Thermal Comfort Evaluation Focused on Occupants' Thermal Preferences:

A Thermal Satisfaction Model for Small Groups of Occupants

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The thermal comfort indices contained in international standards are developed by statistical methods using data from a large number of people (e.g., the Predicted Mean Vote index of ISO 7730) which hardly reflect individual differences in thermal sensation. Therefore, in order to improve the thermal satisfaction of building occupants in an air-conditioned environment, an evaluation system that reflects their actual individual feelings is needed. The technology presented here enables evaluation of the thermal environmental satisfaction level of occupants based on their perceptions by constructing data models which describe the relationship between indoor environmental data and occupants' feedback to the heating, ventilating, and air conditioning (HVAC) system by means of their thermal sensation votes. This paper reports the results of constructed models using real data from an office and presents sample applications of those models.

1. Introduction

Perceived thermal satisfaction of occupants affects office work performance.(1) Thermal comfort and thermal satisfaction in an office are key factors in determining the quality of the indoor environment. In recent years, there has been a focus internationally on real estate that fosters workers' wellness and comfort, to promote workplace productivity and to secure excellent human resources. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism is considering a certification system for judging whether buildings meet those requirements.(2) Along with societal trends such as Japan's "work-style reform," those requirements have led to a demand for thermal environments with high occupant satisfaction.

However, since thermal sensations ("I feel hot" / "I feel cold") differ depending on the individual, actual offices have a mix of occupants, some of whom feel hot even in the same environment where others feel cold. Predicted mean vote (PMV), which is the thermal comfort index of ISO 7730, is often used for the assessment of comfort in buildings, but PMV is a statistically processed index based on the results of experiments with over 1,300 people, and can hardly be expected to reflect different individuals' feelings. For that reason, a new heating, ventilating, and air conditioning (HVAC) solution to improve the environmental satisfaction of occupants in real offices has been proposed. It allows occupants to freely vote, entering their own hot/cold thermal sensation feedback into the HVAC control loop through a Web browser screen or dedicated device.(3), (4) This method is also expected to improve the satisfaction of occupants by giving them the ability to control their environment.(5)

We developed a technology which enables comfort evaluation by building an environmental satisfaction model for groups composed of multiple occupants in different HVAC zones. The model describes the relationship between information on thermal sensations and indoor thermal environment determined by temperature, humidity, etc., at the time when the thermal sensation votes were made. Using this model, a comfort evaluation method that quantifies a group's degree of satisfaction on the basis of their thermal sensations has become possible. Also, we report on a trial experiment in which environmental satisfaction models were created for an actual office.

In this paper, the differences between representative thermal sensations and the thermal sensations of actual occupants are described in section 2. In section 3, problems for the use of thermal sensation voting data in an actual office, and countermeasures, as well as technical concepts of the environmental satisfaction model are described. Then, after explaining the procedure for generating the training data necessary to create the model in section 4, we present the results of our trial experiment of model creation in an actual office and simulations of environmental satisfaction using the created model in section 5.

2. Thermal Comfort Index vs. Actual Feeling

2.1 PMV Thermal Comfort Index

The PMV thermal comfort index standardized by ISO 7730 links the state of thermal equilibrium between the human body and the ambient environment to human thermal sensations. The method of calculation and program code are also published in an ANSI/ASHRAE standard, so this section merely gives an overview of PMV.

The heat load of a human body (amount of heat stored in the body) that is affected by its thermal equilibrium state is determined by the metabolic rate, which is the calorific value in the body, and the amount of heat transferred by convection, radiation, and evaporation*1 between the body and the surrounding environment (see fig. 1 and equation 1).

$$L = M - (C + R + E) \qquad \text{Equation 1}$$

Where:

L: Heat load of human body (W/m^2)

M: Metabolic rate (met) Note: 1.0 met = 58.2 W/m^2

C: Heat transferred by convection (W/m^2)

R: Heat transferred by radiation (W/m^2)

E: Heat transferred by evaporation (W/m^2)

PMV is calculated by equation 2 using the heat load given by equation 1 and function G(M), which converts the heat load into a statistical representation of thermal sensation. Here, C, R, and E are calculated by four physical environmental parameters (T_a: ambient air temperature, RH: humidity, T_r: mean radiant temperature) and two human-related parameters (M: metabolic rate and I_{cl}: clothing insulation). C, R, and E are determined by these six parameters.

$$PMV = G(M) \times L = F_{pmv}(T_a, T_r, v, RH, M, I_{cl}) \qquad \text{Equation 2}$$

Where:

G(M) = 0.303 × exp(−0.036 × M) + 0.028

F_{pmv}: PMV function, T_a: air temperature (°C),

T_r: mean radiant temperature (°C), v: air velocity (m/s), RH: humidity (%),

M: metabolic rate (met), I_{cl}: clothing insulation (clo)

*1 Both C and E include heat transferred by breathing.

PMV is defined as a dimensionless number in the range of −3 ≤ PMV ≤ +3 (−3: cold, +3: hot).[6] The negative side refers to "cold," the positive side to "hot." PMV = 0 is neither hot nor cold (neutral). −0.5 ≤ PMV ≤ +0.5 is the comfort zone recommended by ISO 7730. The expected percentage of those who feel dissatisfied with any given PMV environment is defined as the predicted percentage of dissatisfied or (PPD) and is calculated by the following equation.

$$PPD = 100 - 95 \times exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \qquad \text{Equation 3}$$

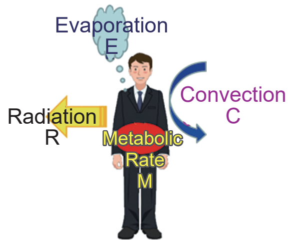


Figure 1. Human body and surrounding environment

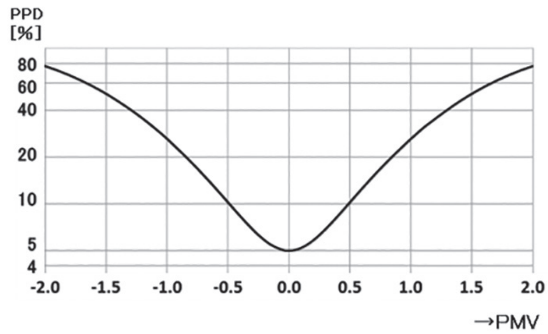


Figure 2. PMV and PPD

2.2 Actual Feeling of Occupants

Since the PMV and PPD described above are indicators of the representative feeling, they may not always match the feeling of people working in an actual office (see fig.3). Even in an environment in the PMV comfort zone, the actual feelings of the occupants regarding the thermal environment are often different from the representative feeling.

PMV = 0
(Neither hot nor cold:
environment
in the comfort zone)

Slightly cold Comfortable Hot

Figure 3. Differences of thermal sensation

3. Environmental Satisfaction Model

3.1 Utilizing Data of the Indoor Environment and Thermal Sensation Votes

Knowing the relationship between the occupants' actual thermal sensation (TS) and the PMV, which indicates the representative sensation, the TS of the actual occupant at any PMV can be predicted (see fig. 4). At a site where the HVAC system uses thermal sensation voting, the thermal sensation of the occupants is fed back to the HVAC system as thermal sensation votes. On that basis the setpoint of the HVAC system is changed to make it more comfortable for occupants.[4] In addition to environmental data on temperature, humidity, etc., collected for HVAC control, the system can collect data on the thermal sensation votes of occupants. Other PMVs can be calculated based on the environmental data (for the metabolic rate and the clothing insulation, typical or measured values can be applied appropriately), so it is possible to know the actual thermal sensations of the occupants corresponding to a certain PMV.

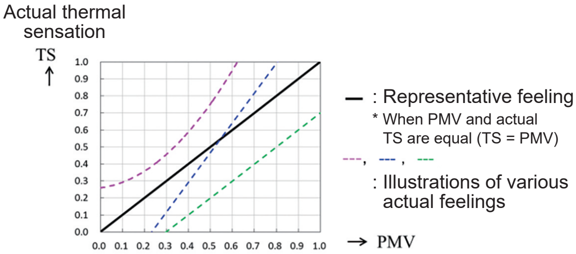


Figure 4. Relation between PMV and actual thermal sensation

3.2 Issues of Utilizing Thermal Sensation Voting Data in an Actual Office

This section describes two major issues that may arise when using the thermal sensation voting data collected by an HVAC system.

3.2.1 Data Quality—Granularity of Thermal Sensation Votes

When modeling correspondences as shown in figure 4, the actual TS voting data (the vertical axis in fig. 4) must provide more detailed data on the intensity of “cold” or “hot” sensations.[7] However, if occupants who are busily working in an actual office are asked to give numerical values for thermal sensation intensity, or to choose between detailed levels such as Cold, Cool, Slightly Cool, Neutral, Slightly Warm, Warm, and Hot (a 7-level scale), occupants may be lost in the selection details or vacillate in making a thermal sensation vote, so this may not be a practical method. On the other hand, with a simple binary thermal sensation vote of “I feel cold” or “I feel hot,” it would not be possible to get sufficient resolution to build a relationship model.

3.2.2 Data Quantity—Securing Sufficient Thermal Sensation Votes

Even if office workers feel hot or cold, they may not submit a thermal sensation vote because they are busy. In addition, it should be noted that the range of environmental fluctuation around office occupants limits the submitting environmental range of thermal sensation votes. Figure 5 is an example of the frequency of PMV in an actual office, counted at 10-minute intervals in different HVAC zones (in the summer of 2017, for one month of work days). It can be seen that the shape of the distribution and the upper and lower limits of the votes differ depending on the HVAC zone. In the PMV areas where the frequency is very low, thermal sensation voting would hardly occur. In areas where the PMV exceeds the upper limit and the frequency of voting drops to 0, the “I feel hot” thermal sensation vote would never be issued despite the hot environment. For example, in the PMV areas hotter than their PMV upper limits, such as P of zone Z3 (see fig. 5), or Q of zone Z1, we cannot expect to obtain a “hot” thermal sensation vote.

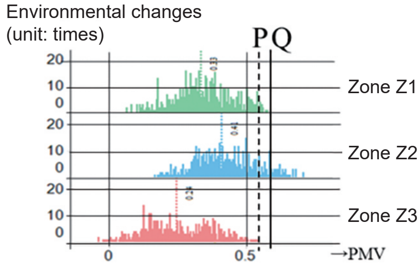


Figure 5. Frequency of PMV in HVAC zone

3.3 Concepts of the Environmental Satisfaction Model for Individual Units

In this section, we give countermeasures for the issues mentioned in section 3.2, and describe the concepts of the environmental satisfaction model.

3.3.1 Countermeasures for Data Quality

Data models that reflect differences in thermal sensation are likely to be nonlinear functions, and low data resolution also makes model construction difficult. As a solution, we can consider multiple occupants to be one group (an individual unit) and consider the number of occupants making thermal sensation votes as the group’s degree of satisfaction with the surrounding environment. In other words, we do not focus on the direct relationship between PMV and TS, but rather on the relationship between PMV and the degree of environmental (thermal) satisfaction due to TS in individual occupant units. Although the unit of the voting group can be designed arbitrarily, if the relationship model is constructed using the HVAC zone as the individual unit, the degree of satisfaction with the TS can be quantitatively grasped. That means that important information enabling HVAC control in each zone to be more comfortable can be obtained.

We employ the PPD function (equation 3 in fig. 2) as the basic function of our environmental satisfaction model. Since the “I feel hot” or “I feel cold” TS vote presents information on the occupants’ actual feelings related to thermal dissatisfaction with the ambient environment, the environmental satisfaction model is made by modifying the PPD function based on the PMV and its corresponding rate of occupants who make TS votes in an individual unit. We refer to this below as the predicted percentage of voting occupants (PPV). Figure 6 shows a schematic drawing of the PPV model modified with TS vote data. Equation 4 shows the basic PPV model function. Even in the same PMV environment, the rate of those who feel hot varies from unit to unit. An individual unit that is sensitive to heat (i.e., more people in the group are sensitive to heat) often has a higher “I feel hot” ratio, and a unit that is more tolerant of heat (i.e., many people in the group are insensitive to heat) has a lower “I feel hot” ratio. So it is possible with the model to express differences in thermal sensation for each individual unit.

$$PPV = a - b \times exp\,(c \times (PMV - e)^4 + d \times (PMV - e)^2) \qquad \text{Equation 4}$$

Where:

a, b, c, d, e: search parameters

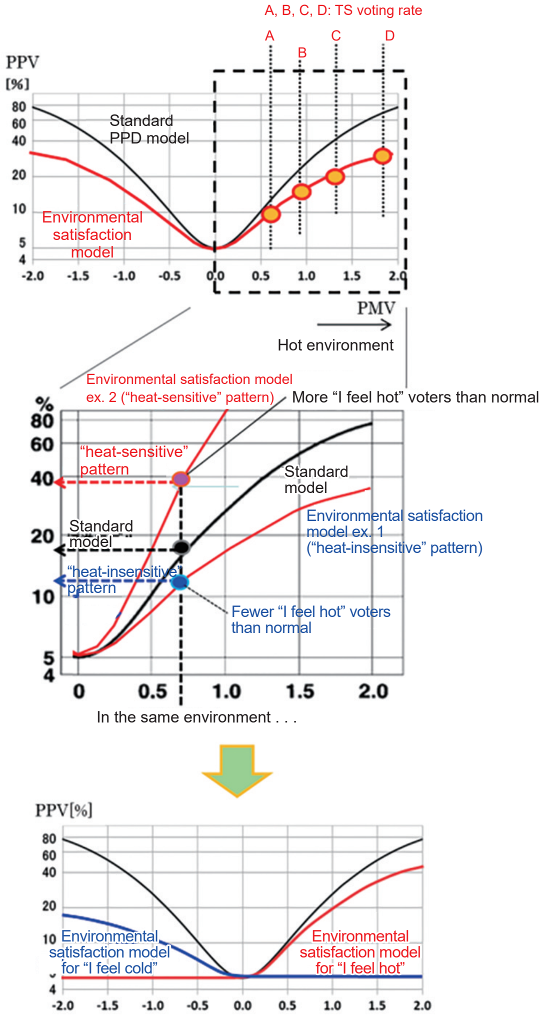


Figure 6. Thermal satisfaction model

Furthermore, by setting the "I feel hot" model using the "I feel hot" votes and the "I feel cold" model using the "I feel cold" votes separately*2 (see the bottom of fig. 6), the "I feel hot" and "I feel cold" sensations can become asymmetric. By this technique, both the "I feel hot" and the "I feel cold" mathematical models are considered to be environmental satisfaction models, but for the sake of simplicity, the following explanation and trial results pertain only to the "I feel hot" environmental satisfaction model.

3.3.2 Countermeasures for Data Quantity—Latching Method for Thermal Sensation Votes

Figure 7 shows the method of calculating the number of voters by determining the correspondence between the thermal sensation votes from the occupants, assuming an actual office and the PMV at the time the votes were made (an example of "I feel hot" votes from persons P1 to P4). As described in 3.2.2, if the occurrence of "I feel hot" TS votes depends on the busyness of the occupants and the frequency of environmental changes, the relationship between the PMV and the number of "I feel hot" voters does not increase monotonically. (The circular dotted lines in figure 7A, and figure 7A′, show the data in an actual office as an example.) As stated in 2.1, it is not possible to ensure the thermal physiological validity of the relationship between the heat load of the human body and thermal sensation.

Therefore, in our technology development activity, we devised a TS vote latch method that complements the TS votes of occupants. Our method of calculating the number of voters is shown in figure 7B. In the vote latch method, in an area where the PMV is larger than the smallest PMV (PMV_{start} in fig. 7B) where each occupant has made an "I feel hot" vote, even if there is no subsequent "I feel hot" vote, the vote is considered to be continuing. By applying this method, the relationship between the PMV and the number of voters who feel "hot" maintains a monotonous increase and thermal physiological validity is ensured.

*2 For equation 4, the parameters a, b, c, d, and e are searched for by the following conditions. For the "I feel hot" model, when PMV < e, PPV = a – b. For the "I feel cold" model, when PMV > e, PPV = a – b.

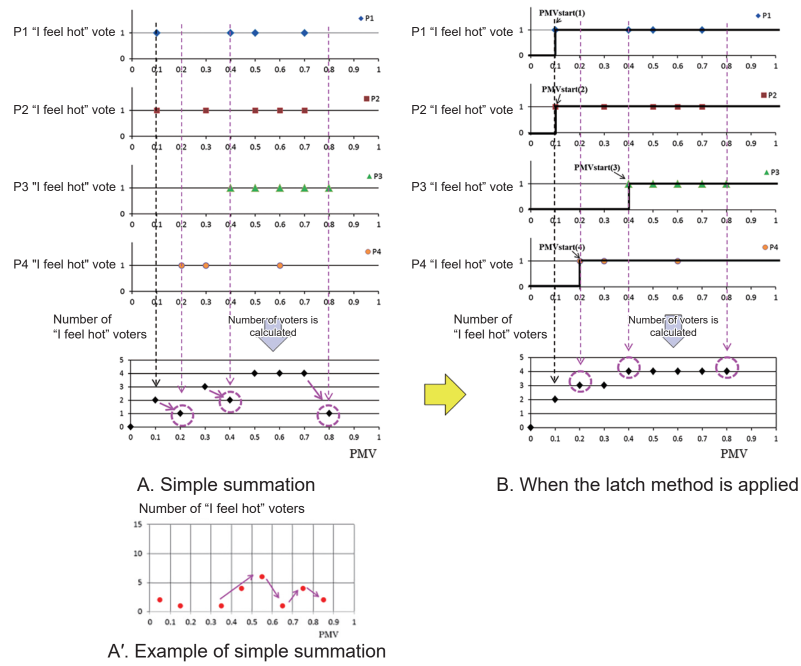


Figure 7. Calculating the number of voters

4. Generating the Training Data

This section gives an overview of how to generate training data in order to build the environmental satisfaction model.

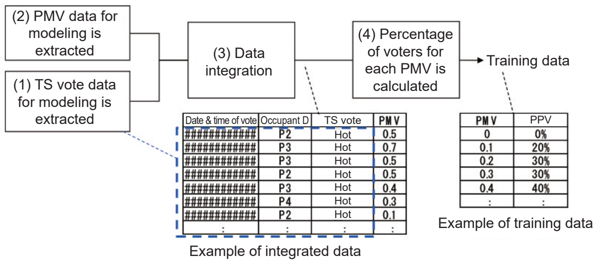


Figure 8. Training data generation procedure

Figure 8 shows an example of the procedure for processing the TS voting data and PMV data to generate training data. The collected TS voting data consists of vote date and time, occupant ID, and thermal sensation vote. It is assumed that the individual unit (such as an HVAC zone) where the occupant is located can be identified by the occupant ID. The PMV data consists of the measured date and time and the PMV, calculated using the metabolic rate and amount of clothing (for the particular building and occupants, using representative seasonal values) and the accumulated time series data of environmental measurements (of temperature, humidity, etc.).

Training data is generated for each specific TS vote ("I feel hot" or "I feel cold") in the individual units to be modeled. (If modeling is carried out for multiple individual units or thermal sensation votes, the same processes are repeated for each individual unit or TS vote.)

Assuming that the individual unit is HVAC zone A and that the TS vote to be modeled is "I feel hot," the processes in figure 8 are as follows.

(1) Extraction of TS voting data
   The "I feel hot" votes from all occupant IDs are extracted from the TS data. (See the table surrounded by the blue dotted line in fig. 8, "Training data generation procedure.")

(2) Extraction of PMV data
   The PMV data for HVAC zone A is extracted from the PMV data.

(3) Data integration
   The PMV data at the dates and times of measurements (2) corresponding to the dates and times of the votes in (1) are integrated (see fig. 8).

(4) After the PMV data for each occupant who made an "I feel hot" vote is extracted, the number of voters for each PMV in HVAC zone A is obtained using the latching method for TS votes described in section 3.3.2. The number of voters for each PMV is divided by the number of occupants in HVAC zone A to obtain the percentages of voters, which yields the PPV data for each PMV in the training data. Then, using the training data, the search parameters of equation 4 are determined by a general-purpose optimization method to create the environmental satisfaction model.

5. A Modeling Experiment

An experiment to generate an environmental satisfaction model was carried out for an actual office where an HVAC control system using TS voting is implemented. The individual unit for generating the model was a zone where the indoor temperature was controlled with a variable air volume (VAV) HVAC system. In the following, we give an overview of the experiment, including the thermal environment and TS vote data in the trial period, the results of modeling, and application examples of the model.

5.1 Overview of Trial Experiment

5.1.1 Target Building

The experiment was held on the fifth floor of an office building at Azbil Corporation's Fujisawa Technology Center. Some details about the building are shown in table 1.

5.1.2 HVAC Control by Occupants' Thermal Sensation Feedback[4], [8]

A dedicated device shaped like a credit card and used for thermal sensation voting was distributed to 227 employees (194 males and 33 females) on the floor, allowing three types of TS vote ("I feel hot," "I feel cold," or "I'm fine") to be issued from the employees' own seat at any time in the course of their work. The HVAC system, upon receiving an "I feel cold" vote, raised the setpoint by 0.5 °C. Upon receiving an "I feel hot" vote, the system's immediate response was to lower the setpoint by 2 °C for 10 minutes, and then to raise it back again by 1.5 °C.

5.1.3 HVAC Zoning

The HVAC zoning is shown in figure 9. The area was divided into 4 air handling unit (AHU) divisions (NW, NE, SE, and SW) along east-west and north-south lines, and each division was further split into 3 VAV zones (zones 1 to zone 3) from the east and west outside walls into the center of the floor. (Each VAV zone was identified by a combination of the air handling unit division and the VAV zone number: NW-1, etc.) Table 2 shows the number of occupants in each VAV zone. The gender ratio was almost the same as that of the entire floor (male 85 %, female 15 %), so the variation between zones was small.

Table 1. Overview of building

Building	Office building of Company A (7 floors)
Location	City of Fujisawa, Kanagawa Prefecture
Usage	Office building
Area	2,810 m^2
Total floor space	17,918 m^2
Number of occupants	Approx. 1,000
HVAC system	VAV centralized system

Table 2. Occupants per zone

VAV zone No.	Occupants	VAV zone No.	Occupants
NW-1	20	SE-1	14
NW-2	35	SE-2	19
NE-3	21	SE-3	9
NE-1	14	SW-1	14
NE-2	27	SW-2	26
NE-3	25	SW-3	3

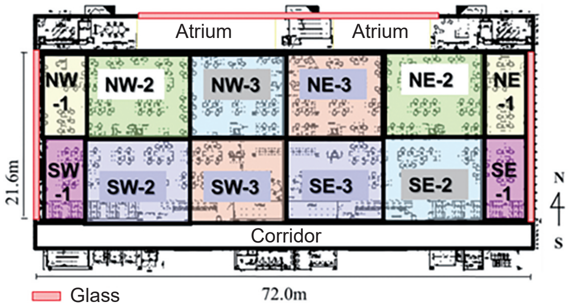


Figure 9. VAV zoning

5.1.4 Indoor Environmental Data

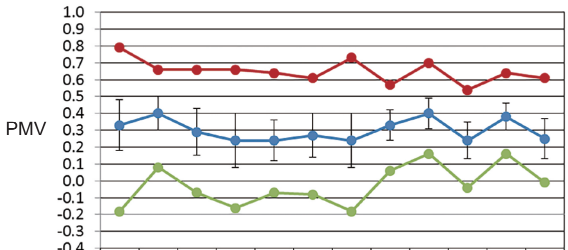
The temperatures in each VAV zone and return air humidity for each AHU were collected by the building automation system. This temperature and relative humidity data was used for calculating the training data PMV. In order to calculate the mean radiant temperature,[*3] the surface temperature of the walls in each zone was measured using infrared array sensors. Air velocity was measured at several points on the floor and it was found to be 0.1 m/s or less.

5.2 Thermal Environment of An Actual Office and TS Votes

Table 3 shows statistical values for temperature, humidity, and PMV during working hours (8:00 to 18:00) for one month in the summer (22 work days from Aug. 21 to Sept. 20, 2017). The average PMV of all VAV zones was 0.3 ± 0.1, which is within the comfort range (between −0.5 and 0.5). For PMV calculation the parameters were: air velocity = 0.1 m/s, clothing insulation = 0.5 clo (typical value for an office), metabolic rate = 1.0 met (typical value for a summer office), and a mean radiant temperature which was calculated from the temperatures of the surfaces surrounding each VAV zone.[*3] The statistical values for PMV for each VAV zone and the number of "I feel hot" votes are shown in figure 10.

Table 3. Office thermal environment statistics

	Average value ± standard deviation	Max. value	Min. value
Air temperature	26.5 ± 0.5 °C	28.7 °C	24.9 °C
Relative humidity	62 ± 5 %	77 %	45 %
PMV	0.3 ± 0.1	0.8	−0.2



	NW-1	NW-2	NW-3	NE-1	NE-2	NE-3	SE-1	SE-2	SE-3	SW-1	SW-2	SW-3
Average	0.3	0.4	0.3	0.2	0.2	0.3	0.2	0.3	0.4	0.2	0.4	0.3
Minimum	-0.2	0.1	-0.1	-0.2	-0.1	-0.1	-0.2	0.1	0.2	0.0	0.2	0.0
Maximum	0.8	0.7	0.7	0.7	0.6	0.6	0.7	0.6	0.7	0.5	0.6	0.6
Standard deviation	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Number of votes	192	134	117	62	455	297	45	58	83	114	161	

Figure 10. PMV statistical value and number of votes in the period

5.3 Environmental Satisfaction Model for an Actual Office

5.3.1 Generating the Environmental Satisfaction Model

Training data was generated following the procedure in section 4 using the "I feel hot" temperature sensation votes and the PMV data[*4] for one month in summer (22 work days from Aug. 21 to Sept. 20, 2017) and environmental satisfaction models for each VAV zone were constructed. In addition, as a reference for comparing the zone models, a floor model (for 227 occupants) was also generated with the entire floor as one individual unit. A general-purpose optimization method based on the least-squares method was used to determine the parameters of the model. There were 11 VAV zones to be modeled, rather than 12, because SW-3, which had an extremely small number of occupants (3), was excluded.

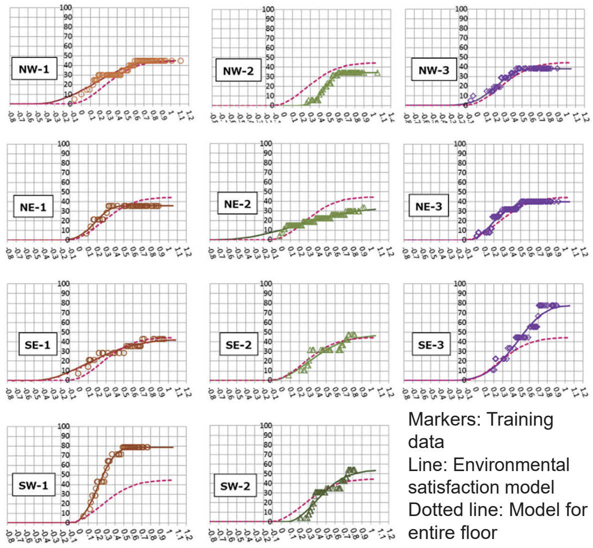
5.3.2 Environmental Satisfaction Models for Each VAV Zone

Figure 11 shows the environmental satisfaction models for each VAV zone. Generating a model of all 11 VAV zones and of the entire floor (the identical red dotted line in each VAV model diagram) showed that the characteristics of each VAV zone model were different.

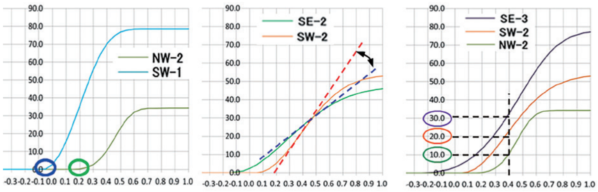
When models with different characteristics are overlapped and compared, as on the left of figure 11B, it can be seen that, even though the shape of the curves is similar, the PMVs (circled in the figure) from which the "I feel hot" votes start occurring and the saturation values of PPV are different. Also, in the central diagram of figure 11B, the PPV of SW-2, whose PMV had a delayed beginning, overtakes the PPV of SE-2 around PMV = 0.5. The slope of PPV to PMV (ΔPPV ÷ PMV) indicates how "I feel hot" voter ratio increases along with increasing PMV, that is, it indicates the sensitivity to a "hot" feeling of occupants in each zone. This slope is large for SW-2. (The dotted lines in the central diagram of fig. 11B are tangents showing the slopes at PMV = 0.5.) Furthermore, in the diagram on the right in figure 11B, the PPVs in the three zones is about 10 %, 20 %, and 30 % respectively (circled in the figure) in the environment of PMV = 0.4, which means that there is a difference in the "I feel hot" voter ratio for the same PMV. Here, PMV = 0.4 corresponds to a room temperature 27.0 °C in the case of the environment, air velocity (v) = 0.1 m/s, relative humidity (RH) = 56 %, amount of clothing insulation (I_{cl}) = 0.5 clo, metabolic rate (M) = 1.0 met, and the radiation effect is small (mean radiant temperature T_r is equal to the air temperature).

*3 The mean radiant temperature was calculated by the following equation using the wall/floor/ceiling surface temperature in six directions and the angle factor between the human body at the center position of each zone and the wall surface. In order to calculate the angle factor, a tool conforming to ASHRAE standard 55-2010 was used. $T_r = \sum_{N=1}^{6} T_N \times F_{P-N}$, where: T_r: mean radiant temperature in °C, T_N: temperature of surface N in °C, F_{P-N}: angle factor of surface N

*4 The PMV data was calculated based on the following conditions. The PMV calculation parameters were set as the same as in section 5.2, but the metabolic rate was set to 1.2 met only during the time slots Start–9:30 and 12:00–13:30, when the occupants' metabolic rate increased after arriving at the office or after lunch.[(9)]



(A) Environmental satisfaction model for VAV zones



(B) Comparison of environmental satisfaction models

Figure 11. Environmental satisfaction model for each VAV zone

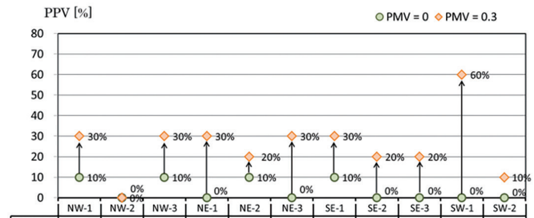
Note: All horizontal axes: PMV, vertical axes: PPV

5.4 Environmental Satisfaction Model Simulation

The environmental satisfaction models for each VAV zone generated in section 5.3 can be used to study how various indoor environments affect the thermal satisfaction of occupants in each VAV zone. This section gives some simulated examples.

5.4.1 Occupants' Thermal Satisfaction with Environmental Changes

As mentioned above concerning the diagram on the right in figure 11B, it is possible to simulate PPV values for each VAV zone when the PMV environments of the VAV zones controlled by the HVAC system are equal. The numerical values in the table in figure 12 show the estimated PPV values for each VAV zone when PMV = 0 and PMV = 0.3, and the graph shows the increase in PPV for each VAV zone when PMV is changed from 0 to 0.3. (The PPV values in the graph show the numbers in the table rounded off to multiples of 10 to make it easy to compare PPV increase trends among zones.) The PPV values of most zones are PPV = 0 % or 10 % at PMV = 0 and PPV = 20 % or 30 % at PMV = 0.3. But there are some zones like NW-2 where PPV changes are small. It can be seen that zones with a low level of PPV and small changes are candidates for accepting a warmer, energy-saving environment. On the other hand, in zones like SW-1 where the PPV increases significantly and occupant comfort is largely lost, the environment of PMV = 0.3 would not be acceptable.



	NW-1	NW-2	NW-3	NE-1	NE-2	NE-3	SE-1	SE-2	SE-3	SW-1	SW-2
PMV = 0.3	29%	3%	27%	30%	18%	28%	27%	19%	22%	56%	13%
PMV = 0	14%	0%	6%	4%	10%	2%	14%	2%	3%	3%	0%

Figure 12. PPV when PMV is 0 and 0.3

5.4.2 Study of Temperature Setpoint of Each VAV Zone with PPV as Target Value

It is also possible to simulate temperature setpoints of each VAV zone for the same arbitrary PPV environment. For example, as shown in figure 13, the PMV values for a PPV environment of each VAV zone of 20 % (PMV_20 %) is back-calculated from each environmental satisfaction model (circled in the figure), and the air temperature (T_a_20 %) corresponding to this PMV_20 % is calculated as shown in 5.3.2 (in comments on the diagram on the right of fig. 11B).

The PMV values of each VAV zone equivalent to the environment of which sets the PPV = 10 % (PMV_10 %) are calculated. Figure 14 shows the estimated results, assuming that the temperatures corresponding to each PMV_10 % are the recommended temperature setpoints of each VAV zone (approximate numbers in 0.5 °C increments). To estimate the temperatures, the environmental conditions described in section 5.2 and the average relative humidity in table 3 were used. They were v = 0.1 m/s, RH = 62 %, M = 1.0 met, I_{cl} = 0.5 clo, and T_r = T_a (assuming little influence from heat radiation). As seen in figure 14, the temperature setpoints of each VAV zone corresponding to the same PPV of 10 % were not constant. There are 2 zones at 25.5 °C, 5 zones at 26.0 °C, 3 zones at 26.5 °C, and 1 zone at 27.0 °C. There is a maximum of 1.5 °C variance.

Figure 15 shows PPV estimations for each zone when PMV values of all zones are equally controlled. A PMV of 0.1, which is the average of PMV_10 % for all zones above, is set uniformly While the PPV values in the NW-1 and SE-1 zones are close to 20 %, those in NW-2 and SW-2 are around 0 %. This shows that there is a significant difference in thermal sensations among zones that belong to the same environment. As shown in figure 14, by setting temperature setpoints suitable for each zone according to its environmental satisfaction model, it is possible not to have VAV zones with extremely low environmental satisfaction (where "I feel hot" voter percentage is extremely high).

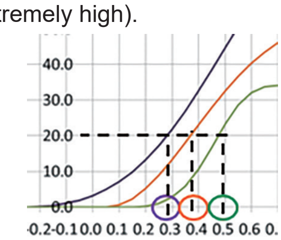


Figure 13. PMV when PPV is constant

Note: Horizontal axis: PMV, vertical axis: PPV

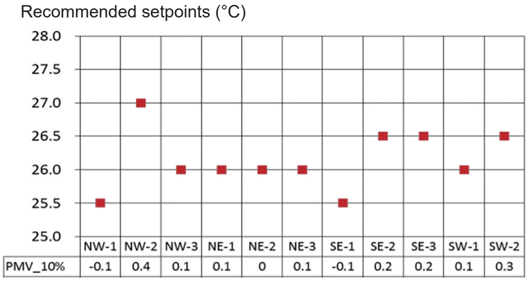


Figure 14. PMV_10 % and recommended temperature setpoints for each VAV zone

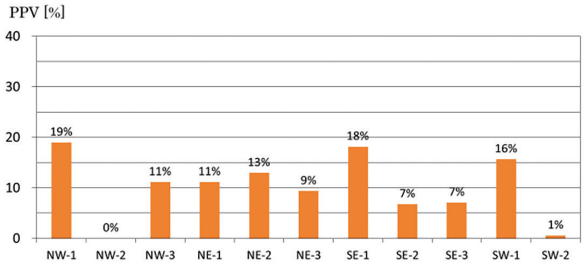


Figure 15. PPV with uniformly controlled PMV = 0.1 (equivalent to a room temperature of 26.1 °C)

6. Conclusions

An environmental satisfaction model was developed in order to devise a method of evaluating indoor environments that reflects the actual thermal sensations of the occupants. Environmental satisfaction models for each VAV zone were generated using measured environmental data and occupants' thermal sensation votes collected by the HVAC system in an actual office. The simulation results using the generated models have shown that the environments in each VAV zone can be maintained at a certain quality level (degree of environmental thermal satisfaction) by setting different control parameters suitable for the thermal satisfaction models of occupants in each zone. In the future, we would like to continue verification testing of HVAC controls that use the degree of environmental satisfaction as the target value, that optimize energy savings and environmental satisfaction, that use demand-response measures without a significant burden on occupants, etc. In addition, according to our long-term analysis and examination of data from actual office environments, the environmental satisfaction model should change with seasonal transitions. We are examining the appropriate update cycle for the model and automatic methods of updating.

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