Effects of Air Velocity on Thermal Comfort in Hot and Humid Climates

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Abstract

A subjective experiment was conducted to investigate the effects of high air velocity on thermal comfort. A total of 128 college-age students (64 males, 64 females) were asked to participate in the research work. Experiments were conducted in the environmental chamber at Chulalongkorn University from April to December 2002. The scope of the experiments were limited to the most common application where the subjects wore normal working dress and do office work. The study shows that Fanger's PMV Model [1] cannot correctly predict thermal sensation at high air velocity. A modified SET* for this experiment was determined and used as an environmental index in this study. This modified SET* provides an excellent fit to a large group of thermal sensation votes form the experiment. The study shows that a range of design air velocities, where most people (80 % or more) can accept is between a modified SET*=23.0 to 26.3 C, and the best value where subjects give the highest percentage of satisfaction is at modified SET*=24.3 C. Results from air velocity sensation and preference vote indicated that 80% of the subjects were satisfied and felt NOT DRAUGHTY and NOT DISTURBED if air velocity was not greater than approximately 0.9 m/s. Air velocity greater than 0.9 m/s was acceptable only in situations where there were no other choices and the subjects were working under no stress conditions.

Keywords: Thermal comfort, High air velocity, High air movement, Hot and humid climate, Preferred air velocity, Draughty.

1. Introduction

In hot and humid countries like Thailand, the combined use of a small room air conditioner and an ordinary floor-mounted propeller fan to increase comfort has long been used for energy saving and has become common practice. Such a hybrid system could decrease the energy consumption because the thermostat set point can be increased to 28 degrees C while the comfort is still maintained by the reinforcement of the extra air circulation from an ordinary floor-mounted fan. The energy consumption increased by the fan can be easily compensated by the higher set point changed at the room air conditioner. This energy saving opportunity can be applied in certain types of commercial applications as well if the designer can easily access the necessary design data. The other benefits include the industrial evaporative cooling applications where high air velocity is required to meet comfort need. There are many certain applications in factory conditions where the result of this study could provide an alternative method to solve thermal comfort problems. For countries where hot and humid climates are common all year round, the energy saving opportunity is even much greater than countries with cold climates.

Research on this topic has been limited. Tanabe et al. [2] has done some extensive investigations on this type of topic using 64 college-age persons (32 males, 32 females) during summer of 1986 in Tokyo to predict thermal sensation under high levels of air movement. Tanabe also discussed and gave some explanations why Fanger's PMV model [1] could not predict thermal sensation well at higher air velocities. Tanabe et al. [3] had further suggested that clothing insulation and skin moisture may be decreased at higher air velocity.

This research had further extended the scope of Tanabe's work to cover a wider range of relative humidity, air velocity and acceptability limits against the given air velocity. The main objective of this research is to find and provide an explicit method for a design engineer to use in the actual application. Some extended sets of data and findings are presented and compared with Tanabe's results.

2. Experimental Methods

This experiment can be roughly described as a subjective evaluation of how a large group of persons or subjects feel about the air draught, the degrees of air temperature flowing through his or her body in a uniform pattern while the subject is doing some light activity such as sitting on a chair reading a book or working on a computer. One of the most difficult tasks of this experiment is how to find a large number of subjects and the time to spend with each subject — approximately 3 hours for each subject, and only two subjects per working day. At each experiment, only one subject can perform the test due to the limited size of the room and the fan box.

A total of 128 students (64 males, 64 females) in the Department of Mechanical Engineering at Chulalongkorn University were asked to participate in this research work. Most of the subjects were postgraduate students in good health. Before participating in the experiment, they had enough rest, and performed normal activities. All of them were between 20 to 30 years old. The anthropometric data of the subjects is shown in Table 1.

Table 1. Anthropometric Data of the Subjects.

SEX		Age (year)	Height (m)	Weight (kg)	Body Surface Area [(2)] m^2
Female	mean	25.87	1.61	55.93	1.57
	SD[(1)]	2.93	0.06	11.35	0.17
Male	mean	25.44	1.69	65.39	1.72
	SD	2.05	0.22	12.16	0.34
Female & Male	mean	25.66	1.65	60.66	1.65
	SD	2.54	0.17	12.67	0.27

(1) Standard Deviation
(2) Calcution by Du Bois Equation
Area = 0.202 x $(\text{Weight})^{0.425}$ x $(\text{Height})^{0.725}$

Since the objective of the experiment was limited to the most common application where the subjects wore normal working dress and did office work, therefore the clo-value was limited only to 0.48 (at air velocity of 0.1 m/s) and activity level was limited to 1.2 met. The rest of the scope of the experiment is summarized in Table 2.

Table 2. Scope of the Experiment

Parameter	Details
Subjet	College-age (20-30 years) Female 64 and Male 64 ; Total 128
Experiment Time	3 hours
Clothing[(1)]	0.48 clo
Activity[(1)]	1.2 met (office work)
Air Temperature (°C)	25.79 ± 0.14 , 27.83 ± 0.12, 29.77 ± 0.36 , 31.84 ± 0.15
Mean Radiant Temperature (°C)	Equal Air Temperature
Relative Humidity (% rh)	50.16 ± 2.35 , 59.99 ± 2.12 , 69.99 ± 2.16 , 79.72 ± 2.39
Mean Air Velocity (m/s)	0.10 , 0.25 , 0.90 , 1.64 , 1.74 , 1.94, 2.47

(1) Calculation follow ASHRAE Standard 55-1992 [4]

There are two types of questionnaires. The first type concerns preliminary information. It is used to check the readiness of the subjects before the experiment and also to collect some necessary basic information. It has to be completed in the ante room where the subjects can also rest before the experiment. The second type evaluates the thermal sensation, comfort sensation and acceptability against the given air movement. There are 15 copies of this type of questionnaire for each experiment. Each of them has to be completed at the specific time signalled by the operator. There are 10 questions in the second type questionnaire. Each question was carefully written in Thai and has been tested several times before being put into use. Every subject was briefed about details in every step of the experiment and about the meaning of each question in the questionnaire before entering the environmental chamber. Details of the second questionnaire are shown in Figure 1.

3. Experimental procedure

One session of the whole experiment takes about 3 hours. Most of the sessions are performed during 9 to 12 a.m. and 1 to 4 p.m., and sometimes at night. Each session has three periods where the first period was performed in the ante room; the second and the third in the environmental test chamber.

Questionnaire about Environmental Conditions in the Test Chamber

Day/Month/Year................................Time..................Questionnaire Number.....................

Please answer the following questions about your feeling on the environmental conditions in the test chamber at this moment.

1. How do you feel about the thermal environment in the chamber at this moment?

   ☐ Cold ☐ Cool ☐ Slightly cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot

2. How do you want to change the air temperature in the chamber at this moment?

   ☐ Warmer ☐ No change ☐ Cooler

3. How do you feel about the air movement in the chamber at this moment?

   ☐ Not Draughty ☐ Slightly Draughty ☐ Draughty ☐ Very Draughty

4. How do you want to change the air movement in the chamber at this moment?

   ☐ Less air movement ☐ No change ☐ More Air Movement

5. How do you feel about the acoustics level in the chamber at this moment?

   ☐ Very Quiet ☐ Quiet ☐ Slightly Loud ☐ Loud ☐ Very Loud

6. Can you accept the acoustics level in the chamber at this moment?

   ☐ Yes ☐ No

7. How do you feel about the lighting level in the chamber at this moment?

   ☐ Dark ☐ Slightly Dark ☐ Suitable ☐ Slightly Bright ☐ Very Bright

8. Can you accept the lighting level in the chamber at this moment?

   ☐ Yes ☐ No

9. How do you feel about the thermal environment (comfortable or uncomfortable)?

   ☐ Comfortable ☐ Slightly Uncomfortable ☐ Uncomfortable ☐ Very Uncomfortable

10. Can you accept this thermal environment in the chamber at this moment?

    ☐ Yes ☐ No (Why...)

Figure 1. Questionnaire about Thermal Sensation, Comfort Sensation and Acceptability of the given air movements

The first period takes about 15 minutes. The subject fills in the first questionnaire, takes the necessary measurements such as weight, height, and listens to the operator's explanations about what to do and the exact meaning of every question in the questionnaire.

The second session takes about 150 minutes. The subject will sit at the working station where he or she could perform a normal office work activity. The working station is 2.5 meters from the fan box. At this distance, the velocity profile from six units of propeller fan becomes uniform. During the first 30 minutes, the air velocity is set at 0.1 m/s, thereafter varied every 20 minutes to a value among 0.25, 0.90, 1.64, 1.74, 1.94 and 2.47 m/s in a random manner so that the subject will not know the value of the exposed air velocity. During this 150 minutes period, the subject will be asked to fill in the second questionnaire at the 5th, 15th, 25th, 35th, 45th, 55th, 65th, 75th, 85th, 95th, 105th, 115th, 125th, 135th, and 145th minute respectively.

The last part of the experiment (takes 15 minutes) in which the subject is tested to determine a preferred air velocity. The operator starts the experiment by fixing the air velocity at one value and then asks the subject whether the air velocity is TOO HIGH, TOO LOW, or JUST RIGHT. The subject responds by raising the signal board to tell the operator to LOWER, INCREASE, or DO NOT CHANGE the air velocity. The operator would adjust the fan speed in response to the subject request. Each time the operator waits about two minutes then asks the subject's feeling about air velocity again. The operator would repeat this experiment until the subject has confirmed the same preferred air velocity three times in a row.

4. Outline of the environmental test chamber

The environmental chamber is located on the third floor of a three story building in the Faculty of Engineering at Chulalongkorn University. The width and length of the chamber are approximately 2.9 by 5.8 meters respectively. The height is approximately 2.55 meters. The chamber is surrounded by the adjacent interior non air conditioning spaces except on one side that is the outside shaded wall. The inner wall of the outside shaded wall is heavily insulated to make sure that the mean radiant temperature is very close to the chamber air temperature. The ante room is at an end of the test chamber as shown in Figure 2. The operator can see and communicate with the subject through a small observation glass window.

The subject has a working station in the middle of the room. There are magazines, newspaper, candy, a bottle of drinking water and a computer with internet connection for the subject to spend time just like he or she is sitting in the office. The subject is welcome to bring his or her own paper to read or do homework in the environmental chamber.

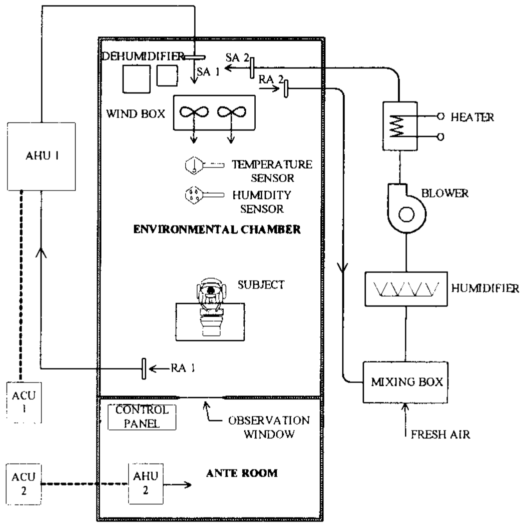

Figure 2. Schematic Diagram of HVAC System and of Environmental Test Chamber.

High air movements passing through the subject work station are created by a fan box. The fan box has a dimension of 1.0 meter by 1.5 meter with 6 propeller fans. The air velocity is controlled by a variac and a fan speed selector. The box can deliver a uniform air speed from 0.10 to 2.47 meter/sec to the subject work station at 2.5 meter in front of the fan box. A part of a return air will move up to the air handling unit in the ceiling and deliver cool air back to the supply mixing box located right behind the fan box. The hot and humid fresh air from outside will be mixed with return air and conditioned as required before being sent back via air duct to the supply mixing box. This conditioned air is then mixed with the room return air before being drawn through the fan box to the subject work station. The final room air temperature and humidity are controlled by the temperature and humidity sensors located midway between the fan box and the subject work station. The temperature of the walls, floor, and ceiling at 9 locations is monitored and recorded by a data logger every minute. Temperature and humidity in the room are recorded every 5 minutes. The noise level and the lighting level are adjusted to an acceptable level.

5. Prediction of thermal sensation under high air movements

The PMV model cannot predict thermal sensation (question no. 1 in the questionnaire) correctly at high air velocity as shown in Figure 3. Points on the diagonal line indicate the location where the experimental result should have been if PMV model could give a good prediction. The thermal sensation vote obtained from the experiment was much less than the value predicted by PMV. Therefore most of the points from experiment lied below the diagonal line. The same result was observed by Tanabe et al. (1994). As the velocity increased, the deviation from diagonal line increased. Tanabe also tried to explain that this was because Fanger's PMV model had neglected the increased heat loss from skin surface under high air velocity, and others thermal indices may have been more suitable.

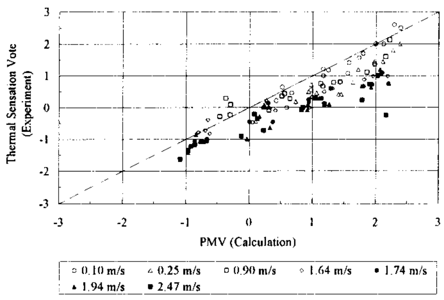

Figure 3. Thermal Sensation Vote (Experiment) VS. Calculated PMV.

Figure 4 is the plot of thermal sensation vote (question no. 1 in the questionnaire) against ET* at seven values of mean air velocity. ASHRAE Fundamental Handbook 2001 [5] publishes the relationship between ET* and air temperature, air humidity and mean radiant temperature.

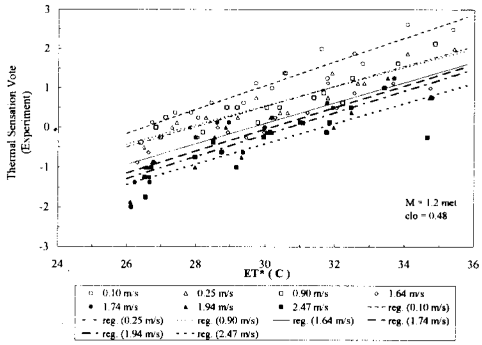

Figure 4. Thermal Sensation Vote (Experiment) VS. ET*.

The final attempt was to group these seven lines of Figure 4 into one single line. Figure 5 is the plot of the same thermal sensation vote from experiment against SET* defined by Gagge et al. [6]. The bandwidth of all 7 regression lines decreased significantly (from about 2.0 to about 0.82 on thermal sensation vote scale) due to the fact that SET* included some of the velocity effects.

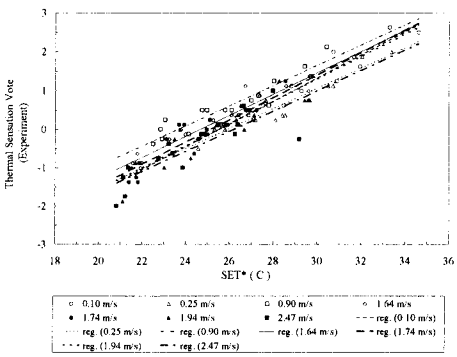

Figure 5. Relationship between Original SET* and Thermal Sensation Vote from Experiment at Several Values of Air Velocity.

This original SET* can be modified to decrease the bandwidth of the regression lines further. As suggested by Tanabe at al. [3], skin moisture should be decreased from the original value given by Gagge et al. [6] if a subject is under high air velocity, and the clo-value should be decreased as a function of air the velocity as well. Extensive study has been made to determine the best value of skin moisture and a modified clo-value to give the best possible fit of the experimental thermal sensation vote against a new modified SET*. The best possible fit of thermal sensation vote against new modified SET* is shown in Figure 6.

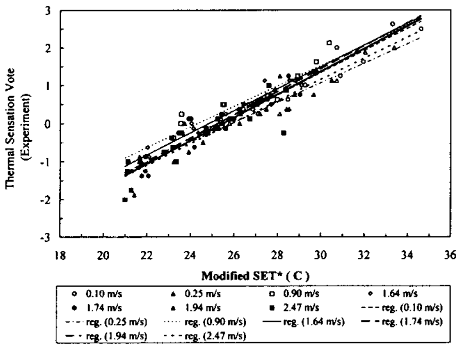

Figure 6. Relationship between Modified SET* and Thermal Sensation Vote form experiment.

Comparison between the bandwidth of the regression lines from Figure 5 and 6 indicates that the new bandwidth decreased significantly (from 0.82 to 0.44), and the accuracy on the SET* scale doubles.

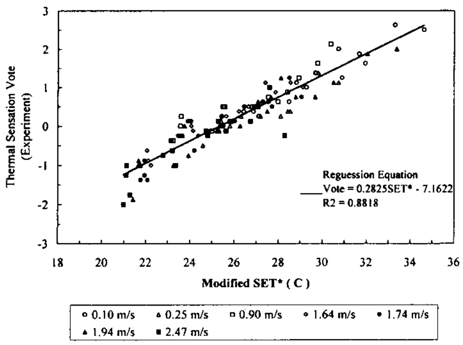

Figure 7. Relationship between Modified SET* and Thermal Sensation Vote form experiment.

Figure 7 shows the plot of one single regression equation on a total group of data points from the experiment. This regression equation may be used to approximate the thermal sensation vote of subject at any air velocity, metabolic rate, and clo-value.

To simplify the use of regression equation in Figure 7, Figure 8 shows the relationship between the value of Modified SET* and air temperature for a typical values of relative humidity, metabolic rate, clo-value and mean radiant temperature.

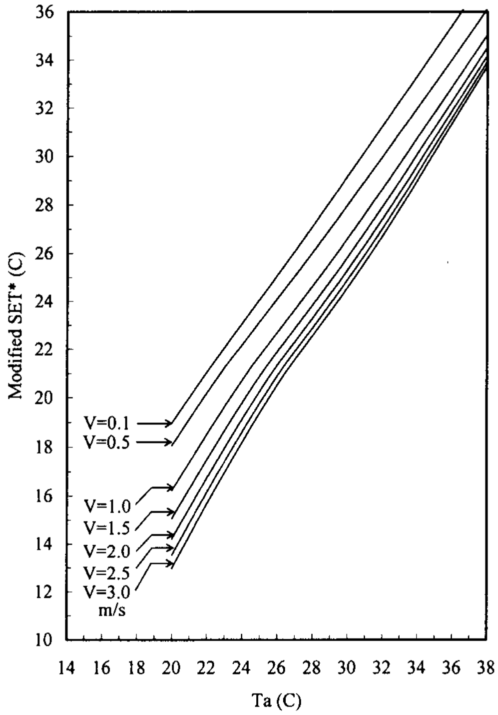

Figure 8. Relationship between Modified SET* and Environmental Parameters at rh=65%, M=1.2 met, clo=0.48, Tmrt=Tair

6. Acceptable range of design air velocity

In actual application, it is important to know the range of applicable air velocity that most people (80% or more) can accept. Question no. 10 in the questionnaire can be summarized in terms of PERCENTAGE OF ACCEPTABILITY and plotted against Modified SET* as shown in Figure 9. If a horizontal line drawn from 80% satisfied intersects the regression line at T1 and T2, the downward projection from T1 and T2 which intersect x-axis at SET*1 and SET*2 give a range of Modified SET* value where 80% or more of subjects accept a condition of thermal comfort in high air velocity. These two points are located approximately at Modified SET*=23.0 C and Modified SET*=26.3 C. The downward projection from the peak value of the regression line gives the value of Modified SET* where subjects give the highest percentage of vote. The value of Modified SET* at this point is at 24.3 C. These sets of values for Modified SET* can be used directly in the design for thermal comfort using high air movements.

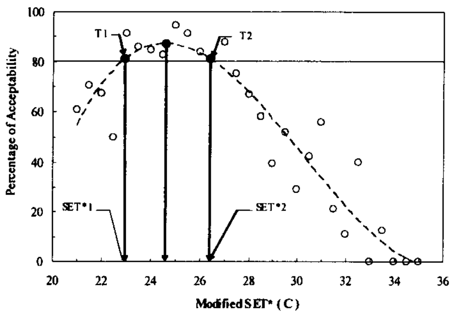

Figure 9. Relationship between Percentage of Acceptability and Modified SET*.

Information from question no. 1 and 9 from the questionnaire were also use to recheck the applicable range of Modified SET* obtained from question no. 10 as discussed in the previous paragraph. In Figure 10, PERCENTAGE OF SATISFIED with temperature for 0 vote (neutral) and -1 to +1 vote (slightly cool to slightly warm) are plotted against Modified SET*. In Figure 11, PERCENTAGE OF COMFORTABLE for 0 vote (comfortable) and -1 to 0 vote (slightly uncomfortable to comfortable) are plotted against Modified SET*. A range of Modified SET* obtains from the upper regression curve indicates the widest possible range or the upper and lower limits of Modified SET* for thermal comfort application under high air velocity. At the left end of the upper curves, subjects will feel slightly cool and slightly uncomfortable and at the right end subjects will feel slightly hot and also slightly uncomfortable. These values serve as a cross-check figure for the upper and lower limit for an acceptable Modified SET*. A downward projection form peak value of a smaller regression curves in both Figures indicate neutral SET* and the comfortable SET* that received the highest vote respectively.

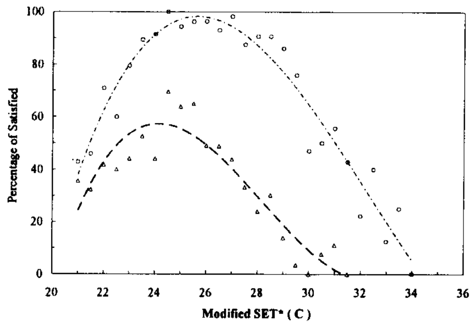

Figure 10. Relationship between Percentage of Satisfied and Modified SET*.

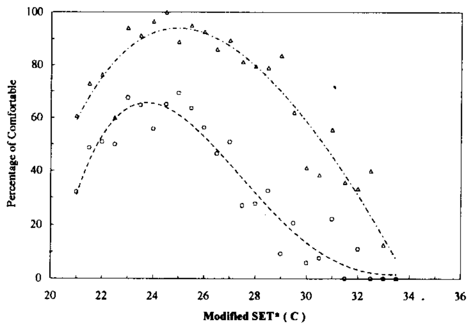

Figure 11. Relationship between Percentage of Comfortable and Modified SET*.

7. Air velocity for not draughty sensation

Air velocity sensation and preference vote indicate whether air velocity is draughty or not. They are summarized from question number 3 and 4. Question number 3 asked the subject about his or her feeing on the air-draught velocity (Not Draughty, Slightly Draughty, Draughty, and Very Draughty). Question number 4 asked the subject whether he or she wants to alter the existing air velocity (Less Air Velocity, No Change, and More Air Velocity). The answer from both questions could be translated to air velocity sensation and preference in terms of PERCENTAGE OF NOT DRAUGHTY and PERCENTAGE OF NOT DISTURBED and plotted against air velocity as shown in Figure 12 to 15. Results indicated that

80% of subjects felt satisfied NOT DRAUGHTY and NOT DISTURBED if the air velocity was not greater than approximately 0.9 m/s.

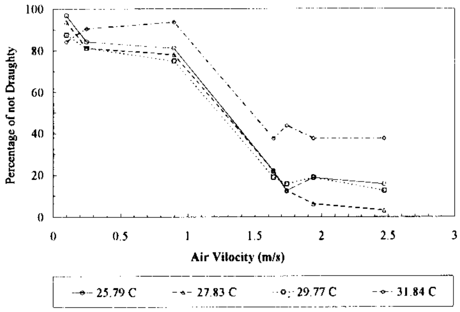

Figure 12. Percentage of not Draughty (vary temperature).

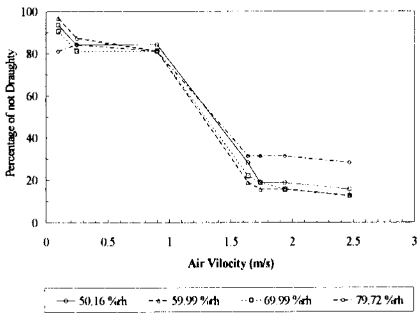

Figure 13. Percentage of not Draughty (vary relative humidity).

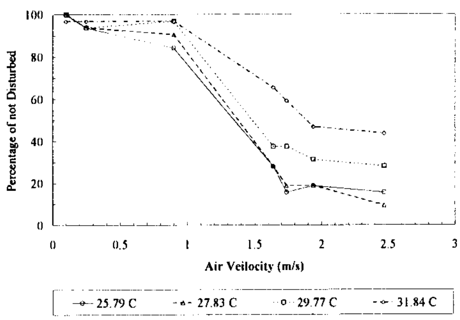

Figure 14. Percentage of not Disturbed (vary temperature).

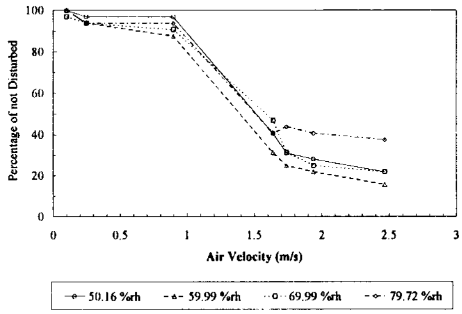

Figure 15. Percentage of not Disturbed (vary relative humidity).

8. Preferred air velocity

From experiment for preferred air velocity as described in 3, the results are shown in Table 3 and also plot in Figure 16 and 17. The value at each set of temperature and relative humidity for male is the average from four male college students and the value for female is the average from four female students. There was no significant difference in preferred air velocity between genders.

Table 3. Preferred Air Velocity.

Ta (°C)	% rh	female (m/s)	male (m/s)	female& male (m/s)
26	50	0.38	0.41	0.39
	60	0.41	0.41	0.41
	70	0.58	0.58	0.58
	80	0.74	0.76	0.75
28	50	0.98	1.09	1.03
	60	1.05	1.05	1.05
	70	1.27	1.16	1.22
	80	1.35	1.27	1.31
30	50	1.74	1.69	1.72
	60	1.64	1.72	1.68
	70	1.72	1.69	1.70
	80	1.79	1.84	1.82
32	50	1.87	1.74	1.81
	60	1.92	1.97	1.95
	70	2.16	2.21	2.18
	80	2.21	2.34	2.27

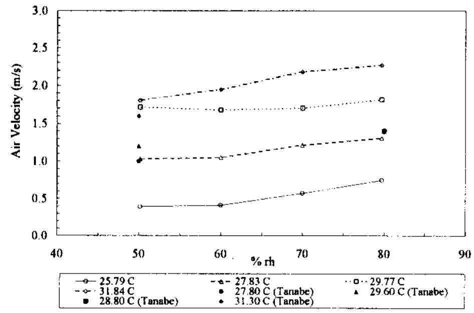

Figure 16. Preferred Air Velocity VS. Relative Humidity.

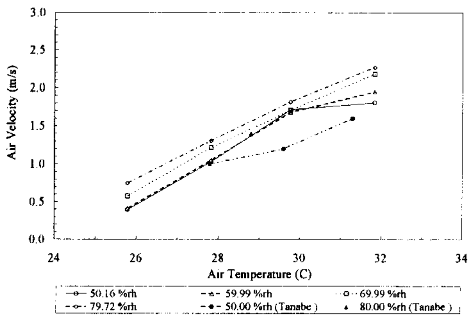

Figure 17. Preferred air Velocity VS. Air Temperature.

Figure 16 indicated that subjects preferred a slightly higher air velocity as the relative humidity increased especially between 60 to 80%. Figure 17 indicated that relative humidity had much less effect on the value of preferred air velocity than air temperature. However, one should keep in mind that the velocity above 0.9 m/s is undesirable (from previous discussion in 7) and the value of preferred air velocity above 0.9 m/s should be applied only in the situation where the subject is working in no stress condition.

Comparisons between the results obtained and the value given by Tanabe et al. (1994) are also included in Figure 16 and 17. The results obtained agree quite well with the values given by Tanabe.

9. Conclusions

A subjective experiment was conducted to find the effects of air velocity on thermal comfort under high air velocity. A total of 128 college-age students were asked to participate in the research work. An experiment was conducted in the environmental chamber at Chulalongkorn University during April to December 2002. Major points of the findings can be summarized as follows;

1. PMV model cannot predict thermal sensation correctly at high air velocity as shown in Figure 3. The same result was observed by Tanabe et al. [2]. Tanabe also tried to explain that this was because Fanger's PMV model had neglected the increased heat loss from skin surface under high air velocity, and other thermal indices may be more suitable.
2. The original SET* defined by Gagge et al. [6] needs to be modified further for the prediction of thermal sensation under high air velocity. Modification to decrease clo-value as a function of air velocity is necessary. Modification on skin moisture had very small effect, and could be neglected. The original skin moisture proposed by Gagge et al. provides satisfying results.
3. Results from air velocity sensation and preference vote indicated that 80% of the subjects were satisfied and felt NOT DRAUGHTY and NOT DISTURBED if air velocity was not greater than approximately 0.9 m/s. The air velocity greater than approximately 0.9 m/s should be applied only in the situation where there are no other choices and the subject is working under no stress conditions.
4. In natural ventilated space, preferred air velocity in Table 3 can be used to increase personal thermal comfort in hot and humid climates. Figure 16 indicated that subjects preferred a slightly higher air velocity as the relative humidity increased especially between 60 to 80%. Figure 17 indicated that relative humidity had much less effect on the value of preferred air velocity than air temperature. However, one should keep in mind that the velocity above 0.9 m/s is undesirable.
5. In general, a range of design air velocities applicable to most people (80 % or more) is between Modified SET*=23.0 C and Modified SET*=26.3 C. The best value where subjects give the highest vote is at Modified SET*=24.3 C. These values of

Modified SET* can be translated back to a more familiar set of environmental parameters by using Figure 8. These sets of values for Modified SET* can be used directly in the design for thermal comfort under high air movements. Boundary values of Modified SET* from Figure 10 and 11 can also be used to predict thermal sensation and acceptability of people under extreme conditions.

10. Acknowledgements

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