2 Understanding Comfort, Behavior, and Productivity

Variations in people's perceptions of thermal comfort and individual energy-management behavior can have profound impacts on the energy used for space conditioning. While the savings from technical fixes are more difficult to predict than engineering models would suggest, technical improvements do narrow the absolute range of variation caused by diverse behavior and thus reduce the level of uncertainty and risk that utility load planners must accommodate in their forecasts. Building owners and occupants also glean additional benefits from improved buildings, in the form of enhanced worker productivity and satisfaction.

2.1 Thermal Comfort

Understanding what makes people thermally comfortable is the starting point in providing efficient space-conditioning services. Yet many of the professionals engaged in promoting energy-efficient space heating—architects, engineers, utilities, and field staff—know surprisingly little about comfort. For these professionals' efforts to be well directed, the principles that underpin their work should be, as Einstein said of physical theories, "as simple as possible, but not more so." Unfortunately, the engineering "rules of thumb" that are the basis for most designers' efforts are probably *too simple:* They ignore important dimensions of comfort that present opportunities to make building occupants happier at lower cost.

2.1.1 Differences in Personal Preferences

Not surprisingly, when it comes to finding the "right" indoor air temperature, differences in individual preferences are often quite substantial. These differences—and the behaviors associated with them—can have large impacts on space-heating energy use in homes and offices.

Individual perceptions of thermal comfort are related to a variety of physiological and psychological factors, including clothing, metabolic rate, body build, evaporative heat loss, acclimatization, circadian rhythm, color, noise, and crowding. To illustrate the magnitude of interpersonal variation in just one of these parameters, rates of evaporative heat

HIGHLIGHTS

- Thermal comfort preferences vary substantially among individuals and are subject to a wide range of influences. Heating approaches that can accommodate these differences are likely to provide greater comfort.
- Radiant heat losses or gains from the body play a major role in winter thermal comfort.
- Differences in thermostat settings account for large variations in space heating energy use by families living in similar dwellings. People operate thermostats on the basis of complex belief systems, but most are responsive to real-time feedback on their energy use.

loss have been measured among individuals under similar conditions—and can vary by a factor of up to six![1] The amount of heat dissipated evaporatively by an individual can vary from about one-eighth to more than three-fourths of total body heat loss. People who differ that much in sweatiness will have profoundly different sensitivities to humidity and air movement, not just to air temperature.

Combining physiological diversity with the complex set of motivations and beliefs that affect perceptions and behavior yields substantial differences in thermal comfort preferences among individuals and even groups of individuals. International comparative studies of households with similar incomes and energy prices show that people choose winter indoor temperatures ranging from 57° to 70° Fahrenheit (F) (14° to 21° Centigrade [C]).[2] Moreover, average winter household temperatures vary significantly among different countries, ranging from about 57°F (14°C) in Japan to 62°F (17°C) in Norway and 70°F (21°C) in Sweden.[3] A nationwide field survey of 1,000 houses in the United Kingdom revealed a surprisingly low average dwelling temperature of 60.4°F (15.8°C). Taking into consideration the average clothing insulation level observed in the study, the authors concluded that, "It seems that the British have a greater tolerance of cold temperatures in their homes than suggested by comfort standards."[4]

In Japan, a detailed study of thermal comfort concluded that the percentage of Japanese subjects indicating dissatisfaction because of too cold a temperature was significantly lower than that predicted by the classic comfort studies of Danish and American subjects—studies that provide the foundation for most comfort engineering.[5]

Interestingly, some evidence suggests that indoor comfort standards (but not the physiology that underpins them) have systematically changed over the past several decades. U.S. indoor thermal standards for winter comfort have risen from 64°F (18°C) in 1923 to 76°F (24.6°C) in 1986. In the 1920s, 90 percent of workers in a U.S. light industrial plant rated 70° to 72.5°F (21° to 22.5°C) "too warm." British household temperatures have risen by 1.8°F (1°C) per decade for the past 30 years. Some of these changes are due to clothing—a wool sweater is equivalent to about 3.6°F (2°C)—but more to changing perceptions of comfort.[6] The changes may also be related to increasingly sedentary lifestyles.

Overall, the magnitude of individual variations in thermal comfort perceptions suggests that heating systems that provide for greater spatial variation in heat distribution may have an advantage. For example, a system of radiators or baseboard heaters that allows individuals to move closer to or farther away from the source of heat as a means of achieving comfort may be more efficient than a forced-air system for which the thermostat must be constantly adjusted to satisfy the "coldest" person.

2.1.2 Thermal Comfort Fundamentals

The physiological fundamentals that relate to thermal comfort have to do with the heat balance of the human body. The body's core temperature is kept at around 98.6°F by complex temperature-regulating mechanisms within the body so that overall heat balance is maintained: The heat produced by the body through metabolism equals the heat lost through evaporation, radiation, and convection.

Figure 2-1 illustrates the heat balance for a sedentary office worker at typical indoor conditions.[7] The body's heat production (117 watts) equals the sum of radiant loss (44 watts), evaporative loss (29 watts), and convective loss (44 watts). The magnitudes of these heat flows are affected by four principal factors in the environment: radiant temperature, air movement, air temperature, and humidity.

Radiant temperature. The body gains or loses heat by radiation depending on the difference between the body surface temperature (bare skin and clothing) and the mean radiant temperature of the environment (the weighted average of the temperatures of all surfaces in direct line of sight of the body). For example, you may feel comfortable sitting in front of a roaring fire even though the air temperature is quite cool, by virtue of significant radiant heat gains. Conversely, you might find yourself turning the thermostat higher than you normally would if you are sitting in front of a large single-pane window when it's cold outside.

The body's radiant heat loss can be reduced by measures as simple as pulling shades or drapes, which effectively "warms up" cold interior surfaces. Attention to radiant heat loss may help to explain why some in-room thermal storage devices appear to save energy (since occupants may be able to sit near the heat source) and why some homeowners tend to set thermostats high to "warm up" a cold house (until the radiant temperature of walls and other surfaces rises to a warmer air temperature). Moreover, radiant heat loss may make superinsulated windows a more cost-effective option than conduction losses alone would indicate (see Section **5.5**).

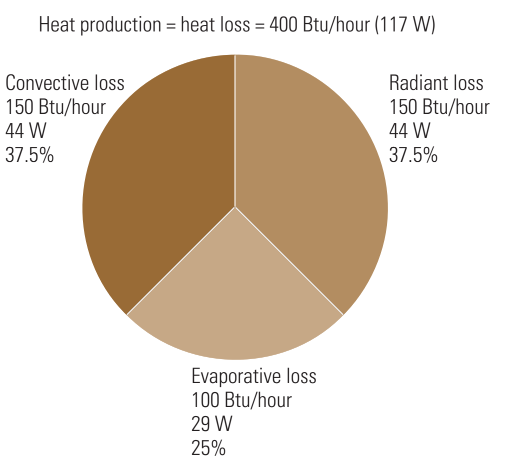
- *Air movement.* Air movement, especially drafts from cracks around doors or windows, is often a cause of thermal discomfort. As with other comfort factors, air temperature and air movement are interrelated. For example, each 15 foot per minute (fpm) increase in air movement has a similar effect on comfort as a 1°F drop in air temperature at air velocities above 30 fpm.[8] Some individuals' dissatisfaction with heat pumps is related to their preferences for slower air movement in winter.

- *Air temperature.* The temperature difference between air and skin is one of the principal determinants of sensible heat loss. Problems with the location or calibration of thermostats—and, accordingly, improper regulation of air temperatures—are a common cause of dissatisfaction with household heating systems. Some systems allow wide fluctuations in temperature as the heating system cycles on and off. In some homes equipped with electric baseboard heat, temperatures vary by 7° to 10°F during such cycles. Thermostats with a "heat anticipator" feature reduce room temperature swings to 3° to 5°, allowing a lower temperature setting while providing greater comfort.

- *Humidity.* Many homeowners run humidifiers or leave pots of water on woodstoves to maintain adequate indoor humidity in the winter. Leaky homes are more prone to dryness than tight homes, because humidity from indoor sources escapes through air leakage and is replaced with drier outside air. After houses are weatherized, the need for additional humidification is thus likely to diminish.

Figure 2-1: Heat balance for a sedentary office worker

At typical indoor winter conditions (air and mean radiant temperatures of 70°F), the body loses roughly equal amounts of heat by convection, radiation, and evaporation.



Source: E SOURCE; data from Honeywell [7]

2.1.3 Implications of a Comfort-based Approach

Focusing on human comfort as the starting point for the design of energy-efficient space-conditioning systems has a variety of implications, including:

- Modern "comfort engineering" rests on an insecure foundation of assumptions with respect to the consistency of individual preferences, which are, in fact, subject to a wide range of psychological and physiological influences. Acknowledging these differences may affect the choice of space heating technologies.

■ Space heating designs that take into consideration the magnitude of variations in individual preferences—by allowing some thermal differentials within occupied spaces—may deliver comfort more efficiently than those that do not.

■ Sealing air leaks in commonly occupied areas may have an impact on comfort that is more significant than the impact on the overall thermal performance of the building. Air flow is from higher to lower pressure areas; cool air descends. A thin sheet of cold air from a window, for example, is given a vector toward the inside of a room by the horizontal windowsill. The resulting draft, which becomes more pronounced as outside temperatures get colder, can cause discomfort to an occupant nearby. Better sill design or drapes solve the problem quite satisfactorily.

■ With a better understanding of radiant heat loss, homeowners may be able to improve comfort and reduce energy costs by drawing shades, installing storm windows, or relocating furniture to reduce radiant heat loss in areas where they spend lots of time. Radiant heat is transferred from warmer bodies to cooler ones depending on temperature differences and the relative sizes and properties of the surfaces.

■ "Spot" radiant heating can be used to provide comfort for workers in some contexts, such as warehouses, where maintaining air temperatures at 70°F is costly and inefficient.

2.2 Behavior

The actual performance of space heating systems depends on how those systems are operated by homeowners or building managers. Field studies reveal that occupant behaviors are complex and often unexpected.

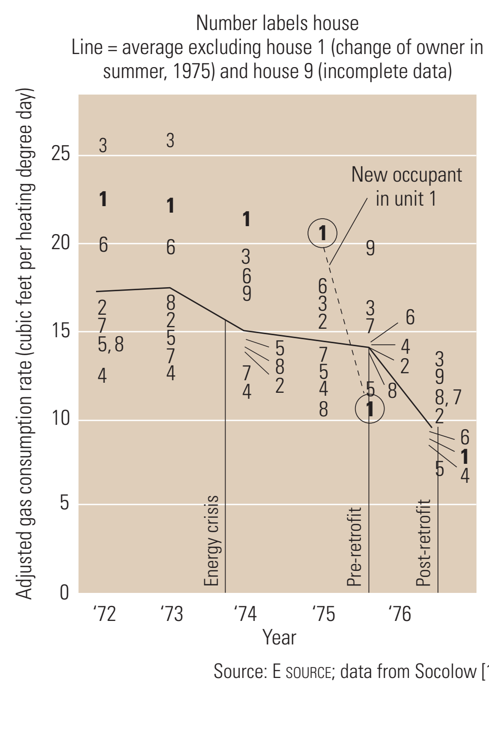
2.2.1 Space Heating Energy Use Depends on Who's Driving the System

Energy use for space heating can vary by a factor of two or more among families living under similar conditions. To a surprising degree, homeowner lifestyles—not qualitative differences between structures—account for this variation.[9] Such lifestyle factors include selection of thermostat setpoints, hours of home occupancy, ages of occupants, personal values, comfort preferences, and understanding of heating system controls. This is not a new finding, though it remains a challenging one, defying both straightforward explanation and simple solutions.

As early as the mid-1970s, the pioneering Twin Rivers, New Jersey, study showed that winter gas consumption for space heating varied by a factor of two among 32 townhomes with identical floorplans, furnaces, appliances, building orientation, and energy features.[10] As **Figure 2-2** indicates, occupants in units 1 and 3 consumed about twice as

Figure 2-2: Five-year history of space heating energy use by nine similar Princeton townhomes

Winter gas consumption for space heating varied by a factor of two among a group of townhomes with identical floorplans, furnaces, appliances, building orientation, and energy features. The houses were retrofitted with energy-efficiency measures in 1976. Winter comfort is a subjective matter; note the dramatic decrease in consumption when a different occupant moved into unit 1.



Source: E SOURCE; data from Socolow [10]