4.3 Thermal Comfort

4.3.1: Thermal Comfort Systems (1 Credit: Implement 4 of 6)

- Thermal comfort systems provide constant and uniform temperatures within a zone.
- Thermal comfort systems are zoned to allow personal control of spaces.
- Thermal comfort systems eliminate drafts through controlling air flow and wall and window insulation.
- Thermal comfort systems are supplemented by ceiling or personal fans with multiple speed settings and occupancy sensors.
- Thermal comfort systems incorporate personal environmental modules at individual task areas.
- Thermal comfort systems are commissioned as per ASHRAE guide.

4.3.2: Temperature Controls (1 Credit: Implement 3 of 5)

- Thermal comfort system controls are within reach.
- Operable windows are provided with controls within reach.
- Thermal comfort system can be programmed for different settings based on time of day and season.
- Thermal comfort system controls for public or common use follow a common conceptual model.
- Thermal comfort system can be adjusted by remote control.

1. Overview

Maintaining indoor thermal comfort is a fundamental requirement for the building envelope and mechanical systems. Comfortable interior environments can both improve the satisfaction of people and increase productivity. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation”[1]. Although thermal comfort is subjective, it is heavily influenced by factors like temperature, humidity, air speed, clothing levels and an individual’s metabolic rate. These physical and individual factors are included in two commonly used thermal comfort standards: ASHRAE Standard 55 and International Organization for Standardization (ISO) Standard 7730.

In addition to the above factors, thermal comfort is also influenced by whether or not a building is naturally conditioned and if occupants have control over these systems[2]. Other important considerations like age, sex, climate, season, and expectations can play an important role in determining a person’s satisfaction with the thermal environment[3]. These issues are incorporated to various extents into the two main models of thermal comfort: the “static” model used for mechanically conditioned buildings where occupants are engaged in primarily sedentary tasks, and the “adaptive” model typically used in naturally conditioned buildings where occupants are able to modify their environment and behaviors to improve comfort levels[4].

1.1 The Static Thermal Comfort Model

Developed by P.O. Fanger in the 1960s and 70s, the static model relies on a predicted mean vote/predicted percentage dissatisfied (PMV/PPD) scale which uses air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation to predict a person’s thermal sensation. An individual’s thermal sensation is recorded on a survey on a seven point scale ranging from cold (-3) to hot (+3), with a value of (0) indicating thermal neutrality[5]. A central principle of the static model that thermal neutrality is preferred by occupants; as thermal sensation moves toward either cold or hot the expected percentage of occupants that would be dissatisfied with the thermal environment is expected to increase.

The PMV/PPD framework has historically been used in thermal comfort standards like ASHRAE Standard 55 and ISO 7730. Both of standards require that at least 80% of occupants must be “satisfied” with the thermal environment to comply with the standard[1, 6]. Calculating the combination of physical and individual variables that produce comfort for these standards can be completed either by using software or by using the Graphical Comfort Zone Method, an annotated psychometric chart outlining temperature and humidity ranges applicable for environments where occupants are engaged in primarily sedentary tasks[1, 7].

However, the static model assumes that all occupants experience thermal sensation in a similar way and that the indoor thermal environment should remain consistent across climates and seasons[5]. This assumption has been criticized because of age, gender, and physiological differences among people[8]; the static model has also led to designers avoiding the use of natural conditioning systems in order to achieve a tight range of interior temperatures. To provide greater flexibility in how people achieve thermal comfort, and to promote natural conditioning, researchers developed an alternative called the adaptive thermal comfort model.

1.2 The Adaptive Thermal Comfort Model

Originally conceived as a challenge to the static model, the adaptive thermal comfort model was recently added to ASHRAE Standard 55 as an alternative approach for naturally conditioned spaces[9]. Rather than basing thermal comfort entirely on six physical and personal variables to calculate comfort, with the goal of a neutral thermal environment, the adaptive model is based on the principle that if a change in the thermal environment occurs that produces discomfort, people will react in ways to restore their comfort[10]. As long as an occupant has an ability to adapt (e.g., opening and closing windows, using personal fans, drinking cool beverages), they will be satisfied with the thermal environment. Using the adaptive model results in a wider range of interior conditions which may better match local climate and seasonal shifts, resulting in significant energy savings.

One of the challenges with using the adaptive model is that it is contingent on a wider range of factors than the six that are incorporated into the static model; designers need to do more up front work with surveys or focus groups to understand the adaptive mechanisms that will be available to future building tenants to increase their own comfort[11]. In addition, naturally conditioning a building can be challenging in many climates. However, because the static model fails to account for issues like body fit and cultural appropriateness, the adaptive model may be a more appropriate approach for a universally designed building.

2. Issues to Consider

Codes and Commissioning: Building codes frequently require that a building design meets the provisions of ASHRAE Standard 55 or ISO 7730. However, enforcement of this provision is rare, and often times the building conditioning systems are not commissioned to determine if they are performing to specification. This can result in discomfort, dissatisfaction with an interior environment, complaints to building management, and a loss of productivity.

Adaptive Opportunities: A large percentage of the population may desire additional control over their interior thermal environmental conditions to manage their own comfort. In extreme cases, if occupants are unable to adapt to their surroundings, they may be subject to hypo- and hyperthermia which can lead to illness or death[12, 13]. Unfortunately, due to global warming, it is expected that cases of heat-related morbidity and mortality will increase in the future[14]; heat waves disproportionately affect the elderly and people with preexisting medical conditions.

Advanced Age: Older adults are at risk because thermoregulation mechanisms in the peripheral nervous system are affected by age; they often perceive interior temperatures to be cooler than younger adults which can result in hyperthermia. In addition, decreased organ function, interactions between medications and heat-compensation mechanisms, and poor health status can all alter the perception of temperature[15]. Because the proportion of persons aged 60 years and older is expected to double by 2050[16], it is important to consider how the elderly may perceive interior temperatures to not only combat heat stress but improve thermal comfort.

Chronic Disease: Younger individuals suffering from chronic diseases like obesity, hypertension, diabetes, addiction, and cardiovascular disease are also at risk when exposed to high or low temperatures, as these conditions can also impair thermoregulation. In addition, some medications used to treat these diseases may alter blood flow to the extremities or impair the ability of the peripheral nervous system to perceive temperature[17].

Gender and Sex: Gender expectations can play a role in thermal comfort. A field study of residential buildings in China found that thermal sensations of males and females are different because of how male versus female clothing covers the body[18]. A 2015 study documented that metabolic rates used in the static thermal comfort model for females are often incorrect, and can overestimate a woman's metabolic rate by up to 35%[19]. Both of these issues result in women more frequently reporting dissatisfaction with the indoor thermal environment than men.

Localized Discomfort: Finally, local factors like the location of a space in a building (e.g., on the north or south side), the presence or absence of sunlight directly heating the body, drafts, and warm or cool surfaces causing radiant temperature asymmetry can create localized discomfort. Attention should be paid to how spaces will perform over the course of the day with diurnal temperature swings and movement of the sun, the insulation value of walls/windows/doors, and the presence of hot or cold surfaces (e.g., radiators, cold windows) in a space.

For all of the above reasons, designers are encouraged to conduct focus groups and/or distribute surveys prior to the design of a building to better understand the needs of the occupants who will eventually occupy the spaces. These qualitative methods should pay close attention to the issues outlined above. After developing a better understanding of how to tailor the thermal envelope and systems to the needs of the occupants, a designer can decide which thermal comfort model(s) are appropriate for the design. In some heating dominated climates, it may be necessary to use a hybrid approach: the static comfort model applied for winter months and the adaptive model applied in the spring, summer, and fall months when the building can be naturally conditioned. After construction, conducting a thermal comfort survey can help with commissioning of the thermal envelop and mechanical equipment.

Providing systems that can accommodate a wide range of users, and allow for adaptation to variable conditions, not only improves thermal comfort but can reduce energy use. While this may require additional time on the part of the design team, a higher level of thermal comfort will result in greater satisfaction, fewer complaints, and better overall health for occupants.

3. Referenced Standards

ANSI/ASHRAE STANDARD 55—Thermal Environmental Conditions for Human Occupancy defines the range of indoor thermal environmental conditions deemed to be acceptable for a majority of occupants. It includes both a static and adaptive thermal comfort model provision.

ISO 7730—Ergonomics of the thermal environment (Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria) presents methods for predicting the general thermal sensation and degree of discomfort of people of people in moderate indoor environments. It enables the analytical determination and interpretation of thermal comfort using the static model.

ISO/TS 14415:2005—Ergonomics of the thermal environment (Application of International Standards to people with special requirements) provides background information on the thermal responses and needs of groups of persons with special requirements (e.g., paralysis, sensory impairment, obesity, variations in metabolic rate, etc.) so that international standards like ASHRAE 55 and ISO 7730 can be appropriately applied.

ISO 7726:1998—Ergonomics of the thermal environment (Instruments for measuring physical quantities) specifies the minimum characteristics of instruments for measuring physical quantities characterizing a thermal environment as well as the methods for measuring the physical quantities of this environment. It does not aim to define an overall index of comfort or thermal stress but simply to standardize the process of recording information leading to the determination of such indices.

Other standards and projects under the direct responsibility of ISO/TC 159/SC 5 Secretariat include guidance for the prevention of thermal stress, assessment of the contact with warm or cool objects, and the evaluation of thermal environments in vehicles.

4. Measurement and Verification

In Section 6 of ASHRAE Standard 55 provides guidance on the correct measurement of the indoor thermal environment. This guidance is in close alignment with ISO 7726. To verify that a building is in conformance with the standards, it is necessary to measure at least the four environmental factors (i.e., air temperature, mean radiant temperature, air speed, and humidity) at a variety of heights; it is also necessary to estimate the clothing level and metabolic rate of occupants. In addition, identification of local effects which can cause discomfort (like a drafts or radiant temperature asymmetry) is required, which may necessitate multiple visits to a site at different times of day.

Because a field evaluation can be a time consuming process and require specialized monitoring equipment, and because thermal comfort also requires subjective evaluation, many commissioning agents will first rely on a post-occupancy evaluation to determine if occupants are comfortable. ASHRAE Standard 55, Section 7, provides an example of how to conduct this type of survey; several informative appendices in the standard (i.e., Appendices D, E, H, J, and K) have additional guidance. In addition, a number of research organizations like the U.C. Berkeley Center for the Built Environment have developed standardized online surveys to assist design teams; this can allow a designer to compare their building's results to similar structures.

5. Design Considerations

For 4.3.1, Thermal Comfort Systems (1 Credit: Implement 4 of 6):

1. *Thermal comfort systems provide constant and uniform temperatures within a zone.* In a mechanically conditioned building, it is important to provide thermal consistency among spaces, and uniform temperatures within spaces, to avoid local discomfort caused by issues like radiant temperature asymmetry or solar gain. This can be achieved by paying careful attention to insulation levels in walls/doors/windows, and thoughtful placement of heating coils, diffusers, and exhaust elements. However, this does not mean that all spaces should be the same temperature at all times; spaces with different expectations of metabolic rates (e.g., gym vs. office) or seasonal variations may necessitate different thermal conditions. Designers should consult ASHRAE Standard 55 and ISO 7730 to

better understand these issues.

2. *Thermal comfort systems are zoned to allow personal control of spaces.* Historically, it was difficult to provide multiple zones and controls for buildings because of the cost of actuated dampers and controls. However, the price of these systems have come down significantly in the last decade, and even some single family residences now have multi-zone systems actuated by a separate thermostat. In most cases, this is done to improve building energy performance, but the additional level of control also helps to improve thermal comfort. Effective thermal zoning, such as one thermostat and damper per enclosed office or room, allows for individuals to set their preferences for thermal control and can help a building system quickly respond to changes in weather or insolation.
3. *Thermal comfort systems eliminate drafts through controlling air flow and wall and window insulation.* Drafts are frequently caused by unwanted air leakage through the thermal envelope, as air moves across a cold surface like a window, or by the improper placement of diffusers in an occupied space. Careful attention to the detailing of the thermal envelope, providing adequate insulation levels in walls/doors/windows, and thoughtful placement of heating coils, diffusers, and exhaust elements can help to eliminate this problem in buildings.
4. *Thermal comfort systems are supplemented by ceiling or personal fans with multiple speed settings and occupancy sensors.* The static model of thermal comfort accounts for elevated airspeeds as a way to offset increased indoor temperatures. The adaptive thermal comfort model relies on the ability of occupants to modify their thermal environment to achieve comfort. Therefore, energy efficient ceiling or personal fans with multiple speed settings are a recommended method for extending the comfort zone in increments, though they only provide a cooling benefit if they are directly increasing the air speed over a person's body. Therefore, occupancy sensors should be used to turn the fan off when a space is unoccupied, avoiding excessive consumption of energy. In addition, if the air-conditioning system of a building can either be shut off or the set point temperature increased, the fans can help save energy.
5. *Thermal comfort systems incorporate personal environmental modules at individual task areas.* Personal environmental modules are a system where individual occupants in an open floor plan environment are given control over their local thermal environment by ducting or piping heating and cooling to each cubicle. Increasing individual control over the thermal environment increases occupant comfort and satisfaction, and may improve overall office productivity[20-22].
6. *Thermal comfort systems are commissioned as per ASHRAE guide.* According to the Whole Building Design Guide, building commissioning is the professional practice that ensures buildings are delivered according to the Owner's Project Requirements (OPR). The OPR should include thermal comfort requirements, like conducting focus groups or a survey prior to design or evaluation of comfort after construction is substantially complete. Buildings that are correctly commissioned have fewer change orders, tend to be more energy efficient, and have lower operation and maintenance costs. Commissioning of thermal comfort systems is typically done in accordance with ASHRAE Standard 202-2013, The Commissioning Process for Buildings and Systems, and ASHRAE Guideline 0. As mentioned above, ASHRAE Standard 55 and the ISO standards also contain guidance on correct measurement of the thermal environment.

For 4.3.2, Temperature Controls (1 Credit: Implement 3 of 5):

1. *Thermal comfort system controls are within reach.* Environmental controls should be within the reach ranges specified in the Space Clearances section of the isUD, including those with restricted access. These controls include, but are not limited to, light switches,

circuit breakers, duplexes and other convenience receptacles, environmental and appliance controls, plumbing fixture controls, and security and intercom systems. Thermostats and switches to actuate mechanical equipment or fans should be within reach for all occupants because an inability to reach and operate these controls can result in discomfort and/or temperature-related illness, and ensures equitable use.

2. *Operable windows and other ventilation elements like operable skylights are provided with controls within reach.* For the same reasons that thermostats and switches for mechanical equipment should be within reach, operable windows should provide opening mechanisms and locks that are within reach. This is especially important in buildings reliant on the adaptive thermal comfort model where operable windows are necessary for maintaining a comfortable interior environment. Providing window controls within reach may require using different types of windows (i.e., casement vs. double hung windows), using balancing mechanisms to assist with lifting, or providing electric actuators to allow for easy operation (e.g. operable skylights).
3. *Thermal comfort system can be programmed for different settings based on time of day and season.* Although temperature control is vital to for occupant comfort, control design is often an afterthought[23]. In a review of how thermostats are used at home, it was found that many people experienced issues with the visibility of buttons and text, as well as confusion related to programming[24]. This is important because many manufacturers provide thermostats with setback functions to reduce energy use in a building at night. A new generation of controls, like the Nest Thermostat, attempt to learn occupant habits to improve comfort and reduce energy use. This type of thermostat does not require programming, though it requires access to a Wi-Fi signal and the internet to operate.
4. *Thermal comfort system controls for public or common use follow a common conceptual model.* Having a common conceptual model for all controls can make it easier for an occupant to operate lights, receptacles, environmental controls, and security systems at their convenience. This may require installing an integrated controls system that controls these subsystems based on a standardized communications protocol like Zigbee. Although a number of manufacturers now offer these controls as part of the “internet of things,” careful attention needs to be paid to how systems will perform during or after a power outage, and how the system protects privacy and security.
5. *Thermal comfort system can be adjusted by remote control.* In many buildings, especially single family residences, there is only one thermostat or control for the entire building. This may make it difficult for people with limited mobility to adjust interior temperatures. A number of manufacturers now make thermostats, mechanical equipment, and window actuators with a remote control for their operation. Some manufacturers also offer apps for smart phones or computers for the same purpose.

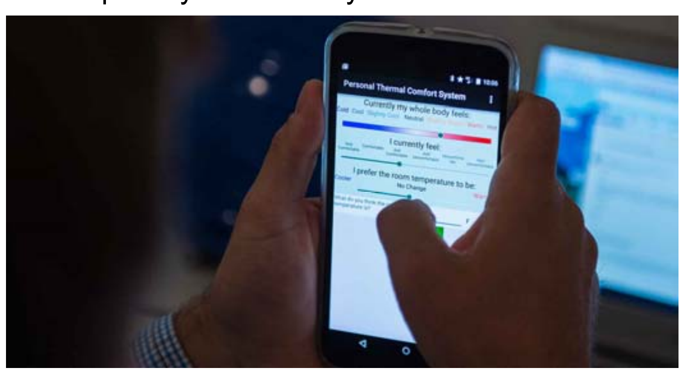

Figure 1: Researchers at the National Renewable Energy Laboratory (NREL) are testing new personal controls for building mechanical systems to improve comfort and reduce energy use. Photo by Dennis Schroeder, image courtesy of NREL.

6. Definitions

The following definitions are adapted from [ASHRAE Standard 55-2013.](#)

Air speed	The rate of air movement in a space without regard to direction.
Air Temperature	The temperature of the air at a given point.
Clothing level (clo)	A unit of measurement used to express the thermal insulation provided by garments and clothing ensembles.
Comfort zone	The combination of physical factors like air temperature, mean radiant temperature, humidity and air speed with personal factors like metabolic rate and clothing level that are predicted to provide a comfortable interior environment.
Draft	Unwanted local cooling of the body caused by air movement.
Humidity	The moisture content of the air.
Local thermal discomfort	Thermal discomfort caused by local conditions such as a vertical air temperature difference, radiant temperature asymmetry, or local convective cooling (e.g., contact with a hot or cold object like a floor).
Mean radiant temperature	The temperature of uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual enclosure. It is a measurement of the radiant temperatures surrounding an occupant in a space.
Metabolic rate (met)	The rate of that an individual's body transforms chemical energy into heat energy.
Operative temperature	A combination of air temperature and mean radiant temperature (typically the average) used in the calculation of the comfort zone.
Predicted mean vote (PMV)	An index that predicts the mean value of the thermal sensation votes on a seven point scale, expressed from -3 to +3, corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot."
Predicted percentage of dissatisfied (PPD)	An index that predicts the percentage of people thermally dissatisfied with a space; it is determined by the PMV.
Radiant temperature asymmetry	A difference in the radiant temperatures of surfaces which can lead to discomfort; it is typically caused by warm ceilings or cold walls/windows.
Thermal comfort	The condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.
Thermal sensation	A conscious subjective expression of an occupant's thermal perception of the environment, commonly expressed using the categories "cold," "cool," "slightly cool," "neutral", "slightly warm," "warm", "hot". Used in the PMV model.

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