A Study on Thermal Comfort Range Considering Adjustment Actions by Residents

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ABSTRACT: The purpose of this study is to propose a thermal performance evaluation method for passive and low-energy houses that considers the effects of the residents' behaviors in real life. In this paper, after the structure of the evaluation method is illustrated, the results of experiments with subjects to learn their thermal sense and thermal comfort zone in real life are described. In these experiments, the subjects live in an actual house without heating/cooling equipment and follow a realistic schedule that includes movement between rooms and different actions such as reading books, eating and exercising, all under the condition that they can change their clothes freely. From the experiments, it is clarified that 1) the Thermal Sensation Vote (TSV) is more influenced by the air temperature than by SET* (Standard Effective Temperature) and other elements of indoor climate, 2) the unevenness of the Comfort Sensation Vote (CSV) is wider than that of TSV, 3) the air temperature and TSV have a linear relation, 4) TSV and CSV have a linear relation in both the plus and the minus part of TSV, 5) the comfort range based on the experiments is wider than ASHRAE's comfort range.

Keywords: thermal performance, evaluation, comfort, experiment

1. INTRODUCTION

In recent years, passive and low-energy houses have been attracting attention, and the techniques for building them continue to grow. The ideal passive and low-energy houses should be comfortable to live in without heating/cooling equipment and they should be evaluated by the thermal comfort of the residents, not by heat loads or energy consumption. In addition, the resident's behaviors in real life need to be considered: the residents move between rooms which have different thermal environments, and the residents perform actions to adjust to the environment, such as changing clothes and opening or closing windows.

We propose a thermal performance evaluation method for passive and low-energy houses that considers the residents' behaviors in real life. In this paper, the structure of the evaluation method proposed by T. Fukazawa and N. Sunaga [1][2] is illustrated and the results of experiments with subjects to know their thermal sense and thermal comfort zones in real life are described.

2. STRUCTURE OF EVALUATION METHOD

2.1 Concept of the evaluation method

From the standpoint of a built environment, a house should feel comfortable to the residents. But all residents have their own ideals for houses, and their requirements and preferences for a built environment are different. Furthermore, a resident's thermal sense varies according to which room he is in and what action he is doing.

Therefore, the thermal performance evaluation for houses should be based on thermal comfort, which varies by the resident's preferences and conditions. Figure 1 shows the relation between the fluctuation parameters of the human condition and the elements of SET*(Standard Effective Temperature). SET* is a physical and physiological index considering the six elements (air temperature, radiation temperature, relative humidity, wind velocity, quantities of clothes, metabolic rates) that influence thermal comfort. But SET* is limited in its use and is determined in a steady state. On the other hand, a person in a house has various fluctuation parameters because residents move between rooms, perform an array of actions, change clothes, and so on. So, the evaluation method

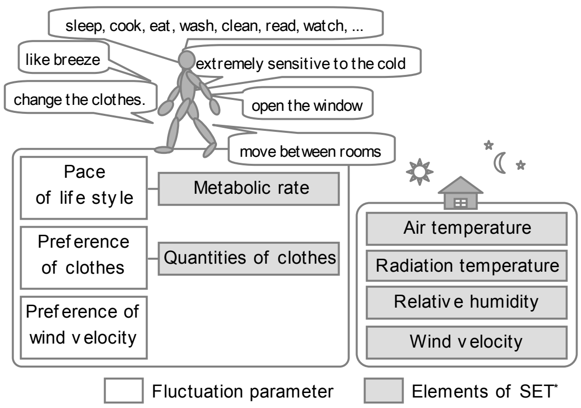


Figure 1: Relation between fluctuation parameters and elements of SET*.

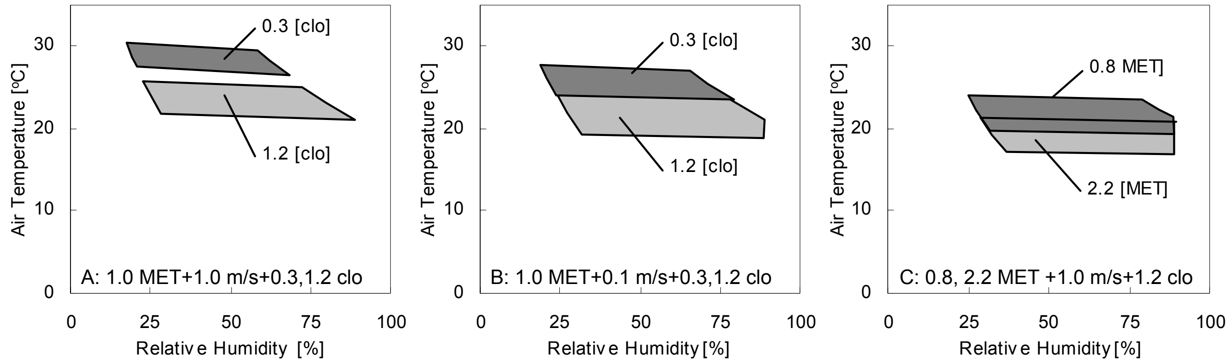


Figure 2: Examples of the fluctuation comfort zones (different metabolic rates, wind velocities and quantity of clothes).

should use the combination of fluctuation parameters and indoor climate elements. Also, the room environments to which the resident are exposed (the exposure environment) must be used as indoor climate elements. The exposure environment is created by merging the room environments where the resident is throughout a day and is evaluated by the fluctuation comfort zones that fit in with the resident's conditions [1][2]. Figure 2 shows examples of these fluctuation comfort zones for different metabolic rates, wind velocities and quantity of clothes. The fluctuation comfort zones are made from ASHRAE's comfort zone [3] by using SET*. The fluctuation comfort zones indicated by air temperature and relative humidity to easier understand for architect and the general public.

2.2 Procedure of the evaluation method

The thermal performance evaluation for houses should be done by estimating how long the resident's exposure environment is comfortable when the resident adjusts oneself to the exposure environment and doesn't use heating/cooling equipment. Figure 3 shows the flow of the thermal performance evaluation method with some of the fluctuation comfort zones shown in Figure 2. First, the thermal environment of each room in the house—the air temperature, the relative humidity, the air velocity and so on—is measured or simulated. Next, the resident's exposure environment is composed for the environment in each room according to the resident's schedule of when and in which rooms the resident occupies. Third, the resident's exposure environment is evaluated by the fluctuation comfort zones, which depend on the resident's conditions. The indices of the thermal performance evaluation method are the percentage of comfortable hours (CH) for the total time the resident is in the house and the difference of the air temperature (TD) between the fluctuation comfort zone and the resident's exposure environment. If the resident's exposure environment is within the fluctuation comfort zones, then it is counted as CH. But, if the resident's exposure environment is out of the fluctuation comfort zones, then it is counted as TD.

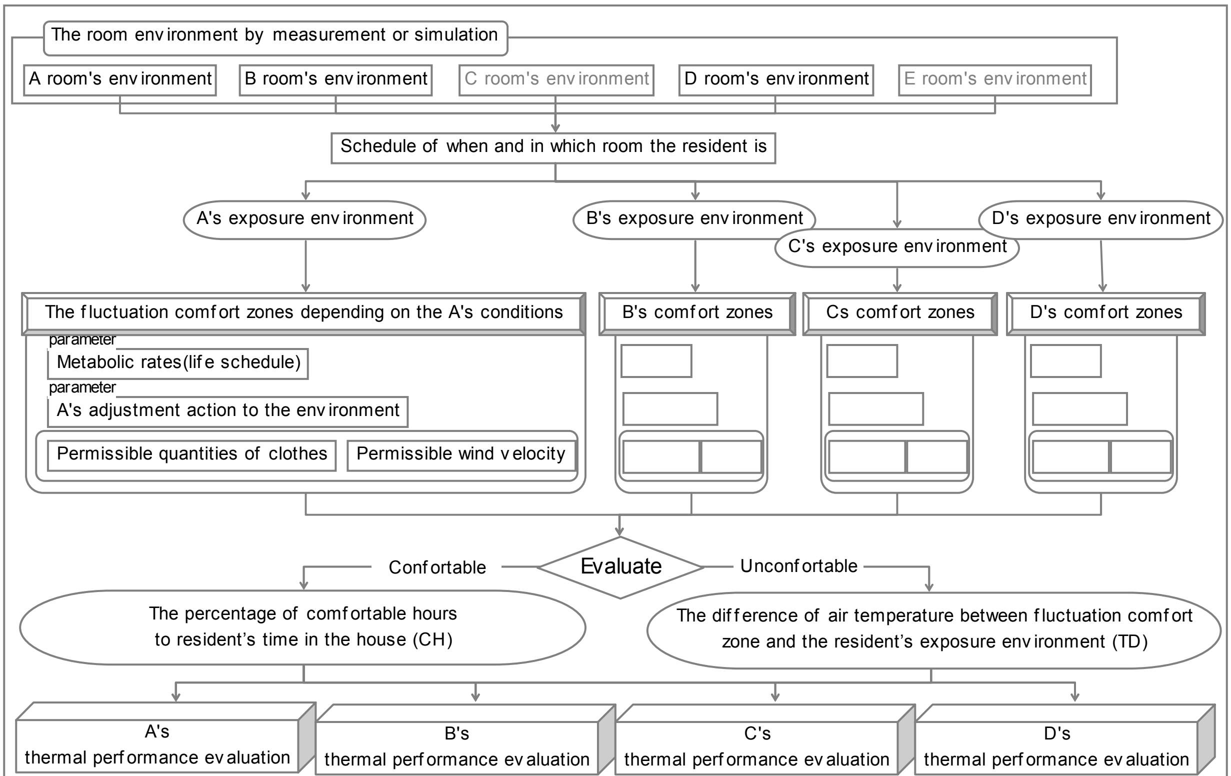


Figure 3: Flow of the thermal performance evaluation method using fluctuation comfort zones.

3. EXPERIMENT WITH SUBJECTS

3.1 Purpose of the experiment

In the previous section, the concept and procedure of the thermal performance evaluation method is described. In that concept, as shown in Figure 2, ASHRAE's comfort zone is transformed with SET* to the fluctuation comfort zones. But, SET* is defined in a steady state and is used in the restricted condition. Therefore, there is some doubt about the reliance of the fluctuation comfort zone due to its natural irregular state and wide range of conditions. Also, in the thermal environment where the resident feel comfortable in real life (i.e., where the resident's relationship with the environment is comfortable) are still not clear. This experiment with subjects, therefore, investigates the resident's thermal senses, such as thermal sensation and comfort sensation in real life, especially in a natural irregular state, e.g., in an environment where the resident can open the windows or let the sunshine in. As a final result of this experiment, the fluctuation comfort zones in a natural irregular environment will be created, and the concept and procedure of the thermal performance evaluation of the resident's behavior is confirmed.

3.2 Outline of the experiment with subjects

3.2.1 Date and the place

A series of experiments with human subjects was carried out in former of the rainy season (May 17-19, 2005), midsummer (August 22-26, 2005) and in midwinter (January 10-18, 2006). The experiments were carried out in Tokyo, Japan.

3.2.2 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 4 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. The experiment had two window conditions (open and closed) in May, but only one condition in August (open) and in January (closed).

3.2.3 Measurement of the thermal environment

Table 1 shows the measurement data categories and instruments that were used. The measurement equipment was selected to measure and record 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 1 minute.

3.2.4 Experiment condition

Table 2 shows 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. Figure 5 shows examples of two subjects' schedules. There was a maximum of six subjects at a time in the test house, and each subject's schedule included actions such as

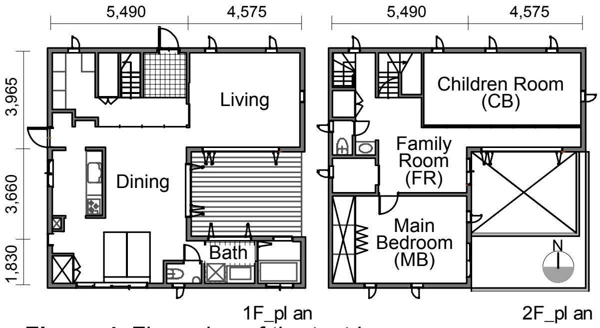


Figure 4: Floor plan of the test house.

Table 1: 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-160 N	HONFIELD
OUT	Air temperature [°C] Relative Humidity [%] Wind velocity [m/s] Wind vector [-]	VantagePro2	Davis

Table 2: 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

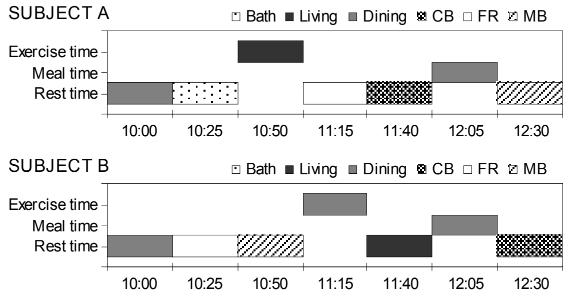


Figure 5: Example of the subject's schedule.

A: Rest time B: Meal time C: Exercise time

Figure 6: States of the experiment.

"rest time", "meal time" and "exercise time" and the subject spent time by himself in different rooms except for the "meal time". At a first "rest time", the subjects were instructed to follow a given schedule and move between rooms in accordance with his or her schedule. When the schedule was "rest time", the subject had free time which could be spent reading books, watching TV, listening to music, and so on, as shown in Figure 6A. When the schedule was "meal time", the subject ate lunch or dinner with all the other subjects, as shown in Figure 6B. When the subject's schedule was "exercise time", he or she walked slowly with a stepper, as shown in Figure 6C. If a subject felt hot or cool, the subject could put on or take off some clothes, and wrote the clothing change and time of the change on a prepared form.

3.3 Thermal comfort questionnaire

The following questionnaire was used to collect the subject's thermal feelings. The questionnaire items were as follows: 1) thermal sensation (TSV, 9 steps); 2) comfort sensation (CSV, 7 steps); 3) satisfaction sensation (7 steps); 4) current sensation (4 steps); 5) demand for wind (7 steps); 6) radiation sensation (7 steps); 7) extent of perspiration (4 steps). Figure 7 shows the scales of TSV and TCV. The questionnaire could be filled out within 3 minutes to lighten the burden imposed on the subjects, because the subjects filled out a questionnaire 3 times; just after he moved into a room, after 10 minutes, and 20 minutes.

4. RESULTS AND DISCUSSIONS

The approach employed in this analysis is as follows. In order to evaluate the room environment which the subjects had occupied and evaluated, each subjects' exposure environments were adopted. The environments adopted were the average of the environments from the time the subject finished filling out the previous questionnaire to the time the subject finished the questionnaire in the present time.

4.1 Subjects' exposure environment.

This section gives an example of one subject's exposure environment (August 22, 2005). Figure 8 shows the air temperatures in each room. The difference between the air temperatures in the rooms is a maximum of 1.9 [^oC] and average of 1.1 [^oC]. Such differences appeared in the other elements of indoor climate, too. Figure 9 shows the fluctuation of the exposure environment, TSV, CSV, the current sensation and the demand for wind for one subject (August 22, 2005). The TSV and CSV are marked on the time that the subject started to fill out the questionnaire. The comparison of the fluctuation between the sensation value and the exposure environments shows that the subject evaluated the exposure environment clearly. At "exercise time" [2.0 MET], TSV shifts to the hot side, CSV shifts to the uncomfortable side. Despite the rise of the metabolic rate at "meal time" [1.4 MET], the TSV shift is parallel, and the CSV shifts to the comfort side.

4.2 Thermal environments

To be able to apply the results more widely, it is important to clarify the range of the measured environment. Figure 10 shows the climograph of the

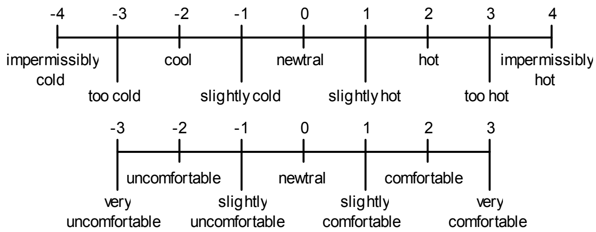


Figure 7: Scales of TSV (upper) and TCV (lower).

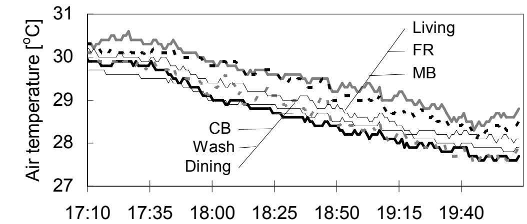


Figure 8: Air temperatures in each room (8/22/2005)

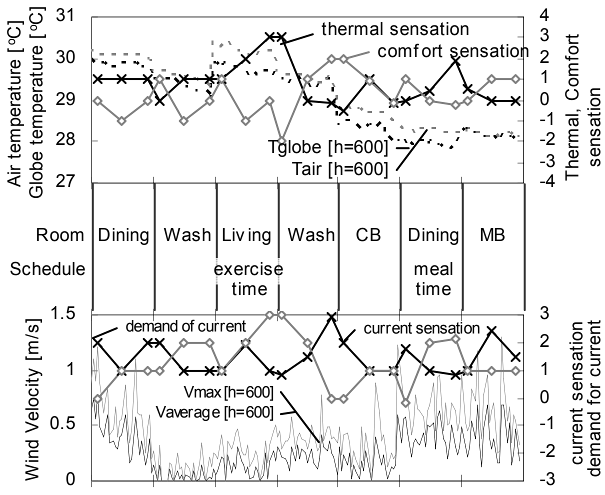


Figure 9: Example of the exposure environments and sensations (8/22/2005).

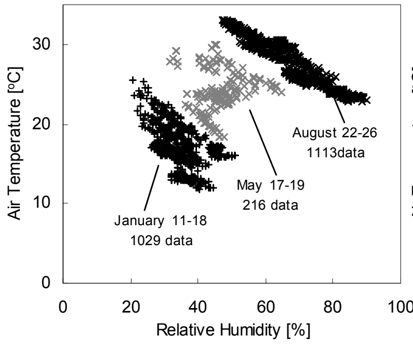


Figure 10: Climograph of subjects' exposure environment.

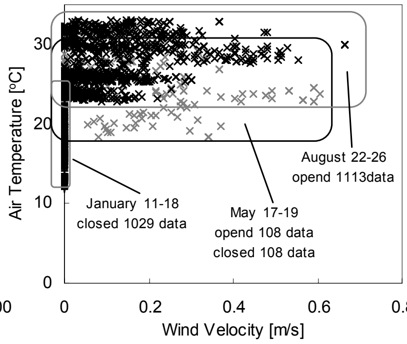


Figure 11: Relation between air temperature and wind velocity.

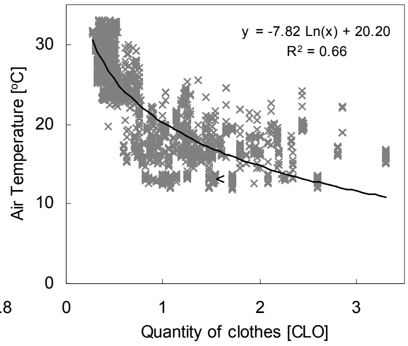


Figure 12: Relation between air temperature and quantity of clothes.

subjects' exposure environment. It shows 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], the relative humidity from 20.6 [%] to 90 [%]. Figure 11 shows the relation 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 0.66 [m/s] and the air temperature of opened windows was over 18.4 [°C]. Figure 12 shows the relation between the air temperature and the quantity of clothes worn. It shows subjects adapted the quantity of their clothes: the hotter the exposure environment, the thinner the subjects' clothes. In addition, the colder the exposure environment, the wider the range of the quantity of clothes.

4.3 Thermal sensation Vote

Figure 13 shows the relation between SET* and PMV, and Figure 14 shows the relation between SET* and TSV. These show that SET* correlates closely with PMV (R^2=0.88), but there is a low correlation between SET* and TSV (R^2=0.20). The correlation is lower than that between the air temperature and TSV (R^2=0.42). Also, there is a low correlation between the other elements of indoor climate and TSV. It follows from these that TSV is strongly influenced by the air temperature. Figure 15 shows the relation between the wind velocity and TSV (left) and CSV (right). It shows the unevenness of CSV is wider than that of TSV for the same wind velocity. Similarly, there is a low correlation between any elements of indoor climate and CSV.

For such reasons and to make the evaluation easier, the relation with air temperature is determined. Figure 16 shows the relation with the air temperature and TSV in each behavior; "rest time" [1.1 MET], "meal time" [1.4 MET] and "exercise time" [2.0 MET]. It will reveal that the neutral of TSV is different by metabolic rate. At the same time, it is illustrated that

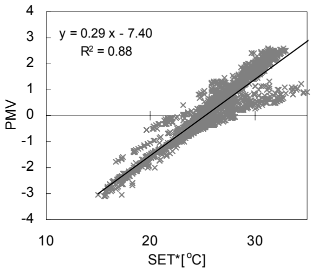


Figure 13: Relation between SET* and PMV

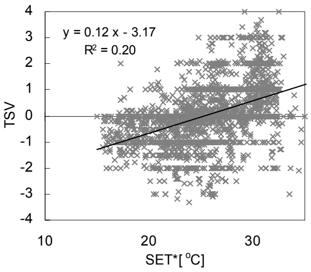


Figure 14: Relation between SET* and TSV.

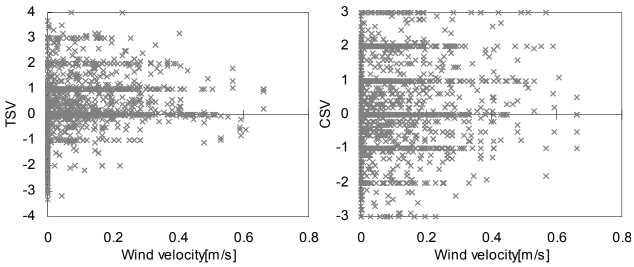
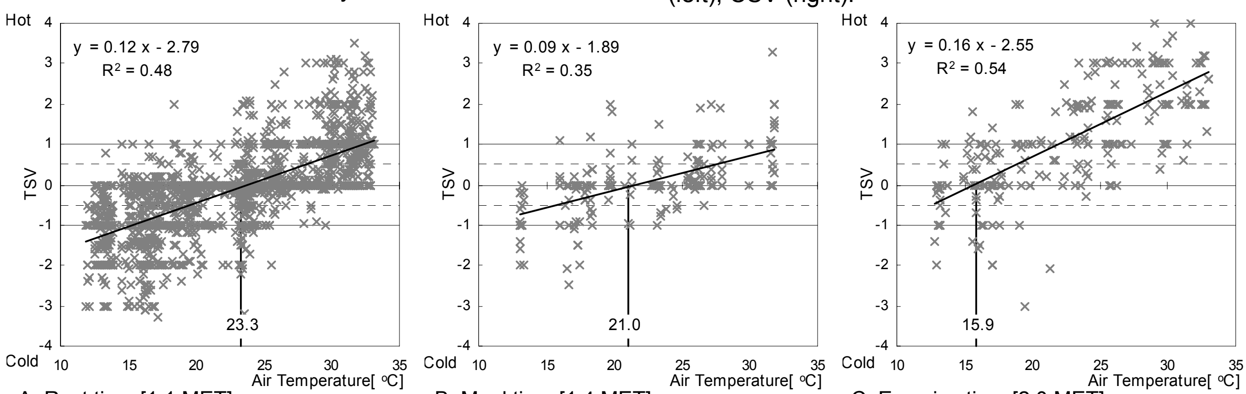
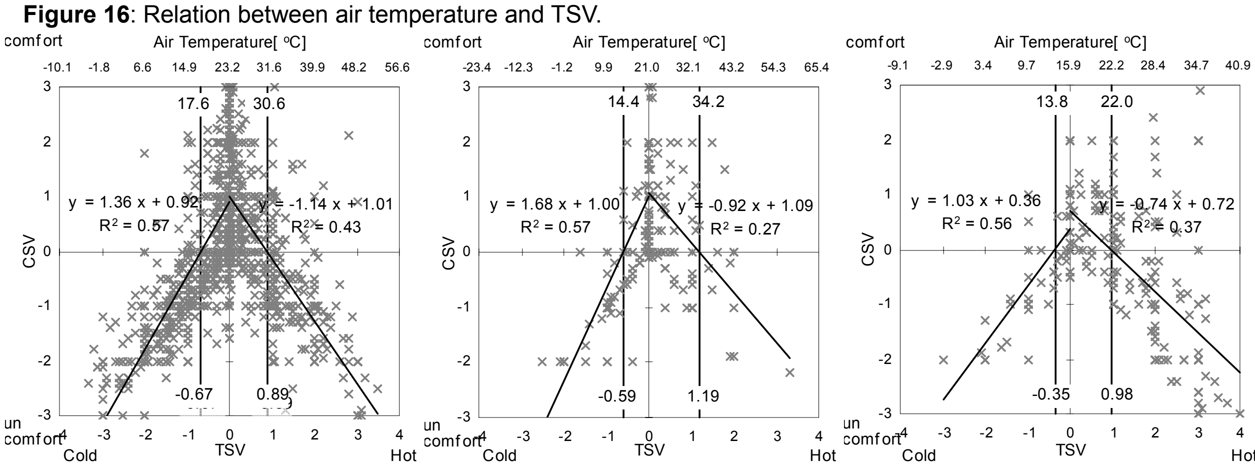


Figure 15: Relation between wind velocity and TSV (left), CSV (right).



A: Rest time [1.1 MET] B: Meal time [1.4 MET] C: Exercise time [2.0 MET]

Figure 16: Relation between air temperature and TSV.



A: Rest time [1.1 MET] B: Meal time [1.4 MET] C: Exercise time [2.0 MET]

Figure 17: Relation between TSV and CSV.

Table 3: Summarization of the relations among TSV, CSV and the air temperature

Limit	Expressions in figure15	R^2	TSV	Expressions in figure16	R^2	± 0.5 TSV	CSV	Ta	± 1 TSV	CSV	Ta	TSV	0 CSV	Ta	ASHRAE Winter	ASHRAE Summer
Rest time [1.1MET]																
Upper	TSV = 0.12 xTa - 2.79	0.5	-	CSV =1.36 xTSV+ 0.92	1	-0.5	0.2	**19.1**	-1	-0.4	**14.9**	-0.7	0.0	**17.6**	**20.0**	**22.8**
Lower			+	CSV =-1.14 xTSV + 1.01	0	0.5	0.4	**27.4**	1	-0.1	**31.6**	0.89	0.0	**30.6**	**23.6**	**26.1**
Meal time[1.4MET]															RH = 50 [%] V = 0.15 [m/s] MET = 1.1 [met] CLO = 0.9[clo](winter) 0.5[clo](summer)	
Upper	TSV = 0.09 xTa - 1.89	0.4	-	CSV =1.68 xTSV + 1.00	1	-0.5	0.2	**15.4**	-1	-0.7	**9.9**	-0.6	0.0	**14.4**		
Lower			+	CSV =-0.92 xTSV + 1.09	0	0.5	0.6	**26.6**	1	0.2	**32.1**	1.18	0.0	**34.2**		
Exercise time [2.0MET]																
Upper	TSV = 0.16 xTa - 2.55	0.5	-	CSV =1.03 xTSV + 0.36	1	-0.5	-0.2	**12.8**	-1	-0.7	**9.7**	-0.3	0.0	**13.8**		
Lower			+	CSV =-0.74 xTSV + 0.72	0	0.5	0.4	**19.1**	1	0.0	**22.2**	0.97	0.0	**22.0**		

the relation between the air temperature and TSV is a linear relation. It has a wide scatter, but the linear relation is taken in near the average. So, it is considered that a linear relation can estimate the relation between the air temperature and TSV.

The relation between TSV and CSV in each behavior ("rest time", "meal time" and "exercise time") are represented in Figure 17. Considering the plus and minus part of TSV, it appears that the relation between TSV and CSV has a linear relation. It has also shows wide scatter, but the linear relation is taken near the average. So, the linear relation can estimate the relation between TSV and CSV.

4.5 Examination of the comfort range.

Table 3 summarizes the relations among TSV, CSV and the air temperature based on the expressions of Figure 15 and Figure 16. It illustrates that, given that the range of TSV is -0.5 to 0.5, what is called the comfortable range of TSV, the air temperature ranges from 19.1 [°C] to 27.4 [°C] when the subjects carried out "rest time". When subjects carried out the "meal time", the permissible air temperature is 15.4 [°C] to 26.6 [°C]. And when subjects carried out "exercise time", the permissible air temperature is 12.8 [°C] to 19.1 [°C]. Further, in the same way, given the range of TSV from -1 to 1, the air temperature is from 14.9 [°C] to 31.6 [°C] when subjects carried out "rest time". When subjects carried out "meal time", the permissible air temperature is 9.9 [°C] to 32.1 [°C]. And when subjects carried out "exercise time", the permissible air temperature is 9.7 [°C] to 22.2 [°C]. And also, for thermal comfort, it seemed reasonable to think that the comfortable air temperature is that when CSV is above 0. So, given a range of CSV above 0, the permissible air temperature is 17.6 [°C] to 30.6 [°C] when the subjects carried out "rest time". When subjects carried out the "meal time", the permissible air temperature is 14.4 [°C] to 34.2 [°C]. And when the subjects carried out "exercise time", the permissible air temperature is 13.8 [°C] to 22.0 [°C]. Figure 18 shows the diagram of the comfort range based on Table 3. It shows clearly that the comfort ranges based on the expressions are wider than ASHRAE's comfort range. And, looking at "meal time", the upper limit is wider than the others. It can be considered that there is peculiar thing caused by eating a "meal time".

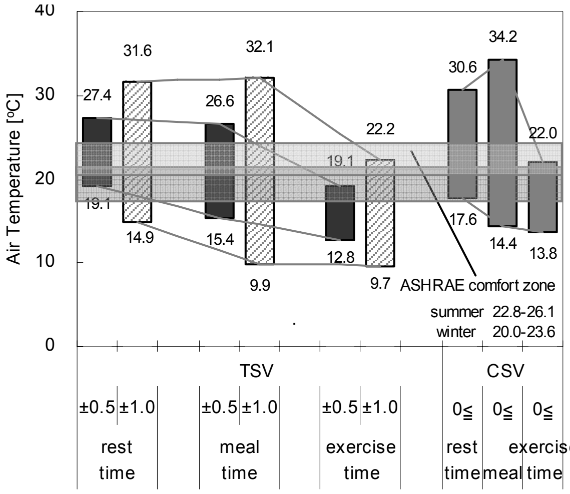


Figure 18: Comfort range based on the expression of Figure 15 and Figure 16.

CONCLUSION

The purpose of this study is to propose a thermal performance evaluation method for passive and low-energy houses that considers the effects of residents' behaviors in actual life. In this paper, after the structure of the evaluation method was illustrated, the results of a series of experiments with subjects in an actual house without heating/cooling equipment were described in order to know the residents' thermal sense and thermal comfort zone in real life. From the experiment, it was clarified that 1) TSV is more influenced by the air temperature than by SET* and the other elements of indoor climate, 2) the unevenness of CSV is wider than that of TSV, 3) the air temperature and TSV are in a linear relation, 4) TSV and CSV are in a linear relation on both the plus and minus part of TSV, 5) the comfort range based on the experiments is wider than ASHRAE's comfort range.

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