THERMAL COMFORT AND RADIANT HEAT

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ABSTRACT

In passive solar buildings the air and mean radiant temperatures are seldom equal. Comfort conditions in such buildings can be conveniently described in terms of the operative temperature. Operative temperature is approximately the average of the air and mean radiant temperatures present. Humidity control is rather unimportant for sedentary comfort as are air velocities below 30 fpm. Slow temperature drifts as occur in passive structures are essentially unnoticeable to occupants when the operative temperature is in or near the comfort zone. If the passive building can be designed to provide operative temperatures between 68 and 80°F and the occupants make appropriate and reasonable clothing adjustments the environment will be thermally acceptable to 80% or more of the occupants.

INTRODUCTION

Man's presence and dominance in all parts of the world is due in part to his ability to modify his thermal environment through buildings and clothing and thus promote his health, comfort and productivity. To maintain our economic and energy health, we must now be as efficient as possible in providing thermal comfort. Hence the current interest and demand for passive solar systems.

For the maintenance of constant body temperatures and the prevention of heat storage (S) humans must continuously transfer heat to the environment. A person's perception of thermal comfort is to a large part determined by the ease with which this balance between heat production and loss can be made. At rest metabolic energy production (M) is about 100 watts, while walking at 3 mph it is about 300 watts and at maximum exertion it is from 1000-1500 watts. Some of this internal energy is lost by respired heat (Q_{res}) and by external work (W). The remainder is brought to the skin by circulating blood and by conduction. From the skin surface it flows to the environment by convection to air, radiation to surrounding surfaces and the evaporation (E_{sk}) of sweat. Clothing slows this flow. In warm environments the body may increase blood flow to the skin thereby raising its temperature to promote heat transfer and the skin may sweat. To conserve body temperature in the cold, blood flow to the skin is reduced and metabolic heat production may be increased by tensing muscles and by shivering. Thermal comfort is achieved when body temperatures can be maintained within certain limits with the minimum amount of physiological effort. Heat dissipation from the body and therefore thermal comfort are affected by the environmental parameters of air temperature, radiation, humidity and air movement and the human factors of clothing and activity or metabolism.

The heat exchange at the skin surface may be simply stated using thermal equations as follows: From the body interior to the skin surface

$$M_{sk} = M - Q_{res} - W \pm S \quad . \qquad [1]$$

For an unclothed person the heat loss from the skin (M_{sk}) is

$$M_{sk} = h_c(T_{sk} - T_a) + h_r(T_{sk} - MRT) + E_{sk} \quad , \qquad [2]$$

where

- h_c is the convective heat transfer coefficient
- h_r is the linearized radiant heat transfer coefficient
- T_a is air temperature
- MRT is the mean radiant temperature

When $T_a \neq MRT$ as often is the case in passive solar buildings and perimeter zones, it is convenient to characterize the environment in terms of its operative temperature (T_o)

$$(h_c + h_r)(T_{sk} - T_o) = h_c(T_{sk} - T_a) + h_r(T_{sk} - MRT) \qquad [3]$$

or

$$T_o = (h_c T_a + h_r MRT)/h \qquad [4]$$

where

$$h = h_c + h_r \quad .$$

Evaluating h_c and h_r for indoor conditions with air velocities of 40 fpm or less

$$T_o \cong .5\,T_a + .5\,MRT \quad .$$

Operative temperature is the equivalent uniform temperature of a black environment that would transfer the same dry heat as the real one.

Another way of dealing with radiation in nonuniform environments is by using the effective radiant field (ERF) concept. Equation [2] can be rearranged to

$$\dot{M}_{sk} = h_c(T_{sk} - T_a) + h_r(T_{sk} - T_a) - h_r(MRT - T_a) + E_{sk} \qquad [5]$$

or

$$\dot{M}_{sk} + ERF = h(T_{sk} - T_a) + E_{sk} \quad . \qquad [6]$$

where

$$ERF = h_r(MRT - T_a); \quad MRT = T_a + ERF/h_r$$

and

$$T_o = T_a + ERF/h; \quad ERF = h(T_o - T_a) \quad .$$

ERF in words is the additional radiant energy received by the Body System from the environment when the temperature of the enclosing wall surfaces or the resulting mean radiant temperature differs from the air temperature. ERF is an energy flux. It is +, when $MRT > T_a$, and radiant energy is added to the body system. This is also called "warm" radiation. When $MRT < T_a$ or ERF it is negative and the body system loses energy by cold radiation.

Clothing adds an impedance to the flow of heat from the skin to the environment. It is thus a very effective passive device for modifying heat loss and improving thermal comfort. With clothing the combined heat transfer coefficient h in eq. [6] above is now replaced by $1/(I_a + I_{cl})$. I_a is the insulation of the ambient environment and given by $1/h$. I_{cl} is the insulation of the clothing worn.

The insulation value of clothing is usually expressed in terms of "clo" units. 1 clo unit of thermal insulation equals 0.155 m^2K/W. A heavy business suit has an insulation value of about 1 clo, while a bikini bathing suit is about 0.05 clo. Typical clothing of a long sleeved shirt and trousers or skirt is about 0.6-0.7 clo. The operative temperature range in which 80% or more of the occupants wearing a given level of clothing will find the indoor environment thermally acceptable is illustrated in Fig. 1 (1). For example, with 1 clo the temperature range is 19 to 23°C (67 to 74° F) and with summer clothing of short sleeved shirt and lightweight trousers or skirt (0.3-0.4 clo) it is from 24 to 27°C (75 to 81° F). Also notice that at 65° F a sedentary person needs about 1.4 clo to be optimally comfortable. This corresponds to a heavy vested business suit over long underwear. If interior temperatures are altered to conserve energy, corresponding clothing changes must be encouraged to ensure comfort. In passive solar buildings comfort is possible over a wide range of operative temperatures if the occupants make appropriate clothing adjustments.

People tend to dress for the season or outside conditions. That is people will in general wear less clothing in the summer and more in the winter. We observed in a survey of a large New York City office building that in summer the women wore on the average 0.43 clo while the men wore 0.57 clo (2). In the winter the women wore 0.81 clo while the men wore 0.9 clo. Thus the seasons should also be considered if possible when designing comfort conditions.

Humidity has a relatively small effect on the comfort of sedentary persons though low humidities seem to correlate with respiratory distress. Raising the humidity from 20 to 50% will allow the temperature to be decreased by about 1° C (2° F) for the same comfort level (1).

Air motion is not necessary for thermal comfort though it does help to provide a uniform air temperature in the space. However increased air velocity is an effective mechanism for increasing the evaporative loss from skin surface and improving comfort in warm environments. If air velocity is raised from 30 to 50 fpm the temperature can be raised 1.6° C (3° F) while maintaining the same level of comfort (1).

A person's activity level can have a large effect on comfort conditions. If a person's metabolism is doubled the operative temperature can be decreased by 5.5° C (10° F) and still have the same comfort sensation (1). Periodic increases in activity (walking) for sedentary persons can be effective in eliminating cold hands and feet during long exposures to 65-68° F temperatures.

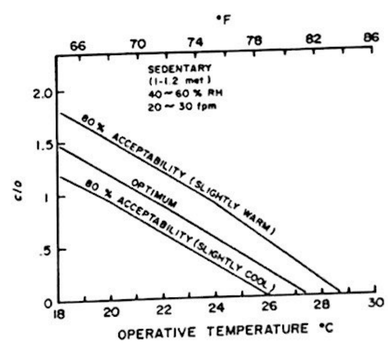

Fig. 1. Clothing insulation required for comfort.

RADIANT HEAT

The majority of our indoor environments have their surrounding surfaces at the same temperature as that of the ambient air. Radiant heat (i.e. ERF) whether "warm" or "cold", only plays a role per se in producing thermal comfort or discomfort, when the temperature of the man-made or natural radiation source differs in temperature from the ambient or surrounding air.

There are a host of physical factors involved in any quantitative assessment of the ERF present in the thermal environment, e.g. the 4th power of Kelvin or absolute temperature of the radiating and receiving sources; the emissivity of the sources and the absorptivity of the receiving sources, such as absorbtance of body clothing on skin surface; the shape factors involved, or rather the solid angles governing the radiant paths between emitter and receiver, the fraction of the human body surface that can receive radiation, the orientation of the body to the radiant source and other such factors. A detailed discussion of radiation exchange has been presented in many textbooks and the ASHRAE guides. Suffice it to say here that values of ERF associated with Comfort are quantitatively rarely above 150 W/m^2, which level would occur on one of our western deserts; with man-made spot heating by quartz radiant lamps, ERF values above 100 W/m^2 become impractical and difficult. Other sources of radiant heat, such as a hot stove or a fireplace with hot coals, rarely give practical ERF values greater than 50 W/m^2 without getting too close to be burned. A single cold wall at 20°C (68°F) in a room whose other 5 wall-floor surfaces are at an air temperature of 25°C (77°F) would result only in a "cold" negative radiation of about 15 W/m^2. The metabolic energy, produced by an average sedentary human, and lost from his skin and outer clothing surfaces is approximately 60 W/m^2 or 100 W for any average size man. Thus it is very difficult to add heat to the body system by thermal radiation at a rate more than double the rate of his normal sedentary metabolic energy. Obviously, if a human subject should wish to get warm in a cold environment, he could raise his body heat quicker by light exercise than by just sitting in front of a warm fireplace or electric radiant heater.

There is a fairly simple but fundamental relationship between ERF and thermal comfort at any given ambient air temperature. At our Pierce Laboratory we derived this relationship experimentally by use of two IR quartz lamps directed at 45° downward on a seated subject (3). At any air temperature which varied upward and downward in 1° steps, the subject (see Fig. 2) was asked to adjust the wattage to the IR heater as necessary for Thermal Comfort, which was defined as a "State of satisfaction by the subject with his thermal environment." Simultaneous observations of ERF and T_a, chosen for comfort by four normal male subjects, both unclothed and clothed, are shown in Fig. 3 and 4 for 4 subjects. The negative slopes of ERF vs T_a lines for either clothed or unclothed are essentially identical, as expected from eq. [6]. The values of ERF and T_a describe a locus with a constant Operative Temperature, T_o, which value is indicated by the intercept with ERF = 0 abscissa. The T_o for Comfort lowers approximately 6.7°C/Clo (12°F/Clo) as clothing insulation is added. Increasing air movement would lower this value and steepen the ERF-T_a loci.

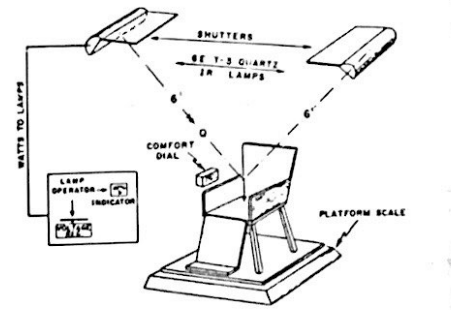

Fig. 2. Diagram showing relation of subject's chair on platform scale to the two radiant lamps. The comfort-dial and its methods of use are also indicated.

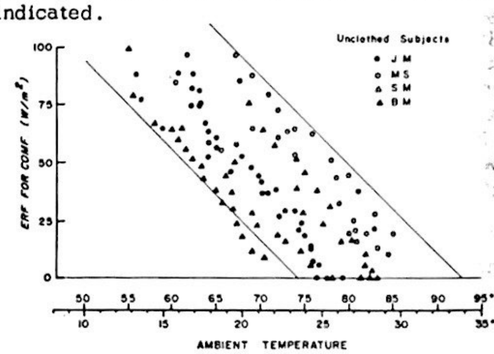

Fig. 3. Radiant heat required for comfort of unclothed sedentary subjects.

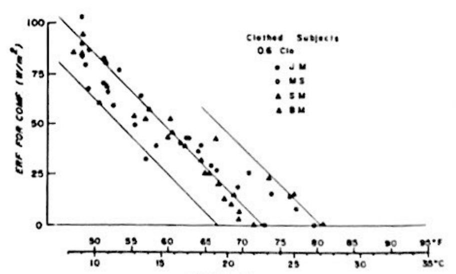

Fig. 4. Radiant heat required for comfort of sedentary subjects in normal clothing.

In Fig. 5, loci of ERF and T_a have been drawn for three clothing insulations - unclothed, 0.6 clo and 1.2 clo. "0.6 clo" is comparable to the everyday clothing of a North American. 1.2 clo would correspond to a heavy wool suit with vest. The curves have been calculated by a dynamic digital model of temperature regulation (1). Each locus represents a condition when regulatory sweating is negligible and a state of thermal comfort exists. The negative slope of each loci is approximately h. Increasing air movement (v) causes the loci to become more vertical and thus reduces the effectiveness of ERF on producing comfort. Increased clothing insulation as noted experimentally in Fig. 3 and 4 does not change these negative slopes but only displaces the Comfort loci to lower temperatures.

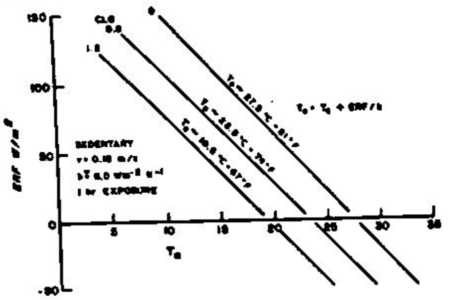

Fig. 5. ERF for Comfort with various levels of clothing insulation.

As observed experimentally in Fig. 3 and 4, the response of each of the four subjects to radiant heat was consistent but varied greatly between subjects. In their Comfort Standard (55-74) ASHRAE has recognized this wide variability between human subjects and has established the criterion that the prevailing environment, described by T_a, MRT, v, clo and activity, (to be "Comfortable") must be acceptable to 80% of those exposed. In Fig. 6, the range of 80% acceptability corresponding to the three loci in Fig. 5 have been drawn.

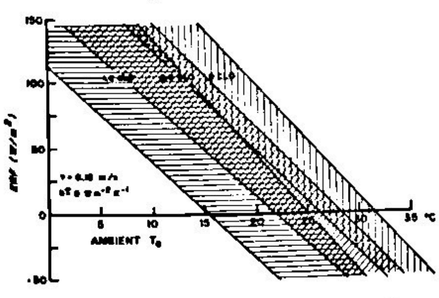

Fig. 6. ERF for 80% acceptability at various levels of clothing.

At a given level of ERF, the T_a range for 80% acceptability increases with clothing insulation. The great overlap between Comfort Zones for the three clothing levels, indicated in Fig. 6, demonstrates the practicality of using radiant heat for thermal comfort at exhibition swimming pools in winter, since Comfort is required simultaneously at a given location by both swimmers, by swimmers in bathrobes and by a fully clothed audience.

A significant conclusion that may be reached as a result of the above experimental analysis is that a human when given control of its radiant-thermal environment always seeks an optimum Operative Temperature of the environment, at which mean skin temperature $\bar{T}_{sk}$ is near 33-34°C (91-93°F) and insensible loss by sweating is minimal. Each human seeks a characteristic T_o for Comfort, which also depends on the local air movement and clothing worn.

MEASUREMENT OF ERF AND OPERATIVE TEMPERATURE

The simplest measure of ERF is by the use of a black globe (unheated) thermometer, (6" dia.), such as used by Bedford and others. The difference between the globe temperature (T_g) and an ambient air (T_a) is directly proportional to the ERF for Comfort present and may be evaluated by the relation:

$$ERF = 0.72[6.1 + 13.6\, v^{0.5}](T_g - T_a) \quad W/m^2 \quad [7]$$

where

0.72 is the average fraction of the total body surface exposed to thermal radiation; 6.1 $Wm^{-2}C^{-1}$ is the linear radiation exchange coefficient (h_r) for a 4π solid angle at 25°C (77°F); 13.6 $v^{0.5}$ is the forced convective heat transfer coefficient (h_c) for a 6" sphere and v is air movement in m/s. By painting the globe surface with a skin color paint instead of black, the above equation would be valid for radiating sources with temperatures up to 5000 K.

Another simple feature of the globe is that its uncorrected temperature (T_g) is a direct measure of the Operative temperature (T_o) of the environment, as would be experienced by the human subject. For example in Fig. 5-6, the comfort point at T_a of 10.5°C (51°F), while wearing 0.6 clo, is an ERF of 100 W/m^2. By [7] the T_g should be 23°C (73.4°F). The T_o selected for Comfort in Fig. 4 is also 23°, which is found at the intersection of 0.6 clo locus with abscissa for ERF = 0. This first order equivalence between T_g and T_o can be shown to hold up for air movements as high as 200 fpm (1 m/s). For field survey purposes the black or skin colored globe is a useful quick, cheap analytic instrument.

The many sophisticated and rigorous methods of calculating and measuring MRT are well summarized in the engineering literature (4, 5). As shown above the (MRT - T_a) gradient is directly proportional to ERF, which is given exactly by

$$ERF = h_r\,(MRT - T_a)$$

where

$$h_r = 4 \cdot (0.72) \cdot (5.67 \times 10^{-8}) \cdot ((MRT + T_a)/2 + 273)^3 \quad [8]$$

For the case illustrated in Fig. 2, where the subject was exposed to two radiant beam heaters, we were able to measure directly the ERF received by the subject by observing the change in evaporative rate of sweating with changing wattage to lamps, i.e. the sweating human body, when T_a is constant, is an accurate "radiometer". For Fig. 2 we found an ERF of 35 W/m^2 corresponded to 1 kW supplied to the pair of lamps. For an average size subject (1.7 m^2), the effective shape factor between man and lamp proved by experiment to be $(35 \times 1.7 \times 0.72)/(1000)$ or 0.043. In other words, with our current interest in energy conservation, the two radiant quartz IR lamps may be an inefficient way of keeping the subject warm in the cold, even as spot heaters.

HEDONIC EFFECTS OF THERMAL RADIATION

Our experience with radiant heat can be very pleasurable. The glowing fireplace, when coming indoors on a cold winter day, is one. The exposed skin surface, specially on the forehead, is on first exposure very sensitive to the presence of thermal radiation, whether it be heat or cold. Thermal sensation of warmth or cold by the hand has proved a simple index of Comfort and a source of a "pleasant" sensation (6). Cabanac has shown that the hand can sense the same water temperature, as either hot or cold, very pleasant or unpleasant, depending on whether the internal body temperature is colder or warmer than normal (7). Marks and Gonzalez have demonstrated for a normal internal temperature, spot radiant heat on the forehead can be either pleasant or unpleasant, depending on whether the overall $\bar{T}_{sk}$ is below or above 33-34°C (91-93°F)(8). Unfortunately, popular experiences, such as the above, have lead to the general belief that radiant heating has some special therapeutic quality and is therefore more desirable than air conditioning. Actually all the above pleasurable and unpleasurable sensations are transient and disappear quickly after a few minutes of exposure.

The skin surface of the human body has another remarkable property and that is its ability to summate thermal sensations derived from widely differing temperatures over the body surface into a single judgment of warmth, neutral or cold. In our heater experiments above (see Fig. 2), we observed that temperature differences of 5°C (9°F) about the mean $\bar{T}_{sk}$ of 33°C are also considered neutral and Comfortable. Fanger has shown that two opposed walls with difference in temperature 15°C (27°F) above and below Comfort (25°C, 77°F) would be found acceptable. For practical purposes the nonuniformity of the radiant environment is, within these limits, an insignificant factor in producing Discomfort.

TEMPERATURE DRIFTS

Indoor environments traditionally have had constant temperatures. However, energy and cost savings are possible if inside temperatures are allowed to drift somewhat with outside conditions and internal loads. In passive buildings, temperature drifts are often unavoidable. At the Pierce Labs we have recently studied the building occupants' acceptance of slow temperature drifts (9, 10). In these tests the subjects periodically indicated their response to the environment by marking a ballot. Their response to constant temperature comfortable environments was constant. Their responses to 4 1/2 hour long environments whose temperatures drifted steadily up or down at 0.5°C/hr (1°F/hr) was nearly indistinguishable from the constant temperature responses (Fig. 7 and 8). Drifts during a simulated 8 1/2 hour long work day were also tested with similar results. Thus it appears that people are rather insensitive to slow temperature changes in and near the comfort zone. We found that with lightweight or summer clothing (0.4-0.5 clo) operative temperatures can drift in the 22 to 27°C (72 to 81°F) region and maintain thermal acceptability above 80%. With normal clothing (0.6-0.7 clo) the drifts can be in the 21 to 26°C (70 to 79°F) range and with winter or 0.9 clo the temperature drifts can be from 20 to 25°C (68-77°F).

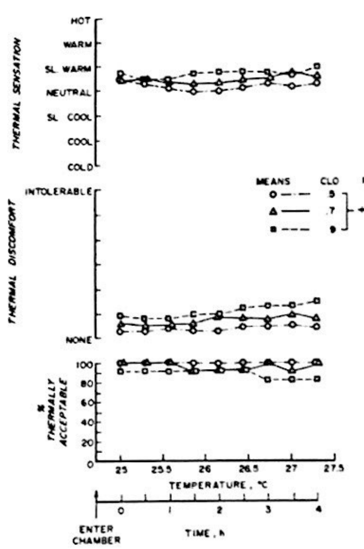

Fig. 7. Mean of subject responses to +0.5 C/h temperature ramp.

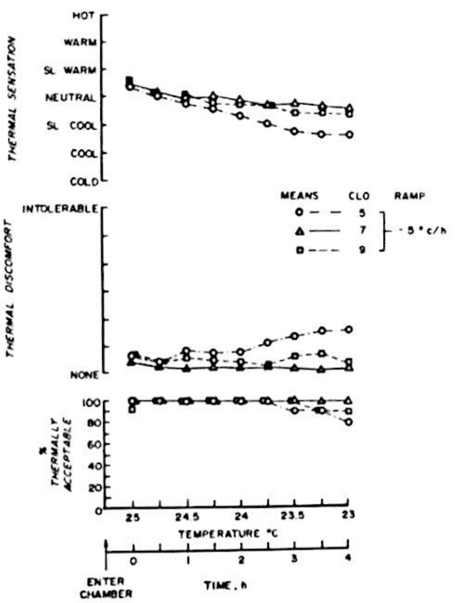

Fig. 8. Mean of subject responses to the - 0.5 C/h temperature ramp.

Therefore temperature drifts in passive solar buildings are acceptable provided that the temperatures remain in or near the comfort zone for the particular clothing level of the occupants. If clothing adjustments are made, as presumably occupants would normally do, the range of temperature variation possible becomes substantial.

CONCLUSIONS

In passive solar buildings the air and mean radiant temperatures are seldom equal. Comfort conditions in such buildings can be conveniently described in terms of the operative temperature of the environment. Operative temperature is approximately the average of the air and mean radiant temperatures present. Techniques for predicting the mean radiant temperature from the expected surface temperatures of the space are clearly described by Fanger (5). Fortunately for the passive building, humidity control is rather unimportant for comfort as is air movement below 30 fpm. An environment expected to be thermally acceptable to 80% or more of its sedentary occupants would have operative temperatures between 68 and 80° F. Of course, over this large temperature range appropriate clothing adjustments (from 1 to .3 clo) would be necessary.

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