THE EFFECT OF AIR VELOCITY ON THERMAL COMFORT WITH MODERATE ACTIVITY

by

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Chapter 1

INTRODUCTION

ASHRAE Standard 55-1981 (ASHRAE 1981) defines thermal comfort as "That condition of mind which expresses satisfaction with the thermal environment ". This definition implies that psychlogical response to an environment which is determined by stimuli which affect all body senses is an important part of a feeling of comfort. Physiological responses are determined essentially by the thermal exchange between the occupant and the thermal parameters of the environment. A human response of "thermal comfort" is a complex physiological and psychological reaction, many factors will influence the reaction.

The ASHRAE Standard also indicates that the most important variables directly affecting thermal comfort are : (1) Environmental factors - dry bulb temperature (ta), relative humidity (rh), air movement (v), and mean radiant temperature (tmr), and (2) Personal factors - activity (heat production by the body) and clothing (thermal insulation). Individual differences such as age, sex and race are assumed to be second order variables. Fanger (1970) had made limited investigations of some of these second order variables and had found that age difference, sex difference, geographic difference, and race difference appear to have little effect on the preferred "comfort" temperature.

Usually research in thermal comfort and conditions affecting the thermal environment has been conducted in one of two ways. The first is to establish the parameters to be evaluated, expose subjects to these conditions and then obtain results based upon physiological measurements (skin temperature, heart rate, sweat rate, etc) and/or comfort ballots completed by the subject, then a physiological response model is developed to predict the "thermal comfort". The second method is to establish the parameters to be evaluated, allow control of those parameters by the subject, and have the comfort ballots completed by the subjects, then a thermal environment parameter model is developed to predict the "thermal comfort".

Fanger (1970) combined all the variables (air temperature, mean radiant temperature, water vapor pressure, air movement, activity level, insulation value of clothing) to develop a mathematical model which predicts thermal comfort at different environmental conditions. He also used the assumption that the thermal sensation, at a given activity level, is a function of thermal load (which he defines as the difference between the internal heat production and the heat loss to the environment under comfort conditions.) He correlated the sensation with the thermal load and developed a mathematical model to predict the thermal sensation index, PMV (predicted mean vote), expressed by a 7-point scale, for any combination of environmental variables, activity level and clothing. He also developed a PPD (predicted percentage of dissatisfication) model through the PMV model, an indication of the number who will be inclined to complain about the environment. This model can be used for rating the thermal quality of a given indoor environment. In Fanger's experiment for sedentary subjects, the optimum comfort occurs at the neutral condition (sensation = 0). It doesn`t tell whether the optimum comfort will occur higher or lower than the neutral condition with moderate activity.

Azer (1977) modelled the human body as two concentric cylinders. The inner cylinder represents the body core and the outer cylinder represents the skin. Energy is exchanged between the core and the skin through conduction and blood flow (convection). The skin exchanges energy with the environment by convection and radiation. Heat is dissipated through evaporation of sweat, and through water vapor diffusion of the skin. He developed a two-node thermoregulatory model which is expressed by two equations, for any combination of environmental parameters (ta, tmr, rh and v), clothing insulation, and metabolic heat production M, the integration results give the variation in core temperature and skin temperature. He also correlated the thermal sensation with the physiological responses at various temperature , then developed a thermal sensation model, he indicated that the warm thermal sensation correlated with wettedness factor and the cold thermal sensation correlated with vasoconstriction factor.

In modern industrial factories workers may spend as much as 95% of their time in artificial (air-conditioned) climates. The so called air-conditioned climates require the control of one or more of the four factors (dry bulb temperature, humidity, air movement and mean radiant temperature) of the thermal environment to create a "comfortable" environment for humans. It many require a lot of energy and money to maintain the comfort condition. Previous studies have been done that show elevated air velocities can be used to attain thermal comfort thereby reducing air-conditioning requirements. However, little research has been done showing the interaction of air velocity and activity and their effect on comfort at moderate activity levels typical of modern factories.

The purpose of this study is to compare the present experimental data with the predictions of the Fanger comfort model and the Azer thermal response model with elevated velocities and moderate activity. Also it will be determined whether the optimum comfort attainable is higher or lower at elevated air velocity than with no noticeable air movement. Also it will be determined whether the optimum comfort occurs in the neutral, cold or warm condition at moderate activity.

Chapter 2

BACKGROUND INFORMATION

The new ASHRAE comfort standard, ASHRAE Standard 55-1981 "Thermal Environment Condition for Human Occupancy" spcifies two comfort zones, one for winter and the other for summer. It places the upper limit of the summer comfort range at 79 F (26.1 C), when the air velocity is equal to or less than 50 fpm (0.25 m/s). The Standard states that if the air velocity is increased to 160 fpm (0.8 m/s), the comfort range could be extended to 82 F (27.8 C). Rohles et al. (1983) conducted a study in which 256 subjects were exposed to 4 temperatures (76 F [24.4 C], 79 F [26.1 C], 82 F [27.8 C], 85 F [29.4 C]) and different velocities ("still air", 30 fpm [0.15 m/s], 50 fpm [0.25 m/s], 90 fpm [0.45 m/s] and 200 fpm [1 m/s]), at constant 50% relative humidity. Their activity was sedentary with 0.5 clo of clothing. It was concluded that a ceiling fan may extend the upper limit of the summer comfort envelope from 79 F (26.1 C) to 85 F (29.4 C). Since ceiling fans are cheaper to operate than air-conditioning to operate, Rohles concluded that ceiling fans could represent a large energy saving without affecting human comfort.

Rohles (1965) made a hypothesis for sedentary activity that when the ambient temperature is low, a given velocity is unpleasant, when the temperature is slightly above the comfort zone (80-90 F), the same velocity is pleasant; and when the temperature is high, the velocity is again unpleasant.

Rohles et al. (1974) determined the effect of the affectivity on thermal sensation of sedentary human subjects when exposed to various conditions of air movement at different amibient temperatures. Forty five men and 45 women were exposed to the temperatures of 72 F (22.2 C), 78 F (25.6 C), and 85.2 F (29.5 C), and air velocities of 40, 80 and 160 fpm (0.2, 0.4, 0.8 m/s). The clo value was 0.6 and humidity was 50%. There were significant difference in thermal sensation due to temperature and air movement. Therefore a multiple regression equation for men and women combined after three hours' exposure was determined for the various temperature and air velocities at the constant relative humidity of 50%.

The result was:

$Y = 0.157*ET - 0.003*V - 8.416$

Y = thermal sensation for seven point scale

ET = ASHRAE old effective temperature (F)

V = air movement (fpm) when $V > 30$ fpm

Rohles et al. used this regression equation to predict the preferred ambient temperature for comfort. The study shows that the pleasant sensation increased with increasing temperatures for the air velocities of 80 and 160 fpm (0.4, 0.8 m/s). The pleasant sensation of air motion decreased as the temperature increased for the lowest tested velocity of 40 fpm (0.2 m/s), and the 78.6 F (25.9 C) and 72 F (22.2 C) conditions. This indicated that an increase in air movement was accompanied by a decrease in skin temperature and this was more pronounced in the case of the 72 F (22.2 C) condition than in the 78.6 F (25.9 C) condition.

McIntyre (1978) dealt with the maximum temperature elevation at which the increased air movement cannot provide a satisfactory condition. Six young males and six young females were exposed to different temperatures in the range from 22 to 30 C at 50% relative humidity. Subjects had light clothing and light activity. The experiment allowed subjects to regulate the speed of an overhead ceiling fan to get the optimum condition. The air velocity ranged from 0 to 1.86 m/s.

It was found that: 1) In warm amibient temperature, the subject found the use of an overhead fan reduced discomfort. 2) The air movement chosen did not fully compensate for the increase in air temperature. At the higher air temperature subjects felt warmer and had higher skin temperature than they did at the lower air temperature. 3) The upper limit of temperature for comfort is about 28 C. Above that temperature, the air speed required to decrease warmth discomfort produces too much disturbance. 4) Some subjects preferred air speeds at low temperatures which were too high for thermal comfort; possibly there was a benefit from "freshness".

Konz et al. (1983) investigated oscillating and fixed personal fans. Eight males were exposed to seven conditions at each of three temperatures (25.6, 27.8, 30 C) (78, 82, 86 F), all at 50% RH. The seven condition were : still air, velocities of 0.4, 0.8 and 1.2 m/s from a fixed fan and mean velocities of 0.3, 0.5 and 0.7 m/s, from an oscillating fan. The subjects performed a light pegboard task to keep constant activity, clothing value was 0.6 clo. The study showed that, for equal comfort, for every increase of mean air velocity of 0.1 m/s (between 0.4 and 1.2 m/s) the temperature can be increased by 0.27 C for the oscillating fan and by 0.4 C for the fixed fan. At the same mean velocity, the oscillating fan was voted more comfortable than the fixed fan.

There were two possibilities for the improved comfort for the oscillating fans. One is that fluctuation in air velocities are preferred to steady air velocities. Usually, the popular ceiling fans have quite variable velocities. The other one is that people react to the peak velocity rather than the average.

Satisfactory comfort conditions for a worker in a factory depend upon the rate of work (level of activity) and the type of clothing worn, in addition to the amibent conditions. In general, the greater the degree of activity, the lower the temperature required for thermal comfort. Previous studies of comfort conditions and work have concentrated mainly on determining the response of sedentary and slightly active subjects to different dry bulb temperatures and relative humidities.

McNall et al. (1967) determined the neutral temperature and comfort zone for men and women with activity levels resulting in metabolic rates of approximately 600, 800, 1000 Btuh (176, 234 and 293 W) for the average male subject. In addition to the votes of thermal sensation, observations were made of several physiological responses to the work rate. Two hundred and ten males and 210 females with the clo value of 0.6 were exposed to the temperature range of 54 - 78 F (12.2 - 25.6 C), relative humidities were 25, 45, 65%, and the air movement was still. Their activity was similar to that described for Master's (1950) two-step test. The subjects walked over two 9-in steps. The ratio of standing and walking was : stand 25 minutes - walk 5 minutes for the low activity level (600 Btuh [176 W]); stand 10 minutes - walk 5 minutes for the medium activity level (800 Btuh [234 W]); stand 5 minutes - walk 5 minutes for the high activity level (1000 Btuh [293 W]). The accuracy of the three activity levels was verified by using the evaporative heat loss and applicable heat transfer equations . This study indicated that for metabolic rates of 600, 800, and 1000 Btuh (approximately), the neutral thermal temperatures were 72, 66, and 60 F (22.2, 18.9, 15.6 C) respectively. Men and women indicated similar thermally neutral temperatures.

Fig. 1 and Fig. 2 are presented for comparison of thermal sensation at three activity levels and different dry bulb temperatures. A thermal sensation line for sedentary conditions was used from Nevins et al. (1966). From the diagram it is shown that females were more sensitive to thermal conditions for each activity than males. For three activity levels, a range of 25% to 65% relative humidity caused little effect upon men and women's "thermal comfort" at the 600 and 800 Btuh metabolic rates, it only affected the thermal comfort region for women at the 1000 Btuh metabolic rate.

Later McNall (1968), using oxygen consumption, determined the accuracy of the metabolic rates in the previous study of four activity levels (sedentary, low, medium, high activity). For the sedentary studies, 30 males and 30 females were exposed to the three temperatures (66 F [18.9 C], 72 F [22.2 C], 78 F [25.6 C]). Relative humidity was 50% for the low, medimum and high level of activity; 10 males and 10 females were exposed to the three temperatures (72 F [22.2 C], 66 F [18.9 C], 60 F [15.6 C]) for

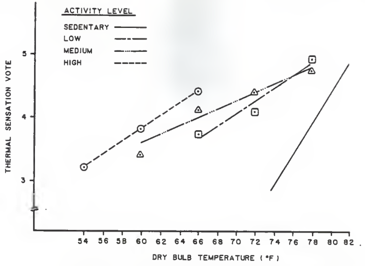

FIG. 1. THERMAL SENSATION VOTE vs DBT FOR MALES AT FOUR LEVELS OF ACTIVITY AFTER THREE HR EXPOSURE (McNALL 1967)

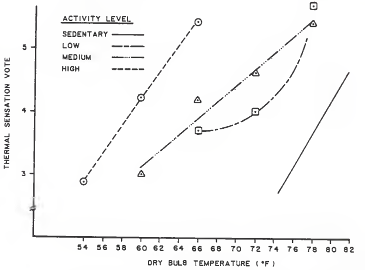

FIG. 2. THERMAL SENSATION VOTE vs DBT FOR FEMALES AT FOUR LEVELS OF ACTIVITY AFTER THREE HR EXPOSURE (McNALL 1967)

each activity. Relative humidity was 45%, their clothing value was 0.6, and the air velocity was "still".

The mean metabolic rates for the third hour of the three-hour test period, at the four levels of activity, were 389, 622, 829, 1061 Btuh (114, 182, 243, 311 W) for the men and 301, 492, 653 and 826 Btuh (88, 144, 192, 242 W) for the women. A regression equation to predict the metabolic rate (MR) and evaporative heat loss (E) for each activity was:

$$\text{Model 1: } MR = a(wt)^{b}$$
$$E = a(wt)^{b}$$
$$\text{Model 2: } MR = a(wt)^{b1}(ht)^{b2}$$
$$E = a(wt)^{b1}(ht)^{b2}$$

Where:

MR = metabolic rates (Btuh)

E = evaporative heat loss (Btuh)

a,b,bl,b2 = constant value of exponent for each activity

wt = individual's nude weight (lb)

ht = individual's height (in)

These equations predict metabolic rates for sedentary, standing and walking subjects, based on their height and weight, and are determined from a regression analysis; these indicate that the subject's weight is the principal variable governing walking and standing metabolic rates and evaporative heat losses.

Chapter 3

METHOD

Experiment Design

For this study, college student volunteers were exposed for 120 minutes to each of the combinations of work and heat given in Table 1 :

1) Metabolic level was approximately 2.3 Met (133 w/m^2).
2) Relative humidity was 50%.
3) Clo value was 0.65.
4) Mean radiant temperature was equal to the dry bulb temperature.

5a) Relative air velocity was approximately 42 fpm (0.21 m/s) and dry bulb temperature ranged from 55 F to 73 F (10 C to 23 C).

5b) Relative air velocity was approximately 264 fpm (1.32 m/s) and dry bulb temperature ranged from 61.5 F to 78 F (16 C to 26 C).

These test conditions were based on calculations with the Fanger model and were intended to yield mean thermal sensation votes ranging from -1 (slightly cool) to +1 (slightly warm).

The subjects were tested in groups of 4 (2 men and 2 women). The total time of each test was 2.5 hours. Subjects spent one half hour in the orientation room and two hours in the test chamber.

Table. 1. Test Condition

Test No	Temp F (C)	Velocity fpm (m/s)	Time*
1	66.2 (19.0)	42 (0.21)	A
2	71.6 (22.0)	264 (1.32)	E
3	55.0 (12.8)	42 (0.21)	A
4	61.5 (16.4)	264 (1.32)	E
5	70.5 (21.4)	42 (0.21)	A
6	74.2 (23.4)	264 (1.32)	E
7	66.5 (19.2)	264 (1.32)	A
8	60.5 (15.8)	42 (0.21)	E
9	78.0 (25.6)	264 (1.32)	A
10	73.0 (22.8)	42 (0.21)	E
11	74.2 (23.4)	264 (1.32)	A
12	70.5 (21.4)	42 (0.21)	E
13	63.0 (17.2)	264 (1.32)	A
14	70.0 (21.1)	42 (0.21)	E

* A - Afternoon from 2:00 pm to 4:30 pm.

E - Evening from 6:30 pm to 9:00 pm.

Activity Level

The task for each test condition was similar to that described for Master's (1950) two-step test. McNall (1968) conducted an experiment to determine the metabolic rates of different activity levels with the two-step test by measuring oxygen consumption. The metabolic rate for the medium activity (stand 10 minutes - walk 5 minutes) was between 800 - 850 Btuh (2.2 - 2.4 Met). In the present study, subjects walked over a set of two 9 inch steps (Fig. 3) once every 15 seconds. They stood approximately 10 seconds and walked approximately 5 seconds. The continuous activity of the subjects kept more steady metabolic rates. Subjects had a 5 minutes rest for each half hour experiment. The calculation of metabolic rates is shown in appendix D. The average metabolic rates were approximately 2.35 Met for males and 2.02 Met for females.

Subjects

The subjects were 56 college students (29 men and 27 women) ranging in age from 18 to 26 years. Their physical characteristics (weight, height) are shown in Appendix E . Each subject must have resided in the continental U. S. for at least six months prior to the test and each was paid $ 10 for participating. No one served as a subject more than once during the study.

Subjects completed a release form prior to begining the test. An informed constant statement and subject orientation and test procedure form are included in appendix A and B.

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Fig. 3 Subjects performing the stand-walk activity.

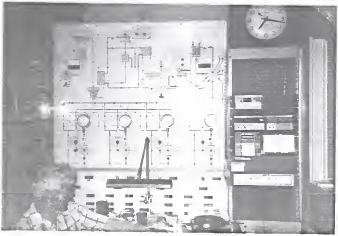

Fig. 4 Temperature-humidity control room and room temperature recorder.

Clothing

The clothing workers wear when working in a factory varies considerly. In this experiment a standard K.S.U uniform was chosen to simulate the worker's clothing. Each subject wore a long sleeve shirt (shirt tail out) and trousers, plus their own socks and a pair of comfortable shoes.

The insulation of the uniform was measured by using a heated manikin (Fig. 5). The measured value of clo (Icl) is 0.65 which is slightly different from the previous reported value of 0.6 clo for the KSU uniform.

Air Velocity Determination

Fig. 7 shows the test room layout, work-stations and air motion. The air movement measurements were taken using 2 TSI model 1620 anemometers which were calibrated before taking measurements, and 1 microcomputer equipped with a data acquisition system. The anemometers were calibrated and the resulting data were fit to polynominal equation for use with computer.

In this experiment, subjects performed the activity of a stand-walk cycle. The relative air velocity was a combination of air movement and subject's motion . Air velocities were measured at 4 ft (121 cm) and 6 ft (182 cm) from the floor when standing. Anemometers were moved the same as stand-walk cycle for each of the four locations. Data were collected for 5 minutes at each location and recorded on the computer. Mean and standard deviations then were determined using 150 values from the recording, equally spaced in time over the 5 minutes. These measurements

Fig. 5 Thermal manikin and KSU standard uniform.

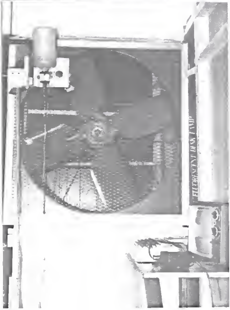

Fig. 6 Fan, temperature sensor and a computer for auditory buzzer.

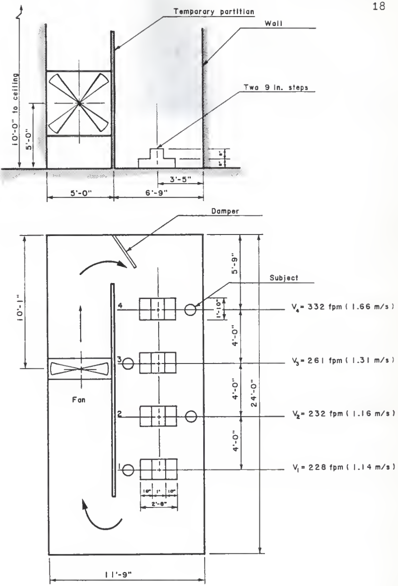

FIG. 7. LAYOUT OF WORK STATION WITHIN THE CHAMBER AND AIR DISTRIBUTION AT EACH WORK STATION

were repeated 4 times at each location to verify the results. Table 2 and Fig. 7 present the results of these mesurements.

The air movement in the chamber was "turbulent"; this caused a fluctuation of the velocity. The standard deviation was quite large for each location. It was difficult to accurately measure and average the air velocity for the stand-walk cycle. Tolerances of 20% should be assigned to the numbers reported here. The mean relative air velocity with the fan was 264 fpm (1.32 m/s) and the mean relative air velocity without the fan was 42 fpm (0.21 m/s).

Table. 2

Mean velocities and Standard Deviation at
The 4 Work-stations

Work-Station	Velocities fpm (m/s)	Standard Deviation fpm (m/s)
Location 1	228 (1.14)	38.5 (0.19)
Location 2	232 (1.16)	43.0 (0.22)
Location 3	261 (1.31)	47.5 (0.24)
Location 4	332 (1.66)	52.2 (0.26)
Without Fan (All 4 Locations)	41.5 (0.21)	15.5 (0.08)

Apparatus and Facilities

The experiment was conducted in the Institute for Environment Research (IER) KSU - ASHRAE chamber. The dimensions of the test chamber are 24 ft (7.3 m) by 12 ft (3.64 m) with a 10 ft (3.03 m) ceiling height. The chamber has its own chiller , air handling system and temperature - humidity control system (Fig. 4). The test room temperature was recorded every minute during the test.

A 48 in (122 cm) diameter fan (Fig. 6) was installed at the center of a 10 ft ceiling height and located at the 10 ft (305 cm) distance from inner wall (Fig. 7). It has 4 blades and the driving motor was 1.5 HP. In order to produce a more uniform air movement, a damper was used to direct the air flow away from the wall (Fig. 7).

Each subject was assigned a set of two 9 inch steps to perform the stand-walk cycle, and a chair to sit on during the 5 minute break. A computer was used to make a sound as a signal for the subjects to start walking over to the steps.

Procedure

When the subjects reported for the experiment they went first to the pre-test room and their oral temperatures and heart rates were taken. If the oral temperature was not above 99.1 F and the heart rate was below 90, they were allowed to proceed.

Then the subjects went to the clothing rack to pick out their size and changed into the clothing required for the experiment. When the dressed subjects returned to the pretest room, their weight and height were measured and recorded for reference.

When all 4 subjects were dressed and assembled in the pretest room the oriention started. The pre-test room temperature ranged from 72 F (22.2 C) to 78 F (25.6 C). The subjects stayed in the pre-test room for approximately 30 minutes. During this time, an orientation (appendix A) was read to the subjects, and the subjects were shown the three types of ballots (thermal sensation, thermal comfort, thermal environment) that were distributed among them every half hour of the experiment (Fig. 8, 9, 10). After the subjects learned and practiced how to fill out the ballots and fully understood the procedure, they entered the chamber and the experiment began.

Upon entering the test chamber, each subject was assigned a work-station. In order to keep their metabolic rate constant , an auditory buzzer was used to signal when subjects should walk over the step. The activity cycle then began with a computer sound. This cycle continued for two hours, for each one half hour, there was a 5 minutes break for subjects. During the break, three comfort ballots were given to them to vote. The first ballot, the thermal sensation response, was measured on a 9 category rating scale (Fig. 8). The second ballot measured thermal comfort. There were seven bi-polar adjective pairs arranged in a semantic-differential scale format (Fig. 9). The third subjective scale measured thermal satisfaction and dissatisfaction. The 32 item scale for evaluating the thermal environment is presented in Fig 10. The subjects were allowed to drink as much water as desired, but no food or beverage was consumed during the experiment. They were allowed to freely converse during the experiment but could not discuss their thermal comfort. At the end of the two and half hours (two hours in chamber). Subjects were asked to dress back into their own clothing, paid $10, and were dismissed.

Study________Name________________________NO_________

Test No__________Sex_____________Vote____________

Comfortable__ __ __ __ __ __ __ __ __Uncomfortable

bad temperature__ __ __ __ __ __ __ __ __Good Temperature

Pleasant__ __ __ __ __ __ __ __ __Unpleasant

Warm__ __ __ __ __ __ __ __ __Cool

Unacceptable__ __ __ __ __ __ __ __ __Acceptable

Satisfied__ __ __ __ __ __ __ __ __Dissatisfied

Uncomfortable__ __ __ __ __ __ __ __ __Comfortable
Temperature Temperature

Fig. 9. Thermal Comfort Ballot

study_________Name____________________No___________________

test No____________Sex_______________Vote_______________

___ VERY HOT

___ HOT

___ WARM

___ SLIGHTLY WARM

___ NEUTRAL

___ SLIGHTLY COOL

___ COOL

___ COLD

___ VERY COLD

Fig. 8. Thermal Sensation Ballot

7 = very accurate

6 = accurate

5 = slightly accurate

4 = NEUTRAL, neither accurate nor inaccurate

3 = slightly inaccurate

2 = inaccurate

1 = very inaccurate

1. uncomfortable.....______
2. content with......______
3. agreeable.........______
4. tolerable.........______
5. unpleasant........______
6. inadequate........______
7. Annoyiny..........______
8. undesirable.......______
9. satisfactory......______
10. miserable.........______
11. satisfied with....______
12. good..............______
13. unacceptable......______
14. enjoyable.........______
15. great.............______
16. distressful.......______
17. bad...............______
18. acceptable........______
19. discontent with...______
20. pleasant..........______
21. dissatisfied with.______
22. comfortable.......______
23. intolerable.......______
24. disagreeable......______
25. adequate..........______
26. desirable.........______
27. unsatisfactory....______
28. gratifying........______
29. pleasing..........______
30. poor..............______
31. appealing.........______
32. delightful........______

Fig. 10. Thermal Environment Ballot

Chapter 4

EVALUATION OF COMFORT

The measurement of the human response to the thermal environment or how one feels has been a topics of behavioral research for many years. Rohles et al. (1981) discussed how to measure humans' feeling. There were three perspectives for human response to the environment. The first is physiology and involved the physical factor of body temperature, heart rate, blood pressure and respiration. These measures are clearly defined, objective, and readily obtained and standardized. The second is performance which depends heavily upon drive or motivation. These motivational factors are difficult to control and more difficult to assess. The third criterion is affectivity or the way in which one feels. To measure the affective mental process, an experiment is designed to obtain a descriptive account of the subjects' feeling by having them make reports, judgments, or evaluations. The affectivity measures lack standardization and are highly subjective. The rating scale is almost universally selected as the measuring tool to assess feelings of comfort or discomfort or warmth or coldness. According to Rohles, the techniques and devices are continually under study and the semantic differential scale appears to be the most valid and reliable instrument that has been developed to date.

Most of the previous studies dealt experimentally with human physiological response when exposed to various level of thermal environment. But it was very difficult work. Physiological activity, dry bulb temperature, vapor pressure, and mean radiant temperature all influence physiological response and must be controlled and systematically varied for complete experimental evaluation. This process is very time consuming and expensive. An alternative approach to this problem is through mathematical modeling of the thermoregulatory system.

Recently, through the development of thermal comfort research, subjective measures have gained wide acceptance. Most researchers use a rating scale to measure the human reponse. These measures allow judgment of thermal comfort without unduly interfering with the subjects (particularly important when physical movement is involved). Thus more realistic situations can be judged for thermal comfort.

In order to compare the results with previous research, the affective mental process was used to measure the subjects' response in this study. The three measures are : thermal sensation, thermal comfort, thermal environment. The first two measures have gained acceptance as standard measures, and the third is still somewhat experimental. All measures are collected via balloting, and although all are measures of thermal comfort, each approaches the subject in a slightly different way, so that a full impression of the environment is ensured.

Thermal Sensation

Thermal sensation has been defined as a conscious experience resulting from exposure to a group of variables making up the thermal environment. Previous studies used a seven category rating scale to assess the "conscious experience". The subject chose a value from the ranges from hot, warm, slightly warm, neutral, slightly cool, cool, cold which described how he feels at the time of the balloting. To increase the variability, Rohles (1974) proposed a nine category scale by adding the terms "very hot" and "very cold" at either end of the scale. The reason is raters tend to spread the overall distribution of ratings and tend to avoid the terminal categories. In this experiment the nine category scale (see Fig. 8) to measure the subjects' response was used.

Thermal Comfort

The ASHRAE Standard defines thermal comfort as that "state of mind that expresses satisfaction with thermal environment". As in the case of thermal sensation, a subjective rating scale was required to measure this condition. Rohles (1978) conducted a study to deal with the development of the rating scale, and suggested the use of the semantic differential scale as the best way to assess feelings of thermal comfort. Later Rohles et al. (1981) conducted another study to determine how to develop a scaling procedure to evaluate the affective characteristics of the environment and the various features it contains.

Previous research has shown that accurate data can be accumulated using the standard seven bi-polar adjective pairs (Fig. 9). Rohles et al. (1984) suggested the use of six bi-polar adjective pairs (Fig. 11) instead of the previous seven adjective pairs. In this study, for all six bi-polar adjective pairs, each subject is required to check one of the nine spaces that best describes how he feels at that time.

Comfortable	9: 8: 7: 6: 5: 4: 3: 2: 1	Uncomfortable
Bad Temperature	1: 2: 3: 4: 5: 6: 7: 8: 9	Good Temperature
Pleasant	9: 8: 7: 6: 5: 4: 3: 2: 1	Unpleasant
Unacceptable	1: 2: 3: 4: 5: 6: 7: 8: 9	Acceptable
Uncomfortable Temperature	1: 2: 3: 4: 5: 6: 7: 8: 9	Comfortable Temperature
Satisfied	9: 8: 7: 6: 5: 4: 3: 2: 1	Dissatisfied

Number in Cells are the values assigned to the ratings; loading are as following: Comfortable - Uncomfortable, .555; Bad Temperature - Good Temperature, .693; Pleasant - Unpleasant, .628 ; Unacceptable - Acceptable, .521; Uncomfortable Temperature - Comfortable Temperature, .726 ; Satisfied - Dissatisfied, .568. The sum of the loading = 3.691. The thermal comfort in the form of a index is computed from the formula.

$$Tc = (\ (\text{rating}*\text{loading}) - 3.691^{*}\ )*3.87^{**}$$

* Gives minimum vaule of 0.

** Scaling factor to yield a maximum vaule of 100.

Fig. 11. Theraml Comfort Ballot Scoring

The calculation of an average score for a theraml comfort vote is somewhat complicated. The spaces between each adjective pair are assigned a value from 9 for the most favorable of the adjective pairs to 1 for the least favorable of the adjective pairs. A weighted loading factor formula has been derived through a statistical method published by Rohles and Milliken (1981). This weighted average is then compared to the maximum and minimum scores possible considering the loading factors, converting the average score to an index from 0 to 100. The resulting value constituted the thermal comfort vote in the form of an index (Fig. 11).

Thermal Environment

The differential attribute scale developed by Rohles and Laviana (1985) at Kansas State University represents a recent extension of the semantic differential scale. This new scale is experimental and has not yet been widely used. There are 32 adjectives for evaluating the thermal environment, The votes were evaluated by assigning a value from 1 for the least inaccurate of the adjectives to a value of 7 for the most accurate. A factor analysis was performed which resulted in 15 of the adjectives being divided into two factors which were thermal satifaction and thermal dissatisfaction. Adjectives associated with each factor and the loading of each adjective are listed in Table 3.

The scale also measures thermal comfort . It does not measure the same dimension as the thermal comfort scale , but, according to Rohles and Laviana (1985), it offers a novel approach to measuring affective qualities.

Table. 3. Factors and Loading Derived from the Thermal Environment Vote

Factor 1	Thermal satisfaction
Enjoyable	.783
Great	.800
Desirable	.700
Gratifying	.764
Pleasing	.825
Appealing	.816
Sum	4.688

The thermal satisfaction in the form of an index is computed from the formula:

$$\text{Tsat} = ((\text{rating}*\text{loading}) - 4.688^{*})*3.556^{**}$$

Factor 2	Thermal Dissatisfaction
Annoying	.761
Undesirable	.710
Unacceptable	.728
Bad	.763
Discontent with	.729
Intolerable	.719
Disagreeable	.739
Unsatisfactory	.737
Poor	.753
Sum	6.639

The thermal dissatisfaction in the form of an index is computed from the formula:

$$\mathrm{Tdis} = (\,(\mathrm{rating}*\mathrm{load}) - 6.639^{*}\,)*2.511^{**}$$

* Gives minimum vaule of 0.

** Scaling factor to yield a maximum value of 100.

Chapter 5

RESULTS AND DISCUSSION

Results

The twelve test conditions analyzed are described in Table 1. The purpose of this study was to determine the subjects' responses to the different thermal environments. The room temperatures were controlled and recorded during each test, the average temperature for each test was very close (± 0.5 F) to the experimental requirement.

The voting data were entered into a computer file, identified by temperature, sex, location and test duration for two conditions (fan ,no fan). These data were treated by analysis of variance to determine the significant influence of temperature, sex, location and test duration) on the four comfort measures. A significance level of $p < 0.05$ was used.

Thermal Sensation

The thermal sensation votes were rated as followed : very hot = 9, hot = 8, warm = 7, slightly warm = 6, neutral = 5, slightly cool = 4, cool = 3, cold = 2, very cold = 1. Each subject voted 4 times during each test. These multiple votes were averaged by each group of subjects so that the mean vote values can be determined for each set of test conditions and group of subjects.

The mean votes at the end of the second hour of testing for male and female and subjects combined at the two air velocities are shown in Appendix E and presented graphically in Fig. 12.

An analysis of variance was performed on the votes for the two conditions (fan, no fan); see Tables 4 and 5. Temperature is significant for both the fan and no fan conditions.

Tables 6 and 7 show Duncan's (1955) multiple range test for the various means for both conditions. The letters indicating different groupings in the tables show those mean temperatures that are significantly different from each other.

Thermal Comfort

Fig. 9 shows the thermal comfort ballot. The assigned rating values were multipled by the weighted factor, then a comfort index vote for each ballot was obtained. The male, female and combined mean thermal comfort votes after the second hour exposure to each experiment condition are shown in Appendix E and presented graphically in Fig. 13.

An analysis of variance was performed on the votes for both conditions (Tables 8 and 9). Temperature was significant for both the fan and non-fan condition.

Tables 10 and 11 show the Duncan's multiple range test for the mean votes of each temperature for both conditions. The Letters indicating different groupings in the tables show those mean temperatures that are significantly different from each other.

Fig. 13 shows the combined mean thermal comfort at different temperatures for the two air velocities. Maximum comfort is at approximately 63 F (17.2 C) with a velocity of 0.21 m/s and at approximately 71.6 F (22 C) for the fan condition . The maximum for the fan condition is higher than with the 0.21 m/s condition.

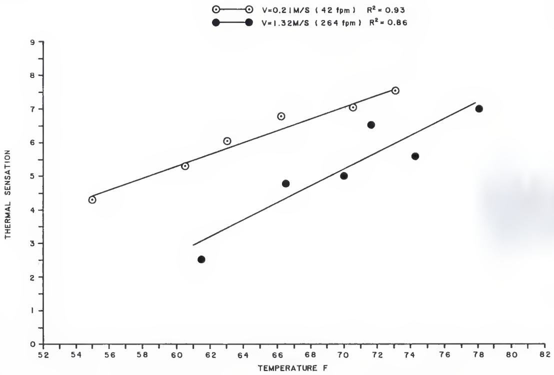

FIG. 12. MEAN THERMAL SENSATION VS. TEMPERATURE FOR TWO AIR VELOCITIES. (LINES BASED ON LINEAR REGRESSION)

Table. 4. Analysis of Variance for Thermal Sensation Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	15.7	10.22	0.0001
Sex	1	0.2	0.12	0.7299
Temp*Sex	5	5.7	3.69	0.0047
Time	3	2.2	1.44	0.2357
Temp*Time	15	0.6	0.36	0.9848
Error	82			
Total	111			

Table. 5. Analysis of Variance for Thermal Sensation Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	38.7	30.62	0.0001
Sex	1	0.2	0.19	0.6634
Temp*Sex	5	2.3	2.14	0.0677
Time	3	3.1	2.49	0.0651
Temp*Time	15	0.5	0.38	0.9801
Error	82			
Total	111			

Table. 6. Mean Thermal Sensation Votes For Each Temperature without Fan

Temperature (F)	Mean	Grouping*
73	6.94	A
70.5	6.55	A B
66.2	6.19	A B
63	5.89	B
60.5	5.69	B
55	4.19	C

* Means with the same letter are not significantly different at $p < 0.05$

Table. 7. Mean Thermal Sensation Votes for Each Temperature with Fan

Temperature (F)	Mean	Grouping*
78	6.88	A
71.6	5.94	B
74.2	5.59	B
66.5	4.63	C
70	4.44	C
61.5	2.44	D

* Means with the same letter are not significantly different at $p < 0.05$

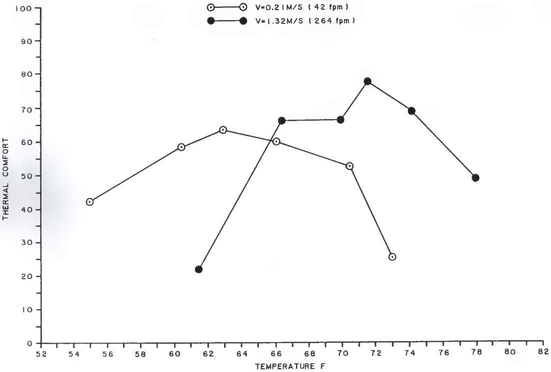

FIG. 13. MEAN THERMAL COMFORT VS. TEMPERATURE FOR TWO AIR VELOCITIES.

Table. 8. Analysis of Variance for Thermal Comfort Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	2423.5	5.09	0.0005
Sex	1	367.8	0.77	0.3819
Temp*Sex	5	1845.7	3.88	0.0034
Time	3	929.1	1.95	0.1260
Temp*Time	15	239.3	0.50	0.9325
Error	82			
Total	111			

Table. 9. Analysis of Variance for Thermal Comfort Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	6507.7	23.45	0.0001
Sex	1	27.9	0.10	0.7519
Temp*Sex	5	1539.3	5.55	0.0002
Time	3	50.1	0.18	0.9071
Temp*Time	15	208.8	0.51	0.9272
Error	82			
Total	111			

Table. 10. Mean Thermal Comfort Votes For Each Temperature without Fan

Temperature	Mean	Grouping*
66.2	64.86	A
63	60.39	A
70.5	58.35	A
60.5	57.87	A
55	38.48	B
73	36.49	B

* Means with the same letter are not significantly different at $p < 0.05$

Table. 11. Mean Thermal Comfort Votes for Each Temperature with Fan

Temperature	Mean	Grouping*
71.6	76.95	A
74.2	70.08	A B
66.5	59.37	B
70	56.49	C
78	50.45	C
61.5	21.64	D

* Means with the same letter are not significantly different at $p < 0.05$

This result verifies and is consistent with previous research that concluded that a fan can improve thermal comfort in warm conditions (Rohles et al. 1982, Vanduke et al. 1983).

Thermal Satisfaction

Table 3 shows the thermal satisfaction scoring. A satisfaction index vote for each ballot was obtained by using the thermal satisfaction equation. The male, female and combined mean thermal satisfaction votes after the second hour exposure to each condition are shown in Appendix E and are presented graphically in Fig. 14.

The data were subjected to an analysis of variance for two conditions (Tables 12 and 13). Temperature was significant with the 0.21 m/s condition at $p<0.1$ (but not at $p<0.05$) and was significant in the fan condition. Tables 14 and 15 show the Duncan's multiple range test for the mean votes of each temperature for both conditions respectively. The letters indicating different groupings in the tables show those mean temperatures that are significantly different from each other.

Fig. 14 shows the combined mean thermal satisfaction at different temperature for the two air velocities. Maximum satisfaction is at approximately 63 F (17.2 C) for 0.21 m/s and at approximately 74.2 F (23.4 C) for 1.32 m/s, the peak satisfaction with the fan condition is higher than in still air. The result is consistent with the thermal comfort votes showing that the fan can improve thermal satisfaction in warm conditions.

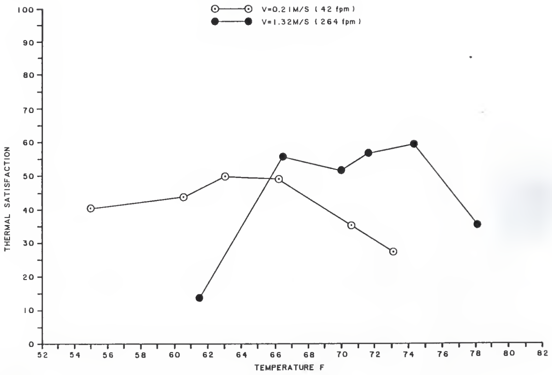

FIG. 14. MEAN THERMAL SATISFACTION VS. TEMPERATURE FOR TWO AIR VELOCITIES.

Table. 12. Analysis of Variance for Thermal Satisfaction Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	1291.2	2.16	0.0655
Sex	1	797.8	1.34	0.2510
Temp*Sex	5	1988.3	3.33	0.0087
Time	3	774.0	1.30	0.2805
Temp*Time	15	336.8	0.56	0.8939
Error	82			
Total	111			

Table. 13. Analysis of Variance for Thermal Satisfaction Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	4359.9	12.05	0.0001
Sex	1	1746.5	4.83	0.0309
Temp*Sex	5	1720.9	4.75	0.0008
Time	3	130.8	0.36	0.7838
Temp*Time	15	100.5	0.28	0.9959
Error	82			
Total	111			

Table. 14. Mean Thermal Satisfaction Votes For Each Temperature without Fan

Temperature	Mean	Grouping*
66.2	55.04	A
63	48.98	A B
55	43.22	A B
70.5	40.17	A B
60.5	33.32	B
73	31.90	B

* Means with the same letter are not significantly different at $p < 0.05$

Table. 15. Mean Thermal Satisfaction Votes for Each Temperature with Fan

Temperature	Mean	Grouping*
71.6	64.66	A
66.5	51.92	A B
74.2	51.47	A B
70	46.97	B C
78	36.43	C
61.5	17.23	D

* Means with the same letter are not significantly different at $p < 0.05$

Thermal Dissatisfaction

The calculation of thermal dissatisfaction index is done by the same method as thermal satisfaction. The calculation is shown in Table 3. The male, female and combined subjects' mean thermal dissatisfaction for different temperatures and air velocities are shown in Appendix E and presented graphically in Fig. 15.

Tables 16 and 17 show the analysis of variance which indicates temperature is significant for both with and without the fan. Tables 18 and 19 show the Duncan's multiple range test for fan and non-fan condition respectively. The letters indicating different groupings in the tables show those mean temperatures that are significantly different from each other.

Fig. 15 shows the combined subjects' mean thermal dissatisfaction at different temperatures for the two air velocities. The minimum dissatisfaction is at approximately 60.5 F (15.8 C) for still air and at approximately 74 F (23.3 C) for the fan condition, the minimum of the fan condition is lower than it in still air. These results are consistent with thermal comfort and thermal satisfaction votes.

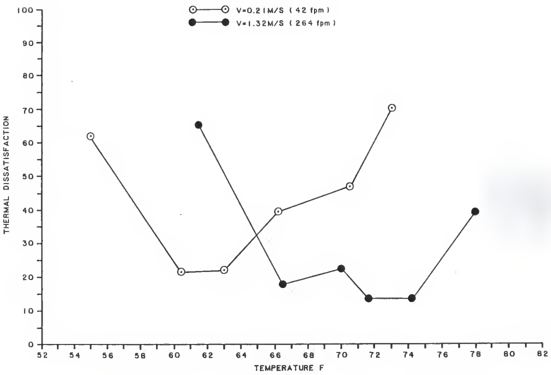

FIG. 15. MEAN THERMAL DISSATISFACTION VS. TEMPERATURE FOR TWO AIR VELOCITIES.

Table. 16. Analysis of Variance for Thermal Dissatisfaction Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	3087.7	9.13	0.0001
Sex	1	674.4	1.99	0.1617
Temp*Sex	5	2213.5	6.55	0.0001
Time	3	983.6	2.91	0.0389
Temp*Time	15	335.1	0.99	0.4726
Error	82			
Total	111			

Table. 17. Analysis of Variance for Thermal Dissatisfaction Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	6793.8	20.36	0.0001
Sex	1	766.8	2.30	0.1334
Temp*Sex	5	1270.8	3.81	0.0039
Time	3	2.9	0.01	0.9960
Temp*Time	15	40.8	0.12	1.0000
Error	82			
Total	111			

Table. 18. Mean Thermal Dissatisfaction Votes For Each Temperature without Fan

Temperature	Mean	Grouping*
73	58.16	A
55	54.64	A
70.5	39.26	B
66.2	31.96	B C
60.5	28.57	B C
63	24.98	C

* Means with the same letter are not significantly different at $p < 0.05$

Table. 19. Mean Thermal Dissatisfaction Votes for Each Temperature with Fan

Temperature	Mean	Grouping*
61.5	64.25	A
78	39.78	B
70	36.86	B
66.5	19.26	C
74.2	17.45	C
71.6	10.50	C

* Means with the same letter are not significantly different at $p < 0.05$

Discussion

ASHRAE Standard 55-1981 places the upper limit of the summer comfort range at 79 F (26.1 C) when the air velocity is equal to or less than 50 fpm (0.25 m/s). However, the comfort zones may be extended to 82 F (27.8 C) if the air velocity is increased to 160 fpm (0.8 m/s). In the study on ceiling fans, Rohles et al. (1982) suggested an increase in the upper limit of the summer comfort envelope to 85 F (29.4 C) with a velocity of 200 fpm (1.0 m/s). These values are all based on sedentary activity. The data from the present study is based on the medium activity level of approximately 2.3 met. Fig 13 shows that a maximum comfort index of 63 is experienced at 63 F (17.2 C) in 0.21 m/s and also a maximum comfort index of 78 at 71.6 F (22 C) with 1.32 m/s. The 8.6 F (4.8 C) temperature difference is based on the comparison of maximum comfort at 42 fpm (0.21 m/s) and 264 fpm (1.32 m/s). It points out an increase of 25.8 ft/min air velocity for each degree F (0.23 m/s = 1 C). The value of 25.8 fpm/F is consistent with the value of 24 fpm/F in the "ceiling fans" study by Rohles et al. (1982). The results demonstrate that subjects feel the same or better at higher temperatures with a fan as at a lower temperature without a fan. It indicates that elevated air velocity can be used to improve thermal comfort and reduce the demand on energy.

The Effect of Air Velocity on Optimum Comfort

Fig. 16 shows the effect of air velocity on comfort as a function of thermal sensation. A maximum comfort index of 63 is

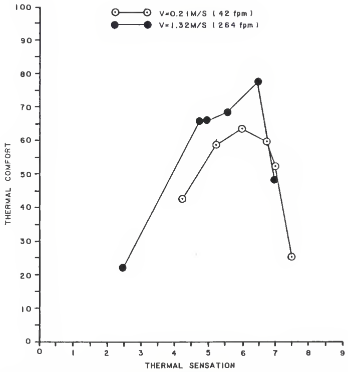

FIG. 16. MEAN THERMAL COMFORT VS. MEAN THERMAL SENSATION FOR TWO AIR VELOCITIES.

experienced at a thermal sensation of 6 with 0.21 m/s air and a maximum comfort index of 78 at a thermal sensation of 6.5 with 1.32 m/s. This results indicates that an increased air velocity not only can compensate air for temperature but also the optimum comfort is better with the higher velocity. The reason that a fan improves thermal comfort may have two possibilities. One possibility is that when a human is exposed to a given combination of environmental variables, clothing and activity level, his thermoregulatory system adjusts automatically to regulate the heat exchange of the body with the environment. In this study subjects had a medium activity level which increased the heat generation. The sweating is enhanced to increase the heat loss by evaporation. Based on the paper of Azer (1977), the warm thermal sensation is a function of the wettedness factor. A fan will increase the evaporation of sweat to balance the internal heat production and the heat loss to the environment. It will make subjects feel more comfortable than in still air. The other possibility is that fluctuations in air velocity are preferred to still air. The activity of the subjects was a walk-stand cycle and the air flow was not uniform. This combination made the air movement somewhat like a oscillating fan from the subjects point-of-view. The paper of Konz et al. (1983), as already discussed, indicated that thermal comfort for oscillating fans is higher than for fixed fans.

Previous research usually demonstrated that the optimum comfort occurred at neutral for sedentary activity. In this experiment, Fig. 16 also indicates that the optimum comfort for both conditions occurred above neutral. One possibility is that the medium activity level makes subjects feel better in the warm condition. Sweating in the warm condition is preferred to no sweating in the cold or neutral condition. Another possibility is that the experiment was performed in the winter time (February and March), and the subjects perferred to be warm. Fig. 16 also shows that the two curves intersect between thermal sensations of 6.5 and 7. This indicates that there is a maximum sensation above which a fan will be less comfortable than still air. Rohles (1965) made a hypothesis that when the ambient temperature is low, a wind of a given velocity is unpleasant; when the temperature is slightly above the comfort zone (80-90 F), the same wind is pleasant; and when the temperature is high, the wind is again unpleasant. His hypothesis was based on the sedentary condition. The results of this experiment are consistent with his hypothesis. In Fig. 16 the two curves don't intersect in the cold condition. It is not easy to determine the minimum sensation. Further investigation may be needed to determine this point.

Fig. 17 shows comparisons of thermal comfort and thermal satisfaction at different thermal sensations for the two air velocities. The maximum satisfaction index of 50 is at a thermal sensation of 6 for 0.21 m/s and maximum index of 59.3 is at a thermal sensation of 5.6 for 1.32 m/s. The results are consistent with thermal comfort results in that maximum thermal satisfaction is greater with the fan and the maximums for both conditions are above neutral.

Fig. 18 shows comparisons of thermal comfort and thermal dissatisfaction at different thermal sensations for two air velo-

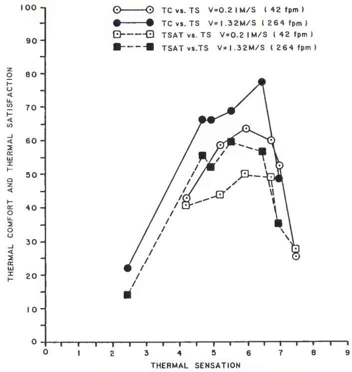

FIG. 17. MEAN THERMAL COMFORT AND MEAN THERMAL SATISFACTION VS. MEAN THERMAL SENSATION FOR TWO AIR VELOCITIES.

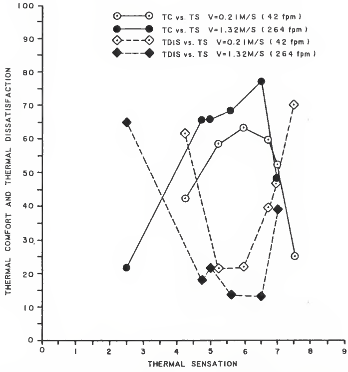

FIG. 18. THERMAL COMFORT AND THERMAL DISSATISFACTION VS. THERMAL SENSATION FOR TWO AIR VELOCITIES.

cities. The minimum thermal dissatisfaction index for 0.21 m/s is 21 at a thermal sensation of approximately 5.5 and the minimum thermal dissatisfaction index for 1.32 m/s is 13 at a thermal sensation of approximately 6.5. This result is also consistent with the thermal comfort and thermal satisfaction result in that the effect of air velocity on optimum dissatisfaction is similar and the optimum for both conditions is above the neutral condition.

The Effect of Sex on Comfort

Figures 19, 20, 21 and 22 show male and female mean votes of thermal sensation, thermal comfort, thermal satisfaction and thermal dissatisfaction at different temperatures after the second hour of exposure to two air velocities. These data of both conditions (fan, no fan) were subjected to an analysis of variance, see Tables 4, 5, 6, 7, 8, 9, 12, 13, 16 and 17. Sex is not significant for comfort votes except thermal satifaction votes with the fan condition. A Duncan's Multiple range tests for the four comfort votes are shown in Tables 20, 21, 22, 23, 24, 25, 26 and 27. There were no significant differences between male and female mean comfort votes except for thermal satisfaction votes with the fan.

McNall et al. (1968) indicated that men and women performing the same activity have a similar thermally neutral condition, but that women were more sensitive to small changes in the thermal enviroment than men.

A statistical analysis was made of the data. The following

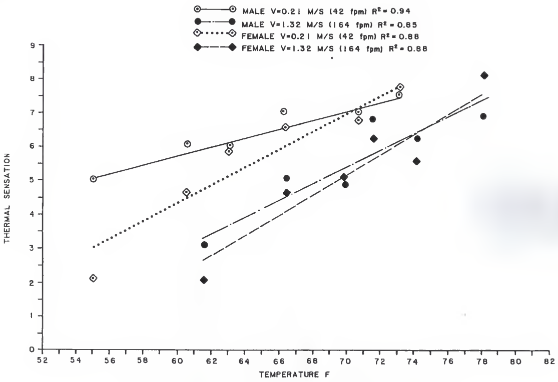

FIG. 19. MALE AND FEMALE THERMAL SENSATION
VS. TEMPERATURE FOR TWO AIR VELOCITIES
(LINES BASED ON LINEAR REGRESSION)

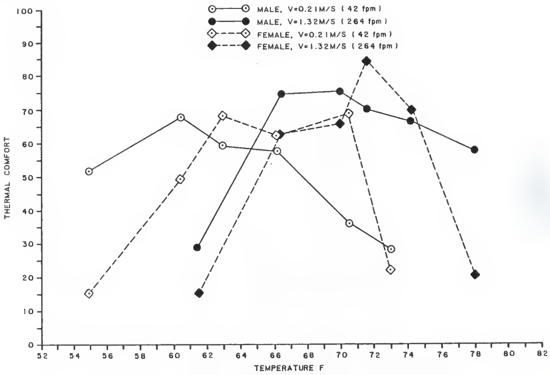

FIG. 20. MALE AND FEMALE MEAN THERMAL COMFORT VS. TEMPERATURE FOR TWO AIR VELOCITIES.

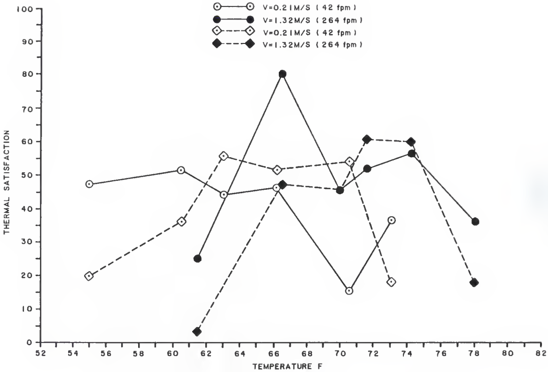

FIG. 21. MALE AND FEMALE MEAN THERMAL SATISFACTION VS. TEMPERATURE FOR TWO AIR VELOCITIES.

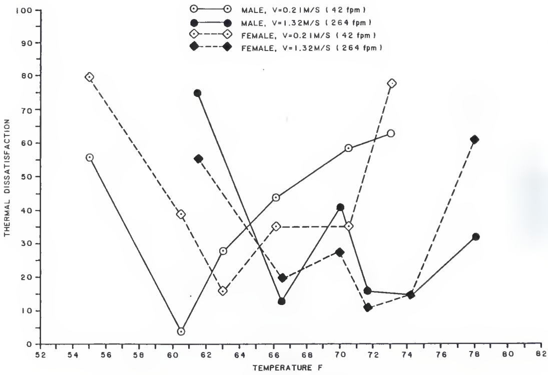

FIG. 22. MALE AND FEMALE MEAN THERMAL DISSATISFACTION VS. TEMPERATURE FOR TWO AIR VELOCITIES.

Table. 20. Mean Thermal Sensation Votes For the Males and Females without Fan

Sex	Mean	Grouping *
Male	6.03	A
Female	5.95	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 21. Mean Thermal Sensation Votes for the Males and Females with Fan

Sex	Mean	Grouping *
Male	5.13	A
Female	5.03	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 22. Mean Thermal Comfort Votes For the Males and Females without Fan

Sex	Mean	Grouping*
Male	55.49	A
Female	51.86	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 23. Mean Thermal Comfort Votes for the Males and Females with Fan

Sex	Mean	Grouping*
Male	58.30	A
Female	57.30	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 24. Mean Thermal Satisfaction Votes for the Males and Female without Fan

Sex	Mean	Grouping*
Male	44.70	A
Female	39.35	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 25. Mean Thermal Satisfaction Votes for the Males and Female with Fan

Sex	Mean	Grouping*
Male	50.29	A
Female	42.31	B

* Mean with the same letter are not significantly different at $p < 0.05$

Table. 26. Mean Thermal Dissatisfaction Votes for the Males and Females without Fan

Sex	Mean	Grouping*
Male	41.83	A
Female	36.91	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 27. Mean Thermal Dissatisfaction Votes for the Males and Females With Fan

Sex	Mean	Grouping*
Male	32.39	A
Female	27.10	A

* Means with the same letter are not significantly different at $p < 0.05$

results were obtained from a linear regression analysis of male and female mean thermal sensations for the two air velocities.

A. In still air V = 42 fpm (0.21 m/s)
male: Ym = -2.268 + 0.134*T $R^2 = 0.94$ SE = 0.017
female: Ym = -13.319 + 0.292*T $R^2 = 0.88$ SE = 0.048 .

B. With fan V = 264 fpm (1.32 m/s)
male: Ym = -9.91 + 0.217*T $R^2 = 0.85$ SE = 0.046
female: Ym = -17.517 + 0.324*T $R^2 = 0.88$ SE = 0.060

Where:

Ym = Estimated population mean vote for college-age subjects.
T = Dry bulb temperature F.
R^2 = Square of the correlation coefficient of determination.
SE = Standard error of parameter estimate of slope.

Fig. 19 shows the regression curve of male and female mean thermal sensation for the two conditions. In still air, the estimate of slope for females is significantly different than for males (difference in slope > 2 times the standard error in slope); it means that females are more sensitive to temperature than males. In the fan condition, the estimate of slope for females is not significantly different than for males . In both conditions, the difference between male and female response is greatest at the lower temperature. It seems that males have a higher activity level than females. McNall et al. (1968) indicated that metabolic rates of different activities were based on the height and weight of subjects; even though subjects had the same activity levels, they might have different metalbolic rates.

In this experiment the calculation of metabolic rate was based on Konz's equation (Appendix D). Appendix C gives the data of height, weight and body surfaces area for the average male and female subjects participating in the test. Appendix C shows the comparison between the present data and the McNall data of metabolic rates for average males and females for the medium activity. Because of the difference in weight and height, the metabolic rates of the females are lower than those of the males. This difference may explain why female thermal sensation votes are shifted to higher temperatures as compared to males at the same sensation.

The Effect of Test Duration on Comfort

The test duration was 2 hours. Subjects voted once every half hour during each test. The data were subjected to an analysis of variance (Tables 4, 5, 8, 9, 12, 13, 16 and 17). The test duration is not significant on the four measures for both fan and non-fan condition except for thermal dissatisfaction votes with the fan. Tables 28, 29, 30, 31, 32, 33, 34, and 35 show a Duncan's multiple range tests for test duration. There were no significant differences between mean votes for each half hour with the exception of the thermal comfort and dissatisfaction vote with the non-fan condition where the first half hour votes were found to be significantly different from the other three votes.

The Effect of Location on Comfort

There were four work-station in this experiment, different

Table. 28. Mean Thermal Sensation Votes For Each Test Time without Fan

Time (hr)	Mean	Grouping*
2	6.25	A
1.5	6.14	A
1	5.98	A
0.5	5.60	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 29. Mean Thermal Sensation Votes for Each Test Time with Fan

Time (hr)	Mean	Grouping*
2	5.29	A
1	5.21	A
1.5	5.21	A
0.5	4.57	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 30. Mean Thermal Comfort Votes For Each Test Time without Fan

Time (hr)	Mean	Grouping *
0.5	60.30	A
1	56.03	A B
2	50.33	A B
1.5	47.45	B

* Means with the same letter are not significantly different at $p < 0.05$

Table. 31. Mean Thermal Comfort Votes for Each Test Time with Fan

Time (hr)	Mean	Grouping *
2	59.50	A
0.5	58.35	A
1	56.79	A
1.5	56.78	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 32. Mean Thermal Satisfaction Votes For Each Test Time without Fan

Time (hr)	Mean	Grouping*
0.5	49.13	A
1	41.59	A
2	39.85	A
1.5	36.76	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 33. Mean Thermal Satisfaction Votes for Each Test Time with Fan

Time (hr)	Mean	Grouping*
0.5	48.91	A
1.5	45.15	A
1	44.75	A
2	44.13	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 34. Mean Thermal Dissatisfaction Votes For Each Test Time without Fan

Time (hr)	Mean	Grouping*
2	43.96	A
1	41.84	A
1.5	41.58	A
0.5	30.80	B

* Means with the same letter are not significantly different at $p < 0.05$

Table. 35. Mean Thermal Dissatisfaction Votes for Each Test Time with Fan

Time (hr)	Mean	Grouping*
1	29.65	A
1.5	29.47	A
2	29.44	A
0.5	28.91	A

* Means with the same letter are not significantly different at $p < 0.05$

velocities for each location are shown in Fig. 7. The analysis of variance already showed that sex and test duration had little effect (not significant on the four measures for both the fan and no fan conditions), so that the votes of each location were separately treated to an analysis of variance. The analysis of variance in Tables 36, 37, 38, 39, 40, 41, 42 and 43 show that the location is not significant for both fan and no fan conditions except for the thermal comfort and dissatisfaction votes with the fan. Tables 44, 45, 46, 47, 48, 49, 50 and 51 show Duncan's multiple ranges tests for location. There were no significant differences between each location for the no fan condition. But location 4 was significantly different from the other three locations in thermal sensation, comfort and dissatisfaction votes with the fan.

Table. 36. Analysis of Variance for Thermal Sensation Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	15.7	9.65	0.0001
Location	3	0.6	0.39	0.7645
Error	103			
Total	111			

Table. 37. Analysis of Variance for Thermal Sensation Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	38.7	31.45	0.0001
Location	3	2.4	1.99	0.1179
Error	103			
Total	111			

Table. 38. Analysis of Variance for Thermal Comfort Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	2423.5	4.59	0.0009
Location	3	203.1	0.38	0.7673
Error	103			
Total	111			

Table. 39. Analysis of Variance for Thermal Comfort Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	6507.7	22.64	0.0001
Location	3	1052.8	3.66	0.0148
Error	103			
Total	111			

Table. 40. Analysis of Variance for Thermal Satisfaction Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	1291.2	2.10	0.0710
Location	3	1206.0	1.96	0.1233
Error	103			
Total	111			

Table. 41. Analysis of Variance for Thermal Satisfaction Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	4359.9	11.20	0.0001
Location	3	609.4	1.57	0.2009
Error	103			
Total	111			

Table. 42. Analysis of Variance for Thermal Dissatisfaction Votes without Fan

Source	d.f.	Mean Square	F	P
Temperature	5	3087.7	6.96	0.0001
Location	3	576.6	1.30	0.2781
Error	103			
Total	111			

Table. 43. Analysis of Variance for Thermal Dissatisfaction Votes with Fan

Source	d.f.	Mean Square	F	P
Temperature	5	6793.9	23.9	0.0001
Location	3	1943.7	6.84	0.0004
Error	103			
Total	111			

Table. 44. Mean Thermal Sensation Votes For Each Location without Fan

Location	Mean	Grouping*
3	6.21	A
1	5.96	A
2	5.93	A
4	5.88	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 45. Mean Thermal Sensation Votes for Each Location with Fan

Location	Mean	Grouping*
3	5.43	A
1	5.18	A B
2	4.93	A B
4	4.75	B

* Means with the same letter are not significantly different at $p < 0.05$

Table. 46. Mean Thermal Comfort Votes For Each Location without Fan

Location	Mean	Grouping*
3	56.24	A
2	55.36	A
4	51.97	A
1	50.59	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 47. Mean Thermal Comfort Votes for Each Location with Fan

Location	Mean	Grouping*
1	61.63	A
3	60.67	A
2	60.46	A
4	48.70	B

* Means with the same letter are not significantly different at $p < 0.05$

Table. 48. Mean Thermal Satisfaction Votes For Each Location without Fan

Location	Mean	Grouping *
2	47.64	A
3	47.39	A
4	36.35	A
1	35.95	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 49. Mean Thermal Satisfaction Votes for Each Location with Fan

Location	Mean	Grouping *
2	50.28	A
4	46.95	A
3	46.50	A
1	39.21	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 50. Mean Thermal Dissatisfaction Votes For Each Location without Fan

Location	Mean	Grouping*
4	44.73	A
1	41.04	A
3	38.50	A
2	33.92	A

* Means with the same letter are not significantly different at $p < 0.05$

Table. 51. Mean Thermal Dissatisfaction Votes for Each Location with Fan

Location	Mean	Grouping*
4	39.64	A
3	29.98	B
2	28.56	B
1	19.29	C

* Means with the same letter are not significantly different at $p < 0.05$

Comparison of Results with other Studies

In Fig. 23, present experimental data are compared with the experimental results of Vandyke et al. (1983) for sedentary male and female subjects, dressed in 0.5 clo uniform, 2.5 hours exposure in still air and with a small fan. The experiments were performed at dry bulb temperatures of 76 F (24.4 C), 79 F (26.1 C), 82 F (27.8 C) and 50% relative humidity. The maximum comfort is at a 5.3 thermal sensation for still air and a 5.0 thermal sensation for the fan condition. It is shown that the maximum thermal comfort is greater with fan, which agrees with the present experiment. But, the optimum comfort occurred near a neutral thermal sensation which disagrees with the present experiment. It is possible that the difference is due to activity level.

Fig. 24 compare the present experimental data with the experimental data of Rohles et. al. (1982) for sedentary subjects dressed in a 0.5 clo uniform, 3 hours exposure in temperatures of 76 F (24.4 C), 79 F (26.1 C), 82 F (27.8 C), 85 F (29.4 C) and 50% RH. The air velocity was 0.06 m/s (still air) and 0.5 m/s (average with a fan). The maximum comfort index of 70 is at a thermal sensation of 5.2 for still air and the maximum comfort index of 73 is at a thermal sensation of 4.8 for the fan condition. It is verified again that comfort is higher for the fan condition, although marginally so in this case. The optimum comfort for both conditions is close to the neutral, probably because of the sedentary activity.

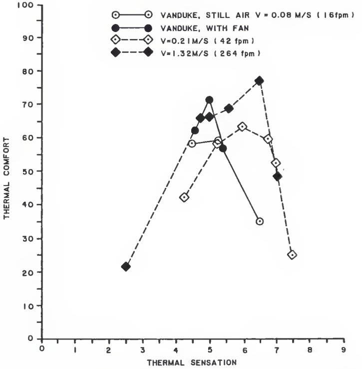

FIG. 23. COMPARISON OF PREVIOUS RESEARCH (VANDUKE, et. al. 1983) WITH PRESENT EXPERIMENT DATA.

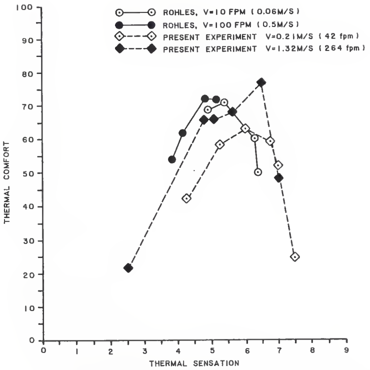

FIG. 24. COMPARISON OF PREVIOUS RESEARCH (ROHLES, et. al. 1982) WITH PRESENT EXPERIMENT DATA.

Comparison of Results with the Azer and Fanger Models

One objective of the study is to compare the results to predictions by the Azer thermal response model and the Fanger comfort model. A statistical analysis was made of the data. The following results for two air velocities were obtained from a linear regression analysis of mean thermal sensation votes after the second hour of exposure:

A. In "still air" V = 42 fpm (0.21 m/s)

$Pm = -4.33 + 0.163*T$

$R^2 = 0.93$

B. In fan condition V = 264 fpm (1.32 m/s)

$Pm = -12.66 + 0.254*T$

$R^2 = 0.86$

Where:

Pm = Estimated population thermal sensation mean vote for college-age subjects.

T = Dry bulb temperature (F).

R^2 = Square of the correlation coefficient of determination.

The method of least squares was used to fit data through the means of the thermal sensation votes at the different temperatures. A 95% confidence interval (CI) was used for the test of significance for both models.

Figures 25 and 26 show a comparison between the experimental thermal sensation measurements and the predictions by the Azer and Fanger models at 0.21 m/s and 1.32 m/s respectively. The results in Fig. 25 show the present data agree with the Azer

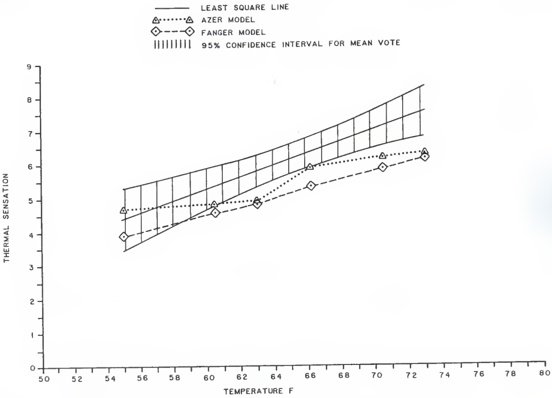

FIG. 25. COMPARISON OF AZER'S AND FANGER'S MODEL TO THE PRESENT DATA WITHOUT FAN

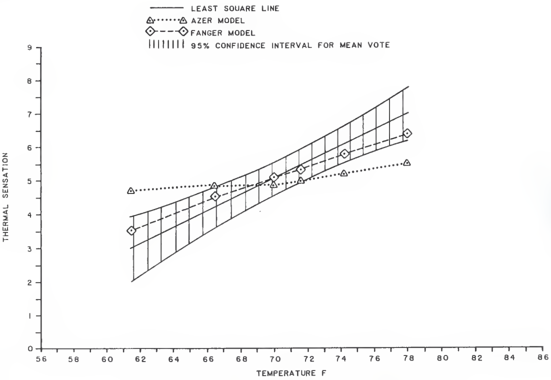

FIG. 26. COMPARISON OF AZER'S AND FANGER'S MODEL TO THE PRESENT DATA WITH FAN.

model at slightly cool and neutral thermal sensation (Ta = 55-60 F) in the 95% confidence range, but disagree at higher temperatures. The agreement between the predictions of thermal sensation with the present data and Fanger model are only satisfied at the slightly cool condition (Ta = 55 F). All of the Fanger data are out of the 95% confidence range at higher temperatures. Fig. 25 also indicates that the sensitivity to temperature of the present data are greater than for the Fanger and Azer models.

The results in Fig. 26 show that with the fan, the present data agree fairly accurately with the thermal sensation for the Fanger model. The comparison between the predicted thermal sensation and Azer model are only satisfied at the neutral condition. It is also indicated that the sensitivity to temperature of present data are still greater than for the Fanger and Azer models.

Chapter 6

SUMMARY AND CONCLUSION

The research reported in this paper measured the thermal comfort of college-age males and females performing a medium activity level at different temperatures and air velocities. The purpose of this study was to determine the effect of air velocity on optimum comfort and determine whether the optimum comfort occurs in the neutral, cold, or warm condition and to compare the experimental results with the predictions of the Fanger comfort model and the Azer thermal response model. The experimental conditions were 0.65 clo of clothing insulation, 50% RH, 2.3 Met metabolic activity, temperature range from 55 F to 78 F (10-26 C), and air velocities of 42 fpm (0.21 m/s) and 264 fpm (1.32 m/s). The test duration was always 2.5 hours, one half hour in the orientation room and two hours in the test chamber. All the data discussed here are after two hours exposure in the test chamber.

The results show the following :

1. The maximum comfort index is approximately 63 at 63 F with an air velocity of 0.21 m/s and the maximum comfort index is approximately 78 at 71.6 F with an air velocity of 1.32 m/s. This results indicates that the optimum comfort is higher with the fan than without the fan at the same activity. These results also indicate that an increase in air velocity of 26 fpm will offset a temperature increase of 1 F (0.23 m/s per 1 C). The fan not only improved thermal comfort but may also represent an energy saving without affecting human comfort.

2. The experiment indicates that the optimum comfort both with and without the fan occurred above a neutral thermal sensation for the medium activity level. This result is different from previous studies for sedentary activity, where the optimum comfort occurred at a neutral thermal sensation.

3. Metabolic rates of the females were lower than for the males. Females are more sensitive to thermal sensation in still air, but are not significantly different from males with the fan. Male and female mean comfort votes are not significantly different except for thermal satisfaction votes with the fan condition.

4. There were no significant differences between each half hourly mean comfort votes except thermal comfort and dissatisfaction for the no fan condition where the first half hour votes were significantly different from the other 3 votes.

5. There were no significant differences between each location in still air. But, location 4 was significantly different from the other three locations in thermal sensation, comfort and dissatisfaction votes with the fan.

6. The sensitivity to temperature shown by the present study is significantly greater than for the Azer and Fanger models at both the 0.21 m/s and 1.32 m/s conditions.

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Appendix A. Subject Orientation and Test Procedure Thermal Comfort Research

The purpose of this experiment is to evaluate the effect of air velocity on the worker's performance and his/her perception of the pleasantness of the thermal environment.

The test will last 2-1/2 hours. You together with 3 other students will report to the Institute for Environment Research at the time of scheduled test. Your oral temperature will be taken and if you are not running a fever (98.6 F + 0.5 F) you will be asked to change into a shirt and slack ensemble that we provide. Then after being instructed on the test procedure, you will enter the environment chamber. There you will be assigned a set of 9-in. steps (see diagram). For the next 2 hours you will be walking over the steps about once every 15 seconds to simulate moderate activity typical of a modern factory worker.

We will provide you with water but you may not bring any food or beverage with you into the experiment. Several times during the test we will ask you to indicate how you feel on ballots that we will provide and you will have a 5 minute break for each half hour of experiment. At the end of the 2-1/2 hours, you will be asked to dress into your own clothes, paid $10, and will be dismissed.

Participation in this research should involve no appreciable risk to healthy volunteers. However, if you become unduly fatigued or experimence dizzyness, muscle cramps, or shortness of breath you should drop out of the research project.

If you have any medical condition that would prohibit you from engaging in moderate physical exercise over a 2-1/2 period, you should not participate in this research.

Your resting heart rate will be measured, and if it is more than 90 beats per minute you will not be allowed to participate in this project.

If you are interested in participating, you may sign up on the second floor of the Institute for Environment Research.

Appendix B. Informed Consent Statement Thermal Comfort Research

1. I,_______________________ volunteer to participate in a project in connection with research studies to be conducted by Kansas State University.
2. I fully understand the purpose of the study as outlined in the orientation statement and test protocol.
3. I understand that I may be observed during my participation and that my conduct and/or voice may be recorded by photographic and/or recording devices. I also realize that public reports and articles may be made of the experiments and all of the observation, and I consent to publication of such including the use of photographs if my faces is "blanked" out.
4. I also understand that my performance as an individual will be treated as research data and will in no way be associated with me for other than identification purposes, thereby assuring anonymity of my performance and response.
5. I understand that I will be permitted to leave the test at any time and I may discontinue participation without penalty or loss of benefits to which I am otherwise entitled. This will be pro-rated with no more than 50 percent of the total payment being used as a bonus for successful completion of the project.
6. As compensation for my voluntary services as a participant in the aforesaid studies, Kansas State University may pay me. It is clearly understood and agreed, however, that in no event am I to be considered an employee of Kansas State University during such participation. Therefore, no Social Security, income tax, retirement or other benefits of employment will be deducted or accurred.
7. I hereby agree, under penalty of forfeiture of all compensation due me, not to give information regarding these studies to any public news media nor to publicize any articles or other accounts thereof without prior written approval of Kansas State University.
8. If I have any question concerning my rights as a test subject, injuries or emergencies resulting from my participation or any question concerning the study I understand that I can contact_________________at______________________.

I have read the Subject information Fact Sheet and Test protocol statement and signed the herein Agreement and Release, this__________day of___________, 19____.

____
Signature

Sign and return one copy. The second copy is for your records.

Appendix C. Comparison of Present Subjects Data and Metabolic Rates with McNall's (1968) Study

	Present Experiment Once each 15 Sec stand -walk cycle		P.E. McNall Experiment 10 Min stand 5 Min walk cycle	
Subjects	Male	Female	Male	Female
Average Height (in)	71.7	66.2	69.8	64.8
Average Weight (lb)	182.0	137.0	163.4	130.4
Met Rates (Met)	2.4	2.0	2.3	1.8

* The Met Rates of present experiment are based on the calculation with the Konz's equation . (Appendix D).

Appendix D. The Calculation of Metabolic Rates for Males and Females

Based on Konz's equation (Konz 1979) to determine the metabolic rate in the experiment.

Total MET = BASALMET + ACTMET + SDAMET (Konz, page 187)

SDAMET = 0.1 * (BASALMET + ACTMET) (Konz, page 188)

For Body Surface Area

$SA = 0.007184\ (HT)^{.725}\ (WT)^{.425}$

From Appendix C Subjects Data

Suject	Height (in)	Weight (lb)	Body Surface Area ft^2	(M^2)
Average Male	71.7	182	22.5	(2.03)
Average Female	66.2	137	18.5	(1.7)

1) BASALMET (Energy Cost) (Konz, page 190)

Male : 1.28 W/kg * 182 lb / 2.2 lb/kg = 105.9 W

Female : 1.16 * 137 / 2.2 = 72.2 W

2) ACTMET

A) Lifting (Engery Cost)

Male : 1 cycle 2 * 182 lb * 9 ft / 12 = 273 ft-lb

1 minute 273 * 4 cycle / min = 1092 ft-lb / min

Unit Convert 100 kg-m/min = 723 ft-lb/min = 16.35 w

1092 ft-lb/min * 16.35 W / 723 ft-lb/min = 24.7 W

Female : 2 * 137 * 9/12 = 205.5 ft-lb

4 * 205.5 = 822 ft-lb/min

822 * 16.35 / 723 = 18.6 W

B) Walking (Enery Cost) (Konz, page 190)

Assume V = 3 km/h (approximately)

Male: $W/Kg = 2.0314 + .12415 * V^2 = 3.15$

$3.15 * 182/2.2 = 260.9$ W

Female: $3.15 * 137/2.2 = 196.2$ W

Total MET for Male = (105.9 W + 24.7 W + 260 W) * 1.1 = 429.7 W

Total Met for Female = (72.2 + 196.2 + 18.6) * 1.1 = 315.7 W

Metabolic Rate per unit surface area during the walking activity For 1 MET = 58 W/M^2

Male : $W/M^2 = 429.7 / 2.03 = 217\ W/M^2 = 3.65$ MET

Female : W/M2 = 315.7 / 1.7 = 185.7 W/M2 = 3.2 MET

MET Rates during the standing activity

Male : Standing (talking) 0.9 W/Kg = 0.9 * 182 / 2.2 = 74.5 W

BASALMET = 105.9 W

Total MET = (74.5 + 105.9) * 1.1 = 198.4 W

$W/M^2 = 198.4 / 2.03 = 97.3\ W/M^2 = 1.69$ MET

Female : Standing 0.9 * 137 / 2.2 = 56 W

BASALMET = 72.2 W

Total MET = (56 + 72.2) * 1.1 = 141 W

$W/M^2 = 141 / 1.7 = 83\ W/M^2 = 1.43$ W

For 5 s walking and 10 s standing

The average MET

Male : (3.65 * 5 + 1.69 * 10) / 15 = 2.35 MET

Female : (3.2 * 5 + 1.43 * 10) / 15 = 2.02 MET

The Metabolic rates for males and females combined is approximately 2.3 Met

Appendix E. Detailed Experiment Data

Test condition: 66.2 F Without Fan

Date : 22th FEB 1985

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	M	M	Male	Female	Combined
Height (in)		67	68	73	71	72	67.5	69.9
Weight (lb)		129	166	199	163	181	147.5	164.3
PM 2:30	Ts	5	5	6	5	5.5	5	5.3
	Tc	56.6	78.4	60	93	76.5	67.5	71.8
	Tsat	30.1	83.4	50	74.7	63.4	56.8	59.6
	Tdis	22.3	5.5	27.8	27.3	27.6	13.9	20.8
PM 3:00	Ts	6	6	5	6	5.5	5	5.3
	Tc	43	89.2	49.9	94.8	72.4	66.1	69.2
	Tsat	21.9	83.4	50	83.4	66.7	52.7	59.7
	Tdis	29.9	11.2	42.6	14.9	28.8	20.6	24.7
PM 3:30	Ts	7	5	4	7	5.5	6	5.8
	Tc	35.6	85.4	75.4	87.5	81.5	60.5	71
	Tsat	27.6	83.4	50	77.9	64	55.5	59.7
	Tdis	53.7	9.3	40.6	16.7	28.7	31.7	30.1
PM 4:00	Ts	7	6	6	7	6.5	6.5	6.5
	Tc	35.2	87.5	39.3	76.8	58.1	61.4	60
	Tsat	16.3	83.4	41.5	66.5	54	49.9	51.9
	Tdis	53.6	11	53.6	16.7	35.2	32.3	33.7
PM 4:30	Ts	7	6	7	7	7	6.5	6.8
	Tc	35.6	87.5	27.5	87.5	57.5	61.6	59.5
	Tsat	19.7	83.4	22.3	70	46.2	51.4	48.8
	Tdis	57.4	13	70.4	16.7	43.6	35.2	39.4

Test condition: 71.6 F With Fan

Date : 22th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	M	M	Male	Female	Combined
Height (in)		67	67	69	75	72	67	69.5
Weight (lb)		131	174	193	191	192	152.5	172.3
PM 7:00	Ts	5	5	6	7	6.5	5	5.8
	Tc	95.2	89.4	65	51.7	58.4	92.3	75.3
	Tsat	100	69.4	36.1	52.8	44.5	84.7	64.6
	Tdis	0	13	13	14.5	13.8	6.5	10.1
PM 7:30	Ts	4	5	5	4	4.5	4.5	4.5
	Tc	87.5	100	66.3	90	78.2	93.8	86
	Tsat	74.9	94.8	50	94.4	72.2	84.9	78.5
	Tdis	11	0	14.8	0	7.4	5.5	12.9
PM 8:00	Ts	6	7	6	6	6	6.5	6.3
	Tc	85.2	89.5	60.7	54	57.4	87.4	72.4
	Tsat	77.6	66.5	52.5	55.7	54.1	72.1	63.1
	Tdis	12.9	5.7	14.8	16.5	15.7	9.3	12.5
PM 8:30	Ts	7	6	6	7	6.5	6.5	6.5
	Tc	70	93.7	75.1	49.4	62.3	81.9	72
	Tsat	55.6	77.7	55.4	53.1	54.3	66.7	60.5
	Tdis	11.1	3.7	5.5	18.5	12	7.7	9.7
PM 9:00	Ts	7	6	6	7	6.5	6.5	6.5
	Tc	75	94	87.1	53.7	70.4	84.5	77.5
	Tsat	47.2	74.8	52	52.3	52.2	61	56.6
	Tdis	11	11	18.7	12.9	15.8	11	13.4

Test condition: 55 F Without Fan

Date : 25th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		F	M	M	M	Male	Female	Combined
Height (in)		67	68	79	76	74.3	67	72.5
Weight (lb)		126	158	226	236	206.7	126	186.5
PM 2:30	Ts	5	6	5	5	5.3	5	5.3
	Tc	63	51.3	100	0	50.4	63	53.6
	Tsat	66.7	44.3	51.2	57.5	51	66.7	54.9
	Tdis	9.2	49.8	35.5	9.2	31.5	9.2	25.9
PM 3:00	Ts	2	3	7	4	4.7	2	4
	Tc	10.2	55	60	25	46.7	10.2	37.6
	Tsat	16	39	56.1	54.3	49.8	16	41.3
	Tdis	85.3	50	33.1	59	47.4	85.3	56.9
PM 3:30	Ts	3	3	7	4	4.7	3	4.3
	Tc	25.2	50	50	48	49.3	25.2	43.3
	Tsat	26.7	33	58.5	72.7	54.7	16.7	45.2
	Tdis	81.5	38.7	27.6	63.2	43.2	81.5	52.8
PM 4:00	Ts	2	3	8	4	5	2	4.3
	Tc	10	48	50	15	37.7	10	31
	Tsat	16.7	47.1	53	50	50	16.7	41.7
	Tdis	85.3	52	42.6	55.5	58.9	85.3	58.9
PM 4:30	Ts	2	3	8	4	5	2	4.3
	Tc	15	47	51	56.3	51.4	15	42.3
	Tsat	19.6	47	44.8	50	47.2	19.6	40.4
	Tdis	79.6	50	67	50	55.7	79.6	61.7

Test condition: 61.5 F With Fan

Date : 25th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	M	M	Male	Female	Combined
Height (in)		69	64	72	68	70	66.5	68.3
Weight (lb)		126	148	163	149	156	137	146.5
PM 7:00	Ts	5	4	5	4	4.5	4.5	4.5
	Tc	98.2	71.3	100	78.5	89.3	84.8	87
	Tsat	58.1	49.7	50	25.3	37.7	53.9	45.8
	Tdis	7.4	20.4	0	29.6	14.8	13.9	14.4
PM 7:30	Ts	2	1	5	1	3	1.5	2.3
	Tc	16.4	0	55.6	0	18.5	8.2	18
	Tsat	0	8.2	50	16.3	33.2	4.1	18.6
	Tdis	64.9	62.9	50	100	75	63.9	69.5
PM 8:00	Ts	3	1	5	1	3	2	2.5
	Tc	22.5	12.5	57.5	0	28.8	17.5	23.1
	Tsat	0	0	50	31.6	40.8	0	20.4
	Tdis	27.9	57.4	50	100	75	42.7	58.8
PM 8:30	Ts	3	1	5	1	3	2	2.5
	Tc	27.1	10	57.5	0	28.8	17.5	23.1
	Tsat	0	14.2	50	0	25	7.1	32.1
	Tdis	31.6	72	50	100	75	51.8	63.4
PM 9:00	Ts	3	1	5	1	3	2	2.5
	Tc	20.6	9.1	57.5	0	28.8	14.9	22
	Tsat	0	5.4	50	0	25	2.7	13.9
	Tdis	35.3	76	50	100	75	55.7	65.3

Test condition: 70.5 F Without Fan

Date : 26th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	M	M	Male	Female	Combined
Height (in)		63	66	69	76	72.5	64.5	68.5
Weight (lb)		131	131	134	215	174.5	131	152.8
PM 2:30	Ts	5	4	5	6	5.5	4.5	5
	Tc	87.5	100	95.5	90.4	93	93.8	93.4
	Tsat	66.3	100	63.4	74.9	69.1	83.2	76.2
	Tdis	12.9	0	16.6	1.8	9.2	6.5	7.8
PM 3:00	Ts	4	4	5	6	5.5	4	4.8
	Tc	100	98.1	98.1	50	74.1	99.1	86.6
	Tsat	92	97.2	83.4	5.3	44.4	94.6	69.5
	Tdis	0	0	23.9	55.5	39.7	0	19.9
PM 3:30	Ts	5	6	5	7	6	5.5	5.8
	Tc	87.5	83.3	86.8	20.7	53.8	85.4	69.6
	Tsat	83.4	83.4	66.9	0	33.5	83.4	58.4
	Tdis	14.8	0	35.3	90.7	63	7.4	35.2
PM 4:00	Ts	6	7	4	5	4.5	6.5	5.5
	Tc	71.2	79.2	89.4	62.6	76	75.2	75.6
	Tsat	49.6	66.7	75.2	13.4	44.3	58.2	51.2
	Tdis	14.8	16.7	14.9	44.4	29.7	15.8	22.7
PM 4:30	Ts	6	7	6	6	6	6.5	6.3
	Tc	71.2	75	60	33.1	46.6	73.1	60
	Tsat	52.1	66.7	27.7	5.7	16.7	59.4	38.5
	Tdis	38.6	37.2	40.7	64.9	52.8	37.9	45.4

Test condition: 74.2 F With Fan

Date : 26th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	F	M	Male	Female	Combined
Height (in)		64	70	67	72	72	67	68.3
Weight (lb)		137	137	126	175	175	133.3	143.8
PM 7:00	Ts	6	6	5	6	6	5.7	5.8
	Tc	97.9	47.3	100	85.7	85.7	81.7	82.7
	Tsat	63.4	80.4	67.5	52.9	52.9	70.4	66.1
	Tdis	5.5	14.8	7.3	9.3	9.2	9.2	9.2
PM 7:30	Ts	7	5	4	5	5	5.3	5.3
	Tc	89.3	78.8	64.3	88.4	88.4	77.5	80.2
	Tsat	38.8	47.2	39.6	60.8	60.8	41.9	46.6
	Tdis	22.2	35.4	7.3	14.9	14.9	21.7	20
PM 8:00	Ts	7	6	4	5	5	5.7	5.5
	Tc	89.3	68.9	60.7	80.1	80.1	73	74.8
	Tsat	24.6	64.3	25	83.4	83.4	38	49.3
	Tdis	23.9	14.8	51.6	0	0	30.1	22.6
PM 8:30	Ts	7	6	4	4	4	5.7	5.3
	Tc	91.6	81.1	60.6	67.8	67.8	77.8	75
	Tsat	44.7	74.8	22.1	83.4	83.4	47.2	56.2
	Tdis	14.8	16.6	35.1	0	0	22.2	16.6
PM 9:00	Ts	6	5	4	5	5	5	5
	Tc	96	87.4	60.6	78.7	78.7	81.3	80.7
	Tsat	47.2	80.5	8.2	86.1	80.5	12.9	55.5
	Tdis	16.5	12.9	38.5	3.7	47.2	19.6	17.9

Test condition: 66.5 F With Fan

Date : 27th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		F	M	F	F	Male	Female	Combined
Height (in)		66	73	65	67	73	66	67.8
Weight (lb)		109	170	153	135	170	132.3	141.8
PM 2:30	Ts	6	4	5	5	4	5.3	5.0
	Tc	95.8	85.3	75	75.6	85.3	82.1	82.9
	Tsat	63.4	80.4	67.5	52.9	80.4	61.3	66.1
	Tdis	5.5	14.8	7.3	9.3	14.8	7.4	9.2
PM 3:00	Ts	4	3	6	4	3	4.7	4.3
	Tc	36.6	41.6	60.4	68.4	41.6	55.1	51.8
	Tsat	38.8	47.2	39.6	60.8	47.2	46.4	46.6
	Tdis	22.2	35.4	7.3	14.9	35.4	14.8	20
PM 3:30	Ts	3	5	6	5	5	4.7	4.8
	Tc	61.4	67.3	35	69.3	67.3	55.2	58.3
	Tsat	24.6	64.3	25	83.4	64.3	44.3	49.3
	Tdis	23.9	14.8	51.6	0	14.8	25.2	22.6
PM 4:00	Ts	3	5	6	5	5	4.7	4.8
	Tc	66.7	64.3	40.3	74.7	64.3	60.6	61.5
	Tsat	44.7	74.8	22.1	83.4	74.8	50.1	56.3
	Tdis	14.8	16.6	35.1	0	16.6	16.7	16.6
PM 4:30	Ts	3	5	6	5	5	4.7	4.8
	Tc	62.4	74.6	35	91.9	74.6	63.1	66
	Tsat	47.2	80.5	8.2	86.1	80.5	47.2	55.5
	Tdis	16.5	12.9	38.5	3.7	12.9	19.6	17.9

Test condition: 60.5 F Without Fan

Date : 27th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		M	M	F	F	Male	Female	Combined
Height (in)		69	73	67	66	71	66.5	68.8
Weight (lb)		178	279	151	158	228.5	154.5	191.5
PM 7:00	Ts	7	5	7	7	6	7	6.5
	Tc	80.6	69	41.2	100	74.8	70.6	72.7
	Tsat	19.3	50	22.1	69.8	34.2	46	40.3
	Tdis	9.1	5.7	46.3	0	7.4	23.2	15.3
PM 7:30	Ts	5	6	5	6	5.5	5.5	5.5
	Tc	100	66	64.4	54	83	59.2	71.1
	Tsat	100	10.3	66.5	30.5	55.1	48.5	51.8
	Tdis	0	0	16.7	37.1	0	26.9	13.5
PM 8:00	Ts	7	6	7	4	6.5	5.5	6
	Tc	83	30.6	45.2	45.7	56.8	45.5	51.2
	Tsat	5.4	0	32.7	33.2	2.7	33	17.8
	Tdis	29.6	68.5	29.5	44.5	49.1	37	43
PM 8:30	Ts	7	7	5	5	7	5	6
	Tc	75	24.4	57.7	47	49.7	52.4	51
	Tsat	5.3	0	41.5	33.2	2.7	37.4	20
	Tdis	20.4	48.1	24	53.6	34.3	38.8	36.5
PM 9:00	Ts	5	7	5	4	6	4.5	5.3
	Tc	100	34.5	56.4	42	67.3	49.2	58.3
	Tsat	100	2.5	33	39	51.3	36	43.6
	Tdis	0	7.5	22.1	55.5	3.8	38.8	21.3

Test condition: 78 F With Fan

Date : 28th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		M	M	M	F	Male	Female	Combined
Height (in)		66	73	67	67	68.7	67	68.3
Weight (lb)		125	164	159	139	149.3	139	146.8
PM 2:30	Ts	5	6	6	8	5.5	8	6.3
	Tc	96	77.6	83.6	40.2	85.7	40.2	74.4
	Tsat	88.6	17.1	75	42	60.2	42	55.7
	Tdis	0	48.1	24	44.6	24	44.6	29.2
PM 3:00	Ts	6	5	7	8	6	8	6.5
	Tc	47.8	67.1	76.2	18.3	63.7	18.3	53.4
	Tsat	21.6	50	71.9	13.8	47.8	13.8	35.4
	Tdis	22	38.9	35.3	70.4	32.1	70.4	41.7
PM 3:30	Ts	7	6	7	8	6.7	8	7
	Tc	56.3	51.5	79.1	22.5	62.3	22.5	52.4
	Tsat	24.7	16.3	66.6	16.7	35.9	16.7	31.1
	Tdis	7.4	42.4	40.7	64.7	30.2	64.7	38.8
PM 4:00	Ts	7	6	7	8	6.7	8	7.0
	Tc	73.3	49	56.1	16.6	59.4	16.6	48.7
	Tsat	52.1	33	61	13.8	48.7	13.8	40
	Tdis	1.9	48	38.9	68.6	29.6	68.6	39.4
PM 4:30	Ts	6	7	7	8	6.7	8	7
	Tc	79.9	39.3	54	20.2	57.7	20.2	48.4
	Tsat	47.1	28	50	16.3	41.7	16.3	35.4
	Tdis	1.8	50	44.5	61	32.1	61	39.3

Test condition: 73 F Without Fan

Date : 28th FEB

Subject&location		1	2	3	4	Mean Value		
Sex		M	M	F	F	Male	Female	Combined
Height (in)		75	75	65	67	75	66	70.5
Weight (lb)		216	212	131	118	214	124.5	169.3
PM 7:00	Ts	6	6	6	6	6	6	6
	Tc	75	53	43	89.3	64	66.2	65
	Tsat	5.3	28.6	38.6	52.1	17	45.4	31.2
	Tdis	18	42.5	42.4	1.8	30.3	22.1	26.2
PM 7:30	Ts	8	7	7	6	7.5	6.5	7.0
	Tc	48.5	54.4	12.5	20	51.5	16.3	33.9
	Tsat	22.4	56.3	58	63.8	39.4	60.9	50.1
	Tdis	51.4	46.5	31.4	13	49	22.2	35.6
PM 8:00	Ts	7	5	7	7	6	7	6.5
	Tc	23	47.6	55	82.9	35.3	69	52.1
	Tsat	13.7	55.1	16.7	16.9	34.4	16.8	25.6
	Tdis	27.6	42.5	83.4	74.1	35.1	78.8	56.9
PM 8:30	Ts	6	6	7	8	6	7.5	6.8
	Tc	27.1	58.4	44.6	10.6	42.8	27.6	35.2
	Tsat	16.7	41.3	36	5.3	29	20.7	24.9
	Tdis	72	63	57.4	87.2	67.5	72.3	69.9
PM 9:00	Ts	8	7	8	7	7.5	7.5	7.5
	Tc	14.4	41.2	7	36.9	27.8	21.9	25
	Tsat	16.7	56	11.1	24.9	36.4	18	27.2
	Tdis	81.5	44	87	68.6	62.6	77.8	70.3

Test condition: 74.2 F With Fan

Date : 1st MAR

Subject&location		1	2	3	4	Mean Value		
Sex		F	M	F	F	Male	Female	Combined
Height (in)		64	75	68	62	75	64.7	67.3
Weight (lb)		129	199	128	128	199	128.3	146
PM 2:30	Ts	6	7	6	7	7	6.3	6.5
	Tc	78.9	46.6	83.2	37.5	46.6	66.5	61.6
	Tsat	50	55.2	80.5	24.3	55.2	51.6	52.5
	Tdis	0	16.7	9.3	46.2	16.7	18.5	18.1
PM 3:00	Ts	6	7	5	4	7	5	5.5
	Tc	69.2	64.5	78.5	81.4	64.5	76.4	73.4
	Tsat	50	61.7	77.7	61.1	61.7	62.9	72.7
	Tdis	5.6	11	9.2	7.3	11	7.4	8.3
PM 3:30	Ts	6	7	5	6	7	5.7	6.0
	Tc	54.3	73	63	54.3	73	57.2	61.2
	Tsat	50	55.2	50	50	55.2	50	51.3
	Tdis	3.7	7.4	29.6	16.5	7.4	16.6	14.3
PM 4:00	Ts	6	6	7	5	6	6	6
	Tc	68.8	74.3	34.5	54.3	74.3	52.5	58
	Tsat	36.1	61	24.8	53	61	38	43.8
	Tdis	3.7	16.3	50.1	18.3	16.3	24	22.1
PM 4:30	Ts	7	7	6	5	7	6	6.3
	Tc	49.3	54	61.2	64.3	54	58.3	57.2
	Tsat	36.1	55.2	39	55.3	55.2	43.5	46.4
	Tdis	10.9	9.2	31.5	20	9.2	25.8	17.9

Test condition: 70.5 F Without Fan

Date : 1st MAR

Subject&location		1	2	3	4	Mean Value		
Sex		M	M	F	F	Male	Female	Combined
Height (in)		72	74	70	64	73	67	70
Weight (lb)		187	199	140	133	193	136.5	164.8
PM 7:00	Ts	6	7	6	6	6.5	6	6.3
	Tc	59.5	65.5	100	93.6	62.5	96.8	79.7
	Tsat	46.7	38.6	68.8	74.8	42.7	71.8	57.3
	Tdis	9.1	57.6	66.9	7.4	33.4	37.2	35.3
PM 7:30	Ts	7	8	6	7	7.5	6.5	7
	Tc	68.8	16.6	89.4	63.9	42.7	76.7	59.6
	Tsat	36.1	21.5	49.8	11.1	28.8	30.5	29.6
	Tdis	7.3	68.6	22.1	48.2	38	35.2	36.6
PM 8:00	Ts	8	8	7	7.5	8	7.3	7.6
	Tc	40.5	10	83.3	34.2	25.3	58.8	42
	Tsat	16.6	16.6	58	8.3	16.6	33.2	24.9
	Tdis	53.8	79.7	23.9	53.8	66.8	38.9	52.8
PM 8:30	Ts	8	8	7	8	8	7.5	7.8
	Tc	22.5	10.6	45.4	39	16.6	42.2	29.4
	Tsat	8.2	18.6	33.4	13.9	13.4	23.7	18.5
	Tdis	65	68.5	31.1	49.8	66.8	40.5	53.6
PM 9:00	Ts	8	8	8	7	8	7.5	7.8
	Tc	24.4	24.6	53.7	74.2	24.5	64	44.2
	Tsat	5.2	22.4	55.2	41.9	13.8	48.6	31.2
	Tdis	66.5	61.1	40.4	24.1	63.8	32.3	48

Test condition: 63 F Without Fan

Date : 4th MAR

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	M	M	Male	Female	Combined
Height (in)		68	61	71	69	70	64.5	67.3
Weight (lb)		137	109	151	160	155.5	123	139.3
PM 2:30	Ts	4	5	7	6	4.5	6.5	5.5
	Tc	42	63.9	47.5	45	46.3	53	50
	Tsat	74.7	50	52.5	52.5	52.5	62.4	57.4
	Tdis	14.8	38.8	25.9	20.3	23.1	26.8	25
PM 3:00	Ts	6	6	4	5	6	4.5	5.3
	Tc	62.5	58.4	69.2	66.4	67.8	60.5	64.1
	Tsat	24	50	50	43.3	46.7	37	41.8
	Tdis	29.6	20.3	29.6	35.2	32.4	25	28.7
PM 3:30	Ts	7	6	6	5	6.5	5.5	6
	Tc	76.3	61.3	47.8	68.8	58.2	68.8	63.6
	Tsat	80	52.5	55.7	32.6	44.2	66.2	55.2
	Tdis	11.1	18.5	27.7	37	32.4	14.8	23.6
PM 4:00	Ts	7	6	7	5	6.5	6	6.3
	Tc	45.9	55.5	43.3	57.5	50.4	50.7	50.6
	Tsat	63.8	50	50	32.7	41.4	56.9	49.1
	Tdis	22.1	14.8	35.2	31.4	33.3	18.5	25.9
PM 4:30	Ts	6	6	6	6	6	6	6
	Tc	65	70.8	62.5	55	58.8	67.9	63.3
	Tsat	61	50	50	38	44	55.5	49.8
	Tdis	16.7	14.8	24.1	31.5	27.8	15.8	26

Test condition: 70 F With Fan

Date : 4th MAR

Subject&location		1	2	3	4	Mean Value		
Sex		F	F	M	M	Male	Female	Combined
Height (in)		67	68	66	69	67.5	67.5	67.5
Weight (lb)		149	152	141	180	160.5	150.5	155.5
PM 7:00	Ts	6	6	6	5	5.5	6	5.8
	Tc	87.5	71.1	85.6	93.5	89.6	79.3	84.4
	Tsat	47.1	50.1	66.7	74.9	70.8	48.6	59.7
	Tdis	18.4	0	5.7	5.5	5.6	9.2	7.4
PM 7:30	Ts	4	4	4	3	3.5	4	3.8
	Tc	39.8	56.5	54.9	35.9	45.4	48.2	46.8
	Tsat	50	55.3	66.8	28.3	47.6	52.7	50.1
	Tdis	31.6	31.7	9.2	74	41.6	31.7	36.6
PM 8:00	Ts	5	5	5	3	4	5	4.5
	Tc	65.1	57.2	75	25	50	61.2	55.6
	Tsat	55.8	52.8	69.6	16.7	43.2	54.3	48.7
	Tdis	29.7	29.7	9.3	83.4	46.4	29.7	38
PM 8:30	Ts	5	5	4	4	4	5	4.5
	Tc	64	73.1	56.6	39.4	48	68.6	58.3
	Tsat	52.8	28	61.5	31	46.3	40.4	43.3
	Tdis	29.7	42.6	11.2	70.3	40.8	36.2	38.6
PM 9:00	Ts	5	5	5	5	5	5	5
	Tc	60.3	60.6	75.5	65	70.3	60.5	65.4
	Tsat	55.7	36.2	63.3	27.7	45.5	46	45.8
	Tdis	31.5	24.3	11.1	70.4	40.8	27.9	34.4

THE EFFECT OF AIR VELOCITY ON THERMAL COMFORT WITH MODERATE ACTIVITY

by

KAI - AN HSIEH

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