Effects of indoor environmental factors on human metabolic CO2 emission rate and physiological responses

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Master Thesis

Effects of Indoor Environmental Factors on Human Metabolic CO_2 Emission Rate and Physiological Responses

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Abstract

Carbon dioxide (CO_2) concentration is an important indicator of indoor air quality. CO_2 is a pollutant exhaled only by humans in non-industrial environments. Existing formulas for predicting CO_2 emission rates, ISO 8996 and ASTM DS 6245, which involve the main parameters such as physical activity, age, gender, weight, and diet, are parameters related to the occupants, do not consider the effects of the indoor environment on CO_2 emission rates. Therefore, this study aims to discuss the effects of indoor environmental factors, including indoor temperature and CO_2 concentration, on CO_2 emission rates. Based on this research purpose, two experiments on CO_2 emission rates were designed and conducted.

The first experiment investigated the effects of indoor temperature and activity level on CO_2 emission rates, and the experiment was set up with four different indoor temperatures and three different activity levels. The results showed that the CO_2 emission rate increased dramatically with the increase in physical activity, and the CO_2 emission rate increased with indoor temperature at higher physical activity. At low physical activity levels, there was no significant relationship between CO_2 emission rate and indoor temperature. In addition, thermal sensation increased significantly with temperature and activity level, and temperature had less effect on thermal comfort at high activity levels compared to low activity levels. Females appeared to be more sensitive to temperature and had lower thermal comfort in the same indoor environment.

The second experiment investigated the effect of indoor CO_2 concentration on CO_2 emission rates. Two measurement methods, indirect calorimetry and chamber method, were used in the experiment, and the indoor CO_2 concentration was controlled by reducing the ventilation rate and dosing pure CO_2 into the chamber, respectively, to achieve three different concentration levels. The results showed that the indirect calorimetry is more accurate than the chamber method. Measurements by indirect calorimetry showed that the CO_2 emission rate decreased gradually with increasing CO_2 concentration, and the decrease in CO_2 emission rate was greater when the ventilation rate was lowered, which was considered to be also affected by the increase in the bioeffluents concentration. In contrast, measurements by the chamber method showed that the CO_2 emission rate decreased with increasing CO_2 concentration when the ventilation rate was reduced, and the CO_2 emission rate decreased after pure CO_2 was introduced into the chamber, but did not decrease with increasing CO_2 concentration.

This study has implications for optimizing the prediction equations for the CO_2 emission rates.

Contents

1 Introduction

1.1 Background

In modern society, people spend about 80% of their time in indoor environments, so indoor air quality is essential, and carbon dioxide (CO_2) concentration is one of the most important indicators of indoor air quality, also carbon dioxide is a major human metabolite.

In outdoor environments, the CO_2 concentration is about 400 ppm, and the indoor CO_2 concentration is an important parameter for ventilation design and monitoring of air quality levels. After German hygienists made a recommendation to use 1000 ppm as a hygienic limit value in 1858 [1-1], indoor CO_2 concentrations below 1000 ppm are regarded as a marker of good indoor air quality that is harmless. CO_2 levels between 1000-2000 ppm represent an elevated interval of harmfulness and should be subject to increased ventilation rate or ventilation efficiency, while carbon dioxide between 2000-5000 ppm requires attention for elevated risk [1-2].

Previously, it was widely predicted that CO_2 concentrations below 5000 ppm would not affect blood CO_2. However, reports in recent years have shown that the partial pressure of CO_2 in the blood is also elevated in the low concentration range of 500-4000 ppm, with changes in heart rate variability and terminal circulation [1-3, 1-4]. In several publications on CO_2 concentrations and health effects in office buildings, CO_2 below 800 ppm, the risk of sick building syndrome (SBS) symptoms decreased with lower CO_2 concentrations in half of the studies[1-5].In such a context, the prediction of CO_2 emission rates from the human body is important to maintain a comfortable indoor carbon dioxide concentration.

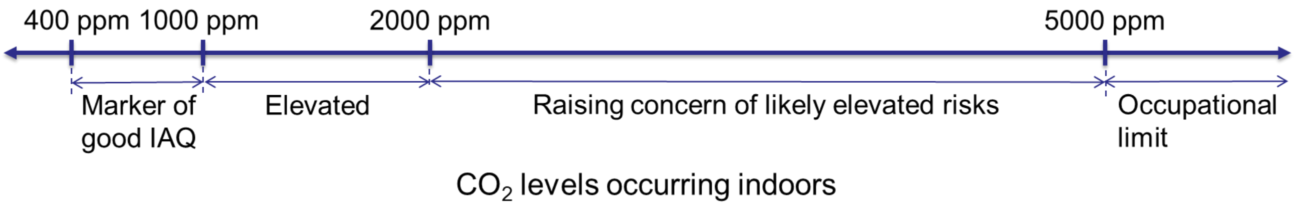

Fig. 1.1 Indoor air quality evaluation by CO_2 concentration

Existing formulas for predicting CO_2 emission rates, the models in the ASHRAE Handbook [1-6] and ASTM DS 6245 [1-7] are the most representative, and the models in the ASHRAE Handbook [1-6] are covered by ISO 8996:2021 [1-8]. The metabolic rate can be calculated regarding the oxygen consumption, CO_2 emission, and body surface area,

$$RQ = \frac{\dot{V}CO_2}{\dot{V}O_2} \tag{1.1}$$

$$EE = (0.23RQ + 0.77) \times 5.88 \tag{1.2}$$

$$M = EE \times \dot{V}O_2 \times \frac{1}{A_{D_u}} \tag{1.3}$$

Here, RQ is the respiratory quotient, is the ratio of CO_2 emissions (h^{-1}) to O_2 consumption (h^{-1}), generally around 0.85. EE is the energetic equivalent ($W{\cdot}h{\cdot}l\ O_2^{-1}$), M is the metabolic rate (W/m^2), the reference values are shown in Table 1.1, A_{D_u} is the body surface area (m^2), it can be calculated by the Du-Bois formula [1-9],

$$A_{D_u} = 0.202 \times Weight^{0.425} \times Height^{0.725} \tag{1.4}$$

The prediction formula for the CO_2 emission rate can be obtained by transforming the relationship between VO_2, VCO_2, and RQ,

$$VCO_2 = RQ\frac{A_d M}{5.88(0.23RQ + 0.77)} \tag{1.5}$$

Also, ASTM D6245-18 [1-7] predicts the CO_2 emission rate based on Persily and Jonge's formula [1-10] with the following equation,

$$VCO_2 = RQ \times BMR \times M' \times 0.000569 \tag{1.6}$$

Here, BMR is the basal metabolic rate (MJ/day), which is determined by age, gender, and body weight, the equations for calculating BMR are shown in Table 1.2. M' is the metabolic rate per unit of surface area (Met), the values of office activities can be found in Table 1.3 and Table 1.4, which are extracted from ASTM D6245-18 [1-7] and 2024 Adult Compendium of Physical Activities [1-11].

In summary, the main parameters involved in the prediction formulas, including activity level, age, gender, body weight, and diet, are all relevant to the indoor personnel themselves and do not consider the effect of environmental factors on human CO_2 emission rates.

Therefore, this study aims to discuss the effects of indoor environmental factors, including indoor temperature and carbon dioxide concentration, on human CO_2 emission rates, and based on this research objective, two experiments on human carbon dioxide emission rates were carried out, first one discussed the impact of different air temperatures on CO_2 emission rates at different physical activity levels, and the second one discussed impact of different indoor CO_2 concentration on CO_2 emission rates.

Table. 1.1 Classification of metabolic rate by category given in ISO 8996:2021 [1-8]

Class	Range of metabolic rates (W)	Examples
0 Resting	100 to 125	Resting, sitting at ease
1 Low metabolic rate	125 to 235	Sedentary activity (office, dwelling, school, laboratory: writing, typing, drawing, sewing, book keeping). Standing, light activity (shopping, laboratory, light industry). Hand and arm work (small bench tools, inspection, assembly or sorting of light materials). Light arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). Machining with low power tools [drilling (small parts), milling (small parts), coil winding, sawing]. Casual walking (2 km·h−1) on a level, even path, solid with load ≤ 30 kg.
2 Moderate metabolic rate	235 to 360	Sustained hand and arm work (hammering in nails, filing, loading, polishing). Arm and leg work (off-road operation of lorries, tractors or construction equipment). Arm and trunk work (work with pneumatic hammer, tractor assembly, plastering). Weeding, hoeing, picking fruits or vegetables. Pushing or pulling lightweight carts or wheelbarrows. Bricklaying, 5 bricks/min. Intermittent handling of moderately heavy material. Walking (2,5 to 5 km · h−1) on a level, even path, solid with load ≤ 20 kg. Walking (2,5 to 3 km · h−1) on levelled but irregular to unstable ground with load ≤ 20 kg. Walking (≤2,5 km·h−1) on stable ground uphill (≤5 %) with load ≤ 20 kg.
3 High metabolic rate	360 to 465	Intense arm and trunk work with hand tools or machines. Carrying heavy material, shovelling. Sledgehammer work, sawing, planing or chiselling hard wood, hand mowing, digging. Walking (5,5 to 7 km·h−1) on a level, even path, solid with load ≤ 20 kg. Walking (3,5 to 5 km · h−1) on levelled but irregular to unstable ground with load ≤ 20 kg. Walking (2,5 to 3 km·h−1) on stable ground uphill (≤5 %) with load ≤ 10 kg. Pushing or pulling heavily loaded hand carts or wheelbarrows. Chipping castings, concrete block laying.
4 Very high metabolic rate	> 465	Intense activity at fast to maximum pace. Working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder. Walking (>7 km·h−1) on a level, even path, solid, with or without load. Walking (>5 km·h−1) on levelled but irregular to unstable ground with or without

		load. Walking (>3 km·h−1) on stable ground uphill (≥5 %) with or without load. Running (>6 km·h−1).

Table 1.2 Equations for calculating BMR given in ASTM D6245-18 [1-7]

Age (y)	**BMR: MJ/Day**	
	Males	**Females**
<3	0.249 m – 0.127	0.244 m – 0.130
3 to 10	0.095 m + 2.110	0.085 m +2.033
10 to 18	0.074 m + 2.754	0.056 m +2.898
18 to 30	0.063 m +2.896	0.062 m + 2.036
30 to 60	0.048 m +3.653	0.034 m +3.538
≥60	0.049 m + 2.459	0.038 m + 2.755

Table. 1.3 Metabolic rates (*M* in Met) for various physical activities given in ASTM D6245-18 [1-7]

Activity	**Metabolic rates (Met)**	
	Males	**Females**
Climbing stairs	5.0	
Eating and drinking	1.4	1.6
Office worker – Filing	1.3	1.5
Office worker – Reading	1.3	1.5
Office worker – Sitting at desk	1.3	
Office worker – Standing/moving around	1.6	
Office worker – Typing	1.8	1.8
Office worker – Writing	1.4	1.4
Reading	1.22	1.25
Sitting quietly	1.2	1.2
Standing	1.4	1.5
Walking around/strolling	2.0 to 2.2	2.1 to 2.9
Walking quickly	3.8	
Walking slowly	2.8 to 3.0	3.0

Table. 1.4 MET value from 2024 Adult Compendium of Physical Activities [1-11]

Activity Description	**MET Value**
Sitting quietly, general	1.0
Sitting quietly, fidgeting, general, fidgeting hands	1.5
Sitting, fidget feet	1.8
Sitting at a desk, resting head in hands	1.3
Standing quietly (standing in a line)	1.3
Standing (fidgeting)	1.5
Active workstation, treadmill desk, walking slowly 1.0 mph or less	2.0
Active workstation, treadmill desk, walking 1.0 - 2.0 mph	2.8
Sitting tasks, light effort (e.g., office work, chemistry lab work, light assembly repair, watch repair, reading, desk work)	1.5
Sitting, computer work	1.3
Sitting meetings, light effort, general, and/or with talking involved (e.g., eating at a business meeting)	1.3
Standing tasks, light effort (e.g., bartending, store clerk, assembling, filing, duplicating, librarian, putting up a Christmas tree, standing and talking at work, changing clothes when teaching physical education)	1.8
Walking on job, less than 2.0 mph, very slow speed, in office or lab area	2.0
Walking on job, 2.8 to 3.4 mph, in office, moderate speed, not carrying anything	3.8
Walking on job, 2.5 mph, slow speed, carrying light objects less than 25 lbs	3.5
Walking, gathering things at work, ready to leave	3.0
Walking, 2.5 mph, slow speed, carrying heavy objects more than 25 lbs	3.8
Walking, 3.0 mph, moderately and carrying light objects less than 25 lbs	4.5
Eating, sitting	1.5
Walking, treadmill, less than 1.0 mph, 0% grade	2.1
Walking, treadmill, 1.0 mph, 0% grade	2.3
Walking, treadmill, 1.2 to 1.9 mph (1.9 to 3.0 km/h), 0% grade	2.8
Walking, treadmill, 2.0 to 2.4 mph (3.2 to 3.9 km/h), 0% grade	3.0

1.2 Relevant previous researches

In related studies, many researchers have conducted experiments related to the factors affecting the human metabolic rate, which is closely related to the CO_2 emission rate, and has a great reference value for the study of the CO_2 emission rate.

Effect of indoor temperature on human metabolic rate, Luo et al. [1-12] (2016) investigated the effect of indoor thermal conditions on the metabolic rate by conducting experiments in a climatic chamber with temperatures ranging from cold to hot, two levels of clothing insulation were set, and consisting of physiological measurements and subjective questionnaires, the results showed that human metabolic rate was significantly affected by ambient temperature and clothing insulation, with neutral thermal sensations corresponding to the lowest metabolic values, and an increase in metabolic rate when thermal sensations deviated from neutral to cold or warm. It can be seen that indoor temperature has an impact on human thermal sensation, which in turn affects human metabolic rate and CO_2 emission rate. Kuga et al. [1-13] (2021) conducted similar experiments and confirmed this idea.

However, some studies [1-14, 1-15] have shown that there can be some differences between men and women regarding thermal perception of the indoor environment. Yang et al. [1-16] (2021) investigated the effects of different temperatures on human metabolic rate and subjective thermal comfort of a sedentary state and discussed the gender differences. They found that females had lower metabolic rates than males at all temperatures. Also, females were more likely to feel cool and uncomfortable than males under cool indoor temperatures. It was speculated that this was due to lower metabolic rates and skin temperatures of females. In contrast, males were more likely to feel warm and uncomfortable under warmer indoor temperatures, which was speculated to be due to high metabolic rates and skin humidity. Gao et al. [1-17] (2023) measured metabolic rates under 18 activities in Chinese men and women aged 20-69 years and showed that women had lower metabolic thermogenesis rates than men in all activities regardless of age.

In addition to indoor temperature, activity intensity can have a significant impact on CO_2 emission rate as well as human metabolic rate, with corresponding effects on thermal sensation and thermal evaluation as addressed above. This was confirmed by a study by Ji et al. [1-18] (2018), who measured cumulative CO_2 emissions in a closed room and had subjects ride an exercise bike for 8 minutes at varying intensities and then remain seated for 22 minutes. Their results showed that the body needed 5-6 minutes before reaching a new level of exercise metabolism and 7-9 minutes to recover from exercise to a sedentary state and that drastic changes in metabolic rate significantly affected subjects' thermal sensation and thermal comfort. Zhai et al. [1-19] (2018) measured the metabolic rates of 60 college students in a total of 13 activities under lying down, sitting, and standing states. Compared to the data obtained from the measurements, the prediction metabolic rates in the ISO and ASHRAE standards were overestimated by 10-20% for sitting and standing, underestimated by 5-9% for walking in the ISO, and underestimated by more than 20% in the ASHRAE. And no gender differences were found in the metabolic rates tested, this result is different from the findings in the study above. Other studies support this conclusion regarding the discrepancy between measured data and metabolic rates obtained based on standardized predictions. Nomoto et al. [1-20] (2021) measured the accurate metabolic rates of Japanese people performing different office activities using accurate body surface area data obtained from three-dimensional measurements and indirect calorimetry, and the results were all significantly lower than the standardized values in the current international standards. Furthermore, the metabolic rates of females were generally lower than males, and there was a significant difference in the levels of all activities except walking between males and females. Liu et al. [1-21] (2023) investigated the effects of activity intensity, ambient temperature, and clothing insulation on metabolic rate through experiments in a climatic chamber, and their results showed that metabolic rate was positively correlated with activity intensity under a variety of ambient temperature and clothing insulation conditions.

In the same way as the effect on human metabolic rate, indoor temperature can affect the CO_2 emission rate of occupants. Sakamoto et al. [1-22] (2022) investigated the CO_2 emission rates of sedentary subjects performing light work under controlled exposure conditions and found that CO_2 emission rates increased with temperature when subjects felt warm but did not change with increases in relative humidity and ozone concentration. Similarly, gender differences and deviations from international standard projections are reflected in CO_2 emission rates. Yang et al. [1-23] (2020) measured CO_2 emission rates at 18 activities in subjects between the ages of 20 and 70 years by an indirect calorimetry system and showed that CO_2 emission rates increased significantly with increasing activity levels, but the effect of age was small. The gender differences were significant, females had lower CO_2 emission rates than males at the same level of activity, primarily due to lower body weights of females. The regression model developed from the data of this experiment to predict carbon dioxide emission rates differed significantly from the carbon dioxide emission rates predicted by the models in ASHRAE 62.1-16 and ASTM D6245-18, especially at higher activity levels.

Indoor CO_2 concentration, as an important indoor environmental parameter, affects human perception and physiological responses, Zhang et al. [1-24] (2017) investigated the effects of exposure to CO_2 and bioeffluents on humans, where subjects were exposed to environments with bioeffluents and CO_2 as well as pure CO_2 environments without bioeffluents, subjective ratings, physiological responses, and cognitive performance were measured. Perceptions of air quality were reduced in the presence of biofluids at 3000 ppm CO_2; headaches, fatigue, drowsiness, and difficulty in thinking were increased in intensity compared to the CO_2-only environment. The experimental results suggest that moderate concentrations of bioeffluents (rather than pure CO_2) can have detrimental effects on occupants during typical indoor exposures. In addition, during exposure to a 3000 ppm CO_2 environment, when CO_2 was added or ventilation was restricted, there was a greater increase in $ETCO_2$ and less of a decrease in heart rate than the changes that occurred under the 500 ppm reference condition. Kuga et al. [1-25] (2021) investigated the effects of indoor CO_2 concentration and indoor temperature on CO_2 emission rates and showed that CO_2 emission rates were higher at higher temperatures, where subjects felt warmer, and lower under all conditions where CO_2 concentration increased.

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2 Impact of indoor temperature on the CO_2 emission rates at different activity levels

2.1 Introduction

Human metabolic rate is closely related to the CO_2 emission rate, and there are several studies on the factors affecting human metabolic rate in past research. Luo et al.[2-1] (2016) and Yang et al.[2-2] (2021) measured the human metabolic rate at different indoor temperatures and discussed the relationship between metabolic rate and thermal sensation, where the metabolic rate was lowest when the thermal sensation was neutral and increased when the thermal sensation was skewed toward cold or warm. As well as gender differences in metabolic rate and thermal sensation, the average metabolic rate of females was lower than males at all different temperatures, and females were more likely to be uncomfortable at cooler temperatures, while males were more likely to be uncomfortable at warmer temperatures.

Ji et al. [2-3] (2018), Zhai et al. [2-4] (2018), Nomoto et al. [2-5] (2021), and Gao et al. [2-6] (2023), measured the human metabolic rate at different activity levels. The metabolic rates of females were also generally lower than males at different activity levels, and the measured data deviated to some extent from the values calculated by the prediction models in the ASHRAE Handbook [2-7] and ASTM DS 62451 [2-8].

However, fewer studies have been conducted so far on the CO_2 emission rate under the combined effect of indoor temperature and activity level. Therefore, this experiment aims to discuss the effect of temperature on the CO_2 emission rate under step-up activity level.

2.2 Experimental methods

2.2.1 Experimental environment and subject characteristics

This experiment was conducted in a well-ventilated classroom, where the indoor temperature was controlled at 17, 20, 25, and 28°C through the air conditioner in the room, and the air conditioner outflow was avoided as much as possible to affect the subjects. To avoid memory exposure affecting thermal sensation, the subjects rested for 20 minutes in another room with the temperature controlled at 26°C before each experiment. The experiments were conducted from late October to mid-December 2022 and were scheduled between 10 am and 5 pm.

A total of 14 subjects (7 males and 7 females) were enrolled in the experiment, they were asked to participate in all four experiments at different temperatures and to perform physiological measurements and subjective responses during the experiment. Subjects reported their age and height, and before each experiment, their weight and body fat rate were measured by a digital balance, the anthropometric data obtained from the measurements are shown in Table. 2.1. Males have a higher average BMI than females, but a lower body fat rate compared to females. Also, to avoid the effect of metabolism from digestion on CO_2 emission rates, subjects were asked to abstain from eating and drinking beverages other than water for 3 hours before each experiment.

Table. 2.1 Subjects' anthropometric information

	Age (years)	**Height (m)**	**Weight (kg)**	**BMI [2] (kg/m^2)**	**Body surface area [3] (m^2)**	**Body fat rate (%)**
All	24.4 ± 3.6 [1]	1.67 ± 0.07	63.3 ± 12.4	22.5 ± 3.8	1.71 ± 0.18	27.1 ± 6.3
Males	23.6 ± 3.1	1.72 ± 0.06	69.1 ± 10.5	23.2 ± 3.3	1.82 ± 0.13	24.1 ± 3.8
Females	25.1 ± 3.9	1.62 ± 0.04	57.6 ± 11.5	21.8 ± 4.1	1.60 ± 0.15	30.1 ± 6.9

[1] SD = standard deviation

[2] BMI [2-9] (Body Mass Index) = Weight (kg)/ [Height (m)]^2

[3] Body Surface Area (Du Bois's equation [2-10]) = 0.202×(Weight)$^{0.425}$×(Height)$^{0.725}$

2.2.2 Experimental procedures

The experimental flow is shown in Figure 2.1. Before the start of each experiment, subjects were asked to arrive early and change into uniform summer typical clothing consisting of a short-sleeved T-shirt and thin long pants, as well as the subject's underwear, socks, and athletic shoes, which in total clothing insulation of 0.5 clo according to the clo table in ASHRAE 55 [2-7]. Preparation for the experiments took place for approximately 20 minutes in a preparation room of a neutral thermal environment with a controlled room temperature of 26 °C and included wearing a heart sensor as well as skin temperature sensors and sitting still for rest. After the preparation, a comfort survey was conducted in the preparation room.

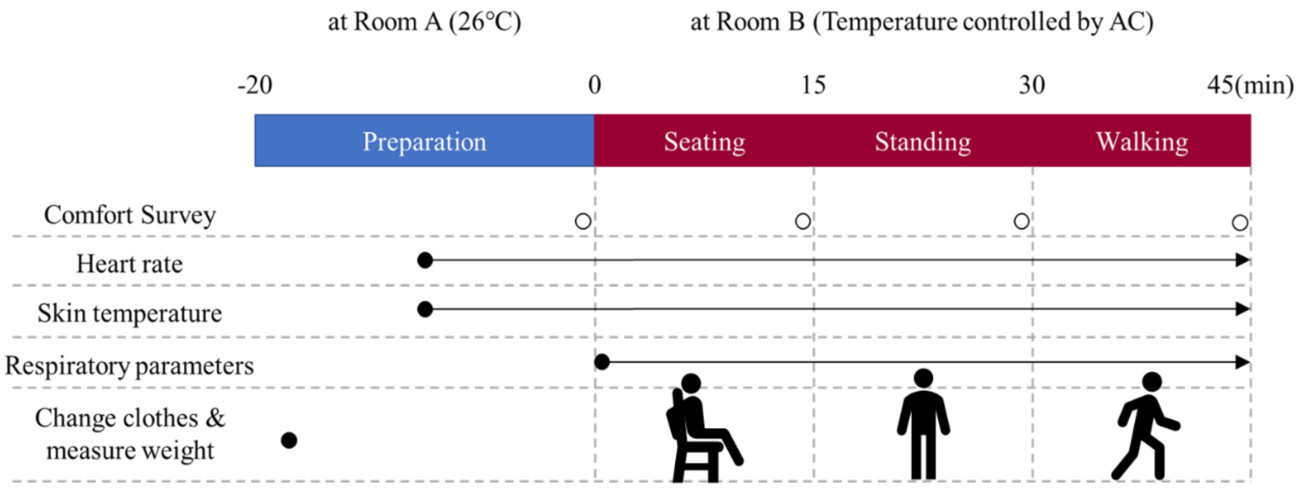
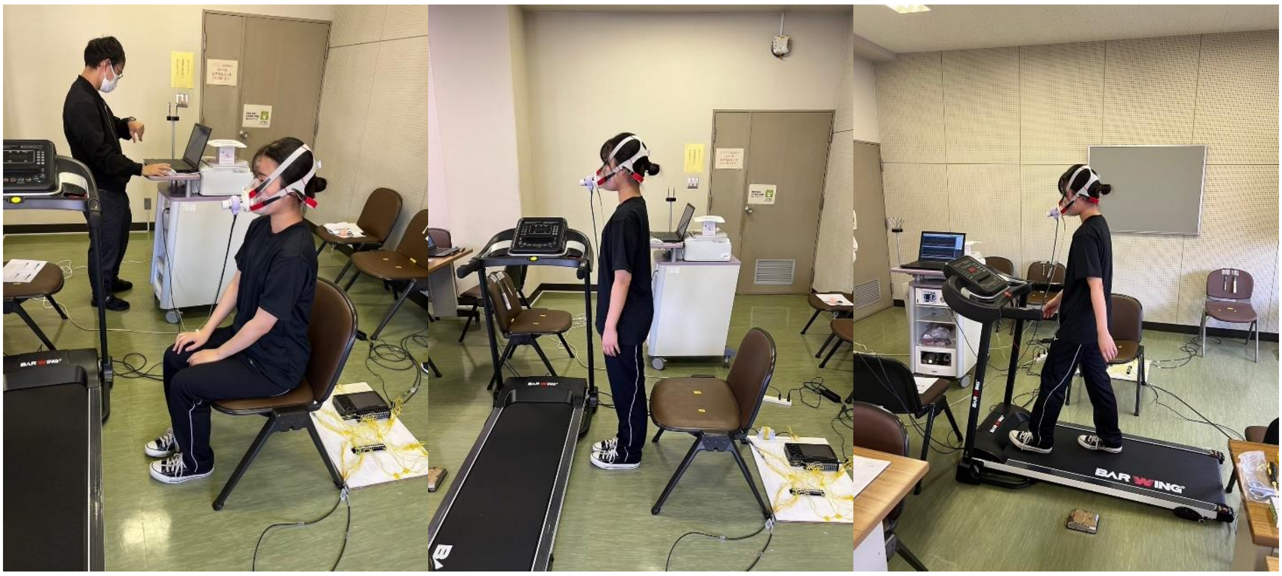


Fig. 2.1 Experimental procedure design

Subjects then entered the room, donned an indirect calorimeter to measure CO_2 emission rates, and began a 15-minute sitting down, 15-minute standing up, and 15-minute 2 km/h walking activity, which was performed on a treadmill. After the completion of each 15-minute activity, a comfort survey was conducted. The activity states during the experiments for the three different activity levels are shown in Fig. 2.2.



a. Sitting b. Standing c. Walking in 2km/h

Fig. 2.2 Different activity levels

2.2.3 Environmental and physiological measurements

Environmental measurements include room temperature, relative humidity, and CO_2 concentration. A temperature and humidity sensor and a CO_2 concentration sensor were set up in each of the four directions of 1.5-meter distance and 1-meter height in the northeast, southeast, southwest, and northwest directions of the subject's location, to monitor and record environmental parameters in real-time. The accuracy of temperature and humidity sensors and CO_2 concentration sensors is shown in Table 2.2.

Table. 2.2 Accuracy of physical monitoring instruments

Instrument	Parameter	Measuring range	Accuracy
HMP60	Air temperature	-40~+60°C	+10~+30°C ±0.5°C -40~+10°C & +30~+60°C ±0.6°C
	Relative Humidity (RH)	0~100%RH	+0~+40°C ±3%RH (0～90%RH) ±5%RH (90~100%RH) -40~0°C & +40~+60°C ±5%RH (0~90%RH) ±7%RH (90~100%RH)
GMP252	Carbon dioxide (CO_2)	0~10000ppm CO_2 (can measure up to 30000 ppm CO_2 but accuracy is lower)	0~3000ppm CO_2 ±40ppm CO_2 3000~10000ppm CO_2 ±2% 10000ppm~30000ppm CO_2 ±3.5%

Physiological measurements included respiratory parameters, heart rate, and skin temperature, all of which were continuously measured during the experiment. To avoid the effect of sudden changes in activity levels on physiological responses, all data were selected only for the last 10 minutes of each 15-minute activity.

The respiratory parameters are measured by the respiratory monitor AE-310S (Fig. 2.3 a), which uses a free fit mask (Fig. 2.3 b) covering the nose and mouth to capture the exhaled gases of the subject, and a hot-wire flowmeter to measure respiratory metabolism, which provides several parameters such as CO_2 emission rate, O_2 consumption, minute ventilation (the volume of gas inhaled or exhaled from a person in one minute), RQ (respiratory quotient, is the ratio of CO_2 emissions to O_2 consumption) and ETO_2 (end-tidal oxygen, O_2 concentration in an exhaled breath at the end of expiration), and the measurement accuracy of AE-310S is ±3%. The respiratory monitor works on the principle of indirect calorimetry, a method of measuring the body's carbon dioxide production and oxygen consumption to calculate the amount of body heat produced, with the advantages of high accuracy and low impact on the subject. The device measures data using the breath-by-breath method, which has the advantage that measurements can be made even if the inhaled gas varies randomly. Before each use of the device, it is necessary to check the respiratory gas sampling circuit and calibrate the flow sensor and gas flow meter, and replace the filter in the mask, clean the mask.

a. AE-310S b. free fit mask

Fig. 2.3 Respiratory monitor

The skin temperature was measured by the small wireless temperature sensor DS1922L (Fig. 2.4 a, thermal button), at ten different locations (Fig. 2.5) on the human body (including forehead, forehead, chest, back, upper arm, forearm, hand back, thigh, calf, ankle, and finger), and the sensors were attached to each location by skin-friendly adhesive tape to take measurements every 5 seconds, with a measurement accuracy of ±0.5°C. For the mean skin temperatures (T_{sk}), calculations were made using the following equation [2-11],

$$T_{sk} = 0.07T_{forehead} + 0.18T_{chest} + 0.18T_{back} + 0.07T_{upperarm} + 0.07T_{forearm} + 0.05T_{handback} + 0.19T_{thigh} + 0.13T_{calf} + 0.06T_{ankle} \quad (2.1)$$

a. DS1922L b. Polar H10

Fig. 2.4 Wireless temperature sensor and heart rate sensor

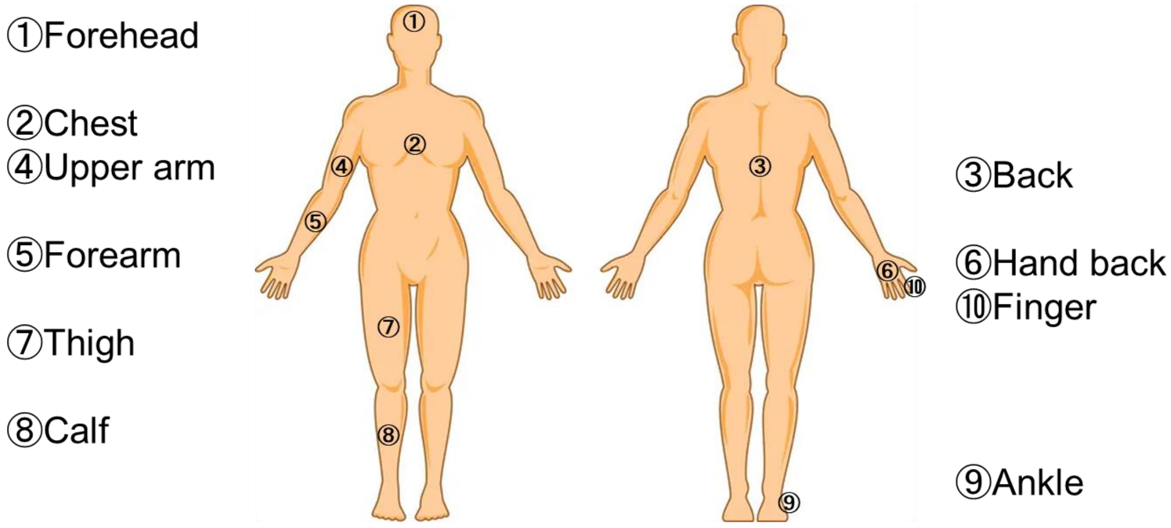


Fig. 2.5 Measurement point of skin temperature

The Polar H10 heart rate sensor was used to measure the subject's heart rate at a rate of one measurement per second. The sensor needed to be moistened with water and worn on the chest in direct contact with the skin to ensure its accuracy.

Table. 2.3 Measurement and calculation methods for all parameters of subjects

Parameter	**Measurement or calculation method**
Age, Body height	Self-report
Body weight, Body fat rate, BMI	Digital balance
Body surface area	Estimated by the Du-Bois equation
Physiological respiratory responses (CO_2 emission rate, respiratory quotient, minute ventilation, $ETCO_2$, etc.)	Respiratory monitor AE-310S (Indirect calorimeter)
Skin temperature	Wireless temperature sensor DS1922L (thermal button)
Heart rate	Polar H10

2.2.4 Subjective survey

As described in section 2.2.2 above, a subjective thermal comfort survey was administered at a total of four time points, before leaving the preparation room and after completing each 15-minute activity. The subjective questionnaire consisted of three sections, thermal sensation, thermal comfort, and thermal preference, and the contents are shown in Fig. 2.6. The questionnaire referred to the subjective questionnaire used by Yang et al. [2-2] (2021) in their study of metabolic rate and thermal comfort in young males and females at different temperatures.

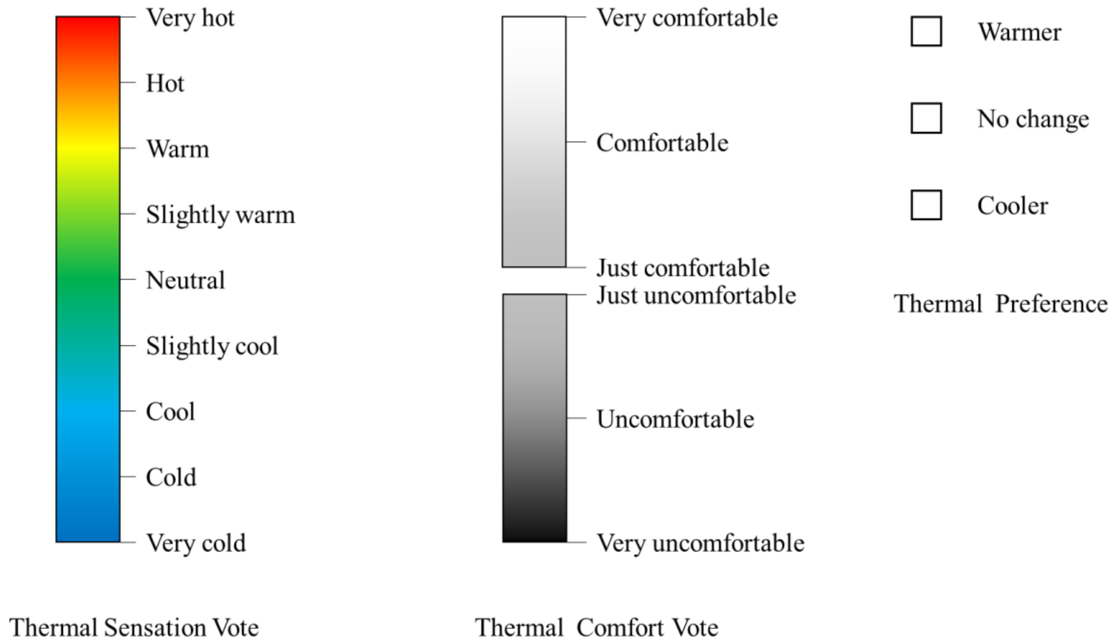


Fig.2.6 Sample subjective questionnaire

In the thermal sensation Vote, different from the 7-point scale in ASHRAE [2-7], this scale is divided into 9 points from very cold to very hot. The thermal comfort vote is divided into 6 levels, with "just acceptable" as the cut-off. The thermal preference is to choose whether you want the indoor environment to be "Warmer", "No change" or "Cooler".

In conducting the thermal sensation vote and the thermal comfort vote, the scale is used as a ruler, with lines drawn at the appropriate locations, and the votes are counted in the manner shown in Table 2.4.

Table. 2.4 Counting manner of thermal sensation vote and thermal comfort vote

Thermal sensation vote				**Thermal comfort vote**	
Very hot	+4	Cool	-2	Very comfortable	+4
Hot	+3	Cold	-3	Comfortable	+2
Warm	+2	Very cold	-4	Just comfortable	+0.01
Slightly warm	+1			Just uncomfortable	-0.01
Neutral	0			Uncomfortable	-2
Slightly cool	-1			Very uncomfortable	-4

2.3 Experimental results

2.3.1 Physiological responses

The average **CO_2 emission rates** at different indoor temperatures for the different activity levels are shown in Fig.2.7 and Fig. 2.8. It can be seen that the CO_2 emission rate during walking activity is much higher than that during sitting and standing activities due to the increased activity level. The CO_2 emission rate during walking activity is about 2.8 times that of sitting activity and 2.6 times that of standing activity, compared with the metabolic equivalent reference values given by the 2024 Adult Compendium of Physical Activities [2-12] (Table 2.5), sitting (1.0 MET) and walking by a treadmill in 2.0 km/h (2.8 MET) correspond to the reference values while standing (1.3 MET) is substantially lower than the reference values.

In both the sitting and standing activities, the CO_2 emission rates decreased from 17°C to 20°C, increased at 25°C, and then decreased again at 28°C. Compared with previous studies [2-1], the CO_2 emission rate did not show a tendency to be lowest in a neutral environment and increase as the environment became cold or warm, which is hypothesized that the lower CO_2 emission rate was due to the sleepiness of the subjects sitting and standing in a warm environment at 28°C. In the walking condition, the CO_2 emission rate increased with increasing temperature from 17°C to 28°C.

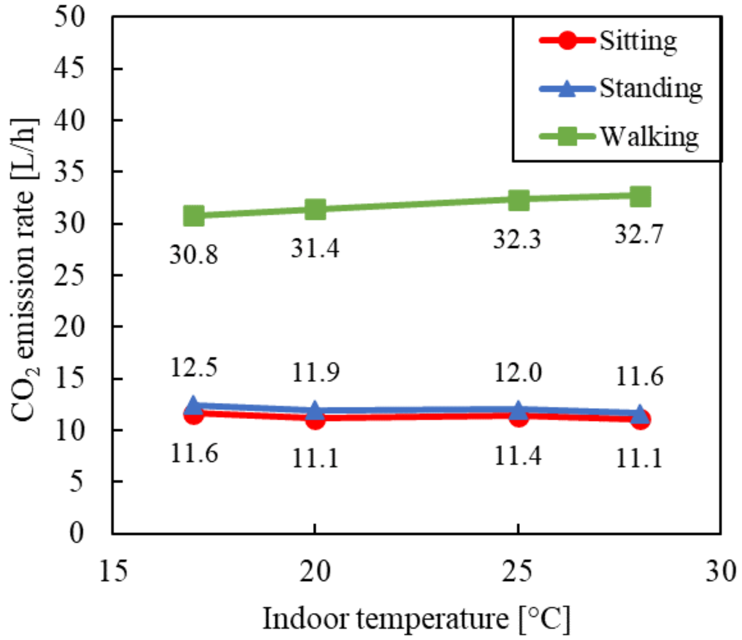


Fig. 2.7 Average CO_2 emission rate according to indoor temperature and activity level

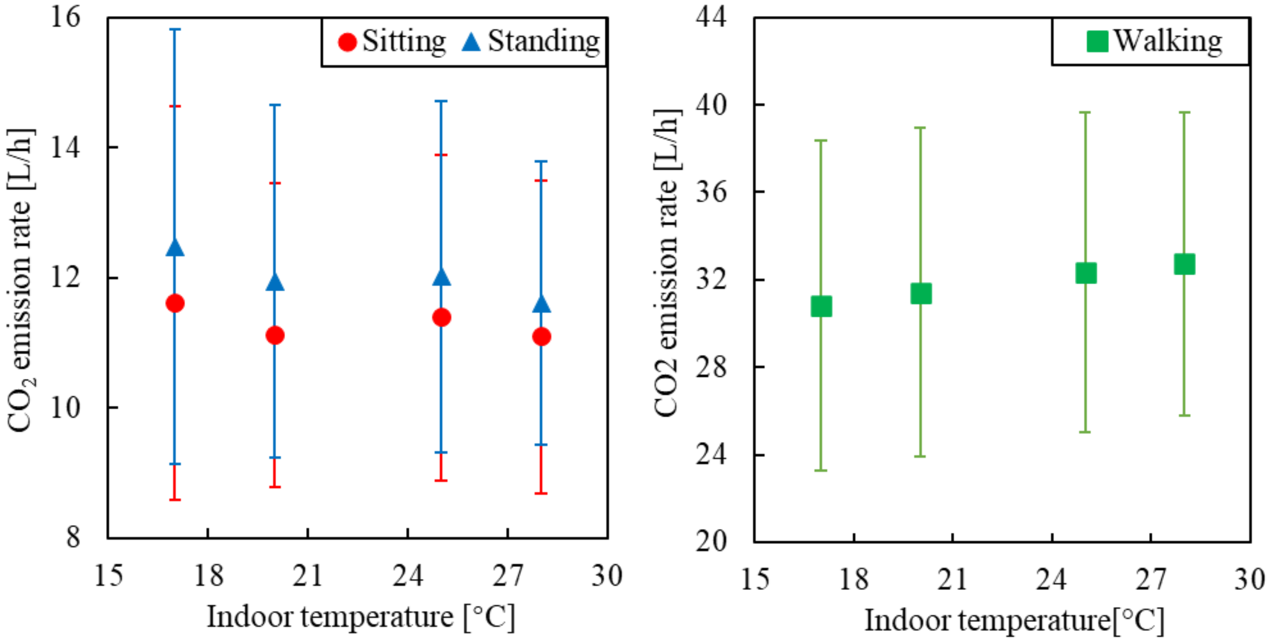


Fig. 2.8 Average CO_2 emission rate according to indoor temperature separated by activities (The error bars mean the standard deviation)

Table. 2.5 MET value from the 2024 Adult Compendium of Physical Activities [2-12]

Activity Description	**MET Value**
Sitting quietly, general	1.0
Standing quietly (standing in a line)	1.3
Walking, treadmill, 1.2 to 1.9 mph (1.9 to 3.0 km/h), 0% grade	2.8

The average CO_2 emission rates of males and females at different activity levels are shown in Fig. 2.9. Regardless of the activity level, the CO_2 emission rates of males are higher than females, and the CO_2 emission rates are 1.3, 1.4, and 1.3 times of females during sitting, standing and walking, respectively. According to the equations given in ASTM 6245-18 (Table 1.2), and the estimation method given in ISO 8996:2021, for example, while resting,

$$M_0 = 60 \cdot A_{\mathrm{Du}} \tag{2.2}$$

$$M_0 = 55 \cdot A_{\mathrm{Du}} \tag{2.3}$$

Where M_0 is the metabolic rate (W), A_{Du} is the body surface area (m^2), and for walking at velocities (< 6 $km \cdot h^{-1}$),

$$M = (0.5 + 0.37 \cdot v_{\mathrm{w}} + 0.2 \cdot v_{\mathrm{w}} \cdot G) \cdot (W_{\mathrm{b}} + L) \quad (2.4)$$

Where M is the metabolic rate (W), L is the load carried by the person (kg), v_{w} is the walking or running speed ($km \cdot h^{-1}$), G is the ground slope (%). Thus, men have higher CO_2 emission rates mainly because males generally have greater body weight and body surface area.

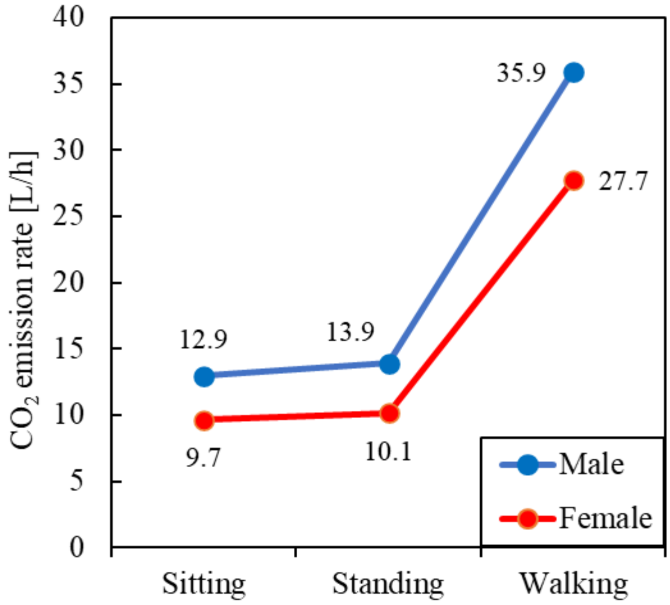


Fig. 2.9 Average CO_2 emission rate according to activity level separated by gender

Minute ventilation is the volume of gas inhaled or exhaled from a person in one minute, it generally decreases when at rest, and increases with exercise. The average minute ventilation at different indoor temperatures separated by activity levels and gender are shown in Fig. 2.10 and Fig. 2.11. Minute ventilation significantly increased with the activity level. In sitting and standing activities, minute ventilation was high at lower temperatures (17°C and 20°C) and low at higher temperatures (25°C and 28°C). In walking activity, as with the CO_2 emission rate, it increased with indoor temperature. Also, for minute ventilation, regardless of activity level, males are higher than females, are 1.16, 1.19, and 1.1 times females during sitting, standing, and walking, respectively.

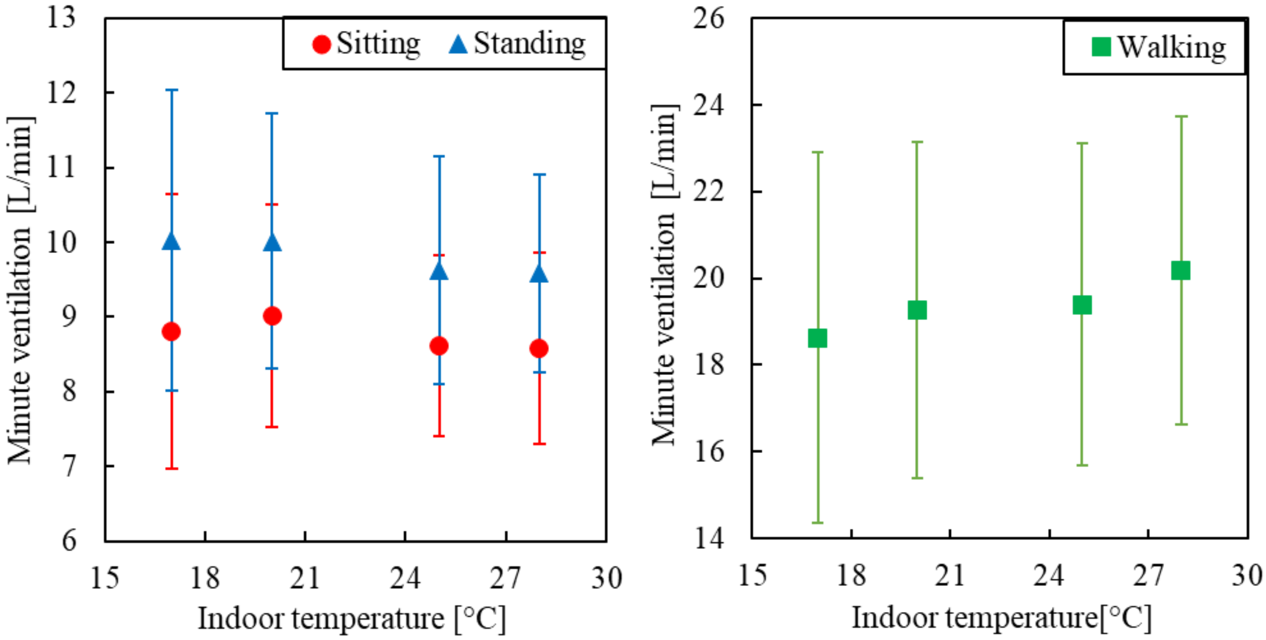


Fig. 2.10 Average minute ventilation according to indoor temperature separated by physical activity (The error bars mean the standard deviation)

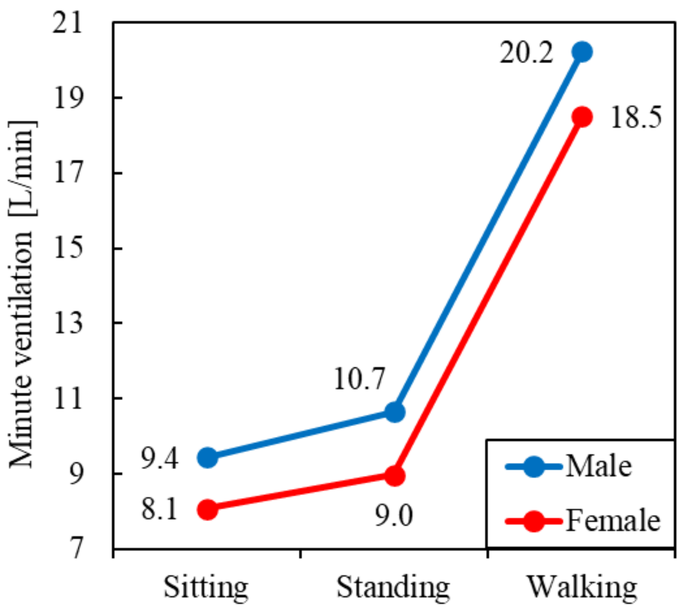


Fig. 2.11 Average minute ventilation according to activity level separated by gender

ETCO₂ means end-tidal carbon dioxide, which is the CO_2 concentration in an exhaled breath at the end of expiration. The average $ETCO_2$ with different indoor temperatures in different activity levels is shown in Fig.2.11. $ETCO_2$ was lowest during standing activity and highest during walking activity. At the same activity level, $ETCO_2$ decreased progressively with increasing indoor temperature. $ETCO_2$ was also higher in males than females at all activity levels, presumably due to males having higher CO_2 emission rates.

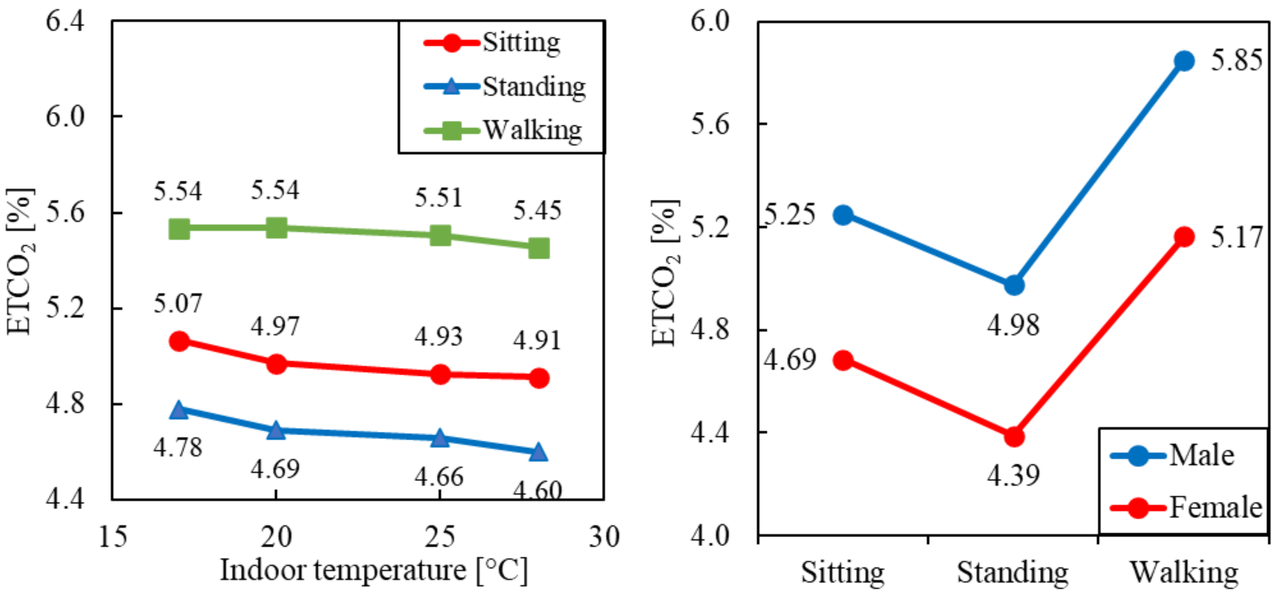


Fig. 2.12 Average $ETCO_2$ according to indoor temperature and activity level and Average $ETCO_2$ according to activity level separated by gender

The calculated mean **skin temperature** with different indoor temperatures in different activity levels is shown in Fig. 2.13. Skin temperature increases with indoor temperature, while the increase in skin temperature with temperature increases with increasing activity level. The skin temperature in different activity levels with the same indoor temperature is shown in Figure 2.14. Skin temperatures decreased significantly with increasing activity levels at 17°C and 20°C, and decreased slightly with increasing activity at 25°C. At 28°C, skin temperatures were lowest during walking activity and highest during standing activity, it may be because some of the heat generated while walking is released through heat dissipation such as sweating.

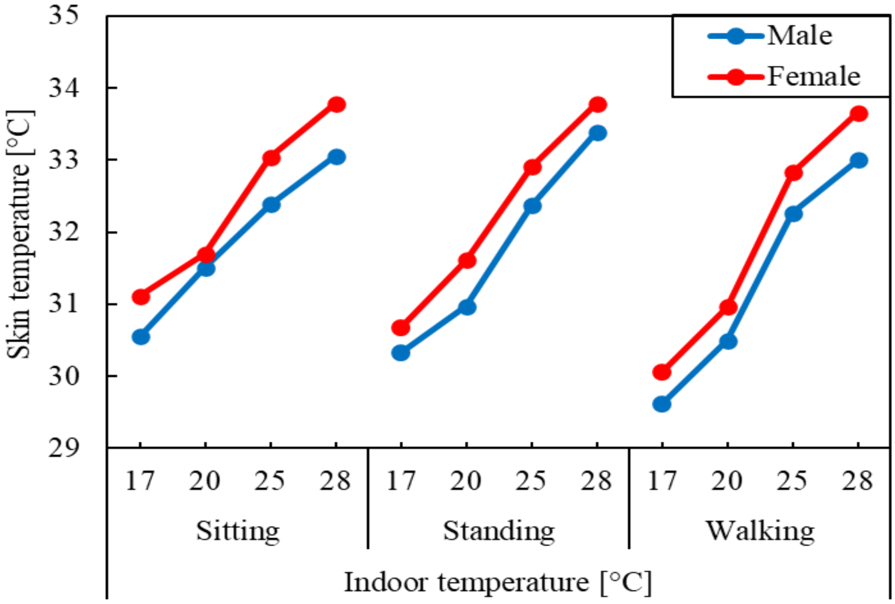


Fig. 2.13 Average mean skin temperature according to indoor temperature and activity level

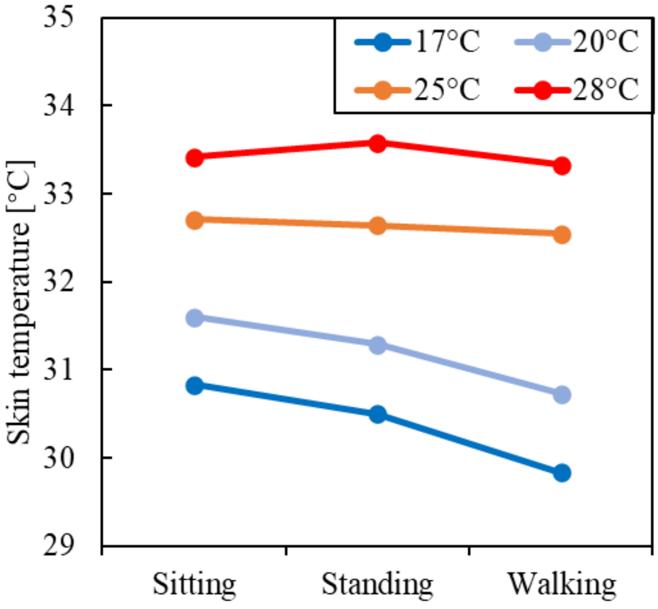


Fig. 2.14 Average mean skin temperature according to activity level separated by indoor temperature

2.3.2 Subjective survey

The mean **thermal sensations** with different indoor temperatures in different activity levels are shown in Figure 2.15, the range of variation in thermal sensation is much smaller in males than in females. At lower temperatures (17°C and 20°C), females felt significantly colder compared to males. At higher temperatures (25°C and 28°C), thermal sensations were closer for males and females, but females felt slightly cooler at 25°C and slightly warmer at 28°C compared to males. The preferred neutral temperatures for males and females in different activity levels, calculated from the thermal sensation vote results, are shown in Figure 2.16. The preferred neutral temperatures for males and females show a similar decreasing trend with increasing activity levels, but for females are about 2°C higher than for males.

Combining thermal sensation results with skin temperature results of males and females (Fig. 2.17) shows that the range of variation in skin temperature, as well as thermal perception, is smaller for males than for females, which shows that females are more sensitive to thermal environments in both physiological and psychological.

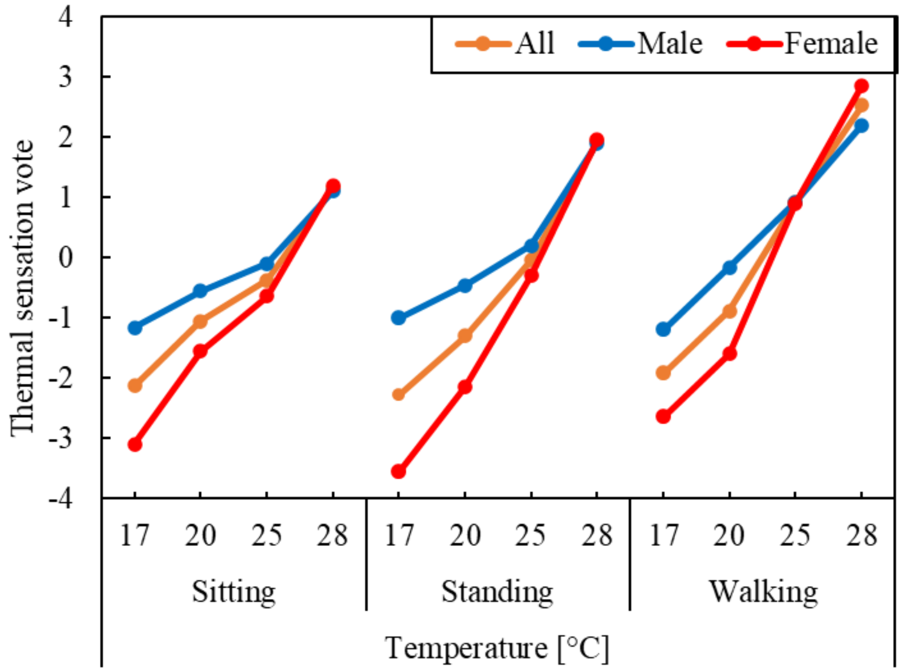


Fig. 2.15 Mean thermal sensation according to indoor temperature and activity level

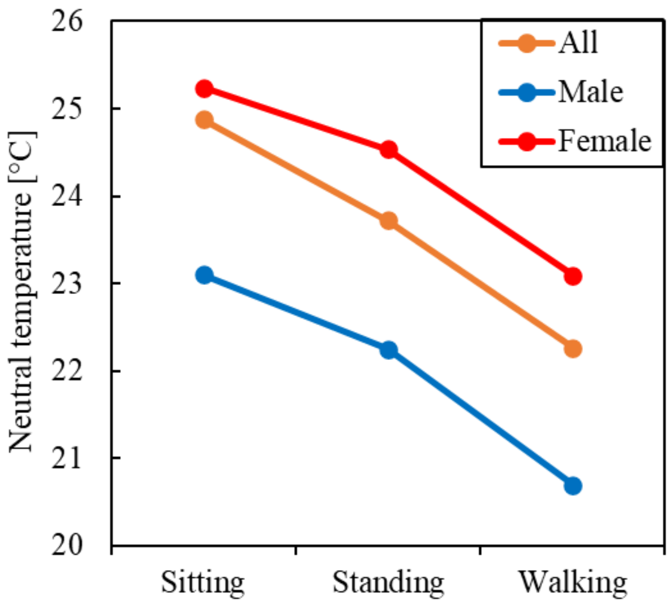


Fig. 2.16 Neutral temperature according to activity level separated by gender

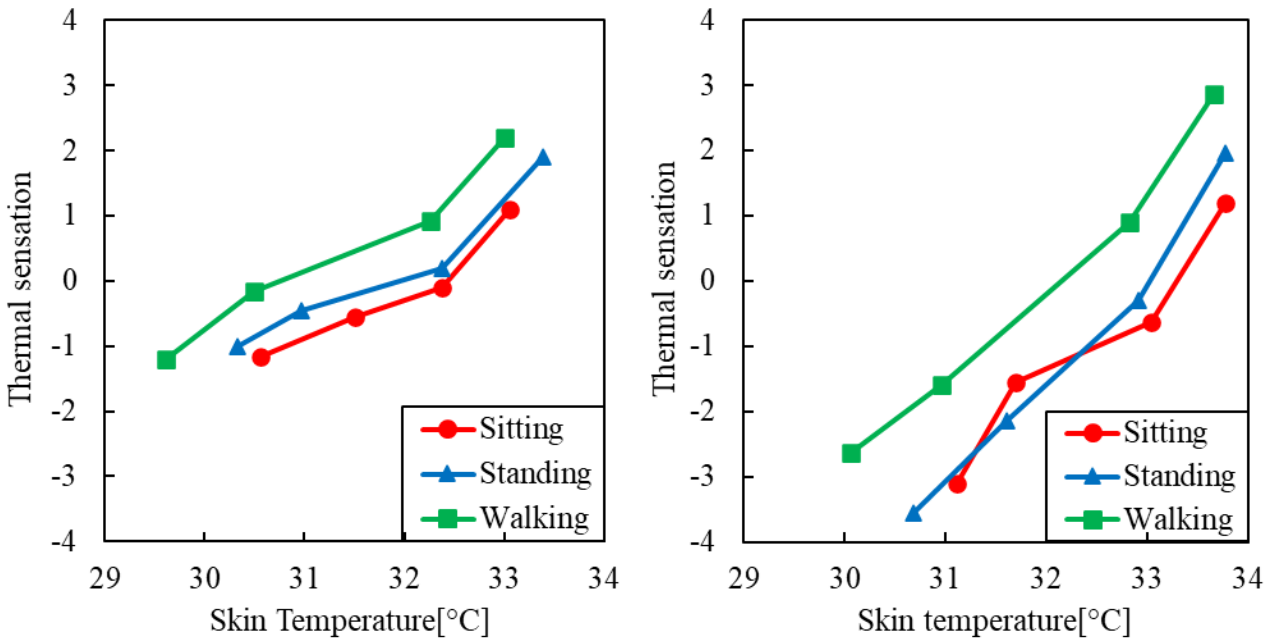


Fig. 2.17 Relationship between thermal sensation and skin temperature in males (left) and females (right)

The average **thermal comfort** at different room temperatures for different activity levels is shown in Figure 2.18. All of the thermal comfort ratings for males were higher than those for females, and males were rated as in a state of thermal comfort, while females were not rated as in a state of thermal comfort, except for sitting and standing at 25°C and sitting at 28°C. Males had the highest thermal comfort ratings of 25°C under sitting and standing activities and 20°C under walking activities. Females had the highest thermal comfort ratings of 25°C and 28°C under sitting activities and 25°C under standing and walking activities.

Combining the thermal sensation with thermal comfort for males (Fig. 2.19) and females (Fig. 2.20) shows that, at the same activity level, the closer the thermal sensation to neutral (at a value of 0), the higher level of thermal comfort is. It can also be seen that thermal sensations between slightly cool (-1) and warm (+2) are thermal comfortable environments.

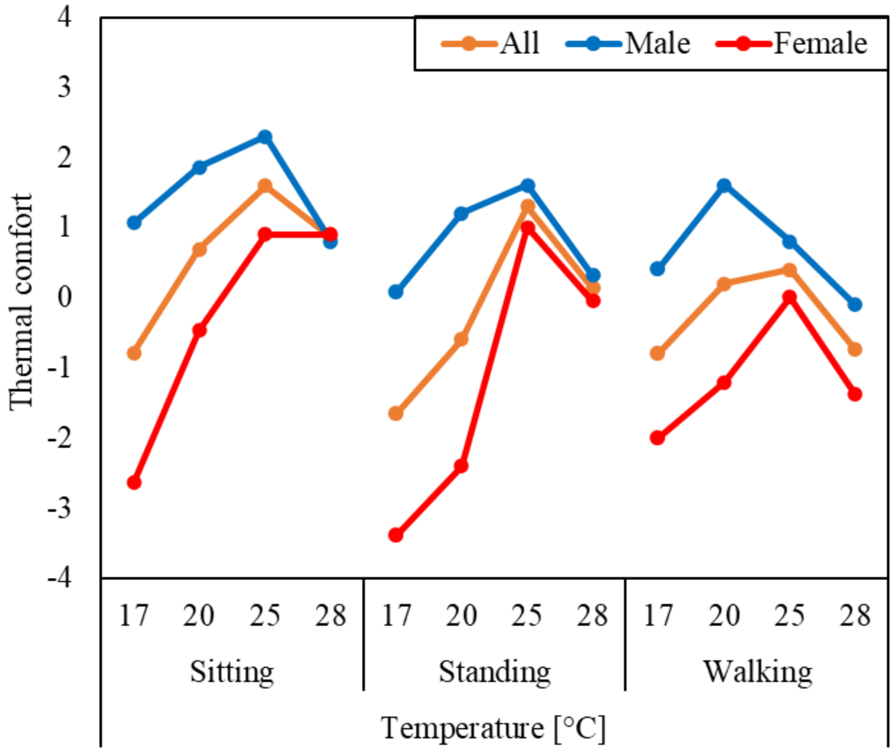


Fig. 2.18 Mean thermal comfort according to indoor temperature and activity level

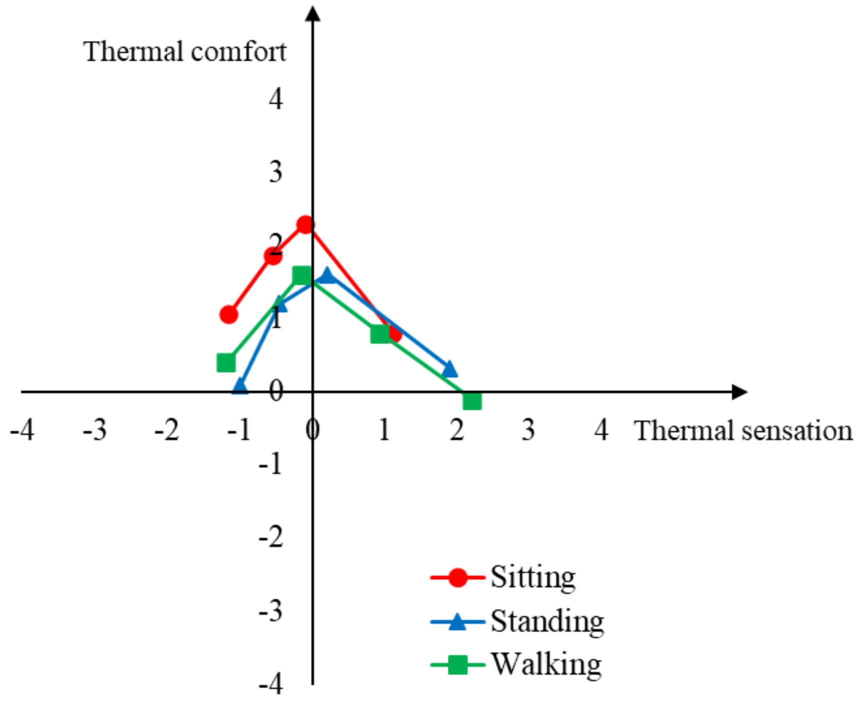


Fig. 2.19 Relationship between thermal sensation and thermal comfort in males

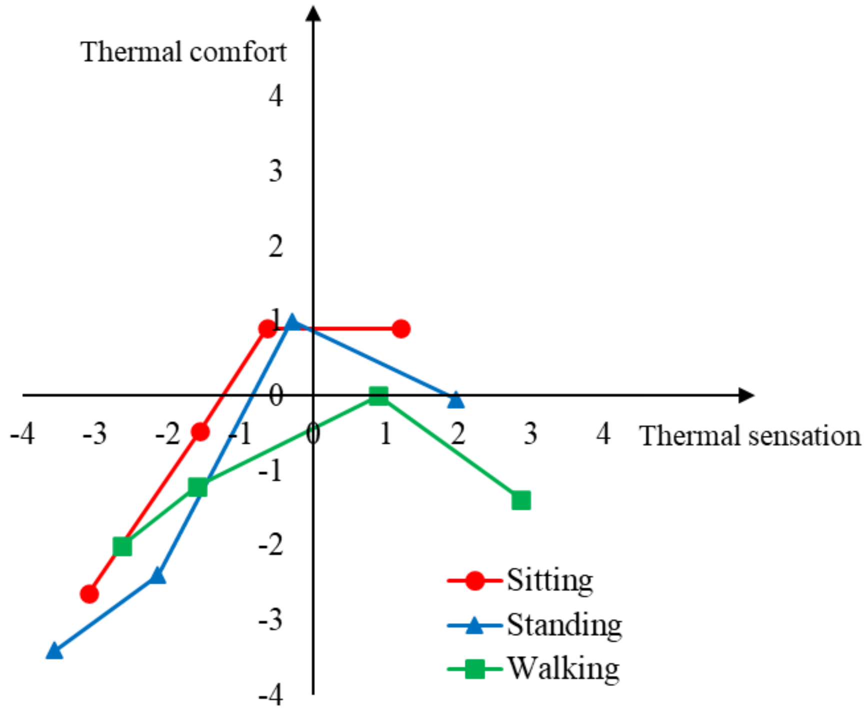


Fig. 2.20 Relationship between thermal sensation and thermal comfort in females

2.4 Discussion

The prediction formulas for CO_2 emission rates given in ISO 8996 and ASTM D6245 were utilized, and subject characteristics (e.g., gender, body weight, and body surface area) as well as the values of different activity levels were substituted into the formulas for the calculations. The results of the calculations were compared with the results of this experiment, as shown in Fig. 2.21, 2.22, and 2.23.

Box plots are used here. A boxplot is a statistical chart that displays the distribution of a dataset using a rectangular box and whiskers. It shows the median, quartiles, and potential outliers, providing a visual summary of central tendency and spread.

The prediction formulas in ISO 8996 and ASTM D6245 slightly overestimate the CO_2 emission rates in sitting activity, significantly overestimate the rates in standing activity, especially ISO 8996, and provide more accurate estimates for walking activity.

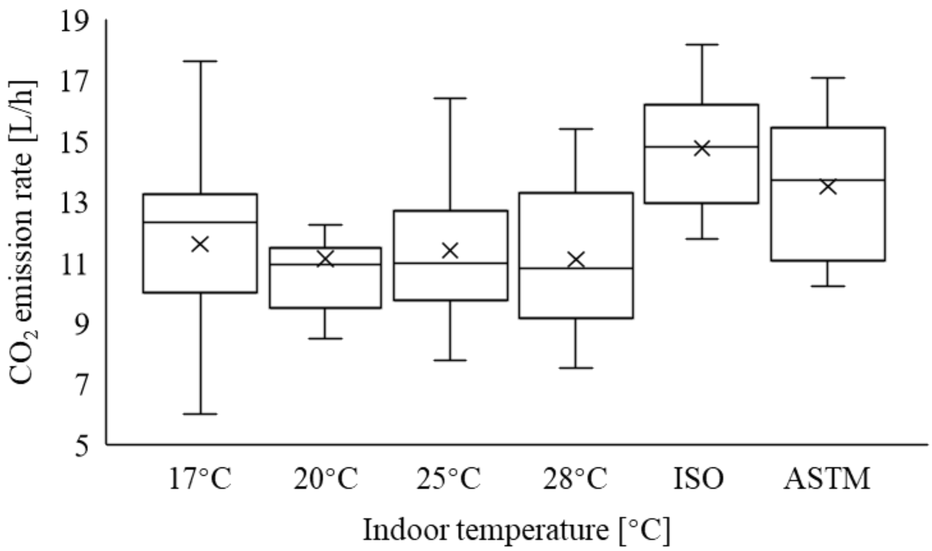


Fig. 2.21 Experiment result and calculated result (by ISO 8996 and ASTM D6245) of CO_2 emission rate in sitting activity

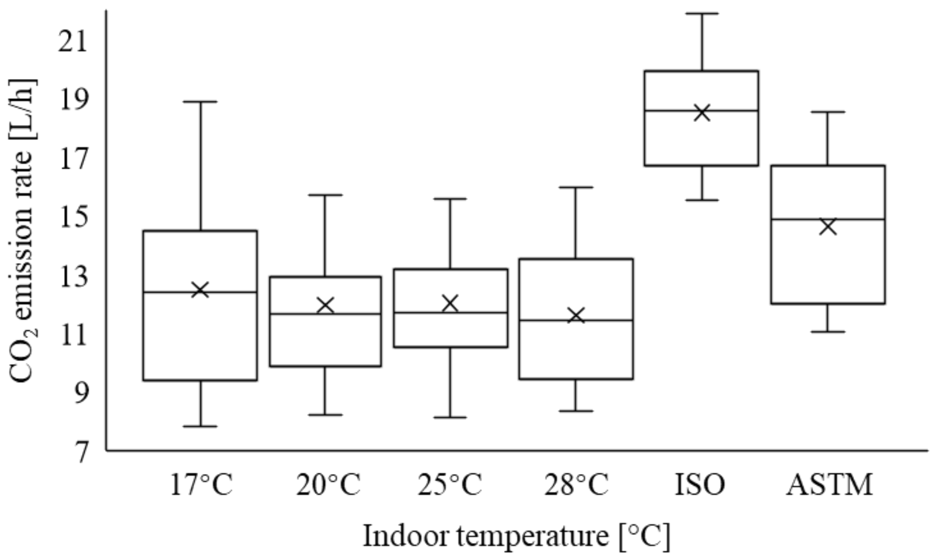


Fig. 2.22 Experiment result and calculated result (by ISO 8996 and ASTM D6245) of CO_2 emission rate in standing activity

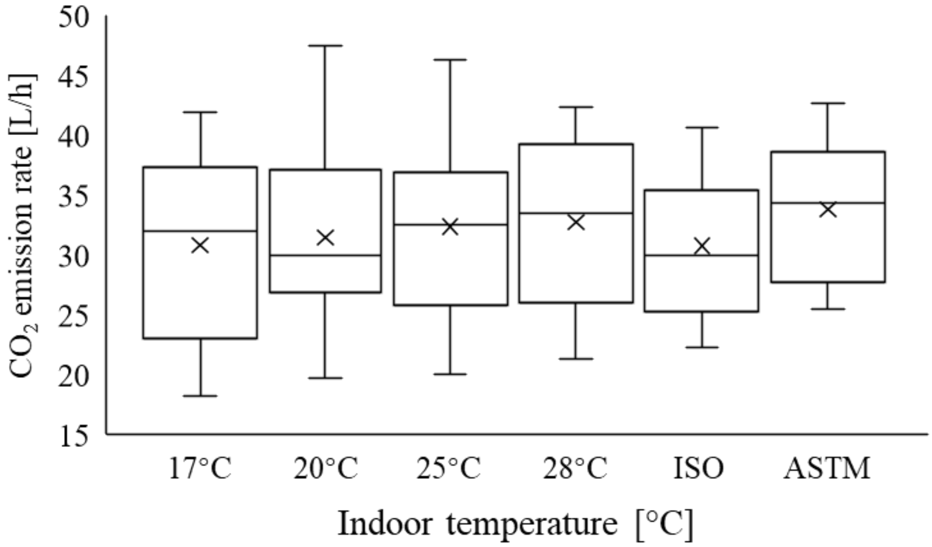


Fig. 2.23 Experiment result and calculated result (by ISO 8996 and ASTM D6245) of CO_2 emission rate in walking activity

For the results of the subjective survey in the experiment, males and females showed great differences compared to previous studies, such as the difference in preferred thermal neutral temperatures amounted to 2°C. The number of subjects in this experiment was small, and while females generally showed more sensitivity to thermal environments during the experiment, about half of the males showed low sensitivity to thermal environments, giving subjective ratings of lower differences for all four different indoor temperature environments. Therefore, experiments with a larger number of subjects are needed to obtain more generally applicable conclusions.

During the experiment, some problems were encountered that were caused by the lack of consideration in designing the experimental procedure.

This experiment was conducted in a classroom with a large indoor space, so it was difficult to control the indoor temperature, and also difficult to ensure that the room temperature was constantly stable during the experiment. To avoid this problem as much as possible, the outdoor weather on the day of the experiment and the required temperature for the experiment were taken into consideration, and preparations were made in advance for adjusting the indoor temperature. Concerning the tendency of subjects to feel sleepy in warm environments, which in turn affects experimental results such as carbon dioxide emission rates and thermal sensory evaluations, it is considered that in future experiments, subjects will be allowed to perform light office activities such as reading on electronic devices during the experimental to prevent this from occurring. In addition, communication of experimental information (e.g., indoor temperature in this experiment) to subjects should be avoided before the experiment; advance notice may lead to psychological factors affecting subjects' perception of temperature, which in turn may have an impact on the results of the experiment.

For the problems mentioned above, the design of the experimental process will be optimized in future experiments to avoid any impact on the experimental results.

2.5 Conclusion

For this experiment, the effects of indoor temperature and activity level on the CO_2 emission rate by humans are discussed. The experiment was set up with 4 different indoor temperature conditions and 3 different activity levels.

In conclusion, the result of this experiment suggested that CO_2 emission rates substantially increased with elevated physical activity levels and increased with the indoor temperature in the higher physical activity level. No clear relationship was found between CO_2 emission rate and indoor temperature in low physical activity levels.

Besides, thermal sensation significantly increases with temperature and activity level, and there's minimal effect of temperature on thermal comfort under higher activity levels compared to lower activity levels. Also, females seem to be more sensitive to temperature and have lower thermal comfort ratings at the same indoor temperature.

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3 Impact of indoor CO_2 concentration on the CO_2 emission rates

3.1 Introduction

Carbon dioxide (CO_2) is a major human metabolite, so CO_2 concentration, as an indicator of ventilation level, is also one of the most important indicators of indoor air quality. A CO_2 concentration of 400 ppm is the average outdoor air level, from 400 to 1,000 ppm is the typical level found in occupied spaces with good air exchange, from 1000 to 2000 ppm is the level associated with complaints of drowsiness and poor air, from 2000 to 5000 ppm is the level associated with headaches, sleepiness, and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate, and slight nausea may also be present, over 5000 ppm indicates unusual air conditions where high levels of other gases could also be present, which is the permissible exposure limit for daily workplace exposures, also toxicity or oxygen deprivation could occur.

Indoor CO_2 concentration levels can have an impact on human physiological responses as well as health, and may also have an impact on human CO_2 emission rates. As mentioned above, in indoor environments with high CO_2 concentrations, it is possible that high concentrations of other gases, such as bioeffluents produced by metabolism, may also be present due to inadequate ventilation levels. Therefore, experiments on the effect of indoor CO_2 concentration on CO_2 emission rates are divided into two different forms, one in which an indoor environment with high CO_2 concentration and a certain amount of bioeffluents is achieved by decreasing the ventilation rate, and the other in which the ventilation rate is kept constant and pure CO_2 gas is dosing into the indoor environment to achieve an environment with the corresponding CO_2 concentration. Utilizing the experimental methods described above, in previous studies, Zhang et al. (2017) [3-1] investigated the effects of exposure to CO_2 and biofluids on humans, measuring subjective ratings, physiological responses, and cognitive performance. Perceived levels of air quality were reduced and headaches, fatigue, sleepiness, and difficulty in thinking were increased in the presence of bioeffluents and a CO_2 concentration of 3000 ppm compared to a CO_2-only environment. Their results suggest that moderate concentrations of bioeffluents can have deleterious effects on occupants during typical indoor exposures. Kuga et al. (2021) [3-2] investigated the effects of ambient CO_2 concentration and indoor temperature on CO_2 emission rates, which were higher at higher temperatures where subjects felt warmer, and lower under all conditions of increased ambient CO_2 concentration.

Based on the above background, the purpose of this experiment is to discuss the effect of indoor CO2 concentration on CO2 emission rate under two different conditions of changing indoor CO2 concentration at the same indoor temperature and activity level.

3.2 Experimental methods

3.2.1 Description of the climate chamber

This experiment was conducted in a small climate chamber (Fig. 3.1) with a volume of 1.911 m^3 (1.4 × 0.75 × 1.82 m), which had a frame made of aluminum and walls made of acrylic plates. At the top of the chamber, there was a ceiling with a height of 20 cm and outdoor air was introduced to the ceiling through ducts and an intake fan, then outdoor air was supplied to the chamber by metal perforated panels at a very low air velocity. The exhaust port was located at a height of 10 cm above the floor, and exhaust air from the chamber through the exhaust fan and ducts. The supply and exhaust air volume are changed by adjusting the valve on the pipeline, and the flow meters are installed on the pipeline to measure the ventilation flow rate, and the supply and exhaust air volumes are set to the same value when in use. Besides, two silent fans were placed on the floor of the climatic chamber for mixing the indoor gases, in front of the right and behind the left side of the subject's position.

Since the walls of the climate chamber were made of acrylic plates with gaps at the joints, silicone, and tape were used to fill the gaps during the preparation of the experiments to ensure airtightness as well as possible. The temperature and humidity in the laboratory, where the small chamber is located are controlled by an integrated air-conditioning unit. To avoid the influence of the outdoor temperature on the temperature in the chamber, it is necessary to turn on the air-conditioning unit 1 to 2 hours before each experiment to control the indoor temperature at 21 to 24°C.

The environmental measurements include indoor temperature, relative humidity, and CO_2 concentration in the climate chamber. As shown in Figure 3.1, a temperature and relative humidity sensor and a CO_2 concentration sensor were placed at 1/3 and 2/3 of the height below the ceiling in the climate chamber (0.54 m and 1.08 m above the floor) to monitor and record environmental parameters in real time. The temperature and humidity sensors and CO_2 concentration sensors used in this experiment were the same as in the previous experiment, and the measurement accuracy is shown in Table 2.2 in Section 2.2.3.

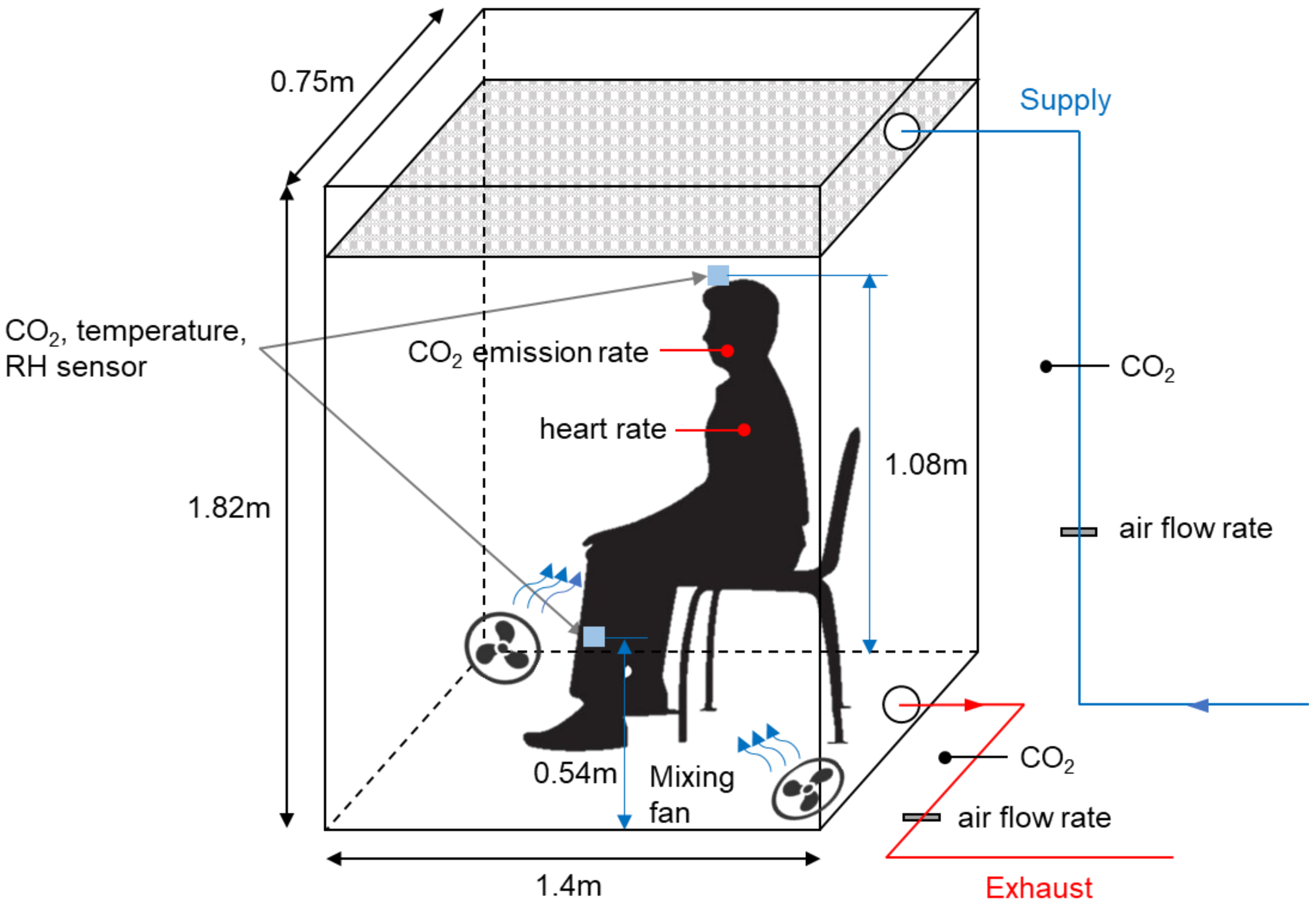

Fig. 3.1 Schematic of the climate chamber and experimental setup

3.2.2 Subject characteristics

A total of 14 subjects (10 males and 4 females) were enrolled in the experiment and they were asked to participate in both experiments in which indoor CO_2 concentrations were controlled in two different ways (by reducing the outdoor air supply rate and by dosing pure CO_2 gas), and during which physiological measurements were taken. As in the previous experiment, subjects reported their age and height, and before each experiment, their weight and body fat rate were measured, the collated anthropometric data are shown in Table 3.1. It can be seen that males have a higher average body surface area compared to females, but a lower body fat rate compared to females.

Table. 3.1 Subjects' anthropometric information

	Age (years)	**Height (m)**	**Weight (kg)**	**BMI (kg/m^2)**	**Body surface area (m^2)**	**Body fat rate (%)**
All	26.2 ± 3.4	1.69 ± 0.07	65.5 ± 13.0	22.7 ± 3.7	1.75 ± 0.18	24.3 ± 8.8
Males	25.5 ± 2.8	1.71 ± 0.07	66.6 ± 12.6	22.6 ± 2.8	1.77 ± 0.18	20.9 ± 6.9
Females	28.0 ± 3.7	1.66 ± 0.02	62.7 ± 12.0	23.0 ± 4.8	1.68 ± 0.13	32.7 ± 6.0

In addition, to avoid the effect of metabolism from digestion on CO_2 emission rates, subjects were asked to abstain from eating and drinking beverages other than water for 3 hours before each experiment. The experiment was conducted from late October 2023 to mid-January 2024 and was scheduled between 10:00 a.m. and 12:30 p.m. and between 4:00 p.m. and 6:30 p.m., to minimize disruption of the subjects' mealtimes.

3.2.3 Experimental procedures

As in the previous experiment, before the start of each experiment, subjects were asked to arrive early, change into uniform typical summer clothing (clothing insulation is 0.5 clo) consisting of a short-sleeved T-shirt and thin pants, as well as the subject's underwear, socks, and shoes, also wear a heart-rate sensor, and have their body weight and body fat rate measured.

Due to the limited space of the climatic chamber, subjects can only remain seated in the chamber, while due to the long duration of the experiment, subjects were allowed to use electronic devices such as smartphones and tablets for light office activities during the experiment.

One experiment was conducted for each of the two different ways of changing indoor CO_2 concentrations, by reducing the outdoor air supply rate and by dosing pure CO_2. The experiment was set up with three indoor CO_2 concentration levels of 800 ppm, 1400 ppm, and 3000 ppm, corresponding to the three different hazardous CO_2 concentration levels introduced in 3.1. Based on the average CO_2 emission rate of 12 liters/hour obtained from the previous experiment, experimental procedures for two different ways of changing the CO_2 concentration were calculated and designed, and all the experimental conditions are shown in Table 3.2. M800, M1400, and M3000 are the three experimental conditions for reducing outdoor air supply rate, and MP800, MP1400, and MP3000 are the three experimental conditions for dosing pure CO_2.

Table 3.2 Designed conditions for different indoor CO_2 concentrations

Condition	**Outdoor air supply rate (m^3/h)**	**Air change rate (h^{-1})**	**Pure CO_2 dosed (L/h)**	**CO2 level in the chamber (ppm)**
M800	30	15.7	–	800
M1400	12	6.3	–	1400
M3000	4.6	2.4	–	3000
MP800	30	15.7	0	800
MP1400	30	15.7	18	1400
MP3000	30	15.7	66	3000

To facilitate the estimation of the ventilation rate in the climate chamber and the CO_2 emission rate, the process of rising, smoothing, and decaying CO_2 concentration was designed for both of the experimental processes, and the design of the experimental procedures are shown in Figures 3.2 and 3.3.

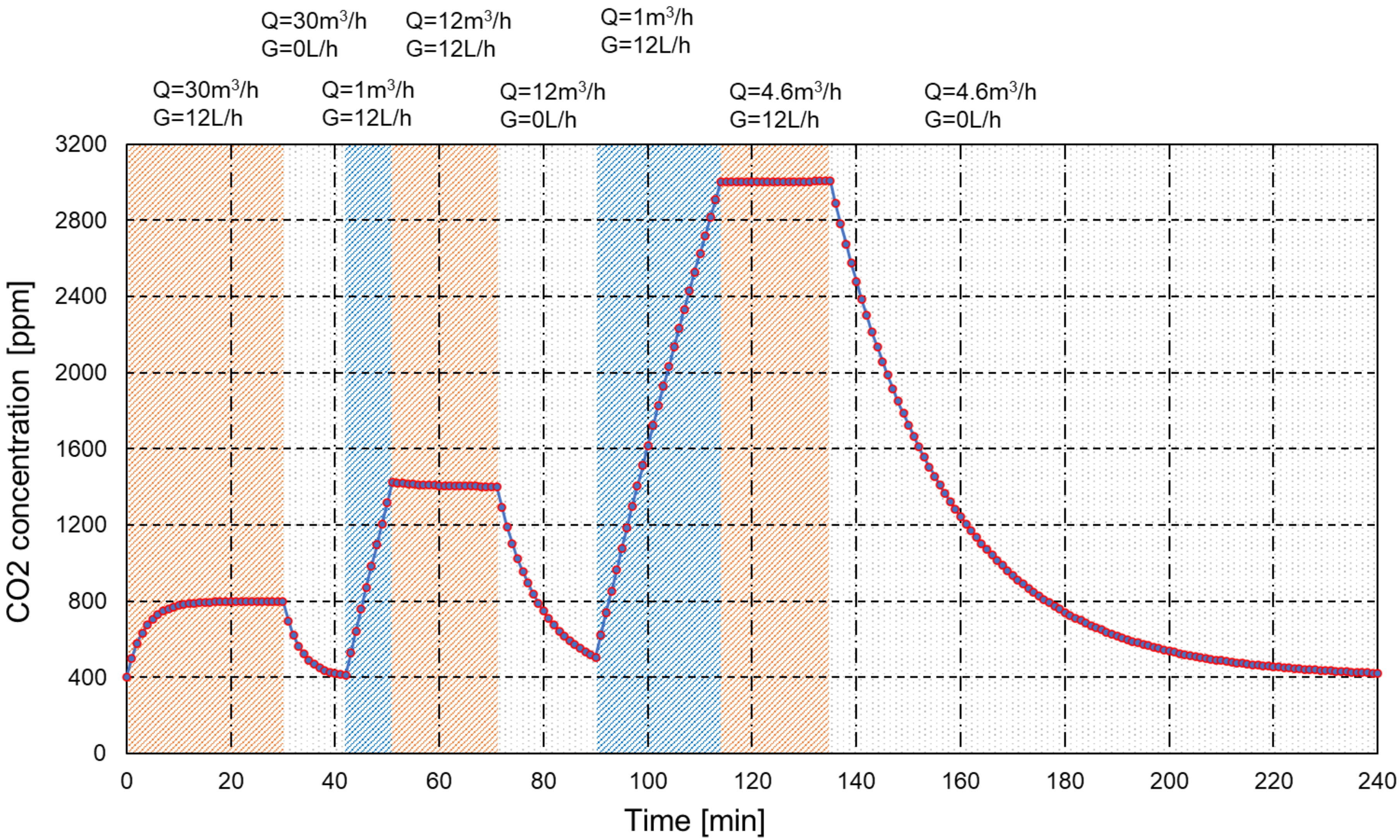

Fig. 3.2 Experimental procedure design for reducing outdoor air supply rate

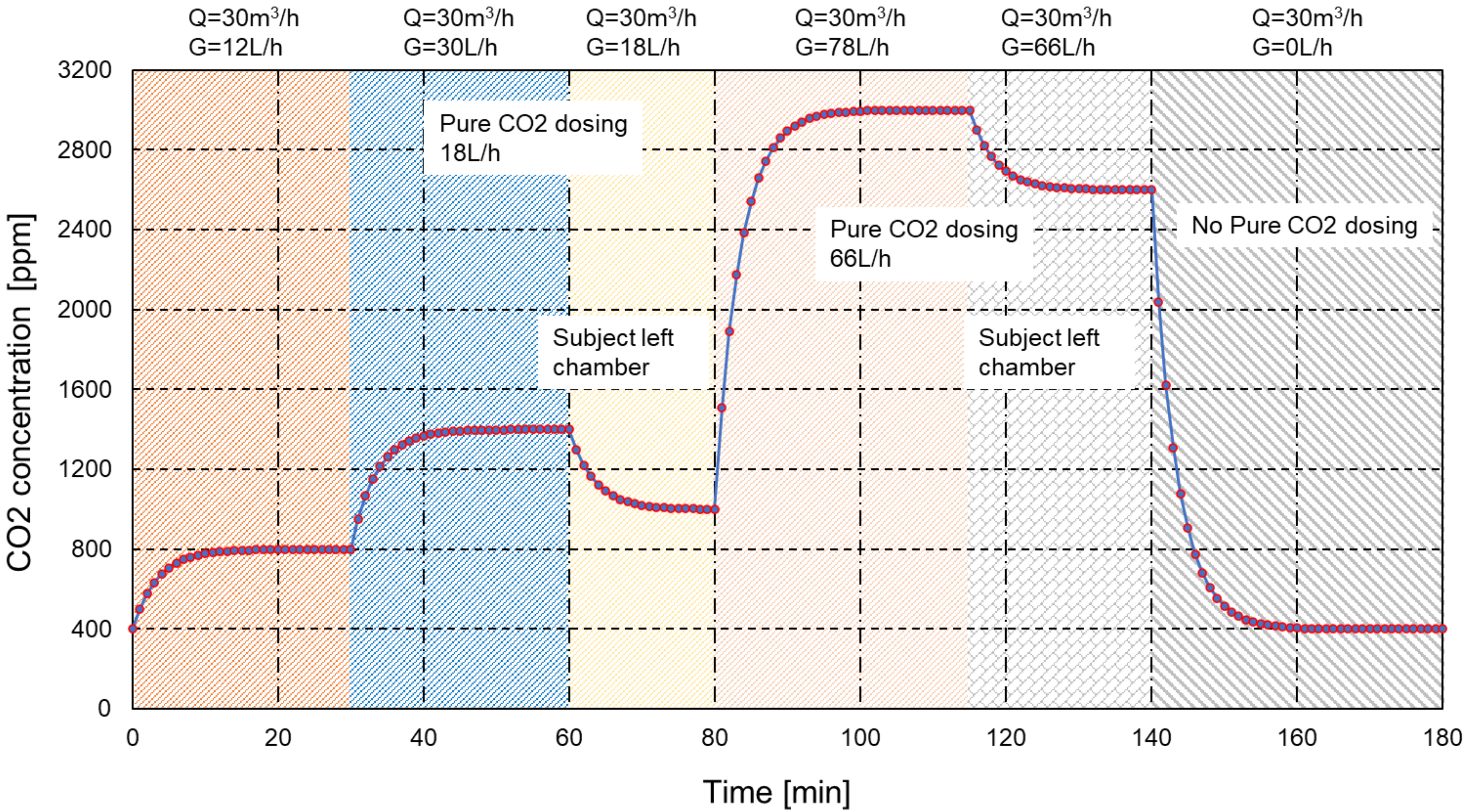

Fig. 3.3 Experimental procedure design for dosing pure CO_2 from cylinders

The experimental procedure design of reducing the outdoor air supply rate is shown in Fig. 3.2, and the whole experiment can be divided into three parts according to the indoor CO_2 concentration level. The outdoor air supply rate is gradually reduced in the three parts. Each part includes the concentration increase process, steady state (about 20 minutes), and decay process, counterpart subjects enter the chamber, remain for approximately 20 minutes after reaching the CO_2 concentration level, then leave the chamber and wait for the CO_2 concentration to decay. For the conditions of the CO_2 concentration level at 1400 ppm and 3000 ppm, to shorten the experimental time, the outdoor air supply rate was reduced to the smallest at first, and then adjusted to the calculated steady-state outdoor air supply rate after the corresponding concentration was reached.

The experimental procedure design of dosing pure CO_2 from cylinders into the chamber is shown in Fig. 3.3, and the outdoor air supply rate is maintained constant during this experiment. The whole experiment can be divided into four parts. In the first part, the indoor CO_2 concentration gradually reached 800 ppm without dosing pure CO_2 and maintained a steady state for 20 minutes. In the second part, pure CO_2 was dosed into the chamber at a flow rate of 18 L/h, after the indoor CO_2 concentration reached 1400 ppm level, it remained stable state for about 20 minutes, then asked subjects to leave the chamber and waited for the indoor CO_2 concentration to decay to steady state, and maintained for 10 minutes. In the third part, similar to the last part, after subjects re-entered the climate chamber, pure CO_2 was dosed into the chamber at a flow rate of 66 L/h, after indoor CO_2 concentration reached 3000 ppm level, and remained stable for about 20 minutes, then asked subjects to leave the chamber. Later, waited for the CO_2 concentration to decay to a steady state and maintained for 10 minutes. In the last part, pure CO_2 was no longer dosing in the chamber, and the indoor CO_2 concentration decayed.

3.2.4 CO_2 measurement

The CO_2 emission rates were measured using two methods, indirect calorimetry and chamber method, and the results obtained from the two measurement methods were compared.

The indirect calorimetry method can confirm the time variation of CO_2 emission rate with high time resolution and also measure other physiological parameters. It was measured by the respiratory monitor AE-310S to measure several respiratory parameters, including CO_2 emission rate, O_2 consumption, respiratory quotient, ETO2, and ETCO2, when the subjects were in a climatic chamber (i.e. during the CO_2 concentration was rising and the maintain steady state), and all respiratory parameters were selected in the last 20 min of each experimental condition when statistical data, to avoid the effect of acclimatization to the chamber environment. The operating principle and use of this respiratory monitor are described in section 2.2.4.

The chamber method uses sensors to measure and record the CO_2 concentration in the inlet and exhaust ducts of the climate chamber continuously during the experiment, the air change rate of the climate chamber was estimated by the concentration decay process, and the CO_2 emission rate was estimated by the difference between the CO_2 concentrations in the exhaust and inlet air at the concentration steady state. The sensors used in the experiment are GMP252, which is the same as the one used in the previous experiment, and the measurement range and accuracy are shown in Table 2.2 in Section 2.2.3.

For the data measured by the CO_2 concentration sensors, the decay of CO_2 concentration over time can be modeled using an exponential decay equation,

$$C_t = C_0 \times e^{(-k \times \Delta t)} \tag{3.1}$$

Where k is the decay constant, C_0 is the initial CO_2 concentration of the decay process (ppm), C_t is the final CO_2 concentration of the decay process (ppm), Δt is the time of decay process (min).

To calculate the decay constant k, take the natural logarithm of both sides of the equation, and solve for k,

$$k = \frac{(\ln(C_0) - \ln(C_t))}{\Delta t} \tag{3.2}$$

$$ACH = 60 \times k \tag{3.3}$$

Where ACH is the air change rate (h^{-1}), and the factor of 60 is used to convert the time interval Δt from minutes to hours.

The outdoor air supply rate to the chamber can be calculated by the following equation,

$$Q = ACH \times V$$

Where Q is the outdoor air supply rate (m^3/h), V is the room volume (m^3), in this experiment is 1.911 m^3.

The CO_2 emission rate with the condition of reducing the ventilation rate was calculated by the following equation,

$$G = Q(C_{in} - C_{out}) \tag{3.3}$$

Where G is the CO_2 emission rate (mL/h), Q is the outdoor air supply rate as described above, C_{in} is the indoor CO_2 concentration (ppm) at steady state, and C_{out} is the outdoor CO_2 concentration (ppm).

The CO_2 emission rate with the condition of dosing pure CO_2 was calculated by the following equation,

$$G = Q\left(C_{pure+met} - C_{pure}\right) \tag{3.4}$$

Where $C_{pure+met}$ is the indoor CO_2 concentration (ppm) including pure CO_2 dosing into the chamber and CO_2 produced by subjects,C_{pure} is the indoor CO_2 concentration (ppm) with only pure CO_2 dosing.

3.2.5 Environmental and other physiological measurements

Environmental measurements include indoor temperature, relative humidity, and CO_2 concentration in the climate chamber. As shown in Figure 3.1, a temperature and humidity sensor and a CO_2 concentration sensor were placed at 1/3 and 2/3 of the height under the ceiling (0.54 m and 1.08 m above the floor) in the climate chamber to monitor and record the environmental parameters in real-time. The temperature and humidity sensors and CO_2 concentration sensors used in this experiment were the same as in the previous experiment, and their measurement accuracies are shown in Table 2.2 in Section 2.2.3.

A Polar H10 heart rate sensor was also used to measure the heart rate of the subjects while they were in the climatic chamber at a frequency of once per second.

3.3 Experimental results

3.3.1 CO_2 emission rate

First are all the experimental results of the indoor CO_2 concentration in the climate chamber for the two experiments; two CO_2 concentration sensors were set up in the room, so this data is taken as the average of the concentrations obtained from the measurements of the two sensors.

The process of indoor CO_2 concentration change for the experiment of reducing the outdoor air supply rate is shown in Fig. 3.4, and the black dotted line is the designed experimental process described above. The trend of CO_2 concentration change in the actual experimental process corresponds to the experimental design, in which it can be seen that the CO_2 concentration rises, stays steady, and decays under the three experimental conditions. The actual experimental process takes longer time, compared to the design of the experimental process, and there are two main reasons for this. On the one hand, because the actual CO_2 concentration at steady state was higher than expected in some of the experiments (most of the experiments at 800 ppm level condition, more than half of the experiments at 1400 ppm level condition, and a few experiments at 3000 ppm level condition), also the CO_2 concentration in the outdoor air was slightly above 400 ppm and generally in the range of 450 to 500 ppm, the concentration rise and decay processes take longer time. On the other hand, in the experiments at 1400 and 3000 ppm CO_2 levels, it was difficult to reduce the outdoor air supply rate as the design rate of 1 m^3/h in the climatic chamber, therefore the time for the concentration rise process was very long, especially in the 3000 ppm experimental conditions.

The process of indoor CO_2 concentration change for the experiment of dosing pure CO_2 from the cylinder is shown in Figure 3.5, and the black dotted line is the designed experimental process. The process of CO_2 concentration change for the actual experimental process can be seen in three clear different CO_2 concentration levels. Since it is difficult to maintain a stable air pressure when pure CO_2 is dosed into the chamber through the cylinder, the CO_2 concentration in the chamber shows a continuous fluctuation when pure CO_2 is dosed (under the experimental conditions of 1400 and 3000 ppm).

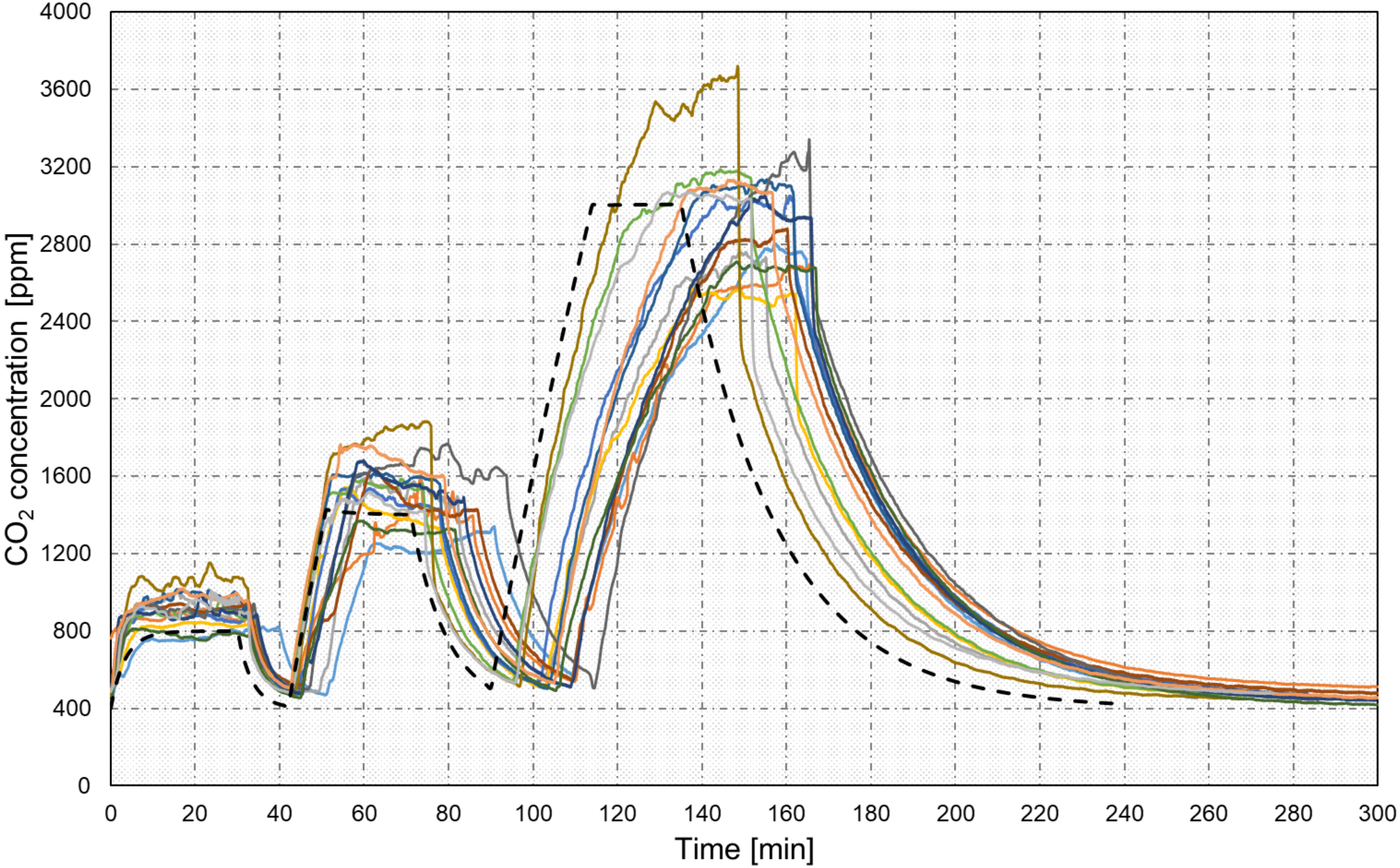

Fig. 3.4 Experimental result of indoor CO_2 concentration change for reducing outdoor air supply rate

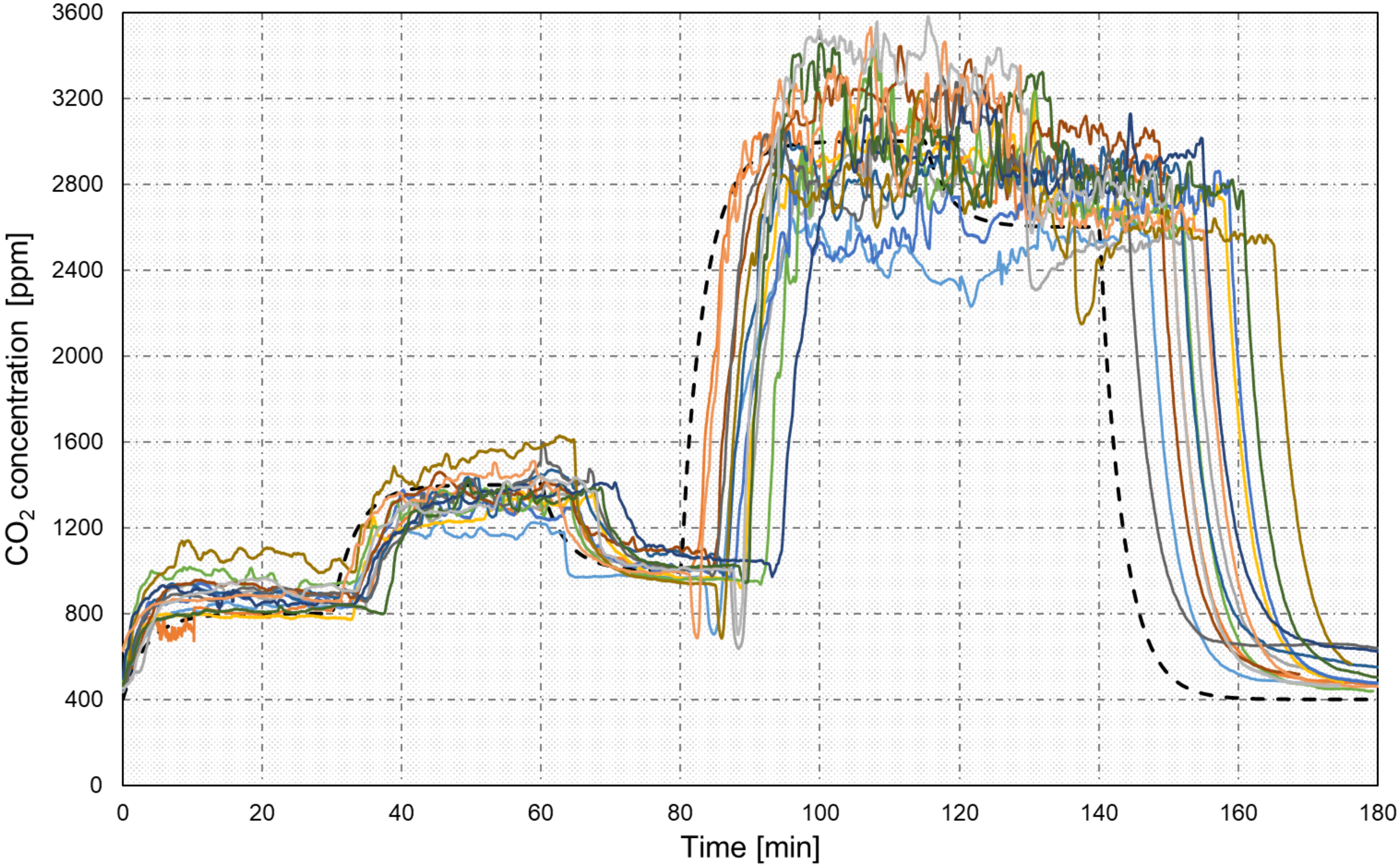

Fig. 3.5 Experimental result of indoor CO_2 concentration for dosing pure CO_2

The data calculated from the two CO_2 emission rate measurements are shown in Fig. 3.6 and 3.7. The box plots are used here, where the upper and lower boundaries of the box represent the upper and lower quartiles of the overall set of data (Q3 and Q1), the height of the box represents the range of the middle 50% of the distribution of the data, and the line in the middle of the box is the median line, which represents the median of the data (the second quartile, Q2), the fork point inside the box is the average of the data, and the upper and lower whiskers of the box whiskers extend from the boundaries of the box and represent the overall extent of the data.

The data from the measurement method of indirect calorimetry (Fig. 3.6) show that during the experiments of reducing the outdoor air supply rate, the CO_2 emission rate decreases gradually with increasing indoor CO_2 concentration and decreasing outdoor air supply rate. During the experiments of dosing pure CO_2 from the cylinder, the CO_2 emission rate also showed a trend of decreasing with increasing CO_2 concentration.

Besides, the experimental condition settings for M800 and MP800 were the same, but the measured data showed different results. For the same subject, the two experiments were conducted on two separate days, and the CO_2 emission rate may be affected by other factors, such as diet, activity level, and health conditions on the day of the experiment. This issue did not affect the trends in CO_2 emission rates for the three conditions in the two experiments.

The data measured using the chamber method (Fig. 3.7) show that under the experimental conditions of reducing outdoor air supply rate, the CO_2 emission rate decreases significantly with increasing indoor CO_2 concentration, i.e., it decreases significantly with decreasing outdoor air supply rate. However, under the experimental condition of dosing pure CO_2, the CO_2 emission rate firstly decreased with the increase of CO_2 concentration, and then increased slightly, which is different from the results obtained using the indirect calorimetry method.

For the experiments of dosing pure CO_2, the two measurement methods presented different results, which were considered to be since a large amount of CO_2 gas was discharged through the exhaust ducts during the experiments, especially during 3000 ppm level, and the inlet and exhaust ducts were not sufficiently far from each other, which resulted the CO_2 concentrations in the inlet ducts higher than normal in the experiments, which in turn affected the accuracy of the calculation of the air change rate and the CO_2 emission rate.

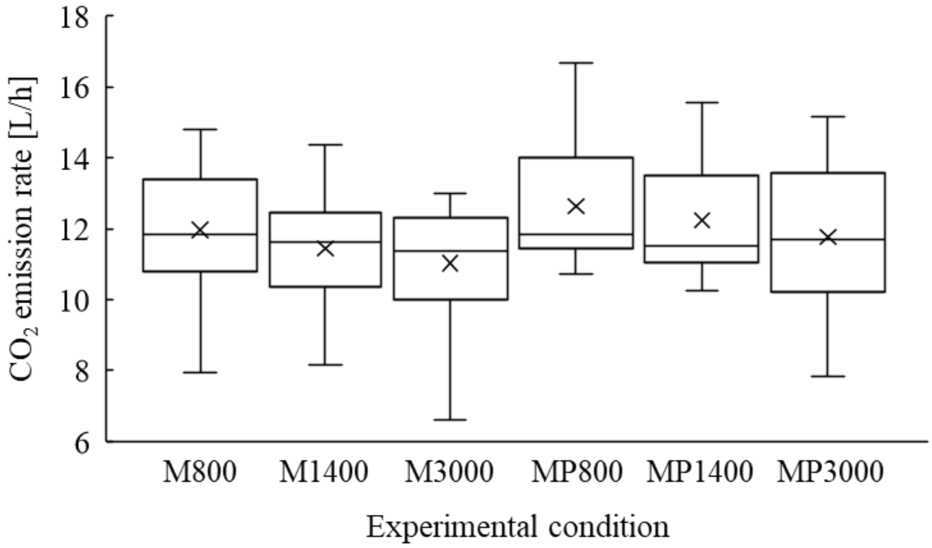

Fig. 3.6 The CO_2 emission rates from indirect calorimetry measurements

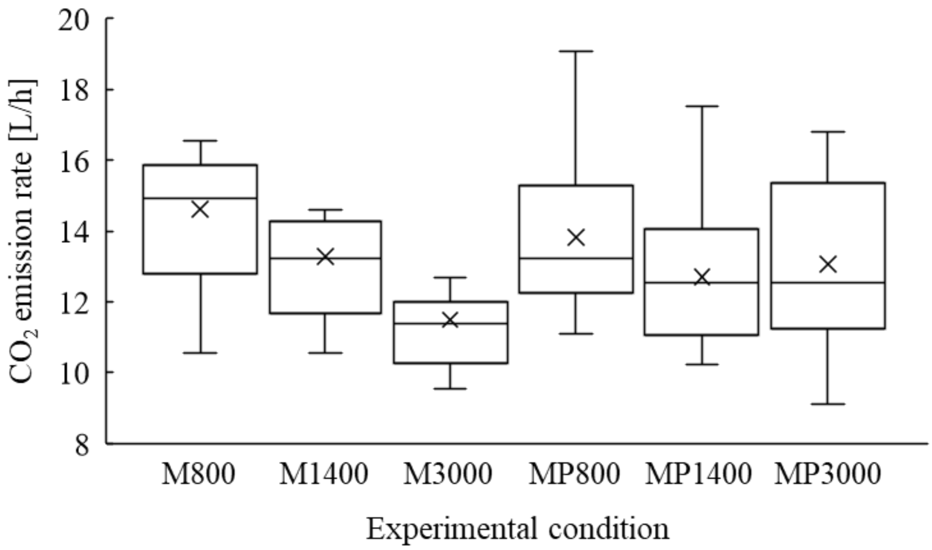

Fig. 3.7 The CO_2 emission rates from chamber method measurements

Comparing the average values of the CO_2 emission rates by the two measurement methods (Fig. 3.8), the CO_2 emission rate measured by the indirect calorimetry method is lower than the chamber method, and the variation with the decrease of indoor CO_2 concentration is smaller. In the experiment of reducing the outdoor air supply rate, the difference between the two measurement methods gradually decreased with the decrease of the air change rate, which is considered to be since the air change rate can be estimated more accurately by the long time concentration decay process under the condition of lower air change rate.

For the two measurement methods, indirect calorimetry analyzes the data by directly collecting the exhaled gas from subjects and therefore is considered to be more accurate, while the chamber method calculates the ventilation rate based on the process of the CO_2 concentration decay, as well as based on the change of the concentration in the climate chamber with and without the subjects in the chamber. However, during this experiment, it was found that the indirect calorimetry could be affected by the subject's position, and therefore, more experiments are needed to verify the accuracy of these two test methods.

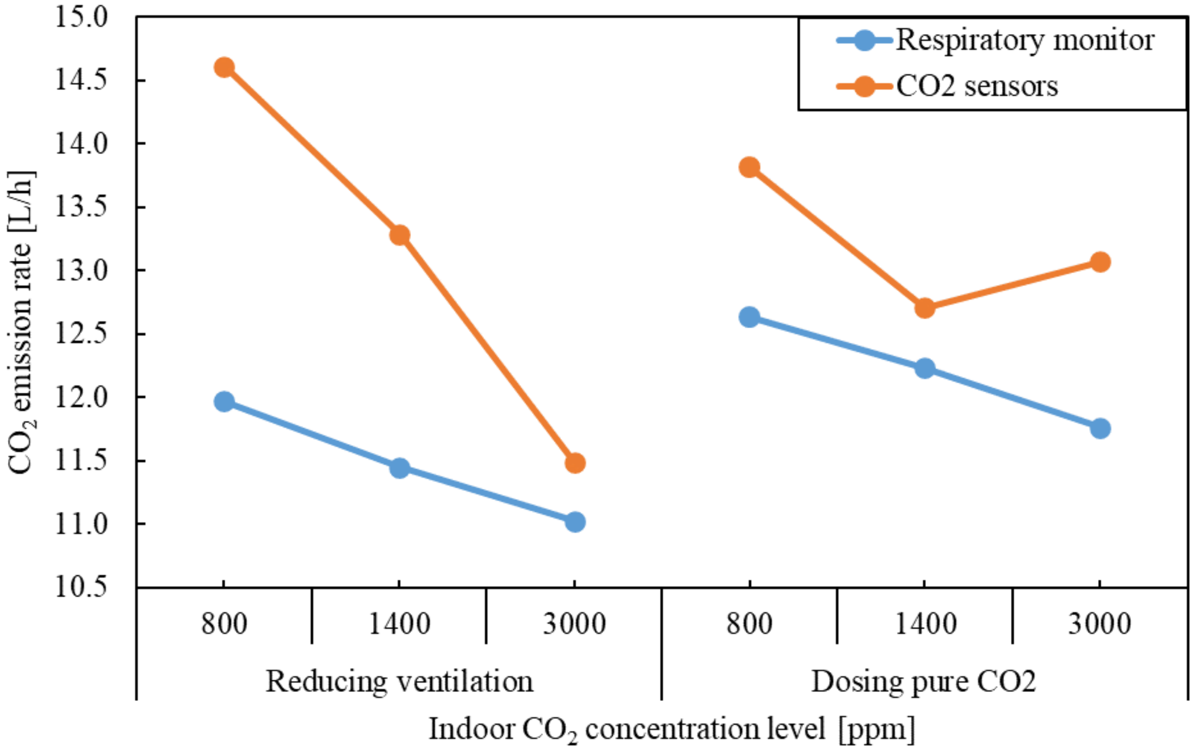

Fig. 3.8 Average CO_2 emission rate according to indoor CO_2 concentration by different methods

The results of the outdoor air supply rates calculated by the chamber method are shown in Table 3.3, which shows that the error generated by the operation during the experiment is greater in the experimental conditions with higher ventilation rates compared to the designed experimental conditions. The relationship between the outdoor air supply rate and the CO_2 emission rate calculated by the chamber method is shown in Fig. 3.9, the error bars are standard deviations, and the CO_2 emission rate is positively correlated with the outdoor air supply rate.

Table 3.3 Calculated outdoor air supply rate for different experimental conditions

Experimental condition	**Outdoor air supply rate (m^3/h)**
M800	34.44 ± 2.13 [1]
M1400	13.06 ± 0.48
M3000	4.57 ± 0.26
MP800/MP1400/MP3000	33.96 ±1.36

[1] SD = standard deviation

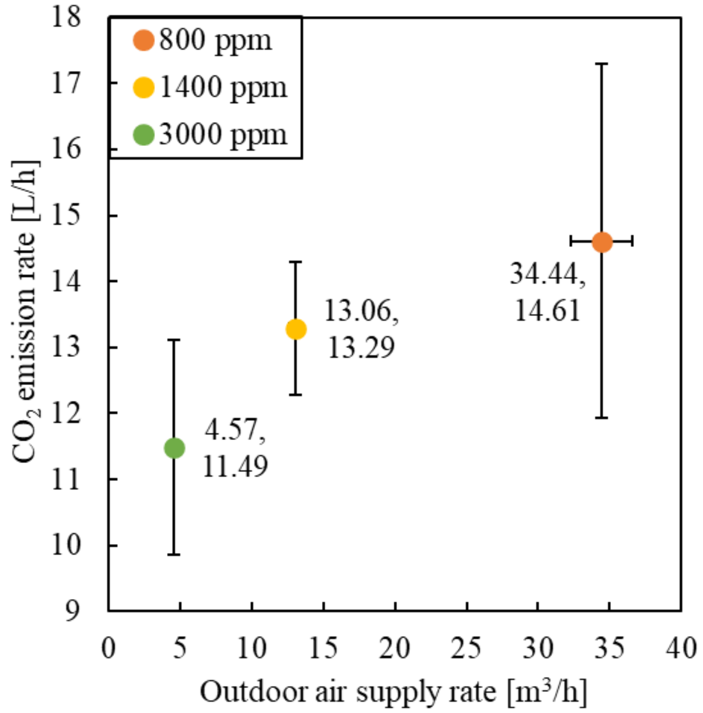

Fig. 3.9 Relationship between outdoor air supply rate and CO_2 emission rate based on the chamber method

3.3.2 Other physiological parameters

The **oxygen consumption** and **respiratory quotient (RQ)** measured by indirect calorimetry are shown in Fig. 3.10 and 3.11. The results in Figure 3.10 show that in both experiments oxygen consumption did not change significantly with increasing CO_2 concentration, and the average value remained at about 14 L/h. The results in Fig. 3.11 show that the RQ gradually decreases with increasing indoor CO_2 concentration in both experiments.

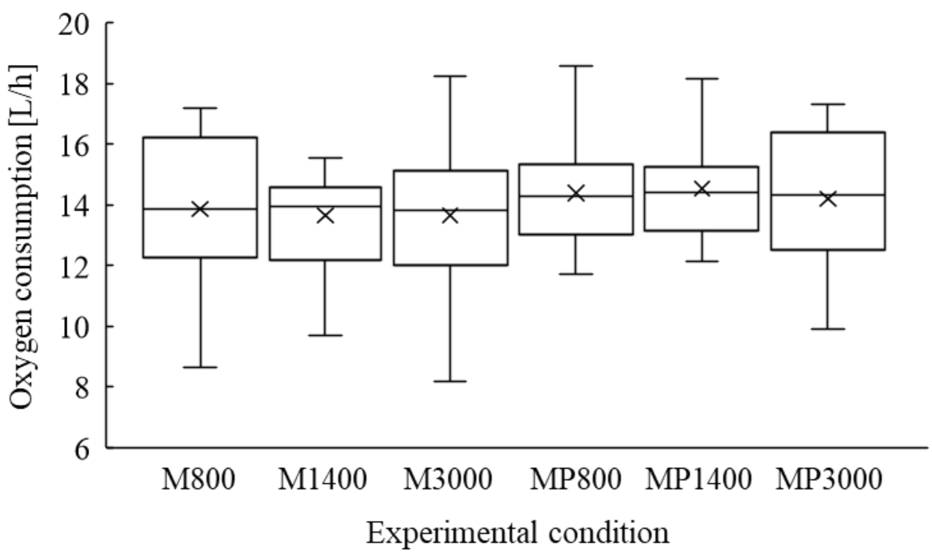

Fig. 3.10 Oxygen consumption according to different experimental conditions

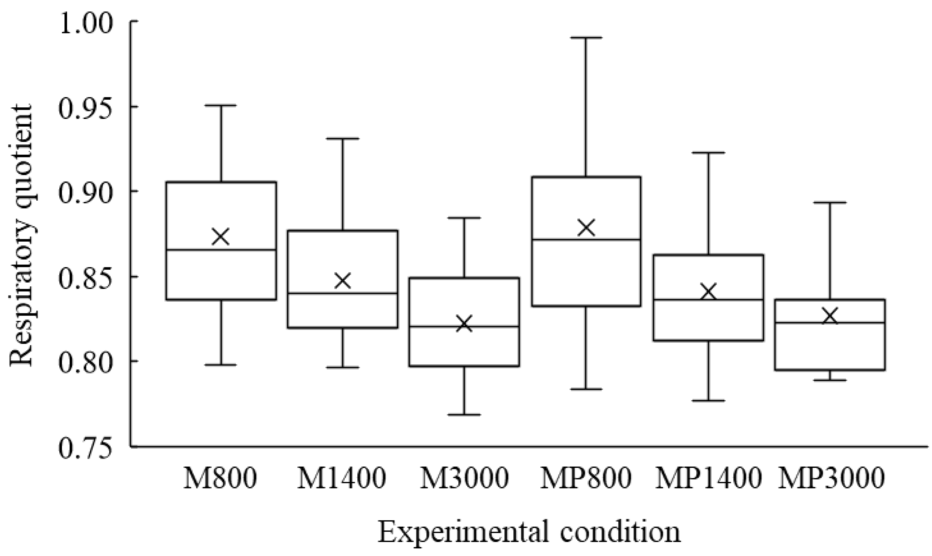

Fig. 3.11 Respiratory quotient according to different experimental conditions

RQ is the ratio of CO_2 emission rate to oxygen consumption, the above results show that there is no significant change in oxygen consumption with increasing indoor CO_2 concentration (whether it is reducing the outdoor air supply rate or the dosing pure CO_2 into the chamber), and the CO_2 emission rate gradually decreases, therefore the RQ also shows a trend of gradual decrease.

The **minute ventilation (MV)** and **respiratory frequency** obtained by indirect calorimetry are shown in Fig. 3.12 and 3.13. Minute ventilation is the volume of air breathed in and out by an individual in one minute, respiratory frequency is the number of breaths taken per minute, and minute ventilation is equal to the product of respiratory frequency and tidal volume, which is the volume of air moved in and out with each breath.

Minute ventilation and respiratory frequency did not change significantly with increasing CO_2 concentration but were significantly lower after the chamber was dosed with pure CO_2 than it was not.

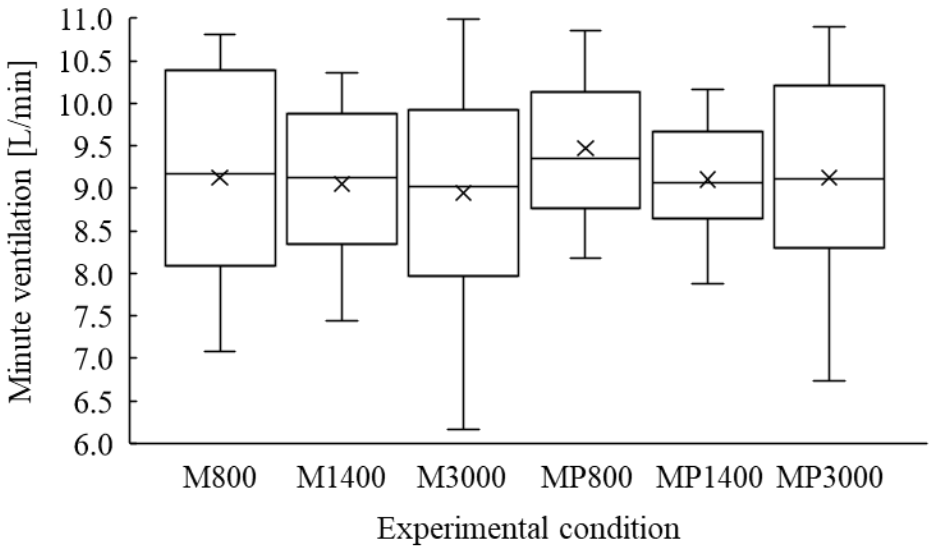

Fig. 3.12 Minute ventilation according to different experimental conditions

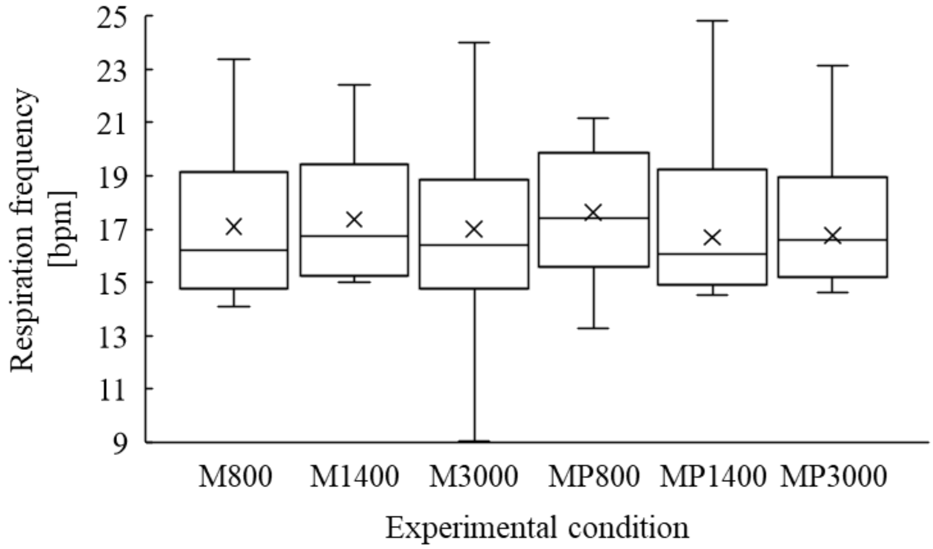

Fig. 3.13 Respiration frequency according to different experimental conditions

The **end-tidal oxygen (ETO_2)** and **end-tidal carbon dioxide ($ETCO_2$)** measured by indirect calorimetry are shown in Fig. 3.14 and 3.15. The results in Fig. 3.14 show that in both experiments, ETO_2 showed a decreasing trend with increasing CO_2 concentration, and the decreasing trend was even more when reducing the outdoor air supply rate. Excluding health reasons, the main reason for the decrease in ETO_2 is that not enough oxygen is inhaled during respiration, for example, insufficient oxygen concentration or insufficient ventilation in the environment. The results of this experiment therefore suggest that elevated CO_2 concentrations affect the oxygen intake during respiration, especially in environments with low ventilation rates. The results in Fig. 3.15 show that there is no significant change in ETO_2 when the outdoor air supply rate was reduced, and a small increase in ETO_2 with increasing indoor CO_2 concentration when pure CO_2 was dosing.

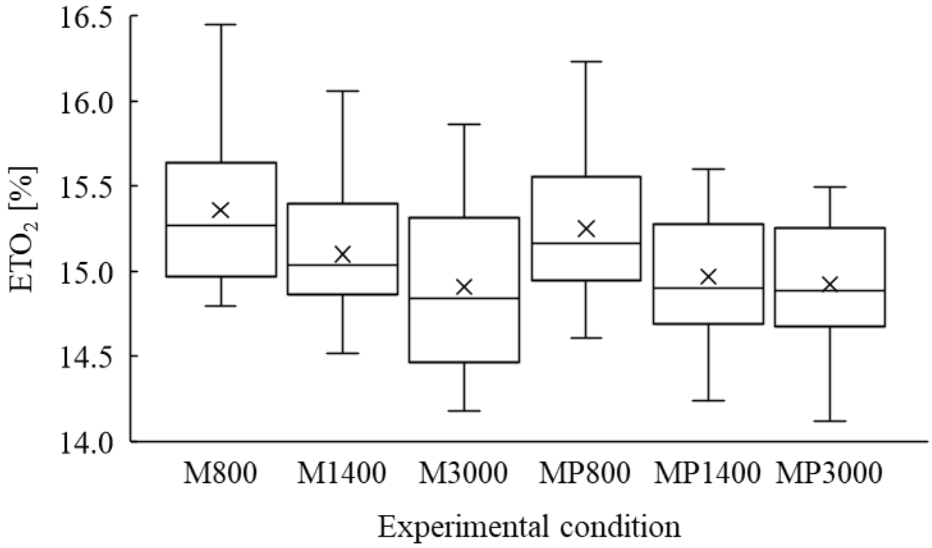

Fig. 3.14 ETO_2 according to different experimental conditions

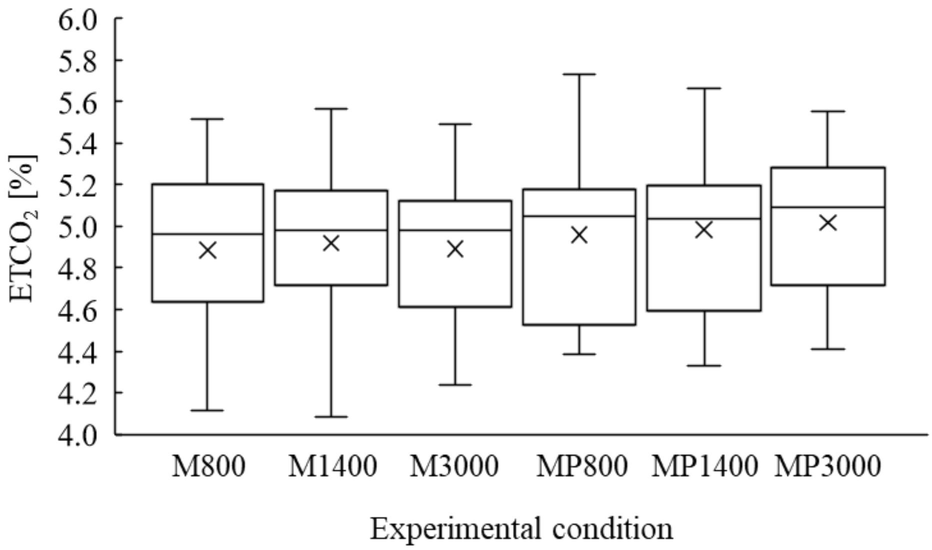

Fig. 3.15 $ETCO_2$ according to different experimental conditions

3.4 Discussion

For the two measurement methods of CO_2 emission rate, the chamber method has been used extensively in many past studies related to CO_2 emission rate because of the simplicity of the measurement, the inexpensive and compact sensors required for the measurement, and the ease of placement, but it is difficult to ensure the accuracy of the measurement, for example, if the indoor air cannot be mixed evenly in a large indoor space, the number of measurement points needs to be increased or the mixing effect of the indoor air needs to be improved. In recent years, indirect calorimetry has been more frequently applied to the study of metabolic rate and CO_2 emission rate because it can avoid the above problems well by directly collecting the exhaled gases of people with high measurement accuracy.

In this experiment, as described in section 3.3.1 above, when the chamber method was used, the CO_2 concentration in the air supplied to the chamber was unstable during some of the experiments, and generally increased as the experiment progressed, since the inlet and exhaust air ducts were not sufficiently far apart, and that the climate chamber was not sufficiently airtight. In addition, since the supplied air was not filtered, the possibility of other gases affecting the CO_2 concentration cannot be ruled out. Therefore, in future experiments, we will consider filtering the outdoor air supplied to the climatic chamber to remove other gaseous pollutants that may be present in the air and to maintain the CO_2 concentration in a stable range (e.g., between 430 and 480 ppm). When using indirect calorimetry, the accuracy of the measurement can be ensured as long as the gas is collected correctly. In this experiment, it was found that in addition to the fit of the mask to the face, the subject's posture also affected the measured CO_2 emission rate, for example, the CO_2 emission rate measured with the head down was less than that with the head looking straight ahead. Therefore, when using indirect calorimetry, subjects should keep the posture of looking forward without lowering the head. The use of indirect calorimetry can be somewhat limited compared to the chamber method which allows for more freedom to change positions. Therefore more experiments are needed to verify the accuracy of these two measurement methods.

For the two methods of changing the indoor CO_2 concentration, the main difference is that when the outdoor air supply rate is reduced, not only the CO_2 concentration increases but also the concentration of bioeffluents produced by the human body, whereas when pure CO_2 gas is dosed, only the CO_2 concentration increases. As can be seen from the results in this experiment, when gradually reducing the outdoor air supply rate, with two levels of CO_2 concentration increase, the results of the indirect calorimetry showed that the CO_2 emission rate was reduced by 4.34% and 7.94%, respectively (calculated from the average value, the same below), and the results of the chamber method showed that it was reduced by 9.03% and 21.36%, respectively. When pure CO_2 was dosed into the chamber, the results of the indirect calorimetry showed that the CO_2 emission rate decreased by 3.17% and 6.89%, respectively, as the CO_2 concentration increased by two levels, but the results of the chamber method did not show a gradually decreasing trend.

Based on the discussion of the two measurement methods above, the results of the indirect calorimetry are analyzed here due to its higher measurement accuracy. Compared with dosing pure CO_2, the reduction of CO_2 emission rate was greater when the outdoor air supply rate was lowered, which shows that the increase of bioeffluents concentration also had an effect on the CO_2 emission rate. Since only three CO_2 concentration levels were set in this experiment, it is difficult to obtain a functional relationship between the effect of CO_2 concentration (and biofluid interference) on the CO_2 emission rates. Measuring the CO_2 emission rate at several different CO_2 concentrations by indirect calorimetry will help to obtain the functional relationship.

As in the previous experiment, the prediction formulas for the CO_2 emission rate given in ISO 8996 and ASTM D6245 were utilized and the subject characteristics were substituted into the formula for calculation. The results of the calculations were compared with the results from the indirect calorimeter measurements in this experiment, as shown in Fig. 3.16.

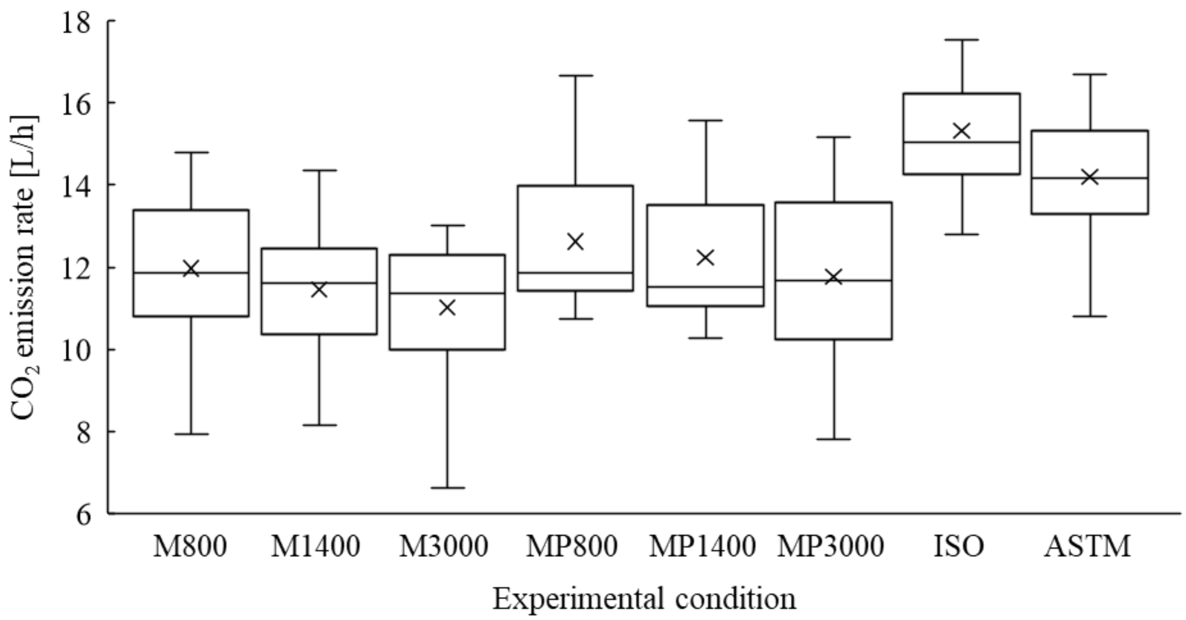

Fig. 3.16 Experiment result (measured by indirect calorimeter) and calculated result (by ISO 8996 and ASTM D6245) of CO_2 emission rate

The prediction formulas in both ISO 8996 and ASTM D6245 overestimated the rate of CO2 emission rate from sedentary activities in environments with different indoor CO_2 concentrations, with ISO overestimating the CO_2 emission rate more. Compared to the experimental results, ISO overestimated by 21.30% to 39.02% and ASTM overestimated by 12.43% to 28.86%. Consider the possibility of conducting multiple similar experiments and obtaining an indoor CO_2 concentration correction factor for the prediction formulas of CO_2 emission rate.

3.5 Conclusion

For this experiment, the effect of indoor CO_2 concentration on the CO_2 emission rate is discussed. Two measurement methods, indirect calorimetry and chamber method, were used in the experiment, and the indoor CO_2 concentration was controlled by reducing the ventilation rate and by dosing pure CO_2 into the chamber, respectively. The experiment was set up with three indoor CO_2 concentration levels, 800, 1400, and 3000 ppm.

The results of this experiment suggested that the indirect calorimetry was more accurate than the chamber method. The data from the indirect calorimetry showed a gradual decrease in CO_2 emission rate with a levels increase of carbon dioxide concentration, and a greater decrease in carbon dioxide emission rate when the ventilation rate was lowered, which was considered to be also affected by the increase in the concentration of the biofluid. In contrast, data from the chamber method showed that the CO_2 emission rate decreased with increasing CO_2 concentration when the ventilation rate was reduced and that the CO_2 emission rate decreased when pure CO2 was introduced into the chamber, but not with increasing CO_2 concentration. In addition, there was no significant change in oxygen consumption with increasing indoor CO_2 concentration, and the CO_2 emission rate gradually decreased, so the respiratory quotient also showed a gradual decrease.

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4 Conclusion

In this study, the effects of indoor temperature and CO_2 concentration on CO_2 emission rate were discussed by conducting two experiments, and the conclusions obtained from the experimental results are as follows,

- Effect of temperature and activity level on CO_2 emission rate

CO_2 emission rates significantly increased with elevated physical activity levels. CO_2 emission rates also increased with indoor temperature, particularly in higher physical activity levels. No clear relationship between CO_2 emission rate and indoor temperature was found in low physical activity levels.

- Thermal comfort and sensation

The thermal sensation increased with temperature and activity level. Minimal effect of temperature on thermal comfort under higher activity levels compared to lower activity levels. Females exhibited higher sensitivity to temperature and lower thermal comfort ratings at the same indoor temperature.

- Effect of indoor CO_2 concentration on CO_2 emission rate

Two measurement methods (indirect calorimetry and chamber method) were employed in the experiment. Indoor CO_2 concentration was controlled at three levels: 800, 1400, and 3000 ppm. Indirect calorimetry was found to be more accurate than the chamber method. The CO_2 emission rate showed a gradual decrease with increasing CO_2 concentration, especially when the ventilation rate was lowered. Oxygen consumption did not show significant changes with increasing indoor CO_2 concentration.

- Comparison of measurement methods

The indirect calorimetry showed a greater decrease in CO_2 emission rate with increasing CO_2 concentration and reduced ventilation rates. The chamber method indicated a decrease in CO_2 emission rate when pure CO_2 was introduced but not necessarily with increasing CO_2 concentration.

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