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Applicability of whole-body heat balance models for evaluating thermal sensation under non-uniform air movement in warm environments

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Abstract

In ASHRAE Standard 55-2010, the comfort 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. This paper addresses two of such potential inaccuracies: 1) indoor airflows may affect only a portion of the body surface (e.g., above desktop), and the affected body surface might be variably nude (e.g. face) or clothed, 2) the turbulence intensity (TI) in some typical airstreams (e.g., those created by fans) might have a different impact on heat transfer than the TI implicit in 2-Node's single convective heat transfer coefficient. For both these issues, can a whole-body index like SET represent such a wide range of possible exposures to airflow?

Measurements of thermal sensation were obtained from human subjects using face-level fans in warm environments. Previous laboratory studies of a range of airstream sources were also analyzed. The effects of turbulence intensity were examined with manikin tests.

The results show that indices derived from the 2-Node model of whole-body heat balance are effective at predicting thermal sensation under most non-uniform air movement. In contrast, the PMV index underestimates cooling in warm conditions. Turbulence increases the cooling effect of air movement, but by amounts that might be neglected for most design purposes.

Keywords

SET, 2-Node, Comfort model, Air movement, Thermal sensation, Turbulence intensity

1. Introduction

Air movement has a significant cooling effect, increasing the acceptable range of indoor temperatures [1-4]. 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 [5].

The SET index is derived from Gagge's 2-Node model, which was introduced in 1970

[6]. 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 [7, 8]. 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 [9]. 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.

Finally, a given airspeed's transient flow characteristics (intensity and scale of turbulence) are likely to be different from the fixed level of turbulence assumed in the 2-Node model. Nishi and Gagge [10] experimentally developed the model's forced-convection equation by having subjects walk through still air at a fixed speed. Turbulence was not measured in their experiment, and is not an input variable to 2-Node. In reality, however, turbulence from different air movement sources will differ, and will affect heat transfer. Mayer's research with a manikin head [11] showed an increase in heat transfer with increasing turbulence intensity (TI) when TI is above 40%. It would be desirable to know whether the differences in turbulence intensity found in typical air movement sources like ceiling or desk fans significantly affect body cooling, and whether 2-Node predictions using only one implied turbulence level accurately predict these differences.

This paper 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) [12]. 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.

3) Finally, we determined the turbulence intensity that had occurred in the Nishi/Gagge experiment [10], since this TI is inherent in the 2-Node convection algorithm. We repeated the conditions of the Nishi and Gagge experiment and directly measured the TI. The heat loss from this TI was then measured with a manikin, and compared with heat losses from a range of TI values occurring from

fans and other indoor sources. A relationship describing the difference in heat loss and thermal comfort could be developed from this.

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 [13].

(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 [14-23]

Researcher	Location	RH (%)	Local control	Air movement supply device	Body part directly exposed to the air movement
D. Mclntyre (1978)[14]	UK	50	Yes	Ceiling fan	Head
Y. Zhai (2013)[15]	USA	60/80	No	Ceiling fan	Head
M. Fountain (1994)[16]	USA	50	Yes	Desk fan	Face and chest
S. Atthajariyakul (2008)[17]	Thailand	45-80	No	Desk fan	Face and chest
T.T.Chowa (2010)[18]	Hong Kong	50	No	Tower fan	Back
S. Tanabe (1994)[19]	Japan	50	Yes	Wind box	Back
H. Kubo (1997)[20]	Japan	50	Yes	Wind box	Front
N. Gong (2006)[21]	Singapore	40-55	No	Nozzle	Face
B. Yang (2010)[22]	Singapore	-	No	Nozzle	Head
H. Zhang (2010)[23]	USA	50	Yes	Nozzle	Head

2.3 Test of the impact of turbulence intensity (TI)

A thermal manikin (Figure 2) was used to measure the convective heat transfer coefficients for air flows of different turbulence intensity, following the method described in [24]. Analysis was done for the manikin's head alone, without hair. The manikin consists of 20 thermal segments, electrically heated at the surface to simulate metabolic heat output, and surface temperature is measured for the entire segment surface. Heat losses and surface temperatures were recorded in 30s intervals. Mean values were calculated for 1-hour measurements after the manikin reached steady state for each variant of the experimental conditions. Each test was repeated three times. The manikin heater was controlled under "comfort mode" to maintain a realistic skin temperature for the conditions.

The same fan used in the human subject thermal comfort study described above (a 0.6m diameter fan) was adjusted to produce three different mean air speeds: 0.6m/s, 0.8m/s, and 1m/s. Air flows with different turbulence intensities ranging from 20% to 42% were produced by increasing the distance from fan to manikin. An omnidirectional anemometer was used to measure the air speed, sampling 10 values every second. The anemometers (Swema) have a rated frequency response of 20 Hz. TI was calculated using the standard deviation of the sampled speeds divided by the mean speed. The air flow from the fan mostly reached the face and chest.

The experimental air flows are listed in Table 2. The average TI produced by the frontal fan for all the listed conditions is around 30%.

Figure 2. Convective heat transfer coefficient measurement with manikin ‘Newton’

Table 2. Experimental airspeeds and turbulence intensities, measured 4.5 cm in front of the face

Average air velocity (m/s)	Turbulence intensity (%)	Distance from fan to manikin (m)
0.63	20	0.6
0.62	28	0.8
0.60	32	1

0.58	40	1.5
0.82	21	0.7
0.82	28	0.9
0.79	30	1
0.81	38	1.5
1.03	22	0.8
1.02	27	1
1.00	31	1.1
0.98	42	1.6

The Nishi and Gagge [10] experiment had measured time-averaged local heat transfer coefficients and air speeds for walking people at 10 locations around the body (front head, chest, back, upper arm, lower arm, hand, thigh, and lower leg). The sensors (sublimating naphthalene balls) were attached to the body at a fixed offset of 4.5 cm from the skin. The local TI values were not quantified.

In order to determine the TI that would have existed during the Nishi/Gagge tests, we repeated their test protocol, measuring airspeed and TI at the same 10 body locations with our omnidirectional anemometers positioned 4.5 cm away from the skin. The subject walked at the speed of 1m/s in still air. The setup is shown in Figure 3.

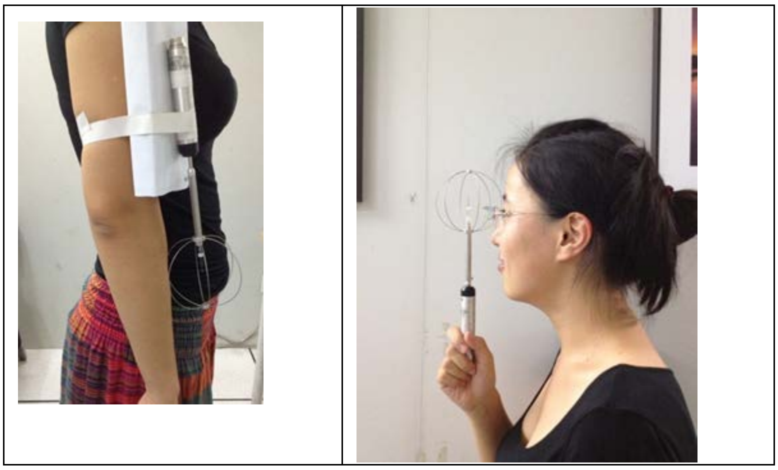

Figure 3. Turbulence intensity test for walking people

3. Results

3.1 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 [25]. 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 4 (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 4 (b)) also shows them to be linearly and closely related. The slope is higher and the intercept is lower for the whole-body SET ($TSV=0.3106SET_{whole-body} - 8.1165$, $R^2=0.93$) 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.

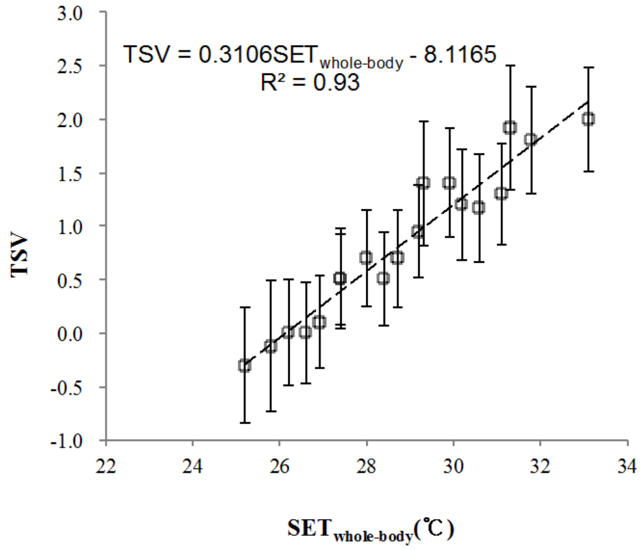

Figure 4. (a) Relationship between SET using the whole-body air speed and TSV

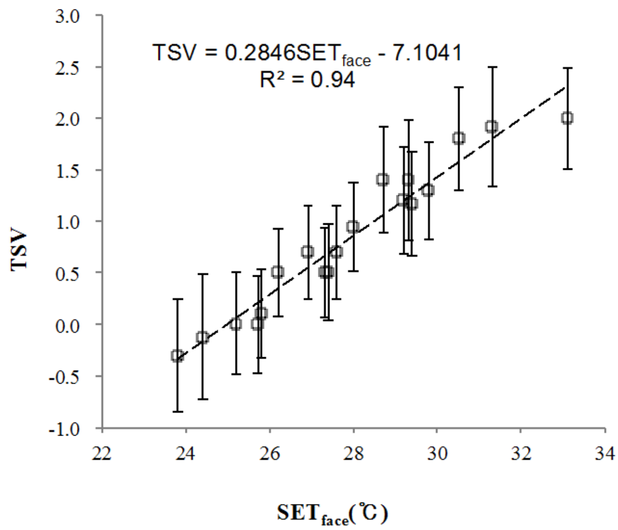

Figure 4. (b) Relationship between SET using the facial air speed and TSV

Figure 5 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 [17] 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 [15] and jets [22] 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 [26]. For the experiment in which subjects’ whole back was exposed to the air flow from a large-area wind box [19], 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 5). 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 5).

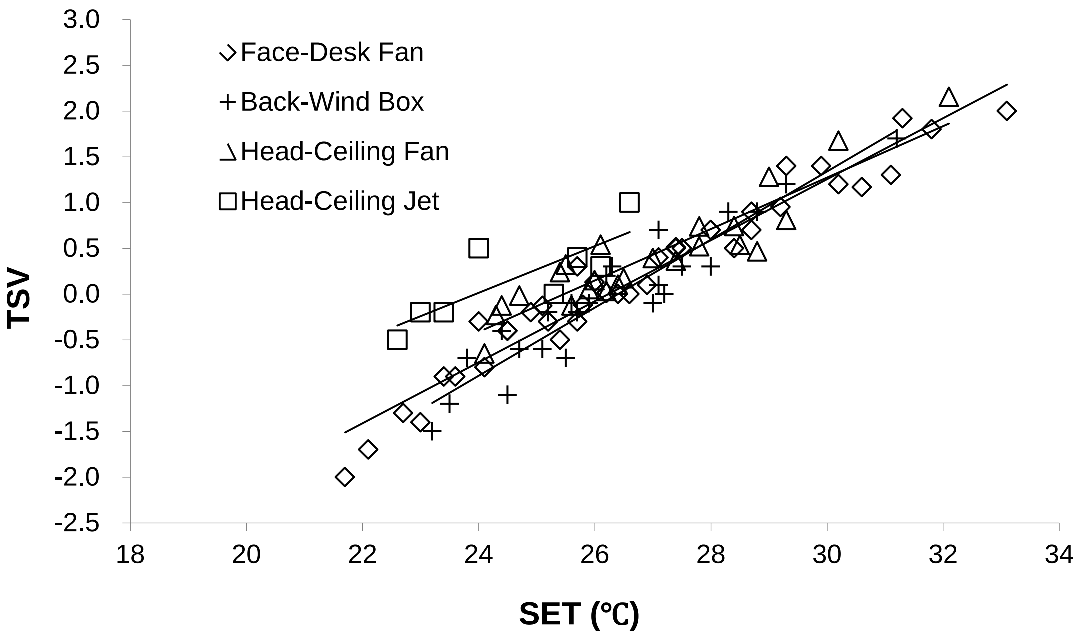

Figure 5. Relationship between TSV and SET in different experiments

Table 3. Linear regression equations of TSV and SET

Exposed body part-Air flow facility	Linear regression equation	R^2
Back - Wind Box [19]	TSV=0.37SET-9.82	0.89
Face - Desk Fan [current and 17]	TSV=0.33SET-8.74	0.95
Head - Ceiling Fan [15]	TSV=0.28SET-7.15	0.85
Head - Ceiling Jet [22]	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 ($p<0.05$)

3.3 The effect of turbulence intensity on convective heat transfer coefficient

The total dry heat transfer of the head was measured with the manikin as described in 2.3. The radiation heat transfer coefficient for the head region was obtained from previous research (3.9 W/m^2 per K) [24]. Subtracting this radiative coefficient from the total dry heat transfer coefficient gives the convective heat transfer coefficient h_c for the head. In Figure 6, each of the dots represents the mean value of three repeated measurements at the indicated airspeed and TI. For a given mean airspeed, the convective heat transfer coefficient increases with turbulence intensity, and the contribution from a given increment of additional turbulence intensity increases with airspeed.

Mayer [27] found that the convective heat transfer coefficient depends on air speed only at lower TI; and is a function of the product of TI and air speed at higher TI. His approach requires a piecewise calculation. Others [28-31] have generally related the convective heat transfer coefficient to mean air speed and TI as follows:

$$h_c = A \cdot v^{0.5} + B \cdot TI \cdot v$$

where A and B are constants.

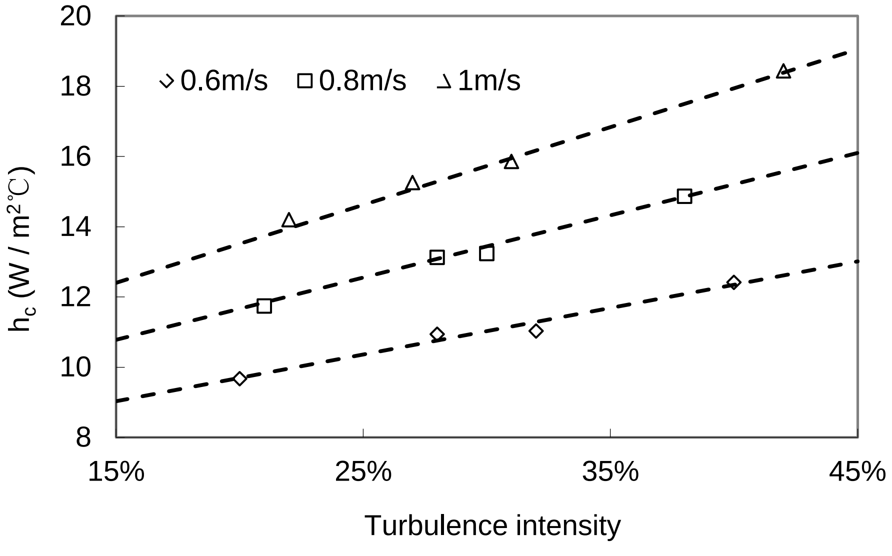

Figure 6. Bivariate linear regression of air velocity and turbulence intensity

The coefficients for the equation can be obtained from the Figure 6 data by bivariate linear regression.

$$h_c = 9.08v^{0.5} + 22.16TI \cdot v$$

These coefficients produce a good fit to Mayer's measured data, within 20%.

Using the linear relationship between SET and TSV given above for the desk fan (Table 3), TSV was predicted from SET as calculated with the new (airspeed+TI) heat transfer coefficient. Table 5 shows the drop in TSV for a wide range of TI levels (10, 30, 60%). The theoretical base case for each drop is TI = 0. For TI levels of 10%, 30%, and 60%, the TSV drops are about 0.1, 0.3, and 0.4 TSV scale units. One must interpolate between these drops to account for the 2-Node model's base case TI of 24%. This value, the area-weighted average of TI at the 10 measurement locations in Nishi/Gagge's experiment, was obtained in our test of a subject walking at 1 m/s (shown in Figure 3).

In our walking TI test, the TI for head was found to be 19%, for chest 16%, and for forearm 29%. These would be the local TI values implicit in 2-Node. When comparing 2-Node's head value of 19% with the TI that occurs at the head in the airstream of a frontal fan (Table 2; average value around 30%), the SET prediction of 2-Node should underestimate the cooling by about 0.1 TSV scale units.

Table 5. Effect of TI level on TSV, compared to a zero TI base case

Air temperature	Air velocity	Predicted drop of TSV (TI=10%)	Predicted drop of TSV (TI=30%)	Predicted drop of TSV (TI=60%)
28	0.6	0.13	0.31	0.49
28	1	0.14	0.34	0.51
28	1.5	0.16	0.35	0.50
30	0.6	0.13	0.30	0.47
30	1	0.14	0.31	0.46
30	1.5	0.14	0.31	0.44
30	2	0.15	0.31	0.43
32	0.6	0.13	0.30	0.46
32	1	0.13	0.30	0.43
32	1.5	0.13	0.29	0.41
32	2	0.14	0.28	0.39
34	0.6	0.12	0.29	0.44
34	1	0.13	0.28	0.40
34	1.5	0.13	0.27	0.37
34	2	0.13	0.26	0.35

For comparison, measured indoor TI values range from 10-60%, most typically between 20-40% [32]. In the current fan test, TI ranged from 20-40% (Table 1).

4. Discussion

4.1 Use of the PMV model for predicting thermal sensation under air movement

The PMV model is a whole-body model used in Standard 55 for determining the still-air comfort zone. It is worth comparing its performance to that of the SET approach. PMV values were calculated for all the conditions in the human subject experiments described in Table 3. Unlike SET, the cooling effect of air flow on sweat evaporation is not taken into account in the PMV model. In Figure 7, the solid symbols represent results in which the skin wettedness is 0.06, meaning the skin has not begun to sweat. In this condition, heat transfer by evaporation at skin surface is small, and PMV is seen to predict thermal sensation fairly well, with the PMV values near the TSV values. However when skin wettedness is higher than 0.06, represented by the hollow marks in the figure, the evaporative heat transfer is larger and strongly affected by air speed. This leads to the result that PMV overestimates subjects' actual thermal sensation votes, and underestimates the cooling effect of air speed.

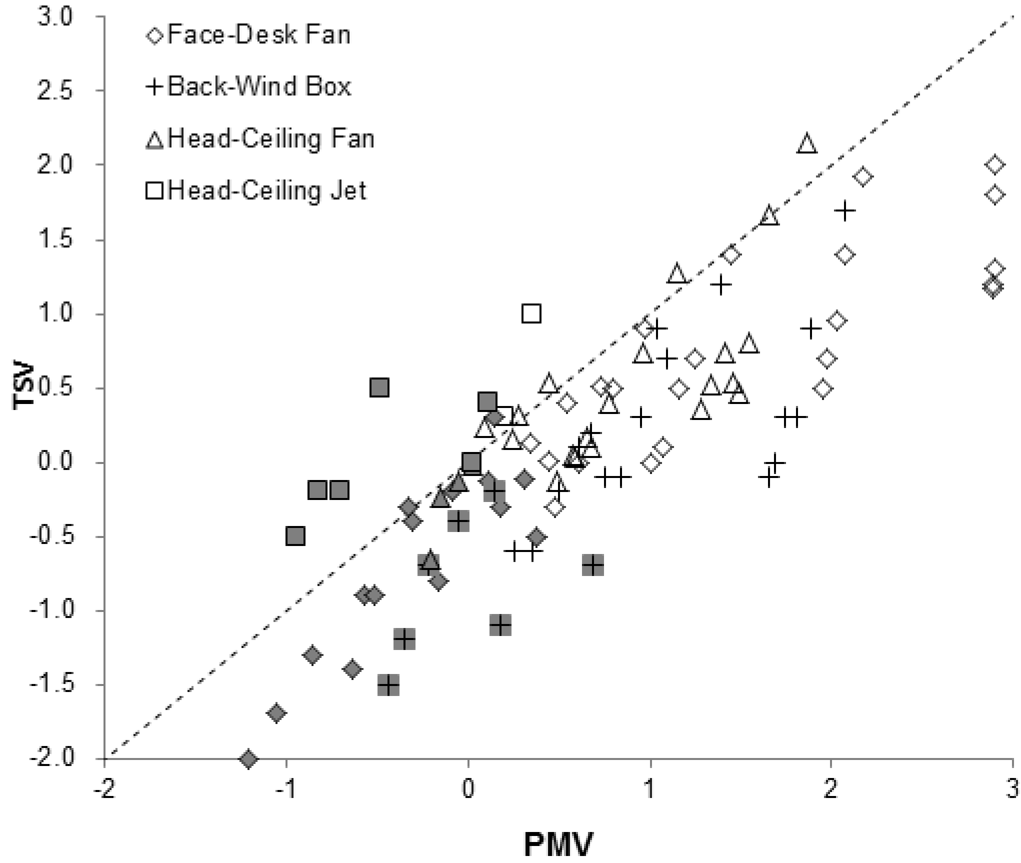

Figure 7. Relationship between TSV and PMV

5. Conclusions

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.

The PMV model does not take into account the cooling effect of air flow on sweat evaporation, causing PMV to overestimate subjects' thermal sensation in warm conditions when the fraction of skin wettedness is above 0.06. This cannot be easily corrected by simple regression.

The 2-Node model implicitly involves a TI of 19% for the head and 24% for the whole-body average. In the current study, TI in the front of the face created by fans is around 30%. The differences between 19% and 30% in predicting in heat transfer coefficients and thermal sensation is small (within 0.1 TSV scale unit). For most design purposes, it is not necessary to consider TI differences.

Acknowledgements

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