Study on air-conditioning control system considering individual thermal sensation

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Abstract. Increased satisfaction with thermal environments in office significantly affects workplace productivity. Conventional air-conditioning systems are intended to achieve a uniform thermal environment across the entire air-conditioned space. However, due to differences in thermal sensation among individuals, it is difficult to improve occupants’ thermal satisfaction merely by providing a uniform thermal environment. In this study, we developed an air-conditioning system called the Smart Wellness Control System with the aim of realizing air conditioning that responds to individual variance in thermal satisfaction. The system collects data from sensors about the locations of individual occupants and the thermal environments to which they are exposed, records this data together with their votes on their thermal sensation, and modifies and learns their comfort indices accordingly to control the speeds of personal fans and the air temperature setting. We conducted a questionnaire survey of occupants in an actual office building equipped with this system; the results indicated that use of the Smart Wellness Control System increased their satisfaction with the thermal environment by about 50% and increased their productivity by about 25%.

1. Introduction
Conventional air conditioning is intended to achieve a uniform thermal environment across the entire air-conditioned space. Requirements for thermal comfort are provided in ISO 7730, ASHRAE Standard 55 [1,2], and other standards that have been established based on average values obtained from experiments on large groups of people. However, due to differences in thermal sensation among individuals, it is difficult to improve occupants’ thermal satisfaction merely by providing a uniform thermal environment. For example, a report [3] stated that about 30% of the occupants of an air-conditioned office set to a temperature of 26°C expressed thermal dissatisfaction. To achieve more comfortable air conditioning, it is considered necessary to develop air-conditioning systems that can reduce the impact of individual differences in thermal sensation.

In this study, we developed an air-conditioning system called the Smart Wellness Control System with the aim of realizing air conditioning that responds to differences in thermal sensation, which is not constant and varies from person to person, in thermal environments as an important element of intellectual productivity. The system collects data from various sensors to grasp the locations of individual occupants and the thermal environments to which they are exposed, records this data together with their votes on their thermal sensation, and modifies and learns their comfort indices
accordingly to control the speeds of personal fans and the air temperature setting. This report presents
the results of environment measurements taken in an actual office equipped with this system and the
results of a questionnaire survey conducted to evaluate how the Smart Wellness Control System
affects occupants’ thermal satisfaction and productivity.

2. Overview of the Smart Wellness Control System

Figure 1 shows the configuration of the Smart Wellness Control System. This system has three main
capabilities: (1) to acquire environmental data, (2) to enable users to vote on their bodily sensations,
and (3) to control air conditioning in response to the personal thermal sensations expressed by such
votes.

\[
\text{Metabolic rate [MET]} = 1.05 \times \text{METs} \times m \times 4186 / (A_D \times 58.2) \quad (1)
\]

\[
A_D = 0.202 \times m^{0.425} \times l^{0.725} \quad (2)
\]

\[A_D = \text{Body surface area } [m^2], \ m = \text{Mass[kg], } l = \text{Height[m]}\]

This enables the system to grasp each user’s PMV, which varies depending on the space, time, and
action. Clothing insulation is set in advance, and each user’s height and weight are set by the user
himself/herself via smartphone.
Using a smartphone application, users can vote based on a 6-point thermal dissatisfaction scale. Their votes are stored in a cloud database together with their PMV at the time of voting. Figure 2 shows the application screen for voting. Besides voting, the application enables users to view the temperature, humidity, and other environmental conditions at their current locations as well as their own metabolic rates. User voting is voluntary. Users are prompted to vote by notifications on their smartphones and smartwatches that pop up about twice a day while they are in the room.

![Application screens](image)

**Figure 2.** Application screens

The Smart Wellness Control System expresses the relationship between the thermal dissatisfaction indicated by users’ votes (hereinafter referred to as the personalized PPD*) and their PMV at the time of voting in Equation (3), and it stores such data separately for each user (Figure 3).

\[
\text{Personalized PPD} = 1 - (1 - y) \times \exp[a(\text{PMV} - x)^4 + b(\text{PMV} - x)^2]
\]  

(3)

* PPD (predicted percentage dissatisfied) is an index that quantitatively predicts the percentage of thermally dissatisfied people. ISO 7730 defines thermally dissatisfied people as those who will vote hot, warm, cool, or cold on a 7-point thermal sensation scale. In this report, the personalized PPD is defined as the value expressed by each user to quantify his/her thermal dissatisfaction in terms of a percentage between 0 and 100.

![Relationship between PMV and personalized PPD](image)

**Figure 3.** Relationship between PMV and personalized PPD, and how to modify the relationship

The coefficients \( a, b, x \) and \( y \) of this curve are parameters that are updated after each vote by the least-squares method. After receiving several votes from a user, the system can draw the user’s own characteristic curves of personalized PPD versus PMV. From the characteristic curves so obtained, the Smart Wellness Control System determines the settings that make the personalized PPD equal to or
lower than the target value (PPD ≤ 0.1) and operates each air conditioner accordingly. This is one technology for reflecting personal preferences in air-conditioner control.

Figure 3 shows how a personal fan’s speed was changed when it was operated by the Smart Wellness Control System. The figure also shows the user’s metabolic rate and PMV measured when the user was doing step aerobics to increase the metabolic rate and then sat down. As the figure shows, the metabolic rate and the PMV increased while doing step aerobics. When the user sat down, a beacon detected this action and the personal fan operated to make the personalized PPD reach the target value. Also note that the personal fan continued to operate at "High" speed for a certain amount of time after the user sat down, and then the fan speed was decreased in response to the decrease in metabolic rate.

![Figure 4. Example of fan operation with the Smart Wellness Control System](image)

### 3. Example of applying the system to an office building

The following is an example of applying the Smart Wellness Control System to an office building. The target was a small two-story building with a total floor space of approx. 1,300 m\(^2\). It is the first small- to medium-sized office building to be remodeled into a zero-energy building (ZEB) while being occupied [6]. The office area is air conditioned with a radiant air-conditioning system together with personal fans installed on the ceiling (Photo 1). The radiant air conditioning system creates a uniform ambient environment. When the occupants feel slightly hot in the air-conditioned area, they can operate their personal fans to generate air currents to make themselves feel cool. With high directionality, each personal fan blows out air directed precisely toward each occupant’s face. Table 1 shows the specifications of the personal fans, and Figure 5 shows the results of measurements of the air velocity distributions. The fan speed can be adjusted to one of four levels: Off, Low, Medium, and High. The air velocity at the level of the face of an occupant while seated (FL + 1.2 m) was about 0.5 m/s when the fan was operated at Medium speed and about 0.8 m/s at High speed.

To examine the cooling effect produced by changing the personal fan speed, verification was conducted using a thermal manikin, and the results are described below. Measurements were taken on August 31, 2016 during the season when air conditioning is in use. Figure 5 shows the equivalent temperatures of different parts of the thermal manikin’s body with the personal fan operating at the
speeds of Off, Medium, and High. The room had a temperature of 27.5ºC and humidity of 43% during these measurements. The equivalent temperatures were calculated based on the environmental conditions with no air current from the personal fan. Figure 6 shows that the personal fan cooled the body, particularly the front (face, chest, arms, and front thighs) exposed to air currents. The equivalent temperature of the entire body was 27.1ºC when the fan speed was Off and 26.2ºC at High. These results indicate that it is possible to decrease equivalent temperatures by about 1.0ºC by adjusting personal fan speed.

![Photo 1. Personal fan](image1.png)

**Figure 5.** Measurements of personal fan air velocity distributions

**Table 1.** Personal fan specifications and air velocities in the occupied area

| Fan speed | Low | Medium | High |
|-----------|-----|--------|------|
| Power consumption [W] | 3 | 4 | 5 |
| Airflow at outlet [m³/h] | 20 | 30 | 40 |
| Air velocity at outlet [m/s] | 3.3 | 5.5 | 7.2 |
| Air velocity [m/s] | FL+1.2 m | 0.32 | 0.54 | 0.80 |
| | FL+1.0 m | 0.28 | 0.48 | 0.71 |
| | FL+0.6 m | < 0.25 | 0.39 | 0.58 |

![Figure 6. Thermal manikin equivalent temperatures](image2.png)

**Figure 6.** Thermal manikin equivalent temperatures

The remodeled office building is equipped with one personal fan per occupant. When the personal fans are operating in normal mode, occupants can freely adjust the fan speed to one of four levels. When the personal fans are operating in Wellness Control mode, the system controls the fan speed based on the calculations described in the preceding section.
4. Experimental methods
To examine how the Smart Wellness Control System affects occupants’ thermal sensations and satisfaction, two runs of an experiment were conducted as Case 1 and Case 2. In Case 1, users were allowed to freely adjust the speeds of their personal fans. In Case 2, the personal fans were operated in Wellness Control mode. Each run was conducted during office hours from 9:00 to 18:00 over a period of one week, and the results were compared between Case 1 and Case 2. In addition, a questionnaire survey was conducted in each case regarding thermal sensation, thermal satisfaction, and self-assessed intellectual productivity. Users were asked to vote on three 7-point scales: a thermal sensation scale with scores of -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), and +3 (hot); a thermal satisfaction scale with scores of -3 (very dissatisfied), -2 (dissatisfied), -1 (slightly dissatisfied), 0 (neutral), +1 (slightly satisfied), +2 (satisfied), and +3 (very satisfied); and a productivity scale with scores of -3 (very declined), -2 (declined), -1 (slightly declined), 0 (neutral), +1 (slightly increased), +2 (increased), and +3 (very increased).

Among the 37 users who received the questionnaire form, 26 users replied in Case 1 and 22 users replied in Case 2. In each case, the air temperature setting was 26.5ºC. Table 2 shows the experiment conditions, while Figure 7 shows the air temperature frequency distribution in each case. Though the air temperature frequency distribution in Case 1 is slightly higher than that in Case 2, the air temperature was normally distributed around the set value of 26.5ºC in both cases. Therefore, we consider that users were exposed to nearly the same thermal environment in both cases.

Table 2. Experiment conditions

|                | Case 1          | Case 2          |
|----------------|-----------------|-----------------|
| Period         | Sep. 5 to 9     | Sep. 12 to 16   |
| Fan control    | By users themselves | Wellness Control |
| Mean air       | 26.9ºC          | 26.5ºC          |
| temperature    |                 |                 |
| Mean relative  | 49.8%           | 48.1%           |
| humidity       |                 |                 |

Figure 7. Air temperature frequency distribution in each case

5. Experimental results
5.1. Use Rate of Personal Fans and Effects on Thermal Sensation
Figure 8 shows the results of a survey on occupants’ sitting rates during the two periods of the experiment. In each case, at least 50% of the occupants were seated in the office for at least 60% of the office hours, and there were no major differences between the two cases. Figure 9 shows the results of
calculating the use rate of personal fans at each speed. In Case 1, personal fans were in the "Off" state for 70% and operated for 30% of the office hours. They were operated at "High" speed for 26% of the office hours, and there were few changes in fan speed. As can be seen in Figure 8, the sitting rate was not low, meaning that most occupants did not use the personal fans even while seated. These results show the tendency that, when users are allowed to freely operate their personal fans, some users always use the fans, while others do not use the fans regardless of whether or not they are seated. In contrast, in Case 2 in which Wellness Control was active, the operating time of the personal fans was markedly longer than that of Case 1. This is probably because the percentage dissatisfied, which was calculated from the occupants' PMV, exceeded the tolerance for a large part of the office hours, and the fans were automatically operated to improve such a state.

Table 3 shows the power consumption of the personal fans in each case. In Case 2, due to longer use of the personal fans, the average power consumption per day was about 360 Wh higher than that of Case 1. However, this increase was very small relative to air conditioner power consumption.

Figure 10 shows the frequency distribution of the PMV calculated per occupant in each case. The figure shows that a PMV of 0.4 to 0.6 was frequently observed in Case 1, and a PMV of -0.2 to about 0.2 was frequently observed in Case 2. Based on these results, the Wellness Control is thought to have helped make the environment more thermally neutral with just a small increase in power consumption.
5.2. Effects on Thermal Satisfaction and Intellectual Productivity

Figure 11 shows the results of a comparison of thermal sensation between Case 1 and Case 2. The percentage of respondents who voted "slightly cool" in Case 2 is higher than that in Case 1. To evaluate how thermal satisfaction and intellectual productivity of individual occupants changed from Case 1 to Case 2, occupants’ answers to questions about thermal satisfaction (-3 [very dissatisfied] to +3 [very satisfied]) and self-assessed intellectual productivity (-3 [very declined] to +3 [very increased]) were compared between the two cases. The results shown in Figure 12 indicate that in Case 2, 50% of all respondents expressed higher thermal satisfaction, while 25% expressed lower thermal satisfaction, and 25% expressed higher productivity, while 25% expressed lower productivity. Figure 11 shows the correlation between thermal satisfaction and productivity. As the figure indicates, the higher thermal satisfaction becomes, the higher productivity becomes. We consider the increased satisfaction of occupants due to the Wellness Control to indirectly contribute to increased productivity. In this study, however, about 20% of the occupants expressed decreased satisfaction due to the Wellness Control, and they also expressed declines in productivity. Since this study selected personal fans as the devices controlled by the system, this may have caused low satisfaction among occupants who hate to feel air currents and/or who are dissatisfied with automatic control of fan speed.

Figure 11. Comparison of thermal sensation

Figure 12. Changes in thermal satisfaction and productivity from Case 1 to Case 2

Figure 13. Relationship between thermal satisfaction and self-assessed productivity

6. Conclusions

This report presents the results of an evaluation of an office building remodeled into a ZEB in order to examine how the thermal satisfaction of individual occupants is affected by air-conditioning control technology developed to increase occupants’ thermal satisfaction. We found that Wellness Control can
provide occupants with a more thermally neutral environment with just a small increase in power consumption by controlling the speeds of personal fans that produce a cooling effect. In addition, the results of a questionnaire survey indicated that Wellness Control, which controls air conditioning by learning individuals’ thermal sensations, increased the thermal satisfaction of about 50% of the occupants, thus improving productivity. Nevertheless, about 20% of occupants expressed decreased satisfaction and productivity. We thus consider it necessary to do further studies, including a study of individual factors.

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