Passive Cooling and Human Comfort

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Design Note

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Comfort within buildings is primarily controlled by four major factors: air temperature, mean radiant temperature, humidity and airflow. Each can have a dominating effect. Their effects are not necessarily additive and practically never linear. There are, additionally, other factors which affect comfort including clothing, activity level and climatization. Some psychological triggers, such as certain colors, also seem to affect comfort, and "state of mind" can have major effects on individual comfort sensations. Comfort zones, therefore, are very generally defined as the zone in which 80 percent of the population will experience the sensation of thermal comfort.

Basic psychrometrics

Because comfort is so dependent on temperature **and** humidity (especially at the overheated end of the scale), an understanding of their relationship is very important. To better understand temperature, humidity and the "comfort zone," it is necessary to discuss psychrometric charts.

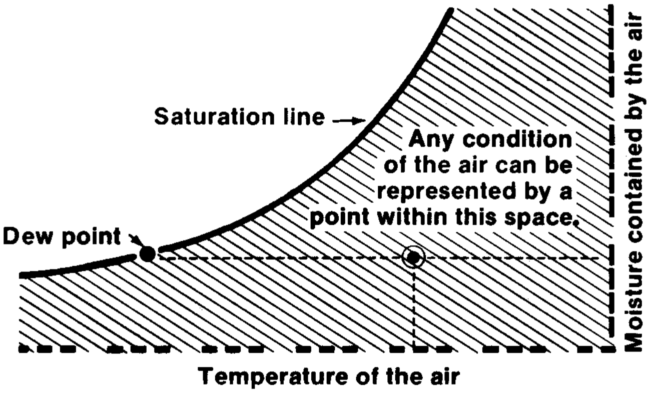

Figure 1. The basic relationship expressed by the psychrometric chart.

Psychrometric charts provide a graphic representation of the state or condition of the air at a given location. They relate temperature on the horizontal scale to moisture on the vertical scale. If the temperature of a given volume of air is decreased to the point at which it can hold no more moisture it becomes saturated. The corresponding temperature is called the dew point. When air is cooled to its dew point it is at 100 percent relative humidity. This saturation point is represented by the outer, curved boundary of the psychrometric chart.

The air temperature represented by the horizontal axis of the psychrometric chart is known as the **dry bulb temperature** and is expressed in either °F or °C. It represents the temperatures which are read by the common thermometer and the common thermostat. The vertical or moisture axis, however, is known by a number of names, including **specific humidity, absolute humidity,** and **humidity ration.** They all represent the same measure: the amount of water by weight in the air. Its numerical value is expressed in one of two ways: 1) pounds of moisture per pound of dry air (or kilograms/kilogram) or 2) grains of moisture per pound of dry air (one pound ≅ 7,000 grains).

Although these are the most common engineering names and units given to the moisture scale, it is sometimes represented by two other names: **vapor pressure,** which is the partial pressure exerted by the moisture in the air (given in inches of water or millimeters of mercury), and **dew point temperature,** an exponential temperature scale representing the temperature, in °F or °C, at which moisture will begin to condense from a given unit of air. Dew point temperature will be used in much of the following discussion.

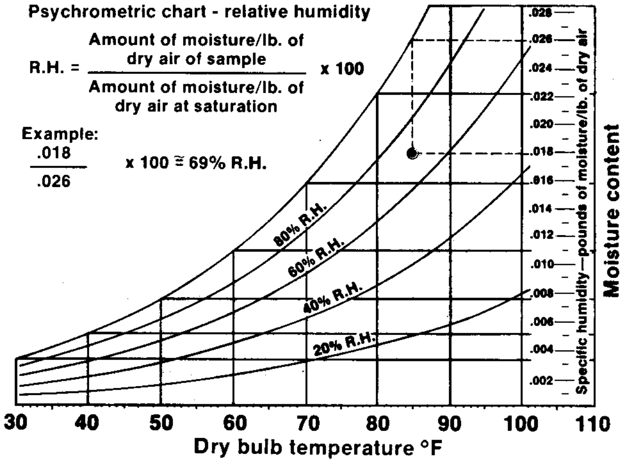

Figure 2. Specific and relative humidity.

Unlike the other measures of moisture, **relative humidity**—the most familiar term—is not an absolute measure of moisture content. Rather, as its name suggest, it is a measure only of the relative amount of moisture contained by air. More specifically, it is the moisture content of the air relative to the maximum amount of moisture which air at a given dry bulb temperature can hold when saturated. If the weatherman says the relative humidity is 70 percent and the temperature is 85°F he means that the air contains 70 percent of the moisture it could possibly hold at 85°F.

One further and important relationship—the energy content of the air—is expressed by the psychrometric chart. This total air energy is the sum of both the temperature content of the air (sensible energy) and the vaporized moisture content of the air (latent energy). Each pound (one pint) of water vapor in the air represents approximately 1,000 Btus of latent heat energy. By contrast, increasing the temperature of one pound of air by 1°F will add only ¼ Btu of energy to the air. The sum of the latent energy and the sensible energy is called the air **enthalpy**. Enthalpy is expressed in units of Btus per pound of dry air and its associated moisture. Air at 32°F (0°C) and zero percent relative humidity is assumed, by convention, to have an enthalpy of zero and is used as the base for the enthalpy scale.

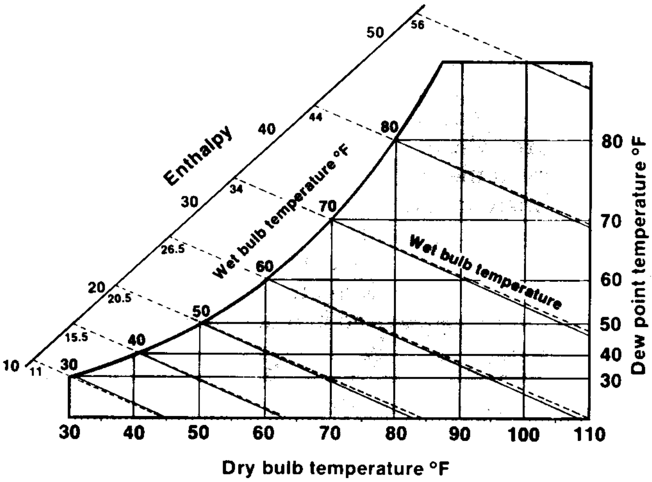

Figure 3. Enthalpy and wet bulb temperature.

Graphically, the lines of constant air enthalpy follow almost exactly the line of constant wet bulb temperature. Therefore, wet bulb temperature, which can be simply measured, provides a relatively accurate measurement of the heat content of the air. The higher the wet bulb temperature, the greater the energy content of the air. Generally, enthalpy is used only for numerical calculations of the energy required to change the conditions of the air (e.g., heating, refrigeration, and air conditioning design and engineering). For the purposes of describing human comfort, however, wet bulb temperature will be used to represent the energy content of the air.

Probably the easiest way to understand wet bulb temperature is to examine the process by which it is most commonly measured.

The wet bulb temperature is rather easily measured with a standard thermometer which has its sensing bulb encased in a wetted wick that is subjected to rapic air motion across its surface. Meteorologist often use a device called a sling psychrometer to make wet bulb temperature measurements.

Rapid air motion across the surface of the wick and wet bulb causes moisture to evaporate from the wick. This evaporation process cools the wick and sensing bulb by an amount which is directly proportional to the additional amount of moisture which the air stream is capable of absorbing. In other words, saturated air would, theoretically, not cool the wetted bulb by a substantial amount. Therefore, the greater the difference in temperature between the wet bulb thermometer and a dry bulb thermometer, the lower the moisture and energy content of that air stream. This is also the method by which evaporative cooling of the skin occurs and is the major reason that relative humidity levels have such great import on the body's ability to maintain comfort.

In arid climates the evaporative principle can be used to great advantage to cool the air. Through devices such as the "swamp cooler," the sensible heat (temperature content) of the air is exchanged with latent heat (moisture content) and the air is thereby cooled along a line of constant wet bulb temperature.

Human body responses to environmental conditions

The human body constantly generates excess heat. This is accomplished through the metabolic process whereby food is converted to body energy through digestion. This energy is in turn used to perform useful work and, as a by-product, heat. The amount of heat produced by the body is proportional to our level of activity, with higher activity levels producing higher levels of thermal energy. Seated and at rest the body produces about 400 Btus per hour of excess heat which must be transferred to the environment. In contrast, climbing a steep set of stairs produces an excess of 4,400 Btus per hour. Since humans are warm-blooded mammals, the body needs to lose this excess heat because deep body temperatures must remain relatively constant at 98.6°F to prevent serious medical complications. The body accomplishes this in rather remarkable ways. For instance, if the environment is very cold the body will involuntarily shiver—work which produces more body heat to keep deep body temperatures at their required levels. Likewise, the body has a number of mechanisms to dissipate heat when the environment is overheated. The human body exhibits all normal heat transfer mechanisms (conduction, convection and radiation) in addition to the rather remarkable ability to perspire and cool itself by evaporative heat loss.

Under desirable temperature and humidity conditions (e.g., 75°F, 50 percent relative humidity) most body heat rejection occurs through convective and radiative heat transfer with only about 20 percent occurring through evaporation. Very little loss occurs by conduction. However, as environmental conditions change, body temperature regulation systems react accordingly. For instance, if activity is held constant and dry bulb temperature rises to 90°F, about 80 percent of the body's heat loss must occur through evaporation, requiring profuse perspiration. Under these conditions radiation and convection are much less important than evaporation.

As air temperature approaches the skin temperature (92°F-94°F), most body heat loss must occur through evaporation. If the air has a high relative humidity, the potential for evaporation to take place is greatly reduced because the air cannot easily absorb more moisture. Theoretically, when the relative humidity reaches 100 percent and the air temperature exceeds skin temperature, the body can no longer evaporate moisture or convect heat away from itself and the potential for very serious and even terminal body overheating exists (i.e., heat stroke).

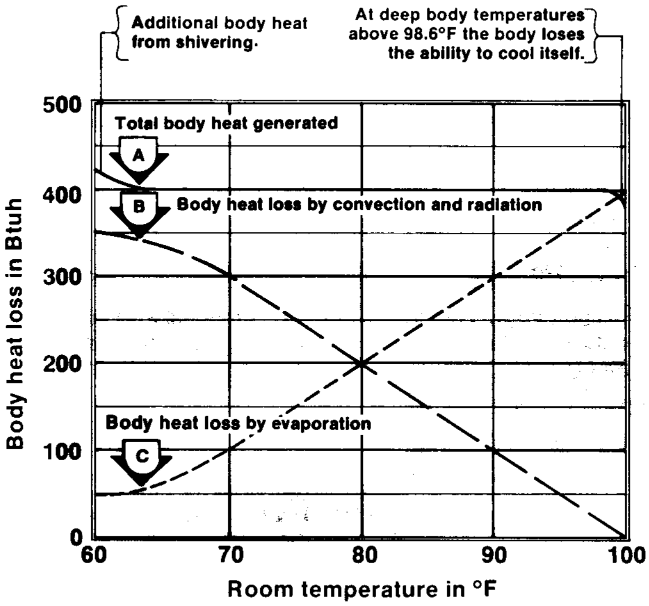

Figure 4. Body heat loss and air temperature.

The comfort zones

Many statistical studies have been performed on large numbers of subjects of all ages, sexes and nationalities to arrive at a quantitative description of human comfort. This is necessary to provide the goals and design paramenters for human comfort in buildings. As previously mentioned, the results of these studies provide a comfort zone with a relatively wide band of acceptability in which 80 percent of the population experiences the sensation of thermal comfort.

The comfort zones are usually expressed graphically as an overlay on the psychrometric chart or some other diagram which shows the relationship between temperature and humidity. Only a few comfort charts attempt to express the additional major comfort variables of mean radiant temperature (MRT) and air motion. When an individual is seated and at rest, and the MRT is equal to air temperature and there is no substantial air motion (less that 50 feet per minute), the comfort chart appears as shown in Figure 5. There are two distinct zones which overlap, one labeled winter and one labeled summer. Their difference is primarily attributable to differences in normal clothing levels between winter and summer.

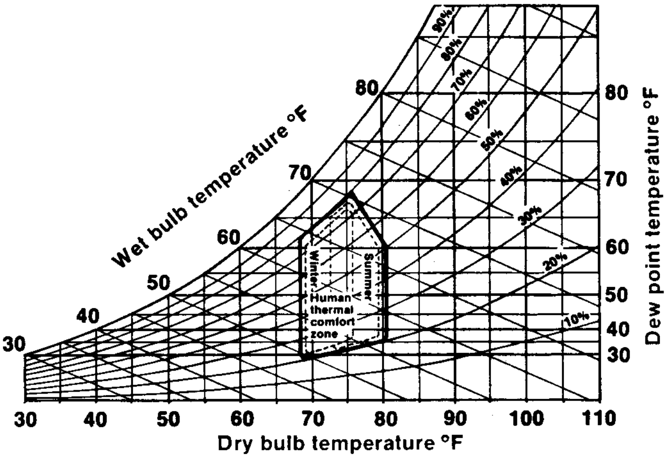

Figure 5. Basic comfort zone, (after B. Givoni, London, 1976).

Other major variables affecting comfort can have overriding effects on human comfort. It is now relatively well known among building analysts, for instance, that the mean radiant temperature of a building environment is of great importance to comfort.

At optimum levels the radiant exchange of the human body with its surroundings can account for almost 50 percent of the body's ability to lose heat. Therefore, if MRT is increased, the net radiant exchange from the body to its surroundings will decrease, and if MRT is decreased, the net radiant exchange from the body to its surroundings will increase. This has proven to be a very powerful passive building technique for both heating and cooling. Through the use of materials capable of storing relatively large amounts of thermal energy (concrete and masonry products, water, and phase change materials) and heat collection and rejection techniques, passive building designers have effectively used this principle in a number of design configurations. The most notable historical examples are the American Indian dwellings in the hot, dry Southwest where large volumes of thermal mass, strategic placement of windows, and large diurnal temperature swings combine to produce dwellings which maintain almost constant internal comfort.

Additionally, ventilation which increases air motion across the skin can greatly increase the tolerance for higher temperature and humidity levels. Research accomplished by P.O. Fanger (New York, 1970) with large numbers of subjects has shown, for instance, that comfort can be maintained at 82°F and 100 percent relative humidity as long as air velocities of 300 feet per minute across the skin are maintained. Most good ceiling fans will produce this degree of air motion. At lower relative humidities (50 percent and below) much higher temperatures (up to 90°F) are comfortable at this air velocity.

Air motion across the skin accomplishes cooling through both convective energy transfer and latent energy transfer (evaporation of perspiration from the skin). Since skin temperatures are relatively high, even 90°F air temperatures can carry off some excess heat. Additionally, at very high relative humidities (even at 100 percent) if dry bulb air temperatures are lower than skin temperatures, evaporation from the skin will ovvur. The skin is surrounded by a thin, still air layer which is close to skin temperature and insulates the body from its environment. If dry bulb air temperatures are less than skin temperature then the relative humidity of the air in contact with the skin is lowered somewhat (due to its increased dry bulb temperature) and skin evaporation and heat loss is increased. Increasing air motion heightens this effect. This is accomplished by both decreasing the thickness of the insulating air layer and carrying off excessively heated and moisture-laden air. Therefore, increases in human comfort due to air motion are rather profound.

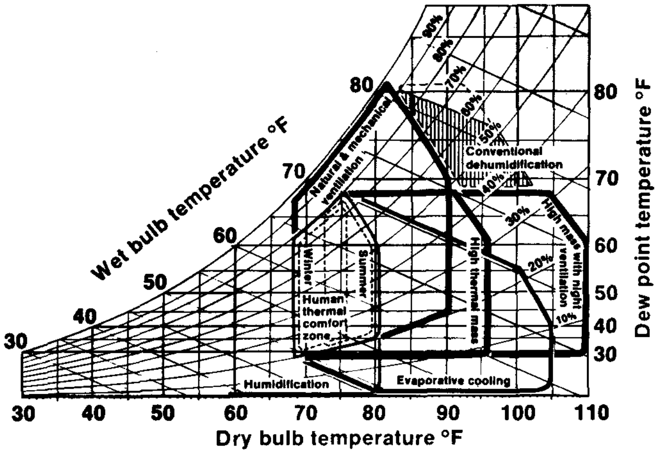

Figure 6. Expanded comfort zones.

Evaporative cooling of the air, although not significant in the warm, humid climates of the southeastern United States, can be extremely useful in hot, dry climates like those of the desert Southwest. Since the process of evaporative cooling occurs along a line of constant wet bulb temperature, its effectiveness is primarily limited to climates having average wet bulb temperature of 70°F or less.

An expanded version of the comfort zone has been provided by Givoni. It shows what can be achieved through effective passive building design. The various zones are based on exterior climate conditions and show building comfort-producing potentials for selected building design techniques. The effect of combined techniques are not shown.

The shaded area has been added by the author to indicate the additional potential of certain combined techniques. For instance, the wise use of thermal mass and ventilation in this zone can produce comfortable interior conditions. Additionally, research conducted by Gene Clark of Trinity University (San Antonio, 1980) indicates that radiative night sky cooling used in conjunction with thermal storage mass and air motion may extend this zone even further, perhaps to the dashed line above the shaded region. The development of hybrid and passive dehumidification systems will further increase the ability of the building designer to produce comfort in buildings.

Even without such techniques, however, there already exists a major body of knowledge which allows sensitively designed buildings to provide desirable comfort levels with much less dependence upon mechanical air conditioning systems.

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