UC Berkeley

Indoor Environmental Quality (IEQ)

Title

Air-conditioning use behaviors when elevated air movement is available

Permalink

<https://escholarship.org/uc/item/9np5x6cv>

Authors

He, Yingdong
Li, Nianping
Zhang, Hui
[et al.](#)

Publication Date

2020-10-01

DOI

10.1016/j.enbuild.2020.110370

Copyright Information

This work is made available under the terms of a Creative Commons Attribution-NonCommercial-ShareAlike License, available at <https://creativecommons.org/licenses/by-nc-sa/4.0/>

Peer reviewed

Air-conditioning use behaviors when elevated air movement is available

Yingdong He^{1, 2}, Nianping Li^{1, *}, Hui Zhang², Yangli Han¹, Jiamin Lu¹, Linxuan Zhou^{1, 2}

¹: College of Civil Engineering, Hunan University, Changsha, Hunan 410082, China

²: Center for the Built Environment, University of California, Berkeley, Berkeley CA 94720, USA

*: Corresponding author. E-mail address: linianping@126.com

Abstract: Many experimental studies demonstrated that elevating indoor temperatures to 28 or 30°C is comfortable if fans are used, while this elevation often is not applied in practice. This study aims to investigate AC thermostat use behaviors when elevated air movement is available, as well as to provide insights at guiding occupants to select warmer environments without reducing their comfort. 20 subjects participated in a series of tests at three initial ambient temperatures (26, 28, and 30°C) with different settings of an AC thermostat and a ceiling fan: (1) a free-controlled thermostat without a fan, (2) a free-controlled thermostat with a free-controlled fan, (3) a free-controlled thermostat with an always-on fan (controllable but not allowed to turn off), (4) a limited thermostat (no lower than 28°C) with a free-controlled fan, and (5) a limited thermostat with an always-on fan. The results show that without the ceiling fan, subjects used AC to lower indoor temperatures to 25.7°C. When the fan was available (free-controlled), they did not only rely on lowering the AC set-point alone but also turned on the fan immediately when starting using AC. This behavior ended a final ambient temperature up to 27.4°C. Under always-on fan conditions, the fan was running at a high speed at the beginning of using AC. Although subjects turned down the fan speed, the final fan speeds were about doubled the speeds as compared with free-controlled fan conditions. This higher initial speed by the always-on fan made subjects select higher indoor temperatures: at the 28°C initial temperature, there was no further lowering of ambient temperatures; at the 30°C initial temperature, the final temperatures were 28.6 and 28.9°C for the free-controlled and limited AC test conditions, about a 3-K set-points extension compared with the no-fan condition. Further, despite different conditions, more than 90% of subjects had comfortable feelings, which indicates that people with adjustable AC prefer a constant thermal perception rather than a constant ambient temperature. Therefore, the strategy of using fans before AC should be adopted to guide people actively to select higher AC set-point temperatures.

Keywords: AC-use behavior; thermal comfort; ceiling fan; thermostat; personal cooling

1 Introduction

Air-conditioning (AC) systems are widely used in modern buildings to provide moderate indoor environments for occupants' well-being and productivity indoors [1]. Correspondingly, much energy is consumed by AC in buildings, which results in adverse effects on the global environment, such as environmental pollution and global warming. Thus, reducing AC energy helps achieve sustainable development of human society.

AC-use behaviors of building occupants are an essential factor influencing AC energy consumption. AC-use behaviors usually include AC-use duration, temperature set-point, times of turning on and off, and so on. Understanding AC-use behaviors play a critical role in balancing the thermal comfort of occupants and the energy efficiency of buildings. Many studies were conducted to investigate AC-use behaviors in buildings. In a field study which was conducted in residential buildings in Indonesia, it was found that the AC-use rate reached 50% to keep 25-26°C indoors and most of residents selected set-points lower than 26°C [2]. Yang and Olofsson [3] did a survey on AC-use during sleeping time in Singapore and they found that more than 75% of the surveyed people use AC for at least three hours during sleeping time and half of them selected indoor set-points lower than 24°C whilst sleeping. Imagawa and Rijal found that people in Japan prefer to set 25-26°C for AC cooling in their bedrooms [4]. Song et al. [5] investigated

AC-use in residential buildings in Tianjin, north China. The results indicate that the average duration of AC cooling in summer was 3.24 hours per house, and the AC-use rate was 16.3%. The relatively lower AC-use rate is mainly due to the moderate climate (average outdoor temperature was lower than 30°C in summer). In a field investigation of He et al. [6], which was carried out in south China, AC-use rates reached nearly 90% in university dormitory buildings in summer. The high AC-use rate resulted from the sweltering climate of southern China (sometimes higher than 40°C outdoors in summer). The study also found that students from different climatic regions had a similar willingness to use AC to reduce warmth. Liu et al. [7] conducted a field study in two office rooms in south China. They found that AC-use behaviors were strongly correlated with outdoor temperatures, and the study established logistic models for predicting AC-use rates. Rijal et al. [8] analyzed long-term data of AC-use rates in office buildings in Europe and they found that 50% of occupants started using AC when it was 24°C indoors. Rijal et al. [9] also investigated AC-use rates of India office buildings and correlated AC-use rates with outdoor daily mean temperatures. They found that 89.4% and 28.5% ACs in office buildings in Chennai and Hyderabad were running when it was 29°C outdoors, respectively. The big difference of AC-use rates probably was caused by the different performances of building envelope which produced different indoor environments with the same outdoor temperature. Kim et al. [10] developed a logistic model to predict AC-use rates of Australian residents after a two-year survey. They pointed out that Australian people relied less on AC in residential buildings than in office buildings because residential AC-use rates reached 50% when it was 35°C outdoors, but the corresponding outdoor temperatures for offices were 28-29°C. Through an analysis of 3962 datasets from 113 Indian respondents, Indraganti [11] stated that people with higher social and economic status used more AC in warm seasons than poor people, who relied more on no-cost methods such as using fans and reducing clothes to ameliorate discomfort. Daniel [12] focused on AC-use behaviors correlated with both indoor/outdoor temperatures and indoor humidity, and he found that the latter even had a stronger association. Chen et al. [13] studied AC-use in university dormitories. It showed that most of the students selected AC set-point temperatures of 26-27°C, and their education levels affected set-point temperatures (Ph.D. students had the highest set-point temperatures). Nakaya et al. [14] surveyed Japanese residential buildings, and they built several models of AC-use rates with indoor and outdoor temperatures, respectively. Their models show that if some passive behaviors such as opening windows and using fans happened before AC, AC-use rates could be cut down by up to 20%. In a simulation study conducted by Zhou et al. [15], when compared to climates and building envelopes, AC-use behaviors exerted a much more significant effect on building cooling energy (up to three times). Similarly, Yun and Steemers [16] analyzed influencing factors of residential cooling energy in U.S., and the results suggested that occupants' behaviors played a more significant role than climates and building types. Ren et al. [17] hold the same opinion that residents' AC-use behaviors strongly affect cooling energy in summer.

One goal of studying AC-use behaviors is to encourage people to rely less on AC, thus decreasing building energy consumption. Therefore, it is vital to propose practical strategies to reduce AC-use behaviors. Fans can effectively cool human bodies via elevated airspeed. Fans contribute to improving human comfort and air quality, reducing AC energy, and raising productivity in warm environments [1, 18, 19]. Fans also provide opportunities to satisfy individuals' different comfort requirements [20]. Some researchers studied combinations of fans and radiant cooling/heating systems to achieve better comfort and greater energy efficiency. He et al. [21] studied human thermal comfort in warm environments with radiant cooled ceilings and desk fans. They found that the desk fan was an effective cooling supplementary for occupants when the cooled ceiling could not thoroughly remove indoor heat gains, and the indoor

comfortable temperature could be as high as 30°C. He et al. [22] also combined desk fans with a novel kind of radiant cooling desk. The radiant cooling desk extended the neutral temperature without the radiant cooling desk from 26 to 28°C. Once it is combined with the desk fans, the neutral temperature further increased to 30 or even 32°C from 28°C, which helps save a large amount of AC energy. Karmann et al. [23] used fans to make up the loss of cooling capacity of cooled ceilings due to suspended acoustical panels. A maximum increase of cooling capacity was 26% with fans compared with conditions without suspended acoustical panels. With the significant advantages of fans, it is possible to adopt fans to guide people using less AC. Our previous study [24] showed that occupants with elevated movement by fans used less AC thermostat. However, it was conducted in a shared room where individuals' AC-use behaviors were limited.

In order to further understand how an individual uses the AC thermostat when the elevated air movement by fans is available, more questions need to be answered:

(1) Can the elevated air movement further improves comfort when people already have an adjustable AC thermostat?

(2) How much do people rely on AC thermostat lowering when elevated air movement is available?

(3) How to balance comfort and energy-efficiency in buildings with occupant-controlled AC thermostat?

To explore the abovementioned issues, we carried out a series of experiments in an experimental room with an adjustable AC thermostat and a ceiling fan in summer. One subject entered the test room each time, so his/her adjustments were not affected by other subjects. First, subjects were given access to control indoor temperatures by using the thermostat of AC with or without a ceiling fan. Then, a limit (28°C) of set-point temperatures was set, and/or the ceiling fan was set with an always-on mode (still adjustable but cannot be turned off). Under these circumstances, subjects were tested on how they use AC thermostat to control indoor environments. Subjects' physiological and psychological responses were recorded at the same time. Subsequently, AC-use behaviors, physiological and psychological responses were analyzed to explain AC-use behaviors in occupant-controlled environments. Some proper strategies of prompting occupants to actively choose a higher set-point temperature of AC were also discussed.

2. Methodology

2.1 Facilities

For creating a realistic environment, an office room, located on the third floor of a building at Hunan University, was retrofitted and used as an experimental room. Fig. 1 shows the layout of the room. The room size was 4.5 m (length) × 3.4 m (width) × 3.4 m (height). The south wall is the only exterior wall with a window. A split-type air conditioner was installed on the west wall, 2.6 m above the floor. The air-conditioner was controlled by a small remote controller, with a set-point temperature range of 18-30°C. A small ventilation fan was installed on the top of the window to supply fresh air from outdoors. A blind curtain and several layers of foam boards (total 50 mm thick) covered the window during the tests, to reduce the influences of outdoor environments. A seat was set at the center of the room, above which a ceiling fan with a diameter of 0.7 m was installed (2 m above the floor). The fan had a step-less controller which can control the fan speed continuously, with a power range of 1.22-19.3 W. There was only one subject performing the test at a time, and a researcher inside the room to communicate with the subject when needed.

Fig. 1. The experimental room: (a) the room layout and (b) the onsite scene.

2.2 Procedure, thermostat, and ceiling fan controls

Test procedure: Fig. 2 represents the experimental procedure. Each test lasted for 75 minutes:

(1) First, after arrival, subjects stayed in a preparation room where the indoor temperature was 25°C for 15 minutes. This is used as the acclimatization period. The precedent activities (like walking) and experienced environments (like outdoor environments) before the tests would affect the initial thermal status and AC-use behaviors once inside the test room. A 15-min period was for stabilizing and standardizing subjects' activities and metabolic rates before tests began.

(2) Then, subjects entered the experimental room where the ambient temperatures were set at 26, 28, 30°C as described in Table 2 (experimental conditions), and started the test. In the first 15 minutes, which is called exposure period (represented by the orange bar), subjects wore skin temperature sensors and did 30 up-down steps in the middle of this period. The subjects were not allowed to change the AC thermostat, and the fan was off. This 15 min serves as another period to stabilize and standardize people's thermal status before using the AC thermostat and the fan.

(3) Subsequently, subjects remained seated for 40 minutes, which is called the control period (represented by the green bar), during which they could control the ceiling fan and/or the air conditioner based on the test conditions described in 2.3 (test conditions).

(4) After the 40 min control period, subjects took off all skin temperature sensors and left the experimental room, which took about five minutes.

Subjective questionnaire schedules. The red and purple triangles in Fig. 2. indicate time points when subjects filled in thermal comfort questionnaires. Red triangles represent questions for the whole-body, and purple triangles represent questions for the whole-body and local body segments. The survey appeared at the 0, 2nd, 5th min of the control period, then with the interval extended to 5 and 10 min in the following 35 min (see Fig. 2). The frequent questions at the beginning is designed to capture the skin and comfort changes during transient periods. Types of the questionnaire and their scales are described in section 2.5.3.

Fan control. There are three types of fan control modes: off, fan speed continuously adjustable including turning off (called free-controlled fan), fan speed continuously adjustable but not allowed to turn off (called always-on fan). The fan controller was put on the table where subjects seated, so they had easy control over the fan.

AC thermostat control. We did not want subjects to see the ambient temperatures shown in the controller, therefore, we designed a way that the thermostat change was done via the communication between subjects and researchers. After each subjective survey (represented by the red and purple triangles in Fig. 2), there is a question to ask the subject whether he/she would like to adjust the thermostat (increase, decrease, or no change) and providing the degrees (in integer unit, e.g., decrease 2°C) of increasing or decreasing if requested. After receiving a requirement, the researcher immediately changed the indoor temperature thermostat by using the remote controller (or no-change if not asked for). The test room ambient temperature cooling speed varies depending on the degrees of changes requested, roughly 1-1.5°C every five minutes once an adjustment request is sent. There are two adjustable modes for the thermostat: one is without any limit, one with a limit not lowering than 28°C (details are described in section 2.3). Moreover, when a subject answered no-change, which means no need to further lower/higher indoor temperatures, the researcher immediately stopped changing the indoor temperatures, although the current temperature may have not reached the temperature level of his or her last request. Such a set-up helped obtain the actual indoor temperatures subjects needed.

Fig. 2. Experimental procedure.

2.3 Test conditions

The experimental conditions are listed in Table 1. Three initial indoor temperatures were tested, 26, 28, and 30°C, while the relative humidity was at about 60% (mainly varied 55-65% during the tests). Conditions 1-6 are named as the non-limited phase, i.e., there were no limitations of adjustments for the thermostat or the fan, while conditions 7-12 are named as limited phase, i.e., there were some limitations for the thermostat or the fan. The detailed description is as follow:

(1) Conditions 1 through 3 were designed to investigate AC-use behaviors without the ceiling fan: subjects were free to control indoor temperatures only. The ceiling fan was off. It serves as reference conditions.

(2) Conditions 4 through 6 were designed to investigate AC-use behaviors with the ceiling fan: subjects were free to control indoor temperatures and the ceiling fan speed. However, the fan was set at the off-level when subjects entered the test room at the beginning of the control period.

(3) Conditions 7 through 12 were intended to investigate AC-use behaviors with some limitations: either the limit for the ceiling fan to keep it *always-on* (conditions 7, 8, 11, 12), which means subjects could adjust it but not turn it off; or the limit for the indoor temperature to be kept no lower than 28°C (conditions 9-12). The subjects did not know that there was a limit at the thermostat adjustment. They provided the thermostat-change requests the same way as all the no limit test conditions, except that the researcher did not lower the thermostat once it reached 28°C. Therefore, for conditions 9-12 in Table 1, there is no test condition under 26°C ambient temperature.

For conditions with the ceiling fan always-on (test conditions 7, 8, 11, 12), at the beginning of the 40 min control

period, the fan was switched to its mediate power (10.5 W) by our researchers. Subjects could control the ceiling fan speed afterward, but could not turn it off. This setting enables the ceiling fan at the running mode at the time when subjects began to adjust the indoor temperature. The condition abbreviations, which will be referred in the text below when describing the results, are shown in the last column of Table 1. Please refer to the note under the table for explanations of the abbreviations. For all tests, subjects did not know indoor temperatures.

Table 1. Experimental conditions.

Condition	Phase	Initial indoor temp. (°C)	Ceiling fan	AC thermostat	Condition abbrev. ¹
1	Non-limited	26	None	Adjustable	initial 26°C: N+A
2	Non-limited	28	None	Adjustable	initial 28°C: N+A
3	Non-limited	30	None	Adjustable	initial 30°C: N+A
4	Non-limited	26	Free control	Adjustable	initial 26°C: F+A
5	Non-limited	28	Free control	Adjustable	initial 28°C: F+A
6	Non-limited	30	Free control	Adjustable	initial 30°C: F+A
7	Limited	28	Always-on	Adjustable	initial 28°C: On+A
8	Limited	30	Always-on	Adjustable	initial 30°C: On+A
9	Limited	28	Free control	Limited (lowest at 28°C)	initial 28°C: F+L
10	Limited	30	Free control	Limited (lowest at 28°C)	initial 30°C: F+L
11	Limited	28	Always-on	Limited (lowest at 28°C)	initial 28°C: On+L
12	Limited	30	Always-on	Limited (lowest at 28°C)	initial 30°C: On+L

¹: The first and second letters under the condition abbreviation represent for fan and control conditions, respectively. For the first letter, N representing no fan, F representing fan freely controlled, On representing fan always on. For the second letter, A-adjustable AC thermostat, L-limited AC thermostat.

2.4 Subjects

Twenty university students (ten males and ten females) aged from 19 to 25 years old were recruited to participate in all tests. The height, weight, and body mass index of males were 173.1±4.2 cm, 64.7±4.6 kg, and 21.6±1.8 kg/m²; the corresponding data of females were 162.5±6.0 cm, 51.3±5.9 kg, and 19.4±1.5 kg/m². The standard clothing ensemble of subjects was a short-sleeve shirt, trousers, ankle socks, and shoes, which was 0.5 clo in total. The subjects wore their own clothing.

2.5 Measurements

During the tests, the indoor temperature and the fan power were recorded every minute. The indoor temperature was measured at 0.1, 0.6, and 1.1 m above the floor by TR-72Ui temperature & humidity meters with a precision of ±0.3°C. Since the temperature changes were not very fast (1-1.5°C every five minutes at most), the vertical temperature differences between 0.1 and 1.1 m were usually less than 3 K. The measurement location was near the subject seat, which could reflect the temperature the subjects experienced (see Fig. 1(a)). The fan power was measured by a UT230A-II electric power meter with a precision of ±1%. A relationship between airspeed and electrical power of the ceiling fan was determined by pre-tests, and thus we only needed to monitor the fan power for obtaining fan's airspeeds.

Skin temperatures of subjects were recorded by iButton DS1922L thermal sensors with the solution of 0.0625°C

on five body parts: cheek (t_{cheek}), upper arm (t_{arm}), abdomen ($t_{abdomen}$), lower back (t_{back}), and thigh (t_{thigh}), and all of them were on the left body side. The mean skin temperature (t_{sk}) was calculated according to the method of reference [25]:

$$t_{sk} = 0.07t_{cheek} + 0.19t_{arm} + 0.175t_{abdomen} + 0.175t_{back} + 0.39t_{thigh} \quad (1)$$

Psychological survey questionnaire parameters include (1) whole-body and local thermal sensations, (2) whole-body and local thermal comfort, (3) thermal acceptability, (4) thermal preference. All the scales are integer, not continuous. Detailed scale-divisions of the psychological questions are shown in Table 2. Local thermal sensation and comfort involve 12 body segments: head, neck, chest, back, abdomen, buttocks, upper arms, lower arms, hands, thighs, calves, and feet.

Table 2. Scale-divisions of thermal sensation, comfort, acceptability, and preference

Scale	Thermal sensation	Thermal comfort	Thermal Preference	Scale	Thermal Acceptability
3	Hot	Very comfortable	Much warmer	6	Totally acceptable
2	Warm	Comfortable	Warmer	5	Acceptable
1	Slightly warm	Slightly comfortable	Slightly warmer	4	Slightly acceptable
0	Neutral	No feeling	No change	3	Slightly unacceptable
-1	Slightly cool	Slightly uncomfortable	Slightly Cooler	2	Unacceptable
-2	Cool	Uncomfortable	Cooler	1	Totally unacceptable
-3	Cold	Very uncomfortable	Much cooler		

2.6 Model establishment

In this study, the data at each time point of the control period when subjects filled out questionnaires were used to establish models. The data of N+A and F+A conditions with the initial 26°C temperatures (test conditions 1 and 4) were not used to establish models because subjects seldom used the AC thermostat at 26°C initial ambient temperature. Although several regression methods were used, only linear regression models fitted all conditions (models are significant and reasonable) and exerted relatively high accuracy. Thus, only linear models are represented.

3 Results

3.1 Indoor environments and AC-use behaviors

3.1.1 Subject-controlled indoor environments

Fig. 3 shows averages of indoor temperatures (Fig. 3(a) and (b), top two figures) and air velocities (Fig. 3(c) and (d), bottom two figures) in different conditions. The main finding is that using the thermostat and the fan made subjects select up to 3°C higher indoor temperatures than using the thermostat alone. In Fig. 3(a), in no-fan conditions (N+A), indoor temperatures gradually decreased to 25.7, 25.7, and 26.5°C with 26, 28, and 30°C initial temperatures, respectively. The free-controlled fan (F+A conditions) resulted in elevations of 0.2, 1.4, and 0.9°C in ambient temperature compared with three no fan conditions, respectively. In Fig. 3(b), for On+A conditions (fan always-on + AC thermostat adjustment), the fan was turned on by experimenters ahead of the time when subjects were allowed to adjust the thermostat and the fan), at the initial 28°C, even when AC-use was available (not limited), the indoor temperatures remained as 28°C until the end of the control period, meaning that the ceiling fan was able to maintain comfort and no

thermostat adjustment was needed; With 30°C initial temperatures, the average final indoor temperatures were about 2°C higher than those of no-fan conditions. The only difference between F+A and On+A conditions is that at the beginning of the control period, the fan was on already for On+A, while for F+A, subjects had to turn on the fan and started from zero speed. This indicates that keeping the fan on as a high priority helps to provide comfort in warmer environments.

In Fig. 3(c) and (d), subjects selected much higher air speed with the always-on than the free-controlled fan. Subjects with the free-controlled fan (F+A) adopted relatively higher airspeed at the beginning of the control period, and then reduced it to about 0.6 m/s with 28 and 30°C initial temperatures. The airspeed of the always-on fan was 1.75 m/s at the beginning (researchers turned it on at the half of the fan's maximum power), but subjects decreased quickly to 1.0-1.3 m/s and kept this value until the end of the tests. Along with the final indoor temperatures in Fig. 3(a) and (b), the results indicate that higher air speed by the always-on fan resulted in higher selected temperatures than the free-controlled fan.

Fig. 3. Average changes in indoor temperatures in (a) the non-limited phase and (b) the limited phase, and average changes in airspeed at 0.6 m height in (c) the non-limited phase and (d) the limited phase.

3.1.2 AC-use behaviors

Fig. 4(a) shows averages of AC-use (thermostat lowering requests) in conditions 1-6 (non-limited phases) and Fig. 4(b) in conditions 7-12 (limited phases). Negative values are the averages of the degrees that subjects requested to turn down the AC thermostat, and the zero-level means no adjustments were requested. The main finding is that using the fan accelerated AC thermostat adjustments to reach to the zero-level in all conditions. In Fig. 4(a), as the control period

began (the 15th minute), the requested turned down thermostat degrees are similar with or without the fan, by about 0.5, 1.5 and 2.5°C for the initial ambient temperature 26, 28, and 30°C, respectively, because the fan was zero at the beginning of the tests. After this, the turn-down requests gradually shifted to zero-level until the end of the tests. With the free-controlled fan, AC thermostat adjustment requests were closer to zero-level in the first 20 minutes of the control period, faster than conditions without the fan, especially for the 30°C initial ambient condition, which did not reach to zero by the end of the 40 min control period. As shown in Fig. 4(b), the changes in AC-use behaviors are similar to those represented in Fig. 4(a): there were big reductions requested at the beginning of the control period, and finally, the reduction reached near zero-level. In F+L conditions, with the free-controlled ceiling fan, the averages of the initial AC thermostat reductions requested were about 1.5 and 2.5°C under initial temperatures of 28 and 30°C, same as conditions 1-6 (non-limited). In On+A and On+L conditions, at the beginning of the control period, because the fan was on, the AC thermostat turned-down amounts requested were about 0.4 and 1.5°C with initial temperatures of 28 and 30°C, respectively, which indicates that an always-on ceiling fan is better for reducing AC-use behaviors than a free-controlled fan.

Fig. 4. Changes in the averages of AC thermostat adjustments in (a) the non-limited phase and (b) the limited phase.

3.1.3 Correlation between AC-use behaviors and indoor temperatures

Fig. 5 illustrates correlations between AC-use behaviors and indoor temperatures averages. Because the correlations show a linear relationship, therefore, we developed linear predictive models, and Table 3 lists model parameters. The most important finding in Fig. 5 is that when the indoor temperature was the same, subjects with fans used less AC than without fans, as shown by the smaller thermostat lower magnitudes (Fig. 5(a)) and smaller percentage of subjects who requested lowering the thermostat (Fig. 5(b)). In Fig. 5(a), for no-fan conditions, the indoor temperatures was about 25.5°C when no one requested to lowering the thermostat, which is about 2°C lower than those in the free-controlled-fan conditions and 2.5°C lower than those in the always-on-fan conditions. As shown in Fig. 5(b), when no subjects requested to turn down the thermostat, indoor temperatures are predicted at about 25°C in the no-fan conditions, 27°C in the free-controlled-fan conditions, and 27.5°C in the always-on-fan conditions. These results indicate that using fans reduces AC thermostat adjustments and promotes people to choose warm environments in summer, and the always-on fan is better than the free-controlled fan.

Fig. 5. Correlations between AC-use behaviors and indoor temperatures: (a) AC thermostat adjustment and (b) percentages of subjects turning down the thermostat.

Table 3. Regression model parameters of AC-use behaviors and indoor temperatures.

Dependent vs. independent variable ¹	Condition	Slope (a)	Intercept (b)	R ²
Thermostat adjustment vs. indoor temperatures	N+A	-0.312	7.912	0.88
	F+A	-0.461	12.518	0.93
	On+A	-0.238	6.639	0.83
	F+L	-0.511	14.049	0.64
	On+L	-0.163	4.499	0.66
Percentages of turning down thermostat vs. indoor temperatures	N+A	0.194	-4.856	0.77
	F+A	0.303	-8.189	0.88
	On+A	0.194	-5.391	0.79
	F+L	0.289	-7.830	0.49
	On+L	0.139	-3.850	0.65

¹: Model format: $y = a \times x + b$, where y is the dependent variable, x is the independent variable.

3.2 Skin temperatures and AC-use behaviors

3.2.1 Skin temperatures

Fig. 6 shows the changes in average skin temperatures of subjects in different conditions during the control period. The values during the exposure period (0-15th minute) were not displayed because subjects were putting on the skin temperature sensors. The common trend is that subjects finally reached a very similar physiological status (represented by the mean skin temperature) in different conditions. As can be seen in Fig. 6(a), a higher initial indoor temperature caused a slightly higher mean skin temperature at the beginning of the control period. The free-controlled fan reduced mean skin temperatures by 0.1-0.2°C until the end of the procedure. While in Fig. 6(b), subjects had very similar mean skin temperatures in F+L and On+L conditions, and slightly lower values in On+A conditions because subjects had lower indoor temperatures in On+A conditions (Fig. 3(b)). Further, at the beginning of the control periods, the average

skin temperatures were between 33.9–34.3°C for conditions 1–6 (Fig. 6(a)), and between 34.3–34.5°C for conditions 7–12 (Fig. 6(b)). At the end of the control periods, the final mean skin temperatures in all conditions were almost the same (33.9–34.2°C).

Fig. 6. Changes in the averages of skin temperatures in (a) the non-limited phase and (b) the limited phase.

3.2.2 Correlation between AC-use behaviors and skin temperatures

Fig. 7 shows the correlations between AC-use behaviors and skin temperatures. Table 4 lists the model parameters. A prominent trend in Fig. 7 is that subjects with the fan used less AC (closer to the zero adjustment and less percentage of thermostat use) compared with the conditions without fan with the same mean skin temperatures. The mean skin temperatures were 34.0–34.1°C when the average thermostat adjustment was 0 (Fig. 7(a)). In Fig. 7(b), when all subjects stopped to request turning down thermostat (the percentage of turning down thermostat reaches 0), the mean skin temperatures were 33.9–34.1°C. These results indicate that subjects would finally reach the same physiological condition even when they had different ways to cool themselves in warm environments.

Fig. 7. AC-use behaviors and skin temperatures: (a) AC thermostat adjustment and (b) percentages of subjects turning down the thermostat

Table 4. Regression model parameters of AC-use behaviors and skin temperatures.

Dependent vs. independent variable ¹	Condition	Slope (a)	Intercept (b)	R ₂
Thermostat adjustment vs. skin temperatures	N+A	-2.73	92.869	0.69
	F+A	-2.99	101.597	0.68
	On+A	-1.416	48.115	0.46
	F+L	-4.306	146.897	0.74
	On+L	-1.580	53.954	0.47
Percentages of turning down thermostat vs. skin temperatures	N+A	1.773	-60.169	0.69
	F+A	1.953	-66.409	0.63
	On+A	1.235	-41.918	0.52
	F+L	2.761	-94.107	0.77
	On+L	1.155	-39.368	0.56

¹: Model format: $y = a \times x + b$, where y is the dependent variable, x is the independent variable.

3.3 Psychological responses and AC-use behaviors

3.3.1 Thermal sensation and comfort

Fig. 8 shows the averages of whole-body thermal sensation and comfort over time, and the final thermal sensation was around the neutral level and comfort was between “Slightly comfortable” (+1) and “Comfortable” (+2) in different conditions. As the control period began (Fig. 8(a)), the averages of whole-body thermal sensations decreased from about 0.3, 1.0, and 1.5 to 0 under the initial temperatures of 26, 28, and 30°C, respectively. As shown in Fig. 8(a), during this procedure, a free-controlled fan accelerated the speed of thermal sensations reaching to the neutral level (0): subjects with the fan felt neutral 5-10 min earlier than when they were without the fan. The sensation with fans was about 0.5 scales cooler than the sensation without fans at the same time, although the ambient temperature was 0.5-1.5°C higher (see Fig. 3(a)). In Fig. 8(b), when the fan was always on, a sharp decrease by 0.7-1 scale appeared at the very beginning of the control period (the 15th min), making the thermal sensation neutral right at the beginning for the 28°C ambient conditions.

As for whole-body thermal comfort, shown in Fig. 8(c) and (d), the changes of averages are similar to those of the whole-body thermal sensation shown in Fig. 8(a) and (b). In Fig. 8(c), the free-controlled fan fastened the increase of whole-body thermal comfort in F+A conditions with the initial 28 and 30°C temperatures: The whole-body thermal comfort was 0.3-0.6 scale higher than that in N+A conditions during the first 30 minutes of the control period (the 15th-45th min), although the ambient temperature was 0.5-1.5°C higher (see Fig. 3(a)). In Fig. 8(d), the always-on fan resulted in a sharp elevation of whole-body thermal comfort by about one scale at the 15th min right after the control period started (the fan was on). This comfort sharp increase associates with the sensation sharp decrease towards neutral (Fig. 8(b)) very well. Moreover, the averages of whole-body thermal comfort in the always-on-fan conditions were about 0.3-1 scale higher during the first 30th min in the test room than that in conditions with the free-controlled fan and the limited thermostat, even at a higher ambient temperature (Fig. 3(b)). The only difference in test conditions was the higher velocity (Fig. 3(d)), which enhanced the comfort levels.

Fig. 8. Changes in the averages of whole-body thermal sensation in (a) the non-limited phase and (b) the limited phase, and whole-body thermal comfort in (c) the non-limited phase and (d) the limited phase.

For a better understanding of the final psychological status of the subjects, the distributions of whole-body and local thermal sensation and comfort votes in the last survey were investigated (Fig. 9). The votes of local thermal sensation and comfort are the averages of those 10 local body parts listed under section 2.5. For whole-body and local thermal sensations (Fig. 9(a) and (b)), more than 90% of subjects had neutral whole-body thermal sensations at the end of the test period (except the N+A condition with the 30°C initial temperature). For whole-body thermal comfort (Fig. 9(c)), in most conditions, less than 10% of subjects felt slightly uncomfortable and no uncomfortable votes in the voting scale. For local thermal comfort (Fig. 9(d)), less than 10% of subjects felt slightly uncomfortable except the N+A condition with the 30°C initial temperature, which reached 20%. Moreover, no significant differences in final thermal sensations or comfort were found among different conditions. The findings in Fig. 9 indicate that subjects were able to get a near-neutral and 90%-comfortable perceptions by adjusting fan speed and thermostat setpoint under all tested conditions.

Fig. 9. Distributions of thermal sensation and comfort votes in the last survey: (a) whole-body thermal sensation, (b) local thermal sensation, (c) whole-body thermal comfort, and (d) local thermal comfort.

3.3.2 Thermal acceptability and preference

Fig. 10 illustrates changes in percentages of acceptable votes (votes on “Slightly acceptable”, “Acceptable”, and “Totally acceptable”) and percentages of prefer-cooler votes (votes on preference “Slightly cooler”, “Cooler” and “Much cooler”) over time. Whatever the condition was, the final acceptable rate was higher than 80% and even 90%, and the prefer-cooler rate was close to 0. In Fig. 10(a) and (b), before the control period, acceptable rates in conditions of 28 or 30°C initial indoor temperatures were lower than 80%. With the free-controlled fan, about 80% of subjects accepted the ambient environment within five minutes since the control period started. While with the always-on fan, more than 80% of subjects immediately felt acceptable at the beginning of the control period due to the higher air movement. In addition, the acceptable rates reached 90% in conditions with the AC thermostat change only. In comparison, the acceptable rates reached 100% in conditions when fan adjustments available, even at higher ambient temperatures. In Fig. 10(c) and (d), for all test conditions (except the condition 30°C N+A), at the end of the test periods, the percentage of subjects preferring to be cooler reached about 10% or lower.

Fig. 10. Changes in percentages of acceptable votes in (a) the non-limited phase and (b) the non-limited phase, and percentages of prefer-cooler votes in (c) the non-limited phase and (d) the non-limited phase.

3.3.3 Correlation between AC-use behaviors and psychological responses

Fig. 11 illustrates the distribution of AC-use behaviors (no change on AC setpoint vs. requesting lowering the setpoint) based on thermal sensation votes (sensation = 0, 1, 2, 3). The results are separated into the 12 tested conditions listed in Table 1 (n is the number of total sensation votes in each condition). In Fig. 11(a), when subjects were neutral, the request to further lowering the AC thermostat is low, mostly lower than 10%. When subjects felt slightly warm (Fig. 11(b)), when asked whether they would like to adjust the AC thermostat, nearly all of them preferred to lower it. The results are the same when they were warm or hot.

Fig. 11. Percentages of subjects requesting to lower thermostat for neutral to warm thermal sensation categories.

Correlations between AC-use behaviors and psychological responses (thermal comfort and acceptability) are represented in Fig. 12, and models are listed in Table 5. An interesting finding is that the associations between AC-use behaviors and psychological responses exerted high similarity in different conditions (fitted lines are almost the same). In Fig. 12(a), every 10% increase in the percentage of subjects on the uncomfortable side (slightly uncomfortable, uncomfortable, and very uncomfortable) results in a 10-15% increase in the percentage of subjects requesting to turn down the thermostat. In Fig. 12 (b), every 10% decrease in the percentage of subjects on the acceptable side results in a 15-20% increase in the percentage of preference to turn down the thermostat.

Fig. 12. Percentages of subjects turning down thermostat with percentages of subjects (a) on the uncomfortable side, and (b) on the acceptable side.

Table 5. Regression model parameters of AC-use behaviors and psychological responses.

Dependent vs. independent variable ¹	Condition	Slope (a)	Intercept (b)	R ²
Percentage of turning down thermostat vs. percentage of subjects on the uncomfortable side	N+A	1.459	0.036	0.88
	F+A	1.256	0.060	0.88
	On+A	1.417	0.019	0.85
	F+L	1.217	0.121	0.84
	On+L	1.127	0.029	0.54
Percentages of turning down thermostat vs. percentages of subjects on the acceptable side	N+A	-1.989	2.116	0.50
	F+A	-2.035	2.179	0.78
	On+A	-1.639	1.735	0.50
	F+L	-2.069	2.281	0.84
	On+L	-1.925	2.034	0.54

¹: Model format: $y = a \times x + b$, where y is the dependent variable, x is the independent variable.

4 Discussion

4.1 different environments and similar requirements

Can the elevated air movement further improves comfort when people already have an adjustable AC thermostat? As shown in Fig. 9, the final comfort status achieved 100% comfortable rate for all the 9 conditions when the fan was used, which is higher than when subjects only had an adjustable thermostat (about 90% comfortable rate). Also, in Fig. 10, adding a fan realized the 100% acceptable rate, which is higher than the acceptable rate with only an adjustable thermostat. Considering subjects selected higher indoor temperatures with the fan (see Fig. 3), it is clear that in even warmer environments, the elevated air movement can realize better comfort than using AC alone.

How much do people rely on AC thermostat lowering when elevated air movement is available? Fig. 8, 9, and 10 indicate that the majority of subjects reached a similar final status, regardless of cooling strategies (AC or fans). Since the subjects could control both AC and the fan, the final status of subjects can be regarded as what they preferred. Moreover, the corresponding final AC thermostat adjustment request was almost zero (Fig. 4). This means that when elevated air movement is working, the reliance of subjects on AC-use depends on the gap between their current and preferred thermal status. If the air movement effectively removes the warm discomfort of the majority of people, AC-use is not needed, and the selected indoor temperatures are higher than when without the air movement; if the air movement is not available or sufficient, people will continue using AC to reduce the warm discomfort. Therefore, in practice, it is better to first offer air movement, like an always-on fan, to fast and efficiently reduce the warm discomfort immediately before people use AC thermostat.

4.2 Fixed or adjustable? A balance between comfort and energy-efficiency

Elevating indoor comfort temperatures contributes to energy savings in summer. Many previous studies indicate that comfort temperatures can be elevated with increased air speed. For example, Humphreys' equation [26] predicts a 3-K increase in comfort temperatures with 0.8 m/s air speed. In the review of Zhang et al. [27] on personal comfort systems (lab studies), 0.6-1 m/s air speed is predicted to result in 3-5 K increase in comfortable temperatures. According to our previous review on many field studies [1], a 3-K increase in neutral temperatures was achieved averagely with

elevated air speed in practice. ASHRAE Standard 55 [28] also indicates that the operative temperature can be extended 3 K with about 1 m/s. In this study, when we setup the ambient temperature high at 30°C, when the subject chose the air movement around 1 m/s, the set-point extension is also about 3 K (2.9 and 3.2 K) compared with no fan conditions. This is very interesting that, when the space condition and control strategy are designed well (e.g. initial ambient temperature is warm, 30°C, and kept fan-on first before lowering the AC set-points) and people had control on both AC set-points and fan speed, they still increased about 3 K of ambient temperatures while keeping the air movement around 1 m/s. Of course when the initial ambient temperature is low (e.g. 26 and 28°C), the set-point extension is smaller than 3 K, with smaller air movement levels as well.

How to balance comfort and energy-efficiency in buildings with occupant-controlled AC thermostat? As compared with the N+A condition where subjects only had the adjustable thermostat, offering occupants free-controlled fans (F+A condition) helps increase the final chosen indoor temperature. However, the increase is no higher than 2°C. An always-on ceiling fan (On+A condition) enables a 2.5-3°C elevation of indoor temperatures, and at a higher thermal comfort level. Limiting the indoor set-point temperature at 28°C (conditions F+L and On+L) indeed exerts a more significant energy-saving possibility (3°C higher than N+A conditions). However, limiting the set-point temperature of the AC thermostat may not meet individuals' comfort requirements due to the significant individual differences. In summary, offering controllable but always-on fans is the best choice for achieving a balance between comfort and energy-efficiency.

4.3 Limitations

The limitations of this study are described below:

(1) In the experimental plan, we did not want subjects to see the ambient temperatures. Therefore, we designed a way that the thermostat change was done via the communication between subjects and researchers. Subjects were asked whether they would prefer to make an adjustment and provide degrees of the adjustment after each comfort survey, which happened every 1-2 min at the beginning and several minutes later in the test period. This setpoint adjusting preference question serves almost like a reminder to people about lowering the setpoint, which might have some difference from the AC thermostat change behavior in real buildings.

(2) Subjects used AC without paying any fees. Thus the results of this study are more proper for conditions where occupants use free AC, such as hotels (customers do not pay for using AC directly) and office buildings (employers pay for AC-use rather than employees). No economic factors are involved in this study.

(3) We found that more than 90% of subjects with the adjustable thermostat felt neutral and comfortable and the indoor set-points can be elevated by 2-3°C with ceiling fans. These findings are consistent with our previous study in a two-person room [24], which means the results might be still valid in shared spaces with limited number of occupants and can be used as the reference for the AC controls. For a large room, setting multiple or large ceiling fans could generate high air speed for a large area with multiple occupants [29]. Nonetheless, more studies in shared space with more occupants should be done to validate the findings of this study.

(4) This study only investigated AC-use behaviors with a ceiling fan in summer, and we don't know whether the AC-use behaviors were similar in winter. For promoting lower set-points in rooms with adjustable thermostat for energy efficiency in winter, a possible way is to use local heating systems and devices which enable people's comfort in cool environments as described in [30-34] (but without adjustable thermostat). No detailed information could be found

regarding using local heating for reducing AC-use behaviors in winter.

5 Conclusions

In this study, subjects had an AC thermostat, and an adjustable ceiling fan with/without some use limitations. The main conclusions are summarized below:

(1) Subjects without the ceiling fan would use AC to lower indoor temperatures to about 25.5°C on average, which was about 2°C and 3°C lower than when the ceiling fan was freely used and kept always-on, respectively.

(2) When the fan was always-on (on at the beginning of the control period), the final fan speeds were about double the speeds for conditions starting with fan speed zero. These higher speeds made subjects actively selected indoor temperatures higher than 28°C, and they were still comfortable.

(3) In all conditions, the mean skin temperatures of subjects were 34.0-34.1°C finally, which indicates that subjects preferred the same physiological status with different ways to cool themselves.

(4) Subjects with adjustable AC and fans had similar comfort requirements in different conditions. Combining adjustable AC thermostat and fans can achieve equal or even better comfort than using AC alone.

(5) Through the comparison of different conditions, offering subjects adjustable and always-on fans is the balanced choice to achieve comfort and energy efficiency in buildings with occupant-controlled AC thermostat.

Acknowledgments

This study was sponsored by the National Natural Science Foundation of China (Project No. 51878255) and the China Scholarship Council (No. 201706130019). The authors would also like to express heartfelt thanks to all subjects who participated in our experiments.

References

- [1] Y. He, W. Chen, Z. Wang, H. Zhang, Review of fan-use rates in field studies and their effects on thermal comfort, energy conservation, and human productivity, *Energy Build.*, 194 (2019) 140-162.
- [2] T. Uno, S. Hokoi, E.S. Nastiti, Survey on thermal environment in residences in Surabaya, Indonesia: use of air conditioner, *Journal of Asian Architecture and Building Engineering*, 2 (2) (2003) b15-b21.
- [3] B. Yang, T. Olofsson, A questionnaire survey on sleep environment conditioned by different cooling modes in multistorey residential buildings of Singapore, *Indoor and Built Environment*, 26 (1) (2017) 21-31.
- [4] H. Imagawa, H.B. Rijal, Field survey of the thermal comfort, quality of sleep and typical occupant behaviour in the bedrooms of Japanese houses during the hot and humid season, *Architectural Science Review*, 58 (1) (2015) 11-23.
- [5] Y. Song, Y. Sun, S. Luo, J. Hou, J. Kim, T. Parkinson, R. de Dear, Indoor environment and adaptive thermal comfort models in residential buildings in Tianjin, China, *Procedia Engineering*, 205 (2017) 1627-1634.
- [6] Y. He, N. Li, J. Peng, W. Zhang, Y. Li, Field study on adaptive comfort in air conditioned dormitories of university with hot-humid climate in summer, *Energy Build.*, 119 (2016) 1-12.
- [7] W. Liu, Y. Zheng, Q. Deng, L. Yang, Human thermal adaptive behaviour in naturally ventilated offices for different outdoor air temperatures: A case study in Changsha China, *Build. Environ.*, 50 (2012) 76-89.
- [8] H.B. Rijal, M.A. Humphreys, J.F. Nicol, Understanding occupant behaviour: the use of controls in mixed-mode office buildings, *Building Research & Information*, 37 (4) (2009) 381-396.

- [9] M. Indraganti, R. Ooka, H.B. Rijal, Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender, *Energy Build.*, 103 (2015) 284-295.
- [10] J. Kim, R. de Dear, T. Parkinson, C. Candido, Understanding patterns of adaptive comfort behaviour in the Sydney mixed-mode residential context, *Energy Build.*, 141 (2017) 274-283.
- [11] M. Indraganti, Thermal comfort in apartments in India: Adaptive use of environmental controls and hindrances, *Renewable Energy*, 36 (4) (2011) 1182-1189.
- [12] L. Daniel, 'We like to live in the weather': Cooling practices in naturally ventilated dwellings in Darwin, Australia, *Energy Build.*, 158 (2018) 549-557.
- [13] S. Chen, Y. Zhuang, J. Zhang, Y. Fu, H. Zhang, Statistical Characteristics of Usage Behavior of Air Conditioners in The University Students' Dormitories, *Procedia Engineering*, 205 (2017) 3593-3598.
- [14] T. Nakaya, N. Matsubara, Y. Kurazumi, Use of occupant behaviour to control the indoor climate in Japanese residences, in: *Proceedings of conference: Air Conditioning and the Low Carbon Cooling Challenge*, Windsor, UK, 2008, pp. 27-29.
- [15] X. Zhou, D. Yan, J. An, T. Hong, X. Shi, X. Jin, Comparative study of air-conditioning energy use of four office buildings in China and USA, *Energy Build.*, 169 (2018) 344-352.
- [16] G.Y. Yun, K. Steemers, Behavioural, physical and socio-economic factors in household cooling energy consumption, *Applied Energy*, 88 (6) (2011) 2191-2200.
- [17] X. Ren, D. Yan, C. Wang, Air-conditioning usage conditional probability model for residential buildings, *Build. Environ.*, 81 (2014) 172-182.
- [18] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system, *Build. Environ.*, 45 (1) (2010) 29-39.
- [19] J. Pantelic, S. Liu, L. Pistore, D. Licina, M. Vannucci, S. Sadrizadeh, A. Ghahramani, B. Gilligan, E. Sternberg, K. Kampschroer, Personal CO₂ cloud: laboratory measurements of metabolic CO₂ inhalation zone concentration and dispersion in a typical office desk setting, *Journal of Exposure Science & Environmental Epidemiology*, 30 (2) (2020) 328-337.
- [20] M. He, N. Li, Y. He, D. He, C. Song, The influence of personally controlled desk fan on comfort and energy consumption in hot and humid environments, *Build. Environ.*, 123 (2017) 378-389.
- [21] Y. He, X. Wang, N. Li, M. He, D. He, K. Wang, Cooling ceiling assisted by desk fans for comfort in hot-humid environment, *Build. Environ.*, 122 (2017) 23-34.
- [22] Y. He, N. Li, X. Wang, M. He, D. He, Comfort, Energy Efficiency and Adoption of Personal Cooling Systems in Warm Environments: A Field Experimental Study, *International journal of environmental research and public health*, 14 (11) (2017) 1408.
- [23] C. Karmann, F. Bauman, P. Raftery, S. Schiavon, M. Koupriyanov, Effect of acoustical clouds coverage and air movement on radiant chilled ceiling cooling capacity, *Energy Build.*, 158 (2018) 939-949.
- [24] Y. He, N. Li, N. Li, J. Li, J. Yan, C. Tan, Control behaviors and thermal comfort in a shared room with desk fans and adjustable thermostat, *Build. Environ.*, 136 (2018) 213-226.
- [25] Y. Houdas, E. Ring, *Human body temperature: its measurement and regulation*, Springer Science & Business Media, 2013.
- [26] M. Humphreys, A simple theoretical derivation of thermal comfort conditions, *JHVE*, 38 (1970) 95-98.

- [27] H. Zhang, E. Arens, Y. Zhai, A review of the corrective power of personal comfort systems in non-neutral ambient environments, *Building & Environment*, 91 (2015) 15–41.
- [28] ANSI/ASHRAE, Standard 55-2017: Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA, (2017).
- [29] P. Raftery, J. Fizer, W. Chen, Y. He, H. Zhang, E. Arens, S. Schiavon, G. Paliaga, Ceiling fans: Predicting indoor air speeds based on full scale laboratory measurements, *Build. Environ.*, 155 (2019) 210-223.
- [30] H. Zhang, E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y.C. Zhai, M. Pigman, Using footwarmers in offices for thermal comfort and energy savings, *Energy Build.*, 104 (2015) 233-243.
- [31] Y. He, N. Li, W. Zhang, L. Zhou, Thermal comfort of sellers with a kind of traditional personal heating device (Huotong) in marketplace in winter, *Build. Environ.*, 106 (2016) 219-228.
- [32] Y. He, N. Li, L. Zhou, K. Wang, W. Zhang, Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel), *Build. Environ.*, 112 (2017) 285-295.
- [33] Y. He, X. Wang, N. Li, M. He, D. He, Heating chair assisted by leg-warmer: A potential way to achieve better thermal comfort and greater energy conservation in winter, *Energy Build.*, 158 (2018) 1106-1116.
- [34] L. Zhou, N. Li, Y. He, J. Peng, C. Wang, Y. A, A field survey on thermal comfort and energy consumption of traditional electric heating devices (Huo Xiang) for residents in regions without central heating systems in China, *Energy Build.*, 196 (2019) 134-144.