EFFECTS OF NON-ISOTHERMAL AND INTERMITTENT AIR MOVEMENT ON HUMAN THERMAL RESPONSES

Zhao Rong-yi , Xia Yi-zai

Dept. of Thermal Engineering, Tsinghua University, Beijing

ABSTRACT

Twenty-four college students are asked about their subjective responses to a dynamic thermal environment with non-isothermal and intermittent air movement. The subjects wear an uniform of 0.6 clo and are sedentary. A rotative air jet can cyclically sweep over the subjects with adjustable air velocity. Each experiment lasts 150 minutes and is performed with three stages. Changing pattern of TSV and TCV over time, the effects of the frequency of the rotative jet on human's thermal sensation and thermal comfort, and the relation between the rotative frequency of the air jet and the velocity sensed by the subjects are studied. Non-isothermal and intermittent cool jet improves the subjects' thermal conditions significantly and increased their acceptance of the thermal environment. The subjects respond immediately to the temperature step-change, and as time passes by, the sensitivity to the cool air is diminishing. The sensed velocities are variable at different rotative speeds of the outlet. Under different air temperature conditions, the preferred speed of rotation is varied.

KEYWORDS

thermal comfort, air movement, intermittent, non-isothermal

INTRODUCTION

To provide a healthy and acceptable thermal environment with minimized energy consumption and environment pollution is valuable for developing countries, especially for those located in tropic and subtropic areas. Although the use of air conditioning could improve the indoor climate by maintaining the room temperature lower(e.g. 24℃--26℃), more complaints come from "non-adaptability of air conditioning". For this reason, a series of experimental studies on human responses to higher room air temperature with non-isothermal and intermittent air movement has been conducted.

Air movement is one of the main variables affecting human thermal responses. Air movement can provide thermal comfort and freshness in hot conditions. At environmental temperatures up to 30℃, the heat balance of the human body can be maintained efficiently by an increased heat loss caused by forced convection with isothermal airflow. Experiments performed by Burton et al. (1975) , Rohles et al. (1983) and Scheatzle et al. (1989) showed that a ceiling fan providing air movement with a velocity up to 1 m/s may extend the upper limit of the summer comfort zone from 26℃ to 29℃.

When the temperature of indoor environment is higher than 30℃, a reduction of heat stress can be achieved by cool air jets. Some experiments made by Azer and Nevins (1974), Melikov et al (1994) showed that the convective spot-cooling can decrease the physiological and subjective thermal stresses of the subjects participating in the experiments and increase the acceptability of the thermal environment. These studies provided useful information about the effect of local cooling by a "still" air jet at room air temperatures of more than 30℃. But what's the human responses when their whole bodies are exposed to the cool air provided by a rotative air jet, which creates a dynamic velocity and temperature fields? In the present study, some experiments are carried out to investigate the effects of this kind of non-isothermal and intermittent air jet to the thermal sensation and thermal acceptance of the subjects .

The experiments contain the following aspects:

1. the transient and mean thermal sensation and thermal comfort over time.
2. the effects of the frequency of the rotative jet on human's thermal sensation and thermal comfort.
3. the relation between the rotative frequency of the air jet and the velocity

sensed by the subjects.

METHOD

Experimental Facilities

Climatic Chamber: The experiments are conducted in an environmental chamber with dimensions of 3.4m by 4.8m by 3m at Tsinghua University. The air is supplied uniformly from the ceiling with a velocity of less than 0.1m/s. The wall temperature is very close to the room air temperature.

Cooling System: An air conditioning unit with heater and cooler is installed to provide the cool air having a certain temperature. A rotary cylindroid terminal with a slotted outlet (width=20) is specially designed to generate the air jet different from the room temperature. The cool air is supplied to the terminal which is drived by an electric motor so that rotative speed could be changed. Therefore, a dynamic temperature and velocity field changed cyclically with the rotative speed of the terminal is then created.

Measurement: The measuring and control system of the climatic chamber is based on the thermal resistance sensors for measuring temperatures of the room air and the six wall surfaces. These data are logged by a data acquisition unit at one-minute intervals. The characteristics of the cooling jets and air flow over the subjects are measured by thermal couples and hot-bulb anemometer. The data are logged at 0.5 second interval and stored in a computer.

Subjects and Clothing

24 college students of Tsinghua University are asked to be the subjects and paid for participating. Each subject is exposed to only one thermal environment for two hours. The anthropometric data for the subjects are listed in table 1.

Table 1 Anthropometric data for the subjects

Sex	Number of subjects	Age (year)	Height (m)	Weight (kg)	Du Bois Area (m^2)
Females	4	19.89±0.76	1.61±0.06	53.50±5.23	1.55±0.05
Males	20	19.44±0.89	1.69±0.05	58.22±6.65	1.66±0.11
Females and Males	24	19.50±0.86	1.68±0.06	57.69±6.43	1.65±0.10

The subjects are instructed to arrive at the climate chamber wearing shoes, socks, trousers, underwear and long-sleeved shirt. For this ensemble, the thermal insulation is about 0.6 clo. During all experiments, the subjects are sedentary. They can chat and do some reading but cannot stand up and walk around.

Experimental Procedure

All experiments were done in November and December,1997. The subjects reported 5 minutes prior to commencing the experiment, and it is ascertained that they do not feel sick. They change clothes for the hot environment for about half an hour in the climate chamber where the air temperature is 32.5℃. At the same time, they are trained the subjective rating scales and the experimental procedure.

Two subjects are arranged to take part in the experiment at the same time. They sit with broadside opposite to the outlet. The distances between the two subjects and the outlet are 0.7m and 1m respectively.

Every experiment is divided into three stages. In the first stage, every other 13 minutes, subjects are asked to write down on the questionnaire their "mean votes" of thermal sensation and thermal comfort which indicate subjects' general evaluation to the thermal environment with non-isothermal and intermittent air movement. Then they are asked to trace their "transient feelings" of thermal sensation and thermal comfort during the two periods of the terminal's rotation. At the end of this stage, the subjects fill in the table in the questionnaire (Fig 1).

In the second stage, the rotative speed of the outlet is changed by a litter knob beside the subjects. The rotary speeds were 3.4 rpm, 4.8 rpm, 6.8rpm and 10.9 rpm respectively. At each speed, the subjects write down the "mean votes" of thermal sensation and thermal comfort, then plot out their transient feeling --thermal sensation vote (TSV) and thermal comfort vote(TCV)-- versus time.

Because the different rotative speed of

the outlet will cause the different "sweeping time" of the air jet upon the human body, the mean velocity sensed by the subjects will also be different. As the limitation of the measuring instrument, it is unable to measure the changing velocity field at the position the subjects sit precisely. So in this experiment, the description of the velocity is based on that sensed by the subjects, and a "sensed velocity" is defined. When the maximum velocity sensed by the subjects while the outlet is rotating is almost equal to the one sensed by the subjects while the outlet is standstill towards the subjects, the latter velocity is measured and regarded as the "sensed velocity" when the outlet is rotating at a certain speed. This is done in the third stage of the experiment.

Fig.1 shows the questionnaire including rating scales used by the subjects during the experiment.

Fig. 1 Questionnaire for subjective survey of thermal environment (every 13 minutes)

Rating scale of thermal sensation and thermal comfort			
TSV		TCV	
+3	hot		
+2	warm	0	comfortable
+1	slightly warm	1	slightly uncomfortable
0	neutral	2	uncomfortable
-1	slight cool	3	very uncomfortable
-2	cool	4	intolerable
-3	cold		

Vote for the mean TSV and TCV and plot out your transient feelings of thermal sensation and thermal comfort during two periods of the terminal's rotation.

Fill in the table to assess the thermal environment.

Can you accept this thermal environment? yes or no	what do you think of the temperature of cool air? ok or high or low	What do you think of the velocity of the jet? ok or high or low

RESULTS

Table 2 lists the experimental conditions in the first stage of the experiment. Fig.2 and 3 show the transient TSV during the two rotative periods of the outlet at different testing time. The subjects respond to the temperature step-change quickly when they are exposed to the cool air. However, when the cool air leaves the subjects, the values of TSV rise slowly to the maximum as the cool air is about to come again. Furthermore, with the time goes on, the maximum of TSV corresponding with the time will decrease in different time period, while the minimum of TSV does not evidently change. So the change of difference between the maximum and minimum of TSV could be explained by the adaptation of the subjects to this kind of thermal environment. The longer the subjects are exposed to the intermittent cool air, the smaller the TSV difference is, and the more satisfactory the subjects feel.

Table 2 Experimental conditions

Exposure time	80 minutes	
Clothing	0.6 clo	
Activity	1 met (sedentary)	
Mean radiant temperature	=Air temperature	
	Condition A	Condition B
Ta (℃)	32	32.5
Tj (℃)	21.2	21.2
L (m)	1.0	0.7
Tjt (℃)	29.4	29.5
F (rpm)	4.8	4.8
Vjt (m/s)	1.5	1.7
Vs (m/s)	0.81	0.91

Fig. 4 shows the ratio of the TSV values voted 2 seconds after the subjects are exposed to the cool air to the maximum of TSV at different time. It is noticed that the ratio is gradually increased from 15 minutes to 80 minutes, and the cool effect is reducing with the time goes by.

In Fig. 5, the mean TSV has been plotted as a function of time. It can be seen that the TSV values tend to be constant after 67 minutes in two conditions. After 80 minutes, the mean general TSV seems to be constant(A-- 0.54 ; B--0.57), which shows that non-isothermal and intermittent cool air can improve the subjects' thermal conditions significantly and increases their acceptance of the thermal environment.

The change of TCV values connects with TSV tightly. When the least value of TSV is greater than zero, the minimum of TCV will appear at the moment the subjects are exposed to the cool air. But when the least value of TSV is smaller than zero, it is deemed that the most comfortable moment will appear at 2 seconds after being swept when TSV value is between 0 and 0.3.

Fig. 6 and 7 show the relationship between TSV and the rotative speed of the outlet in two periods in two experimental conditions. With the increase of the frequency, the effect of the cool air diminishes because of the abatements of the velocity and "sweeping time" of the air jet over the subjects. But at the same time, the increased frequency offsets a certain diminution. So with the interaction of the two sides, different rotative speed is preferred in different thermal conditions. It can be seen in Fig. 8 that 3.4 rpm is preferred in condition A, and 6.8 rpm in condition B.

Table 3 lists the velocities sensed by the subjects at different rotative speeds of the outlet. Standard deviations are also listed in parentheses.

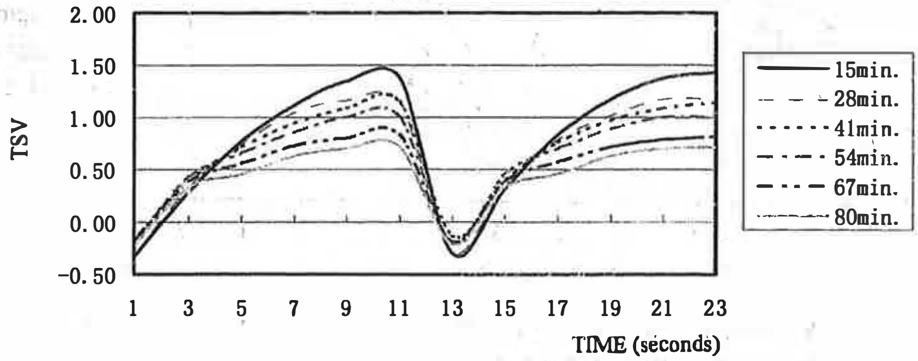

Fig. 2 TSV during two rotative periods of the outlet at different testing time in experimental condition A.

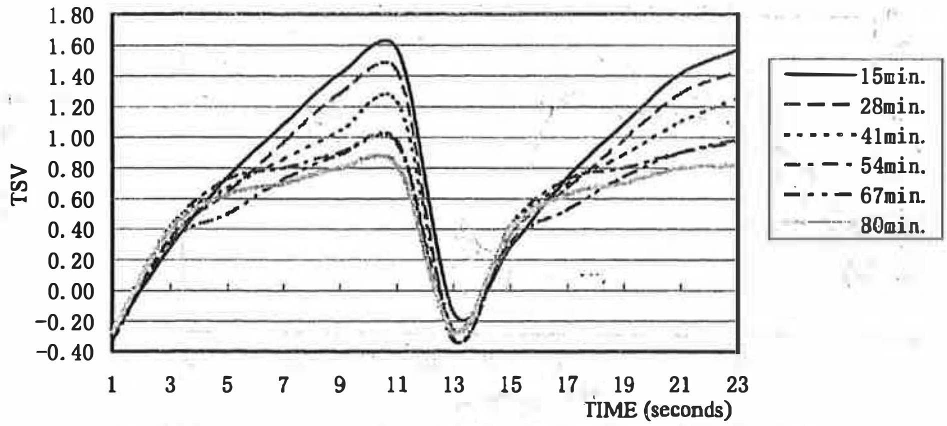

Fig. 3 TSV during two rotative periods of the outlet at different testing time in experimental condition B.

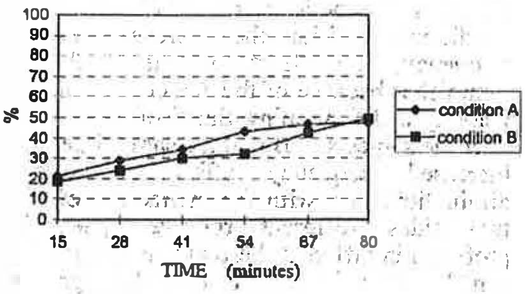

Fig. 4 The ratio of TSV values voted 2 seconds after the subjects are exposed to the cool air to the peak one at different time.

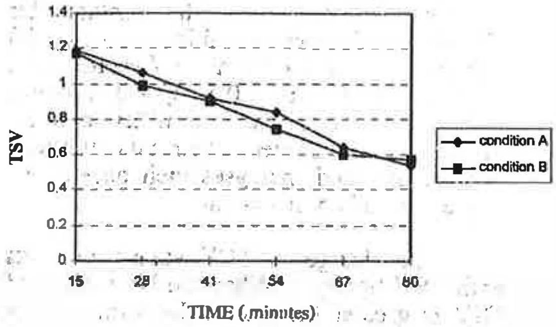

Fig. 5 The mean TSV in two conditions over time.

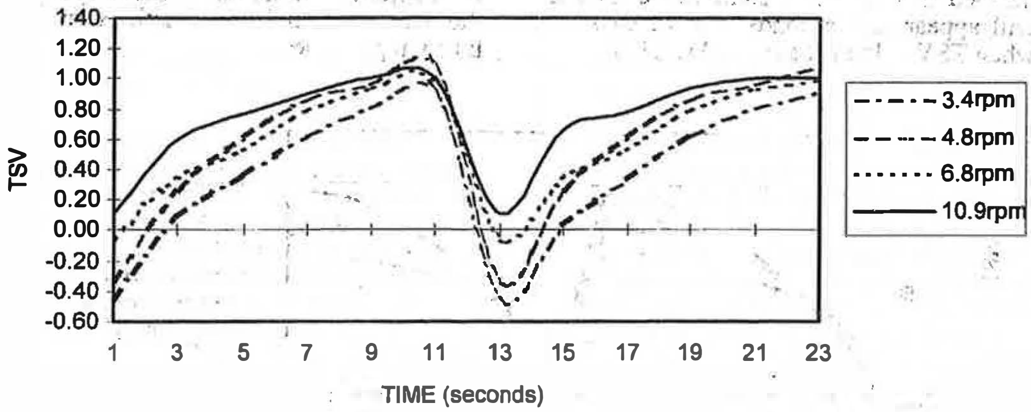

Fig. 6 TSV during the two rotative periods of the outlet at the different rotative speeds in experimental condition A.

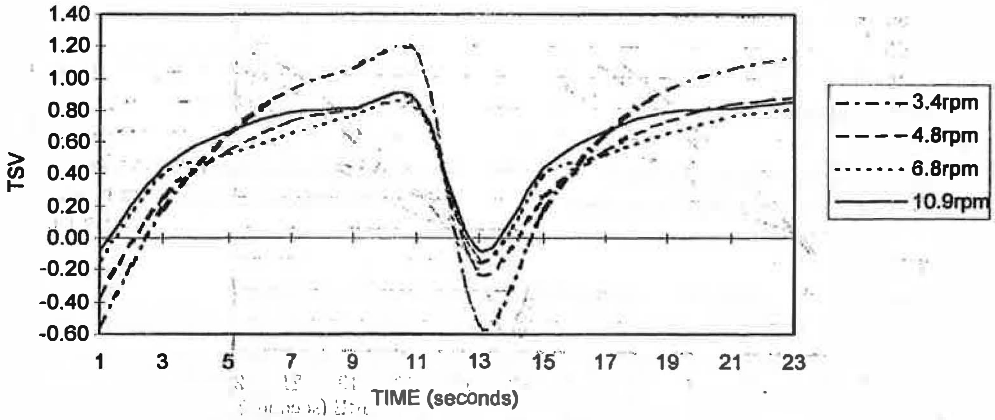

Fig. 7 TSV during the two rotative periods of the outlet at the different rotative speeds in experimental condition B.

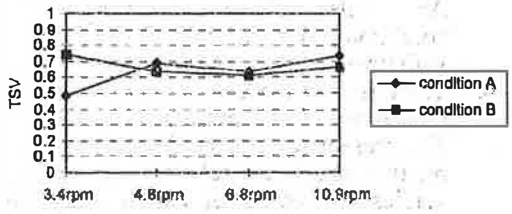

Fig. 8 Mean TSV at different rotative speeds in two experimental conditions.

Table 3 Velocities sensed by the subjects at different rotative speeds of the outlet.

frequency \ Vjt	1.5m/s	1.7m/s
3.4rpm	0.99 (0.195)	1.09 (0.122)
4.8rpm	0.81 (0.217)	0.91 (0.106)
6.8rpm	0.58 (0.121)	0.79 (0.104)
10.9rpm	0.45 (0.198)	0.55 (0.154)

DISCUSSION

Fig. 9 and 10 show the comparison of the measured TSV at 15 and 80 minutes and Fanger's PMV in two experimental conditions. PMV1 is much higher than the peak value of TSV, which indicates the cool air cuts down the human body's heat stress, and improves the subjects' thermal conditions significantly. PMV2 is also greater than the minimum of measured TSV, which can be explained by the overshoot happened when human body is exposed to temperature step. PMV1 and PMV2 correspond to the conditions of (Ta = constant, Vs = 0) and (Tjt = constant, Vs = constant) respectively.

Table 4 indicates the appraisal to the thermal environment after experiencing for 80 minutes. In the two experimental conditions, almost no one complains the low temperature of the cool air jet. According to Fanger's (1988) definition of draught that is an unwanted local cooling of the human body caused by air movement, there is no complaint about draught.

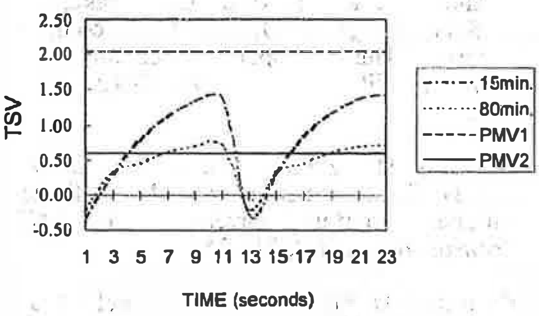

Fig.9 Comparison of the measured TSV at 15 and 80 minutes and Fanger's PMV in condition A.

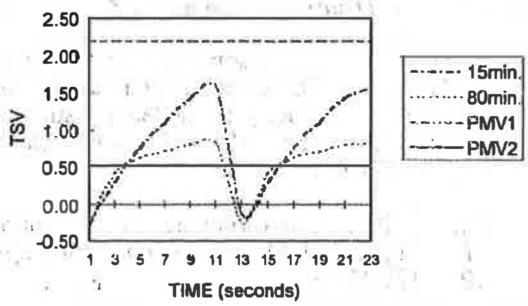

Fig. 10 Comparion of the measured TSV at 15 and 80 minutes and Fanger's PMV in condition B.

Table 4 Appraisal to the thermal environment

	Can you accept this thermal environment?		what do you think of the temperature of cool air?			What do you think of the velocity of the jet?		
	Yes	No	OK	High	Low	OK	High	Low
condition A	87.5%	12.5%	50%	50%	none	37.5%	12.5%	50%
condition B	75%	25%	62.5	37.5%	none	none	25%	75%

CONCLUSIONS

1. Non-isothermal and intermittent cool air jet can be used to improve the subjects' thermal conditions significantly and increase their acceptance of the thermal environment.
2. From the hot environment to the dynamic environment caused by the non-isothermal and intermittent cool jet, there is a course of adaptation during which the sensitivities to the cool air is diminishing, and the cool effect is reducing.
3. The sensed velocities are variable at different rotative speeds of the outlet. And under different air temperature conditions, the thermal sensation is varied with the speed of rotation.
4. There is no complaint about the draught caused by the intermittent cool jet.
5. The present study is performed with the relative humidity below 50%, further studies are recommended to study the effect of non-isothermal and intermittent cool jet in the muggy condition. Likewise, more thermal conditions are recommended for study as well.

NOMENCLATURE

TSV = thermal sensation vote (seven-point scale)
TCV = thermal comfort vote (five-point scale)
PMV = predicted mean vote (seven-point scale)
L = distance from the outlet (m)
F = rotative frequency of the outlet (rpm)
Ta = room air temperature (℃)
Tj = average air temperature at the outlet of the jet (℃)
Tjt = axial temperature of the air jet at the distance where it first meets the person(℃)
Vjt = axial velocity of the air jet at the distance where it first meets the person (m/s)
Vs = sensed velocity by the subjects; averaged for the pools of the subjects (m/s)

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