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Human Thermal Comfort

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HUMAN THERMAL COMFORT

By

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The purpose of this research is to investigate human comfort criteria under steady-state conditions as a function of ambient air temperature, mean radiant temperature, relative humidity, air velocity, level of activity, and clothing insulation. Since the current ASHRAE Standard 55-1994 is for sedentary activity, this study will consider relative humidity (20% to 65%), dry bulb temperature (73 ^{o}F to 82 ^{o}F), air velocity (30 fpm and 50 fpm), and sedentary-to-moderate activity. The mean radiant temperature will be taken to be the same as the ambient air temperature. The experimental results collected at the Kansas State University Environmental Test Chamber are compared with the Fanger (1982) thermal comfort model and with ASHRAE Standard 55-1994. The experimental study results agreed well with ASHARE Standard 55-1994 for 1-met activity level (sedentary), and the thermal comfort for 1-met activity level was predicted with reasonable accuracy by Fanger's (1982) Model. For 2.3 met activity level, the

experimental results did not agree with ASHRAE Standard 55-1994 or the Fanger Model predictions.

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NOMENCLATURE

B_{Icl}	Systematic uncertainty of clothing insulation
B_M	Systematic uncertainty of metabolic rate
B_{PMV}	Systematic uncertainty of PMV
B_{RH}	Systematic uncertainty of relative humidity
B_{ta}	Systematic uncertainty of ambient air temperature
B_{tatr}	Correlated systematic uncertainty of temperature
B_{tr}	Systematic uncertainty of mean radiant temperature
B_V	Systematic uncertainty of air velocity
f_{cl}	Clothing factor
h_c	Sensible heat transfer coefficient, convection at surface
I_{cl}	Clothing insulation
L	Thermal load on body
M	Metabolic rate
p_a	Water vapor pressure of ambient air
P_{Icl}	Random uncertainty of clothing insulation
P_M	Random uncertainty of metabolic rate
PMV	Predicted Mean Vote
P_{PMV}	Random uncertainty of PMV
P_{RH}	Random uncertainty of relative humidity

P_{ta}	Random uncertainty of ambient air temperature
P_{tr}	Random uncertainty of mean radiant temperature
P_V	Random uncertainty of air velocity
R_{cl}	Thermal insulation, clothing
RH	Relative humidity
t_a	Ambient air temperature
t_{cl}	Clothing surface temperature
t_r	Mean radiant temperature
U_Δ	Difference in uncertainty of experiment and Fanger model
$U_{experiment}$	Uncertainty associated with the experiment
U_{Icl}	Overall uncertainty of clothing insulation
U_M	Overall uncertainty of metabolic rate
U_{PMV}	Overall uncertainty of PMV
U_{RH}	Overall uncertainty of relative humidity (vapor pressure)
U_{ta}	Overall uncertainty of ambient air temperature
U_{tr}	Overall uncertainty of mean radiant temperature
U_V	Overall uncertainty of air velocity
UPC	Uncertainty percentage contribution
UPC_{BIcl}	UPC for systematic uncertainty of clothing insulation
UPC_{BM}	UPC for systematic uncertainty of metabolic rate
UPC_{Bpa}	UPC for systematic uncertainty of vapor pressure (RH)
UPC_{Bta}	UPC for systematic uncertainty of ambient air temperature

UPC_{Btr}	UPC for systematic uncertainty of mean radiant temperature
UPC_{BV}	UPC for systematic uncertainty of air velocity
UPC_{Icl}	UPC for overall uncertainty of clothing insulation
UPC_{M}	UPC for overall uncertainty of metabolic rate
UPC_{pa}	UPC for overall uncertainty of vapor pressure (RH)
UPC_{PIcl}	UPC for random uncertainty of clothing insulation
UPC_{PM}	UPC for random uncertainty of metabolic rate
UPC_{Ppa}	UPC for random uncertainty of vapor pressure (RH)
UPC_{Pta}	UPC for random uncertainty of ambient air temperature
UPC_{Ptr}	UPC for random uncertainty of mean radiant temperature
UPC_{PV}	UPC for random uncertainty of air velocity
UPC_{ta}	UPC for overall uncertainty of ambient air temperature
UPC_{tr}	UPC for overall uncertainty of mean radiant temperature
UPC_{V}	UPC for overall uncertainty of air velocity
V	Air velocity
W	External work accomplished
θ_{Icl}	Partial derivative of PMV respect to clothing insulation
θ_{M}	Partial derivative of PMV respect to met
θ_{pa}	Partial derivative of PMV respect to water vapor pressure
θ_{ta}	Partial derivative of PMV respect to ambient air temperature
θ_{tr}	Partial derivative of PMV respect to mean radiant temperature
θ_{V}	Partial derivative of PMV respect to air velocity

δ	Thermal sensation difference of present study and Fanger model

CHAPTER I

INTRODUCTION

Most people who have experienced hot, muggy weather or cold, clammy weather can readily understand the discomfort associated with high humidity conditions. Humidity affects human comfort in various ways, both directly and indirectly. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as "that condition of mind in which satisfaction is expressed with the thermal environment." This definition states that the idea of thermal comfort is a perception process that involves many input variables and is the result of physical, physiological, and psychological processes. Basically, human thermal comfort depends on four environmental parameters and two personal parameters. The four environmental parameters are dry bulb temperature, mean radiant temperature, relative humidity, and air velocity. The two personal parameters are clothing insulation and level of activity.

The purpose of this research is to establish comfort criteria for low relative humidity levels with high dry bulb temperatures. The experiment was conducted at the Kansas State University (KSU) Environmental Test Chamber. The thermal comfort model by Fanger (1982) is introduced. The predictions from the Fanger (1982) Model will be validated with test results will obtained at KSU. Also, an uncertainty analysis associated with the Fanger model been performed.

Chapter 2 gives a review of the literature survey dealing with the previous research. A detail description of the Fanger (1982) Model and the detailed uncertainty associated with it are found in Chapter 3. Chapter 4 discusses the experiment that was conducted at KSU and presents the results. Chapter 5 compares the results from the present study with the Fanger (1982) Model and with ASHRAE Standard 55-1994. Chapter 6 presents the conclusions.

CHAPTER II

REVIEW OF LITERATURE

The Effect of Relative Humidity on Thermal Comfort

The relative humidity range is important not only for comfort, but also for health issues. According to Sterling, Arundel, and Sterling (1985), an increase in relative humidity encourages mildew growth, but low relative humidity can result in respiratory problems due to dryness. The bacterial populations typically increase below 30% and above 60% relative humidity. Relative humidity below 40% may cause respiratory infections. High relative humidity causes chemical reactions to occur. Conversely, low relative humidity produces ozone that irritates the mucous membranes and eyes.

Wright (1968) revealed that bacteria such as mycoplasma laidlawii prefer relative humidity either above 75% or below 25%. From the health literature of relevant biological and chemical interactions, Sterling et al. (1985) identified an optimal range of humidity where overall health risks would be minimized. Sterling et al. concluded that the optimal relative humidity range should be from 40% to 60%. This range of relative humidity is included in the recommendation for ASHRAE Standard 55-1994.

Sprague and McNall (1970) studied the effects of fluctuating temperature and relative humidity on the thermal sensation (thermal comfort) of sedentary subjects. During the test, all other variables except relative humidity were held constant. The exposure time was 3 hours for all tests. The ranges for the relative humidity fluctuation were 3% peak-to-peak fluctuation amplitude with a half-hour fluctuation period and 14% peak-to-peak fluctuation amplitude with a fluctuation period of one hour. From the study, the investigators found that there were no serious occupant complaints from fluctuations of relative humidity. Also, Nevins et al. (1974) found that males sensed a greater discomfort when the humidity was increased from 60% to 80% at an activity level of 1.2 met. In addition, the discomfort at 80% relative humidity was significantly higher in males than in females.

The Effect of Dry Bulb Temperature/Mean Radiant Temperature on Thermal Comfort.

Dry bulb temperature and mean radiant temperature have significant influence on thermal comfort. Basically, the dry bulb temperature is the ambient air temperature. By definition, the radiant temperature is the mean temperature of individual exposed surfaces in the environment.

Rohles and Nevins (1971) studied the nature of thermal comfort for sedentary men. This study involved 160 test conditions that included 20 dry bulb temperatures ranging from 60 ^{o}F to 98 ^{o}F (in 2 ^{o}F increments) at each of 8 relative humidity levels (15, 25, 35, 45, 55, 65, 75, and 85%). The researchers found that some subjects voted "comfortable" for temperatures between 72 ^{o}F to 81 ^{o}F and relative humidities between 15% to 85% for an exposure of 3 hours. Men needed approximately 1.5 hours to adapt to their thermal environments. The results showed that men felt warmer than women during the first hour at a given thermal condition. According to Rohles and Nevins (1971) temperature is seven times more important than relative humidity in influencing how men felt. Furthermore, for women temperature is nine times more important than relative humidity. The investigators found that males adapted to their thermal environments faster than females.

The study carried out by Sprague and McNall (1970) examined the effects of fluctuations in temperature on thermal comfort. The test conditions for the temperature fluctuations ranged from a peak-to-peak amplitude of 5 ^{o}F with a period of a half-hour to a peak-to-peak amplitude of 6 ^{o}F with a period of one hour. They concluded that no serious occupant complaints would occur due to temperature fluctuations.

The Effect of Air Velocity on Thermal Comfort.

Air velocity has profound effects on thermal comfort. In order to keep the same thermal sensation if the temperature increased, then the air velocity also has to be increased. The study conducted by McIntyre (1978) showed that the subjects chose air velocities that increased with air temperature to maximum of about 2 m/s (394 ft/min) at 30 ^{o}C (86 ^{o}F). According to McIntyre, the perception of the strength of an airflow increases as the square of the air velocity while the cooling effect increases as the square root of the velocity. For warmer ambient temperature, regulating the fan speed (increasing air velocity) can reduce discomfort. However, the upper limit for comfort was 28 ^{o}C (82.4 ^{o}F). For a temperature above 28 ^{o}C (82.4 ^{o}F), increased air movement will cause too many disturbances (i.e., noise and papers will be blown off).
ASHRAE Standard 55-1994 recommends that a maximum mean velocity for winter of 30 ft/min and for summer of 50 ft/min. In addition ASHRAE Standard 55-1994 specifies that acceptance of the increased air speed depends on the occupants' abilities to control local air speed.

Rohles et al. (1974) investigated the effects of air movement and temperature on the thermal sensations of sedentary subjects. Ninety subjects (45 male and 45 female) participated in the 3-hour experiment. The air velocities selected for the study were 40, 80, and 160 ft/min, and the temperatures were 72 ^{o}F, 78.6 ^{o}F, and 85.2 ^{o}F. The clothing insulation was 0.6 clo. The relative humidity was 50% throughout the study. The investigators found that air temperature and velocity significantly influenced mean skin temperature. The skin temperature exhibited significant interactions with exposure period. No important gender differences existed in the thermal sensations at the higher velocities in the 3-hour test.

The Effects of Activity Level on Thermal Comfort

Activity level has the largest effect on thermal comfort. To measure how much heat is generated by a body for different activity levels, metabolic rate measurements can be performed. Metabolic rate increases in proportion to exercise intensity. By ASHRAE definition, the metabolic rate is the rate of energy production of the body and is expressed in met units. One met is defined as 58.2 W/m^2 (the energy produced per unit surface area of a seated person).

McNall et al. (1967) tested several metabolic rates and found little humidity effects at low metabolic rates and increased humidity effects at higher metabolic rates. Also, sweating and an increase in skin temperature occur when metabolism is increased. Another hypothesis for discomfort is related to periodic variation in metabolic levels. People at light metabolic level ($\leq$ 1.2 met) may temporarily elevate their met levels by climbing stairs or carrying things. During the elevated activity, a higher heat loss is required for thermal balance. If humidity is high, the heat dissipation ability of the body is reduced and the sweat rate will increase over that of a body in a dry environment. The resulting skin wettedness may persist after the activity rate has subsided and the skin cooled off. Discomfort can result from increased skin temperature during the intermittent exercise or residual skin wettedness left over after the exercise.

CHAPTER III

MODELING OF THERMAL COMFORT

There are four environmental parameters and two personal parameters that influence thermal comfort. In order to determine how these six parameters affect the human comfort, thermal sensation scales were established. Fanger (1970) developed the Predicted Percentage of Dissatisfied (PPD), a method used to estimate unacceptable conditions for occupants. Based on the PPD method, if 95% of the occupants are satisfied then the environment is classified as comfortable. However, PPD is based on the Predicted Mean Vote (PMV), which is used to predict an occupant's thermal sensation based on the environmental parameters. Table 3.1 shows the relationship between the thermal sensation scale and the PMV numerical code.

Table 3.1 Standard Thermal Sensation Scale

Thermal Sensation	**Numerical Code (PMV)**	**Vote Number**
Hot	+3	1
Warm	+2	2
Slightly Warm	+1	3
Neutral	0	4
Slightly Cool	-1	5
Cool	-2	6
Cold	-3	7

Fanger (1970) used a mathematical model based on a steady-state energy balance to calculate the PMV. Fanger (1982) modified the steady-state energy balance and came up with the expression as Equation (3-1)

$$
\begin{aligned}
M\text{-}W = {} & 3.96 \times 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] \\
& + f_{cl}h_c(t_{cl} - t_a) \\
& + 3.05[5.73 - 0.007(M- W) - p_a] \\
& + 0.42[(M - W) - 58.15] \\
& + 0.0173M(5.87 - p_a) \\
& + 0.0014M(34 - t_a) \qquad (3\text{-}1)
\end{aligned}
$$

Equation (3-1) states that heat generation is equal to heat removal when humans are in thermal equilibrium with the environment. The heat generation is the internal heat production, which is the difference between the metabolic rate (M) and the mechanical work (W). However, mechanical work (W) is commonly assumed to be zero for several reasons: (1) the mechanical work produced is small compared to metabolic rate (especially for office activities), (2) estimates for metabolic rate can often be inaccurate, and (3) the assumption results in a more conservative estimate when designing air-conditioning equipment.

The heat removal is the summation of all these items:

$3.96 \times 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4]$	Heat loss by radiation from the skin
$f_{cl}h_c(t_{cl} - t_a)$	Heat loss by convection from the skin
$3.05[5.73 - 0.007(M- W) - p_a]$	Evaporative heat loss from the skin
$0.42[(M - W) - 58.15]$	Sweat secretion rate

$0.0173M(5.87 - p_a)$ Evaporative heat loss due to respiration

$0.0014M(34 - t_a)$ Sensible heat loss due to respiration

The values of h_c, f_{cl} and t_{cl} can be estimated from the following equations:

$$h_c = 12.1(V)^{1/2} \qquad (3\text{-}2)$$

$$f_{cl} = 1.05 + 0.1I_{cl} \qquad (3\text{-}3)$$

$$\begin{aligned} t_{cl} = 35.7 &- 0.0275(M - W) \\ &- R_{cl}\{(M - W) \\ &- 3.05[5.73 - 0.007 (M - W) - p_a] \\ &- 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) \\ &- 0.0014M(34 - t_a)\} \end{aligned} \qquad (3\text{-}4)$$

The relationship between R_{cl} and I_{cl} is

$$R_{cl} = 0.155\, I_{cl} \qquad (3\text{-}5)$$

Fanger related PMV to an imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at a specific activity level. PMV can be expressed as function of metabolic rate (M) and thermal load on the body, which is the difference between the heat generation and the heat removal and is represented by L.

$$PMV = [0.303\exp(-0.036M) + 0.028]L \qquad (3\text{-}6)$$

Furthermore, Fanger related PMV to PPD and expressed PPD as function of PMV

$$PPD = 100 - 95\exp[-(0.03353PMV^4 + 0.2179PMV^2)] \qquad (3\text{-}7)$$

The PMV-PPD model is widely used and accepted for design and field assessment of comfort conditions. Figure 3.1 shows a plot of the PPD as a function of the PMV. For example, for this figure, when the mean vote (PMV) is + 1, 28% of the occupants are dissatisfied. As the mean vote deviates from zero, the value of the PPD increases.

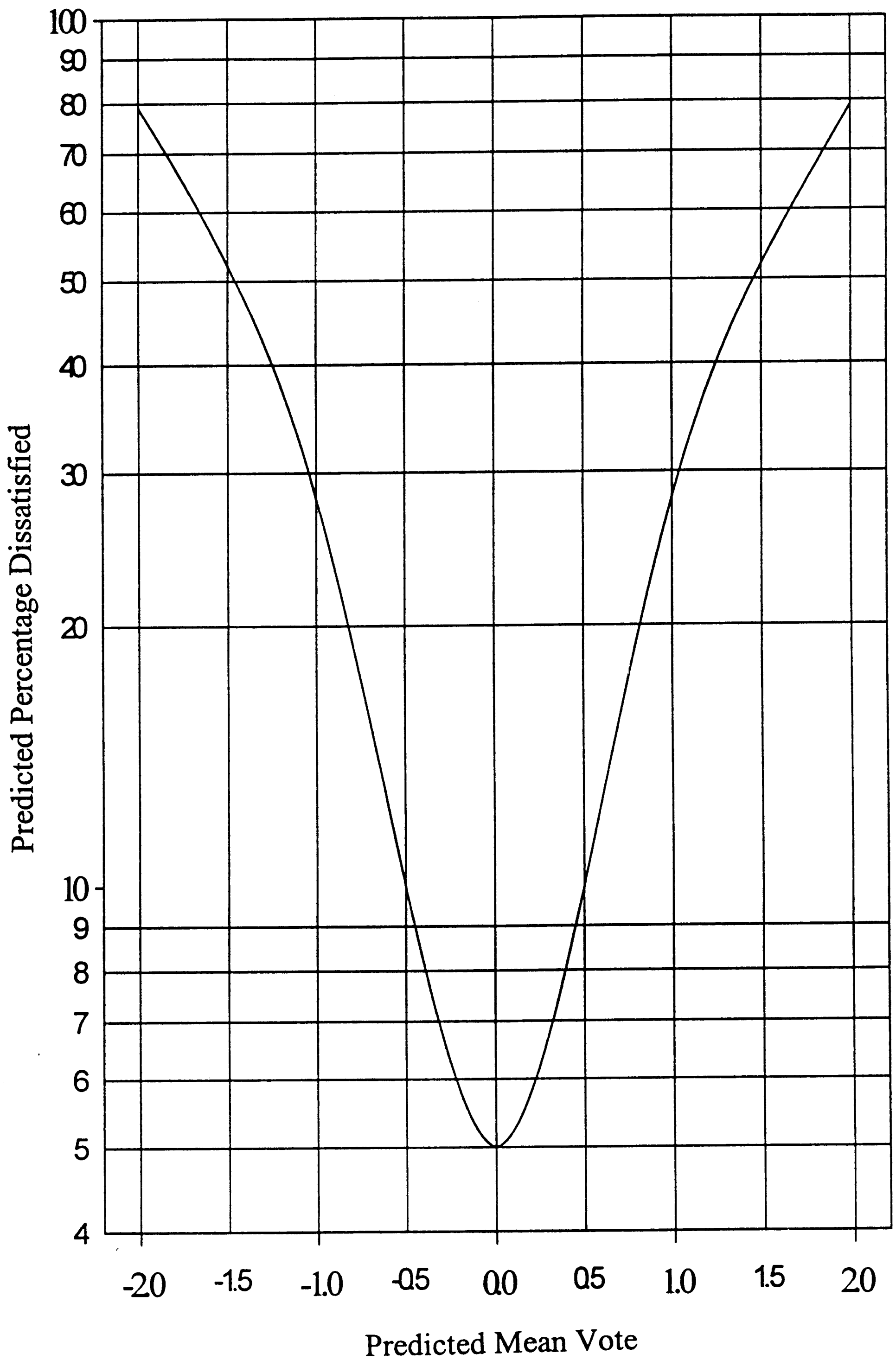

Figure 3.1 PPD as Function of PMV

An uncertainty analysis is necessary in order to fully determine the usefulness of the Fanger (1982) Model. The accuracy of the model will be determined by using the Coleman and Steele (1999) procedure for uncertainty analysis. The first step in Coleman and Steele methodology is to determine the uncertainty estimates for the variables. The detailed uncertainty analysis involves predicting both systematic and random errors associated with each measured variable. Systematic error is that portion of the total error that generally remains constant and is due to the physical limits of the sampling physics. Random error is that portion of the total error which is associated with small changes in operating conditions. The effect of systematic error is to offset the reading from the true value by the amount of the error. The effect of random error is the scatter around the mean value [Coleman and Steele (1999)]. The true value is the actual value of the measured variable but is practically unattainable since there will always be some error in the sampling instruments. Correlated systematic uncertainties are those that are not independent of each other and are typically a result of different measured variables sharing some identical elemental error sources. In this model only the systematic correlation of the ambient air temperature and the mean radiant temperature are considered.

The systematic errors and the random uncertainties used are reasonable assumptions for the errors. Using the approach of Coleman and Steele (1999), an uncertainty analysis was performed. MathCad was used to calculate the numerical number for the uncertainty. The uncertainty analysis procedure will be outlined below.

First, define the nominal value for the environmental parameters and the personal parameters. The systematic and random uncertainty associated with each of the parameters also needs to be determined. Second, express the data reduction equation (DRE) in term of the six thermal comfort parameters,

$$PMV(M,t_a,p_a,I_{cl},V,t_r) = [0.303e^{(-0.036\,M)} + 0.028]L(M,t_a,p_a,I_{cl},V,t_r) \quad (3\text{-}8)$$

where

$$\begin{aligned} L(M,t_a,p_a,I_{cl},V,t_r) = (M\text{-}W) - \{&3.96 \times 10^{-8} f_{cl}(t_{cl} + 273)^4 - (t_r + 273)^4] \\ &+ f_{cl}h_c(t_{cl} - t) \\ &+3.05[5.73 - 0.007(M\text{-} W) - p_a] \\ &+0.42[(M - W) - 58.15] \\ &+0.0173M(5.87 - p_a) \\ &+ 0.0014M(34 - t_a)\} \end{aligned} \quad (3\text{-}9)$$

The mechanical work (W) of the expression above is assumed to be zero. However, the data reduction equation is in terms of vapor pressure. Therefore, the relative humidity must be converted to vapor pressure.

The vapor pressure (p_a) can be found by using the saturation temperature in the psychrometric chart at the given relative humidity and dry bulb temperature. Assuming all other uncertainty is negligible, the only uncertainty associated with the vapor pressure is the uncertainty associated with the relative humidity measurement.

Third, take the partial derivative of PMV with respect to each of the six thermal comfort parameters. The mathematical expression of the partial derivative can be expressed as:

$$\theta_M = \frac{d}{dM} PMV(M, t_a, p_a, I_{cl}, V, t_r) \qquad (3\text{-}10)$$

$$\theta_{ta} = \frac{d}{dt_a} PMV(M, t_a, p_a, I_{cl}, V, t_r) \qquad (3\text{-}11)$$

$$\theta_{pa} = \frac{d}{dp_a} PMV(M, t_a, p_a, I_{cl}, V, t_r) \qquad (3\text{-}12)$$

$$\theta_{Icl} = \frac{d}{dI_{cl}} PMV(M, t_a, p_a, I_{cl}, V, t_r) \qquad (3\text{-}13)$$

$$\theta_V = \frac{d}{dV} PMV(M, t_a, p_a, I_{cl}, V, t_r) \qquad (3\text{-}14)$$

$$\theta_{tr} = \frac{d}{dt_r} PMV(M, t_a, p_a, I_{cl}, V, t_r) \qquad (3\text{-}15)$$

The only two correlated parameters for this particular experiment are the ambient air temperature and the mean radiant temperature. The correlation between the ambient air temperature and the mean radiant temperature can be stated as

$$B_{tatr} = B_{ta}B_{tr} \qquad (3\text{-}16)$$

The systematic uncertainty and the random uncertainty associated with PMV can be expressed using the root-sum-square method from Coleman and Steele (1999).

$$B_{PMV} = [\theta_{ta}^2 B_{ta}^2 + \theta_{tr}^2 B_{tr}^2 + \theta_M^2 B_M^2 + \theta_{Icl}^2 B_{Icl}^2 + \theta_V^2 B_V^2 + \theta_{pa}^2 B_{RH}^2 + 2(\theta_{tr}\theta_{ta}B_{tatr})]^{0.5} \qquad (3\text{-}17)$$

$$P_{PMV} = [\theta_{ta}^2 P_{ta}^2 + \theta_{tr}^2 P_{tr}^2 + \theta_M^2 P_M^2 + \theta_{Icl}^2 P_{Icl}^2 + \theta_V^2 P_V^2 + \theta_{pa}^2 P_{RH}^2]^{0.5} \qquad (3\text{-}18)$$

Finally, the overall absolute uncertainty associated with PMV then becames

$$U_{PMV} = [B_{PMV}^2 + P_{PMV}^2]^{0.5} \qquad (3\text{-}19)$$

The uncertainty percentage contribution (UPC) form has been used for this experiment. The UPC for a given variable gives the percentage contribution of the uncertainty in that variable to the squared uncertainty in the result. The systematic UPC, the random UPC, and the overall UPC are as follows:

Systematic UPC

$$UPC_{Bta} = \frac{(\theta_{ta})^2 (B_{ta})^2}{(B_{PMV})^2} \tag{3-20}$$

$$UPC_{Btr} = \frac{(\theta_{tr})^2 (B_{tr})^2}{(B_{PMV})^2} \tag{3-21}$$

$$UPC_{BV} = \frac{(\theta_{V})^2 (B_{V})^2}{(B_{PMV})^2} \tag{3-22}$$

$$UPC_{BIcl} = \frac{(\theta_{Icl})^2 (B_{Icl})^2}{(B_{PMV})^2} \tag{3-23}$$

$$UPC_{BM} = \frac{(\theta_{M})^2 (B_{M})^2}{(B_{PMV})^2} \tag{3-24}$$

$$UPC_{Bpa} = \frac{(\theta_{pa})^2 (B_{pa})^2}{(B_{PMV})^2} \tag{3-25}$$

Random UPC

$$UPC_{Pta} = \frac{(\theta_{ta})^2 (P_{ta})^2}{(P_{PMV})^2} \tag{3-26}$$

$$UPC_{Ptr} = \frac{(\theta_{tr})^2 (P_{tr})^2}{(P_{PMV})^2} \tag{3-27}$$

$$UPC_{PV} = \frac{(\theta_{V})^2 (P_{V})^2}{(P_{PMV})^2} \tag{3-28}$$

$$UPC_{PIcl} = \frac{(\theta_{Icl})^2 (P_{Icl})^2}{(P_{PMV})^2} \tag{3-29}$$

$$UPC_{PM} = \frac{(\theta_M)^2 (P_M)^2}{(P_{PMV})^2} \tag{3-30}$$

$$UPC_{Ppa} = \frac{(\theta_{pa})^2 (P_{pa})^2}{(P_{PMV})^2} \tag{3-31}$$

In order to obtain the overall UPC, the overall uncertainty associated with each parameter must be found. Again the root-sum-square method from Coleman and Steele (1999) is used.

$$U_{ta} = [B_{ta}^2 + P_{ta}^2]^{0.5} \tag{3-32}$$

$$U_{tr} = [B_{tr}^2 + P_{tr}^2]^{0.5} \tag{3-33}$$

$$U_V = [B_V^2 + P_V^2]^{0.5} \tag{3-34}$$

$$U_{Icl} = [B_{Icl}^2 + P_{Icl}^2]^{0.5} \tag{3-35}$$

$$U_M = [B_M^2 + P_M^2]^{0.5} \tag{3-36}$$

$$U_{RH} = [B_{RH}^2 + P_{RH}^2]^{0.5} \tag{3-37}$$

The overall UPC then became

$$UPC_{ta} = \frac{(\theta_{ta})^2 (U_{ta})^2}{(U_{PMV})^2} \tag{3-38}$$

$$UPC_{tr} = \frac{(\theta_{tr})^2 (U_{tr})^2}{(U_{PMV})^2} \tag{3-39}$$

$$UPC_{V} = \frac{(\theta_{V})^2 (U_{V})^2}{(U_{PMV})^2} \tag{3-40}$$

$$UPC_{Icl} = \frac{(\theta_{Icl})^2 (U_{Icl})^2}{(U_{PMV})^2} \tag{3-41}$$

$$UPC_{M} = \frac{(\theta_{M})^2 (U_{M})^2}{(U_{PMV})^2} \tag{3-42}$$

$$UPC_{pa} = \frac{(\theta_{pa})^2 (U_{pa})^2}{(U_{PMV})^2} \tag{3-43}$$

The results of Fanger (1982) Model will be shown in Chapter 5. Also, the results of the uncertainty associated with the results from the thermal comfort model of Fanger will be presented in the same section.

CHAPTER IV

EXPERIMENTAL STUDY

Method

The experimental study was conducted at the Kansas State University Environmental Test Chamber. Eight thermal conditions were selected for study. These conditions are listed in Table 4.1. A psychrometric chart with both the summer and winter comfort regions identified is presented in Figure 4.1

Two air velocities, 30/fpm and 50/fpm, were employed at each of the eight temperature conditions. Two activity levels, 1.0 met and 2.3 met, were used.

Table 4.1 Eight Thermal Conditions Used in This Study

Condition	**Temperature (^oF, ^oC)/Relative Humidity (%)**
1	79, (26.1)/20
2	82, (27,8)/20
3	77, (25)/35
4	80, (26.7)/35
5	75, (23.9)/50
6	78, (25.6)/50
7	73, (22.8)/65
8	76, (24.4)/65

The 1-met condition is for people doing typical office work. Therefore, the subjects were seated at computers and 1.) typed from selected material, 2.) solved

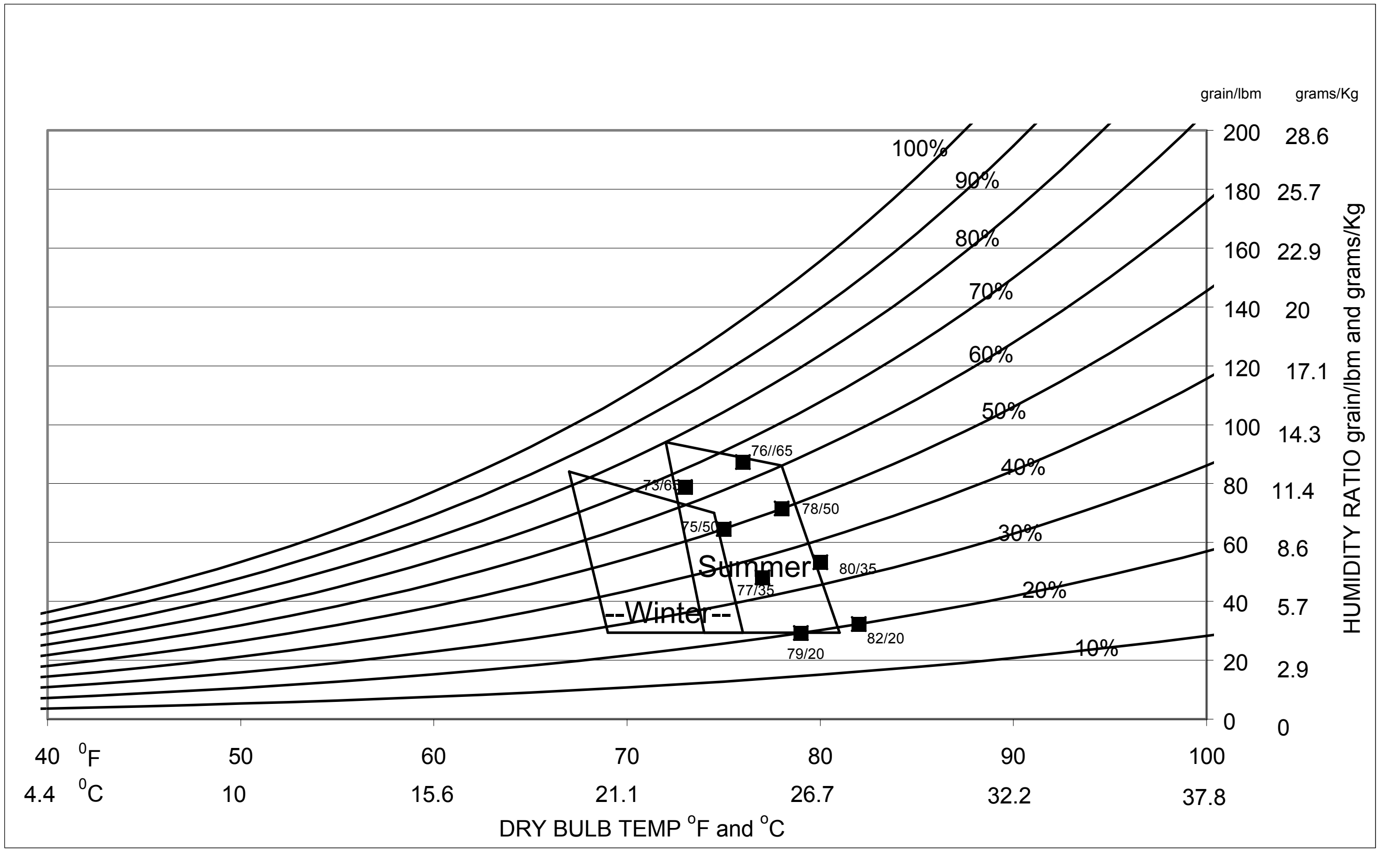

Figure 4.1 Comfort Zones on the Psychrometric Chart

simple arithmetic problems, 3.) solved anagrams, and 4.) worked seek-and-find word games. The typing activity was conducted in the first and third half-hour of the two-hour work session. The reading/writing activity was done in the second and fourth half-hour of the session. For the 2.3 met conditions, the subjects walked half-way across an eleven-foot long environmental chamber, stepped up and down two 9-inch steps (Master Step Test), and continued to the other side of the room and turned around. They rested there for 8 seconds and then repeated the walking and stepping. The total time for walk, step, and rest was 15 seconds. This activity as well as the lower activity level (1 met) lasted for a total of two hours. After each 30 minutes activity, the subjects were given a 3-minute break to fill out the ballots and drink water if needed. The two activity levels, two air velocities, and eight thermal conditions result in 32 conditions. Four men and four women were tested under each condition in two replicates with two of each gender in each replicate. Table 4.2 lists the subjective rating that was used in the test.

Table 4.2 Subjective Thermal Environment Ratings

Rating	**Subjective Rating**
9	Hot
8	Hot/Warm
7	Warm
6	Warm/Comfort
5	Comfort
4	Comfort/Cool
3	Cool
2	Cold/Cool
1	Cold

Subjects

A total of 256 subjects were used, 128 men and 128 women. They were assigned randomly to each of the 32 conditions (8 temperature/humidity x 2 velocities x 2 activity levels). The subjects were recruited from advertisements in the college and local newspapers.

Facilities

All tests took place in two adjacent environmental chambers. These chambers each measured 11ft x 11ft with a ceiling height of 9 feet. Four computer stations were set up in one chamber for the lower activity level (1 met). The second chamber was used for the 2.3 met activity level with four Master Step Tests. The 32 conditions were assigned to the chambers in a completely randomized design with two replicates of each condition. Two men and two women were tested in each chamber. The subjects wore a unisex clothing ensemble consisting of a long-sleeve cotton shirt and chino slacks supplied by KSU. The subjects were also provided cotton socks; however, the subjects wore their own shoes and underwear. This ensemble measured 0.6 clo. The mean radiant temperature was equal to the air temperature.

Procedure

After reading all the procedures and requirements for the tests (Subject Orientation And Informed Consent Statement), the subjects signed up for the experiment and were scheduled. On the day of test, the subjects reported to the Institute for Environmental Research where a nurse ascertained that their oral temperature were normal. They donned the clothing ensemble noted above and were read an orientation statement, which explained the subjective ballots and voting procedures. Two men and two women were randomly assigned to each chamber. The subjects entered the chambers, and the tests began. Votes were taken at half-hour intervals, 0.5, 1.0, 1.5, and 2.0 hours. The reported vote is the average vote of all four ballots taken at 0.5, 1.0, 1.5, and 2.0 hours.

Results

The thermal comfort votes were subjected to a factor analysis with the main sources of variance being temperature/relative humidity, velocity, activity level, and gender. Figure 4.2 presents the mean vote for 1 met and 2.3 met with standard clothing insulation of 0.6 clo and air velocity of 30 fpm for the eight given conditions. Figure 4.2 clearly shows that all conditions range from comfort (vote of 5) to warm/comfort (vote between 5 and 6) for the 1-met level. However, the thermal sensation votes become uncomfortably warm and hot/warm when the activity level increases to 2.3 met. The four combinations (temperature/relative humidity) of 73/65, 75/50, 77/35, and 79/20 resulted in identical mean votes for 1 met. Therefore, increasing temperature and reducing relative humidity can achieve the same thermal sensation. The same trend occurs in the 2.3 met level, even though most subjects felt uncomfortable at the higher activity level.

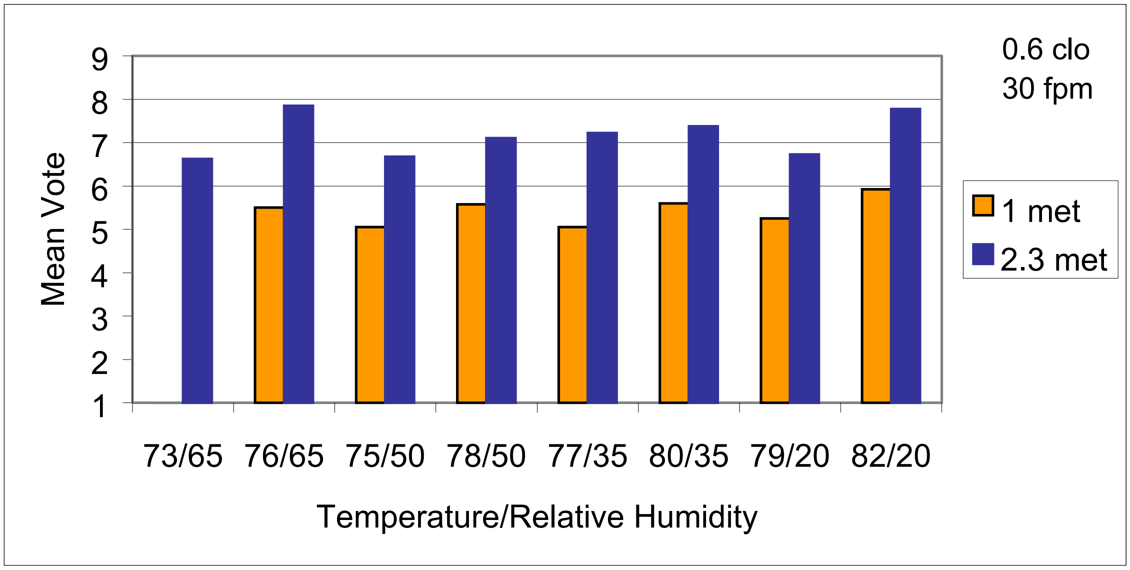

Figure 4.2. Thermal Sensation Results for 30 fpm

Figure 4.3 presents the thermal sensation for 1-met and 2.3-met activity levels when the air velocity is increased to 50 fpm.

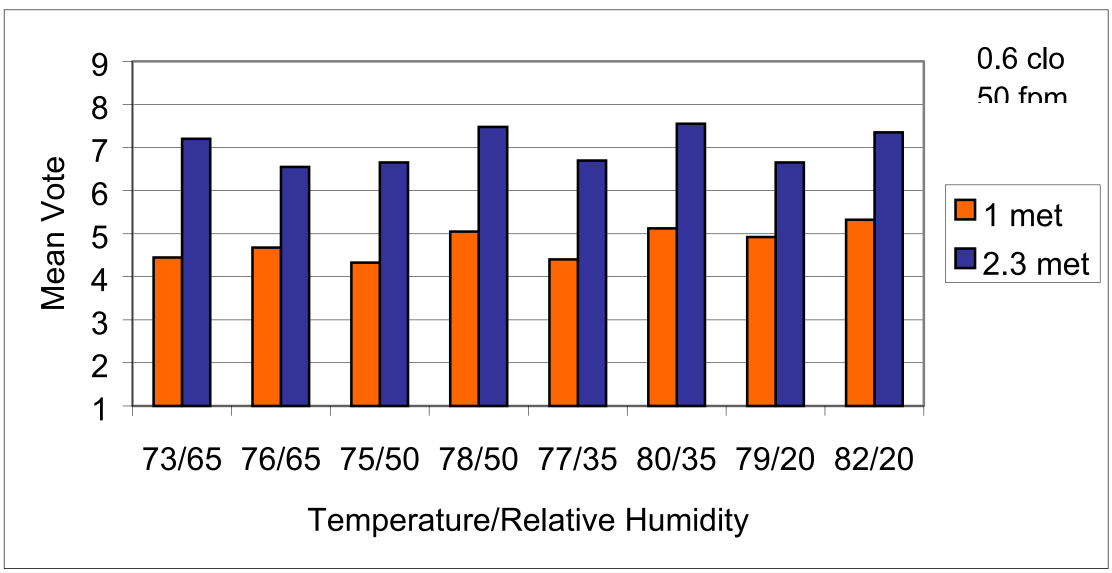

Figure 4.3. Thermal Sensation Results for 50 fpm

At a velocity of 50 fpm, the subjects reported thermal sensations ranging from comfort/cool to comfort for the 1-met activity level. As the activity level increased to 2.3 met, the thermal sensations increased to between warm and hot/warm range. The higher velocity either had a slight effect or no effect on the thermal sensation votes. This outcome is clearly shown in Figures 4.4 and 4.5.

Figure 4.4 depicts the effect of velocity on the thermal sensation for the1-met activity level. Increasing the velocity from 30 fpm to 50 fpm led to a slight decrease in the thermal sensation votes. At 50 fpm, all thermal sensations were in to the cooler range, which is from comfort/cool to comfort. Thus, air velocity has very little effect in thermal sensation at the 1-met activity level. There is only a one to one-half mean vote difference in the results between an air velocity of 30 fpm and an air velocity of 50 fpm. Overall for the 1-met activity level, all the given conditions can be categorized as comfortable for humans.

Figure 4.5 presents the influence of velocity on the thermal sensation at the 2.3-met activity level. Figure 4.5 shows that the thermal sensations range from warm/comfort to hot/warm for both lower and higher air velocities. Therefore, increasing the air velocity had no effect on the thermal sensation for the higher-activity level.

The other variance that might affect thermal sensation is gender. Figures 4.6 to 4.9 illustrate the influence of gender on thermal comfort. Figure 4.6 depicts the thermal sensation of males and females for 1-met activity with 30 fpm and a clo of 0.6. The Figure 4.6 demonstrates that males and females have the same range of thermal comfort.

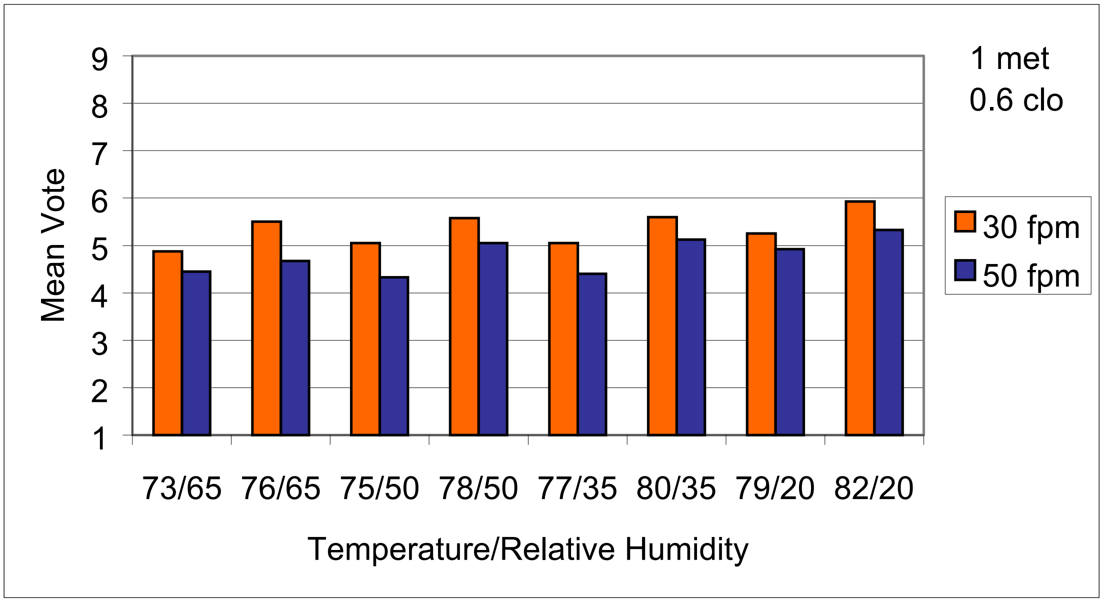

Figure 4.4. Thermal Sensation Results for 1-Met Level

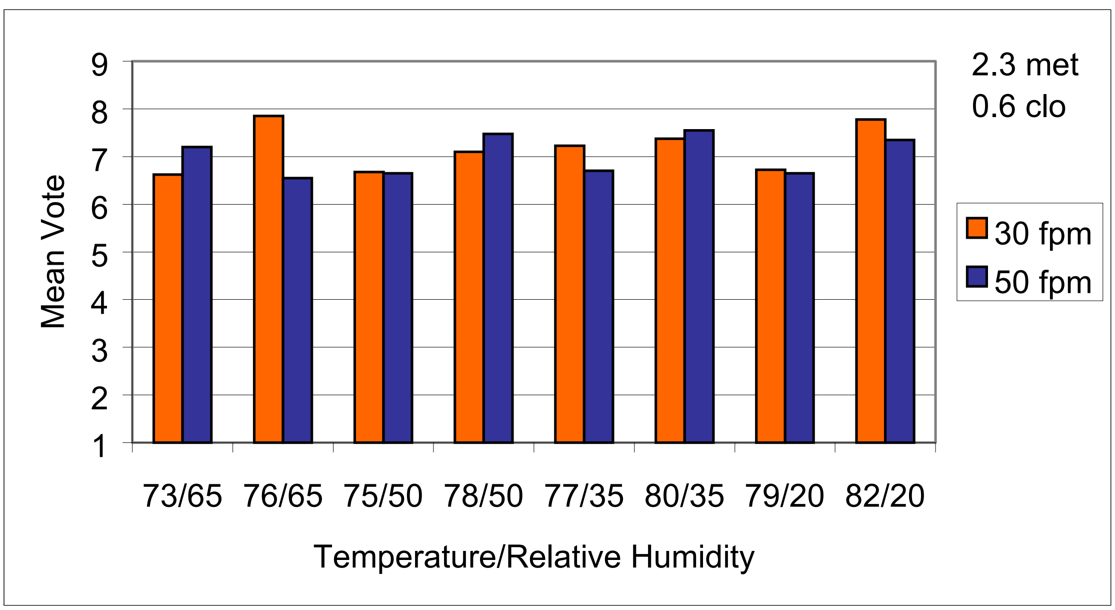

Figure 4.5. Thermal Sensation Results for 2.3-Met Level

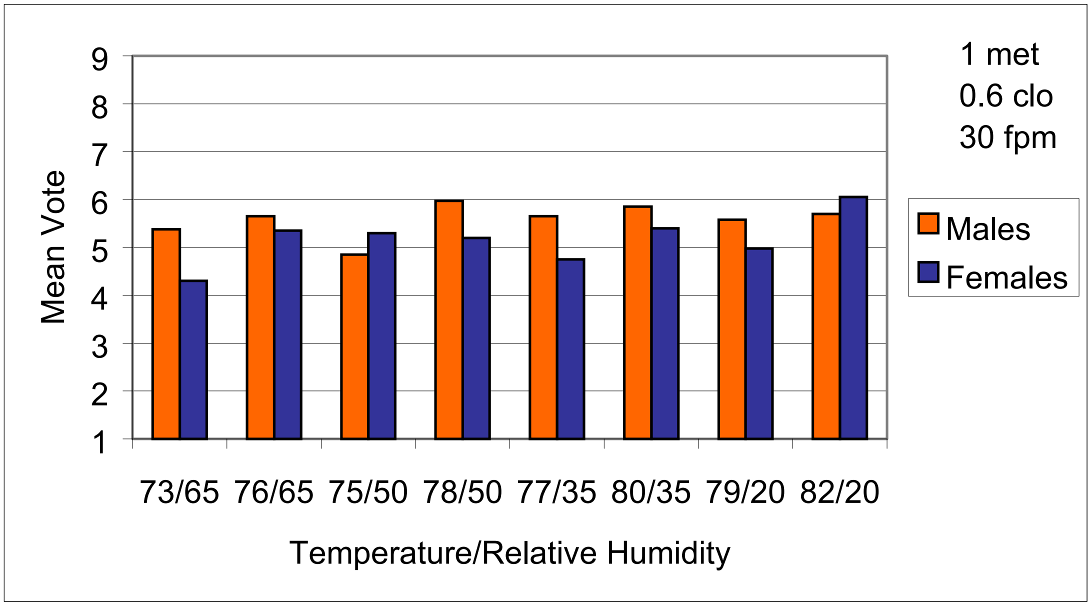

Figure 4.6. Thermal Sensation Results for Gender (1 met, 30 fpm)

As shown in Figure 4.7, males and females subjects experienced the same thermal sensations for the 2.3-met level since all the subjects felt warm for all temperature/relative humidity combinations.

Figure 4.8 presents the change of thermal sensation for gender of air velocity at 50 fpm at the 1-met activity level. The thermal sensations for males stayed in the same range as for 30 fpm. However, the thermal sensations of females was reduced from comfort to slightly cool. Therefore, the higher velocity has produced a slight difference in thermal sensations for males and females.

The thermal sensation comparison between the genders for 50 fpm and the higher activity level of 2.3-met is shown in Figure 4.9. At the 2.3-met level, a comparison of Figure 4.7 and 4.9 indicates the thermal sensations of males and females remained at the same level as for the velocity of 30 fpm.

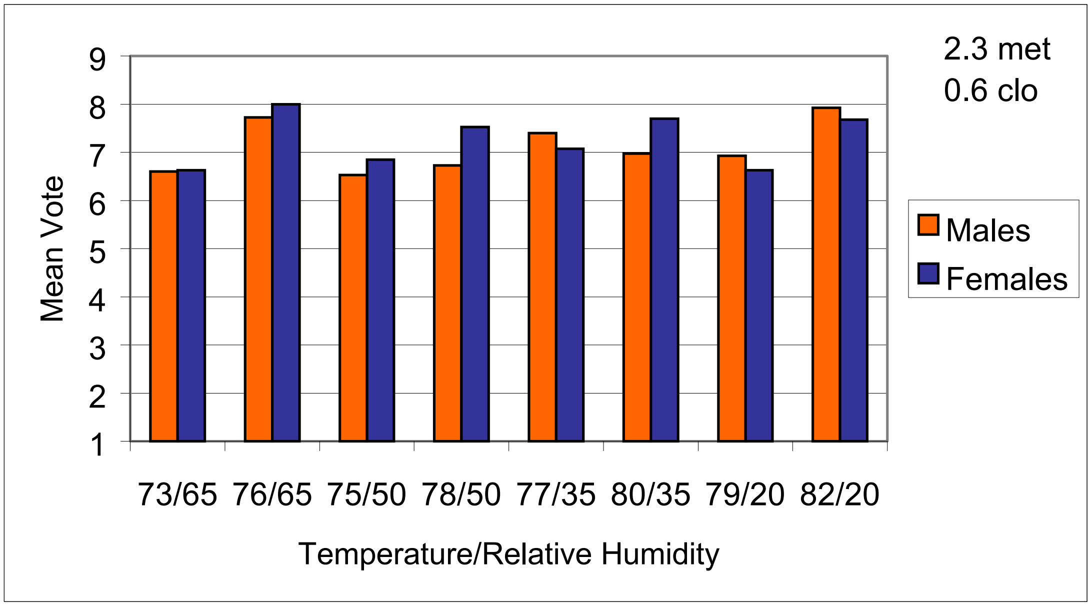

Figure 4.7 Thermal Sensation Results for Gender (2.3 met, 30 fpm)

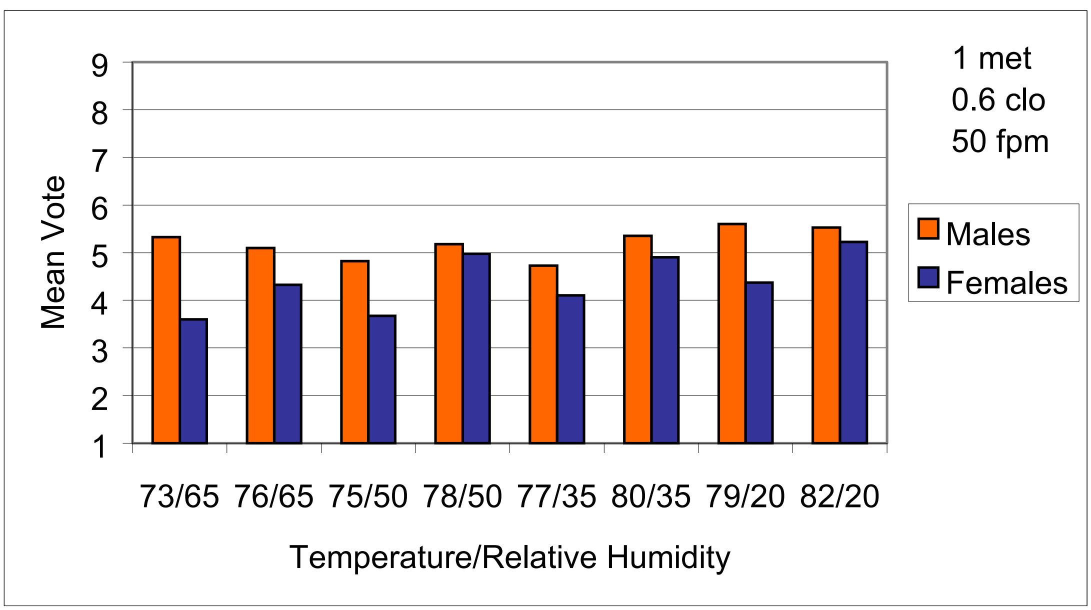

Figure 4.8. Thermal Sensation Results for Gender (1 met, 50 fpm)

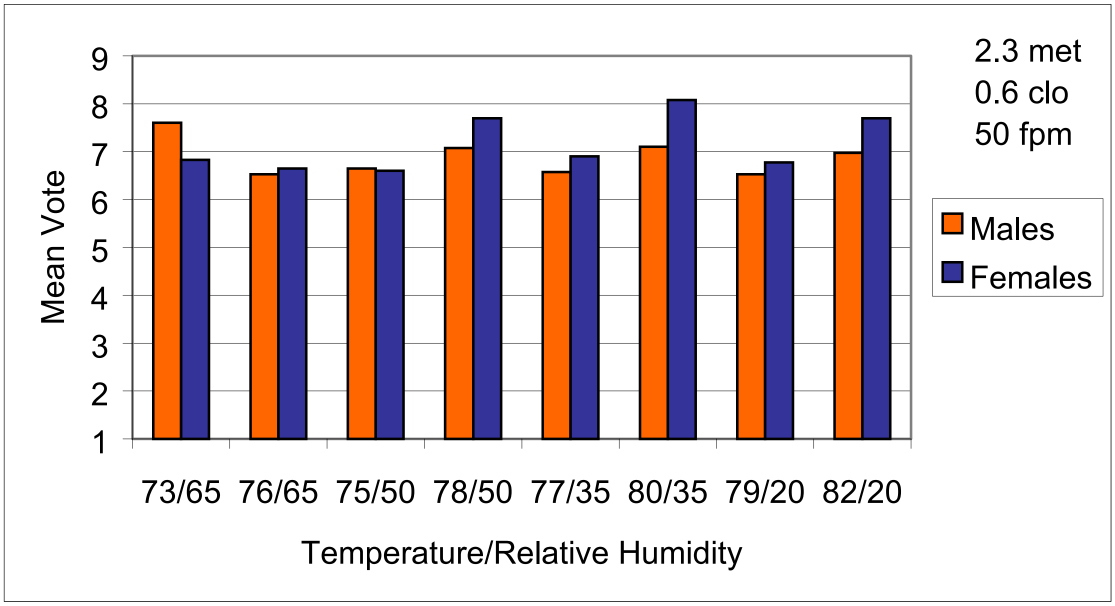

Figure 4.9. Thermal Sensation Results for Gender (2.3 met, 50 fpm)

Uncertainty Analysis of the Experimental Study

An uncertainty analysis was performed for this study. Since this experiment was subjective, only the random uncertainty was considered. The random uncertainty of the experiment will be determined by using the method Coleman and Steele (1999). The expression for determining the random uncertainty for this study is Gaussian Parent Population is

$$U_{experiment} = \frac{2Std}{\sqrt{N}} \tag{4-1}$$

where

Std Standard deviation

N Number of readings

Tables 4.3 through Table 4.6 present the uncertainty analysis results for the experimental study. As shown in Table 4.3 and Table 4.4, the uncertainty results for 1-met are higher than for the 2.3-met level with air velocities of 30 fpm and 0.6 clo insulation except for condition 78/50. The same trends appear for Table 4.5 (1 met) and Table 4.6 (2.3 met) when the air velocity was increased to 50 fpm.

As presented in Table 4.3 and 4.5, the uncertainty associated with the experiment increased for most of the conditions as the air velocity was changed from 30 fpm to 50 fpm for the 1-met activity level. For the 2.3-met level, the uncertainty of the experimental results decreased for most of the conditions when the air velocity was increased from 30 fpm to 50 fpm. (Table 4.4 and Table 4.6)

Table 4.3 Uncertainty Analysis Results for Present Study (1 met, 30 fpm)

Temperature/Relative Humidity	Uncertainty Associated Mean Vote
73/65	0.709
76/65	0.813
75/50	0.610
78/50	0.813
77/35	0.769
80/35	0.767
79/20	0.672
82/20	0.778

Table 4.4 Uncertainty Analysis Results for Present Study (2.3 met, 30 fpm)

Temperature/Relative Humidity	Uncertainty Associated Mean Vote
73/65	0.582
76/65	0.583
75/50	0.573
78/50	1.149
77/35	0.619
80/35	0.680
79/20	0.654
82/20	0.424

Table 4.5 Uncertainty Analysis Results for Present Study (1 met, 50 fpm)

Temperature/Relative Humidity	Uncertainty Associated Mean Vote
73/65	1.025
76/65	1.008
75/50	0.850
78/50	0.636
77/35	0.742
80/35	0.648
79/20	0.648
82/20	0.869

Table 4.6 Uncertainty Analysis Results for Present Study (2.3 met, 50 fpm)

Temperature/Relative Humidity	Uncertainty Associated Mean Vote
73/65	0.442
76/65	0.601
75/50	0.760
78/50	0.424
77/35	0.583
80/35	0.600
79/20	0.678
82/20	0.725

CHAPTER V

COMPARISON OF THE EXPERIMENTAL STUDY RESULTS WITH THE FANGER (1982) MODEL AND ASHRAE STANDARD 55-1994

Comparison of the Experimental Study Results with the Fanger (1982) Model

The experimental results are compared with the calculated PMV for all thirty-two cases using the Fanger (1982) Model. The PMVs generated from the Fanger Model were converted to the thermal sensation scale based on Table 3.1. The thermal sensation scale used a seven-point scale; however the present study uses a nine-point scale. Therefore, the nine-point thermal sensation scale has to be converted to the seven-point scale in order to do a comparison. The following equation is used to convert to the thermal sensation scale of Table 4.2 to the ASHRAE scale:

$$ASHRAE, Scale = 4 - \left(\frac{\Pr esent, Scale - 5}{4}\right) \times 3 \qquad (5\text{-}1)$$

Table 5.1 lists the conversion between both scales.

The PMV predicted from the thermal comfort model is calculated from Equation (3.8),

$$PMV(M,t_a,p_a,I_{cl},V,t_r) = [0.303 \text{ x } e^{(-0.036 \text{ x } M)} + 0.028] \text{ x } L(M,t_a,p_a,I_{cl},V,t_r) \qquad (3\text{-}8)$$

Which depends on the six parameters that affect human thermal comfort.

The vapor pressure of Equation (3-8) can be determined by using a psychrometric chart and a saturated water and steam properties table. Table 5.2 shows the eight conditions and the corresponding vapor pressures in kPa.

Table 5.1 Conversion of Subjective Thermal Environment Ratings

Subjective Rating	Present study scale	Equivalent ASHRAE Scale	ASHRAE Scale	Subjective Rating
Cold	1	7		
Cold/Cool	2	6.25	7	Cold
Cool	3	5.5	6	Cool
Cool/Comfort	4	4.75	5	Slightly cool
Comfort	5	4	4	Neutral
Comfort/ Warm	6	3.25	3	Slightly warm
Warm	7	2.5	2	Warm
Hot/Warm	8	1.75	1	Hot
Hot	9	1		

Table 5.2 Vapor Pressures for Eight Thermal Conditions Used in this Study

Conditions	Temperature (^{o}F, ^{o}C)/Relative Humidity (%)	Vapor Pressure in kpa
1	79, (26.1)/20	1.5268
2	82, (27,8)/20	1.6302
3	77, (25)/35	1.7504
4	80, (26.7)/35	1.8890
5	75, (23.9)/50	1.9520
6	78, (25.6)/50	2.1158
7	73, (22.8)/65	2.1410
8	76, (24.4)/65	2.2670

After determining the vapor pressure, the PMVs were calculated from Equation (3-8). The PMV results for all thirty-two cases are compared and discussed with the results of the present study.

Figure 5.1 through Figure 5.4 present the comparisons of the experimental data with the Fanger model predictions. Figure 5.1 shows the thermal sensation results as compared with Fanger's model for 1-met activity level, 30 fpm air velocity, and 0.6 clo insulation. Figure 5.1 demonstrates that the Fanger model predicts the thermal sensation with reasonable accuracy for the temperature/relative humidity combinations of mid-to-small relative humidity. The comparisons for the 2.3 met level with 30 fpm velocity are depicted in Figure 5.2. The Fanger Model does not agree with the present study for the eight conditions. For the conditions of 82/20 at 2.3 met, the thermal sensation predicted by the Fanger Model is off of the Standard Thermal Sensation Scale and is not shown on Figure 5.2.

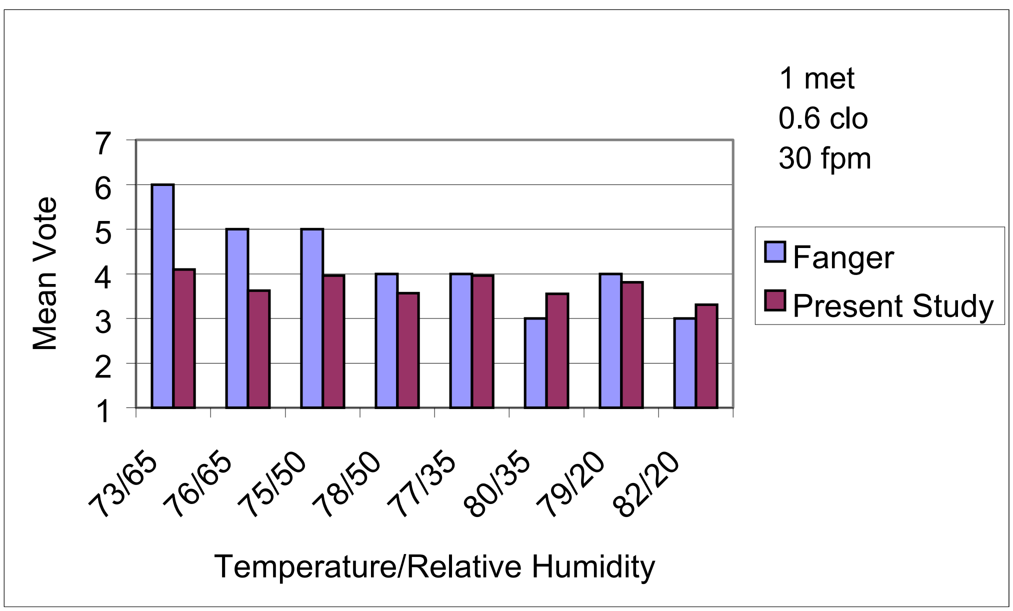

Figure 5.1 Thermal Sensation Results for the Fanger Model and the Present Study (1 met, 30 fpm)

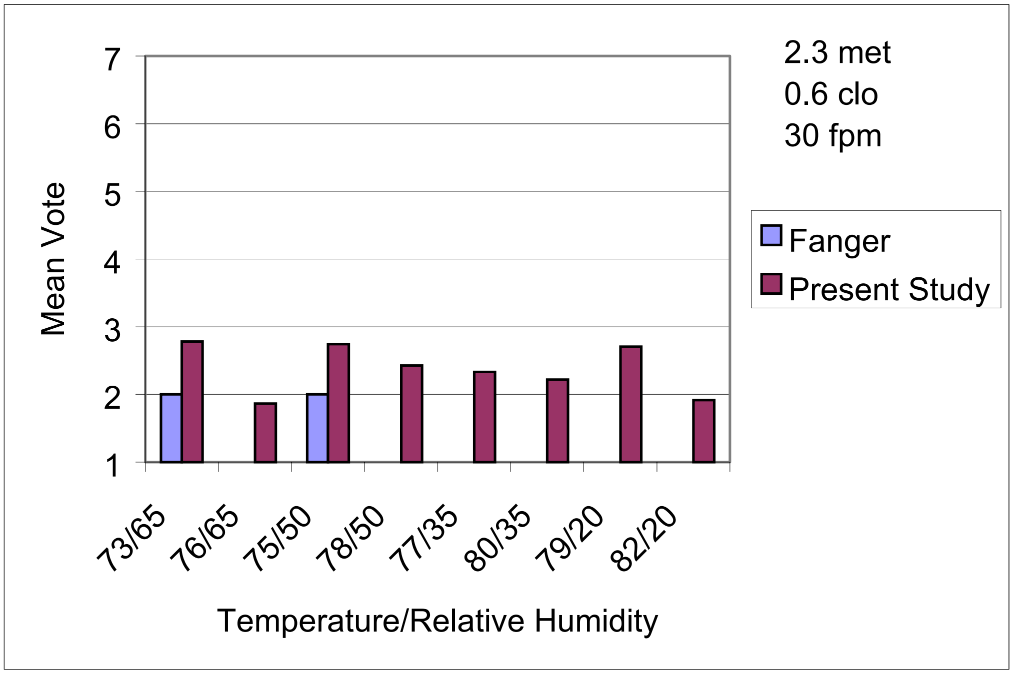

Figure 5.2 Thermal Sensation Results for the Fanger Model and the Present Study (2.3 met, 30 fpm)

Figures 5.3 and 5.4 present the comparisons for an air velocity of 50 fpm with 1-met and 2.3-met activity level, respectively. Figure 5.3 shows the thermal sensations between the Fanger Model and the present study are in a good agreement, except for conditions 73/65 and 75/50. The good agreement appeared in the low-to-moderate relative humidity.

For a velocity of 50 fpm at 2.3 met, Figure 5.4, the thermal sensations for all conditions are similar to those of Figure 5.2 (30 fpm, 2.3 met). The Fanger Model does not accurately predict the results of the experimental study.

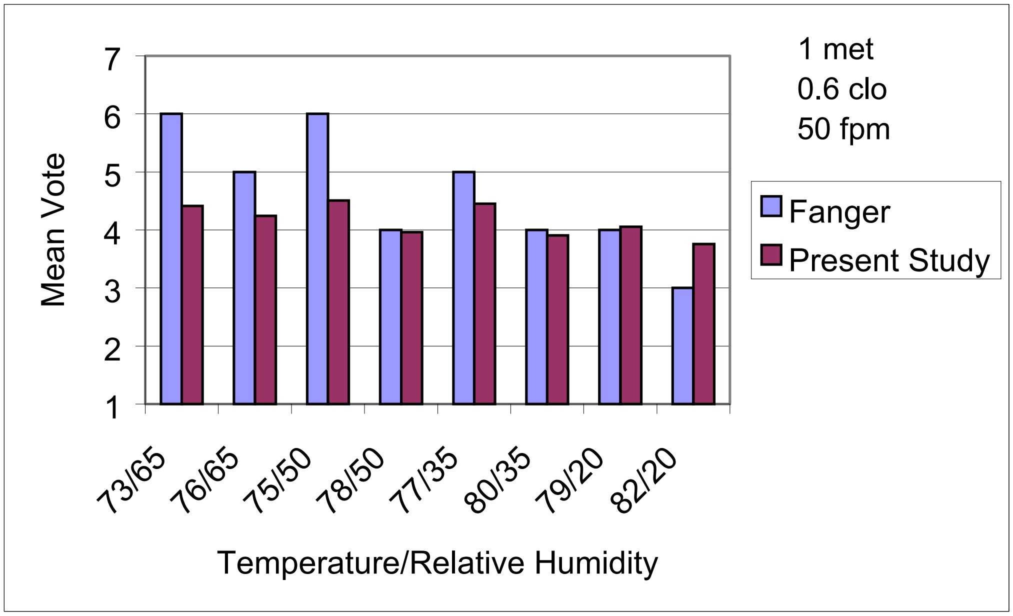

Figure 5.3 Thermal Sensation Results for the Fanger Model and the Present Study (1 met, 50 fpm)

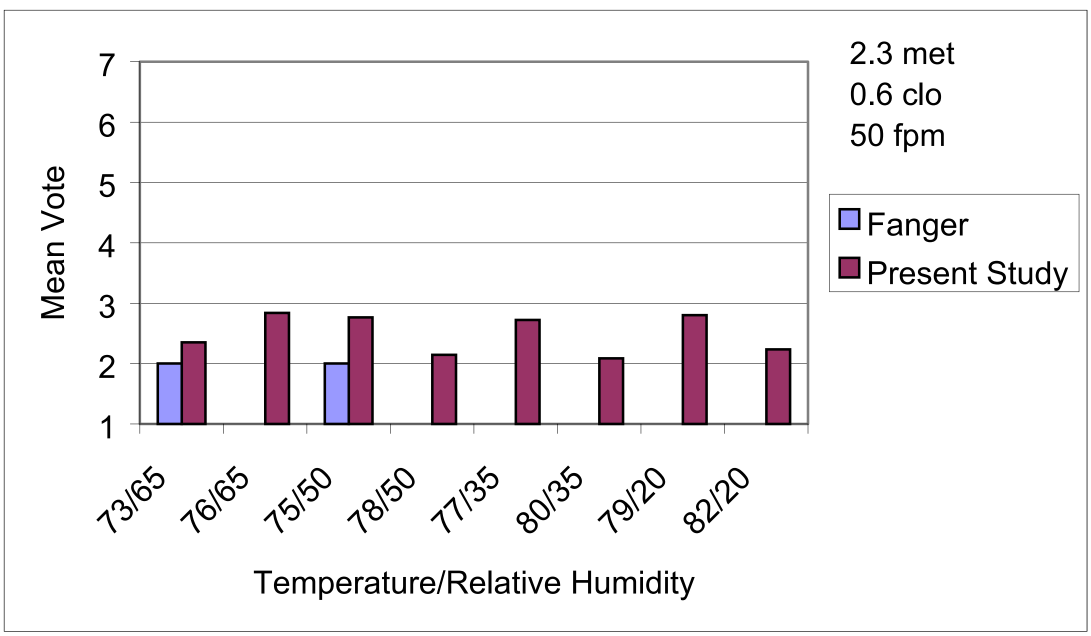

Figure 5.4 Thermal Sensation Results for the Fanger Model and the Present Study (2.3 met, 50 fpm)

The results of the uncertainty analysis of the PMVs determined from the Fanger Model are shown in Tables 5.3 to 5.6. A detailed uncertainty analysis of condition 73/65 with 1-met at an air velocity of 30 fpm and 0.6 clo is presented in Appendix. The systematic and random uncertainty estimates for each variable are given in Appendix.

Table 5.3. Uncertainty Analysis Results (1 met, 30 fpm)

Temperature/Relative Humidity	Uncertainty of Fanger Model (±)
73/65	0.873
76/65	0.777
75/50	0.809
78/50	0.714
77/35	0.747
80/35	0.659
79/20	0.688
82/20	0.610

As shown in Tables 5.3 and 5.4, the uncertainty results for 1 met are higher than for 2.3 met with an air velocity of 30 fpm and 0.6 clo insulation. The same trend appears for Tables 5.5 (1 met) and 5.6 (2.3 met) for an air velocity of 50 fpm. The uncertainties of the PMVs calculated from the Fanger Model increase with increasing air velocity for both met levels. These results are shown in Table 5.3 to Table 5.6.

Table 5.4. Uncertainty Analysis Results (2.3 met, 30 fpm)

Temperature/Relative Humidity	Absolute Uncertainty Associated PMV (±)
73/65	0.507
76/65	0.514
75/50	0.504
78/50	0.512
77/35	0.500
80/35	0.508
79/20	0.497
82/20	0.504

Table 5.5. Uncertainty Analysis Results (1 met, 50 fpm)

Temperature/Relative Humidity	Absolute Uncertainty Associated PMV (±)
73/65	1.019
76/65	0.909
75/50	0.944
78/50	0.834
77/35	0.873
80/35	0.771
79/20	0.804
82/20	0.712

Table 5.6. Uncertainty Analysis Results (2.3 met, 50 fpm)

Temperature/Relative Humidity	Absolute Uncertainty Associated PMV (±)
73/65	0.582
76/65	0.590
75/50	0.578
78/50	0.588
77/35	0.574
80/35	0.583
79/20	0.570
82/20	0.578

In order to reduce the uncertainty, the variables which have the larger uncertainty percentage contributions (UPC) have to be identified. Tables 5.7 through 5.9 and Figures 5.5 through 5.7 summarize the results of the UPCs for conditions 73/65 with 1 met at an air velocity of 30 fpm and 0.6 clo insulation. The results of the UPCs for the systematic uncertainties, the random uncertainties, and the overall uncertainties are presented.

From Figure 5.5, the activity level has the highest systematic UPC and the clothing insulation has the second highest systematic UPC. Air velocity has the next highest systematic UPC. The rest of the parameters have little effect because their UPCs are small. Thus, the systematic uncertainty can be reduced by reducing the systematic uncertainties of the activity level, the clothing insulation, and the air velocity.

Table 5.7 The UPCs for the Systematic Uncertainty

Variables	**UPC**
t_a	0.160
t_r	0.115
V	1.896
I_{cl}	32.514
M	64.932
p_a	0.110

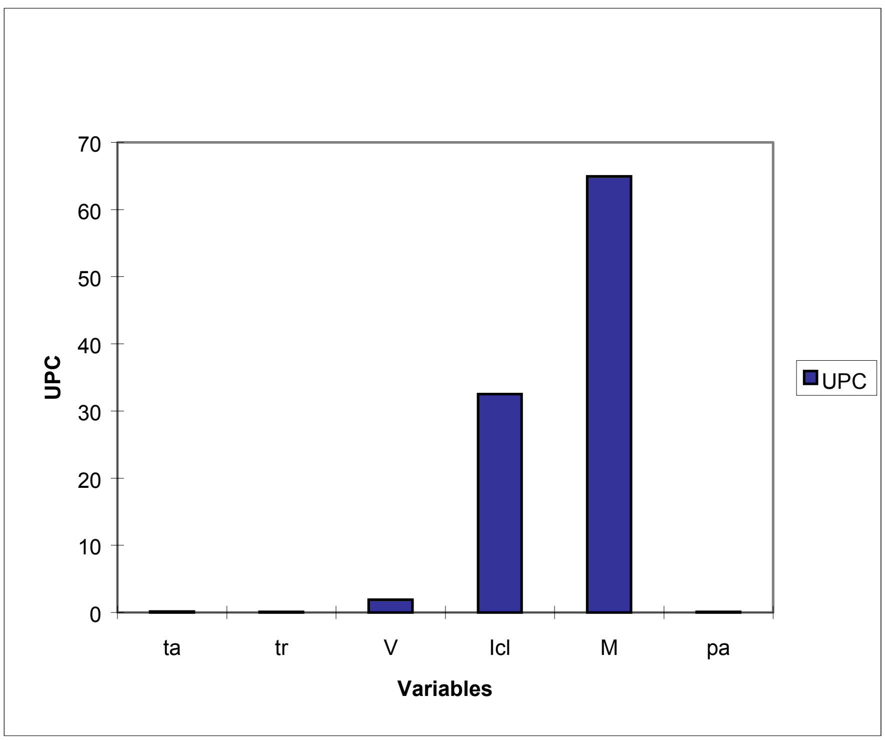

Figure 5.5 The UPCs for the Systematic Uncertainty

Table 5.8 delineates the UPC results for the random uncertainty of the six parameters that are used to calculate the PMVs. In Figure 5.6, the random UPC of the clothing insulation is zero because the KSU standard clothing was used; therefore, there is no random error for I_{cl}. The activity level also has the highest random UPC. The remaining parameters have small random UPCs compared to that of the activity level, so that only the activity level needs to be considered in the random uncertainties of the PMVs.

Table 5.8 The UPCs for the Random Uncertainty

Variables	**UPC**
t_a	0.545
t_r	0.392
V	1.029
I_{cl}	0
M	97.941
p_a	0.093

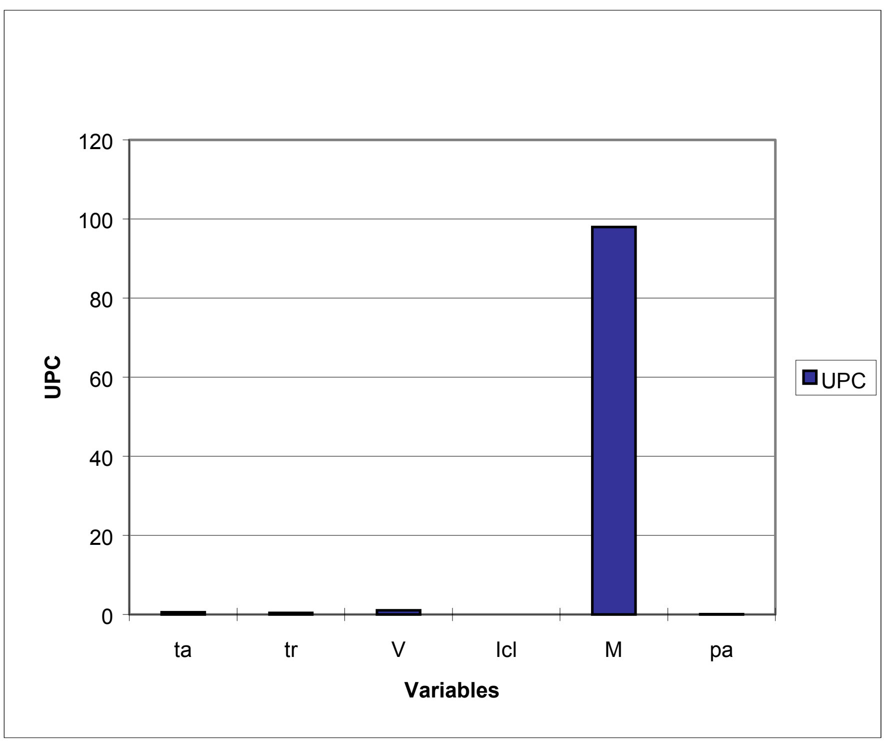

Figure 5.6 The UPC for the Random Uncertainty

The overall UPCs are provided in Table 5.9. The overall uncertainty percentage contribution (UPC) is the combination of the systematic UPC and the random UPC. Figure 5.7 demonstrates that the activity level has the highest overall UPC. Clothing insulation and air velocity are the second and third highest overall UPC, respectively. The UPCs associated with the rest of the variables are very small compared to that of the activity level. Therefore, the uncertainty associated with all but activity level parameters can be neglected. Unfortunately, the met levels for this study are only estimates. In order to improve the accuracy of the met level, significant testing would have had to be done.

Table 5.9 The UPCs for the Overall Uncertainty

Variables	**UPC**
t_a	0.187
t_r	0.134
V	1.836
I_{cl}	30.283
M	67.197
p_a	0.109

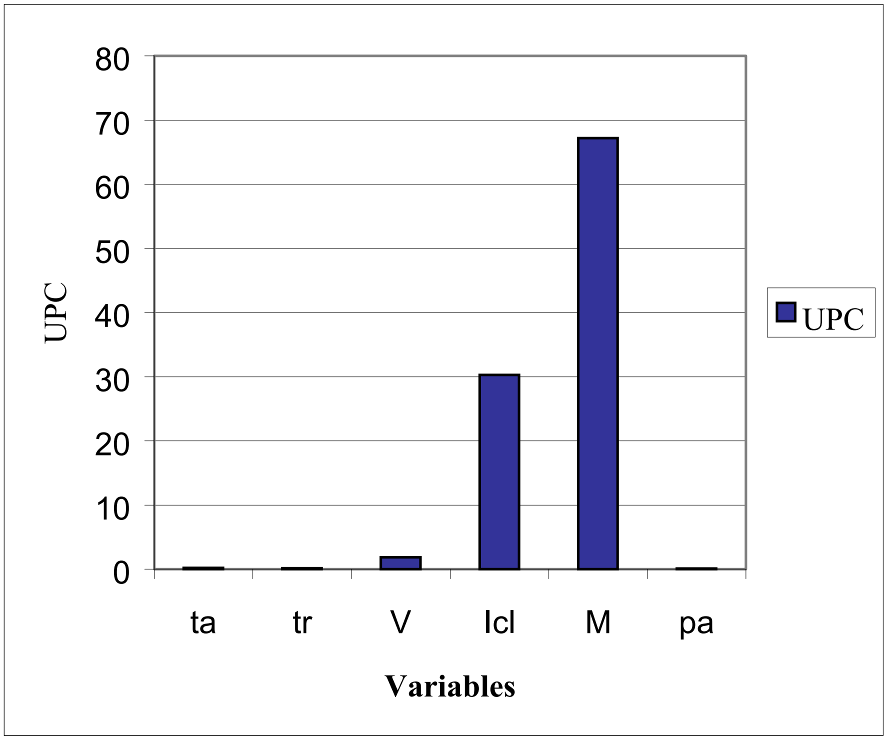

Figure 5.7 The UPC for the Overall Uncertainty

Comparison of the Uncertainties Associated with the Experiment And the Uncertainties Associated with the Fanger (1982) Model

In order to determine the difference in the results of the present study and the Fanger Model, a comparative test has to be considered. A comparative test is the comparison of two test results, either from the same facility or from a different facility. In this case, the two tests are the experimental study and the Fanger Model. First, the differences between the thermal votes of the present study, which was converted into a seven-point scale using Equation (5-1), and the thermal sensations predicted from the Fanger Model (δ) are computed. Second, the uncertainties associated with the differences between the thermal sensation of the present study and the Fanger Model is

$$U_{\Delta} = (U_{experiment}^2 + U_{PMV}^2)^{0.5} \qquad (5\text{-}2)$$

If the thermal sensation difference (δ) is smaller than the uncertainty difference (U_Δ), then there is no indication that the present study and the Fanger Model represent the different physical phenomena [Coleman and Steele (1999)]. Tables 5.10 through 5.13 represent the results of the comparative tests.

Table 5.10 Results for the Comparative Test (1 met, 30 fpm)

Temperature/Relative Humidity	Thermal Sensation Difference	Uncertainty Associate With Difference
73/65	1.9	1.12
76/65	1.4	1.12
75/50	1	1.01
78/50	0.4	1.08
77/35	0	1.07
80/35	0.4	1.01
79/20	0.2	0.96
82/20	0.3	0.99

Table 5.11 Results for the Comparative Test (2.3 met, 30 fpm)

Temperature/Relative Humidity	Thermal Sensation Difference	Uncertainty Associate With Difference
73/65	0.8	0.77
76/65	0.9	0.78
75/50	0.7	0.76
78/50	1.4	1.26
77/35	1.3	0.80
80/35	1.2	0.85
79/20	1.7	0.82
82/20	1.9	0.66

As shown in Tables 5.10 and 5.12 for the 1-met activity level, the thermal sensation differences are smaller than the uncertainty differences so the comparisons between the present study and the Fanger model are acceptable.

For Tables 5.11 and 5.13 for the 2.3-met activity level, the thermal sensation differences are greater than the uncertainty differences so the comparisons between the present study and the Fanger model are unacceptable

Table 5.12 Results for the Comparative Test (1 met, 50 fpm)

Temperature/Relative Humidity	Thermal Sensation Difference	Uncertainty Associate With Difference
73/65	1.6	1.45
76/65	0.8	1.36
75/50	1.5	1.27
78/50	0	1.05
77/35	0.5	1.15
80/35	0.1	1.01
79/20	0.1	1.03
82/20	0.8	1.12

Table 5.13 Results for the Comparative Test (2.3 met, 50 fpm)

Temperature/Relative Humidity	Thermal Sensation Difference	Uncertainty Associate With Difference
73/65	0.4	0.73
76/65	1.8	0.84
75/50	0.8	0.95
78/50	1.1	0.73
77/35	1.7	0.82
80/35	1.1	0.84
79/20	1.8	0.89
82/20	2.2	0.93

Comparison of Experimental Study with ASHRAE Standard 55-1994

As shown in Figure 4.1, the eight thermal conditions selected were within the thermal comfort zone, except for the condition of 80 ^{o}F and 20% relative humidity. ASHRAE Standard 55-1994 was developed for sedentary activity (1.2 met) with clothing insulation of 0.6 clo and velocities between 30 and 50 fpm. ASHRAE uses a seven-point thermal sensation scale. Equation (5.1) was used to convert the nine-point scale to ASHRAE scale (Table 5.1).

The ASHRAE results were generated by using the ASHRAE Thermal Comfort Program version 1.0 [Fountain, et al. (1995)] where the software is based on ASHRAE Standard 55-1994 for 1-met activity level. For non-sedentary activity (higher met level), the program is based on the correlations of other researchers. The Predicted Mean Vote (PMV) generated was converted to the ASHRAE scale based on Table 5.14.

Table 5.14 Predicted Mean Vote (PMV) Conversion to ASHRAE Scale

PMV	ASHRAE Scale	Subjective Rating
-3	7	Cold
-2	6	Cool
-1	5	Slightly cool
0	4	Neutral
+1	3	Slightly warm
+2	2	Warm
+3	1	Hot

Figure 5.8 presents the thermal sensation results of the present study as compared with ASHRAE Standard 55-1994 for 1-met activity, 30 fpm velocity, and 0.6 clo insulation. As expected, the figure shows good agreement. The only exception is the 73/65 condition, which appear slightly cool based on the ASHRAE Comfort Program. The 82/20 thermal condition was chosen outside the ASHRAE comfort zone; therefore, based on ASHRAE Standard 55-1994 people should feel slightly warm. Good agreement with ASHRAE Standard 55-1994 was achieved for the 1-met activity, 50 fpm velocity, and 0.6 clo insulation. The comparison is shown in Figure 5.9. The only exceptions are

the 73/65 and 75/50 thermal conditions where the subjects reported comfortable conditions; however, based on the ASHRAE Comfort Program people should feel slightly cool even though this condition is within the ASHRAE Standard 55-1994 comfort zone.

Figure 5.10 depicts the thermal sensation results as compared with ASHRAE Comfort Program for the 2.3-met activity, 30 fpm velocity, and 0.6 clo insulation. Figure 5.10 illustrates a general agreement between the present results and ASHRAE Comfort Program. None of the temperature/relative humidity combinations produced comfort conditions. The ASHRAE Comfort Program was developed for 1.2 met (sedentary) only.

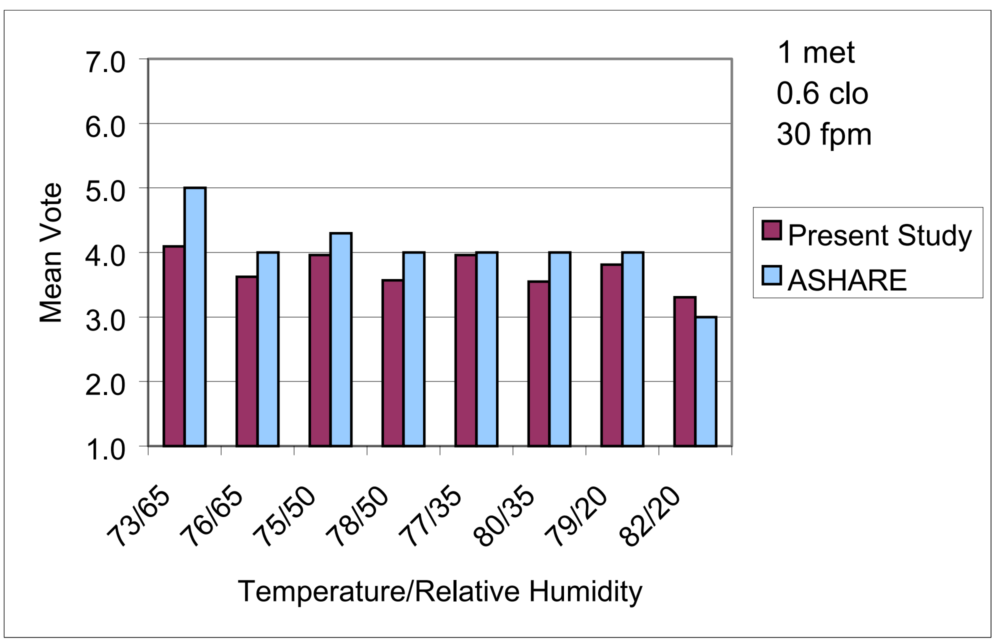

Figure 5.8 Thermal Sensation Results for the Present Study and ASHRAE Standard 55-1994 (1 met, 30 fpm)

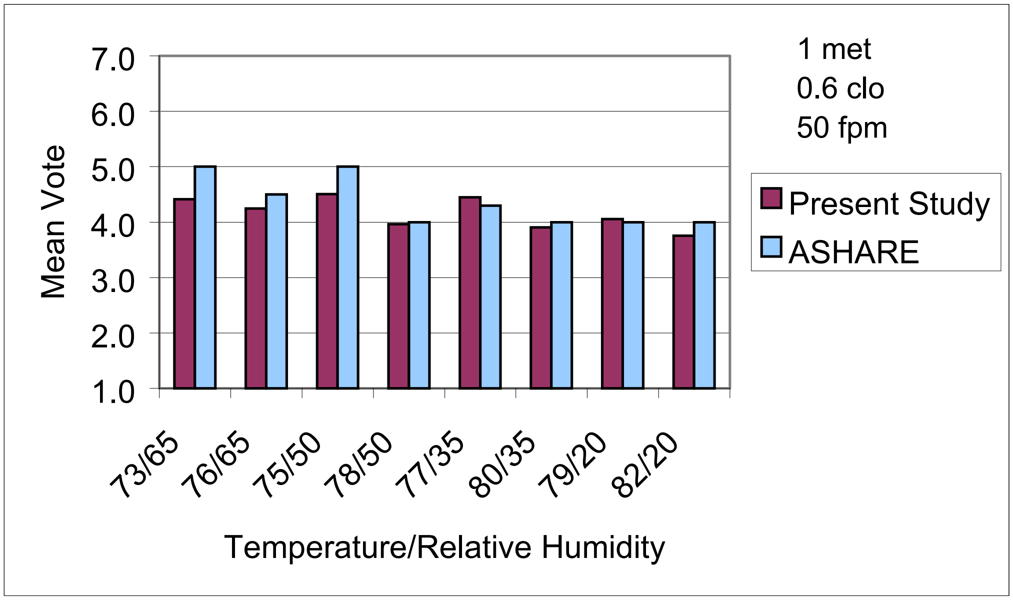

Figure 5.9 Thermal Sensation Results for the Present Study and ASHRAE Standard 55-1994 (1 met, 50 fpm)

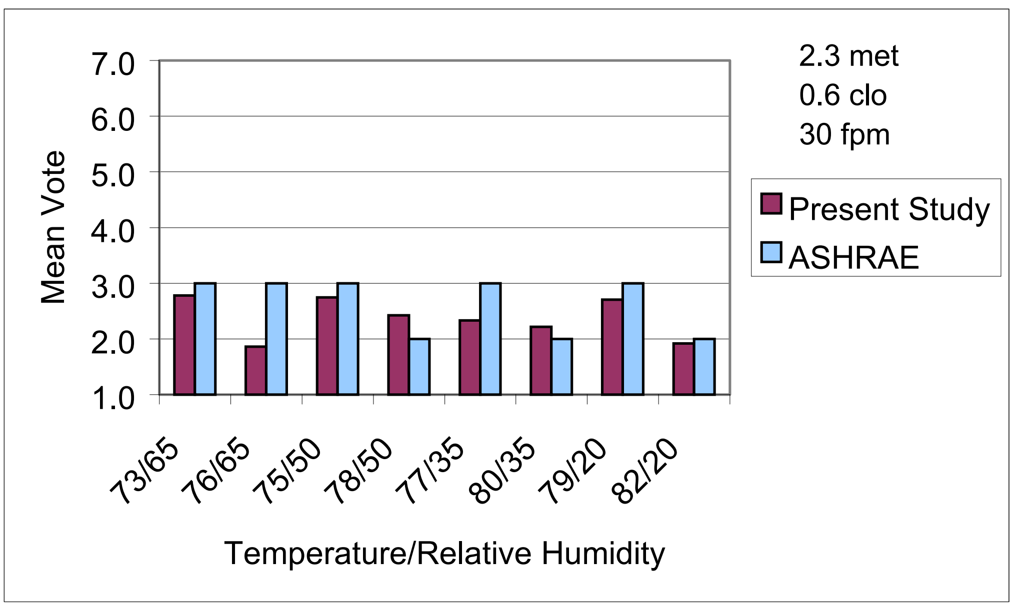

Figure 5.10 Thermal Sensation Results for the Present Study, and ASHRAE Standard 55-1994 (2.3 met, 30 fpm)

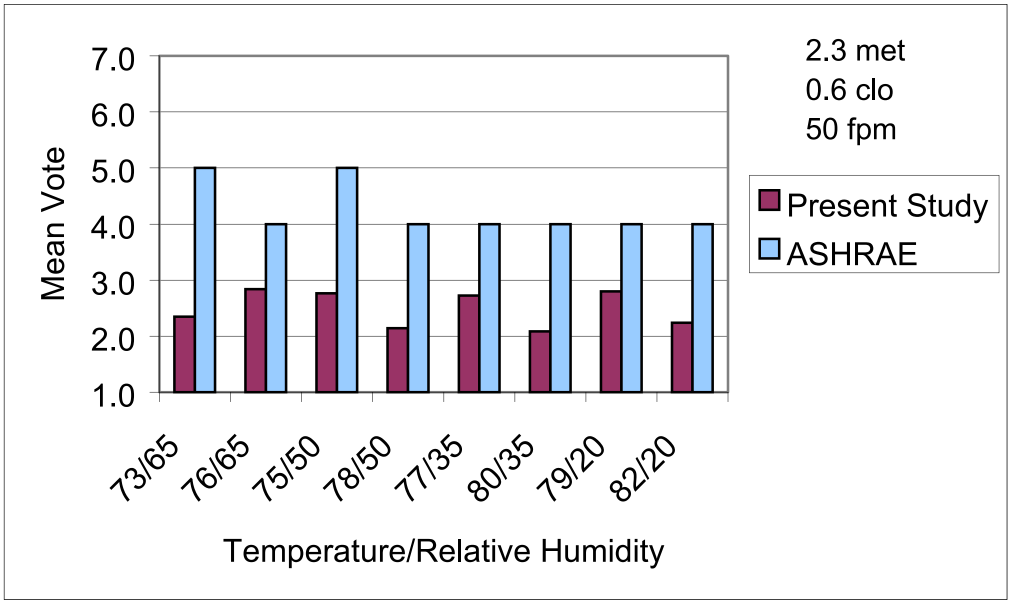

Figure 5.11 Thermal Sensation Results for the Present Study, and ASHRAE Standard 55-1994 (2.3 met, 50 fpm)

As the air velocity increased to 50 fpm at 2.3 met activity level, the figure depicts a significant discrepancy between the ASHRAE Comfort Program results and the present study results. Figure 5.11 shows that none of the temperature/relative humidity combinations had relatively close agreement. An ASHRAE comfort zone should be developed for non-sedentary occupants.

CHAPTER VI

CONCLUSIONS

Human thermal comfort is dependent on four thermal environmental parameters, dry bulb temperature, mean radiant temperature, relative humidity (vapor pressure), air velocity, and two personal parameters (clothing insulation, and activity level). All the parameters are interrelated in affecting the thermal comfort of an individual.

From a review of the literature and from the results of thermal comfort modeling, the lower the relative humidity, the higher the dry bulb temperature can be for thermal comfort. Thus, a lower relative humidity can compensate for a higher dry bulb temperature without sacrificing the occupant's comfort.

In this study, the mean radiant temperature is taken to be equal to the dry bulb temperature. Thus, the effects of radiant heating or cooling from the surroundings are negligible. Based on the present study, the temperature and relative humidity have some effect on the thermal sensation, but they are not the only factors. According to the study results, the temperature instead of the relative humidity is the dominant factor. If the activity level, clothing insulation, and air velocity were constant, increasing the temperature by 1.8 degree Fahrenheit requires reducing the relative humidity from 50% to 30% in order to maintain the same comfort level.

The thermal comfort factor is the combination of all six variables. The activity level is the most important one factor that affects thermal comfort. Subjects that are engaged in the higher-met activity felt significantly warmer than those who were sedentary (1-met activity level). Even if the air velocity were increased from 30 fpm to 50 fpm, the thermal votes changed only slightly. When the air velocity was increased, the thermal sensation votes were reduced slightly at the 1-met level. No changes were observed for the 2.3-met level when the air velocity increased.

The gender variable was coupled with the physical activity. Women and men cast higher (warmer sensations) votes when engaged in the higher met activities. Also, for the lower-met activity level, when air velocity was increased to 50 fpm from 30 fpm, women felt slightly cooler, but the men's thermal sensations remained the same as for an air velocity of 30 fpm. Thus, the air velocity affected the female thermal sensations for sedentary conditions. For non-sedentary condition, the occupants have the same thermal sensation regardless of gender.

Human thermal comfort predicted from the Fanger (1982) Model is also dependent on dry bulb temperature, mean radiant temperature, relative humidity (vapor pressure), air velocity, clothing insulation, and activity level. The results from the Fanger Model agreed well with the present study for the 1-met activity level. However, there are uncertainties associated with Fanger (1982) Model. From the results of a detailed uncertainty analysis, the activity level and the clothing insulation are the two main variables that affect the uncertainty of the PMV. Since standard clothing was used in this study, not much can be done to reduce the clothing insulation uncertainty. Furthermore, to reduce the overall uncertainty associated with the Fanger (1982) Model, the uncertainty associated with the activity-met level would have to be improved. This would require by adding more tests and costs.

In this study except the met level of 2.3-met, the Fanger (1982) Model and the experimental study results exhibit no indication that they represent different physical phenomena. Thus, the Fanger (1982) Model will not be a good model to predict thermal comfort for the 2.3-met activity level.

APPENDIX

DETAIL UNCERTAINTY ANALYSIS FOR PMV CALCULATIONS

(1): Define the nominal value for environmental parameters and personal parameters:

$t_a := 22.8$	Ambient air temperature in ^oC
$t_r := 22.8$	Mean radiant temperature in ^oC
$V := 0.15$	Air velocity in m/s
$I_{cl} := 0.6$	Clothing insulation in clo unit
$M := 60$	Metabolic rate in W/m^2
$RH := 65$	Relative humidity in percent

(2): Express the data reduction equation (DRE) in term of the parameters above.

However, the DRE is not in terms of relative humidity, but is in terms of vapor pressure, so that the relative humidity need to be converted to vapor pressure.

Vapor pressure (p_a) can be found by using the saturation temperature in the psychrometric chart with the given relative humidity and dry bulb temperature. The other uncertainty is neglected so that only the uncertainty for p_a is the uncertainty in how the relative humidity is measured.

For 65% relative humidity and a dry bulb temperature of 22.8^oC from ASHRAE Psychrometric Chart, the saturation temperature is approximately 18.5^oC.

Using that temperature, from the saturated water and steam properties table, the vapor pressure (p_a) can be obtained by interpolation: (temperature in ^oC and pressure in bar)

$T_1 := 15$	$P_1 := 0.0170$
$T_2 := 18.5$	$P_2 = p_a$
$T_3 := 20$	$P_3 := 0.0233$

Thus, after the interpolation and conversion from bar to kPa, the vapor pressure in kPa is

$p_a := 2.141$

The following equations are used to find the results of the data reduction equation. These equations are included the units conversion factor so that the results for the data reduction equation (DRE) are dimensionless.

The mechanical work (W) of the equations can be assumed equal zero because (1) it is small compared to metabolic rate, (2) estimates for metabolic rate can often be inaccurate, and (3) this assumption will result in a more conservative estimate.

$$h_c(V) := 12.1\cdot\sqrt{V}$$

$$f_{cl}(I_{cl}) := 1.05 + 0.1\cdot I_{cl}$$

$$W := 0$$

$$R_{cl}(I_{cl}) := 0.155\cdot I_{cl}$$

$$t_{cl}(M, t_a, p_a, I_{cl}) := 35.7 - 0.0275\cdot(M - W) \ldots + (-R_{cl}(I_{cl}))\cdot\begin{bmatrix} (M - W) \ldots \\ +0 - 3.05\left[5.73 - 0.007(M - W) - p_a\right] \ldots \\ +0 - 0.42[(M - W) - 58.15] \ldots \\ +0 - 0.0173\cdot M\cdot(5.87 - p_a) \ldots \\ +0 - 0.0014\cdot M\cdot(34 - t_a) \end{bmatrix}$$

$$t_{cl}(M, t_a, p_a, I_{cl}) = 29.889$$

The following expression is the steady-state energy balance of the Fanger Model (1982) in the form of thermal load on the body:

$$L(M, t_a, p_a, I_{cl}, V, t_r) := (M - W) \ldots + 0 - \begin{bmatrix} 3.96\cdot 10^{-8}\cdot f_{cl}(I_{cl})\cdot\begin{bmatrix} (t_{cl}(M, t_a, p_a, I_{cl}) + 273)^4 \ldots \\ +0 - (t_r + 273)^4 \end{bmatrix} \ldots \\ + f_{cl}(I_{cl})\cdot h_c(V)\cdot(t_{cl}(M, t_a, p_a, I_{cl}) - t_a) \ldots \\ + 3.05\cdot\left[5.73 - 0.007\cdot(M - W) - p_a\right] \ldots \\ + 0.42\cdot[(M - W) - 58.15] \ldots \\ + \left[0.0173\cdot M\cdot(5.87 - p_a)\right] \ldots \\ + 0.0014\cdot M\cdot(34 - t_a) \end{bmatrix}$$

$$L(M, t_a, p_a, I_{cl}, V, t_r) = -25.563$$

The data reduction equation for PMV is

$$PMV(M, t_a, p_a, I_{cl}, V, t_r) := \left[0.303\cdot e^{(-0.036\cdot M)} + 0.028\right]\cdot L(M, t_a, p_a, I_{cl}, V, t_r) \quad \textbf{DRE}$$

The nominal value of PMV is

$PMV(M, t_a, p_a, I_{cl}, V, t_r) = -1.609$

(3): Perform systematic, random, and overall uncertainty analysis for PMV

(A). Take the partial derivative of the PMV with respect to each of the six parameters

$\theta_M := \frac{d}{dM} PMV(M, t_a, p_a, I_{cl}, V, t_r)$ Partial derivative of the PMV with respect to metabolic rate

$\theta_{ta} := \frac{d}{dt_a} PMV(M, t_a, p_a, I_{cl}, V, t_r)$ Partial derivative of the PMV with respect to ambient air temperature

$\theta_{pa} := \frac{d}{dp_a} PMV(M, t_a, p_a, I_{cl}, V, t_r)$ Partial derivative of the PMV with respect to vapor pressure (relative humidity)

$\theta_{Icl} := \frac{d}{dI_{cl}} PMV(M, t_a, p_a, I_{cl}, V, t_r)$ Partial derivative of the PMV with respect to clothing insulation

$\theta_V := \frac{d}{dV} PMV(M, t_a, p_a, I_{cl}, V, t_r)$ Partial derivative of the PMV with respect to air velocity

$\theta_{tr} := \frac{d}{dt_r} PMV(M, t_a, p_a, I_{cl}, V, t_r)$ Partial derivative of the PMV with respect to mean radiant temperature

$PMV := PMV(M, t_a, p_a, I_{cl}, V, t_r)$

(B). The systematic uncertainties associated with each of the parameters (these are reasonable assumption) are:

$B_{ta} := 0.1$ Systematic uncertainty of the ambient air temperature

$B_{tr} := 0.1$ Systematic uncertainty of the mean radiant temperature

$B_V := 0.015$ Systematic uncertainty of the air velocity

$B_{Icl} := 0.12$ Systematic uncertainty of the clothing insulation

$B_M := 6$ Systematic uncertainty of the activity level

$B_{RH} := 0.056$ Systematic uncertainty of the relative humidity is $\pm 2\%$, which convert to 0.056 vapor pressure in kPa.

(C). The random uncertainties associated with each of the parameters (these are reasonable assumption) are

$P_{ta} := 0.05$	Random uncertainty of the ambient air temperature
$P_{tr} := 0.05$	Random uncertainty of the mean radiant temperature
$P_V := 0.003$	Random uncertainty of the air velocity
$P_{Icl} := 0$	Random uncertainty of the clothing insulation (Assume KSU standard clothing, constant)
$P_M := 2$	Random uncertainty of the activity level
$P_{RH} := 0.014$	Random uncertainty of the relative humidity is $\pm$0.5%, which convert to 0.014 kPa vapor pressure.

No units were given to the systematic and random uncertainty above because of the DRE have already included all the conversion factors. The units for all systematic and random uncertainties associated with the input parameters are

Uncertainty for the ambient air temperature measured in ^{o}C
Uncertainty for the mean radiant temperature measured in ^{o}C
Uncertainty for the velocity measured in m/s
Uncertainty for the clothing insulation measured in clo unit
Uncertainty for the activity level measured in (W/m^2) unit
Uncertainty for the relative humidity measured in $\pm$% but the above value had change to kPa because Vapor pressure in kPa have used in the DRE for PMV calculations.

(D). Calculate the correlation for parameters that are correlated
The only two correlated parameters for this particular experiment are the ambient air temperature and the mean radiant temperature.
Thus, the correlation between the ambient air temperature and the mean radiant temperature became

$$B_{tatr} := B_{ta} \cdot B_{tr}$$

(E). The systematic uncertainty for PMV is

$$B_{PMV} := \left[\theta_{ta}^{\ 2} \cdot B_{ta}^{\ 2} + \theta_{tr}^{\ 2} \cdot B_{tr}^{\ 2} + \theta_M^{\ 2} \cdot B_M^{\ 2} + \theta_{Icl}^{\ 2} \cdot B_{Icl}^{\ 2} + \theta_V^{\ 2} \cdot B_V^{\ 2} \ldots \atop + \theta_{pa}^{\ 2} \cdot B_{RH}^{\ 2} + 2 \cdot \left(\theta_{tr} \cdot \theta_{ta} \cdot B_{tatr} \right) \right]^{0.5}$$

$$B_{PMV} = 0.843$$

(F). The random uncertainty for PMV is

$$P_{PMV} := \left(\theta_{ta}^{2}\cdot P_{ta}^{2} + \theta_{tr}^{2}\cdot P_{tr}^{2} + \theta_{M}^{2}\cdot P_{M}^{2} + \theta_{Icl}^{2}\cdot P_{Icl}^{2} + \theta_{V}^{2}\cdot P_{V}^{2} + \theta_{pa}^{2}\cdot P_{RH}^{2}\right)^{0.5}$$

$$P_{PMV} = 0.229$$

(G). The overall absolute uncertainty can be expressed as

$$U_{PMV} := \sqrt{B_{PMV}^{2} + P_{PMV}^{2}} \qquad U_{PMV} = 0.873$$

<u>(4):</u> The uncertainty percentage contribution (UPC) has been used for this experiment. The UPC for a given variable gives the percentage contribution of the uncertainty in that variable to the squared uncertainty in the result. The systematic UPC, random UPC, and overall UPC are calculated.

(A). The systematic uncertainty percentage contribution (UPC) of each variable to the squared result of systematic uncertainty is

$$UPC_{Bta} := \frac{(\theta_{ta})^{2}\cdot(B_{ta})^{2}}{(B_{PMV})^{2}} \qquad UPC_{Bta} = 0.16\%$$

$$UPC_{Btr} := \frac{(\theta_{tr})^{2}\cdot(B_{tr})^{2}}{(B_{PMV})^{2}} \qquad UPC_{Btr} = 0.115\%$$

$$UPC_{BV} := \frac{(\theta_{V})^{2}\cdot(B_{V})^{2}}{(B_{PMV})^{2}} \qquad UPC_{BV} = 1.896\%$$

$$UPC_{BIcl} := \frac{(\theta_{Icl})^{2}\cdot(B_{Icl})^{2}}{(B_{PMV})^{2}} \qquad UPC_{BIcl} = 32.514\%$$

$$UPC_{BM} := \frac{(\theta_{M})^{2}\cdot(B_{M})^{2}}{(B_{PMV})^{2}} \qquad UPC_{BM} = 64.932\%$$

$$UPC_{Bpa} := \frac{(\theta_{pa})^{2}\cdot(B_{RH})^{2}}{(B_{PMV})^{2}} \qquad UPC_{Bpa} = 0.11\%$$

(B). The random uncertainty percentage contribution (UPC) of each variable to the squared result of random uncertainty is

$$UPC_{Pta} := \frac{(\theta_{ta})^2 \cdot (P_{ta})^2}{(P_{PMV})^2} \qquad UPC_{Pta} = 0.545\%$$

$$UPC_{Ptr} := \frac{(\theta_{tr})^2 \cdot (P_{tr})^2}{(P_{PMV})^2} \qquad UPC_{Ptr} = 0.392\%$$

$$UPC_{PV} := \frac{(\theta_{V})^2 \cdot (P_{V})^2}{(P_{PMV})^2} \qquad UPC_{PV} = 1.029\%$$

$$UPC_{PIcl} := \frac{(\theta_{Icl})^2 \cdot (P_{Icl})^2}{(P_{PMV})^2} \qquad UPC_{PIcl} = 0\%$$

$$UPC_{PM} := \frac{(\theta_{M})^2 \cdot (P_{M})^2}{(P_{PMV})^2} \qquad UPC_{PM} = 97.941\%$$

$$UPC_{Ppa} := \frac{(\theta_{pa})^2 \cdot (P_{RH})^2}{(P_{PMV})^2} \qquad UPC_{Ppa} = 0.093\%$$

(C). The overall uncertainty for each of the variables is

$$U_{ta} := \sqrt{B_{ta}^2 + P_{ta}^2} \qquad U_{ta} = 0.112$$

$$U_{tr} := \sqrt{B_{tr}^2 + P_{tr}^2} \qquad U_{ta} = 0.112$$

$$U_{V} := \sqrt{B_{V}^2 + P_{V}^2} \qquad U_{V} = 0.015$$

$$U_{Icl} := \sqrt{B_{Icl}^2 + P_{Icl}^2} \qquad U_{Icl} = 0.12$$

$$U_{M} := \sqrt{B_{M}^2 + P_{M}^2} \qquad U_{M} = 6.325$$

$$U_{RH} := \sqrt{B_{RH}^2 + P_{RH}^2} \qquad U_{RH} = 0.058$$

(D). The overall uncertainty percentage contribution (UPC) of each variable to the squared result of overall uncertainty is

$$UPC_{ta} := \frac{(\theta_{ta})^2 \cdot (U_{ta})^2}{(U_{PMV})^2} \qquad UPC_{ta} = 0.187\%$$

$$UPC_{tr} := \frac{(\theta_{tr})^2 \cdot (U_{tr})^2}{(U_{PMV})^2} \qquad UPC_{tr} = 0.134\%$$

$$UPC_{V} := \frac{(\theta_{V})^2 \cdot (U_{V})^2}{(U_{PMV})^2} \qquad UPC_{V} = 1.836\%$$

$$UPC_{Icl} := \frac{(\theta_{Icl})^2 \cdot (U_{Icl})^2}{(U_{PMV})^2} \qquad UPC_{Icl} = 30.283\%$$

$$UPC_{M} := \frac{(\theta_{M})^2 \cdot (U_{M})^2}{(U_{PMV})^2} \qquad UPC_{M} = 67.197\%$$

$$UPC_{pa} := \frac{(\theta_{pa})^2 \cdot (U_{RH})^2}{(U_{PMV})^2} \qquad UPC_{pa} = 0.109\%$$

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