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Applicability of elevated air movement for maintaining thermal comfort in warm environments

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Abstract

Providing cooling effect with low energy consumption makes the exploration of air flow utilization significative. In ASHRAE Standard 55-2010, the cooling effects of elevated air movement are evaluated using the SET index as computed by the Gagge 2-Node model of whole-body heat balance. Air movement in reality has many forms, which might create heat flows and thermal sensations that cannot be accurately predicted by a simple whole-body model, and the affected body surface might be variably nude (e.g. face) or clothed. The present study set up experiments in a climate chamber to identify the suitable range of indoor temperature to use desk fans and their corresponding range of air speeds. The proper method to evaluate the cooling effect of air movement is also addressed. The results show that SET index derived from the 2-Node model is effective at predicting thermal sensation even under different non-uniform air movement.

Keywords: SET, 2-Node, Comfort model, Air movement, Thermal sensation

1 Introduction

Studies on air movement cooling have brought substantial attention to the use of elevated air speeds to widen the acceptable range of thermal conditions (Toftum J, 2004; Fountain M and Arens E, 1993; Zhou X et al, 2006; Aynsley R, 2008). Suitable air flow can help to maintain people's thermal comfort in warm seasons during long-term stay in indoor environment. The cooling effect of air flow can raise the indoor set temperature to a certain degree, therefore effectively reduce a building's energy consumption.

Extensive field surveys showed that higher air flow rate was generally expected in neutral and warm environment in many existing buildings. According to the ASHRAE database (de Dear RJ, 1998), field investigations of thermal comfort across the world showed that over 70% of investigated air speed was lower than 0.2m/s, and the mean value of those higher than 0.2m/s was only 0.32m/s. With the sensation range of -0.7 to 1.5, far more people in the scale of 52% versus 3% required more, instead of less, air movement (Arens E et al, 2009). A study by the Berkeley Civic

Center also showed that when people felt neutral and warm, there was a general preference for higher flow rates (Zhang H et al, 2007). In two field experiments inside naturally ventilated buildings in northeastern Brazil, pooling the results for air speed up to 0.4 m/s, the percentage of occupants preferring "more air movement" represented over 70% of dissatisfaction with operative temperature varying from 25 to 31°C (Cândido C et al, 2011).

ASHRAE Standard 55-2010 uses the model PMV to determine comfortable temperatures under still air, and uses the SET (standard effective temperature) index as the basis for extending this still-air comfort zone under elevated air speeds. The SET index is derived from Gagge's 2-Node model, which was introduced in 1970 (Gagge AP et al, 1972). The model considers a human as two concentric thermal compartments representing the skin and core of the body, producing a minute-by-minute simulation of the status of the human thermoregulatory system (Berglund LG and Stolwijk JAJ, 1978; Gagge AP et al, 1986). The model predicts skin temperature, skin wettedness, and thermal status for any combination of environmental and personal variables, including those outside the neutral range, and can be used to find the loci of environmental conditions that produce equal levels of heat loss. Therefore it appears reasonable to use SET as an index to evaluate cooling effect of elevated air movement.

However the environmental surroundings of a simplified model like 2-Node are assumed to be uniform. It is a 'whole-body' model, in which the entire body surface is represented by one average heat transfer coefficient, unlike a 'multi-segmented model', in which body segments are treated individually, and which are necessarily more complex. Recognizing the whole-body nature of SET, ASHRAE Standard 55 specifies that 'average air speed' be used as input to the model, which for sedentary occupants is defined as an average of airspeed measurements at 0.1, 0.6, and 1.1m above the floor.

There are many ways that air movement may be distributed across the body, uniform or non-uniform. The airflow from fans typically reaches only parts of the body surface. The airspeed across these exposed parts is higher than the average airspeed, and the physical and psychological effects may be sensitive to this difference.

In addition, whole-body models use an average clothing resistance value for the whole body surface (Arens E et al, 1986). But the airflow from fans passes over both clothed (e.g., trunk) or unclothed (e.g., face) portions of the body. While the heat loss from clothed and nude surfaces might be linearly related to clothing resistance, the psychological sensitivity may not be.

The present study set up experiments in a climate chamber to identify the suitable range of indoor temperature to use desk fans and their corresponding range of air speeds. It also examines each of the above issues as follows:

1) In a study in which fans provided non-uniform frontal air flow to the upper body, subjects' actual thermal sensation votes (TSV) could be compared to SET values calculated for the experiment's test environmental conditions. The calculations

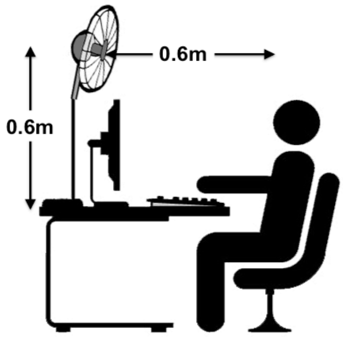
were done in two ways: using only the air speed around the face, and using the average air speed of three heights next to the subjects: 0.1m, 0.6m, and at face level (1.1m). If the calculated indices represent the subject's responses well even under non-uniform flow and non-uniform clothing coverage, then the general use of a whole-body model is supported.

2) A number of published human subject experiments provide TSV results for other types of airflow sources and exposures of the body surface. These experiments involved airflow exposures to a variety of body parts that have differing thermal sensitivity (e.g. face vs. chest vs. back) (Arens E et al, 2006). Differences in subjects' thermal sensations should appear, even at the same air velocity. The regression relationship of TSV against SET value is therefore likely to differ among various types and extent of exposure.

2 Methods

2.1 Test of cooling under non-uniform air flow

A subjective experiment was conducted in a climate chamber in Tsinghua University in Beijing. 30 subjects took part in the experiment, experiencing warm environments with fan-generated frontal air flows to the face and upper body. They wore summer clothing of 0.57 clo. The temperature ranged from 28℃ to 34℃ with relative humidity 40%-50%. At each temperature, air speed ranged from 0.6 m/s to 2 m/s. All the fans were placed in front of the subjects at a horizontal distance of 0.6m and a vertical distance of 0.6m from the desk (Figure 1). The experiments were designed orthogonally with different temperatures and air speeds. Each experiment lasted about 2 hours at a fixed temperature. At the beginning, the subjects were given no air flow for 45 min, and then they voted their thermal sensation. After that, the fans provided air flows with four randomly sequenced speeds in turn, with each air flow lasting for 15 min, for a total duration of 60 min. Subjects' TSV were collected at the end of each 15-min period, using the ASHRAE seven-point thermal sensation scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot). Using the environmental parameters of each experiment, SET values for different conditions were calculated using the SET model and compared with the subjects' thermal sensation votes. The SET calculations were done using air speed measured in front of the face, 1.1m above the floor and 5 cm from the nose. Then they were repeated using the average speed of the three heights (0.1, 0.6, and 1.1m) to represent the whole-body air speed. Further details about this experiment are described in (Huang L et al, 2013).



(a) (b)

Figure 1. The relative position with the subject and fan

2.2 Studies of other air flow sources and exposure types

Table 1 shows published studies from which subjects' thermal sensation values could be obtained, and SET calculated. A variety of different air-movement devices are represented in the studies. We have categorized them as: ceiling fan, desk fan, tower fan, wind box, and nozzle. Subjects' exposures were to air flow on their head, back, and face/chest. SET could be calculated using the reported test conditions. The results are aggregated and compared with those of the fan study described above.

Table 1. Studies of air movement using different air movement devices

Researcher	Location	RH (%)	Local control	Air movement supply device	Body part directly exposed to the air movement
Mclntyre D, 1978	UK	50	Yes	Ceiling fan	Head
Zhai Y, 2013	USA	60/80	No	Ceiling fan	Head
Fountain M et al, 1994	USA	50	Yes	Desk fan	Face and chest
Atthajariyakul S and Lertsatittanakorn C, 2008	Thailand	45-80	No	Desk fan	Face and chest
Chow TT et al, 2010	Hong Kong	50	No	Tower fan	Back
Tanabe S and Kimura K, 1994	Japan	50	Yes	Wind box	Back

Kubo H et al, 1997	Japan	50	Yes	Wind box	Front
Gong N et al, 2006	Singapore	40-55	No	Nozzle	Face
Yang B et al, 2010	Singapore	-	No	Nozzle	Head
Zhang H et al, 2010	USA	50	Yes	Nozzle	Head

3 Results

3.1 Suitable air flows at different temperatures

In the experiment, each subject was asked to report his or her thermal sensation by voting a scale on the seven-level ASHRAE thermal sensation scale.

As showed in Figure 2, each dot in the figure represents the average value of all the votes under the same environmental condition. At the same temperature, the thermal sensation vote turned lower as the air speed turned higher. But the differences of sensation votes between air flows of 1.5m/s and 2m/s were not so obvious, especially when the temperature reached 34°C. In warm environment, the air speed which makes the subjects' thermal sensation +0.5 can be defined as the lower limit of suitable air speed. According to Figure 2, the lower limit of air speeds for 28°C, 30°C, 32°C, 34°C was respectively identified as 0m/s, 1m/s, 2m/s, and over 2m/s.

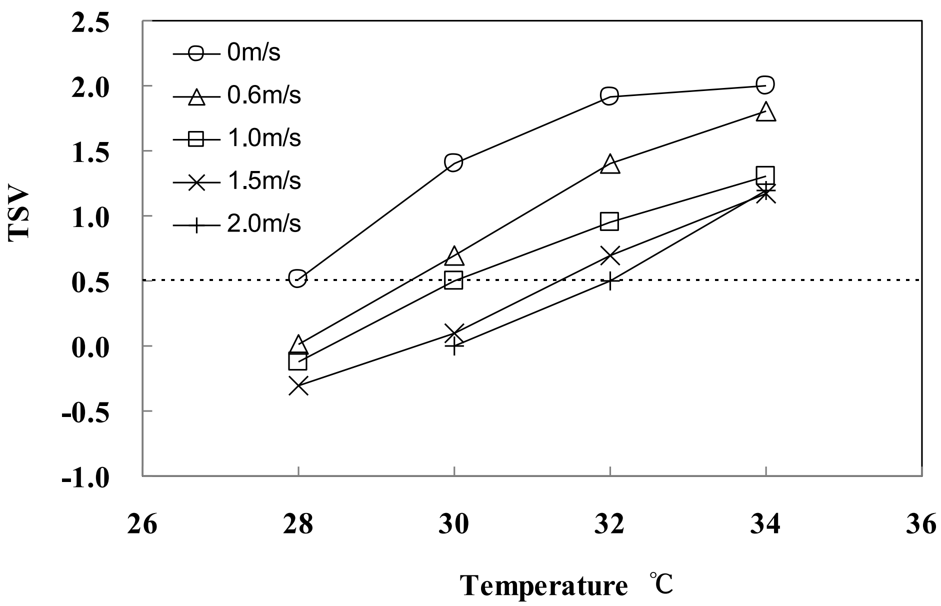


Figure 2. Thermal sensation votes for air speeds at different temperatures

3.2 Use of SET to represent spatially non-uniform air flow cooling

SET values were calculated for each set of environmental conditions in the human subject tests. SET was obtained from 2-Node as embodied in the ASHRAE Thermal Comfort Tool (Zhang H, 2003). Two air speeds were used as input: the airspeed in front of the face, and the average of the speed at three heights, 0.1, 0.6, and 1.1m. In each case the measurements had been taken 5cm in front of the body.

The regression of SET using the whole-body air speed against actual TSV is shown in Figure 3 (a). The SET value and TSV are linearly and closely related. It suggests that SET is a practical index for predicting human thermal sensation in warm environments, even under the non-uniform air flow conditions of this study.

The regression between SET and TSV using the air speed in front of the face (Figure 3 (b)) also shows them to be linearly and closely related. The slope is higher and the intercept is lower for the whole-body SET ($TSV=0.3106SET_{whole\text{-}body} - 8.1165$, $R^2=0.93$) than for the slope and intercept for SET using the air speed in front of the face ($TSV=0.2846SET_{face} - 7.1041$, $R^2=0.94$). This is because the latter uses a greater air speed to calculate the SET, overestimating the cooling effect and producing a lower slope and SET value. The comparison shows that it is fine to use either facial or whole-body-average air speed to calculate SET in order to predict thermal sensation, as long as the corresponding regression equation is used.

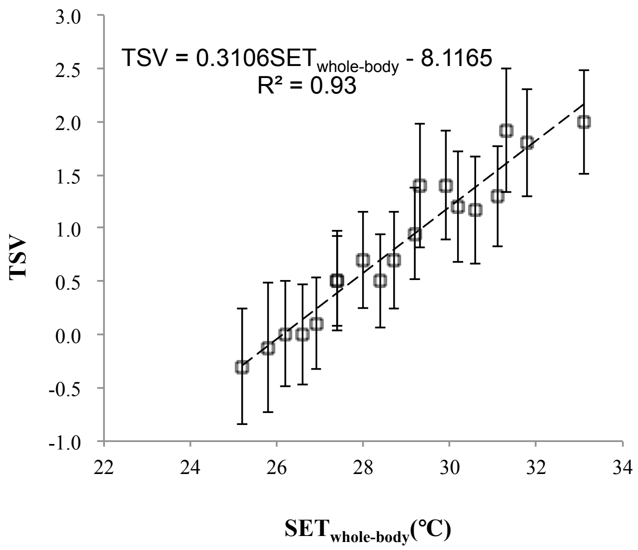


Figure 3. (a) Relationship between SET using the whole-body air speed and TSV

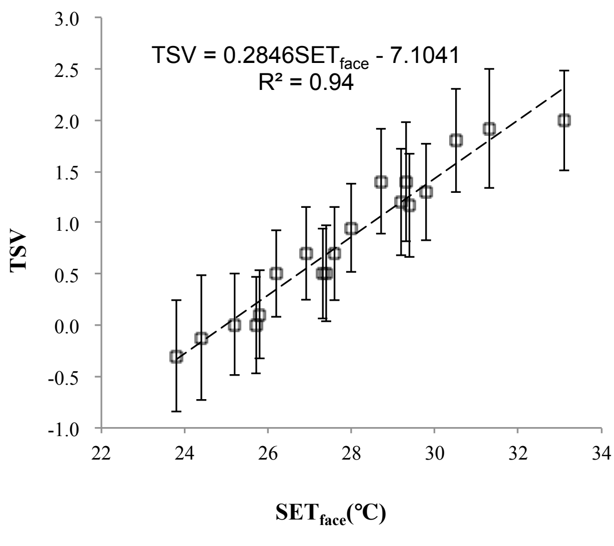


Figure 3. (b) Relationship between SET using the facial air speed and TSV

4 Discussion

4.1 The effect of local control of air speed

In the last step of each experiment session, each subject was asked to adjust the air speed produced by an electric fan till he or she obtained the most comfortable air flow. The thermal sensation votes for personally customized air speeds are shown in Figure 4. With local control of air speed, the thermal sensation was kept in a comfortable range.

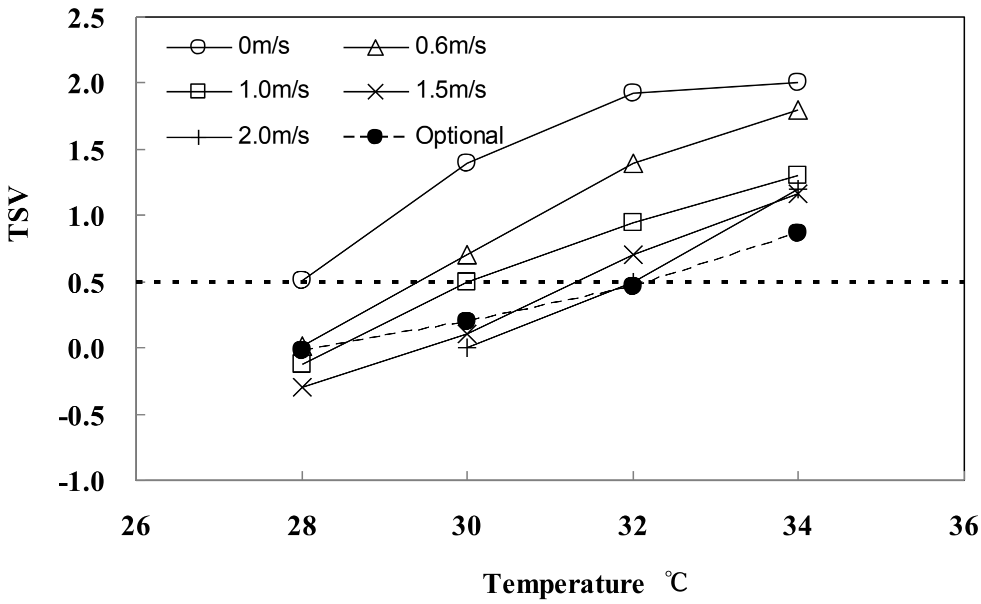


Figure 4. Thermal sensation votes for optional air speeds

Table 2 poses the subject's choices of preferred air speeds with those given by the researcher at the same thermal sensation scale. It shows that with the user's control of air speed, the same thermal sensation can be achieved with a lower speed. The adjustment capacity then improved the subject's thermal sensation to a measurable extent.

Table 2. The optional and given air speeds with the same thermal sensation

Temperature (°C)	TSV	Optional air speed (m/s)	Given air speed (m/s)
28	0	0.5	0.6
30	0.2	1.0	1.4
32	0.5	1.6	2
34	0.9	1.9	>2

The subjects' thermal comfort votes were recorded with a four-level scale from 0 to -3, representing the respective feeling of comfortable, slightly uncomfortable, uncomfortable, and very uncomfortable (Figure 5). The result showed that the subjects gave the highest thermal comfort votes when they could adjust the speed at will at each temperature level. Even at 34°C, the personally controllable air speed could maintain the user's thermal comfort state between "comfort" and "slightly uncomfortable".

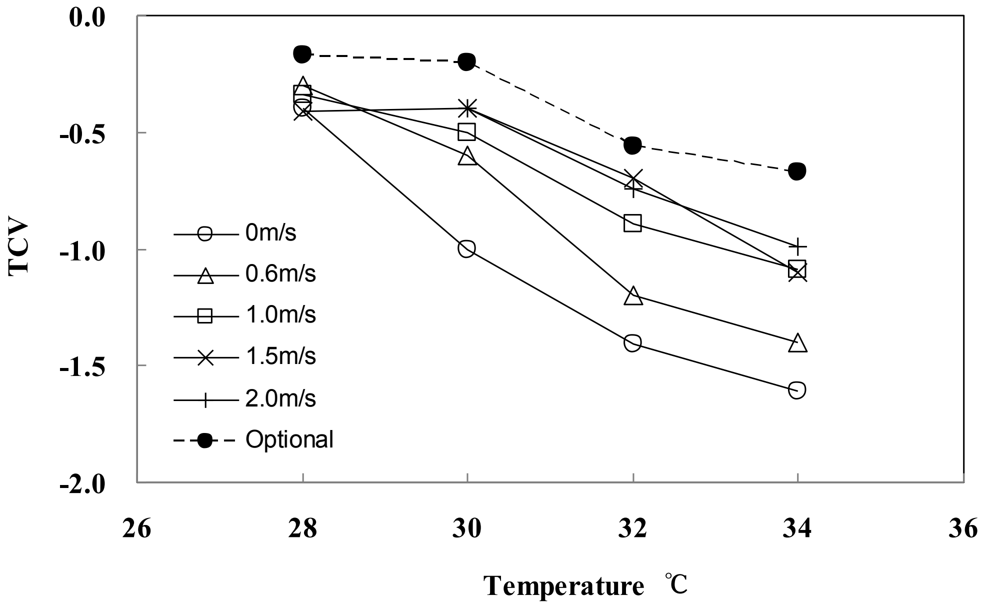


Figure 5. Thermal comfort votes with different air speeds

4.2 Airflow exposures to a variety of body parts

Figure 6 compares the results from this study with studies from the literature in which air temperature and air speed were tested orthogonally. These studies are listed in Table 1. The regression for the device category 'desk fan' is based on the test results from this study and from study (Atthajariyakul S and Lertsatittanakorn C, 2008) in Table 1. It indicates that thermal sensation differs by body part when exposed to the same air speed, which can be seen in the variation of TSV under the same SET. When the SET value was high-- ie, the air speed was low--the difference among the different modes of exposure was not so significant.

Subjects in experiments with their heads exposed to ceiling fans (Zhai Y, 2013) and jets (Yang B et al, 2010) had relatively warmer thermal sensation than subjects with chest and whole-body exposure. This may be because the top of the head exposes a smaller area to the air flow in ceiling fans and jets. The presence of hair may also be a factor. Comparing the ceiling fan and ceiling jet, the jet produced a warmer thermal sensation, again due to the smaller body area impacted. The face appears to be more sensitive to the cooling effect of air movement (Zhang H, 2003). For the experiment in which subjects' whole back was exposed to the air flow from a large-area wind box (Tanabe S and Kimura K, 1994), people had strong cool sensations because the exposed body area was larger than the other exposures.

Table 3 shows the differences in TSV-versus-SET regression coefficients for all these exposure conditions. Statistical analysis shows significant pairwise differences between the regression lines (Table 4). The coefficient for whole-back cooling (0.37) is larger than the coefficient for the desk fan (0.33), ceiling fan (0.28), and ceiling jet (0.26), indicating that cooling effectiveness decreases in this order. In ASHRAE Standard 55, the cooling effect of air movement is calculated with SET, without reference to the type of exposure or wind source. From the analysis above it is seen that variation does exist between different exposures to air movement. However, for the most common airspeed sources (ceiling fan and desk fan), the variation of thermal sensation for a given SET is small (see the open diamonds and triangles in Figure 6). Only when SET is as low as 22℃, a temperature too cool for elevated airspeeds, does the variation between the ceiling fan and desk fan reach 0.5 in the thermal sensation scale (see Figure 6).

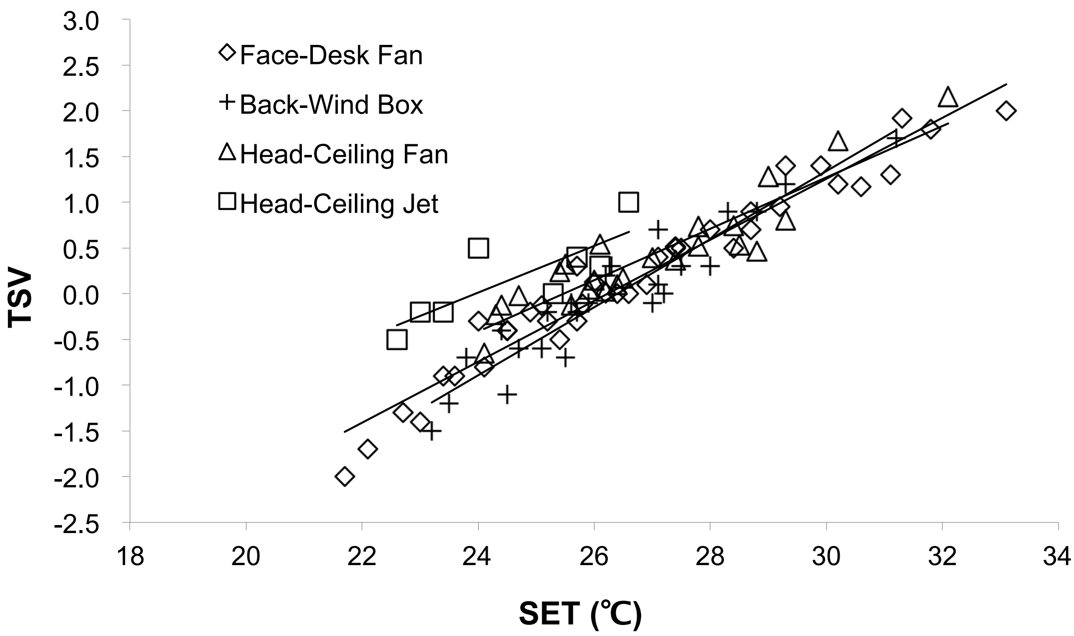


Figure 6. Relationship between TSV and SET in different experiments

Table 3. Linear regression equations of TSV and SET

Exposed body part-Air flow facility	Linear regression equation	R^2
Back - Wind Box (Tanabe S and Kimura K, 1994)	TSV=0.37SET-9.82	0.89
Face - Desk Fan (current &	TSV=0.33SET-8.74	0.95

Atthajariyakul S and Lertsatittanakorn C, 2008)		
Head - Ceiling Fan (Zhai Y, 2013)	TSV=0.28SET-7.15	0.85
Head - Ceiling Jet (Yang B et al, 2010)	TSV=0.26SET-6.12	0.66

Table 4. Pairwise statistical analysis between the linear regression equations of TSV and SET

Pairwise statistical analysis	p value for slope	p value for intercept
Wind Box - Desk Fan	0.188	0.036 *
Wind Box - Ceiling Fan	0.019 *	0.003 *
Wind Box - Ceiling Jet	0.119	0 *
Desk Fan - Ceiling Fan	0.057	0.006 *
Desk Fan - Ceiling Jet	0.199	0 *
Ceiling Fan - Ceiling Jet	0.715	0.002 *

* means significant pairwise difference ($p<0.05$)

5 Conclusions

The climate chamber experimental study identified the lower limit of air speeds for 28°C, 30°C, 32°C was 0m/s, 1m/s, and 2m/s respectively. At 34°C none of the above air speeds could keep human thermal sensation below 0.5.

The above study also showed that the capacity to control an indoor environment could improve the subject's thermal comfort level and extend the acceptable range of thermal environment. When the user's personal control is available, the user would require lower air speed while achieving higher comfort level.

Although it is based on whole-body heat balance, the SET index can be used to predict thermal sensation for air movement that is not uniformly distributed across the body. The SET value and thermal sensation vote TSV are linearly well-related for a variety of non-uniform airflow distributions.

Fan airstreams impacting different body parts require different regression coefficients for predicting TSV from SET. Representative coefficients are provided form an analysis of the existing literature on fan studies. However, the differences in cooling between substantially different types of fans are small. This can be seen in comparing the effects of ceiling fans (fan or jet) with desk fans.

References

Arens E, et al., 2009. Moving Air For Comfort. *ASHRAE Journal*, 51(5), pp 18-28.

Arens E, Gonzalez R, and Berglund LG, 1986. Thermal comfort under an extended range of environmental conditions. *ASHRAE Transactions*, 92, pp 18-26.

Arens E, Zhang H, Huizenga C, 2006. Partial- and whole body thermal sensation and comfort, Part II: non-uniform environmental conditions. *Journal of Thermal Biology*, 31, pp 60-62.

Atthajariyakul S and Lertsatittanakorn C, 2008. Small fan assisted air conditioner for thermal comfort and energy saving in Thailand. *Energy Conversion and Management*, 49(10), pp 2499-2504.

Aynsley R, 2008. Quantifying the Cooling Sensation of Air Movement. *International Journal of Ventilation*, 7(1), pp 67-76.

Berglund LG, Stolwijk JAJ, 1978. The use of simulation models of human thermoregulation in assessing acceptability of complex dynamic thermal environments. *Energy Conservation Strategies in Buildings*, ed. J.A.J. Stolwijk. New Haven.

Cândido C, de Dear RJ, Lamberts R, 2011. Combined thermal acceptability and air movement assessments in a hot humid climate. *Building and Environment*, 46, pp 379-385.

Chow TT, et al., 2010. Thermal sensation of Hong Kong people with increased air speed, temperature and humidity in air-conditioned environment. *Building and Environment*, 45(10), pp 2177-2183.

de Dear RJ, 1998. A global database of thermal comfort field experiments. *ASHRAE Transactions*, 104 (1b), pp 1141-1152.

Fountain M and Arens E, 1993. Air movement and thermal comfort. *ASHRAE Journal*, 35(8), pp 26-30.

Fountain M, et al., 1994. Locally controlled air movement preferred in warm isothermal environments. *ASHRAE Transactions*, 100(2), pp 937-952.

Gagge AP, Fobelets AP, and Berglund LG, 1986. A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*, 92, pp 709-731.

Gagge AP, Stolwijk JAJ, Nishi Y, 1972. An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions*, 77, pp 21-36.

Gong N, et al., 2006. The Acceptable Air Velocity Range for Local Air Movement in

The Tropics. *Hvac&r Research*, 12(4), pp 1065-1076.

Huang L, et al., 2013. A study about the demand for air movement in warm environment. *Building and Environment*, 61(0), pp 27-33.

Kubo H, Isoda N, and Enomoto-Koshimizu H, 1997. Cooling effects of preferred air velocity in muggy conditions. *Building and Environment*, 32(3), pp 211-218.

McIntyre D, 1978. Preferred air speeds for comfort in warm conditions. *ASHRAE Transactions*, 84(2), pp 264-277.

Tanabe S, Kimura K, 1994. Effects of air temperature, humidity and air movementon thermal comfort under hot and humid conditions. *ASHRAE Transactions*, 100(22), pp 953-969.

Toftum J, 2004. Air movement – good or bad? *Indoor Air*, 14, pp 40-45.

Yang B, Sekhar SC, and Melikov AK, 2010. Ceiling-mounted personalized ventilation system integrated with a secondary air distribution system - a human response study in hot and humid climate. *Indoor Air*, 20(4), pp 309-319.

Zhai, Y, 2013. *Low energy comfort with air movement in hot-humid environments*. PhD. South China University of Techonogy.

Zhang H, et al., 2007. Air movement preferences observed in office buildings. *International Journal of Biometeorology*, 51, pp 349–360.

Zhang H, et al., 2010. Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system. *Building and Environment*, 45(1), pp 29-39.

Zhang H, 2003. Human thermal sensation and comfort in transient and non-uniform thermal environments. *CEDR 2003*, University of California at Berkeley.

Zhou X, Ouyang Q, Lin G and Zhu Y, 2006. Impact of dynamic airflow on human thermal response. *Indoor Air*, 16(5), pp 348-355.