Thermal adaptation in residential buildings in the Hot Summer and Winter Cold Zone of China, case study of Wuhan in summer

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ABSTRACT

This field work was conducted in Wuhan in 2007 summer to investigate local residents' thermal adaptation. A total of 367 residents answered questionnaires and 69 families provided 348 data sets including residents' demographics information, thermal sensation, corresponding indoor and outdoor climatic condition, housing characteristic and residents' adaptive behavior. The investigation has shown that local residents can tolerant more rigorous thermal environments comparing with the ranges defined by ASHRAE. A lot of adaptive behaviors have been adopted by residents to restore comfort during their daily life. Some of these behaviors have significant impacts on the residents' thermal sensation.

1. INTRUDUCTION

With the increasing public concern about climate change and building energy conservation, a great number of studies about thermal adaptation have been done around the world (ASHRAE RP-884, de Dear, 1997; SATCs project, McCartney, 2002; ATG, Van Der, 2006). The revision of ASHRAE standard 55-2004 and ISO 7730-2005 have also acknowledged the importance of thermal adaptation mechanism. Investigations in real living conditions have shown that static comfortable temperature is not necessary all the time, especially in residential buildings. By allowing people to control over their indoor environments and allowing temperatures to follow the outdoor climate patterns, there would be potentially significant impacts on both improving thermal comfort and reducing energy consumption.

The demand for comfortable thermal environments and building energy conservation is more obvious in China. Achieving comfortable thermal environment at home has resulted in vast domestic energy consumption in recent years. If China still adopts former European or American thermal comfort standards and every Chinese is to lead a lifestyle same as that in developed countries, Chinese building energy demand will face a big challenge in view of its huge population base (Jiang, 2007).

Hot, humid summer and clammy winter make the building energy consumption for maintaining thermal comfort very huge in Hot Summer and Cold Winter Zone (HS&CW Zone) of China. The HS&CW Zone covers 16 provinces with high developing speed and 5.5 hundred millions people with high density (The Ministry of Construction, JGJ134-2001). This specific climatic zone plays a very important role in the whole Chinese building energy conservation plan.

In China, the discrepancy between existing thermal comfort standard and real thermal environments in residential buildings is asking for new understanding about thermal comfort. However, study focusing on thermal adaptation in residential buildings addressing occupants' living behaviors is very limited, especially for

HS&CW Zone. To address this problem, this research aims to investigate residents' thermal adaptation mechanism and working process based on the field study in Wuhan, one typical city in this climatic zone.

2. METHODOLOGY

2.1. Theoretical work about thermal adaptation

2.1.1 Definition of thermal adaptation

The adaptive principle was defined by Humphreys (1997) as: *If a change occurs such as to produce discomfort, people react in ways tend to restore their comfort*. Person is not a passive receptor of sense-impressions, but a dynamic and active agent responding to thermal environment accounting for the ways in which a person's past experience, future plans, and intentions (de Dear & Brager, 1997). The mechanism of thermal adaptation is different from that of static heat balance. The feedback loop of thermal adaptation implies that what might have been regarded as the final consequence in the static heat balance (the conscious sensation of thermal discomfort), becomes the starting point of the adaptive adjustment (de Dear & Brager, 1997).

There are three operable approaches to achieve thermal adaptation: behavioral adjustment, physiological adjustment and psychological adjustment (Brager, 1998). The behavioral adjustment provides most opportunities for thermal adaptation in real living conditions (de Dear & Brager, 1997). It includes all modifications a person consciously, or unconsciously make, which would modify heat and mass fluxes governing the body's thermal balance (Wohlwill, 1975). Brager has divided behavioral adjustment into three subcategories: (a) adjustment to the surroundings by personal changes; (b) technological or environmental adjustment and (c) cultural adjustment (Brager, 1998).

2.1.2 Thermal adaptation model

Since the adaptation mechanism implies the dynamic trend of comfortable temperature, researchers want to find the relationship of comfortable temperature and corresponding external thermal environments. The most common method is to establish thermal adaptation model to highlight this relationship. The ASHRAE defines *Adaptation model is one model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatologically parameters* (ASHRAE Standard55:2004).

Existing published results about thermal adaptation models can be roughly categorized into two types: prediction of temperature and prediction of behavior. The temperature prediction model describes the regression relationship between comfortable temperature and mean outdoor temperature. Adopting similar methods, some relationship between thermal sensation and other indoor or outdoor climatic parameters can be showed. The representative model form is shown as equation (1):

$$Tc = a*Tout+b \qquad (1)$$

Where:
Tc: Comfortable temperature
Tout: Outdoor temperature
a, b: Coefficient and constant (Nicol & Humphreys, 2007, p298)

Another direction of thermal adaptation model is to predict the potential usage probability of a certain kind of behavioral adjustment by adopting logistic regression analysis (Nicol & Rijal, 2007). These behaviors include opening windows, using fan, using curtain, using heater, etc. in naturally ventilated buildings. The relationship between behavioral controls and objective thermal environment has been proved using stochastic analysis. This kind of prediction can help to get a greater accuracy in building energy simulation. The representative form is shown as equation (2):

$$\text{Log}\,\{p/(1-p)\} = a*T+b \qquad (2)$$

Where:
p: Probability of behavior adopted
T: Indoor or outdoor temperature
a, b: Coefficient and constant (Nicol & Rijal, 2007, p714)

2.2 Research method: field work and statistical analysis

Although there has been some evidence for thermal adaptation in climate chamber (Brager, 1998), field work survey is still the most effective method to investigate human's thermal adaptation process. It guarantees the maximum fidelity of adaptive opportunities and human's adaptive responses in the real thermal environments. Based on the data from field work, some statistical analysis will help to give an insight into the mechanism of thermal adaptation for most occupants.

2.2.1 Data collection

The data collection includes two parts. One is the background information collection about local residents' response to the hot environments using questionnaires, such as about residents' demography, living habits, living conditions and consuming values. The other one is the field measurements of occupants surrounding thermal environments and their thermal sensation. All records can be classified into six categories as (I) basic identifiers and demographics, (II) thermal sensation, (III) indoor physical parameters, (IV) calculated thermal comfort indices, (V) outdoor physical parameters and meteorological data, (VI) personal environmental control and behaviors.

Indoor physical environmental variables including "ta", "tr", "vel", "rh", "met" and "clo" were collected at the same time and place as the questionnaires distributed. (In this paper, all the coding refers to the ASHRAE PR-884 report coding table) Because of the shortage of equipments, this study only recorded physical parameters of one height level (1.1m for standing or 0.6m for sitting) in the middle of living space which is classified as Class II data by Brager (1997). "Ta", "rh" and "tr" were recorded by portable electronic devices automatically. "Vel" was recorded by digital anemoscopes with hot wire probe. "Met", "clo" and other environmental variables were recorded instantaneously by investigators' observations and interviews with residents. In addition, outdoor physical parameters of the investigated houses and the local weather station's climate data also were recorded as references.

To investigate residents' behavioral adjustments, the author lists 18 kinds of behaviors to check residents' response to the hot environment in this study (Table 1).

Table 1: 18 kinds of behavioral adjustments of residents responding to hot environment

Coding	Residential behaviors
PCEF1	Opening doors for NV (natural ventilation)
PCEF2	Opening windows for NV
PCED3	Mechanical fan
PCED4	Curtain or shutter
PCED5	Evaporation effect
PCED6	Air-condition
PCED7	Adjusting thermostat
PCED8	Reducing usage of hotter space
PCED9	Sleeping outdoor at night
PCED10	Walking out in the evening
PCED11	Reducing clothes
PCED12	Swimming or shower
PCED13	Reducing activities
PCED14	Cold or frozen food
PCED15	Keeping calm
PCED16	Lower expectation on thermal environment
PCED17	Vegetation cooling
PCED18	Reduce insulation (clothes excluded)

Most investigated residents have lived in Wuhan for more than ten years and they are healthy person aged 14~50. Male and female sample numbers are roughly equal.

2.2.2 Data analysis

The data was analyzed using statistic mainly including three parts of work as follows:

- Correlation analysis of thermal sensation with indoor climate.
- Correlation analysis of thermal sensation with outdoor climate.
- Comparison of real thermal sensation addressing behavioral adjustments with calculated sensation without considering behavioral adaptation. These correlations are helpful to find out behaviors' impacts on thermal adaptation.

The first two kinds of correlation analysis can help to explain how the indoor and outdoor climate influence residents' thermal sensation votes, neutral temperature, thermal acceptability, thermal preference and behavioral adjustments through regression analysis.

3. RESULTS & DISCUSSIONS

367 questionnaires for background information collection have been received (126 from field survey and 241 from internet survey) and 348 valid measurements (42 in air-condition buildings and 306 in naturally ventilated buildings) have been made in 69 families. In this study, only data from naturally ventilated houses are used to analyze residents' thermal adaptation.

3.1 Residential thermal environments in summer

Through frequency calculation of first kind of questionnaires, some results have been found as following:

- Most households are equipped with individual controlling air-condition (80.4 percents);
- Most residents often open windows or doors for natural ventilation and cooling effect (62.9 percents);
- Most residents won't use air-condition until the indoor temperature is higher than 28 ℃ (25.6% for 28℃to 32℃; 38.4% for 32℃ to 35℃);
- Most residents use air-condition in the noon, evening and night for good rest and sleep;
- Most residents reduce cloth value lower than 0.5clo;
- Residents adopt all kinds of behaviors to reduce discomfort. Among these adaptive behaviors, natural ventilation, mechanical fans, air-condition, reduce clothing, swimming or shower, cold or frozen food, keeping calm and reducing insulation (excluded clothing) are adopted by more than 50% residents.

3.2 Real thermal sensation responding to indoor and outdoor climate

Unfortunately, the linear regression between real thermal sensation ("ash") with indoor and outdoor climate are all non-significant, such as correlation of "ash" with indoor air temperature (ta_m), indoor effective temperature (et) and indoor operative temperature, "ash" with outdoor air temperature, outdoor average air temperature (dayav_ta) and outdoor average effective temperature (dayav_et). The reasons maybe lies in the insufficient data of wider temperature range. In this study, the indoor air temperature is only in the hot range of 27℃ to 37℃.

3.3 Difference of "ash" and "pmv"

Through paired-samples T test (Table 2), there is significant difference between real thermal sensation "ash" and calculated thermal sensation "pmv". Obviously, PMV tool underestimates resident's adaptation in summer in Wuhan.

Table 2: paired-samples T test of "pmv" and "ash"

	Mean	sample number	Std. D	Mean of difference (pmv-ash)	Sig. (significance value)
pmv	0.860	306	0.873	1.104	0.000
ash	1.967	306	0.690		

3.4 Comfortable temperature

Assuming occupants will feel comfortable when "ash" is between "1" and "-1", then logistic regression model of "probability of feel comfortable" and "indoor air temperature" for this study is listed as equation (3).

$$\mathrm{Log}\ \{(p/1-p)\} = 1.827 - 0.013 ta\_m \qquad (3)$$

If 80% occupants in one certain thermal environment feel comfortable, this kind of environment will be acceptable in terms of thermal requirements. In the Equation (3), when ta_m is 33.9℃, the "p" will get 0.8. Hence it means the maximum of comfortable temperature in summer is 33.9℃ for this studying city. It is much higher than the static acceptable temperature defined by ASHRAE. In this study, the outdoor average temperature is 33.4℃, then some comfortable temperatures can be drawn through other researchers' adaptation models (31.6℃ using Netherlands' model, van

Der Linder et al, 2006; 29.82℃ using Nicol's model, 2007; 29.48℃ using McCartney's model, 2002). All this temperatures are all lower than 33.9℃.

Because all the data only came from summer, the minimum of comfortable temperature has not been founded in this study.

3. 5 Behavioral adjustments

Although occupants will decrease their clothing as temperature increases (Table 3), the regression coefficients are very small. Because all the occupants stay at home and get most freedom to change their clothing, the average cloth value is only 0.23 which is lower than 0.5. This gives occupants more opportunities to adapt to hot environments.

Table 3: correlation of cloth value and temperature

	Regression equation	r (correlation coefficient)	Sig. (significance value)
Clo—Ta_m	Clo=0.0426 -0.006T	0.132	0.021
Clo—et	Non-significant		
Clo—dayav_ta	Clo=0.542-0.010T	0.227	0.000
Clo—dayav_et	Clo=0.553-0.010T	0.234	0.000

Metabolic rate also gets reduced in hot environments. But it is only has significant relationship with outdoor temperature (Table 4).

Table 4: correlation of metabolic rate and temperature

	Regression equation	r	Sig.
Met—Ta_m	Non-significant		
Met—et	Non-significant		
Met—dayav_ta	Met =3.25-0.062T	0.242	0.000
Met—dayav_et	Met =3.215-0.060T	0.236	0.000

18 kinds of behaviors' impacts on thermal sensation are also analyzed in this study. Through multiple linear regression of thermal sensation and environmental factors, 9 significant correlative factors have been found (Table 5). It is surprise that "temperature" is not a significant factor for real thermal sensation, while "thermal expectation" is the most significant one.

Through regression analysis of "pmv-ash" (discrepancy of real thermal sensation and calculated thermal sensation) and environmental factors, it shows the behavioral adjustments have significant impacts on occupants' adaptive ability. If there is more behavioral adjustments, the occupant will have higher adaptive ability (Table 6). However, more theoretical interpretation for this correlation is in great need in further work.

Table 5: significant correlative factors on "ash"

	coefficients	r	r^2
(Constant)	-.157		
Thermal expectation	.513	.615	.378
Met	.314	.632	.399
PCEF16	-.177	.645	.416
PCEF12	.156	.656	.430
Duration in home (STIAV)	.020	.667	.445
PCEF7	.111	.677	.458
Vel	-.489	.688	.473
PCEF9	-.149	.696	.484
PCEF4	-.104	.704	.496
Gender	.181	.711	.505

Table 6: Regression analysis of adaptive ability with significant factors

pmv-ash	Sample size	r^2	Significant factors					
all	306	0.521	Constant	TA_M	EX	RH	PCEF7	STIAV
			-11.214	0.395	-0.507	0.017	-0.084	-0.032
pmv-ash<0	44	0.81	Constant	TA_M	EX	PCEF9	PCEF 15	STIAV
			-0.836	0.258	0.405	0.547	0.134	0.027
0<pmv-ash<=1	89	0.307	Constant	PCEF3	VEL_M			
			1.197	0.150	0.312			
1<pmv-ash<=2	111	0.255	Constant	PCEF 15	STIAV	PCEF7	TA_M	
			0.238	0.09	0.017	0.076	0.047	
pmv-ash>2	62	0.372	Constant	VEL_M	CLO	PCEF5	PCEF 16	PCEF 10
			0.130	0.973	1.253	0.232	0.117	0.096

Although the adaptive behaviors affect occupants' thermal sensation, the significant factors are various from different groups. So it is hard to explain the behaviors' impacts in details now and further investigation is needed.

4. CONCLUSIONS

- Real thermal sensation is significantly different from calculated thermal sensation because of occupants' adaptation.
- Air temperature, thermal expectation, and humidity show significant impacts on thermal adaptation for whole data. This result is consistent with previous research. "behavioral adaptation" can be explained by cloth value and metabolic rate ; psychological adaptation can be explained by "expectation".
- Behavioral factors have significant impacts on adaptive ability, especially for high degree of adaptation ability.

5. LIMITATIONS

Although some relationship between thermal sensation and behavioral adjustment can be found, these numerical correlations can not be fully interpreted theoretically until now.

Another limitation of this study is the lack of other seasons' data. This could be a main reason for the non-significant regression between thermal sensation with indoor and outdoor climate comparing other researchers' work. The author is planning to launch investigation in the next winter.

In addition, adaptive behavior selection and classification require further research.

ACKNOWLEDGE

I would show my appreciation for the financial support of the Chinese University of Hong Kong. I am also grateful to Prof. CHAN Ying Keung's help on the statistic analysis and Prof. TSOU Jin Yeu's suggestions for this study. Students coming from Wuhan University and Huazhong Agriculture University made a lot of efforts during the field survey.

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