

649: Thermal Comfort Zone in Daily Life Considering Adjustments by Residents

Tamaki Fukazawa^{1*}, Nobuyuki Sunaga¹, Katsumi Matsuda², Yosuke Chiba², Mitsuo Ozaki²

Dept. of Architecture and Building Engineering, Tokyo Metropolitan University, Hachioji, Tokyo, Japan^{1*}
hukazawa-tamaki@tmu.ac.jp
*R & D Laboratories, Asahi Kasei Homes Corporation, Fuji, Shizuoka, Japan*²

Abstract

The purpose of this study is to propose a thermal performance evaluation method for passive and low-energy buildings that considers the effects of the residents' behavior. In this paper, first, the purpose and outline of the experiment with subjects are described. Second, the relationship of the thermal sensation votes of subjects (TSV) and previous thermal comfort indices (ET*/SET*/PMV), which is calculated from the environments that subjects were exposed in the experiment, are presented. Third, the predicted thermal sensation votes (PTSV) are expressed as a new comfort index, determined from the experiment. The PTSV was obtained by multiple linear regression analysis with five elements of thermal comfort indices, excluding the quantity of clothes, and adding the effect afterwards. As a result, the PTSV shows similar frequency and tendency to the TSV. Finally, the PTSV comfort zone was compared to three previous comfort zones by changing the condition on the human side, and the tendency of the comfort zone consisting of PTSV was examined. Consequently, the PTSV comfort zone with conditions that are suited to the residents is proposed as the thermal comfort zone in daily life.

Keywords: thermal comfort zone, adjustment action, Daily Life, experiments with subject

1. Introduction

The necessity of global warming prevention was recognized in the late 1980s, and since then, much research and technological developments have advanced. In architecture, various studies that aim at reducing energy consumption have been conducted. Furthermore, it is necessary to improve indoor environment without using energy by applying appropriate architectural techniques suitable for regional climates.

In general, the thermal performance of a building is evaluated in terms of energy consumption. However, the buildings that do not consume energy cannot be evaluated in terms of energy consumption, and an appropriate evaluation method is not available for such cases. It is therefore necessary to develop a new method for evaluating the thermal performance of such buildings. We proposed a thermal performance evaluation method based on the thermal comfort of residents for these cases [1, 2].

It is necessary that the thermal comfort zone fits the residents' behavior and the environmental adjustments, in addition to fitting the space and usage. We conducted an experiment with subjects for investigate the thermal comfort zone used to the evaluation method [3]. Subjects were made to the action of same metabolic rate as behavior of house and have adjusted to their thermal environment by changing their clothing accordingly in the experiment. We believe the resulting thermal comfort zone provides the adaptive principle in the house [4].

In this paper, first, the purpose and outline of the experiment with subjects are described. Second, acquired data in the experiment are shown. Third,

the steps of the process are explained to ascertain their thermal comfort index analyzed from the experiment. Fourth, new thermal comfort zones in daily life are described.

2. Experiment with Subjects

2.1 Purpose of the Experiment

ASHRAE's comfort zone is transformed with SET* to the fluctuation comfort zones [5]. SET* is, however, defined in a steady state and is used in the restricted condition. Also, in the thermal environment in which the residents feel comfortable in daily life is still not clear. This experiment, therefore, investigates the residents' thermal senses, such as thermal sensation and comfort sensation in daily life.

2.2 Outline of the Experiment with Subjects

2.2.1 Date and the place

The experiments were carried out in Hachioji, Tokyo, Japan. Because of wide acquisition of data, it is important to clarify the range of the measured environment. A series of experiments with human subjects was carried out late in the rainy season (May 17–19, 2005), midsummer (August 22–26, 2005), and in midwinter (January 11–18, 2006). To investigate the effect of the natural ventilation for the subjects' thermal sensations, the experiment had two window conditions as well as our actual life. We conducted open mode and closed mode in May, but only open mode in August, and closed mode in January.

2.2.2 Description of the test house

Generally, thermal experiments with subjects are carried out in an artificial environment that is only a test room, but the experiment described here was carried out in an actual house with a natural irregular environment. Figure 1 shows the floor plan of the test house. The test house is an exhibition house owned by a housing company that allows one to experience a stay in the house before buying a similar one.

2.2.3 Measurement of the thermal environment

Table 1 shows the measurement data categories and instruments that were used. We measured the environment parameters that influence thermal comfort, such as the air temperature, surface temperature, globe temperature, relative humidity and wind velocity. The measurement data was recorded every one minute.

2.2.4 Experiment condition

In the experiment, the subjects lived in the house without any heating/cooling equipment. They followed a schedule that included movement between the rooms and three types of actions. They were allowed to change their clothes according to their thermal sensation.

2.2.4.1 Description of the subjects.

Table 2 shows the data about the subjects. The subjects were college students and the employees of the housing company. They were paid to take part in the experiment for three hours.

2.2.4.2 Description of the subjects' schedules.

Figure 2 shows the subjects' schedules. There was a maximum of six subjects at a time in the test house, and each subject's schedule is the combination of three actions for 25 minutes, such as recess (1.1 [MET]), mealtime (1.4 [MET]) and exercise (2.0 [MET]). The subject spent time by himself or herself in different rooms except for at mealtime. At first recess, the subjects were instructed to follow a given schedule and move between rooms in accordance with his or her schedule. When the schedule showed recess, the subject had free time, which could be spent reading books, watching TV, listening to music, and so on, as shown in Figure 3A. When the schedule was mealtime, the subject ate lunch or dinner with the other subjects, as shown in Figure 3B. When the subject's schedule showed exercise, he or she walked slowly on a stepper, as shown in Figure 3C.

2.3 Thermal comfort questionnaire

A questionnaire was used to collect the subject's thermal feelings. The subjects filled out the questionnaire three times; just after he or she moved into a room, after 10 minutes, and after 20 minutes. The questionnaire could be filled out within 3 minutes to lighten the burden imposed on the subjects. The questionnaire items were as follows: thermal sensation (TSV); comfort sensation (CSV); satisfaction sensation; radiation sensation; extent of perspiration; current sensation; and demand for wind. Figure 4 shows the scales of TSV and CSV. If the subject felt hot or cold, he or she could put on or take off clothes, and record the clothing change and time of the change on a prepared form.

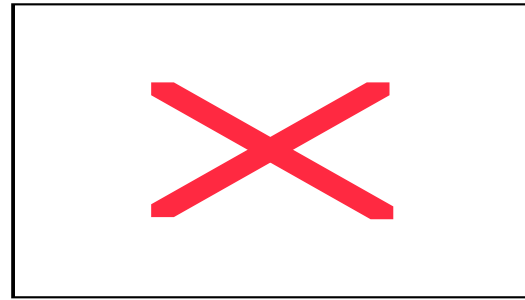


Fig1. Floor plan of the test house

Table1: Data categories and instruments.

	Data categories	Instruments	Companies
IN	Air temperature [°C] Relative humidity [%]	RTR-52,RTR-53	T&D
	Surface temperature [°C]	TH9100 ML/WL Data logger NR-1000 8421-51 memory hilogger	NEC san-ei KEYENCE HIOKI
	Globe temperature [°C]	Fine gage thermocouple Globe thermometer	SHIBATA
	Wind velocity [m/s]	GeT-160N	HONFIELD
OUT	Air temperature [°C] Relative humidity [%] Wind velocity [m/s] Wind vector [-]	VantagePro2	Davis

Table2: Data about the subjects.

NUMBER	Total	Men	Women	AGE	Min	Ave	Max
May	28	17	11	May	21	29.0	54
August	53	34	19	August	19	30.4	56
January	49	28	21	January	20	32.0	54
ALL	130	79	51	ALL	19	30.7	56

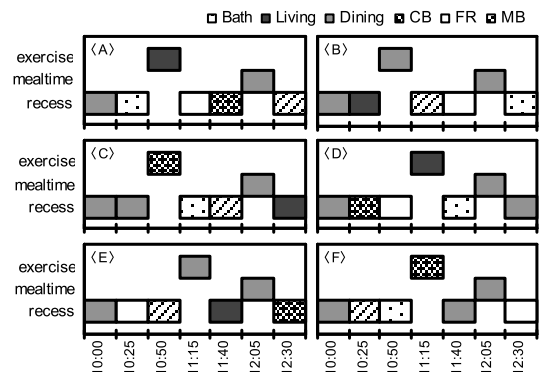


Fig2. Example of subject's schedules



Fig3. States of the experiment

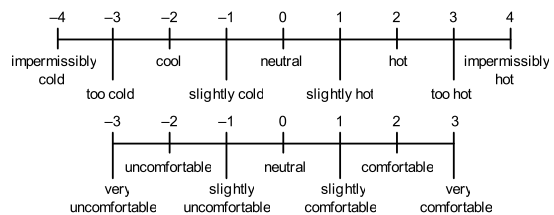


Fig4. Scales of TSV (upper) and CSV (lower)

3. Acquired data

3.1 Subjects' exposure environment

In order to evaluate the room environment that the subjects had occupied and evaluated, each subjects' exposure environments were adopted. The subjects' exposure environments were composed of the elements of the room that he or she is occupying. It is assumed that the subject's thermal sensation recorded in the questionnaire originated from the time the subject entered the room to the time the subject started filling out the questionnaire. The averages of the subjects' exposure environments for the periods were adopted as representative value.

Figure 5 shows the fluctuation of the exposure environment of one subject (August 22, 2005). There are fluctuations of elements that are related to the human sense of thermal comfort: on the space side, air temperature, globe temperature, and wind velocity, and on the human side, metabolic rate and quantity of clothes. Then, the representative values are plotted in Figure 5. In the analysis thereafter, only these value and the answers on the third time questionnaire is used to exclude the influence of irregular and transitional states

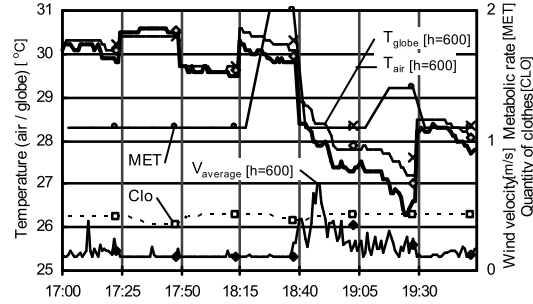


Fig5. Fluctuation of the exposure environment of one subject and the representative value (8/22/2005)

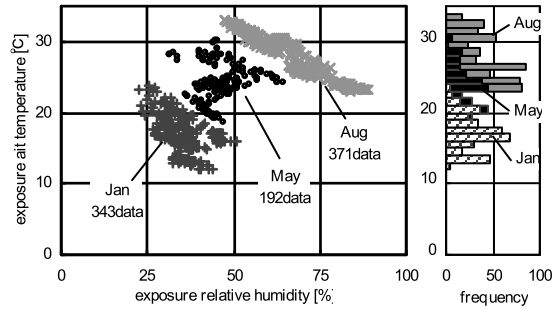


Fig6. Relationship between air temperature, relative humidity, and frequency of air temperature

3.2 Thermal environments

Figure 6 shows the relationship between air temperature, relative humidity, and frequency of air temperature. It shows that the air temperature and the relative humidity of this experiment covers a wide range; the air temperature ranges from 11.9°C to 33.1°C; and the relative humidity from 20.6% to 90%. Figure 7 shows the relationship between the air temperature and the globe temperature of the subjects' exposure environment. It shows that the globe temperature of this experiment is roughly equal. Figure 8 shows the relationship between the air temperature and the wind velocity of the subjects' exposure environment. It shows that the wind velocity of this experiment covers a range of 0.66m/s and the air temperature with open windows was over 18.4°C. Figure 9 shows the relationship between air temperature, quantity of clothes worn, and frequency of quantity of clothes. It shows that subjects adapted their clothes: the hotter the exposure environment, the thinner the subjects' clothes. In addition, the lower the subject's exposure air temperature, the wider the range of clothes.

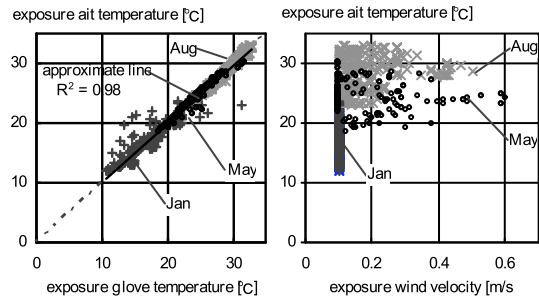


Fig7. Relationship between air temperature and globe temperature

Fig8. Relationship between air temperature and wind velocity

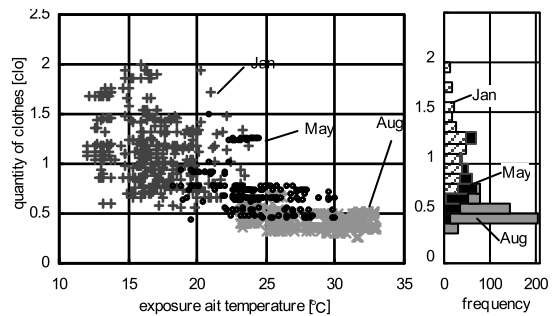


Fig9. Relationship between air temperature, quantity of clothes, and frequency of quantity of clothes

3.3 Frequency of the sensation votes

Figure 10 shows the frequency of the sensation votes acquired in each behavior (recess: 1.1MET, mealtime: 1.4MET, and exercise: 2.0MET). The left panel shows one of the thermal sensation votes (TSV), and the right panel shows one of the comfort sensation votes (TCV). There is the most TSV (0: neutral) in recess and mealtime, but most of the positive votes were acquired in exercise. In recess and mealtime, the TCV was biased to the comfortable side, but in exercise the TCV was to the uncomfortable side. The necessity of watching each behavior was confirmed.

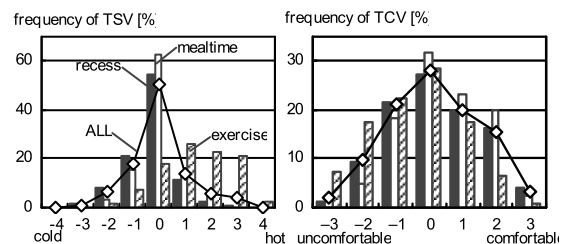


Fig10. Frequency of the sensation votes (left: thermal sensation vote, right: thermal comfort vote)

4. Predicted Thermal Sensation Vote

4.1 Relation between the TSV and the Indices of the Usual Comfort Zones

Table 3 shows the number of exposure environments for this analysis (all), TSV within ±0.5 in the experiment (±0.5), and the ratios of ±0.5 to all for each behavior. The ratio shows 53% in ALL, 81% in recess, 63% in mealttime, and 18% in exercise. It became clear that there is a difference in these ratios due to the action undertaken, and especially during exercise, the ratio was small.

the relationship of the thermal sensation votes of subjects (TSV) and previous thermal comfort indices (ET*/SET*/PMV), which is calculated from the environments that subjects were exposed in the experiment, are presented

Based on these values, it was analyzed how “±0.5” was in usual three previous thermal comfort indices (ET*/SET*/PMV) in ASHRAE [4, 5]. Figure 11 shows the relationship for ALL and each subject’s behavior to the exposure environment numbers of all the dates of the experiment (all), of the TSV within ±0.5 (±0.5), of the data within the index of each comfort zone (CR), and of the CR ∩ ±0.5 data (∩). Each index of thermal comfort is calculated from the subjects’ exposure environment in the experiment. Furthermore, under the figure, the rates of ∩ to ±0.5 and CR are described. The ratios of ∩ (CR ∩ ±0.5) to ±0.5 is not too large; it does not come up to 50% in ALL. It is shown that there are many comfortable environments that are not indicated by the indices of these comfort zones. By paying attention to the change in the ratios of ∩ to CR according to the metabolic rate, the ratios lower as the metabolic rates goes up. Compared to the ratios, PMV showed the TSV the most accurately.

4.2 Examination of PTSV production method

To predict a TSV value corresponds to metabolic rate, we will express the predicted thermal sensation votes (PTSV) as a new comfort index determined from the experiment. Fig 12 shows the flow of the PTSV production. Because we believed that conducting the experiment in actual conditions is important, the six elements of thermal comfort fluctuated simultaneously. We then produced PTSV with multiple linear regression analysis. The influence was taken into the PTSV as operative temperature because air temperature is nearly equal to radiant temperature. Furthermore, in regard to quantity of clothes (CLO), the air temperature is inversely proportional to CLO, as shown in Figure 9. This shows the adaptive principle, but it can be read from the figure as, the subject felt cold because of increasing their CLO, though they increased their CLO because of feeling cold. Therefore, we considered that the acquired CLO should not be treated equally to the other five elements, but is related TSV. The predicted PTSV (PTSV_p) was then obtained by multiple linear regression analysis with five elements of thermal comfort indices, excluding CLO. Afterwards, the PTSV is calculated by adding the effect of CLO.

Table3: Data categories and instruments.

	ALL	recess	mealttime	exercise
number	all data for analysis 905	653	126	126
	TSV within ±0.5 483	378	82	23
ratio: ±0.5 / all data	53%	81%	63%	18%

Number...±0.5: TSV within ±0.5 ∩: “CZ” ∩ “±0.5”
 CR: within targeted comfort range
 Comfort zone... ① ASHRAE55-1992: ET* 20 to 26[°C]
 ② ASHRAE55-1992 conversion: SET* 21.5 to 25.2[°C]

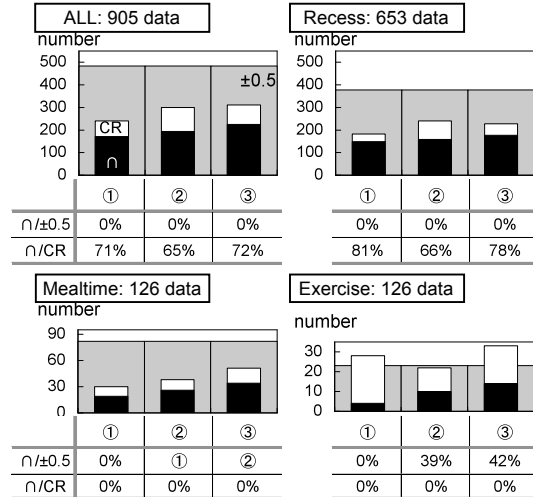
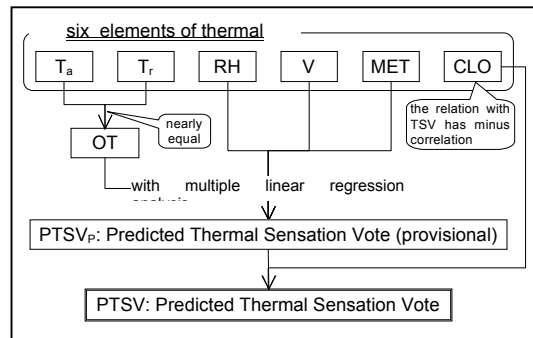


Fig11. Comparison with the number of environment within indices of each comfort zone



T_a: air temperature [°C] T_r: radiant temperature [°C]
 RH: relative humidity [%] V: wind velocity [m/s]
 MET: metabolic rate [MET] CLO: quantity of the clothes [clo]
 OT: operative temperature [°C]

Fig12. Flow of the PTSV production

$$PTSV_p = 0.139 \times OT - 0.0064 \times RH - 1.50 \times V + 1.69 \times MET - 4.72 \dots (1)$$

PTSV_p: Predicted Thermal Sensation Vote (provisional)
 OT: operative temperature [°C] RH: relative humidity [%]
 V: wind velocity [m/s] MET: metabolic rate [MET]

4.3 Multiple regression to PTSV_p

Equation 1 shows the PTSV_p as the product by multiple linear regression analysis with five elements of thermal comfort indices (operative temperature [air temperature and radiant temperature], relative humidity, wind velocity, and metabolic rate). It shows that the higher either the operative temperature or metabolic rate is, the higher the PTSV_p is. The lower either the relative humidity or wind velocity, the lower the PTSV_p is. The standard partial-regression coefficient of air

temperature is 0.7, and it is understood that the relationship is the strongest. $PTSV_P$ have a strong influence on operative temperature. The coefficient of determination between $PTSV$ and TSV in ALL is 0.61, and it is a higher value than the one between previous thermal comfort indices and TSV .

The range where $PTSV_P$ comes within ± 0.5 is defined as the comfortable range of $PTSV_P$. Figure 13 shows a comparison with numbers of exposure environments within the $PTSV_P$ comfort range as in Figure 11. The ratio of Ω to ± 0.5 in ALL is 63%, and the ratio of Ω to CR in ALL is 79%. It shows that there are many actually comfortable environments within the $PTSV_P$ comfort range, and there is higher probability that the environment within the $PTSV_P$ comfort range is actually comfortable. It is proved that $PTSV_P$ expresses TSV accurately.

4.4 Proposal of $PTSV$ by correction of $PTSV_P$

4.4.1 Adding the effect of CLO

To propose $PTSV$ that contained six elements adding the effect of CLO, Figure 14 shows the relationship between the $PTSV_P$ and the CLO when the $TSV=0$. In this figure, it was thought that the gap between the regression line and $TSV=0$ shows the effect of CLO. Correcting the regression equation in the multiple regression equation 1, $PTSV$ with six elements of thermal comfort was produced. Equation 2 shows the $PTSV$ as the product. It shows that the lower the CLO, the lower the $PTSV$.

4.4.2 Analysis of $PTSV$

Figure 15 shows the relationship between the $PTSV$ and the TSV . Table 4 shows data comparison between $PTSV$ and TSV . Figure 16 shows the frequency of TSV , $PTSV_P$, and $PTSV$. The coefficient of determination between $PTSV$ and TSV is 0.48. It is a lower value than the one between $PTSV_P$ and TSV , but higher than the one between usual thermal comfort indices and TSV . The maximum and the minimum values of $PTSV$ are closer to zero than TSV and $PTSV_P$, and the variance is smaller. It shows that the distribution of $PTSV$ is wider than TSV and $PTSV_P$, but it is understood that the frequency of $PTSV$ is more similar to TSV than $PTSV_P$.

The range where $PTSV$ comes within ± 0.5 is defined the $PTSV$ comfortable range. Figure 17 shows a comparison of a number of exposure environments within the $PTSV$ comfortable range, similar to Figure 11 and Figure 13. In comparison with Figure 11 and Figure 13, the ratios of Ω to ± 0.5 are increased except for in exercise. The ratios of Ω to CR in exercise are increased. It shows that there are more actually comfortable environments within the $PTSV$ comfortable range, and there is higher probability that the environment within the $PTSV$ comfortable range is actually comfortable than usual comfort ranges and $PTSV_P$ comfortable range. Further, Figure 18 shows cumulative frequency of TSV , $PTSV$, and PMV . As a result, the $PTSV$ show similar frequency and tendency to the TSV . It is shown that $PTSV$ express TSV accurately corresponding to the change in the metabolic rate.

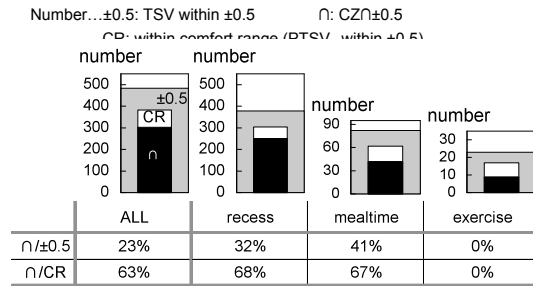


Fig13. Comparison with the number of environment (PTSV_P comfort range: PTSV_P within ±0.5)

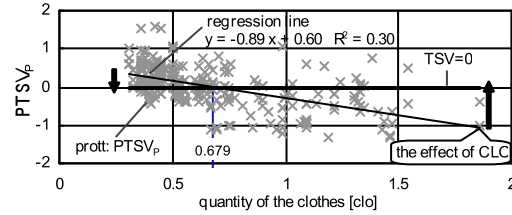


Fig14. Relation between the $PTSV_P$ and the CLO when the TSV is equal {0: neutral}

$$PTSV = 0.139 \times OT - 0.0064 \times RH - 1.50 \times V + 1.69 \times MET + 0.89 \times cl - 5.32 \dots (2)$$

$PTSV$: Predicted Thermal Sensation Vote
 OT : operative temperature [°C] RH : relative humidity [%]
 V : wind velocity [m/s] MET : metabolic rate [MET]
 cl : quantity of the clothes [clo]

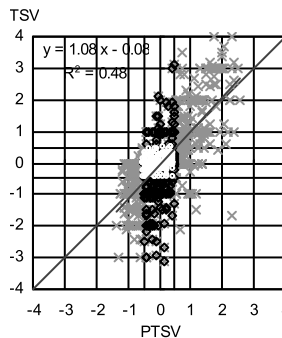


Fig15. Relation between the $PTSV$ and the TSV

Table4: Data comparison.

	max	ave	min	variance
TSV	4.0	0.06	-3.1	1.12
$PTSV$	2.5	0.13	-1.3	0.71
$PTSV_P$	2.7	0.06	-1.7	0.87

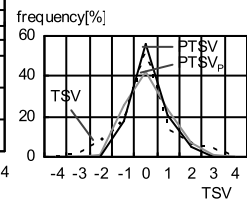


Fig16. Frequency of TSV , $PTSV_P$ and $PTSV$

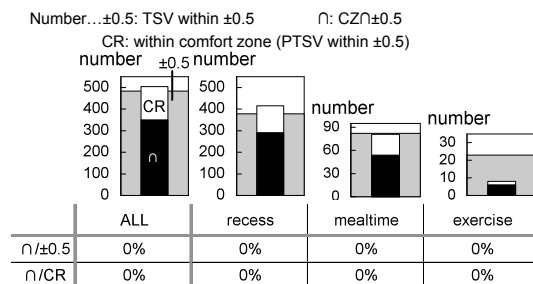


Fig17. Comparison with the number of environment (PTSV comfort range: PTSV within ±0.5)

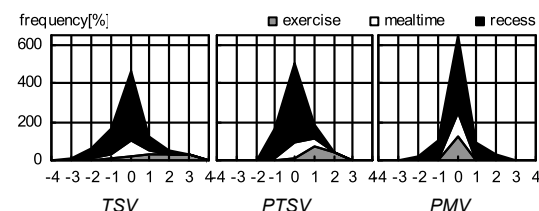


Fig18. Cumulative frequency of TSV , $PTSV$, and PMV

5. Thermal Comfort Zone in Daily Life

The PTSV comfort zone is compared with usual comfort zones, and the thermal comfort zone in daily life considering adjustments by residents was proposed.

5.1 PTSV Comfort Zone

The PTSV comfort zone is assumed to be an environment where PTSV comes within ±0.5, and the humidity condition of the PTSV comfort zone was assumed to follow ASHRAE 55-1992 [4].

Figure 19 shows the PTSV comfort zone and usual three thermal comfort zones in the standard condition (wind velocity: 0.15m/s, metabolic rate: 1.1MET, quantity of the clothes: 0.6CLO). It has been understood to include the comfort zone in ASHRAE 55-2004 in the PTSV comfort zone of the standard completely. However, it has been understood that the higher limit of the air temperature of the PTSV comfort zone, the higher the limit of the relative humidity. Moreover, it spans 7.1°C in air temperature range. It has been clear that the PTSV comfortable zone is wider than the usual three comfort zones. Furthermore it has been confirmed that PTSV comfort zone changes more intensely than the usual three comfort zones by the change in the wind velocity, metabolic rate, and quantity of the clothes from the comparison that changes the condition.

5.2 Thermal Comfort Zone in Daily Life Considering Adjustments by Residents

The thermal comfort zone is present in daily life by matching the environmental condition to the resident's condition. It was arranged that the wind velocity is limited more at the average or the maximum that can be allowed, the metabolic rate is suitable for the actual life, and the quantity of clothes is within a permissible range at the evaluated point.

Figure 20 shows these examples of thermal comfort zone in daily life considering adjustments by residents. It was displayed at the narrow standard condition (V: 0.15m/s, MET: 1.1MET, CLO: 0.6clo), the condition with a range in the wind velocity (V: 0.15–0.6m/s, MET: 1.1MET, CLO: 0.6clo), with a range in the CLO (V: 0.15m/s, MET: 1.1MET, CLO: 0.3–1.2clo), with a range in the wind velocity and CLO (V: 0.15–0.6m/s, MET: 1.1MET, CLO: 0.3–1.2clo). Thus, it is possible to combine the resident's conditions with the environmental conditions as the comfort zone where it suits the individual.

6. Conclusion

The objective of this study is to propose a thermal performance evaluation method for passive and low-energy buildings that considers the effects of the residents' behaviors.

In this paper, the predicted thermal sensation votes (PTSV) are expressed as new comfort index analyzed from the experiment. The PTSV shows more similar frequency and tendency to the TSV for all behaviours than usual indices of thermal comfort. The PTSV comfort zone is

Table5: Data comparison.

	Limit		width
	under	upper	
□ ①	20.1	25.9	5.8
▨ ②	21.4	24.9	3.5
▩ ③	23.7	26.7	3.0
■ ④	21.5	28.6	7.1

- ① ASHRAE55-1992: ET* 20 to 26[°C]
- ② ASHRAE55-1992 conversion: SET* 21.53 to 25.23[°C]
- ③ ASHRAE55-2004: PMV -0.5 to +0.5
- ④ PTSV comfort zone: PTSV -0.5 to +0.5

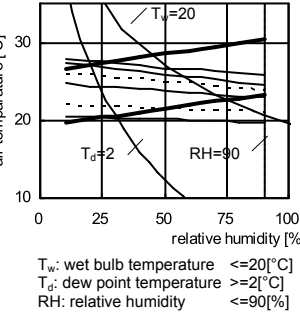


Fig19. PTSV comfort zone (Standard condition)

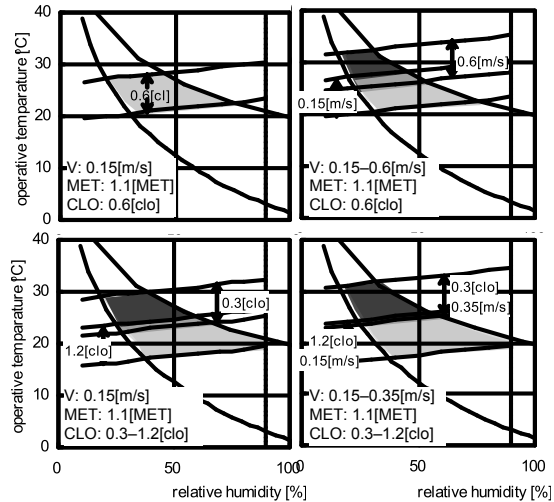


Fig20. Examples of thermal comfort zone in daily life considering adjustments by residents

assumed to be an environment that PTSV comes within ±0.5, and the humidity condition followed ASHRAE 55-1992. It was determined by combining resident's conditions with the environmental conditions as the comfort zone where it suits the individual.

7. References

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