energy crisis, energy efficiency in HVAC systems has become a mainstream trend. By integrating fans with air conditioning systems, it not only avoids the localized discomfort caused by the cold air flow from air conditioners but also maximizes the cooling effect by utilizing the airflow speed. Fans, once considered a low-cost alternative to air conditioning in the early days, have demonstrated significant energy-saving benefits.

5. Limitation

The comfort zone in this study was developed based on subjects aged between 20 and 30 years. The accuracy of applying this zone to other age groups still requires thorough evaluation. Several studies have indicated that middle-aged and older adults exhibit lower metabolic rates and tend to favor higher temperature environments compared to

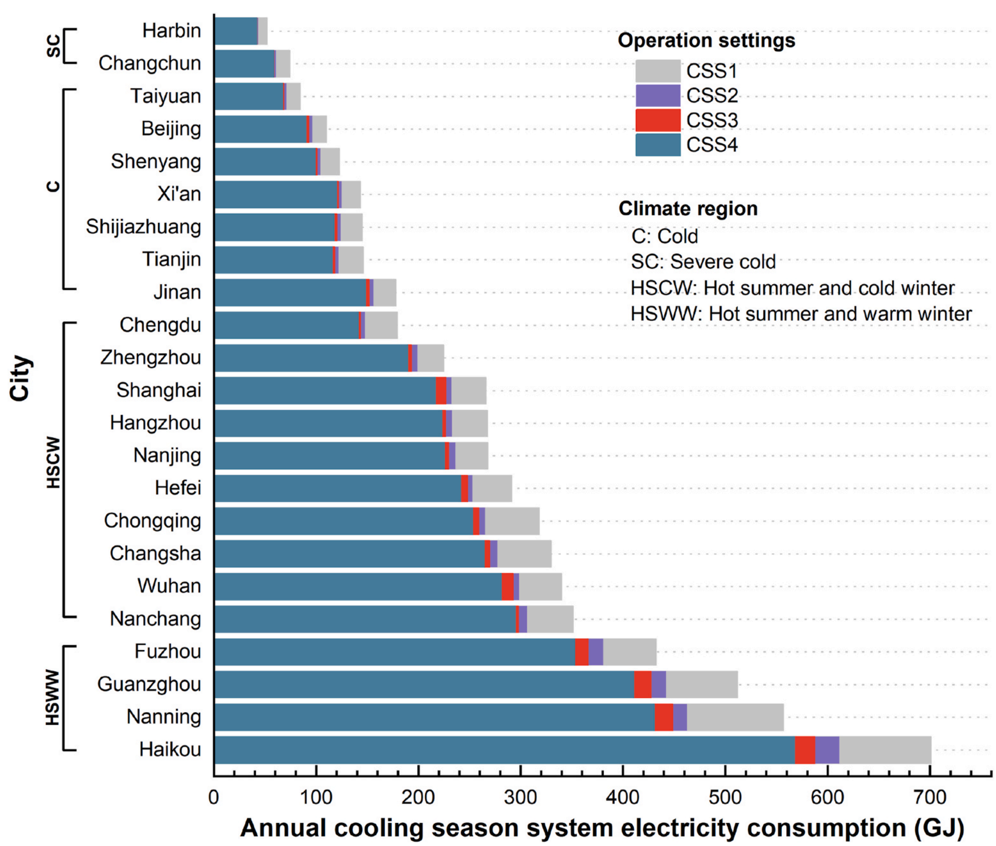

Fig. 10. Annual system electricity consumptions in cooling season of standard building with different operation settings.

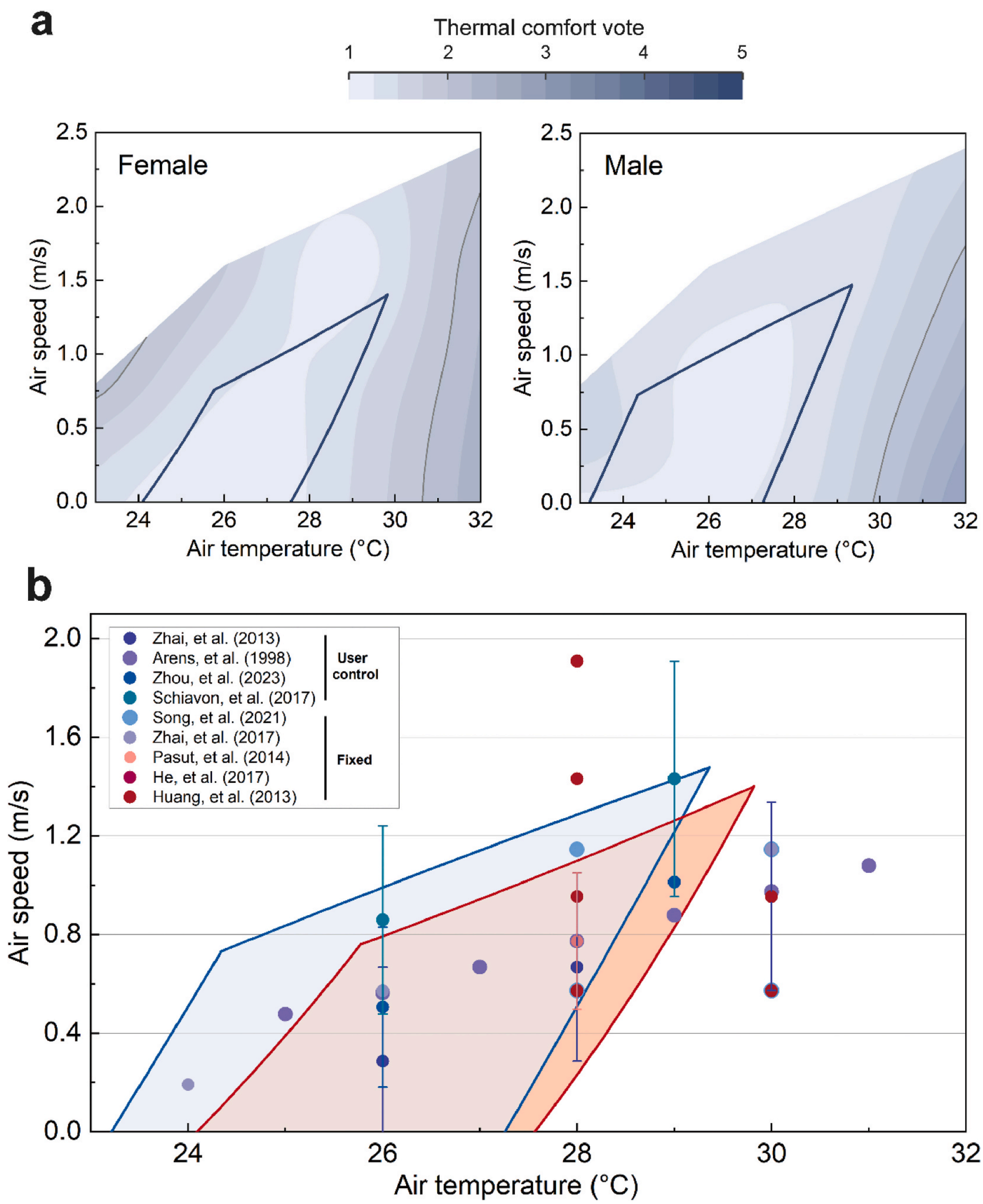

Fig. 11. a) Comparison of actual thermal comfort votes with thermal comfort zone. b) Comparison of thermal comfort votes given in existing studies with thermal comfort zone proposed in this study.

younger individuals [46]. This suggests that for the middle-aged and elderly population, the use of FACS may result in higher energy savings. Another factor that may affect the comfort zone is humidity. The experiments in this study were conducted in a hot summer and cold winter region, with the environment RH controlled between 50 % and 60 %. This leads to the need for further evaluation of the applicability of the established comfort zone in tropical regions characterized by high temperatures and high humidity.

Additionally, in this study, the impact of air conditioning supply air velocity on the occupied zone was reduced by adjusting the direction of the air conditioning vents. This wastes the air distribution created by the air conditioning fan itself. However, if the air conditioning directly blows at the occupants, the low-temperature air released by the air conditioning may cause an unacceptable risk of drafts. Therefore, it is worth considering how to optimize the design of the FACS, maximizing the cooling effect provided by the air conditioning and fan speeds while avoiding discomfort from cold drafts.

Moreover, this study adopts the ASHRAE standard model for energy consumption analysis, aiming to compare the energy-saving potential of systems under a unified standard. While the ASHRAE-90.1 standard models are extensively employed for energy analysis and comparison in numerous studies, it fails to adequately represent the characteristics of real office buildings in China, particularly those with large glass curtain walls. In future research, it is recommended to conduct field studies to assess the comfort and actual energy-saving performance of FACS in actual buildings.

6. Conclusion

In order to analyze the comprehensive impact of FACS on occupant

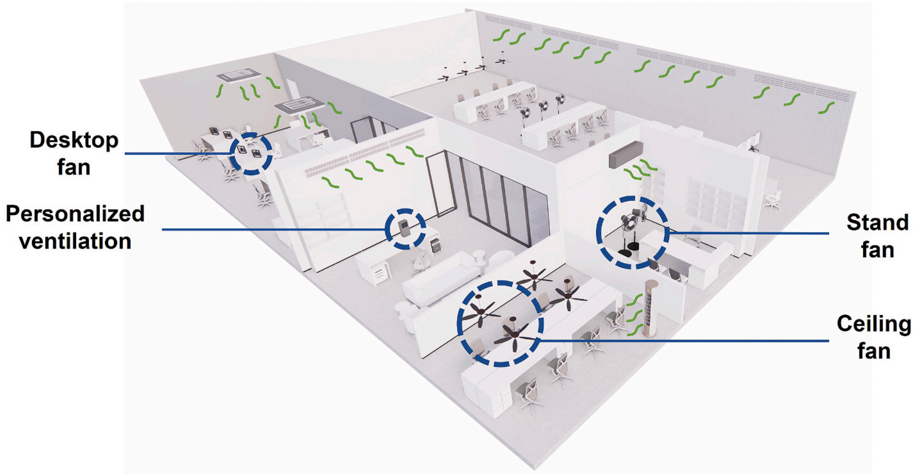

Fig. 12. Practical practice scenario diagram.

comfort and energy efficiency, this study utilized a regression algorithm to establish a range of comfort parameters for air conditioning and fan operation. The comfort zone established demonstrates that the upper limit of air speed for user comfort increases with rising ambient temperature. For females, the upper limit of comfort parameters is an air temperature of 29.8 °C and an air speed of 1.4 m/s, while for males, it is 29.3 °C and 1.5 m/s. In cooler environments, there are noticeable differences in the sensation of draft and thermal comfort between sexes. Specifically, in an environment set at 24 °C, the difference in the upper limit of air speed required to maintain comfort between sexes can reach 0.5 m/s. In spaces where uniform air speed and indoor air temperature are required, the upper limit for environmental parameters to ensure the comfort of all occupants (both sexes) is 29.0 °C and an airspeed of 1.3 m/s. Furthermore, EnergyPlus software was used to simulate the energy consumption of an office building compliant with the ASHRAE standards, considering the application of FACS. The results demonstrate that this system achieves significant energy savings. In regions with hot summers and warm winters, the combined operation of fans and air conditioning can result in energy savings exceeding 100 GJ/year. Overall, compared to creating a uniform indoor environment at 26 °C, buildings utilizing a combined fan and air conditioning system can reduce HVAC system energy consumption by over 16 %. Additionally, considering sex differences when implementing this system can further contribute to energy savings of approximately 4 %.

CRediT authorship contribution statement

Junmeng Lyu: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Yongxiang Shi:** Methodology. **Heng Du:** Methodology, Data curation. **Zhiwei Lian:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.111002.

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