Thermal Comfort

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1 PREAMBLE

Trying to provide a small, concise essay on thermal comfort, defined as "those conditions of mind that express satisfaction with the thermal environment," is a difficult task because it requires the integration of ideas from areas as diverse as thermal physics, physiological systems, environmental engineering, and human perception. Thus, a commentator faces the pervasive problem of breadth versus depth of coverage. I try to provide a compromise between these two and where space restricts a detailed exposition, I can fortunately refer the reader to most useful in-depth treatments such as those presented by Chatonnet and Cabanac (1965), Fanger (1967, 1970), Parsons (1993), Bensel and Santee (1995), and most recently (Konz 1995, 1997).

2 INTRODUCTION

Perhaps the most appropriate place to begin an essay on thermal comfort is within the realm of physiology and especially with the recognition of the regulatory nature of many human physiological processes. Following upon Harvey's discovery of the circulation of blood, perhaps the most important observation on physiological systems was Claude Bernard's identification of the "fixité de la milieu interieur" — the "stability of the internal environment." It is clear that all organisms have, to some extent, to provide such stability in order to deal with the vagaries of an uncertain external environment. This principle holds across multiple levels of detail ranging from the cellular level to the level of the organism itself. Establishment of a stable biochemical platform upon which life processes can proceed without the momentary interference of the "outside" world is crucial. As a consequence, living systems are not "closed" with respect to the environment (they do interact with the environment), but neither are they completely "open" (in which case they would slavishly follow environmental variation). Therefore, living systems exert hybrid control, opposing environmental influences on occasion while selectively permitting a degree of influence at different times (Kenshalo *et al.* 1961; Benzinger 1963).

In his original observations, Claude Bernard referred to temperature control as a primary example of regulation, and regulatory control was also a principal concern of Cannon (1932) in his classic text, for which he employed the term "homeostasis." While the interchange between the human and the environment is more free and dynamic than the term homeostasis implies, the fundamental idea of a temperature balance as a crucial foundation for existence persists. Like many other organisms, human beings are homeotherms. That is, they maintain a resting body temperature that is well above the temperature of the environment that surrounds them. This characteristic is advantageous in that humans can explore many places that would not support the existence of organisms that rely principally upon the environment to warm them. The penalty for such freedom however, is a constant demand for energy to support this elevated temperature. Thus, many animals, and until relatively recently human beings, had to spend much of their time in search of food. What this means is that in most terrestrial conditions, human beings are losing heat to the environment and the rate of this loss is governed by physical laws of heat exchange. Of course, there are hot deserts where this tendency is reversed and the unaided individual experiences considerable heat stress. In order to buffer the effects of excessive heat loss or heat gain, human beings have adopted various forms of clothing and covering. While today clothing serves many different functions, the primary impetus for clothing was as a tool or aid in the process of thermal comfort regulation.

3 DESCRIBING THERMAL INTERACTION

Body temperature is a crucial facet of existence and a vital mediator of many critical biochemical reactions. Activity and performance follow body temperature such that performance is poor when temperature drops in the small hours of the morning and is optimized in the late afternoon and early evening as the circadian rhythm peaks. Disorders of temperature are often symptomatic of more widespread disturbance or illness and excessively high or low body temperatures themselves can result in illness and eventually death. Thus the successful control of body temperature, disturbances to it, and failures of regulation are crucial concerns of the medical, environmental and behavioral sciences (Hardy 1971). To begin to understand thermal regulation, it is necessary to describe the avenues of thermal interaction between the human and the environment. One of the first such descriptions was given in the form of an equation by Burton (1934):

$$M + W - E \pm R \pm C \pm S = 0 \qquad (1)$$

where M is the basal metabolic rate, W is the work rate the individual is engaged in, E is the rate of evaporation of moisture from the body, R is the radiant heat lost or gained from the environment, C is similarly the convective heat lost or gained from the environment, and S is the storage of loss of heat expressed as a change in the deep body temperature of the individual involved.

The equation is stated such that the outcome is zero, which is perhaps the easiest way to see that Burton's model follows the fundamental idea of homeostasis as a highly stable (i.e. zero change) state. As has been noted, this is too rigid a conception and where such rigidity must be tempered provides important clues to the achievement and sustenance of thermal comfort. First, Burton's equation treats the human being in exactly the same fashion as it would treat an inanimate object. What is missing from his picture is the idea of human goal-directed behavior. The idea of behavioral regulation is critical as individuals engage constantly and primarily in behavioral regulation, in part to obviate the need for more effortful physiological regulation. Consider for a moment a specific example. The most effective form of physiological regulation against excessive temperature is sweating. However, on a hot day, the first thing we do in reaction to the weather is not immediately to start sweating. We may stay inside air-conditioned buildings or if we are forced outside we might choose shaded areas to sit in. To reduce thermal stress, we might seek a cooling drink or use a fan to increase evaporation (much of which comes initially from loss from the respiratory tract). Each of these behavioral strategies *precedes* sweating as a way of maintaining temperature balance. Indeed, if these strategies are successful, we might never get to the stage of sweating at all. Thus, while simple linear equations describe heat exchange, they do not capture the subtlety and nuances of behavioral regulation, the prime goal of which is the maintenance of comfort. Hancock and Warm (1989) argued that the primary symptom that describes the limits to physiological compensation is disturbance to the dynamic steady state, e.g. an uncompensative increase in body temperature. In a directly comparable way, the onset of discomfort is the symptom of the limit to behavioral regulation. As a result of this definition and this recognition, we can provide a comfort equation in the form:

$$C = f(\mathrm{Br}) \pm f(\mathrm{Pr}) \qquad (2)$$

where C equals the perceived level of comfort which is expressed as a function (f) of behavioral regulation (Br) combined with a function (f) of the physiological regulation (Pr). Comfort can then be expressed on a 0–100 scale, in which 100 represents a nominal optimal comfort and 0 represents loss of consciousness as a result of the intensity of the stress. Within the present equation, we can describe some points that mean the relationship indicated is more than a descriptive one. For example, assuming that C varies between 0 and 100, where 100 represents optimal comfort, and that Br and Pr also vary between 100% effective and 0% effective, then the value of C is 0 when the value of Br is 0 and the value of Pr is 0. In principle, this general equation can apply to any aspect of comfort, which is a multidimensional construct. However, for the present purposes we can ask what this means in terms of thermal comfort.

4 ASSESSMENT OF THERMAL COMFORT

To assess thermal comfort, a fairly standard experimental procedure has often been employed. An individual is exposed to a thermal condition whose physical characteristics are predefined. Typically, these factors include air temperature, relative humidity, air velocity and radiant heat. In some of the first such experiments, individuals were asked to walk between two rooms and compare their warmth. By matching different combinations of dry bulb temperature, wet bulb temperature and air velocity (derivations of the first three factors noted above), Houghten and Yagloglou (1923) were able to construct an effective temperature (ET) scale (see Parsons 1993, Figures 7.1 and 7.2, pp. 134–135) that could be used to assess thermal comfort. For a number of reasons, the ET scale is not widely used today, although the idea of exposing individuals to different environments and asking them to comment on their comfort rating is still used (Fobelets and Gagge 1988). For example, Rohles and Nevins (1971) derived a relationship between thermal sensation and wet and dry bulb temperatures from just such a set of procedures. As Parsons (1993) correctly indicates, it is important to ascertain whether such measures are made immediately after exposure to the new condition, since such a procedure emphasizes transient influences (see also Houghten and Yagloglou 1923), or whether requests for the perception of thermal comfort are given after the individual has had a chance to adjust to the new conditions for some extended period (see Nevins *et al.* 1966).

Fanger (1970) elaborated upon this conception through exploitation of Burton's (1934) heat balance equation described previously. Fanger realized how crucial fluid exchange was to thermoregulation, especially given that in conditions close to comfort, much of the fluid loss was imperceptible to the individual, through such avenues as respiration. Fanger was also careful to introduce physical heat transfer modifications as a function of clothing. Given that an individual was in a state of thermal balance and that sweat rate and skin temperature were within comfortable limits, Fanger developed his comfort equation. The American Society for Heating, Refrigeration and Air Conditioning Engineer's standard comfort zone (see Figure 1) is derived from this approach using dry bulb temperature, water vapor pressure, air velocity, radiant temperature, metabolic rate, clothing insulation and exposure time. Comfort votes were used to derive acceptable levels and 94% of individuals described themselves as "comfortable," "slightly warm" or "slightly cool" within the illustrated zone. The actual thermal comfort vote could be predicted using the following equations:

$$TS = -1.047 + 0.158\,ET \qquad ET^* < 20.7$$

$$TS = -4.444 + 0.326\,ET^* \qquad 20.7 < ET^* < 31.7$$

$$TS = 2.547 + 0.106\,ET^* \qquad ET^* > 31.7$$

where TS is the thermal sensation vote for individuals engaged in sedentary activity at 0.6 clo, clothing insulation value.

As Konz (1995) notes, even within these boundaries 3% of individuals will vote that they are "cool" and another 3% that they are "hot" and thus comfort is a population-distributed parameter and not an exact value. There are also variations for winter and summer conditions largely because of clothing preferences and further details of this can be found in Konz (1995).

These indices have been used by different scientific, advisory and regulatory agencies (cf., ASHRAE 1989; ISO 1992) as recommendations to professionals such as architects and civil engineers for use in their work. What is clear is that the major efforts to understand human thermal comfort have largely focused on derivations from heat transfer physics and to date, relatively little attention has been paid to behavioral adaptation beyond the use of comparative psychophysical approaches.

For example, the equation presented by Fanger and employed by a number of agencies relies almost completely upon physical values with a subsequent reference to a vote of dissatisfaction. The crucial question becomes, what do dissatisfied people do about their (thermal) environment? The implication of the physical standards is that they continue their present activity at its present level and go through differing degrees of unhappiness over differing specified periods of time. But, of course, this does not happen. Individuals modify their thermal environment almost continuously. They add or shed clothing, take cooling or warming drinks, change and alter the location of furniture, add a small fan or small air-heater to their immediate locale. In fact they engage in a myriad of behavioral adjustments, many of which far supersede in influencing the variation of one or two degrees of temperature or percentage points of humidity. In practical terms, the challenge of the environmental engineer is to present an envelope of acceptable conditions within which the individual is free to engage their own adjustment strategies as is beginning to be seen in production automobiles. The challenge is to maintain an acceptable "envelope" of

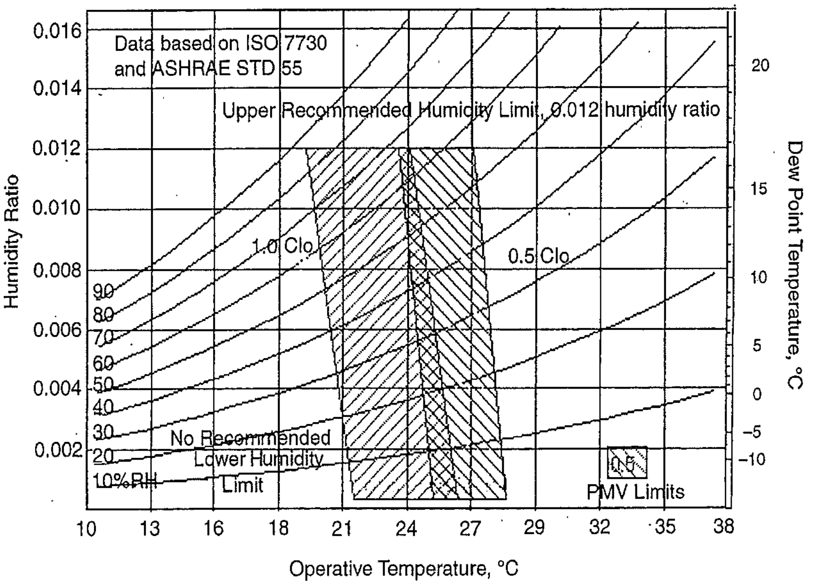

FIGURE 1 The ASHRAE comfort zone shown on a psychometric chart. The slanting dashed lines have equivalent skin wetness and thus approximately the same comfort. Thus a dry bulb temperature (DBT) of 25°C and 80% relative humidity has the same comfort as a DBT of 27.5°C and 20% relative humidity. The line is given a label of "new effective temperature" or ET* where the dashed line crosses the 50% relative humidity line; in this example, it is 26.1°C ET*. (Reproduced from Konz 1995.)

conditions while outside a permanent facility. In really hostile conditions such as the deep desert, the deep oceans and deep space this represents a significant problem.

5 SUMMARY

Thermal comfort is an important issue. Individuals expected to perform outside the ranges of thermal comfort for extended periods will be ineffective, unsafe, unwell and eventually injured. While forms of forced acclimatization can help expand the range of tolerance, this strategy is an attempt to "fit the human to the conditions" in contrast with the efforts of human factors and ergonomics that endeavor to "fit the conditions to the human." Present indices are founded upon engineering approaches that deal with the occupant largely as though they were an insensate object. However, we know this is not true and human beings act to behaviorally regulate their environment as much as they act to physiologically regulate functions of the body. Designers need therefore to facilitate this self-directed, goal-related activity and as much as possible establish an "envelope" of acceptable conditions with sufficient user freedom to easily manipulate local micro-environments. Such opportunities are now becoming available as options on advanced vehicles. Further effort is clearly required to clarify the effects of individual differences on thermal comfort that do not seem related to different intrinsic appreciation of warmth but rather due to the efficiency of behavioral regulation in modulating local conditions on a regular basis. Finally, the extensive database on thermal comfort can be used as a foundation for further research into the larger issue of the more general concept of comfort itself and how it relates to human performance and capability in general.

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