Evaluation of Personalized Thermal Conditioning Chair in Net Zero Energy Building Office

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ABSTRACT

The net Zero Energy Building (ZEB) aims to promote a productive working environment with high occupant satisfaction while minimizing energy input. Personal air-conditioning is a technology which can significantly contribute to ZEB. In this paper, we evaluate the improvement to occupant satisfaction from the use of a personalized thermal conditioning chair (TCC). In our results: (i) The TCC can change the equivalent temperature by −0.7 to 1.2°C. (ii) Users controlled the TCCs according to their thermal comfort. Users chose cooling mode mainly in summer and heating mode in winter according to environmental changes in the ZEB office. (iii) The TCC was controlled to maintain the user's preferred thermal environment. This resulted in the surrounding temperature of each user during TCC operation to vary. (iv) The thermal comfort survey from users converged to "neutral". This shows that users felt improved comfort from the ability to control their own thermal environment.

INTRODUCTION

Personal air-conditioning is a tool for controlling an occupant's individual thermal environment, allowing the autonomous ability to adapt to their personal surroundings. The concept is used when selecting clothes according to climate. People in Japan have a history of changing furniture and furnishings each season to keep their environment comfortable, and personal air-conditioning copies this objective.

There are multiple studies on the effects of personal air conditioning. Tsuzuki et al. evaluated the equivalent temperature of each of the non-isothermal personal air-conditioning (TAM, PEM, ClimaDesk) using a thermal mannequin. Sudo et al. pointed out that the effect of conventional personal air - conditioning is that thermal neutrality can be obtained quickly. However, it is pointed out that the following problems. 1) forgetting to turn off frequently occurs, 2) it is difficult to change the layout, 3) the strength and direction of the airflow are not sufficiently controlled, and 4) the desk space is restricted. Lee et al. Have proposed an isothermal personal air-conditioning mounted on a desk. As a result, it has been shown that autonomous air volume adjustment by the users has improved the feeling of comfort. Yanai et al. introduced personal air conditioning using partitions in practical offices, and observed and analyzed the usage status. Many workers adjust the air volume in response to changes in metabolic rate. Therefore, it has pointed out that adjustment function is necessary for personal air - conditioning. Vesely et al. conducted a literature search on multiple existing personal air-conditionings. Those could reduce the set temperature of the air-conditioning from 1 °C to 4 °C. Therefore energy saving effect of air-conditioning was estimated up to 40% or more.

Personal air-conditioning can contribute to Net Zero Energy Buildings (ZEBs) by minimizing ambient air-conditioning and alleviating the need for its adjustment by allowing occupants to control their personal environment. For example, an office that achieved ZEB with high occupant satisfaction from the introduction of personal air conditioning was reported.

Based on these previous studies, we have developed a thermal conditioning chair (TCC) which is equipped with cooling and heating functions. Its performance was evaluated using a thermal manikin, and then installed at a ZEB office site, in which we observed how the TCCs were operated by users. In this paper, we describe the effect on the equivalent temperature and improved satisfaction for the user.

Figure1. The Thermal Conditioning Chair (TCC)

1. OUTLINE OF THE TCC

The TCC is shown in Figure 1. It has 2 modes, a cooling mode and a heating mode. In the cooling mode, it is possible to promote heat transfer from a human body by isothermal airflow. The airflow from the air outlet on the sides of the seat cools the upper body, in particular the armpits and front chest. The suction airflow inside the seat promotes heat transfer from the back thigh which is in contact with the seat. The wind direction can be adjusted by 60° by rotating the wind direction plate at the tip of the air outlet.

In heating mode, the heater inside the seat surface heats the back thigh and the buttocks. A thermistor is used for the safety circuit. The power is cut off when overheated.

Table 1 shows the specifications of the TCC. The output in cooling mode can be adjusted in the range of 10 to 19 m^3/h. The output of the heating mode can be adjusted from 30 to 200 W/m^2. It has capability to transmit the operating status by Bluetooth for communication with other building equipment.

A rechargeable lithium-ion battery is mounted as the power source. The operable time under the maximum output from fully charged state is 10 hours in cooling mode and 6 hours in heating mode. A switch attached to the chair allows switching between cooling and heating modes and adjustment of output in 5 steps.

2. EVALUATION TEST

2.1 Test of wind-speed and direction

As shown in Figure 2, the wind direction and speed close to the thermal manikin in cooling mode were measured with a three-dimensional ultrasonic anemometer (WA-590, Kaijo Co., Ltd.). The thermal manikin was operated in "Comfort mode".

Figure 3 shows the results of the wind direction and speed test. The wind speed closest to the outlet is about 10 m/s. An upward airflow of 1.9 m/s was observed near the upper arm of the armpit. The wind speed was 0.7 m/s on the front chest. Normally, the natural convection flow velocity due to heat generation from the human body is 0.1 to 0.2 m/s. Therefore, it was confirmed that convection near the human body was promoted by air flow from the TCC.

The body surface area of the upper arm and chest is about 20% of the whole of the body. By reference to previous studies on wind speed and convective heat transfer coefficient, the convective heat transfer coefficient of the whole body is approximately doubled by the TCC's produced air flow, indicating the effect of promoted heat transfer from the human body.

2.2 Equivalent temperature of thermal manikin

The cooling and heating effects in cooling and heating modes of the TCC were evaluated in the equivalent temperature measured by the thermal manikin. The equivalent temperature is the temperature at which the amount of sensible heat transfer is equivalent under certain clothing level and thermal environment. The equivalent temperature calculation method is conformed to the standard of the Architectural Institute of Japan. The experimental conditions are shown in Table 2. The thermal manikin was fixed in a sitting position on the TCC. Both modes were measured for 1 hour in operating and non-operating

Table1. Specification of TCC

Blowing mode	Input power) 5W, Air volume) 10 - 19 CMH
Heating mode	Input power) 7W, Output) 30 - 200 W/m2
ICT	uploading operational data by Bluetooth
Power sorce	Rechargeable Li battery (48 Wh)
Usable time	In blowing mode) 10 hour. - In heating mode) 6 hour. -
Operability	2 modes, 5 output levels switchable Air direction controllable

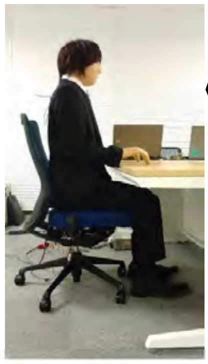

Figure2. Thermal manikin experiment

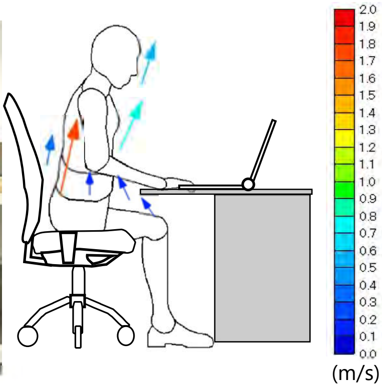

Figure3. Wind-speed around a human body

Table2. Conditions of the thermal manikin's experiments

	Blowing mode	Heating mode
Room temperature	**28** °C	**20** °C
Clothing level of the thermal manikin	**0.5** clo.	**1.0** clo.

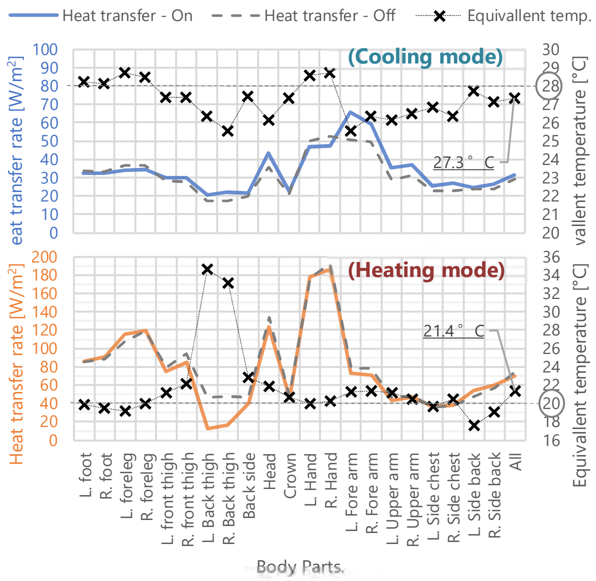

Figure4. Equivalent temperature of whole body

states. The equivalent temperature for the operating state of the TCC was calculated from that in the non-operating state.

The amount of heat transfer from the thermal manikin in cooling mode and equivalent temperature are shown in the upper part of Figure 4. The amount of heat transfer at the back thigh, head, forearm, upper arm, and chest was 1.1 to 1.3 times that in non-operating state. The amount of heat transfer throughout the body increased by 8%.

The equivalent temperature at these body locations were 25 to 27°C. This was lower than the room temperature of 28°C. The equivalent temperature of the entire body was 27.3°C, which was 0.7°C lower than the room temperature. This cooling effect in this condition is equivalent to reducing the clothing level by about 0.2 clo. In other words, it has the effect of reducing thermal resistance by an amount similar to undressing a thin shirt.

The lower part of Figure 4 shows the amount of heat transfer and the equivalent temperature in heating mode. The amount of heat transfer to the back thigh, which is in contact with the seat surface, was about 30% of that when not in operation. The amount of heat transfer from the entire body decreased by 6%.

The equivalent temperature of the back thigh was about 14°C higher than room temperature, while the equivalent temperature of the entire body was 1.4°C higher. In terms of clothing level, this is the same effect as an increase of 0.1 clo. In other words, use of the TCC had the same effect as changing from thin to thick trousers.

3. INSTALLING THE TCC IN THE ZEB OFFICE

3.1 Outline of the ZEB office

The TCC was installed in the ZEB office (Figure 5). Table 3 shows the outline of the building. Constructed in 2019, the three-story reinforced concrete office building has a total floor area of 1,181 m^2. The main air-conditioning system is a variable refrigerant system. The sub air-conditioning system is equipped with a skeleton radiant heating system. It can switch heat sources between an underground borehole and a geothermal heat pump according to the season. In addition, solar power generation is installed. Both the design values and the actual operation values (October 2019 to September 2020) have achieved ZEB requirements.

As shown in Figure 6, TCCs were provided to 6 males (m1 to m6) and 2 females (f1, f2) in room-1 and room-2 on the 2nd floor, aged from 30 to 59 years old. 5 of them were executives (see Table 4). The operational data of the TCC from November 2019 to September 2020 was analyzed. However, participants who had a significantly short seating time or were transferred during the analysis period were excluded.

Figure5. The ZEB office

Table3. Outline of the building

Location	**Takamatsu city, Kagawa, Japan**
Structure	**Reinforced Concrete, 3 stories**, Building type	**Office**
Built year	**2019**, Building area	**481**m^2, Total floor area	**1,181** m^2
HVAC system	(main) **VRF system** (20HP; 56kW), (sub) **GeoTABS** (10kW)
Regeratable energy	**Solar battery** (49kW)
Japanese BELS labeling	***『ZEB』 (net-ZEB)***

Figure 6. Layout of the TCC users (f1, f2: female, m1-m6: male)

Table 4. Attributes of TCC users

ID	sex.	age.	manager.	ID	sex.	age.	manager.
f1	female	30~39		m3	male	50~59	✓
f2	female	30~39	✓	m4	male	50~59	✓
m1	male	50~59	✓	m5	male	30~39	
m2	male	50~59		m6	male	40~49	✓

3.2 Indoor temp. and humidity in each season

Figure 7 shows the indoor temperature and humidity on representative days for the mid-season, summer, and winter. Looking at the mid-season period (November 12, 2019), the temperature in room-1 was 22 to 25°C during business hours (9:00 to 18:00), and 20 to 23°C in room-2. The difference between rooms was due to the air-conditioning machine operating in room-1 and not in room-2. The accuracy of the temperature sensor is ± 0.3 ° C and relative humidity sensor is ± 3%.

In the winter period (December 20, 2019), both room-1 and room-2 remained at 20 to 24°C. In the morning, room-2 did not reach the set temperature of 22°C. In the afternoon, the set temperature was exceeded reaching 23 to 24°C due to sunlight. Relative humidity remained between 40 and 50%.

In the summer period (August 26, 2020), the temperature was 26 to 27°C and the relative humidity was 50 to 60% during business hours. There was a temporary increase in humidity when occupants opened the windows at night (20:00 to 8:00 the next day) and every 2 hours due to the pandemic.

3.3 TCC results from seating time in each season

Figure 8 shows the seating time of each month and the operating time in cooling and heating modes. Seating times ranged from 3 to 82 hours, with an average of 37 hours. Seating time varied for each person depending on job type. Users' seating times differed from month to month according to the frequency of client and business meetings. Since the total monthly business hours are about 160 hours (20 business days × 8 business hours), it can be said that about 25% of business hours were generally seated.

Looking at the mid-season period (November 2019), user m4 worked for 5 hours in cooling mode, and f1 and f2 worked for 7 to 13 hours in heating mode. Although both users f1 and m4 were present in room-2 they worked in different modes. It is presumed that m4, who had a short seating time, had a higher metabolic rate due to job activities in the office compared to f1, who had a long seating time, resulting in individual differences.

In the winter period (December 2019), all of the users analyzed worked in heating mode for 0.3 to 31 hours. In one case, a female operated the TCC until the set temperature was reached, showing that each person evaluated the thermal environment and directly adjusted the temperature. In addition, some periods for f1 was found operating in cooling mode. Since her seating time was shorter than in other months, it is possible that her metabolic rate was higher and necessitated cooling mode.

In the summer period (August 2020), each user's cooling mode operating time was observed to be 5 to 76 hours with an operating rate of 44 to 99%, higher than other periods. This is because indoor temperature and humidity increased due to outside air introduced by the opening of windows.

3.4 TCC operating rate for each room temperature

Figure 9 shows the frequency distribution of the exposed rate of each user and operating rate of the TCC in each temperature range. Looking at the exposed temperature of each user, a tendency for temperatures near the set temperature (22°C in winter and 27°C in summer) to be higher than others can be seen. However, the exposed temperature was in the range 17 to 32°C, deviating from the set temperature by about -5 to 5°C. This was due to the suspension of air conditioning during overtime, non-air conditioning operation during the interim period, and ventilation from window opening.

Looking at the operating rate of the TCC, the lowest values is at 23 to 26° C. The temperatures at which the operating rate was minimum differed for each person, around 23°C for f1, f2, and m4 and 26°C for m2 and m5. It is considered that these individual differences are attributable to thermal environment preference for each person.

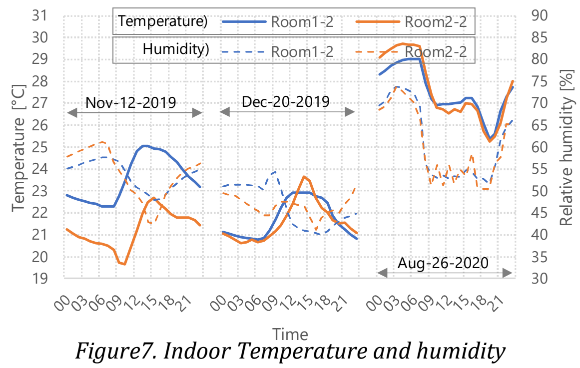

Figure7. Indoor Temperature and humidity

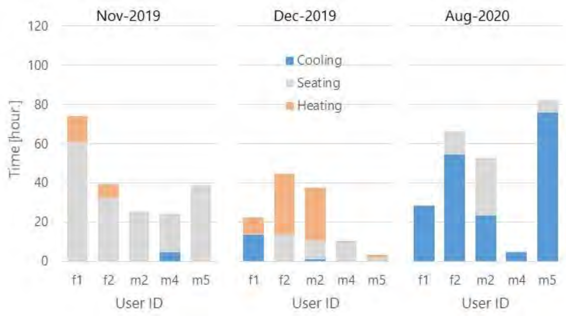

Figure8. Operating time and seating time

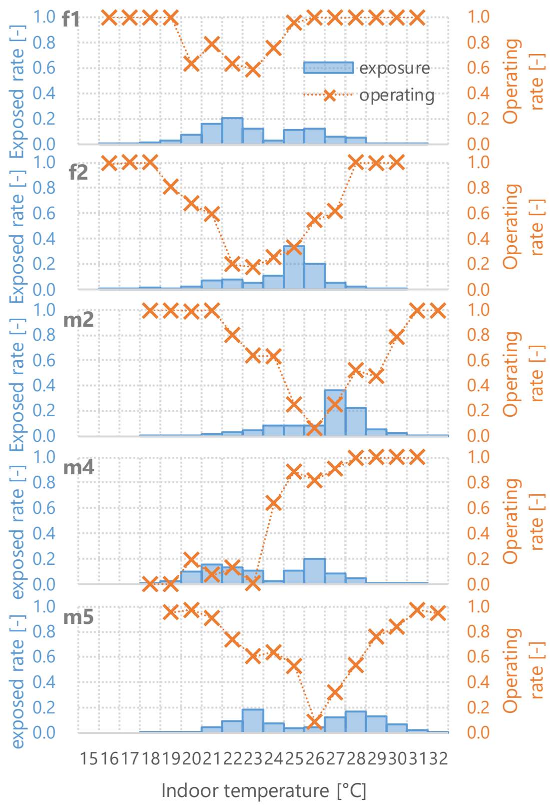

Figure9. TCC usage rate for each temperature

Individual differences can also be seen. For f2, a low operating rate of 0.3 or less appears at 22 to 24°C. A medium operating rate from 0.4 to 0.8 can be seen at 19 to 21°C and 26 to 27°C. High operating rate 1.0 is seen at 19°C or lower and 28°C or higher. Users m2 and m5 show similar tendencies to f2. The temperature for low operation rates was 26 to 27° C, and 22 to 25°C and 28 to 30°C for medium operation rates. For f1, no low operation rate was observed, medium operating rate occurred at 20 to 23°C, and high operating rate at other temperatures. For m4, the absence of operation below 23°C indicated heating was not required.

The results suggest the following reaction by users according to the exposed temperature. At temperatures with low operation rates, the TCC is not operated because thermal discomfort was not sensed. At temperatures with medium operation rates, thermal discomfort was not noticeable normally but became gradually noticeable during temporary increases in metabolic rate, leading to the operating rate increasing. At temperatures with high operation rates, thermal discomfort was present, leading to constant operation. Hence, autonomous control was observed among users.

Even if the room temperature deviates from the set temperature, it can be formed a comfortable thermal environment by controlling the TCC's function autonomously by users. ZEB is required to minimize input energy and to suppress the air-conditioning power. Under this situation, the TCC is effective.

3.5 Effect on thermal sensation vote of TCC users

Figure 10 shows the thermal sensation vote of users and non-users of the TCCs in the 1st year (November 2019) and 2nd year (November 2020). In the 1st year, both users and non-users reported thermal comfort outside neutral ("slightly cold" to "very cold"). In the 2nd year, all of the users' surveys showed neutral declarations.

The users described some of their opinions as follows:

"I don't need to worry about the heat and cold. The TCC plays a role in bridging the difference in thermal comfort."

"I think the frequency of changing the set temperature of the air-conditioning machine has decreased."

From these results, it is suggested that the users learned how to use the TCC according to their level of thermal comfort. They received an expanded range of comfortable thermal conditions owing to the adjustments allowed by the TCC, and hence expressed satisfactory experiences.

CONCLUSION

In this paper, the performance test results of the TCC and the operational results after installation in the ZEB office are described.

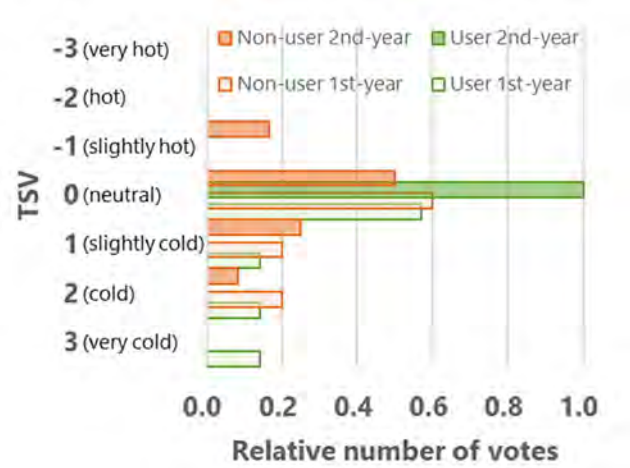

Figure10. TCC user's and non-user's thermal sensation votes difference between 1st year and 2nd year

(1) The equivalent temperature evaluated using a thermal manikin decreased by 0.7°C in cooling mode and increased by 1.2°C in heating mode.

(2) In the operational results of the ZEB office in each season, the TCCs were used in cooling mode in summer and mainly in heating mode in winter. However, in winter, there were cases where it was used in cooling mode in response to temporary increases in metabolic rate. From these results, it was confirmed that the TCCs had been used autonomously according to the thermal comfort of each user.

(3) From the results for exposed temperature and the operating rate of the TCC, the preferred temperature of each person is seen to be different, as the temperature with low operating rate (0.3 or less) varied. It was also confirmed that the operating rate changes according to the temperature range.

(4) The users' thermal comfort survey in the 2nd year of practical use converged to "neutral". This suggested that their ability to adjust thermal conditions improved after learning how to use the TCCs. As a result, the users expressed satisfactory experiences.

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