Research on the effect of air velocity on thermal comfort based on the ramp changing transient environment

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ABSTRACT

By simulating 'the ramp change of thermal environment' in the laboratory, we carried out the thermal comfort experiment and observed the changes of subjects' thermal reaction to the ramp change. We compared the effect of air velocity on the change of subjects' thermal reaction under different conditions, and discuss the improving effect on thermal comfort by reinforcing indoor air velocity. Combined with the research under stable environment, we present the way to set the environmental parameters of short-term staying location in summer.

INDEX TERMS

Transient environment; Ramp change; Thermal comfort; Air velocity

INTRODUCTION

The research on human thermal reaction under transient environment gradually arouses the attention of HVAC researchers. Indoor environment influenced by outdoor environment and adjustment of air condition is mostly in the transient state. Transient environments have various forms including environmental parameters that occur during ramp change, gradual change or periodic change. Different change forms can also cause different influences of human thermal comfort. It is significant to explore the change rule of thermal reaction under transient environment for improving the environmental thermal comfortable condition and extending energy saving.

Under transient environment, the thermal reaction of the human body is so complex that the research in this field relies on the analysis of the experimental phenomenon mainly. The researches under ramp change have obtained certain accomplishments. Gagge and others carried out laboratory research in which they make subjects came through different environmental changes: the neutral environment to the hot environment, or the hot environment to the neutral environment. The result shows: in the change from neutral to hot environment the relation of the thermal sensation corresponding to the skin temperature (T_{sk}) and the skin wetness (W) is similar to that under steady state. But from hot to neutral environment conversely the thermal sensation gets to neutral while T_{sk} and W are still changing to the neutral area. Gagge explains it as: the change rate of T_{sk} creates an 'additional' thermal sensation and this thermal sensation covers the uncomfortable sensation aroused by the higher T_{sk}, so thermal sensation changes in 'advance' to T_{sk}. This phenomenon that the change

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of thermal sensation from uncomfortable to comfortable environment is quicker is helpful for the human body to bear the fluctuation of environmental temperature. This law is significant for the setting of the parameters of temporary locations (such as subway location where passengers experienced the ramp change of thermal environment) because the difference between the indoor and outdoor environments can ensure comfort in the residence.

In the research of steady environment, we have discovered that properly raising air movement of the environment with higher temperature and humidity can make a resident feel neutral and save energy. But because residents' long-term staying in high air velocity would be uncomfortable, the method is limited in the locations where people stay for long periods. But air movement is more endurable to those people who have a short-term stay. So we can think of raising the air velocity in such locations to improve comfortable living conditions to save energy compared with reducing air temperature.

But in the experiments done in the past the neutral environment was always produced by lower air temperature and lower air velocity. So it is worthwhile to research and discuss the change law when people come from a hot environment to the neutral environment with higher air velocity. The laboratory research was carried in Tianjin University in which we had students as subjects and simulated the ramp change of environment.

TEST DESIGN

Subjects

About 100 subjects of this experiment were students in Tianjin University who had an average age of 21 years, 62.3 kg average weight, and 170.4 cm average height. The subjects were asked to be healthy, have good sleep as well as food before attending the experiment, and drink no alcoholic beverage. The subjects were instructed to dress in cotton T-shirt and trousers with ankle socks and slippers in feet, the summer standard dress. The 'Clo' value is about 0.5.

Thermal Environment

The tests were conducted in the environmental test room of dimension 5 m by 4.5 m by 3 m. Air temperature and humidity in the test room was maintained to a certain value by an air conditioning system. The ceiling fan was mounted on the middle of the ceiling to improve indoor air movement and produce different air velocities at different locations.

The detectors of a temperature–humidity instrument (automatically checking) were set at 60 and 140 cm height of test room to monitor indoor air temperature and humidity. Ten fixed seats were set for the subjects. Air velocity at 110 cm height above the floor at these seats was measured by a portable anemometer TSI. Although it was agreed that the velocity at the location other than 110 cm are important, air movement over the upper part of the body has the greatest effect on thermal comfort. For the lack of a more reliable method of determining an appropriate average air velocity, the single 110 cm high velocity was used. Because the test room is in a building, environmental radiation temperature is considered to equal the air temperature.

Test Process

Each subject was allowed to experience the ramp change of environment and was asked to vote for his thermal sensation in time in the test. The subjects arrived in the laboratory at the scheduled time. Before entering the test room, the subjects walked for about 5 min in normal speed led by the test assistant. Then they entered the test room quickly and sat on the seats arranged in advance for 30 min. They fill out questionnaires, respectively, at the end of the outdoor walk and at 0, 3, 6, 15 and 30 min after entering the test room. The questionnaire is concerned mainly with the thermal sensation and thermal comfort of subjects. The seven-level thermal sensation indices of ASHRAE (+3 hot; +2 warm; +1 slightly warm; 0 is neutral; –1 slightly cool; –2 cool; –3 cold) along with the four-level thermal comfort indexes (–3 very uncomfortable; –2 uncomfortable; –1 slightly uncomfortable; 0 comfortable) were used to record the thermal reaction of subjects.

RESULTS

Test Condition

The relative humidity in test room was maintained around 70%, and air temperature maintained between 27 and 30°C. In the test course, the temperature and relative humidity of the measuring point were recorded every 10 min. Then the mean values of temperature and relative humidity of all these points were taken as the parameters of the test room. Table 1 lists the values of each test. The velocity of each seat was recorded every 5 s in 2 min and the average taken. In the test room, ten seats were divided into four kinds according to the average velocity, see Table2.

Table 1 Temperature and relative humidity of test room

Temperature (°C)	26.6	27.3	28.3	28.7	29.5	29.6
Relative humidity (%)	63.4	67.1	68.8	67.8	74.1	68.8

Table 2 Distribution of indoor air velocity

Location	1	2	3	4	5	6	7	8	9	10
Average speed (m/s)	1.10	1.06	0.83	0.78	0.69	0.39	0.36	0.33	0.22	0.12
Classification	1.08		0.79			0.36			0.17	

Analysis

Subjects experienced a ramp change of environment when they walked from outdoor to indoor. The two environments affected their sensation. Statistical analysis was done on their questionnaires to obtain the law of TSV (Thermal Sensation Vote) and TCV (Thermal Comfort Vote) change under ramp change.

Conclusion under stable environment

We have got the conclusion about the effect of air movement on thermal comfort under stable state in the last phases. To compare with this test, we induct it here. In research, we adopted the SET* (Standard Effective Temperature) index introduced by Gagge to evaluate environment. The conclusion is: SET* = 26.3°C when TSV = 0(neutral state); SET* = 25.6°C when the absolute value of TCV is lowest (most comfortable).

Evaluate environment

The temperature, humidity, air movement and solar radiation outdoor can all affect subjects' sensation, but limited by experimental conditions it is difficult to accurately measure some parameters such as radiation temperature and calculate outdoor SET*. According to the subjects' TSV and TCV, which is a result of outdoor environment, the outdoor environment was divided into two species: subjects felt hot and uncomfortable, namely the span of TSV is from 2 (warm) to 3 (hot) and the span of TCV is from –1.5 to –3 when the outdoor air temperature is high and solar radiation is strong; on the other hand, subjects felt slightly warm and relative comfortable, namely TSV is under 2 and the span of TCV is from –1.5 to 0 when the outdoor air temperature is moderate and there maybe certain air movement.

By measuring indoor air temperature, relative humidity and average velocity of every seat, we can calculate the SET* of every seat to evaluate the subjects' environment after they come in test room.

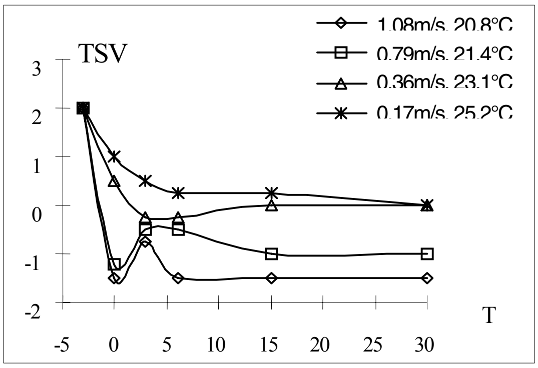

Figure 1 TSV change at 26.6°C/ 63.4 %.

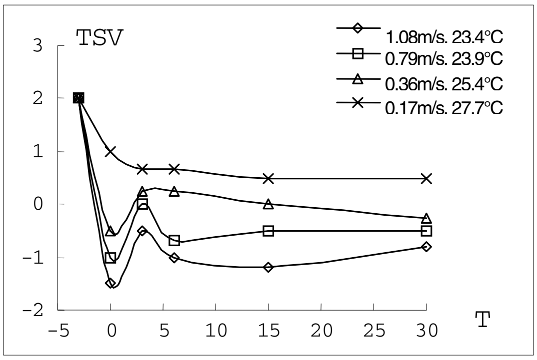

Figure 2 TSV change at 28.3°C/68.8 %.

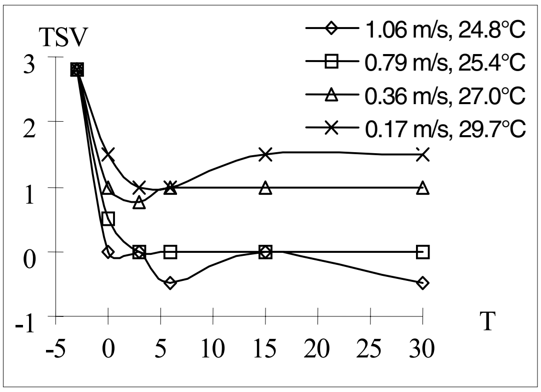

Figure 3 TSV change at 29.5°C/74.1%.

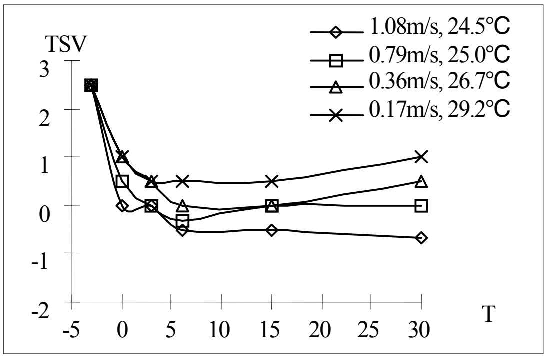

Figure 4 TSV change at29.7°C/68.8 %.

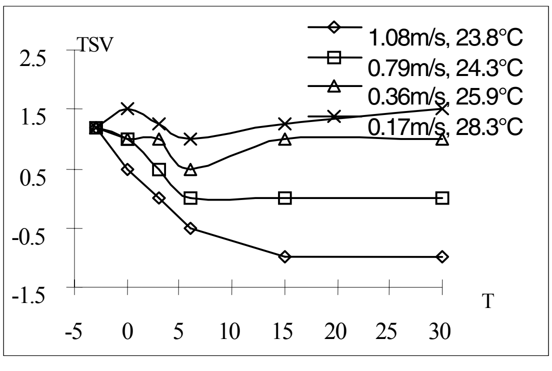

Figure 5 TSV change at 28.7°C/67.8 %.

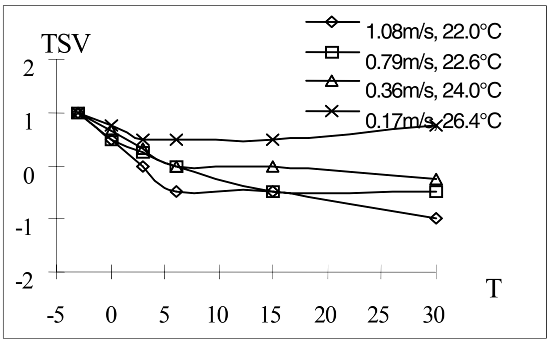

Figure 6 TSV change at 27.3°/67.1 %.

Change of thermal sensation

The subjects' TSV varying with time after they come into the test room are recorded in Figures 1–6. The temperature marked in the figures is SET* of the four kinds of seats in the test room. We take the locations SET* = 25–26°C as neutral environment, according to the conclusion we got in the thermal comfort experiment under stable condition.

We can see how subjects' sensation varied with time after the subjects entered the test room from the first kind of outdoor condition (hot environment) in Figures 1–4. In the first six minutes, TSV falls quickly, then it tends to smooth. At the location of relatively high velocity (1.08 m/s, 0.79 m/s) where there is an obvious difference in SET* between the inside and outside the subjects' thermal sensations fall more quickly at first and have a little recovery, and then tend to a gently fall. The reason is that when the subject went in, the drop of air temperature causes a drop in sensation; at the same time, because the hot outdoor environment make body sweating greater, the air movement indoor quickens sweat evaporation and reduces skin wetness, and thus accelerates the drop of thermal sensation as subjects enter the test room. Compared with those, at the locations of relatively low velocity (0.36 m/s, 0.17 m/s), only a drop in temperature makes subjects' thermal sensation drop once they enter the test room, then the sensation tends towards steady state.

We can see how subjects' sensation varied with time when they went from the second kind of condition (slight warm environment) in Figures 5 and 6. We can find out the change of thermal sensation is not as obvious and quick as that in the first condition. The reason is that there is no distinct temperature difference and also not too much perspiration on the skin when the subject is in more moderate state before entry. For the location of higher velocity, its SET* is lower than outdoor, so the skin wetness reduces gradually under air movement and thermal sensation also reduces• but the dropping speed is lower than in the first condition. And for the location of lower velocity, its SET* is close to or higher than that of outdoor, so thermal sensation may increase gradually after subjects enter indoor.

Therefore from the comparison of two conditions we can see that the sensation of the subjects who came from hot outdoor dropped and reached steady value more quickly than others, and the air movements have obvious effect on the drop of thermal sensation.

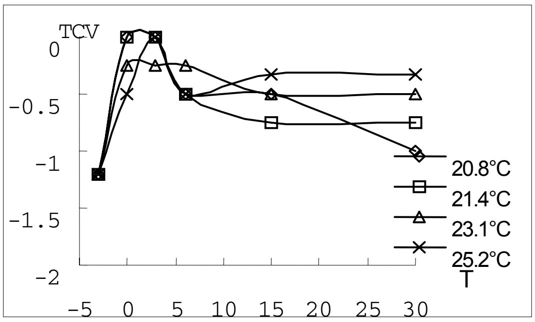

Figure 7 TCV change at 26.6°C/63.4%.

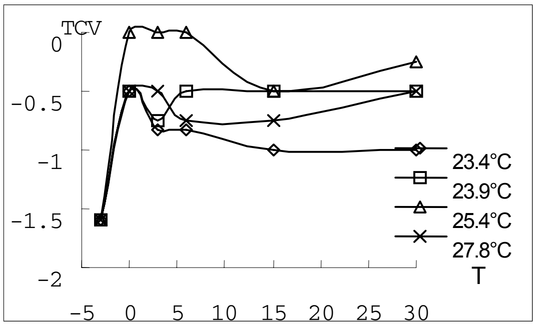

Figure 8 TCV change at 28.3°C/68.8%.

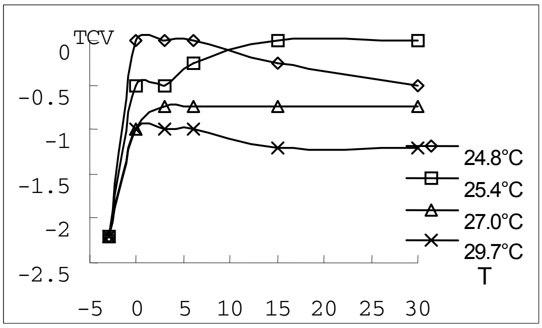

Figure 9 TCV change at 29.5°C/74.17%.

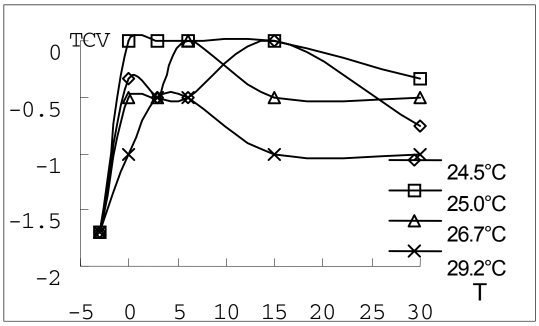

Figure 10 TCV change at 29.6°C/68.8%.

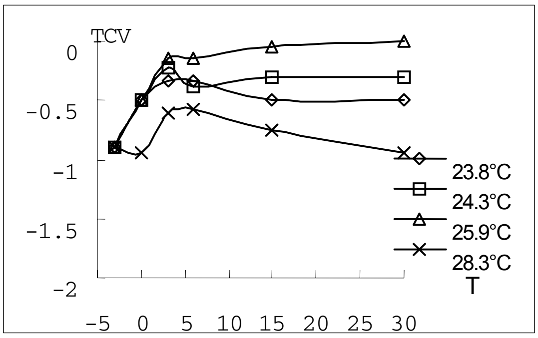

Figure 11 TCV change at 28.7°C/67.8%.

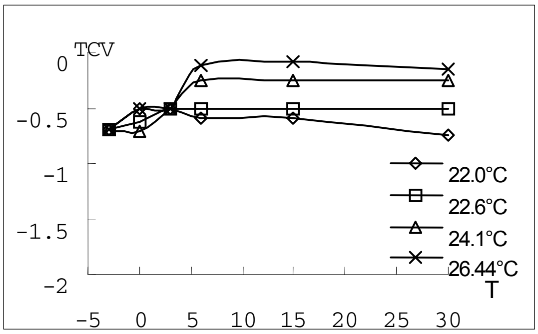

Figure 12 TCV change at 27.3°C/67.1%.

Change of thermal comfort

Figures 7–10 show the thermal comfort change of subjects who enters the test room from the first kind of outdoor environment. Before entering, subjects are in a hotter environment of relatively higher temperature and in uncomfortable environment on the whole. After entering, the change of their TCV is related to the location's SET*. For the subjects who are at the location with SET* under 25°C, their TCV change from a comfortable scope (0 to –1.5) to a more uncomfortable scope (–1.5 to –3). So when a subject went into a cooler environment from hot environment, he felt comfortable at first. But he felt uncomfortable because of environmental over-cooling with too long a stay. For the subjects at the location of higher SET* when just entering, their TCV is in the comfortable scope (0 to –1), then the absolute value of TCV increased gradually. The initial value is low because the temperature difference between outdoor and indoor and sweat evaporating all can reduce thermal sensation and lyses the uncomfortable feeling.

Figures 11 and 12 record the thermal comfort change of the subjects entering from the second kind of environment. The change is relatively gentle. The subjects at the location of high or low SET* felt uncomfortable gradually in the test room. But at the location where SET* is in the neutral area under stable state, the subjects felt comfortable all the time.

Thermal comfort area

For the first kind of outdoor environment, we can see from the group of pictures of thermal sensation (Figures 1–4) that thermal sensation is in the neutral area for SET* = (25°C, 26°C). At the same time, from the group picture of thermal comfort change (Figures 7–10), we can see that the subjects' TCV is in 0–0.5, namely the subjects feel comfortable. Therefore it can be thought that when SET* is in the above area, the environment is acceptable to the subjects. And this area coincides with the thermal comfort area under stable state (SET*|TSV = 0 = 26.3°C • SET*|TCVmin = 25.6°C).

For the second kind of outdoor environment, the subjects' thermal sensation and comfort change slowly after they enter indoors. So for this situation if indoor environment is maintained neutral or slightly cool, subjects would accept it.

In general, we can deem that subjects undergoing the ramp change of environment feel relatively comfortable if the SET* of the indoor environment is in the area of thermal comfort under stable state. Reducing air temperature or raising air velocity to make indoor SET* in comfort scope are all useful.

CONCLUSIONS

1. Reach the change law of thermal sensation under different ramp change.

   The environment before ramp change would effect the thermal sensation of subjects to the environment after ramp change. From hot environment to neutral or slighter cool environment, thermal sensation drops quickly to the value under stable state. But from neutral environment to similar or hotter environment, thermal sensation changes slowly.
2. The cooling effect of air movement is more obvious when people come from hot environment.

   Under ramp change of environment, not only temperature difference can quicken the change of thermal sensation and thermal comfort, but also air movement can make them change, especially when skin wetness is relatively high. It is the law according to which we can improve residence's thermal comfort by improving air movement in the short-term staying location in summer.
3. Get the scope of SET* that satisfies resident's thermal comfort requirement under ramp change.

   After subjects entering from hot environment to the location of SET* = 25–26°C, their TSV is in the neutral area and TCV is close to zero. Furthermore, subjects feel comfort before their thermal sensation drops to moderate, namely the change of thermal sensation is quicker than thermal comfort.

From the above observations we can conclude that if indoor air temperature is no higher than outdoor (2°C lower is better) and SET* is in the scope of 25–26°C, people would feel comfortable when people come from outdoor (hot or warm). As we know, the value of SET* is determined by air temperature and air velocity. So we can strengthen indoor air movement instead of decreasing temperature to improve indoor thermal comfortable condition. It is significant to define environmental parameters of the short-term staying location.

In the stable thermal comfortable experiment, we found subjects can stand air velocity no more than 0.8 m/s. For the sake of security, we take 0.8 m/s as the upper limit of air velocity. As relative humidity are in 60–70%, SET* in 25–26°C, air temperature can get to be 30°C which is 4°C higher than the design value 26°C of a common air-conditioned room which is recommended by the Design Handbook. Thus, by economizing the capacity of air-condition equipment and cutting equipment run time, energy is saved.

It is noticeable that the setting value of indoor environmental parameters should change with outdoors because residents’ thermal reaction depends on the difference between indoors and outdoors. Indoor air temperature and air velocity should be higher when outdoor air temperature is high, while indoor air temperature and air velocity should be lower when outdoor air temperature is low. In common air condition the indoor air temperature is a control object. But in short-term staying location, we can take ‘SET* = 25–26°C’ and ‘•T = Toutdoor – Tindoor = 2°C’ as control object so that we can adjust air condition more efficiently.

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