Thermal Comfort: Designing for People

BY RODRIGO MORA, PH.D., ASSOCIATE MEMBER ASHRAE; ROBERT BEAN, R.E.T., P.L.(ENG.), MEMBER ASHRAE

Meeting and exceeding requirements for indoor air quality, thermal comfort, and acoustic and visual quality[1] can lead to optimized environments that maximize well-being and performance. However, surveys on numerous buildings have revealed that satisfactory indoor environmental conditions are often not achieved.[2,3] This suggests the whole industry needs more systematic methods to analyze and design indoor environments.

This is the first of a series of articles intended to 1) raise the awareness of the building design community of the opportunities provided by thermal comfort analyses and standards to help optimize indoor thermal environments for people, 2) increase the understanding of the underlying principles, assumptions, and modeling simplifications involved in designing spaces for thermal comfort, and 3) provide guidance through examples to demonstrate how to use ASHRAE Standard 55-2017[4] to achieve optimal indoor thermal conditions for occupancy, with minimal reliance on energy-consuming systems.

Thermal environmental quality is one of the most fundamental requirements for human occupancy, second only to indoor air quality (IAQ). Studies have found that the quality of the thermal environment has a particularly high influence on the satisfaction with the overall indoor environment.[3,5] In studying high-performance buildings, the authors have observed that most occupants tend to report dissatisfaction only when thermal conditions become intolerable. Otherwise, they often rely on personal heaters when they are cold, or open windows when they are warm, even when the weather is not appropriate. On one hand, building operators and facility managers are often not aware of any unsatisfactory conditions. On the other hand, post-occupancy evaluations (POE) are still not common, which causes a lack of occupant feedback to designers. As a consequence, occupants' satisfaction, well-being, and performance might be negatively impacted.

Thermal comfort analyses enable architectural and engineering designs that more effectively control solar gains, instead of letting energy-intensive

Rodrigo Mora, Ph.D., P.Eng., is a faculty member in the Building Science Graduate Program at the British Columbia Institute of Technology, Vancouver, BC, Canada. Robert Bean, R.E.T., P.L.(ENG.), is the president, Indoor Climate Consultants Inc., Calgary, AB, Canada.

air-conditioning remove absorbed solar heat on perimeter spaces, while possibly having adjacent interior zones overcool. Thermal comfort analyses permit studying the comfort effects of allowing the building's thermal conditions to "float" to reduce mechanical conditioning instead of imposing an energy-demanding narrow indoor temperature range. Thermal comfort analyses also help designers select and configure proper zone and room level technologies to achieve thermal comfort, such as radiant systems, air distribution outlets, underfloor air distribution, displacement ventilation and chilled beams.

ASHRAE Standard 55-2017 provides a systematic approach to help architects and engineers analyze design alternatives that integrate suitable combinations of enclosure, fenestrations, constructions, terminal HVAC technologies and space layouts and dimensions and meet or exceed function-specific thermal environmental requirements for occupancy. Furthermore, Standard 55-2017 provides methods and metrics to support the evaluation of thermal comfort in existing buildings using a) subjective occupant surveys, b) objective environmental measurements and c) the building automation system as an adjunct to a) and b).

How Can I Analyze if a Space is Thermally Comfortable?

Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation."[4] The assessment of thermal comfort involves three dimensions: physical, physiological and psychological. According to the *2017 ASHRAE Handbook—Fundamentals,*[6] "The conscious mind appears to reach conclusions about thermal comfort and discomfort from direct temperature and moisture sensation from the skin, deep body temperatures, and the efforts necessary to regulate body temperatures… In general, comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of thermoregulation is minimized."

Thermal comfort is predicted using empirically derived thermal comfort models and assessed in existing buildings using objective environmental measurements and subjective questionnaires to occupants. Thermal comfort standards rely on models to assist designers in predicting thermal comfort under a given set of personal and environmental conditions.

Humans are homeotherms: their thermoregulatory system regulates their internal body temperature within a narrow band around 37°C (98.6°F), i.e., homeostasis. The normal body temperature varies daily by about 1°C (1.8°F) based on circadian cycles, but at any given moment, the core temperature is tightly regulated within a few tenths of a degree during the day, with slightly more variability at night.[7] In thermal neutrality the basal or minimal rate of metabolic body heat production is in equilibrium with the rate of heat loss to the environment.

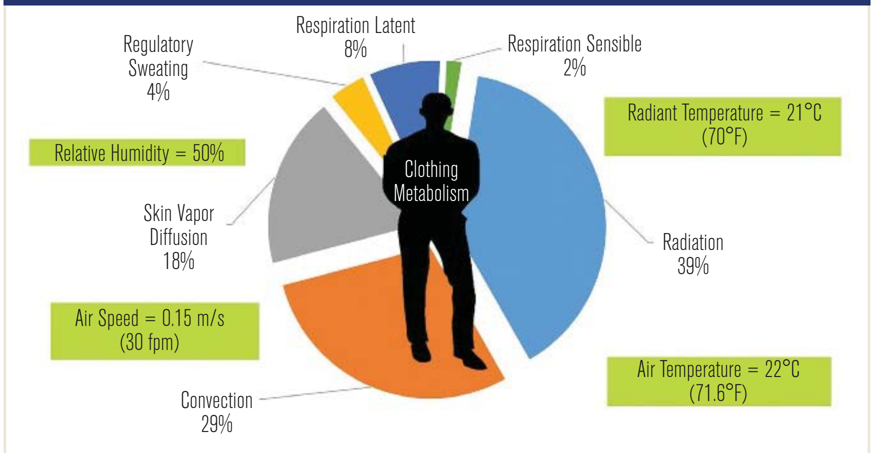
Consequently, a range of thermal conditions of the immediate environment are required in which a person can maintain normal body temperature without needing to use energy above and beyond normal basal metabolic rate. A departure from those conditions triggers physiological responses proportional to the thermal imbalance from thermal neutrality. The fundamental assumption is that the thermal sensation experienced by a person is a function of the physiological strain imposed by the environment. However, the body is an adaptive system that adjusts its thermoregulatory responses (i.e., level of strain) for optimal homeostasis as a function of a person's own conditions (activity level and clothing insulation) and the prevailing environmental conditions.

A main goal in thermal comfort design is to achieve indoor thermal conditions close to thermal neutrality, leading to thermal acceptability for the vast majority of occupants in a space. Thermal comfort models implemented in standards provide the empirical comfort basis that use a comfort metric (e.g., thermal sensation) as its independent variable (rather than the room air temperature) and correlates this comfort metric with the prevailing thermal environment.

What are Thermal Comfort Models?

Thermal comfort models help designers examine combinations of personal and environmental conditions that are acceptable to the occupants in a space. ASHRAE Standard 55-2017 provides analytical methods to assess thermal comfort in moderate environments, with occupants engaged in moderate activities. As indicated in *Figure 1*, to predict thermal comfort, Standard 55-2017 uses two principal thermal comfort models: a whole-body thermal-balance comfort (WBC)[8] model for mechanically conditioned buildings, and the adaptive thermal comfort (ATC) model[9] for naturally conditioned buildings. Both models use the operative temperature as the main independent environmental variable or index in the analyses because they combine the two main modes of heat dissipation by the human body: convection and radiation (*Figure 1*).

FIGURE 1 Body heat loss to the environment for a standing, relaxed individual in typical winter indoor clothing.



The standard effective temperature (SET) model[10] (underlying the elevated air speed comfort zone method[11]) expands the WBC and ATC models when the effects of enhanced convective cooling are required to be analyzed; the SolarCal model[12] expands the WBC model when the effect of direct solar irradiation on occupants needs to be considered.

The whole-body thermal-balance comfort (WBC) model is a thermophysiological and comfort model developed based on occupants engaged in sedentary activities in moderate climate-chamber environments.[8] The model aims to predict the thermal sensation (predicted mean vote, PMV) and percent dissatisfaction (predicted percent dissatisfaction, PPD) of a group of people based on a steady-state thermal balance of the human body with a given level of clothing insulation, while undertaking a certain activity in a given environment.

The model also considers the evaporative heat loss from the human body, which is enhanced by convective air movement around the body (see *Figure 1*). In the WBC model, the thermal balance of the human body results in skin temperatures that should be kept within specified ranges and no accumulation of sweat, depending on metabolic activity and thermoregulation (physiology), to produce a neutral thermal sensation (PMV, sensory psychology) and subsequent conscious thermal satisfaction (PPD, cognitive psychology).

The fundamental assumption of the adaptive thermal comfort model (ATC) is expressed by the adaptive principle: if a change occurs in the environment such as to produce discomfort, people respond in ways that tend to restore their comfort.[13] The type of adaptive response and its efficacy in restoring comfort depend on contextual factors, including the overarching influence of climate, and on the adaptive opportunities available; individuals with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort,[14] and may even be able to optimize the thermal environment to their own preference.

The ATC model is, therefore, a dynamic model. The ATC model in Standard 55-2017 was developed from field studies in naturally ventilated buildings;[9] it correlates revailing mean outdoor temperatures with indoor comfort temperatures. As such, it implicitly accounts for the dynamic thermal response from the building to the varying weather and the adaptive behaviors of the occupants, leading to resulting indoor operative temperatures and comfort votes. The adaptive model implicitly considers the three types of adaptive mechanisms:[9] physiological (short-term acclimatization: diminution of strain by sufficient period of exposure, long term adaptation to climate), behavioral (personal, technological and cultural adjustments that change thermal balance flows, e.g., changing clothing and activity, using operable windows, fans, blinds, doors, awnings, personal environmental controls, etc.) and psychological (changed expectations based on perceived control; past thermal experiences; and social, economic and cultural background). The WBC model is partially adaptive by accounting for behavioral adjustments.[15]

The concept of "perceived control" is also integral to the adaptive theory; it assumes that individuals have relaxed expectations and a higher acceptance to wider temperature bands and thermal environmental changes when these can be perceived to be controllable,[16]

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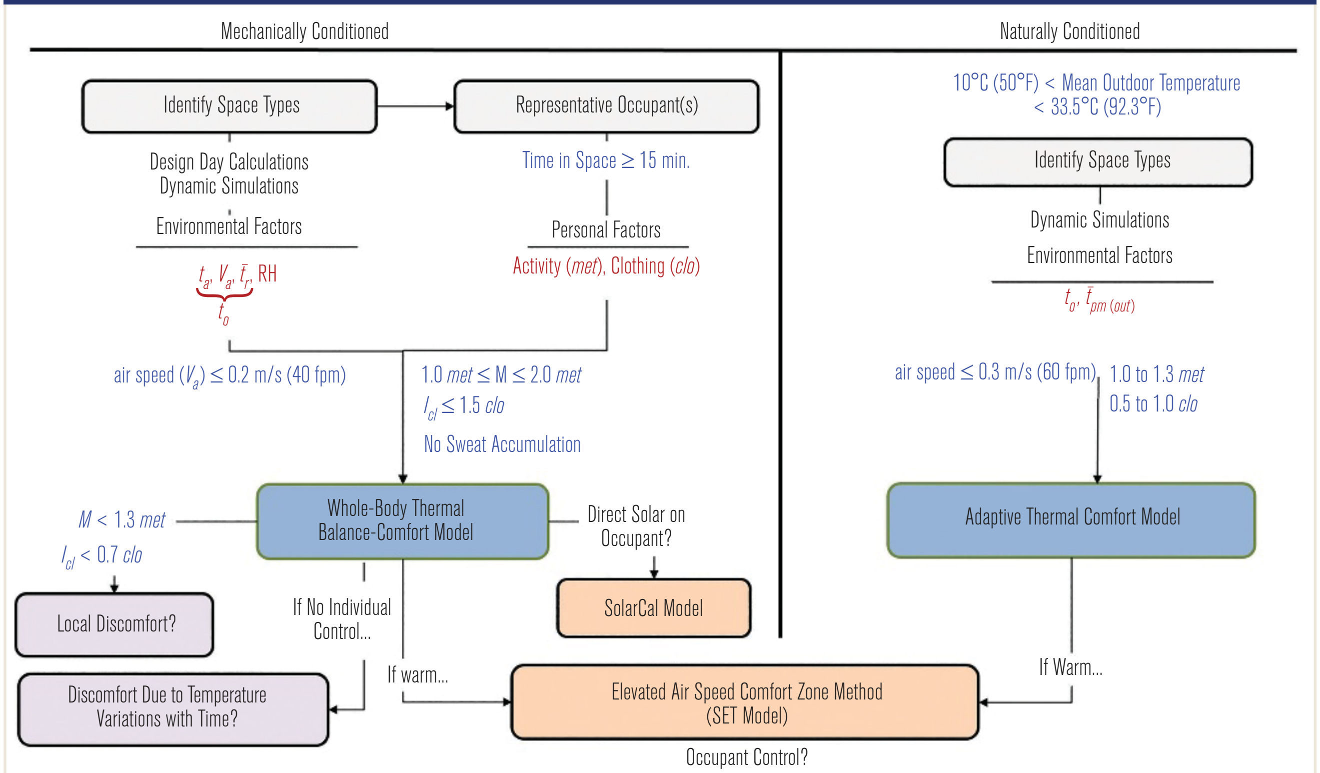
FIGURE 2 Thermal Comfort Analysis steps in ASHRAE Standard 55-2017.



enabling the creation of their own thermal preferences. Adaptive principles assume the persons are able-bodied without physiological and physical challenges (e.g., Raynaud's disease, multiple sclerosis, Parkinson's, arthritis, etc.) or mental health and/or cognitive disabilities preventing the ability to adapt.[17] Designers should note that Standard 55-2017 does not directly cover vulnerable populations.

How Does Standard 55-2017 Support Design?

As indicated in *Figure 2*, for mechanically conditioned buildings, the first step in the thermal comfort assessment is the identification of the relevant spaces, followed by the identification of representative occupant(s) in those spaces. The standard requires occupants excluded from the analysis to be identified; it defines a representative occupant as "an individual or composite or average of several individuals that is representative of the population occupying a space for 15 minutes or more." The designer needs to exercise judgement from experience in selecting representative occupants.

The standard aims to assist designs that provide a thermal environment that at least 80% of the occupants find thermally acceptable. In doing so, it acknowledges that due to individual differences, it is unrealistic to attempt to aim at 100% occupant thermal acceptability, unless personalized control is intended for each occupant.

The prediction of thermal comfort using the WBC model requires six factors, or independent variables, to be specified as inputs (in red in *Figure 2*): two personal factors of the representative occupant, and four environmental factors describing his/her surrounding environment. The personal factors are the level of clothing insulation (*clo*) and metabolic rate (*met*) representing the level of activity. The designer can obtain the personal factors from tables provided by the standard. The environmental factors are: air temperature ($\underline{t_a}$), average air speed (V_a), mean radiant temperature ($\bar{t}_r$ or *MRT*), and relative humidity (*RH*). These factors should represent average environmental conditions immediately surrounding the representative occupant(s).

The air temperature and speed are averaged based on location and time. These are typically obtained from engineering principles or manufacturer data. The mean radiant temperature is a spatial average of the temperature of surfaces surrounding the occupant. Surface temperatures are obtained using dynamic simulation software. The combination of average air temperature and speed and mean radiant temperature results in the operative temperature (t_o) that accounts for the convective and radiative heat exchanges between the occupant and the environment. The WBC model assumptions are indicated in blue in *Figure 2*; these assumptions are consistent with the conditions under which the WBC model was derived.

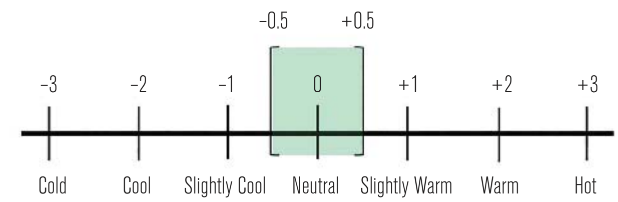
The application of the personal and environmental factors to the WBC model produces a predicted mean vote (PMV) and a predicted percentage of dissatisfied (PPD) occupants. Compliance with Standard 55-2017 requires the following: $-0.5 \leq PMV \leq 0.5$, and $PPD \leq 10\%$. *Figure 3* shows the PMV thermal sensation levels, where the PMV threshold of ±0.5 corresponds to a neutral thermal sensation.

When direct solar irradiation is expected to fall on a representative occupant, the solar SolarCal model adjusts the mean radiant temperature (*MRT*) on the occupant with an equivalent increased mean radiant temperature (ΔMRT), which affects the WBC thermal balance and the PMV comfort vote. Application of the SolarCal model enables addressing direct solar irradiation on occupants through architectural and engineering design, instead of relying entirely on energy-intensive air conditioning.

Under warm conditions, predicted by the PMV thermal sensation, increased air movement can be used to enhance convective cooling of the body to offset high operative temperatures and reduce or even eliminate the need for mechanical cooling. The elevated air speed comfort zone method[9] is based on the SET model.[11] The SET model is used because it combines temperature, humidity and air speed in a single index so two environments with the same SET should evoke the same thermophysiological response even though they have different air speeds. The method enables air speed effects on thermal comfort to be related across a wide range of air temperatures, radiant temperatures and humidity levels. The limits for increased air speed are determined based on results from field surveys, which include air movement preference with and without access to local control, under the assumption that increased levels of occupant control over the air speed leads to increased levels of acceptance of higher air speeds.

Indoor environments can be non-homogeneous and physical quantities (air temperature, air speed, surface temperatures) can vary in a space and fluctuate in time. After the WBC is analyzed, nonuniform spatial and temporal thermal conditions that may cause local discomfort on occupants are addressed, which are local thermal discomfort and air temperature variations with time. Standard 55-2017 provides allowable ranges for the nonuniform conditions discussed in the sidebar, “Nonuniform Conditions.”

FIGURE 3 ASHRAE PMV thermal sensation scale with Standard 55-2017's compliance limits.



Research evidence demonstrates that occupants are more sensitive to temperature fluctuations[18] and local discomfort[19] when their overall thermal sensation is toward the cold side of thermal neutrality, due to a combination of a cooler environment, a lower activity level and/or light clothing. To minimize the risk from cold air draft discomfort, the average room air speed must not exceed 0.15 m/s (30 fpm) if the operative temperature (t_o) is below 22.5°C (72.5°F).[20]

For naturally conditioned buildings, the prediction of thermal comfort using the adaptive thermal comfort (ATC) model requires two environmental factors that are obtained using dynamic simulations: the prevailing mean outdoor temperature, $\bar{t}_{pm\ (out)}$, and the indoor operative temperature (t_o). The prevailing mean outdoor temperature (that represents the outdoor temperature to which occupants have become physiologically, behaviorally, and psychologically adapted while in a naturally ventilated building) is the arithmetic average of the mean daily outdoor temperatures over some period of days.

Unlike the WBC model, the ATC model does not consider personal factors explicitly, because the model correlates occupant comfort directly with operative temperatures and prevailing mean outdoor temperatures. However, from field studies, the model is required to be used within specified thresholds of metabolic rate and clothing insulation. From field studies, the mean air speeds found in naturally conditioned buildings are typically less than or equal to 0.3 m/s (60 fpm).[5,20]

Therefore, the ATC model also uses elevated air speed comfort zone method[9] to account for increased cooling from elevated air speed (for example, using ceiling fans).

A set of software tools can be used to assist in the thermal comfort analysis indicated in *Figure 2*. These can be spreadsheet calculations, generic dynamic simulations and computational fluid dynamics (CFD) software and custom comfort tools implementing the thermal comfort models. Standard 55-2017 provides the ASHRAE Thermal Comfort Tool, which, combined with the online CBE Thermal Comfort Tool (http://comfort.cbe.berkeley.edu/), can be used to study design alternatives for comfort and to verify compliance with Standard 55. The following articles in this series will demonstrate how to use these tools to analyze thermal comfort to assist design decisions for different types of application scenarios.

Conclusions

Thermal comfort analyses allow designers to concentrate on improving the most influential environmental design aspects that will increase the thermal comfort and productivity of the occupants, in alignment with the owners' priorities and requirements. Detailed knowledge and quantification of occupants' comfort perceptions together with their responses to various environmental conditions permit a better planning of low-energy strategies; otherwise, ignoring comfort may lead to uncomfortable occupants that will likely use excessive energy to alleviate discomfort.

Note

These articles represent the views of the authors and does not intend to replace or provide the level of detail and rigor in the Standard 55 User's Manual.[20] The authors hope to provide further insights into the opportunities of conducting thermal comfort analyses by using Standard 55 to support design.

Nonuniform Conditions

Standard 55-2017 provides allowable ranges for these nonuniform conditions.

Spatial Thresholds

Local Discomfort:

- Air drafts: ankle, neck;
- Vertical air temperature difference (thermal stratification): standing, seated;
- Radiant thermal asymmetry: cold/warm wall, cold/warm ceiling; and
- Floor surface temperature.

Temporal Thresholds

Temperature Variations with Time:

- Naturally changing (drifts): amplitude; and
- Mechanical fluctuations (ramps): frequency (minutes, hours, days).

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