Proceedings of 7th Windsor Conference: ***The changing context of comfort in an unpredictable world*** Cumberland Lodge, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Investigation of the comfort temperature and adaptive model in Japanese houses in summer

[1]Jiro Katsuno, [1]Hom B. Rijal and [2]Seohiro Kikuchi

[1]Dept. of Environmental and Information Studies, Tokyo City University, Japan
[2]Dept. of Research and Development, Kawamoto Industries, Ltd, Japan

Abstract
This paper is the result of a field survey on the indoor thermal environment and thermal comfort survey in living rooms of Japanese houses conducted in summer. The residents are highly satisfied with the household thermal environment. The comfort temperature is considerably higher than the conventional standard temperature. The results showed that the residents adapt in the hot environments using behavioural, physiological and psychological adaptation.

Keywords
House, Thermal comfort, Comfort temperature, Air temperature, Adaptive model

1. Introduction

Global warming has caused many disasters in several parts of the world. In Japan, mean highest temperature of 2010 was the highest in 113 years since measurements were started in 1898.
Comfort temperature is regarded as one of the most important factors in comfortable homes. If we can maintain a comfortable thermal environment, we can minimize the air conditioning usage in summer.
Till date, there are many researches about the comfort temperature of the houses in Japan (Nakaya et al. 2005, Tobita et al. 2009), Nepal (Rijal et al. 2010), Pakistan (Nicol et al. 1994) and UK (Rijal and Stevenson 2010). However, some researches have conducted only for a short period of time, and some collected only a few samples. In the context of the Japanese research, there are many researches in the Kansai area (Osaka), but not many in the Kanto area (Tokyo).
In order to estimate the comfort temperature and to develop the adaptive model for Japanese houses, a thermal comfort survey during summer was conducted in the living rooms of residences in the Kanto region of Japan.

2. Field survey

The measurement was conducted in 59 houses in Kanto region in Japan (Tokyo, Kanagawa, Chiba and Saitama). The measurements were performed from August 5 to 18, 2011 and August 24 to September 6, 2011. The mean height of the data loggers was 89 cm (acceptable range was 60~110 cm) above the floor in the living room (Figs. 1 & 2). The indoor air temperature and relative humidity were measured in 10 minute intervals. The outdoor air temperature is obtained from the nearest meteorological station. The thermal comfort survey was conducted several times in a day (Table 1). The ASHRAE scale is often used in thermal comfort surveys in Japan. However, the “warm” and “cool” in this scale have a meaning of comfortably warm in winter and comfortably cool in summer. To avoid this problem, the ASHRAE scale and SHASE (The society of heating, air conditioning and sanitary engineers of Japan) scale are used in this study.

Fig. 1 Data logger

Fig. 2 Example of installation of data logger

Table 1 Scale of the thermal comfort survey

No.	ASHRAE scale	SHASE scale	Overall comfort
1	Cold	Very cold	Very uncomfortable
2	Cool	Cold	Uncomfortable
3	Slightly cool	Slightly cold	Slightly uncomfortable
4	Neural (neither cool nor warm)	Neutral (neither cold nor hot)	Slightly comfortable
5	Slightly warm	Slightly hot	Comfortable
6	Warm	Hot	Very comfortable
7	Hot	Very hot	

3. Analysis

3.1 Calculation of comfort temperature

In this research the comfort temperature was predicted by regression method and Griffiths' method. In the regression method, the comfort temperature is predicted by substituting "4. Neutral" in the linear regression equation of the thermal sensation and indoor air temperature. However, the prediction of the comfort temperature by the regression method may not be suitable in the field survey, and thus the comfort temperature is also investigated by the Griffiths' method (Griffiths 1990).

$$T_c = T_i + (4 - C)/\, a^* \quad (1)$$

Where T_c is the comfort temperature (ºC) by Griffiths' method, T_i is the indoor air temperature (ºC) and a^* is the regression coefficient. In this research, a^* is assumed to be 0.5.

3.2 Calculation of running mean outdoor temperature

Running mean outdoor temperature is the exponentially weighted daily mean outdoor temperature, and it is calculated using the following equation (McCartney and Nicol 2002).

$$T_{rm} = \alpha T_{rm-1} + (1 - \alpha) T_{od-1} \quad (2)$$

Where T_{rm} is running mean outdoor temperature (ºC), T_{od-1} is daily mean outdoor air temperature of the previous day (ºC). T_{rm-1} of the first day is assumed to be T_{od-1}. In this research, α is assumed to be 0.8.

4. Results and discussion

4.1. Thermal environment

Fig. 3 shows distribution of indoor air temperature during the survey. Mean indoor temperature during survey is 29.3ºC in NV (Naturally ventilated) mode and 27.9ºC in AC (Air Conditioned) mode. The NV mode is 1.4 ºC higher than AC mode. The standard deviation is 1.8 ºC in NV mode and 1.3 ºC in AC mode. Fig. 4 shows mean indoor relative humidity during the vote. Mean relative indoor humidity is 77 % in NV mode and 76 % in AC mode. The results showed that the humidity is similar in the both modes.

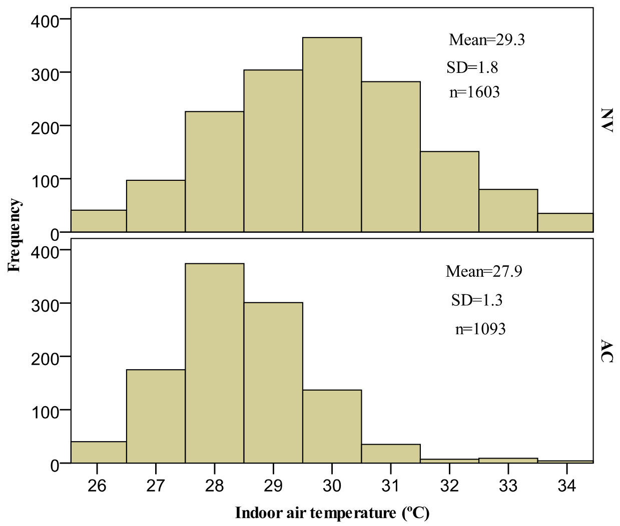

Fig. 3 Distribution of indoor air temperature time during the vote

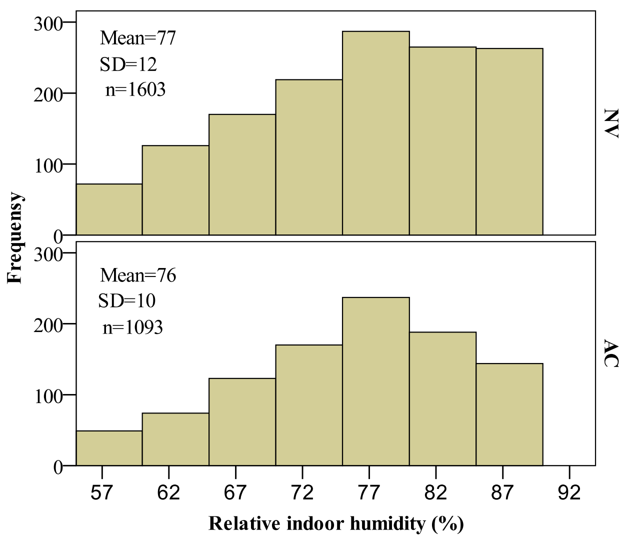

Fig. 4 Distribution of indoor relative humidity during the vote

4.2 Overall comfort

4.2.1 Distribution of the overall comfort

To evaluate the thermal comfort of residents, distribution of overall comfort is shown in Fig. 5. The mean overall comfort of the AC mode is 4.2, and thus it can be said that the overall comfort is high when indoor air temperature is controlled by air conditioning. The mean overall comfort of the NV mode is 3.4. The results show that the overall comfort of NV mode is lower than AC mode.

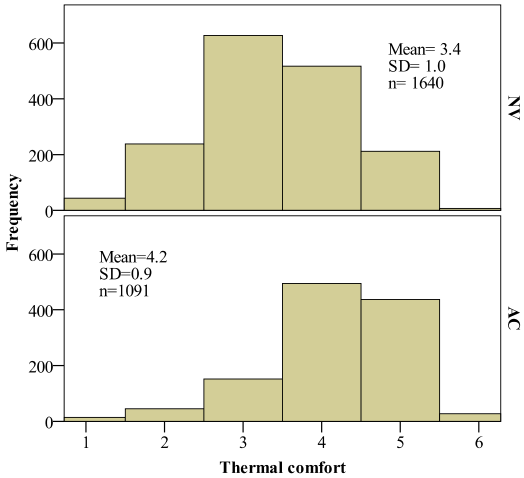

Fig. 5 Distribution of overall comfort

4.2.2 Relation between the overall comfort and indoor air temperature

To investigate the relation between the overall comfort (OC) and the indoor air temperature, the quadratic regression analysis was conducted. The following regression equations are obtained.

NV mode $OC=0.015T_i^2-1.124T_i+23.733$ ($n=1640$, $R^2=0.25$, $p_1=0.001$, $p_2<0.001$) (3)
AC mode $OC=-0.028T_i^2+1.367T_i-12.263$ ($n=1091$, $R^2=0.09$, $p_1=0.001$, $p_2=0.004$) (4)

Where, p_1 and p_2 are the significance levels for the regression coefficients of T_i^2 and T_i respectively. To find the air temperature which corresponds to the peak value of overall comfort, it is necessary to estimate where the curve is horizontal (has a slope of zero). This can be found by differentiating the quadratic equation and equating to zero.

The overall comfort gradually decreases when indoor air temperature is below or above the 24.4 ºC in AC mode. We need to investigate the overall comfort for low indoor air temperature.

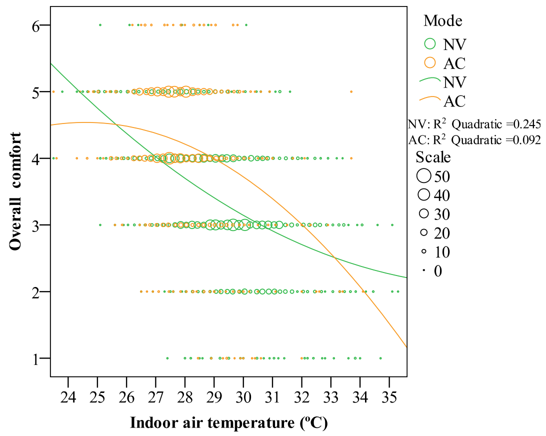

Fig. 6 Relation between overall comfort and indoor air temperature

4.3. Prediction of comfort temperature

4.3.1 Evaluation of thermal sensation

Fig. 7 shows the percentage of the thermal sensation vote of ASHRAE and SHASE scales. Mean value of ASHRAE scale is 4.8 in NV mode and 3.9 in AC mode. AC mode is 1 scale higher than NV mode. The results are different in between the ASHRAE scale and SHASE scale (Fig. 7).

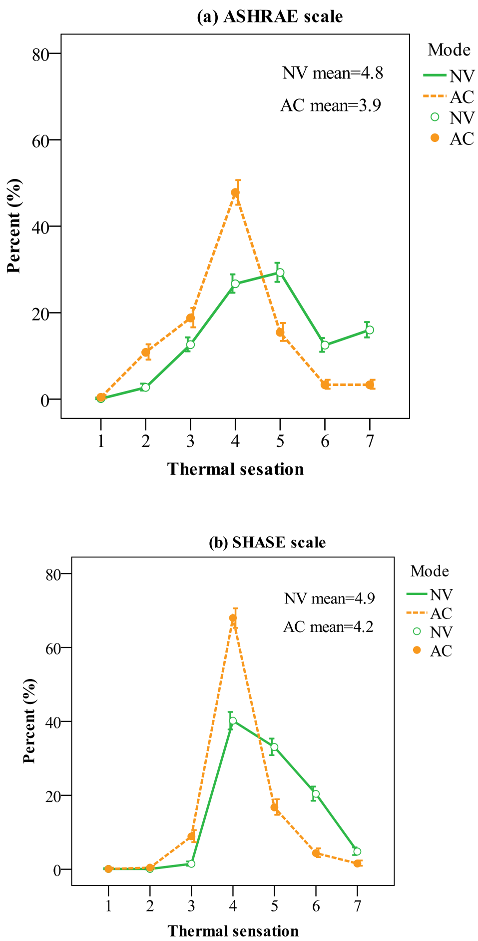

Fig. 7 Evaluation of thermal sensation vote

4.3.2 Prediction of comfort temperature by regression method

To predict the comfort temperature by the regression method, the regression analysis of thermal sensation and indoor air temperature is conducted. Fig. 8 shows the scatter diagram of thermal sensation and indoor air temperature of the NV and AC modes for ASHRAE and SHASE scales. The following equations were obtained by regression analysis.

ASHRAE scale

NV mode $C= 0.403T_i- 6.937$ (n=1,603, R^2=0.30, p<0.001) (5)

AC mode $C= 0.273T_i- 3.705$ (n=1,093, R^2=0.09, p<0.001) (6)

SHASE scale

NV mode $C= 0.269T_i- 2.991$ (n=1,603, R^2=0.28, p<0.001) (7)

AC mode $C= 0.220T_i- 1.928$ (n=1,093, R^2=0.14, p<0.001) (8)

C: Thermal sensation vote, T_i: Indoor air temperature (ºC), n: Number of sample, r: Correlation coefficient, p: Significance level of the regression coefficient

Generally regression coefficient in the field survey is 0.25 which is similar expect for the equation (5). When the comfort temperature is predicted by substituting "4 neutral" in the equations, it is 27.1ºC in the NV mode and 28.2 ºC in the AC mode for ASHARAE scale. Thus, the comfort temperature of the NV mode is 1.1 K lower than the AC mode. The comfort temperature by SHASE scale is 26.0 ºC in the NV mode and 26.9 ºC in AC mode. Thus, the comfort temperature of the NV mode is 0.9 K lower than the AC mode. When the comfort temperature is predicted by substituting "3 slightly cool" and "5 slightly warm" of the ASHRAE scale in the equations, it is 24.7 ºC to 29.6 ºC in the NV mode and 24.6 to 31.9ºC in the AC mode. When the comfort zone is predicted by substituting "3 slightly cold" and "5 slightly hot" of SHASE scale in the equations, it is 22.3 ºC to 29.7 ºC in the NV mode and 22.4 to 31.5ºC in the AC mode. The results show that the comfort zone of the NV & AC mode is wide.

Table 2 shows a comparison of the comfort temperature obtained in this study with earlier research. We have compared with the NV mode because most of the comfort temperature of the existing research might be from the NV mode. The comfort temperature of the existing research is 21 to 30 ºC which is similar to this research. The results showed that the comfort temperature has regional differences. However, there is only a small difference in comfort temperature in the Kanto (Tokyo) and Kansai (Osaka) areas.

Table 2 Comparison of comfort temperature with existing research

Area	Reference	Season	Regression equation	T_c
Japan(This study)	This study	summer	$C = 0.403T_i - 6.937$	27.1
Japan (Kanto)	Rijal & Yoshimura (2011)	summer & autumn	$C=0.257T_i-2.726$	26.2
Japan (Kansai)	Nakaya et al. (2005)	summer	$C_m=0.63T_{om} - 13.45$	27.6
Nepal	Rijal et al. (2010)	summer	$C=0.0576T_g - 1.2669$	21～30
Pakistan	Nicol et al. (1994), Nicol & Roaf (1996)	summer	$C=0.19T_g - 0.59$	26.7～29.9
UK	Rijal & Stevenson (2010)	summer	―	22.9

C: Thermal sensation, C_m: Mean thermal sensation, T_c: Comfort temperature (ºC), T_i: Indoor air temperature (ºC) T_{om}: Mean indoor opertive temperature (ºC), T_g: Grobe temperature (ºC)

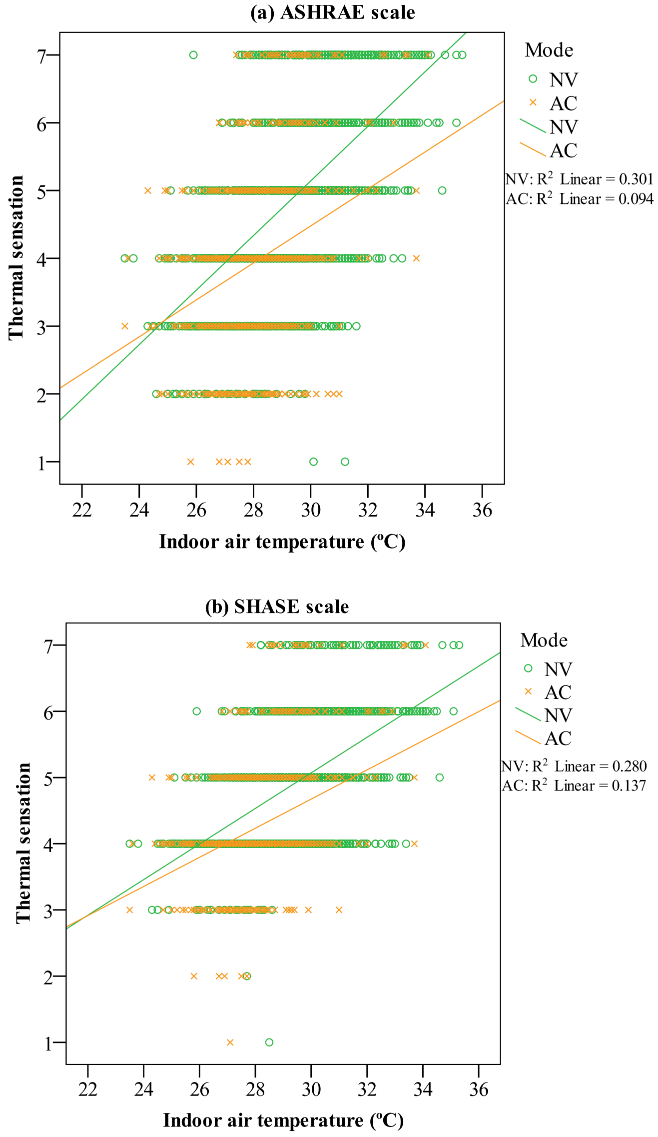

Fig. 8 Relation between thermal sensation and air temperature

4.3.3 Prediction of comfort temperature by Griffiths' method

To predict the comfort temperature by Griffiths' method, the comfort temperature for each thermal sensation vote is calculated. Fig. 9 shows comfort temperature by the ASHRAE and SHASE scales. Mean comfort temperature calculated by the ASHRAE scale is 27.6 ºC in the NV mode and 28.1 ºC in the AC mode. Thus, the comfort temperature of the NV mode is 0.5K lower than the AC mode. The comfort temperature calculated by the SHASE scale is 27.5 ºC in the NV and AC modes.

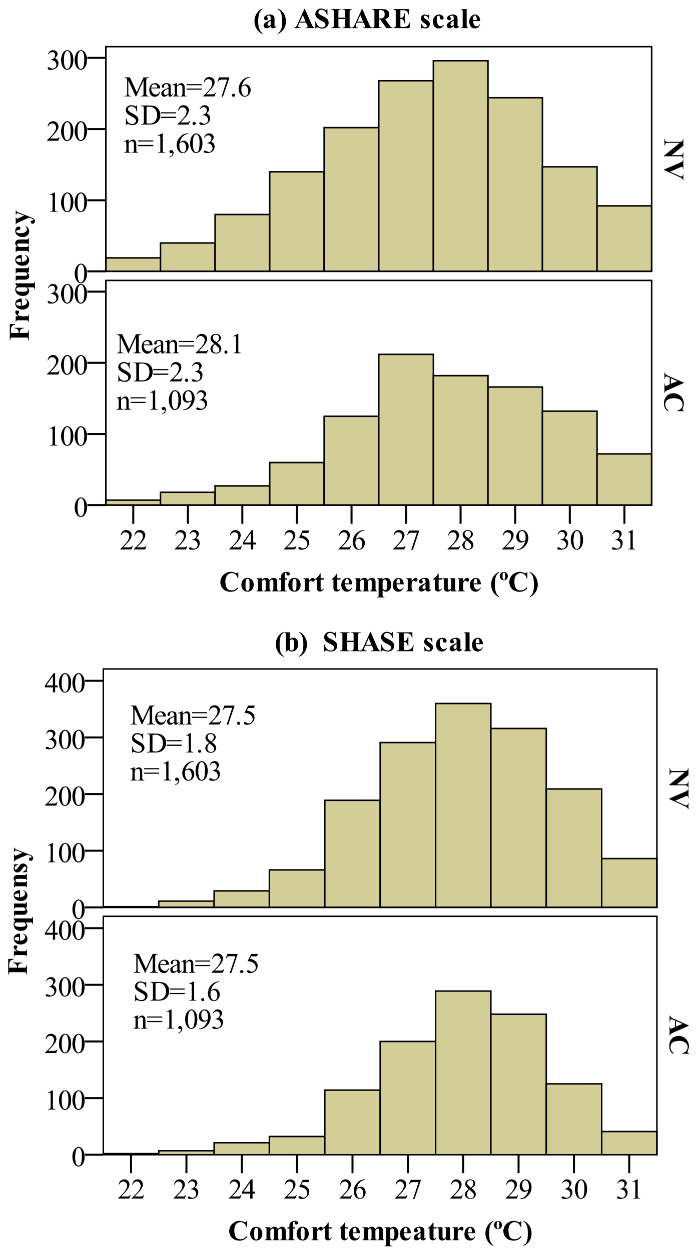

Fig. 9 Comfort temperature by Griffiths' Method

4.4. Adaptive model

4.4.1 Proposal of adaptive model

In the adaptive model, the indoor comfort temperature is predicted using the outdoor air temperature (Humphreys 1978). We have also proposed the adaptive model for the houses. Fig. 10 shows the relation between the comfort temperature and running mean outdoor air temperature. The equations for all houses are given below.

ASHRAE scale

NV mode $T_C = 0.101T_{rm} + 24.889$ (n=1,603, R^2=0.30=0.003, p<0.027) (9)

AC mode $T_C = 0.186T_{rm} + 23.062$ (n=1,093, R^2=0.30=0.01, p<0.001) (10)

SHASE scale

NV mode $T_C = 0.348T_{rm} + 18.268$ (n=1,603, R^2=0.30=0.06, p<0.001) (11)

AC mode $T_C = 0.181T_{rm} + 22.587$ (n=1,093, R^2=0.02, p<0.001) (12)

Regression coefficient of CEN standard is 0.33 in NV mode which is similar to the SHASE scale. When we calculated the comfort temperature using the running mean outdoor air temperature of 28 ºC, the comfort temperature for ASHRAE scale is 27.7 ºC in NV mode and 28.3 ºC in AC mode. The comfort temperature for SHASE scale is 28.0 ºC in NV mode and 27.7 ºC in AC mode.

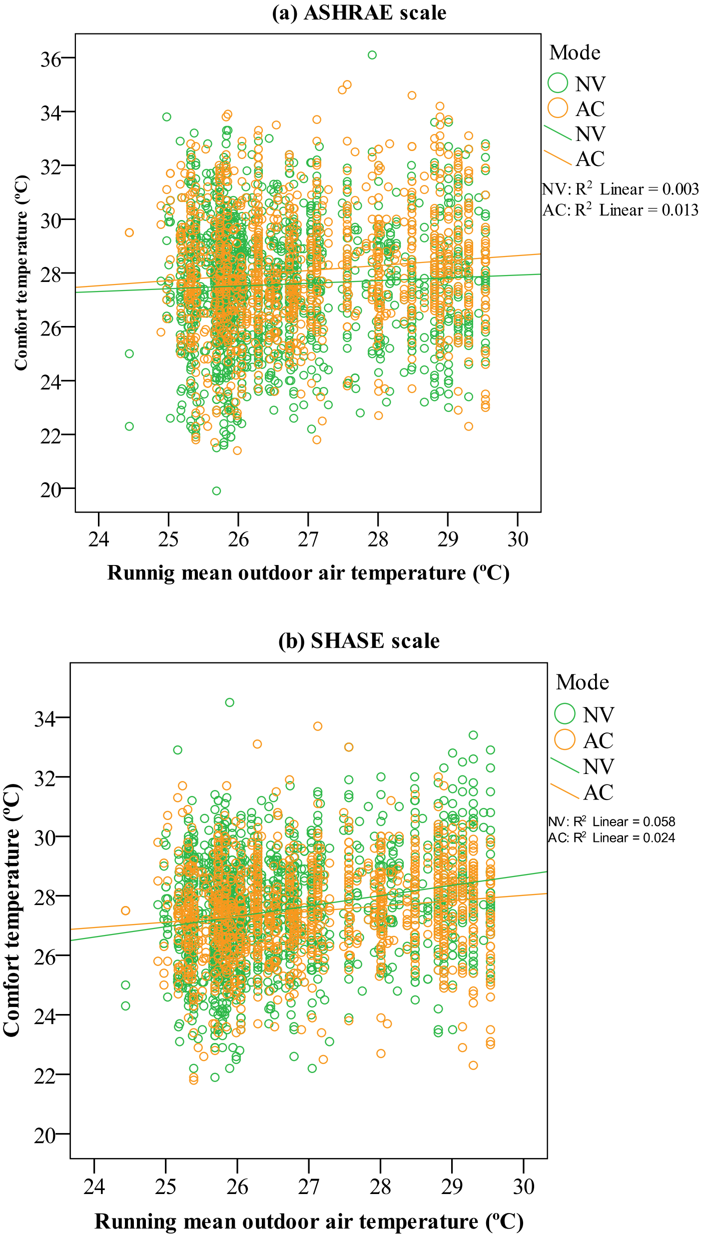

Fig. 10 Relationship between comfort temperature and running mean outdoor air temperature

Fig. 11 shows the relation between the comfort temperature and the running mean outdoor temperature. Six lines in these figures show acceptable zone of the adaptive model (CEN 2007). Generally comfort temperature of this study is within the acceptable zone of the adaptive model. The results showed that the residents are living by adapting to higher indoor air temperature of the houses.

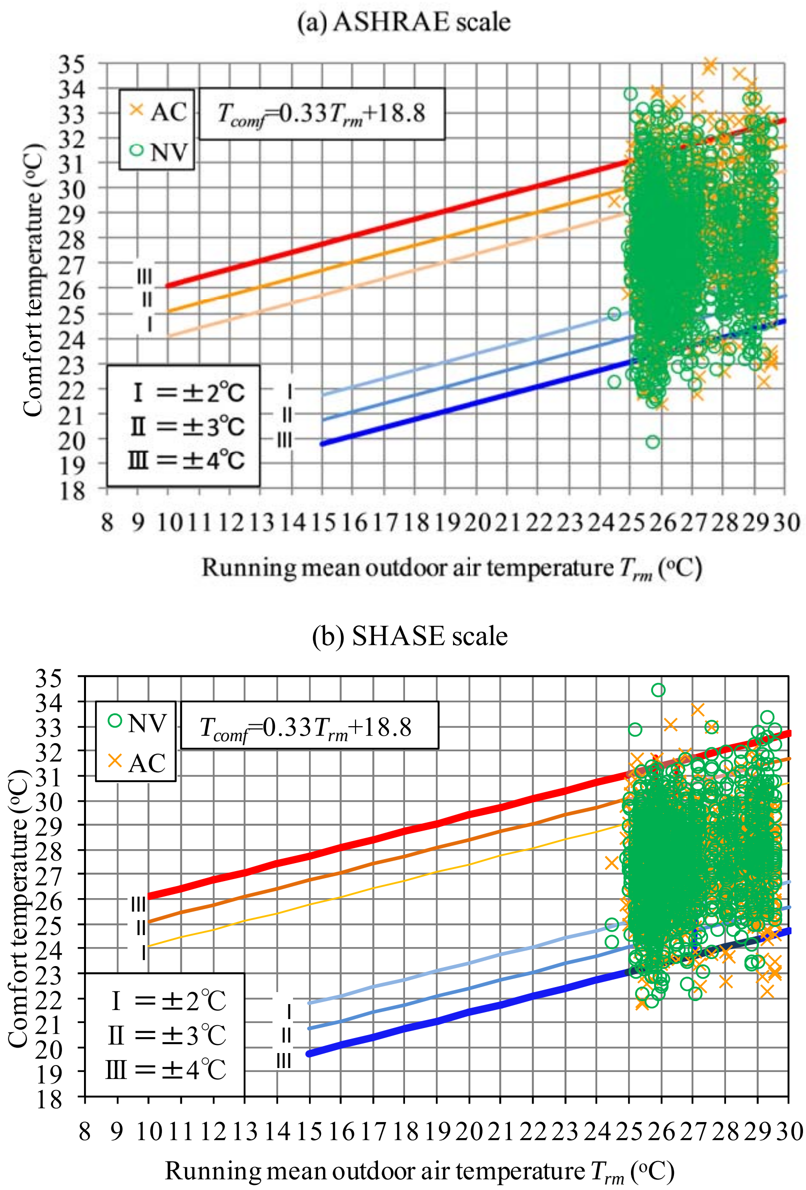

Fig. 11 Relationship between the comfort temperature and running mean outdoor air temperature

4.4.2 Thermal adaptation in summer

Residents can regulate the thermal environments by using various adaptations. This section focuses on about the behavioural adaptation, physiological adaptation and psychological adaptation.

First the behavioural adaptation of the residents is discussed. The adaptive behaviour in a house can be varied. Fig. 12 shows the relationship between the windows open and indoor air temperature. Fig. 13 shows relation the fan use and indoor air temperature. The proportion of windows open varies a little when indoor air temperature is changed. The proportion of fan use is increased when indoor air temperature is risen. Thus, the results showed that residents undertake behavioural adaptation using fan and window opening. Residents are also free to choose the clothes. Due to the air conditioning used, the indoor air temperature and clo are not related in the AC mode (Table 3). However, indoor air temperature and clo are related in the NV mode.

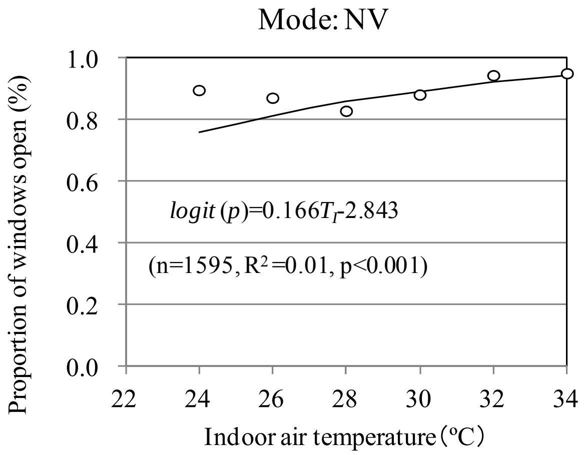

Fig. 12 Relation between the windows open and indoor air temperature

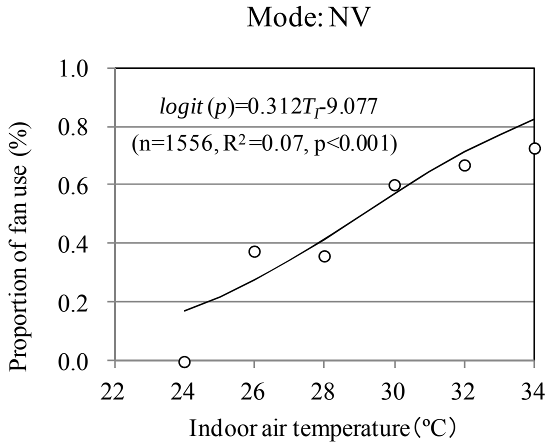

Fig. 13 Relation between the fan use and indoor air temperature

Table 3 Correlation coefficient of the clo value and indoor air temperature

Mode	Item	Clo: T_i
NV	*r*	-0.18
	p	<0.001
	n	1602
AC	*r*	-0.04
	p	0.182
	n	1093

r:Correlation coefficient, *p* : Significant level of the regression coefficient, *n* : Number of sample, T_i: Indoor air temperature (°C)

Sweating as a physiological adaptation: people feel comfortably cool by sweating. The sweating and indoor air temperature are highly related in the NV mode compared to the AC mode (Fig. 14).

Psychological adaptation: Although there is no clear definition of the psychological adaptation, we will focus on the expecting a range of condition. The correlation analysis of indoor air temperature and corresponding behaviour when residents felt uncomfortable was conducted (Table 4). The correlation coefficient of the eating or drinking cold things or using fan or moving to cold room and indoor air temperature are high. When indoor air temperature is high, residents like to feel comfortable by adjusting the indoor environment and their body. Fig. 15 shows difference between indoor air temperature and cognitive temperature (we asked the residents to guess the indoor air temperature). The mean value is 0.8 K in the NV mode and 0.4 K in the AC mode. The cognitive temperature is lower than indoor air temperature for both modes. So, residents actually live in high indoor air temperature, and adapt to the high temperature. That is to say, by assuming low indoor air temperature, psychologically, residents adapt in high indoor air temperature.

Fig.16 shows the differences between indoor air temperature and temperature setting of the cooling. Indoor air temperature is 1 ºC higher than temperature setting of the cooling. Residents may assume that indoor air temperature is the same as temperature setting. Thus, residents again here adapt to the high indoor air temperature psychologically.

The results showed that residents adapt to the hot environments using various methods of adaptation.

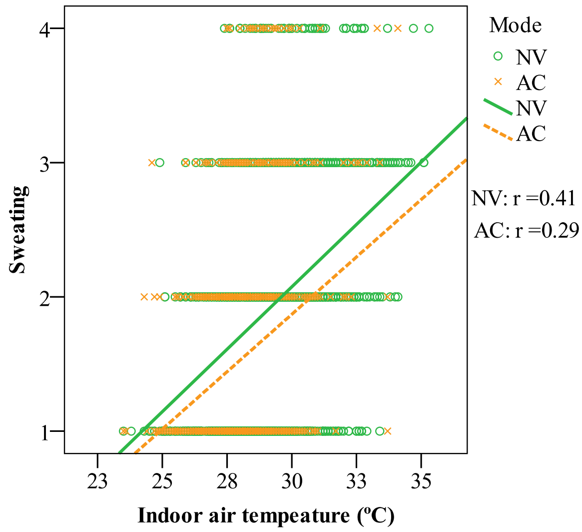

Fig. 14 Relation between the indoor air temperature and sweating

Table 4 Relationship between the indoor air temperature and behavioural adaptation when resident felt uncomfortable (1. Very uncomfortable to 3. Slightly uncomfortable in the overall comfort scale)

Mode	Item	Eat or drink cold things: T_i	Shower : T_i	Wash face, hand and leg : T_i	Use fan: T_i	Move to cold room: T_i
NV	*r*	0.22	0.17	0.14	0.18	0.18
	p	<0.001	<0.001	<0.001	<0.001	<0.001
	n	917	896	896	897	886
AC	*r*	0.19	0.22	0.14	0.34	0.21
	p	0.004	0.001	0.036	<0.001	0.002
	n	228	225	223	223	221

r :Correlation coefficient, *p*:Signi ficant level of the regression coefficient, *n*: Number of sample,
T_i: Indoor air temperature (ºC)

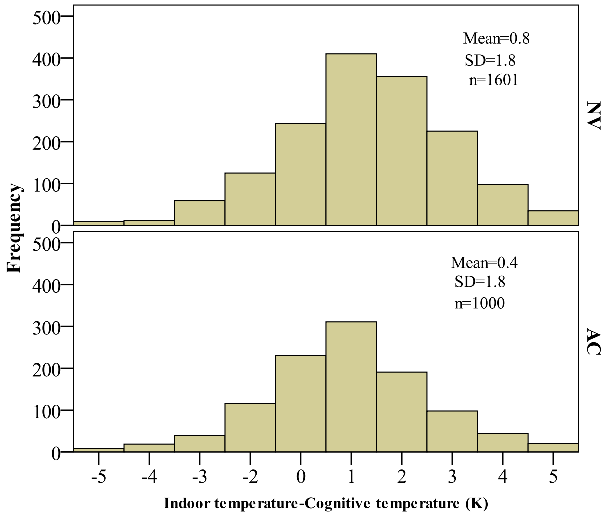

Fig.15 Differences between the indoor air temperature and cognitive temperature

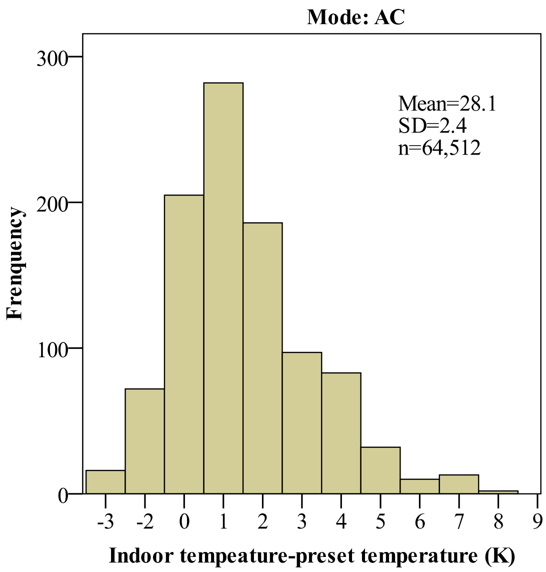

Fig.16 Differences between indoor air temperature and setting temperature

5. Conclusions

In this research, we conducted thermal measurement in the living rooms and a thermal comfort survey of residents in Kanto region of Japan. The following results were found.

1. The mean indoor air temperature during the survey was 29.3ºC in NV mode and 27.9ºC in AC mode. The results showed that indoor air temperature of the NV mode is 1.3 ºC higher than AC mode.
2. The proportion of thermal comfort zone of the thermal sensation is high. The results showed that the residents are highly satisfied with the thermal environment of the houses.
3. The comfort temperature is considerably higher than the conventional standard. The results showed that residents adapt to the hot environments using behavioral adaptation, physiological adaptation and psychological adaptation.

Acknowledgment

We would like to thank to Dr. Madhavi Indraganti for editing the paper.

References

CEN EN 15251 (2007), Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lightning and acoustics. Comite' Europe'en de Normalisation (CEN), Brussels.

Griffths I.D. (1990), Thermal comfort in buildings with passive solar features: field studies. Report to the Commission of the European Communities. EN3S-090UK:University of Surrey Guildford.

Humphreys MA (1978), Outdoor temperatures and comfort indoors. *Building Research and Practice (J. CIB)*, 6(2): 92-105.

McCartney K.J and Nicol J.F. (2002), Developing an Adaptive Control Algorithm for Europe, *Energy and Buildings 34(6)*, pp. 623-635.

Nakaya T., Matsubara N., Kurazumi Y. (2005), A field study of thermal environment and thermal comfort in Kansai region, Japan – Neutral temperature and acceptable zone in summer. *J. Environ. Eng. AIJ 597*: 51- 26 (In Japanese with English abstract).

Nicol F., Jamy G.N., Sykes O., Humphreys M., Roaf S., Hancock M. (1994), A survey of thermal comfort in Pakistan toward new indoor temperature standards. Oxford Brookes University, School of Architecture.

Nicol F. (2008), Adaptive standards for Thermal Comfort in Buildings, In: Adaptive Thermal Comfort in Buildings: 21-30, The Kinki Chapter of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE)

Nicol F., Roaf S. (1996), Pioneering new indoor temperature standards: the Pakistan project. *Energy and Buildings 23*: 169-174.

Rijal H.B., Stevenson F. (2010), Thermal comfort in UK housing to avoid overheating: lessons from a 'Zero Carbon' case study. *Proceedings of Conference: Adapting to change: New thinking on comfort*, Windsor, UK, 9-11 April 2010. London: Net work for Comfort and Energy Use in Buildings.

Rijal H. B., Yoshida H., Umemiya N. (2010), Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses. *Building and Environment 45 (12)*: 2743-2753.

Tobita K., Matsubara N., Kurazumi Y., Shimada R. (2009), Difference of the thermal sensation votes by the scales in the field study of houses during winter. *J. Environ. Eng. AIJ 74 (646)*: 1297- 1297 (In Japanese with English abstract).