## **Predicting Thermal Comfort**

Thermal comfort is largely a state of mind, separate from equations for heat and mass transfer and energy balances. However, the perception of comfort is expected to be influenced by the variables that affect the heat and mass transfer in our energy balance model. The most common approach to characterizing thermal comfort for the purposes of prediction and building design has been to correlate the results of psychological experiments to thermal analysis variables. (A large number of the experiments have been performed at universities with college students as the human subjects.) That is, human subjects with various clothing levels and performing different activities are placed in environments with different air temperatures and surface temperatures, different humidities, and different airflow velocities and patterns. The subjects are then asked to express their level of comfort. The level of comfort is often characterized using the ASHRAE thermal sensation scale, given in Table 1. The average thermal sensation response of a large number of subjects, using the ASHRAE thermal sensation scale, is called the *predicted mean vote* (PMV).

Table 1:	ASHRAE	Thermal Sensatior	n Scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

## Fanger Comfort Analysis

Perhaps the most commonly cited experiments on the human perception of thermal comfort have been performed by Fanger (1982). His analysis indicated that the sensation of thermal comfort was most significantly determined by narrow ranges of skin temperature and sweat evaporation rate, depending on activity level. (More active people were comfortable at low skin temperatures and higher evaporation rates.) By combining this information with the thermal energy balance equations above, he developed a set of correlations giving the PMV as a function of six variables: air temperature, mean radiant temperature, air velocity, air humidity, clothing resistance, and activity level. These equations have been implemented in a software tool that is available for your use on the class website. The equations are presented here for your information.

Fanger's PMV correlation is based on the identification of a skin temperature and sweating rate required for "optimal" comfort conditions, using the data from Rohles and Nevins (1971).

$$T_{sk,req} = 96.3 - 0.156q_{met,heat} \tag{1}$$

$$q_{sweat,req} = 0.42(q_{met,heat} - 18.43)$$
 (2)

The metabolic heat loss is the difference between the metabolic generation and that converted to work (e.g., lifting, running).

$$q_{met,heat} = M - \dot{w} \tag{3}$$

where

$T_{sk}$	=	average skin temperature, °F
М	=	rate of metabolic generation per unit DuBois surface area, Btu/h ft <sup>2</sup>
w	=	human work per unit DuBois surface area, Btu/h ft <sup>2</sup>

However, for our analysis of occupants in most indoor environments, the work production is ironically small.

With these conditions specified, Fanger correlated PMV as a function of the thermal load, L, on the body, defined as the difference between the rate of metabolic heat generation and the calculated heat loss from the body to the actual environmental conditions assuming these optimal comfort conditions. The convection and radiation heat transfer are functions of clothing temperature, which is affected by skin temperature. The evaporative losses are directly influenced by skin temperature.

$$L = q_{met,heat}$$

$$-f_{cl}h_{c}(T_{cl} - T_{a})$$

$$-f_{cl}h_{r}(T_{cl} - T_{r})$$

$$-156(W_{sk,req} - W_{a})$$

$$-0.42(q_{met,heat} - 18.43)$$

$$-0.00077M(93.2 - T_{a})$$

$$-2.78M(0.0365 - W_{a})$$
(4)

where

$T_{cl}$	=	average surface temperature of clothed body, °F
$f_{cl}$	=	ratio of clothed surface area to DuBois surface area $(A_{cl}/A_D)$
$R_{cl}$	=	effective thermal resistance (R-value) of clothing, ft <sup>2</sup> F h/Btu
$T_a$	=	air temperature, °F
$h_c$	=	convection heat transfer coefficient, Btu/h ft <sup>2</sup> °F
$T_r$	=	mean radiant temperature, °F or °R
$h_r$	=	radiative heat transfer coefficient, Btu/h ft <sup>2</sup> °F
$W_a$	=	air humidity ratio
$W_{sk}$	=	saturated humidity ratio at the skin temperature

The humidity ratio of the air in equilibrium with the skin under comfort conditions,  $W_{sk,req}$ , is the saturated humidity ratio evaluated at the required skin temperature.

In the above equations, the clothing temperature is not directly known. However, the clothing temperature can be easily calculated from the required skin temperature, the air temperature, mean radiant temperature, and the thermal resistances.

$$\frac{T_{sk,req} - T_{cl}}{R_{cl}} = f_{cl}h_c(T_{cl} - T_a) + f_{cl}h_r(T_{cl} - T_r)$$

$$T_{cl} = \frac{T_{sk,req} + R_{cl}f_{cl}(h_cT_a + h_rT_r)}{1 + R_{cl}f_{cl}(h_c + h_r)}$$
(5)

The above equation for thermal load uses three other parameters that must be determined  $-f_{cl}$ ,  $h_c$ , and  $h_r$ . There is no definitive set of values for all applications. When Fanger developed his original correlation, he used the following approximations to these parameters:

$$f_{cl} = \begin{cases} 1.0 + 0.2I_{cl} & I_{cl} < 0.5 \text{ clo} \\ 1.05 + 0.1I_{cl} & I_{cl} > 0.5 \text{ clo} \end{cases}$$
(6)

$$h_c = \max\begin{cases} 0.361(T_{cl} - T_a)^{0.25} \\ 0.151\sqrt{V} \end{cases}$$
(7)

$$h_r = 0.7 \text{ Btu/h ft}^{2\circ} \text{F}$$
(8)

Finally, Fanger, developed the following correlation between PMV and the thermal load.

$$PMV = 3.155(0.303e^{-0.114M} + 0.028)L$$
(9)

The predicted mean vote is the average response of a large number of people. Given the subjective nature of comfort, there will actually be a distribution of satisfaction among a large group of people. Figure 1 shows an empirical relationship between the percentage of people dissatisfied (PPD) with a thermal environment as a function of the PMV.



Figure 1 Percentage of People Dissatisfied

## **ASHRAE Comfort Standard**

ASHRAE has developed an industry consensus standard to describe comfort requirements in buildings. The standard is known as ASHRAE Standard 55-2004 Thermal Environmental Conditions for Human Occupancy. The purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space. One of the most recognizable features of Standard 55 is the ASHRAE Comfort Zone as portrayed on a modified psychrometric chart given in Figure 2. The Standard allows the comfort charts to be applied to spaces where the occupants have activity levels that result in metabolic rates between 1.0 met and 1.3 met and where clothing is worn that provides between 0.5 clo and 1.0 clo of thermal insulation. The comfort zone is based on the PMV values between -0.5 and +0.5.

The comfort charts shown here are slightly different than those given in the text and reflect the most recent revision of the standard in 2004.



Figure 2 ASHRAE Comfort Zone