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TITLE: A SIMPLE PROCEDURE FOR ASSESSING THERMAL COMFORT IN PASSIVE SOLAR HEATED BUILDINGS

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A SIMPLE PROCEDURE FOR ASSESSING THERMAL COMFORT IN PASSIVE SOLAR HEATED BUILDINGS*

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ABSTRACT

The Fanger thermal comfort equation is linearized and used to develop a procedure for assessing thermal comfort levels in passive solar heated buildings. In order to relate comfort levels in non-uniform environments to uniform conditions, a new thermal index called the "equivalent uniform temperature" is introduced.

1. INTRODUCTION

The thermal sensation experienced in a given enclosure is a function of several environmental and physiological parameters. Among those parameters are the air temperature, T_a (dry bulb), and the mean radiant temperature, T_{mr}. An environment in which the mean radiant temperature is equal to the air temperature is said to be thermally uniform. In passive solar heated buildings the existence of large glazed areas and massive thermal storage elements tends to produce non-uniform thermal environments.

Two rationally derived thermal indices for non-uniform environments, the "operative temperature" and the "humid operative temperature," are presented in the ASHRAE Handbook[1]. Both of these indices lack generality and neither is explicitly related to thermal comfort. A new thermal index, which we choose to call the equivalent uniform temperature, is, therefore, defined in this paper. The new index is based on the Fanger comfort equation,[2] which is discussed below.

2. THE FANGER COMFORT EQUATION

The Fanger comfort equation is based on the premise that the degree of discomfort experienced in a given thermal environment is a function of the thermal load to which the human body is subjected. The thermal load, L (W/m^2), is defined as the difference between the metabolic rate of heat generation in the body and the rate of heat loss to the environment. When the body is in thermal equilibrium, the heat load is zero and the comfort level is presumed to be at an optimum.

For the purposes of this research, it was found convenient to introduce a linear approximation for the fourth order radiation transport terms appearing in Fanger's equations.

The linear approximation is:

$$(T_{cl}^4 - T_{mr}^4) = 4\,T_{av}^3\,(T_{cl} - T_{mr}) \,, \qquad (1)$$

where $T_{av} = (T_{cl} + T_{mr})/2$,

and T_{cl} = clothing temperature at outer suface (°K) .

Other variables appearing in Fanger's equation are:

A = activity level (W/m^2),
f_{cl} = ratio of surface area of clothed body to surface area of nude body,
h_c = convective heat transfer coefficient (W/m^2 °K), and
I_{cl} = dimensionless expression for thermal resistance of clothing (clo).

Before introducing the equivalent uniform temperature, we will solve the linearized equations under uniform conditions.

3. THE OPTIMUM UNIFORM COMFORT TEMPERATURE

The optimum uniform comfort temperature, T_u, is obtained by solving the linearized Fanger equation under uniform conditions with zero thermal load. Additionally, the

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area ratio, f_{cl}, is set equal to 1.15, which is a value corresponding to medium weight clothing. The convective heat transfer coefficient is held constant at 2.83 (W/m^2 °K), which corresponds to a relative air velocity of 0.1 m/sec. A velocity of 0.1 m/sec is considered representative of free convective conditions likely to exist within a passive solar heated enclosure.

The linearized equations have been solved numerically under the constraints cited above and the results are presented in Figs. 1 through 3, which represent relative humidities of 0, 0.5, and 1.0, respectively. In each figure, the uniform comfort temperature is presented as a function of activity level for four distinct clothing insulation values. In order to provide a feel for the significance of variations in the numerical value of activity level and clothing insulation value, several representative cases are given in Tables I and II, respectively.

Table I

METABOLIC RATES FOR REPRESENTATIVE ACTIVITY LEVELS

Activity	Metabolic Rate, A (W/m^2)
Sedentary (Office work)	58
Medium (domestic work)	116
High activity (garage work)	174

Table II

CLOTHING INSULATION VALUES FOR REPRESENTATIVE ENSEMBLES

Clothing Ensemble	Insulation Value, I_{cl} (clo)
Nude	0.
Light (long lightweight trousers, with short-sleeve shirt)	0.5
Medium (typical business suit)	1.0
Heavy (Traditional business suit plus cotton coat)	1.5

4. THE EQUIVALENT UNIFORM TEMPERATURE

The equivalent uniform temperature, T_{eu}, is here defined as the uniform temperature of an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment. The functional form of T_{eu}

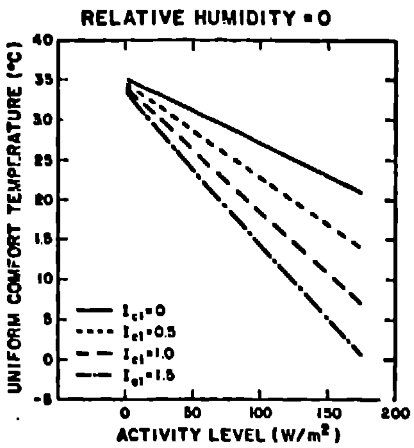

Fig. 1. Uniform comfort temperature (relative humidity = 0.0).

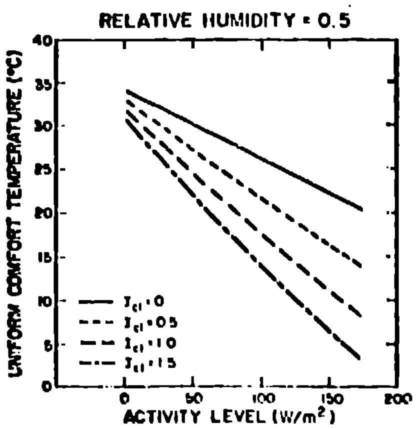

Fig. 2. Uniform comfort temperature (relative humidity = 0.5).

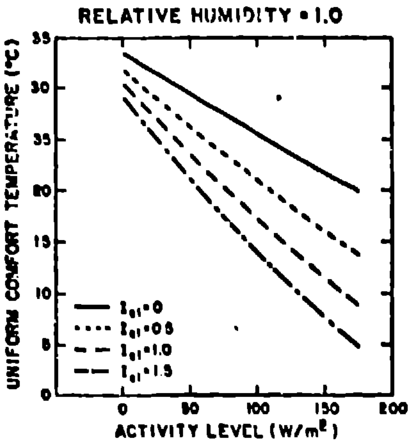

Fig. 3. Uniform comfort temperature (relative humidity = 1.0).

is obtained from the linearized Fanger equations which may be represented as a series of "comfort lines" in (T_{mr}, T_a) space. Each individual line is the locus of all combinations of T_{mr} and T_a which yield an optimal comfort level for a particular set of environmental and physiological parameters. A comfort line can be completely characterized by its uniform temperature intercept, T_u, and its slope, s, as illustrated in Fig. 4. The slope is indicative of the relative importance of the mean radiant temperature and the air temperature.

Now, suppose an occupant of a particular building is not thermally comfortable, i.e., he finds the enclosure either too hot or too cold. For this situation, the point represented by the actual mean radiant temperature, T^*_{mr}, and the actual air temperature, T^*_a, will be displaced from the comfort line as shown in Fig. 4. Any excursion away from (T^*_{mr}, T^*_a) that occurs parallel to the associated comfort line will cause no change in the comfort level of the occupant, because along such a path, variations in T_{mr} and T_a are mutually compensating. Therefore, if a line of slope s is extended from (T^*_{mr}, T^*_a) to the uniform temperature line, the intersection point is the "equivalent uniform temperature." The amount of discomfort experienced at T_{eu} is determined by the difference between T_{eu} and the uniform comfort temperature, T_u. Thus, the concept of an equivalent uniform temperature provides a basis for quantitative determination of comfort levels in non-uniform environments in terms of a single thermal index. Additionally, since most people are already accustomed to relating thermal comfort to the air temperature in uniform environments, the equivalent uniform temperature can be immediately related to subjective comfort expectations on the basis of past experience.

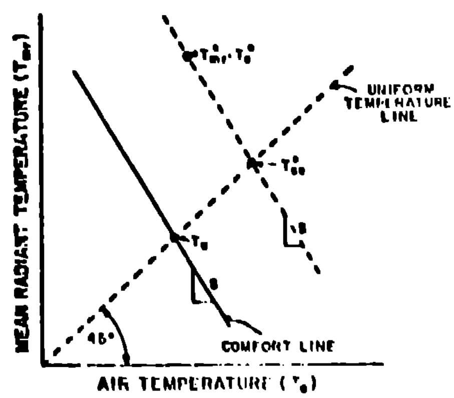

Fig. 4. Relationship of temperature parameters to comfort line.

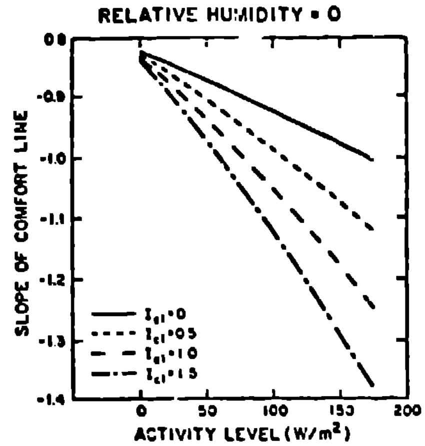

Fig. 5. Comfort line slope (relative humidity = 0.0).

In order to obtain an expression for T_{eu} in terms of the associated comfort line slope, we first write the equation of a line passing through a given point (T^*_{mr}, T^*_a) with a slope s.

$$T_{mr} = T^*_{mr} + s\ (T_a - T^*_a) \tag{1}$$

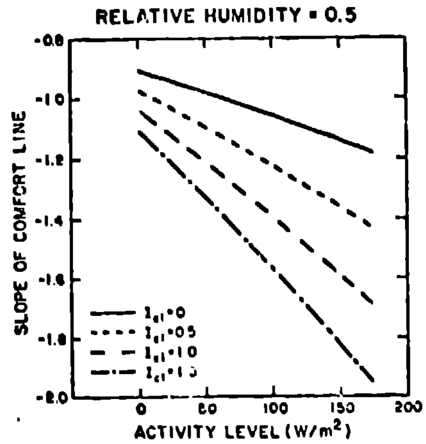

Fig. 6. Comfort line slope (relative humidity = 0.5).

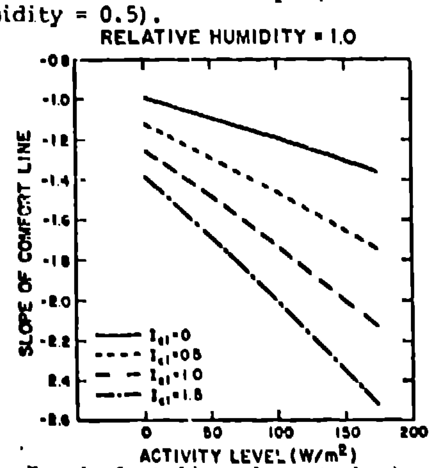

Fig. 7. Comfort line slope (relative humidity = 1.0).

The intersection of this line and the uniform temperature line is obtained by setting T_{mr} and T_a equal to T_{eu} in Eq. 1 and solving for T_{eu}

$$T_{eu} = \left(\frac{1}{1-s}\right) T^*_{mr} + \left(\frac{s}{s-1}\right) T^*_a$$

or, dropping the asterisks to indicate the general case, we have

$$T_{eu} = \left(\frac{1}{1-s}\right) T_{mr} + \left(\frac{s}{s-1}\right) T_a \ . \qquad (2)$$

The slope in Eq. 2 above is obtained from the linearized Fanger equations with the thermal load, L, set equal to zero. The dependence of s on A, I_{cl} and relative humidity is presented in Figs. 5 through 7. The range of independent variables covered in Figs. 5 through 7 is identical to that covered in Figs. 1 through 3 for the uniform comfort temperature, such that there is a one-to-one correspondence of data points in the two sets of figures. Note that the importance of the mean radiant temperature relative to the air temperature is enhanced by low activity levels, low clothing insulation levels, and low relative humidities.

In general, the equivalent uniform temperature will not be equal to the optimum uniform temperature. How much may the two indices differ before excessive discomfort results? This question is addressed in the next section.

5. THE COMFORT RANGE

As a measure for thermal sensation, Fanger chose to use the psycho-physical ASHRAE scale. The numerical values associated with the scale were shifted to provide symmetry about the neutral point.

$$PMV = \begin{cases} -1, & \text{slightly cool} \\ 0, & \text{neutral} \\ +1, & \text{slightly warm} \end{cases} \qquad (3)$$

The PMV (predicted mean vote) is a numerical value for comfort level which is determined for a wide range of environmental parameters on the basis of empirical data. Using his own data and that of Nevins et al[3] and McNoll et al,[4] Fanger determined the following relationship between the predicted mean vote and the thermal load.

$$PMV = (.0352\, e^{-.036A} + 0.032) L \ . \qquad (4)$$

As the thermal load departs from zero, a human subject approaches the slightly warm or slightly cool condition depending on whether the load is positive or negative, respectively. When Eq. 4 is solved simultaneously with the linearized Fanger equation, it is possible to determine the conditions under which the various thermal sensations in Eq. 3 are generated. For our purposes we determine the temperature range $\pm \Delta T$ about the optimum uniform temperature within which a subject will experience only slight discomfort by virtue of being either too warm or too cool (PMV = $\pm$ 1).

A human subject will then experience no more than slight discomfort when the equivalent uniform temperature, T_{eu}, is within the range

$$T_{eu} = T_u \pm \Delta T \ . \qquad (5)$$

The comfort range, ΔT, has been evaluated for the same parameter space previously used for the uniform comfort temperature and the comfort line slope. The results are presented in Figs. 8 through 10. Again, there is a one-to-one correspondence of independent variables appearing in the three sets of figures, 1 through 3, 5 through 7, and 8 through 10.

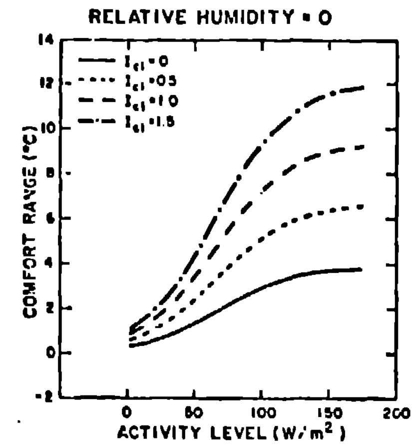

Fig. 8. Comfort range (relative humidity = 0.0).

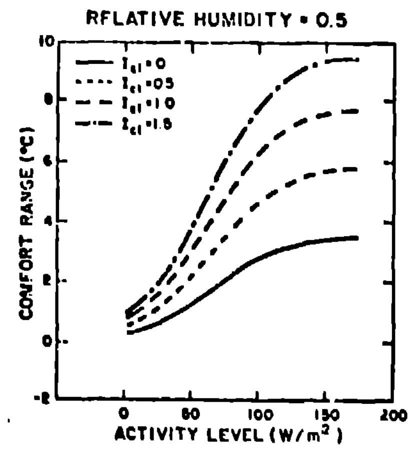

Fig. 9. Comfort range (relative humidity = 0.5).

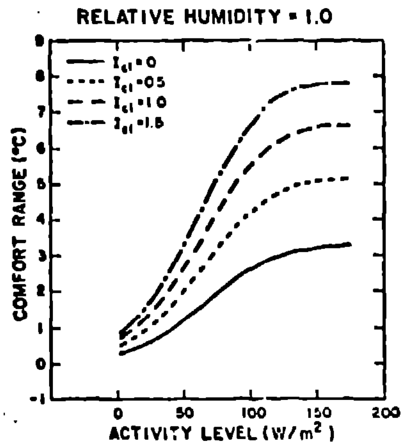

Fig. 10. Comfort range (relative humidity = 1.0).

6. THERMAL COMFORT ASSESSMENT UNDER TYPICAL CONDITIONS

In order to provide some general guidelines for thermal comfort analysis in passive solar heated homes, consider a single case which should be reasonably representative of many situations. A relative humidity of 50% is selected in order to represent an average climatic situation. The selected activity level is sedentary (58 W/m^2) and a medium clothing insulation value of 1.0 is chosen. If the hypothetical occupant chooses to increase his activity level, he can then compensate by decreasing the weight of his clothing and still maintain roughly the same comfort level. From Fig. 2 the optimum uniform comfort temperature is found to be 22°C (72°F). The comfort range of about 4°C (7°F) is read from Fig. 9. Thus, the comfortable temperature interval lies between 18°C to 26°C (or 65°F to 79°F). From Fig. 6 we find the comfort line slope is -1.24. Substituting this slope into Eq. 2 we obtain the following relation for the equivalent uniform temperature.

$$T_{eu} = .45\ T_{mr} + .55\ T_a\ .$$

Although the coefficients of T_{mr} and T_a are actually situationally dependent, the above expression will yield acceptable accuracy in many cases.

7. CONCLUSION

Construction of passive solar heated buildings continues at an accelerating rate, and the effect of their characteristic thermal non-uniformity on occupant comfort has not received adequate attention. As a general rule, existing design procedures do address the comfort problem, but usually only in terms of the air temperature. Other environmental and physiological parameters, the mean radiant temperature in particular, are often ignored.

The equivalent uniform temperature defined in this paper provides a single thermal index which can be used as an indicator of thermal comfort level in non-uniform environments.

8. REFERENCES

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