Indoor Air 2000; 10: 289–296
http://journals.munksgaard.dk/indoorair

Effects of Turbulent Air on Human Thermal Sensations in a Warm Isothermal Environment

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Abstract Air movement can provide desirable cooling in "warm" conditions, but it can also cause discomfort. This study focuses on the effects of turbulent air movements on human thermal sensations through investigating the preferred air velocity within the temperature range of 26°C and 30.5°C at two relative humidity levels of 35% and 65%. Subjects in an environmental chamber were allowed to adjust air movement as they liked while answering a series of questions about their thermal comfort and draft sensation. The results show that operative temperature, turbulent intensity and relative humidity have significant effects on preferred velocities, and that there is a wide variation among subjects in their thermal comfort votes. Most subjects can achieve thermal comfort under the experimental conditions after adjusting the air velocity as they like, except at the relative high temperature of 30.5°C. The results also indicate that turbulence may reduce draft risk in neutral-to-warm conditions. The annoying effect caused by the air pressure and its drying effect at higher velocities should not be ignored. A new model of Percentage Dissatisfied at Preferred Velocities (*PDV*) is presented to predict the percentage of feeling draft in warm isothermal conditions.

Key words Turbulent intensity; Air movement; Draft sensation; Thermal comfort; Preferred velocity; Isothermal.

Practical Implications
The mean value and its cumulative distribution of preferred velocity in the temperature range of 26°C and 30.5°C at relative humidity levels of 35% and 65%, and turbulent intensity of 25% and 40% can be a reference when we design indoor air movement around occupants. Turbulence can be used to reduce preferred velocity and draft feelings in a warm isothermal environment. A model of PDV was put forward to predict the annoying effect caused by air pressure and its drying effects at higher velocities/temperatures.

Received for review 29 December 1999. Accepted for publication 12 March 2000.

Introduction

Complaints about the cool air-conditioned environment and concerns of energy conservation have recently brought substantial attention to the issue of acceptable level of air movement in the office environment. Air movement is one of the most important factors to affect human thermal comfort and is also one of the simplest methods to improve thermal comfort at relatively high temperatures. The studies of its effects on human thermal responses are of great help when designing a building and operating the air-conditioning system. Some experiments (Rohles et al., 1974, 1983; Tanabe and Kimura, 1994; Arens et al., 1998) have shown that air movement, especially an occupant-controlled one, can provide comfort in "warm" conditions where the temperature is above 26°C. Under some circumstances, however, it may also cause undesired local cooling of human body, which is defined as draft (Fanger, 1986, 1988). Studying the impact of turbulent intensity on sensation of draft, Fanger (1988) concluded that airflow with high turbulence caused more complaints of draft than airflow with low turbulence at the same mean velocity and air temperature. A model of draft risk (PD) was presented, which could calculate percentage dissatisfied due to draft. According to the model, for a turbulence of 40%, typical of indoor office environments, air movement should be restricted to 0.12 m/s at 20°C and 0.2 m/s at 26°C at a 15% dissatisfied level. Current ISO standard 7730 also restricts allowable air movement to very low levels to ensure the avoidance of draft. Fountain's experiments (1994) studied the effects of turbulence on the preferred velocity in the temperature range of 25.5°C to 28.5°C, but no significant effects were found.

The random vortex motion in the turbulence, which induces the mixture of fluid micelle, can greatly enhance the dynamic heat transfer. Turbulent intensity,

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derived from the point of statistics, can be used to indicate the intensity of this mixing. Mayer (1984) even suggested that the convective heat transfer grows with increasing turbulence. This may explain why high turbulence was more uncomfortable in Fanger's experiments, in which subjects were situated in cool-to-neutral conditions. Logically, a hypothesis can be surrendered that high turbulence can relax the thermal discomfort in neutral-to-warm or warm environments. This study was designed and performed to test this assumption.

In general, the purpose of the present study is to examine human responses to air movement in "warm" isothermal environment. The specific objectives are to:

- Examine the risk of draft in the neutral-to-warm conditions.
- Investigate the effect of air turbulent intensity on human responses to the air movement.
- Obtain the information of the preferred air velocities in the temperature range from 26°C to 30.5°C, at two relative humidity and two turbulence levels.

Administered human subject tests in a controlled environmental chamber were carried out. In particular, considering the fact that inhabitants can achieve thermal comfort more readily when they are allowed to control the environmental parameters (Xia et al., 1999), subjects were allowed to adjust air movement as they liked. This paper reports the design of the experiments and the preliminary findings.

Experimental Methods

Facilities

The experiments were conducted in the climate chamber, measuring 3.4×4.8×3 m. The chamber was located in a large enclosed room. The ceiling was suspended, through which air can be supplied evenly with a velocity less than 0.1 m/s and return from exhaust outlets near the floor. The control system of the climate chamber was based on the thermal resistance sensors measuring the room air temperatures, which were obtained by a data acquisition unit at 1-min intervals. The research personnel and tested subjects could see each other through an observation window and communicate by means of an intercom.

The mean radiant temperature was very close to the air temperature in the chamber. Semiconductor thermometer and dry- and wet-bulb thermometers were used to measure the air temperature and the relative humidity around the subjects. Air velocity was measured by a hot wire anemometer made by Beijing University with the response of 0.1 s.

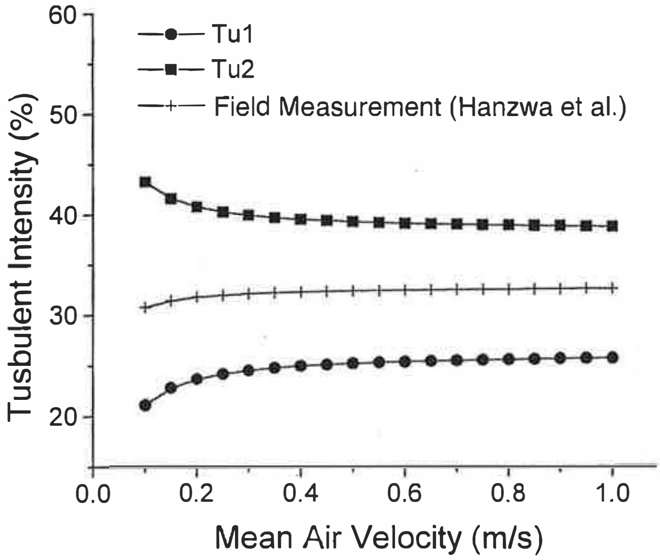

Fig. 1 Turbulent intensity as a function of mean air velocity. Result from field measurements is also plotted as well

A jet was provided through perforated plates of an area of 0.2×0.4 m^2. The air was basically re-circulated isothermal air immediately taken from the chamber. The re-circulation fan speed can be adjusted by an inverter (frequency accuracy: 0.1 Hz). By using a convenient knob, subjects can change the air jet velocity to what they prefer. The air turbulent intensity increases along the distance apart from the outlet, which reaches 25% at 1.2 m and 40% at 2.5 m away from the outlet. The relationships between the mean air velocity and turbulent intensity are shown in Figure 1. Earlier field measurements by Hanzawa et al. (1987) in typically ventilated spaces are plotted as well. When mean air velocity is above 0.2 m/s, turbulent intensity holds approximately constant regardless of the changes of preferred velocities.

Sitting facing the jet, the subjects could feel airflow from chest to knee. This is usually the region exposed to the airflow when most Chinese people use electrical fans in summer. Though the head and neck is the most draft sensitive part, this is the same area to cause headache or giddiness when it is exposed to airflow for a long time. Additionally, only head or neck is far from enough for a person in neutral-to-warm state to cool himself with an isothermal flow. So in this study, this part of body was exposed to the turbulent airflow.

Physical Conditions Tested

Wearing shoes, socks, underwear, trousers and light long-sleeved shirt, the subjects were instructed to enter the climate chamber. This clothing ensemble was about 0.6 clo. Adding the thermal resistance of the metal folding chair referring to the research results of McCul-

Table 1 Experimental conditions for preferred air velocity

Operative temperature (To)	26°C, 27.5°C, 29°C, 30.5°C
Mean radiant temperature (Tmrt)	=air temperature
Turbulent intensity (Tu)	25%, 40%
Relative humidity (Rh)	35%, 65%
Clothing insulation (Icl)	0.7 clo
Metabolism	sedentary (1 met)

Table 2 Anthropometric data for the subjects

Sex	Number of subjects	Age (year)	Height (m)	Weight (kg)
Females	18	20.15±1.46	1.60±0.06	51.39±4.11
Males	88	19.80±2.61	1.72±0.06	63.45±7.04
Total	106	20.09±1.35	1.70±0.07	61.46±8.01

lough and Olesen (1994), the total clothing insulation was about 0.7 clo.

Experiments were performed at the air temperature set points of 26°C, 27.5°C, 29°C and 30.5°C, two turbulences of 25% and 40%, and two relative humidities of 35%, and 65%, which consisted of sixteen tested conditions. Each condition of the lower relative humidity contains 40 sample cases, and each one of the higher relative humidity contains 22 cases. All yielded a target sample size of 496. All the subjects were exposed to two turbulence intensities. There were 13 subjects attending all the sixteen experimental conditions, the others took part in two temperature cases. Several additional experiments were planned in case of instrument malfunction to bring the sample size up to total 106 persons. The experimental conditions are shown in Table 1.

Subjects

All subjects were college students whose ages ranged from 18 to 24 years old. Roughly 17% of them were females and 83% males. They came from the different provinces of the country from the frigid to tropic zone. All persons were in good health and paid for attending the experiments. The anthropometric data are shown in Table 2.

Experimental Procedure

Each time the experiment lasted approximately 2.5 h and included one relative humidity, two air temperature conditions at two turbulence levels. In the first 30 min, the subjects were ushered into the chamber, they then changed clothes and were allowed to adjust to the thermal condition in the chamber. Meanwhile, experimental procedures were explained and participants were asked to fill out the background survey questionnaire. Then they were seated in front of the air box, firstly at the turbulence level of 25% for 30 min, then at turbulence level of 40% for another 30 min. They could adjust the air velocity to maintain comfort and were allowed to do reading or writing work. Every 30 min later, they were asked to fill in the questionnaire (which is attached as an Appendix in this paper) while physical measurements were recorded at the place where the subject just sat. After 1 h, the air temperature set point was raised higher, and the experiment was repeated. At the interval of two temperature conditions, the subject could leave the chair and rest, but they were not allowed to leave the chamber.

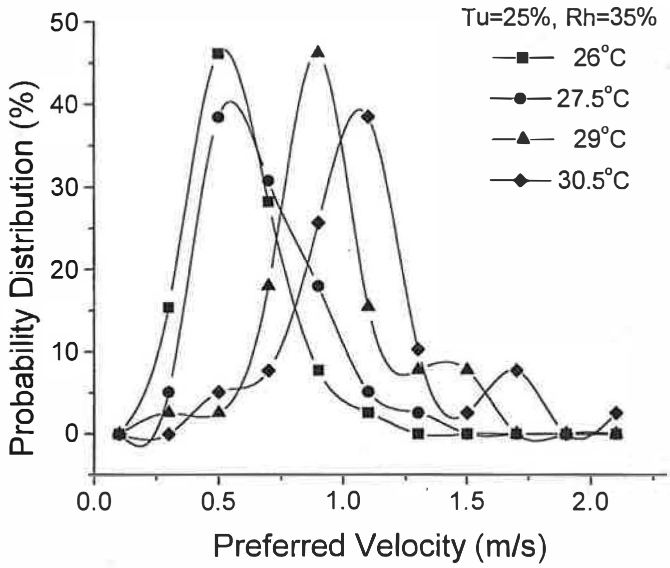

Fig. 2 Probability distribution of preferred velocities in different temperature set points at 25% turbulent intensity and 35% relative humidity

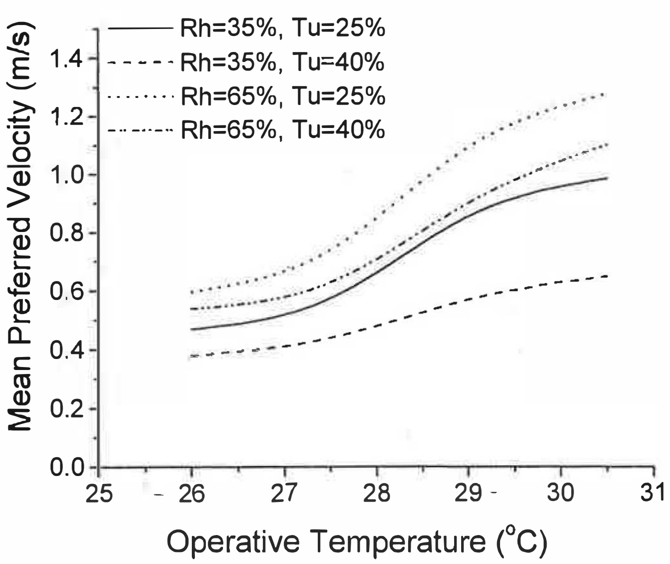

Fig. 3 Mean preferred velocities in experimental conditions

Table 3 Expectation and variance values of preferred velocities in experimental conditions

	To (°C)	26		27.5		29		30.5	
	Tu (%)	25	40	25	40	25	40	25	40
Rh=35%	Expectation (m/s)	0.47	0.38	0.58	0.44	0.86	0.57	0.98	0.65
	Variance (m/s)	0.16	0.11	0.22	0.15	0.26	0.16	0.30	0.17
Rh=65%	Expectation (m/s)	0.60	0.48	0.74	0.63	1.09	0.90	1.28	1.02
	Variance (m/s)	0.24	0.13	0.31	0.16	0.22	0.18	0.24	0.25

Results

The probability distributions of preferred velocities at sixteen experimental conditions were tested with Shapiro-Wilk method. At the acceptable level of 5%, they all matched the normal distribution. Figure 2 is an example of the distribution at turbulence of 25%, relative humidity of 35% under four different temperatures. The mathematical expectation and variance values of preferred velocities are estimated and shown in Table 3, which is also illustrated in Figure 3. The mean preferred velocities go up along with the increase of operative temperature and relative humidity, but the values drop when turbulent intensity is increased. In other words, the preferred velocity used by subjects to gain the same level of thermal comfort in higher turbulent flow is lower than the one in the lower turbulent flow.

In the 496 total thermal sensation votes, there are only eight votes beyond the range between −1 and 1. Following the assumption that the central three categories of the thermal sensation scale are comfortable, which is the premise behind the PMV/PPD model, only 1.6% thermal dissatisfaction was found. If we use the more strict assumption that recommends thermal sensation vote be between −0.5 and 0.5, still only 12% of the subjects are considered unsatisfied. Figure 4 shows the average values of thermal sensation votes in the experimental conditions. It shows a consistent increase in votes with ambient temperature. This may indicate that the subjects either did not attempt or failed to restore "complete" neutrality by adjusting the air movement when the temperature was raised.

The percentage of persons of feeling draft in different turbulence, relative humidity and operative temperature is shown in Figure 5. In the condition of 27.5°C and 35% relative humidity, there are fewest people feeling draft. Below it, high turbulence increases the risk of draft, while the risk drops above 27.5°C. Under the higher relative humidity, there is no such an inflection temperature. The percentage rises with the increasing temperature, and reduces with the increasing turbulence.

Among the sixteen experimental conditions, the one with the operative temperature of 27.5°C, relative hu-

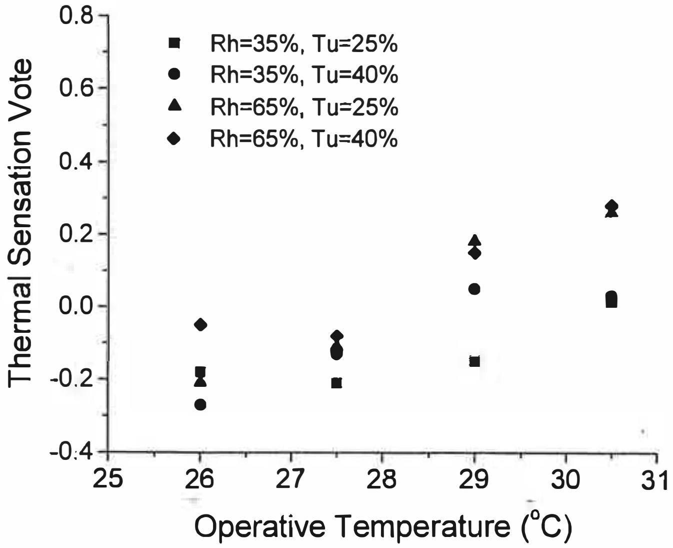

Fig. 4 Mean thermal sensation votes observed during the experiments

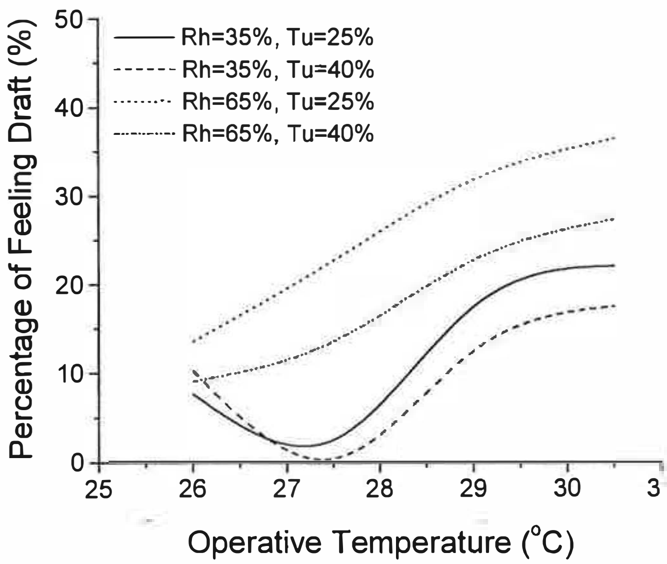

Fig. 5 Percentage of feeling unhappy draft under four experimental conditions

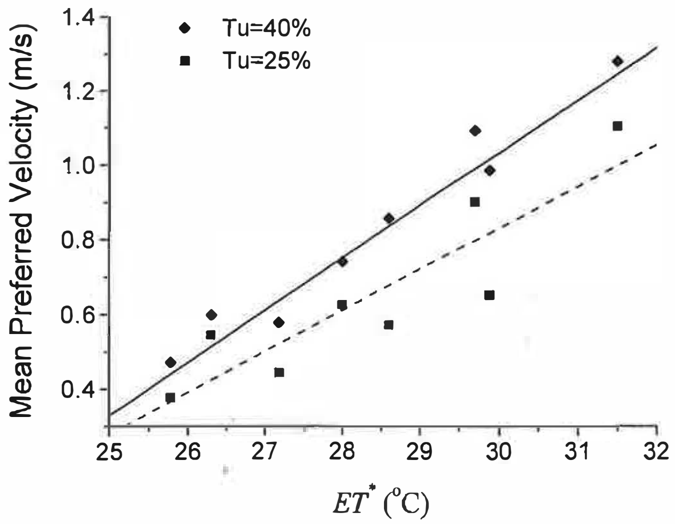

Fig. 6 Mean preferred velocities for different ET*

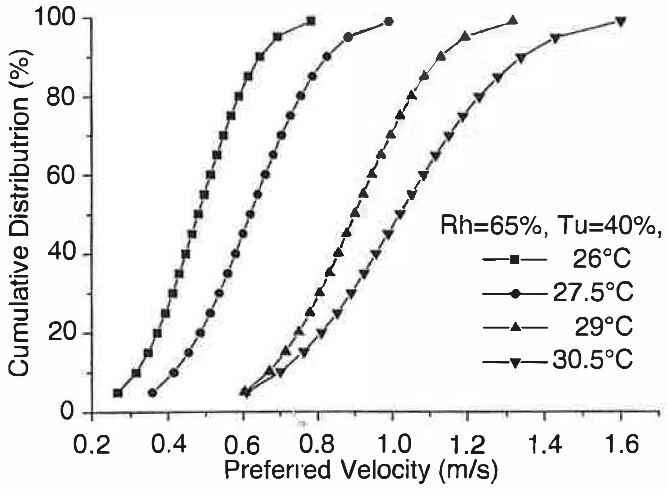

Fig. 7 Cumulative distribution of the sample choosing a particular air velocity at the turbulence of 40% and the relative humidity of 65%

midity of 35% and turbulent intensity of 40% is the most comfortable condition, under which few people feel draft and more people vote comfort. The mean preferred velocity is 0.44 m/s. The mean thermal sensation vote is −0.13.

Discussion

Preferred Velocity

Figure 6 shows a scatter plot of the mean velocities people chose for comfort at each ET* (new effective temperature). ET* (Gagge 1986) normalizes temperature for humidity and radiation, thereby facilitating comparisons of various parameters with a single index. Regression equations of mean preferred velocity ($\overline{\upsilon_p}$) as the function of ET* are presented for two turbulences:

for Tu=25%, ($\overline{\upsilon_p}=0.14\ ET^{*}-3.17$ (R=0.98), (1)

and

for Tu=40%, $\overline{\upsilon_p}=0.11\ ET^{*}-2.47$ (R=0.89), (2)

Since the population of preferred velocity matches the normal distribution, and the expectation and variance values are shown in Table 2, the cumulative distributions can be easily obtained. Figure 7 shows the cumulative distribution of the sample choosing a particular air velocity at the turbulent intensity of 40% and the relative humidity of 65%. For a certain percentage at a specific operative temperature, there is a corresponding velocity below which that percentage of subjects can achieve thermal comfort. The velocity has the same meaning as the one applied in Fountain's PS model (Fountain, 1994). The "unsatisfied" fraction is those occupants with higher preferred velocities. The graph can provide a design reference from which we can know how many percent of persons will be uncomfortable due to lack of air movement. These curves may also be useful to determine the velocity ranges for occupant to adjust to suit their individual requirements.

Draft

According to the Oxford Dictionary, the term "draft" indicates "a current of air in confined spaces". Houghten et al. (1938) developed one of the earliest investigations on discomfort due to draft. They used the term "draft" to indicate an environmental condition, which causes a local sensation of coolness that people could feel in some parts of the body. Fanger et al. (1988) de-

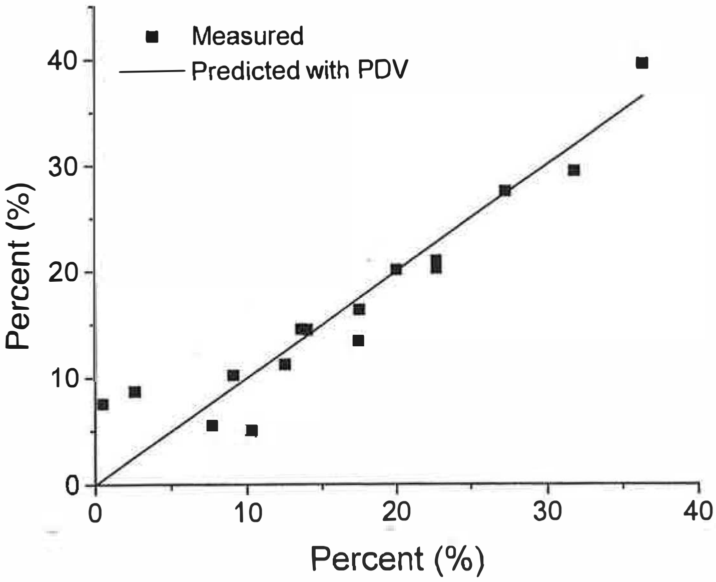

Fig. 8 Comparison of measured percent feeling draft vs. predicted percent feeling draft (r=0.94)

fined the term as "an unwanted local cooling effect of the human body caused by air movement". Both Houghten's and Fanger's definitions were based on the characteristics that air movement might cause cooling feeling in cool-to-neutral conditions. Here we want to discuss the effects of air movements in neutral-to-warm conditions.

The complaints about draft found in this study can be divided into two kinds. One is dry eyes or tensioned skin. The other is blocked breath, being disturbed or even dizziness. But no one complained about cooling draft. Therefore, the definition of draft should be extended when it is used in a wider range of temperatures. It should contain not only the cooling effect at lower temperature, but also the annoying effect caused by the drying effect and air pressure at higher temperatures/velocities.

In Figure 5 there is the least percentage of subjects who have complaints about draft under a 27.5°C operative temperature and 35% relative humidity. The value rises with the increase of temperature and relative humidity, but drops with the increase of turbulent intensity, expect for the conditions with 35% relative humidity and temperature below 27.5°C. As we have known from the above analysis, the same regular pattern happens on preferred velocity. Therefore, in warm conditions, the higher the turbulent intensity, the smaller the preferred velocity, and consequently, the fewer annoying feelings.

Even when the air velocity was under subjects' control, draft feelings still existed in the relatively lower temperature, for example, when the operative temperature is below 27.5°C in Figure 5. It is perhaps because air movement, which is needed by subjects to bring them freshness and amenity, cannot cover the cooling feeling on the other parts of the body. It was noted that the higher the turbulence, the higher the risk of draft. This part of experimental results agrees with Fanger's conclusion. In conclusion, turbulence may induce draft in cool-to-neutral conditions, while it can reduce draft risk in neutral-to-warm conditions.

Because the probability of feeling draft matches a Bernoulli distribution, ordinary least-square regression is inadequate. This kind of regression equation cannot ensure the calculated percentage of feeling draft is always below 100%. Therefore, the logit regression method (Agresti, 1990) was used to analyze the data. SAS program is used for the calculation. A new model of *PDV*, which can predict the percentage dissatisfied due to draft in warm isothermal conditions, is presented. The *V* in *PDV* denotes that this model is suitable for preferred velocity conditions and "neutral-to-warm" environment where air pressure and drying effect are the main causes of draft.

$$PVD=100/[1+\exp(15.5538-04.124*To -0.0872*Rh-0.0774*Tu +0.00219*Tu*To+0.000972*To*Rh +0.00078*Rh*Tu)] \quad (3$$

for

To=26°C~30.5°C, Rh=35%~65%,

and

Tu=25%~40%.

The comparison of measured and predicted PDV i shown in Figure 8. The correlation coefficient is 0.94 In this model, the item of velocity is not included. Th underlying assumption is that velocity can be regu lated by the occupants according to their own prefer ences, and that the preferred velocity is the function o operative temperature (To), relative humidity (Rh) an turbulent intensity (Tu). Therefore, the PDV mode should not be used to predict the percentage dissatis fied at a preset velocity condition.

Effects of Air Movement

Figure 4 shows that preferred velocity can not keep th subjects at the neutral state at relatively high tempera tures. That reflects the two effects of air movement i " warm" conditions. One is the cooling effect that ca greatly reduce the thermal dissatisfaction. The othe one is the annoying effect caused by air motion. Whe subjects select preferred air velocities, they are alway compromising the cooling effect with the annoyin one. The result is that the preferred velocity is lowe than the one needed to restore the neutral state at hig temperature conditions. Yet, it can not be conclude that people will not gain satisfaction when they are no in the thermal neutrality. That depends on the expec tation and the acceptable level of different individual In this study, most subjects achieved thermal comfo with preferred velocity even though they are not in th thermal neutrality state.

Individual Preference

The variance analysis of the preferred velocity an thermal comfort vote apparently show the significan effects of subjects. Hence, the different preference c individuals is an important factor and cannot be over looked. The traditional "uniform" air-conditioned en vironment essentially cannot achieve high satisfactor rate. If occupants in neutral-to-warm state are situate in a more flexibly air-conditioned space given th possibility to adjust temperature and air velocit around them, they might gain higher satisfaction wit smaller energy consumption.

Conclusions

In this paper, experiments were done to study the effects of turbulent air movement on human thermal sensation in warm conditions. One hundred and six subjects dictated their preferred velocities at two turbulent intensity levels in the environments of four operative temperatures and two relative humidities. Physical measurements of the environment were made and subjective votes were collected, including thermal sensation, thermal comfort and draft sensation. The conclusions that can be drawn are as follows:

- Most subjects can achieve comfort under the experimental conditions after adjusting the air velocity as they liked, Although, at the higher temperature, the velocities people chose were possibly lower than the one required to restore thermal neutrality.
- The probability distributions of preferred velocities match the normal distribution. They ascend with the increase of operative temperature and relative humidity, but descend with the rise of turbulent intensity.
- The definition of draft should be extended to cover not only the cooling effect at lower temperatures, but also the annoying effect caused by the air pressure at higher velocities at higher temperatures.
- Turbulence may induce draft in cool-to-neutral conditions, while it can reduce draft risk in neutral-to-warm conditions.
- A new model of PDV is presented to predict the percentage of people feeling draft in warm isothermal conditions when people can adjust the air velocities as they like.

Acknowledgements

We would like to thank Song Sumin for helping with the data collection and Hong Kong Polytechnic University for financial support under Central Research grant No. G-S872.

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Appendix

Questionnaire

1. Please tick (×) the scale below in the place that best represents your overall thermal sensation at present.

2. Please tick (×) the box that describes the kind of air movement you feel at present:
   - ☐ 0 no air movement at all
   - ☐ 1 feel a week air movement, but not constantly
   - ☐ 2 continuously feel a weak air movement
   - ☐ 3 continuously feel an air movement with a certain intensity
   - ☐ 4 continuously feel an intense air movement
3. Please tick (×) the box that describes your thermal comfort condition. If you choose one of the last two boxes, please give a brief explanation.

- ☐ 2 comfortable
- ☐ 1 relatively comfortable
- ☐ 0 not bad
- ☐ -1 slightly uncomfortable
- ☐ -2 uncomfortable

Why?

4. Do you feel any uncomfortable draft?
   - ☐ No
   - ☐ Yes, but I can accept it
   - ☐ Yes, I cannot accept it
   - ☐ if yes, please provide the reason.