A Standard for Natural Ventilation

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Architecture and engineering journals have been increasingly attentive to innovative non-residential buildings designed with operable windows. Such buildings may rely exclusively on natural ventilation for cooling, or may operate as mixed-mode, or "hybrid" buildings that integrate both natural and mechanical cooling. Architects who want to incorporate natural ventilation as an energy-efficient feature need to collaborate closely with mechanical engineers. Unfortunately, engineers often need to veto such natural approaches, citing their professional obligation to adhere to thermal comfort standards such as ASHRAE Standard 55 or ISO 7730. In their current form, these standards establish relatively tight limits on recommended indoor thermal environments, and do not distinguish between what would be considered thermally acceptable in buildings conditioned with natural ventilation vs. air conditioning. In other words, engineers have not had a suitable tool to help decide when and where full HVAC is required in a building, and under what circumstances they can incorporate more energy-conserving strategies without sacrificing comfort.

ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy,* [1] was initially released in 1966. Since then, it has been revised once a decade, incorporating the latest technical advances in our understanding of thermal comfort. Derived from laboratory experiments using a thermal-balance model of the human body, this standard has attempted to provide an objective criterion for thermal comfort — in particular, specifying combinations of personal and environmental factors that will produce interior thermal environments acceptable to at least 80% of a building's occupants. While ASHRAE Standard 55 was originally intended to provide guidelines for centrally controlled HVAC, its broad application in practice is hindering innovative efforts to develop more person-centered strategies for climate control in naturally ventilated or mixed-mode buildings. Such strategies may hold great social and environmental benefits, reducing energy consumption and increasing occupant satisfaction, especially in office buildings.

Based on ASHRAE-funded research, this article argues that adequate scientific basis now exists to amend Standard 55 to include a more "adaptive" field-based alternative for application to naturally ventilated buildings. Such a proposal reflects findings that thermal preference in such buildings varies widely from predictions made by the present laboratory-based standard. The article suggests that one possible reason for this discrepancy may be that the heat-balance model of thermal comfort underlying the present standard cannot account for the complex ways people interact with their environments, modify their behaviors, or gradually adapt their expectations to match their surroundings.

Adaptation in Buildings

Advocates for a more flexible thermal comfort standard have long argued that the primary limitation of Standard 55 is its "one-size-fits-all" approach, where clothing and activity are the only modifications one can make to reflect seasonal differences in occupant requirements. The standard was originally developed through laboratory tests of perceived thermal comfort, with the limited intent to establish optimum HVAC levels for fully climate-controlled buildings. However, in the ab-

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A 1998 article on this topic by Brager and de Dear won the 1998 Crosby Field Award, ASHRAE's highest award for a technical paper.

sence of any credible alternative, Standard 55 is applied universally across *all* building types, climates and populations.

As a consequence, even in relatively mild climatic zones, it is hard to meet the standard's narrow definition of thermal comfort without mechanical systems. Many researchers and designers have argued, for example, that reliance on Standard 55 has allowed important cultural, social and contextual factors to be ignored, leading to an exaggeration of the "need" for air conditioning.[2] Others have argued that allowing people greater control of indoor environments, and allowing temperatures to more closely track patterns in the outdoor climate, could improve levels of occupant satisfaction with indoor environments and reduce energy consumption.[3]

Such issues have particular relevance with regard to naturally ventilated buildings, where occupants are able to open windows, creating indoor conditions that are inherently more variable than buildings with centralized HVAC systems. In such settings, an alternative thermal comfort standard based on field measurements might be able to account for contextual and perceptual factors absent in the laboratory setting. Toward this end, the research began by focusing on three primary modes of adaptation: physiological, behavioral and psychological.

Physiological adaptation, also known as acclimatization, refers to biological responses that result from prolonged exposure to characteristic and relatively extreme thermal conditions. One example in hot climates is a fall in the setpoint body temperature at which sweating is triggered, leading to an increased tolerance for warmer temperatures. Laboratory evidence suggests, however, that such acclimatization does not play a strong role in subjective preferences across the moderate range of activities and thermal conditions present in most buildings.[4]

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Behavioral adaptation refers to any conscious or unconscious action a person might make to alter their body's thermal balance[5]. Examples include changing clothes or activity levels, turning on a fan or heater, or adjusting a diffuser or thermostat. Behavioral adjustments offer the best opportunity for people to participate in maintaining their own thermal comfort. Affording ample opportunities for people to interact with and control the indoor climate is an essential strategy in the design of naturally ventilated buildings.

The psychological dimension of thermal adaptation refers to an altered perception of, and reaction to, physical conditions due to past experience and expectations. It is premised on the generalization, true across all sensory modalities (not just thermal), that repeated exposure to a new stimulus leads to a diminution of the evoked response. It also includes the idea that a person's reaction to a temperature that is less than perfect will depend on expectations and on what that person is doing at the time.[6]

Research Methods

The research described in this article involved assembling a quality-controlled database containing 21,000 sets of raw data compiled from previous thermal comfort field experiments inside 160 different office buildings located on four continents and covering a broad spectrum of climatic zones.[7] The gender and age distribution of the subjects was typical of office building populations. The large sample size reduced the risk of bias that might occur in relatively smaller samples used in climate chamber experiments. The data included a full range of both subjective and physical measurements, including thermal questionnaire responses, clothing and metabolic estimates, concurrent indoor climate measurements, a variety of calculated thermal indices and outdoor meteorological observations. Analysis of data was performed separately for buildings with centralized HVAC systems and naturally ventilated buildings (i.e., where occupants had access to operable windows). The analysis examined thermal comfort responses in terms of both thermal neutrality and preference, as functions of both indoor and outdoor temperatures. Observed responses also were compared to predictions of thermal sensation calculated using the heat-balance-based PMV model.[8] The PMV model is the basis for ISO Standard 7730,[9] and for the next version of Standard 55.

The following sections present select aspects of the research that directly relate to the proposal for an "adaptive" thermal comfort standard to be used as an alternate to PMV for naturally ventilated buildings in the next revision of Standard 55. A more detailed description of the research methods, statistical analysis techniques and results can be found in *ASHRAE Transactions.*[7,10]

HVAC vs. Naturally Ventilated Buildings

To what extent do people behaviorally adapt in the two building types? Behavioral adaptation was analyzed by examining how changes in clothing, metabolic rate and air velocity varied as functions of indoor temperature. Mean metabolic rates in both building types stayed fairly constant at about 1.2 met units regardless of indoor temperature, ranging within a fairly tight cluster of 1.1–1.4 met units. In contrast, changes in clothing and air velocity were both significantly related to changes in mean indoor operative temperatures in all buildings.

Mean clothing insulation values (including the incremental insulation of the chairs) varied seasonally in both building types. Summer vs. winter mean values were 0.70–0.92 clo in the HVAC buildings, compared to 0.66–0.93 in the naturally ventilated buildings. Although the buildings didn't differ significantly in terms of their *mean* clothing values, the total range of clothing worn was much much wider in the naturally ventilated buildings. Occupants of these buildings also demonstrated a stronger relationship between their clothing patterns and indoor temperature, with mean clothing insulation decreasing by an average of 0.1 clo unit for every 2°C (3.6°F) increase in mean indoor temperature.

Air velocity is considered a form of behavioral adaptation when people are able to make the environmental adjustments themselves, such as opening or closing a window, turning on a local fan, or adjusting an air diffuser. Mean air speeds recorded in the HVAC buildings generally were confined to the region below 0.2 m/s (39.4 fpm), as prescribed in Standard 55-1992. In a naturally ventilated building, speeds above this limit were recorded when indoor temperatures extended beyond the upper temperature limit of 26°C (78.8°F) in Standard 55-1992. As will be shown later, however, these forms of behavioral adaptation could account for only part of people's acceptance of higher temperatures in the naturally ventilated buildings.

How do people react as conditions deviate from the optimum? A weighted linear regression model of the relationship between mean thermal sensation (TS) and mean indoor operative temperature (T_{op}) was used to judge how quickly people felt too warm or too cool as temperatures deviated from the optimum:

(Centralized HVAC buildings)

$$TS = 0.51 \times T_{op} - 11.96 \qquad (T_{op} \text{ in } ^\circ C) \qquad (1)$$
$$TS = 0.28 \times T_{op} - 21.03 \qquad (T_{op} \text{ in } ^\circ F)$$

(Naturally ventilated buildings)

$$TS = 0.27 \times T_{op} - 6.65 \qquad (T_{op} \text{ in } ^\circ C) \qquad (2)$$
$$TS = 0.15 \times T_{op} - 11.45 \qquad (T_{op} \text{ in } ^\circ F)$$

In these equations, TS represents a vote on the familiar ASHRAE seven-point thermal sensation scale, where TS=0 is "neutral." This analysis revealed that occupants of centralized HVAC buildings were twice as sensitive to deviations in temperature as were occupants of naturally ventilated buildings. Such a finding suggests that people in air-conditioned buildings have higher expectations for thermal consistency, and quickly become critical if thermal conditions diverge from these expectations. In contrast, people in naturally ventilated buildings seem to demonstrate a preference for a wider range of thermal conditions, perhaps due to their ability to exert control over their environment, or because their expectations match the more variable conditions they are used to experiencing in such buildings.

How does one define a "comfort temperature?" Does everyone always prefer to feel "neutral?" The traditional method of defining a comfortable temperature is to assume that a "neutral thermal sensation" represents ideal conditions, and then to solve a linear regression equation such as those in *Equations 1* and *2* for the "neutral temperature" at which TS=0. However, when surveys include a question about preference (usually expressed as "do you prefer to feel warmer, no change, or cooler?"), one can also calculate a "preferred temperature" in a similar way, assuming that a preference for "no change" represents ideal conditions.

Both types of analyses were conducted in this project, with the result that generally no difference existed in neutral vs. preferred temperatures for occupants of naturally ventilated buildings. However, in the HVAC buildings, the analysis revealed that people preferred slightly warmer-than-neutral temperatures in cold climates, and cooler-than-neutral temperatures in warmer climates (the difference being up to 1°C (1.8°F) at either extreme end). Since we viewed "preference" as being a more appropriate indicator of optimum thermal conditions than the traditional assumption of "neutral thermal sensation," we developed a correction factor to modify calculations of neutral temperatures in HVAC buildings to more accurately reflect preference.

Do indoor comfort temperatures change in relation to outdoor weather and climate? Adaptive theory suggests that the thermal expectations of building occupants, and their subsequent expectations for indoor comfort, will be dependent on outdoor temperature. This relation may vary, however, based on the extent to which the indoor environment is connected to natural seasonal swings in outdoor climate. *Figure 1* shows a regression of indoor comfort temperatures as defined earlier against an outdoor temperature index for centralized HVAC (left graph) and naturally ventilated (right graph) buildings. The outdoor temperature index used was mean effective temperature (ET*). Each graph shows the regressions based on both observed responses in the database and the PMV predictions.

Looking first at observed responses (dotted lines), the gradient for the naturally ventilated buildings was more than twice that found in buildings with centralized HVAC systems. One possible interpretation of this finding is that occupants of the HVAC buildings become more finely adapted to mechanically conditioned, static indoor climates. In comparison, the range in thermal comfort levels in naturally ventilated buildings showed a much larger variation, suggesting that occupants of these buildings preferred conditions that more closely reflected outdoor climate patterns.

How do field-based measurements compare to lab-based predictions, and what does this say about adaptation? The observed and predicted lines within each graph in *Figure 1* provide insight into how adaptation may influence the relationship between indoor comfort and outdoor climate in the two building types. Recall that clothing insulation and air velocity both had a statistical dependence on mean indoor temperatures (and are probably related to outdoor temperature as well). Both are included as inputs to the PMV model. Therefore, one would expect to see that the indoor comfort levels predicted by the PMV model might also show some dependence on outdoor climate. In fact, as seen in *Figure 1,* they do.

In the HVAC buildings (left-hand panel of *Figure 1*), the observed (dotted) and predicted (solid) lines appear very close together, demonstrating that PMV was remarkably successful at predicting comfort temperatures in these buildings. A corollary of this finding is that, in HVAC buildings, behavioral adjustments to clothing and room air speeds fully explain the relationship between indoor comfort temperature and outdoor climatic variation, and that these adaptive behaviors are, in fact, adequately accounted for by the PMV model.

However, the remarkable agreement between PMV and adaptive models in the HVAC buildings clearly breaks down in the context of naturally ventilated buildings (right-hand panel of *Figure 1*), where the observed responses show a gradient almost twice as steep as the PMV model's predicted comfort levels. By logical extension therefore, it appears that behavioral adjustments (clothing and air velocity changes) may account for only half of the climatic dependence of comfort temperatures within naturally ventilated buildings.

What explains the rest? Having accounted for the effects of behavioral adaptations, physiological (acclimatization) and psychological components of adaptation are left to explain the divergence. But, as noted previously, existing literature suggests that acclimatization is unlikely to be a significant factor. This leaves psychological adaptation as the most likely explanation for the difference between field observations and PMV predictions in naturally ventilated buildings. This means the physics governing a body's heat balance must be inadequate to fully explain the relationship between perceived thermal comfort in naturally ventilated buildings and exterior climatic conditions.

An Adaptive Comfort Standard

Using Standard 55 to determine acceptable indoor temperature ranges requires one to know, or at least anticipate, the average metabolic rate and amount of clothing worn by people in a building, regardless of whether that building is already built or occupied. In contrast, an adaptive model relates acceptable indoor temperature ranges to mean monthly outdoor temperature (in this case, defined as the arithmetic average of mean monthly minimum and maximum air temperature). This is a parameter already familiar to engineers and can be found easily by examining readily available climate data, such as that published by the U.S. National Oceanographic and Atmospheric Administration (www.ncdc.noaa.gov). Because the adaptive model is based on extensive field measurements, the relationship between expected clothing and outdoor climate already is built into the empirical statistical relationship.

Although both laboratory and field studies typically collect subjective data in terms of *thermal sensation*, Standard 55 presents temperature limits in terms of *acceptability* (with the goal of achieving 80% acceptability in the field). To create the link between 80% acceptability and measured thermal sensation, we accepted one of the underlying assumptions of Fanger's PMV/PPD indices: namely, that a group mean thermal sensation (PMV) between the limits of ±0.85 corresponds with 20% of the group being dissatisfied (PPD). To apply a more stringent level of acceptability to the adaptive model, or if a building is expected to present greater than normal thermal asymmetries, an acceptability criteria of 90% might be chosen, corresponding to a mean thermal sensation falling within the limits of ±0.5.

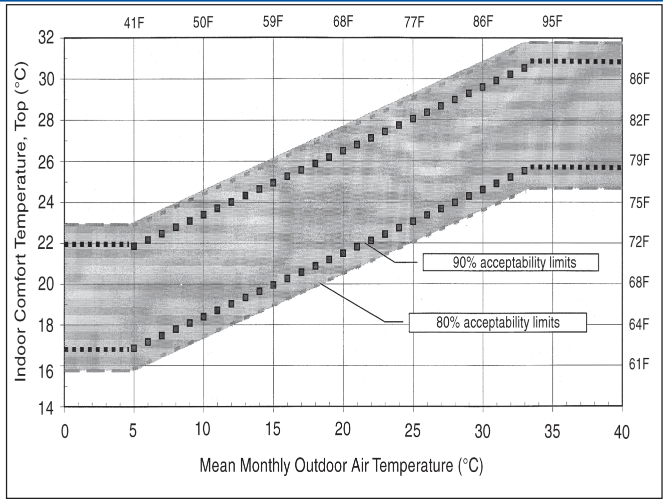

Figure 2: Adaptive standard for naturally ventilated buildings.

For comparison, the 80% acceptability comfort zone in Standard 55 actually is based on a 10% general dissatisfaction criterion for the body as a whole, corresponding to tests performed in the laboratory under uniform conditions. It then allows for an additional average of 10% dissatisfaction that might occur because of local thermal discomfort. Since the adaptive model is based on field measurements, where people are naturally integrating whole body plus local sensations, field votes already account for both sources of discomfort.

A proposed adaptive standard for naturally ventilated buildings is shown in *Figure 2.* To make it easier for engineers to use, the regressions in *Figure 1* (originally using ET*) have been recalculated based on mean monthly outdoor air temperature. At the time this article was written, the exact form and applicability of this proposed revision to Standard 55 were still being discussed. This comfort standard could be applicable to buildings in which occupants control operable windows, and where activity levels are < 1.2 met. As the outdoor temperature extends beyond the outdoor temperature limits included in the RP-884 database, the acceptable indoor temperaure limits could remain constant at the maximum and minimum levels.

To use this standard, engineers simply calculate the average of the mean minimum and maximum air temperatures for a given month, and then use *Figure 2* to determine the acceptable range of indoor operative temperatures for a naturally ventilated building. During the design phase of a building, these numbers could be compared to the output of a thermal simulation model of the proposed building to determine whether the predicted indoor temperatures are likely to be comfortable using natural ventilation, or if air conditioning would be required. The figure also could be used to evaluate the acceptability of thermal conditions in an existing building by comparing the acceptable temperature range obtained from *Figure 2* to indoor temperatures measured in the building.

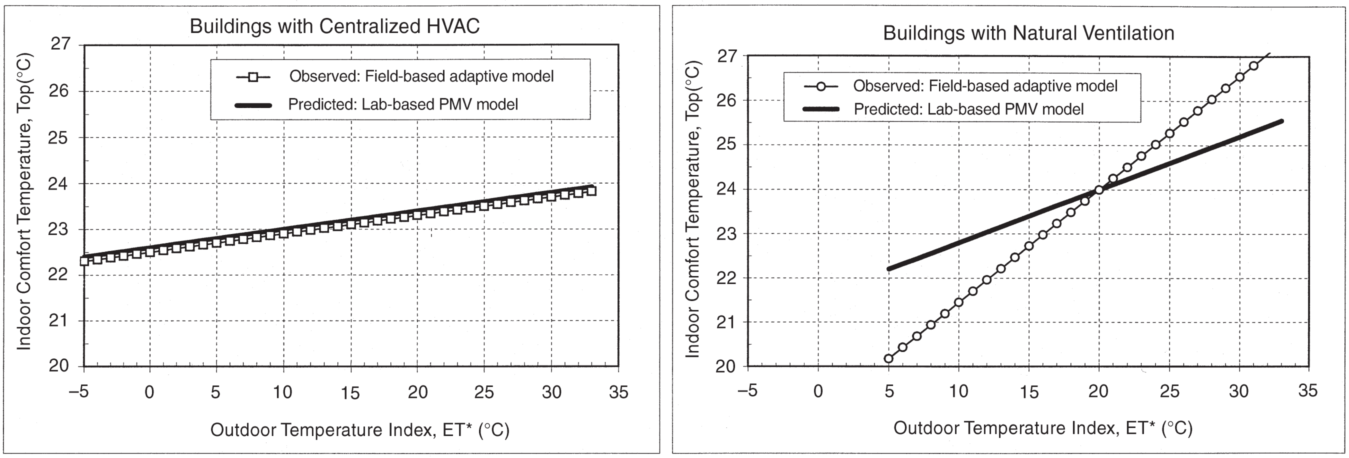

Figure 1: Observed and predicted comfort temperatures.

Conclusions

The research has demonstrated that occupants of buildings with centralized HVAC systems become finely tuned to the very narrow range of indoor temperatures presented by current HVAC practice. They develop high expectations for homogeneity and cool temperatures, and soon became critical if thermal conditions do not match these expectations. In contrast, occupants of naturally ventilated buildings appear tolerant of — and, in fact, prefer — a wider range of temperatures. This range may extend well beyond the comfort zones published in Standard 55-1992, and may more closely reflect the local patterns of outdoor climate change.

Further analysis of research findings established that behavioral adaptations, such as changes in clothing insulation or indoor air speeds, could account for only half the observed variance in thermal preferences of people in naturally ventilated buildings. Since it has been established that physiological adaptation is unlikely to play much of a role in relation to indoor office environments, this suggested the rest of the variance was attributable to psychological factors. Chief among these was a relaxation of thermal expectations, possibly because of a combination of higher levels of perceived control and a greater diversity of thermal experiences in the building.

Such research suggests that accounting for these broader adaptive mechanisms allows mechanical engineers to design and operate buildings in ways that both optimize thermal comfort and reduce energy use. In many climatic settings, the practice of maintaining a narrowly defined, constant range of temperatures in fully air-conditioned buildings is unnecessary, and carries a high-energy cost. Unfortunately, the thermal comfort standards embodied in Standard 55 do not present alternative approaches to building conditioning. One reason is that the heat-balance models, on which the standard is based, were developed in tightly controlled laboratory conditions. In this process, people were considered passive subjects of climate change in artificial settings, and little consideration was given to the broad ways they might naturally adapt to a more wide-ranging thermal environments in realistic settings.

The laboratory context in which Standard 55 was established is similar to that of buildings with fully centralized HVAC systems. A historical connection exists between the two, since the standard originally was intended for application by the HVAC industry to the creation of "artificial climates" in "controlled spaces."[8] Therefore, it is not surprising that this research demonstrated that the PMV model could accurately predict people's patterns of thermal preference in fully air-conditioned buildings. However, the research showed that the PMV model could not predict people's thermal preferences in naturally ventilated buildings. This would seem to indicate the PMV model is an unsuitable guide when deciding whether air conditioning is even necessary in a particular building.

On the strength of this research, we argue that an adaptive model of thermal comfort may usefully augment laboratory-based predictive models in the setting of thermal comfort standards. Furthermore, it appears that such an approach is essential to account for additional contextual factors and individual experiences that appear to modify people's expectations in naturally ventilated buildings. As part of the next round of revisions to Standard 55, adoption of an alternative "adaptive" standard for naturally ventilated buildings may serve as a practical first step towards allowing engineers to adopt a more complex, socially and environmentally responsive approach to evaluating and designing indoor climates. It would reflect growing awareness among researchers that factors beyond the mere passive experience of a body's thermal balance may play a significant role in determining human thermal preferences.

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