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Re-constructing Thermal Comfort

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Abstract

“Thermal comfort” is a, socially- and culturally-determined construct widely used as the design basis of buildings intended for human occupancy. Design for thermal conditions and energy use dominate engineering design to meet consensus and regulatory building design guidelines. While early commentaries by meteorologists focused on human health impacts of thermal conditions, more recently, meteorology has focused attention on thermal comfort requirements and their contribution to increased atmospheric concentrations of greenhouse gases. Global warming concern has stimulated widespread engineering efforts to increase energy efficiency. Examination and refinement of the thermal comfort model is the subject of substantial research activity with conflicting and, at times, inditing results. Responses from mostly non-engineering stakeholders focus on examination of alternatives to the model with its flawed input data, virtual neglect of important factors, and the construct’s implicit assumptions that drive building energy use. Commentators question the construct and the process by which it should be determined or applied. Exploration of the construct and alternatives have important implications for environmental policy as well as human relationships to the buildings we occupy. Application of the standard throughout the world is simply unsustainable. The time has come for re-evaluation of the construct “thermal comfort.”

Keywords: Thermal comfort, construct, occupant control, climate change, sustainability

1 Introduction

“Comfort is a state of mind.” (Rohles, 1988).

In this paper we inquire into the underlying problems associated with the construct of thermal comfort and the thermal comfort model, and we discuss alternatives based on suggestions by Cain. (2002) and Chappells and Shove (2005).

The thermal comfort model used in modern standards and regulations, primarily in “advanced economies” (or industrialized countries) was developed >45 years ago by P. Ole Fanger for use in centrally-controlled environmental control systems (e.g., HVAC) (Fanger, 1970; van Hoof, 2008). Refinements have been made in the data available for use of the model, but many problems still remain.

To be clear, the model and its application have little or no place in the buildings occupied by the vast majority of the Earth’s population and primarily serve the wealthier 15% who live in the advanced, industrialized economies or the wealthier segment of developing economies.

“Rather than figuring out more efficient ways of maintaining 21–23C in the face of global warming, society should be embarking on a much more searching debate about the meaning of comfort and the ways of life associated with it. In this way, it might be possible to exploit existing diversity and variety both in people’s expectations and in the built environment and so avoid a commitment to an unsustainably standardized future.” (Chappells and Shove 2005).

2 The thermal comfort Construct

Thermal comfort is a socially- and culturally defined construct (Cain, 2002; Chappells and Shove, 2005). In spite of its limitations, the “thermal comfort” construct remains the most widely-used and dominant basis for design of and research related to buildings intended for human occupancy. Reducing the construct to an engineering design equation ignores important matters of fact and differences in matters of values while addressing dominant political relationships.

2.1 Re-Examination of the construct

Among the concerns suggested by Chappells and Shove (2005) are the imposition of the model on a global scale through spreading standardization and its associated requirement for air-conditioning as well as the lack of participation by many stakeholders outside the HVAC research and manufacturing industry and their associations.

Adjustments to the model and the input data are partially addressed by establishment of standardized measurement systems, addition of the adaptation version for warmer environments, and additional data on clothing insulation values. Un-addressed or under-addressed are issues related to reliance on lab studies versus field studies; occupant control, changes in metabolic rates in the populations of Europe and North America during the last 55 years (since the referenced 1960s metabolic rate data were derived and published), and the dynamic nature of the indoor environment and occupant activity and human interactions with occupied buildings.

Many of the details of the model’s performance have been studied (van Hoof 2008; Kim et al, 2013; Humphreys and Nicol, 2003; Nakano, 2002; and Parsons, 2003). Issues related to the construct were raised by Cain (2002) and Chappells and Shove (2005). We will try to focus on the implications of the problems and issues in terms of future direction for thermal comfort research and building design/operation.

2.2 Occupant (User) Control

A fundamental and pivotal issue for occupant satisfaction is the question “who decides what for whom?” (Turner, 1972, 1976), ‘The only way to satisfy close to 100% of building occupants is to give occupants control over the microclimate in the spaces they occupy.’ (Stolwijk, 1984). If buildings enabled personal control, there would be no need to refine or re-evaluate the construct of thermal comfort.

In housing, the most important question is always ‘Who Decides What for Whom?’ (Turner, 1972; 1976). Turner showed that the occupants of housing are most satisfied

with their housing to the extent that they control the decisions that are most important to them (Turner, 1972, 1976). Indoor environmental research in office workplaces has shown that a similar effect of control of important decisions is the key to occupant satisfaction (Boerstra, 2013).

User-controlled radiant heaters under the desk, small, desktop variable speed personal fans, and providing more latitude in clothing requirements in offices can enable users to control their own microenvironment with the promise of reaching a dissatisfaction level much closer to 0 % than any possible refinement of the thermal comfort equation, even with "perfect" implementation of the results. There is a large potential for energy saving simply through changes in residential building occupants' behavior without a loss of comfort or well-being. (Dietz et al, 2009).

2.3 Thermal comfort and health

The continuing move to engineered, "thermally comfortable" environments (maintaining a narrow temperature band) has negatively impacted human health by reducing the body's natural ability to respond to environmental challenges. (Marken Lichtenbelt, 2015). Humans' capacity to adapt to their thermal environment is quite large but shrinking among those in carefully managed thermal conditions. "...[A]llowing temperatures to drift may be healthy... and may contribute to a more sustainable built environment." Future thermal comfort models should include Physiology (body composition); individual differences; dynamic indoor environment; optimal comfort, NOT maximal comfort; health; and, other environmental factors (e.g., light/noise)" Marken Lichtenbelt, 2015).

Commentaries written in the 1940s by meteorologists focused on human health impacts of extreme thermal conditions (Brunt 1943, 1945). The human body is an "intricate heat engine, complicated by its possession of a nervous system..." A rise in internal body temperature of ...[5°C] or a drop of ...19°C can be fatal. The body is able to maintain an approximate equilibrium of temperature "...over a wide range of external conditions, and the body's internal temperature will be very nearly the same...when shivering with cold on a winter's day" or when sweating heavily on a summer's day." (Brunt, 1943).

2.4 Responses to Global Warming (Climate change)

Climate plays a new role: global warming focuses our attention on buildings' energy use and contribution to increased atmospheric concentrations of some greenhouse gases (Kingma, 2015; Girman, 2008; Levin, 2008). Concern over global warming stimulates efforts to reduce building energy use by engineering measures to increase energy efficiency (IPCC, 2015; Architecture 2030). Climate-sensitive design is an ancient practice (Olgay, 1963) that is largely neglected today.

An alternative response focuses on examination of the construct's implicit assumptions and its power to drive building energy use. Exploration of the construct and alternatives have important implications for environmental policy as well as humans' relationships to our buildings (Cain, 2002; Chappells and Shove, 2005). Residences and non-residential buildings in the USA and UK consume on the order of one-third of their total energy use for heating and cooling. The fraction of actual building-attributed energy use is even

greater for thermal control when non-building-related energy uses (e.g., kitchen and laundry appliances, televisions, etc.) in buildings are subtracted from the total.

2.5 Sustainability-focused engineering

The model's assumption of mechanically heated and cooled building environmental control is relevant to only a small fraction (ca. $<1/4$) of the Earth's inhabitants. A more widely relevant model will require a change in the reliance on air-conditioning with its installation and operational costs and the consumption of energy necessary for its implementation.

A more universally applicable model for thermal comfort control would rely on only natural (or passive) means of heating and cooling supplemented by centralized systems (where available) based on optimizing the trade-off between reducing the dissatisfied occupants and keeping GHG emissions within a small (e.g., 5%) of the minimum achievable with the best available thermal conditions control technology. High tech solutions implementing evolving sensor technology can be driven by real-time data on thermal conditions within and around a building and by occupant thermal sensation.

2.6 The role and refinement of Thermal Comfort standards

Because ASHRAE Std 55 and ISO 7730 are so widely adopted, (at least in advanced economies), there has been abundant research to try to refine/improve the comfort equation without questioning its alternatives such as passive thermal control - heating and cooling, user control, design responsive to local climate and culture, and healthier indoor environmental conditions. But the overall impact of this research has been to refine the model and reinforce its adoption (van Hoof, 2008) while becoming increasingly irrelevant to a sustainable future. (Chappells and Shove, 2005).

Fixing the PMV equation is a technical matter that has an extremely limited ability to create closer agreement between the PMV or PPD and empirical data gathered in the field. All the attention to uniform measurement instrumentation or to improvements in the data available for modeling in research or design do not address fundamental issues such as local climate, culture, and behavior. PMV is capable of modifications to greatly improve the validity of its predictions. (Humphreys and Nicol, 2002). The fundamental construct of thermal comfort is rarely discussed.

PMV yields predictions that are biased with respect to operative temperature, humidity, air movement, clothing insulation, and metabolic rate, and also with respect to the outdoor temperature. The ranges of the component variables that are consistent with the valid use of PMV are much narrower than those given in ISO 7730 (Humphreys, 2002; Humphreys and Nicol, 2003).

In spite of its enormous impact on building design, the thermal comfort construct and model are used primarily for design and are not enforced by regulatory bodies in completed buildings. Facility managers may use the portions of the standards as guidance for facility operations.

During design, detailed information on building use is not always available. So, designers use "default assumptions" about building use (occupancy, activity, and operational

hours) as well as average weather data in the thermal comfort model. The result is often a design of a highly-engineered, centrally-controlled building for an abstracted occupant and environmental context. Technology is extending the reach of automation and generalized design through automated control of residential thermal environments as part of the so-called “smart house.” Occupants are removed farther from control and awareness of their building’s technical systems. While the designs may be theoretically suitable for the average occupant any place in the world, in reality every occupant and place in the world is unique, and failure to achieve predicted thermal comfort is common.

Is it reasonable to believe that, technically the equation can be 'fixed' to work well everywhere in the world? Or are local climate and human physiological and cultural differences distinct enough to defy universally valid thermal comfort equations unless accurate local factors (climate, expectation, etc.) are introduced into the equation? (Nakano et al, 2002)

Even if the PMV worked well and worked everywhere, do we want to insist that all buildings all over the world have air conditioning? What are the energy and climate implications? Are they "acceptable" or will some of us be "dissatisfied" with the outcome?

3 Thermal comfort model – Why can’t we get it right?

3.1 The ASHRAE PMV model and its PPD output

Guidelines for thermal comfort adopted by ASHRAE (2013) , European Committee for Standardization (CEN), and ISO (2005) are based on the simplified tabular and graphic presentations of the Predicted Mean Vote (PMV model) and associated predicted percent dissatisfied (PPD) equations (Fanger, 1970; ISO, 2003; ASHRAE, 2013). The PPD is calculated from the PMV according to an equation also developed by Fanger (ASHRAE, 2013a, b).

Of the model’s four environmental parameters (temperature, relative humidity, air velocity, and radiant temperature). and two human factors (metabolic rate associated with activity levels and the insulation value of clothing) (ASHRAE 2013a, b; ISO, 2005) only one (temperature) or two (temperature and humidity) of the environmental factors are used to operate buildings. The human factors are often assumed without regard to the actual variations that occur in time and space within and among real buildings and their actual occupants (van Hoof, 2008; Nakano et al, 2002).

The standards set targets for the percentage of occupants “dissatisfied” with their thermal environment. These subjective target values vary among the standards.

“[T]he biggest limitation” to the use of thermal comfort models may be “...the accuracy with which comfort perceptions can be related to the physiological variables simulated in the thermal models.” (Jones, 2002)

Fanger’s equation to calculate PPD from PMV is widely accepted as an essential element of the construct in spite of convincing evidence of its limitations. The ASHRAE

Fundamentals Handbook shows the PMV-PPD relationship as symmetrical around the neutral value of 0 where the lowest number of dissatisfied occupants is approximately 5% based on the PMV translated into PPD. (ASHRAE 2013a).

Humphreys and Nicol (2003) found that responses were asymmetrical on the warmer and colder sides of neutral. (See Figure 1.) The results of their study using the responses in the ASHRAE database of field studies as a single distribution showed the PMV “free from serious bias,” although they found underlying biases in relation to all contributing variables. These biases often combine to produce a substantial bias in PMV. In individual buildings, PMV often “...differs markedly and systematically from the actual mean vote...” in both naturally ventilated and air-conditioned spaces. They concluded that ISO 7730, “in its present form can be seriously misleading when used to estimate thermal comfort in buildings.” The authors examined the biases in each of the variables in the equation at different values of PMV and calculated the effect on PPD of the errors in PMV. A plot of their findings is shown in Figure 1

A weak link in thermal comfort theory is the assignment of set values for satisfaction and dissatisfaction. Votes +2 and higher or -2 and lower are deemed indicative of dissatisfaction although there is little or no scientific basis for this. In fact a comparison of results obtained with the model and results obtained through other research methods shows a disturbing lack of correspondence between the PPD values and other expressions of thermal sensation or satisfaction with the thermal environment (Kim et al 2013) and the need for a more integrative view of the indoor environment. (Humphreys, 2002; deDear and Brager, 2002; van Hoof, 2008). Cultural and climate factors also affect thermal comfort votes (Maiti, 2013; Kim et al, 2013).

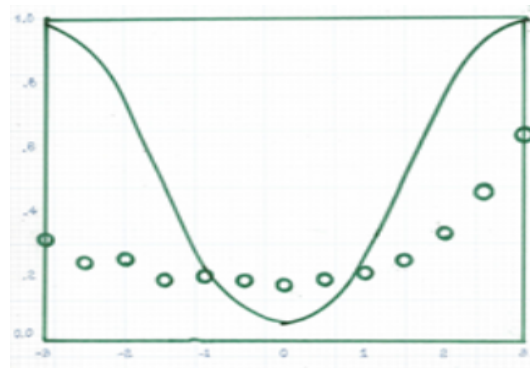


Figure 1 –). Effect of biases in the variables in the thermal comfort equation on the actual percentage of people dissatisfied (APD – open circles) with the thermal environment. Vertical scale is PPD, solid line (based on ISO 7730). Horizontal scale is thermal comfort votes on ASHRAE 7-point scale. (After Humphreys and Nicol, 2003)

There is abundant research testing the accuracy of predictions made with the PMV model that report discrepancies between model predictions and empirical data

collected from building occupants. van Hoof's reviewed the results of thermal comfort model use and documented many of its shortcomings and many common criticisms of it (van Hoof, 2008). One explanation offered is that the model was developed in laboratory settings with primarily student subjects in well-controlled circumstances and standardized clothing and activities whereas the populations occupying "real" buildings in the extensive field studies vary in age, activity, clothing, and thermal comfort preference. An additional explanation is that thermal comfort votes used to calculate the average PMV for a population are influenced by the attitudes of the subjects toward their employer, salary, or co-workers. Others have found a stronger correlation with outdoor temperatures. Finally, some researchers have found problems with the details of the model that are discussed below.

Charles (2003) reviewed the thermal comfort model and concluded that the PMV model...

"...is not always a good predictor of actual thermal sensation, particularly in field study settings. Discrepancies between actual and predicted neutral temperatures reflect the difficulties inherent in obtaining accurate measures of clothing insulation and metabolic rate. In most practical settings, poor estimations of these two variables are likely to reduce the accuracy of PMV predictions."

Some of the controversy reflected in the research associated with the PMV model is related to the model's poor performance in predicting occupant thermal comfort ratings, particularly in building without central thermal control systems ("free-running" or naturally ventilated building) (deDear and Brager, 2002).

3.2 Steady State Assumption

The thermal comfort model is used by engineers with the unrealistic assumption that conditions are at steady state in occupied indoor environments. Building HVAC systems are designed and programmed to be dynamic in their response to typically variable internal loads (usually heat loads, many of which are attributable to the normal ebb and flow of the presence and activities of occupants) and outdoor weather conditions, primarily temperature, wind, insulation, and (often) relative humidity.

Totally neglected in the thermal comfort model is time. The model does not account for changes in the building, the weather, or in occupant activity over time, and these changes can and often do dramatically alter the inputs to the model. Rohles considered time one of the 7 (not 6) factors on which the human response to the thermal environment depends (Rohles, 1981).

3.3 Clothing

Research has focused on reducing the uncertainty of some of the model's parameters, particularly the environmental parameters while the greatest uncertainty tends to be associated with the occupant variables, activity levels and clothing insulation values (van Hoof, 2008). Research results on clothing insulation values have been incorporated into the standard and the supporting handbooks and guidance, but this work largely ignores

issues of clothing fit (looseness), fabric type and density, and the effect on the insulation value of the airspace.

An important aspect of occupant behavior that can neither be controlled nor reliably predicted is clothing. The details of clothing and its interaction with occupant activity (e.g., movement) affect the actual insulation value. The range of clo values associated with any type of clothing and the insulation value of the air gap between layers span such a large range that continually adjusting the values in the standard is unlikely adequately to cover all combinations and variations of the infinitely large number of ensembles, textiles, fit, and activity. By enabling occupants to modify their clothing or local environment modestly, a far larger fraction of occupants are likely to be satisfied with the thermal conditions of their environment.

3.4 Design versus Performance Standards

There is a fundamental difference between design standards and performance specifications as the basis of design. While ASHRAE and ISO thermal comfort standards appear to specify the thermal conditions that must be achieved, the standards' are used only for design - as they are required by regulations and codes in many jurisdictions. The actual control and operation of centrally-controlled buildings is almost universally done on the basis of only dry bulb temperatures, thus ignoring the other three environmental factors: relative humidity, air movement, and radiant temperatures and on the basis of overly simplistic and often incorrect assumptions about the human factors: activity level and clothing insulation values.

In spite of its enormous impact on building design, the thermal comfort construct and model are used primarily for design and are not enforced by regulatory bodies in completed buildings. During design, detailed information on building use is not always available, so, designers use "default assumptions" about building use (occupancy, activity, and operational hours) as well as average weather data in the thermal comfort model. The result is often the design of a highly-engineered, centrally controlled building for an abstracted occupant and environmental context. Technology is extending the reach of automation and generalized design through automated control of both commercial and residential thermal environments as part of the so-called "smart building" Trend, largely a marketing term for equipment manufacturers. Occupants are removed farther from control and awareness of their building's technical systems. While the designs may be theoretically suitable for the average occupant any place in the world, in reality every occupant and place in the world is unique, and failure to achieve predicted thermal comfort is common.

3.5 Model prediction accuracy

Abundant studies of research designed to assess the accuracy of predictions made with the PMV model report discrepancies between model predictions and empirical data collected from building occupants, with much of the literature reporting discrepancies conducted in climates and/or cultures that differ significantly from those of North America and Europe (Maiti, 2013), where the standards based on the PMV model are widely codified into regulations governing the design of buildings (Kim et al, 2013;

Nakano et al, 2002). The model is a design tool and there is limited practical adherence to it in the operation of real buildings where operators adjust system settings to conserve energy or to reduce the level of occupant complaints about thermal conditions.

Figure 16, (in Chapter 9) of 2013 ASHRAE *Fundamentals Handbook* shows the relationship between PMV and PPD as symmetrical around the neutral value (0) where the lowest number of dissatisfied occupants is approximately 5% based on the PMV translated into PPD and at thermal comfort votes of +3 and -3 the PPD is shown as 100% (ASHRAE, 2013a). In Figure 1 (after Humphreys and Nicol, 2003) the PPD is clearly asymmetrical around the zero value (thermal neutrality) possibly reflecting physiological differences (discussed above) and psychological tolerances for the human responses to warmth and coolth.

A comparison of results obtained with the model and results obtained through various other research methods show a disturbing lack of correspondence between the PPD values and other expressions of thermal sensation or satisfaction with the thermal environment. (Humphreys, 2002, Charles, 2003, Humphreys and Hancock, 2007, van Hoof, 2008; Kim et al, 2013;).

In spite of a very large body of literature illustrating substantial deviations between model predictions and actual results from field studies (Charles, 2003), the model continues to dominate the design of buildings through its incorporation in standards that become requirements through regulation. Even if such requirements were not enforced by law and regulation, it is likely that designers would use the model to assist in their design process.

3.6 Activity Levels and Metabolic Rates

The metabolic rates at various activity levels referenced in ASHRAE's Standard 55-2013, in the Normative Appendix Activity Levels. (ASHRAE 2013), are based on research performed in the 1960s (Buskirk, 1960; Passmore, and Durnin. 1967; Webb, 1964) referenced in the ASHRAE *Fundamentals Handbook* (2013a)

3.6.1 Size matters, age matters

Changes in average human body surface area of the American and European populations since the 1960s accompanying the increased individual weight of the general population during the past 45 years results in changes to the metabolic rate at any given activity level. A graph of the U.S. population average body surface area by age and sex is shown in Figure 2. Regional differences within and beyond the U.S. are well-documented. (see Figure 3) Similar changes have been observed in Europe. PMV is strongly determined by metabolic rate used in the calculation. ASHRAE (2013a, b) bases the metabolic rates on a body surface area of 1.8 m². Clearly the body size and surface area and associated metabolic rates have changed since the 1960s due to changes in diet and resulting changes in individual size and weight. Body size and skin surface area also varies by age and sex, as seen in Figure 2. Body surface area and weight are direct determinants of metabolic rate at a given physical activity level.

The default value for body surface area in ASHRAE’s Handbook and Standard 55 is 1.8 m² although it is acknowledged that there is a difference between males and females. Figure 2 shows that adult male body surface area is higher than 1.8 m² and in general, adult female body size is at or below 1.8 m². A proportional change in metabolic rate could improve model performance when evaluated in field settings if values for study subjects are more accurate. Also, metabolic rates must reflect the fact that people commonly move about within a space during the time spent in the space and a single assumed activity level related to the main activity-of the space are generally too low.

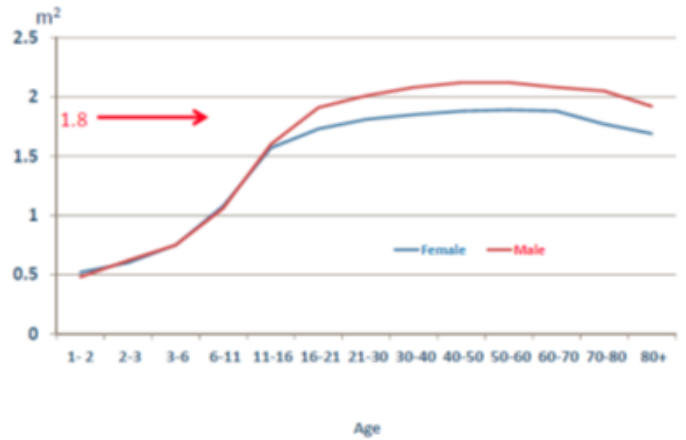


Figure 2. American Male and Female body surface area by age group (based on data in the EPA Exposure Factors Handbook 2011).

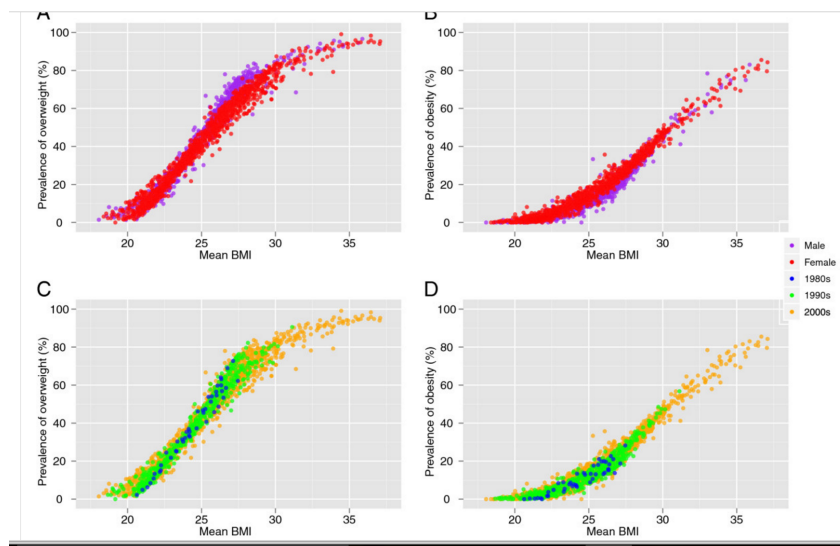


Figure 3. Mean BMI vs. prevalence of overweight (BMI ≥ 25 kg/m²), (A) by gender and (C) by decade; and mean BMI vs. prevalence of obesity (BMI ≥ 30 kg/m²), (B) by gender and (D) by decade. Data are from 243 health examination surveys, by age and sex. (Stevens et al, 2012)

Research supported by the U. S. National Institutes of Health produced metabolic rates associated with a very wide range of activities, (Compendium of Physical Activities,

2016). The values for metabolic rates for a given activity in the Compendium are 10 to 25 % higher than those listed in the ASHRAE *Fundamentals Handbook* Chapter 9, and in Mandatory Appendix A of Standard 55-2013 (ASHRAE, 2013a.).

3.7 Naturally-ventilated buildings

Some of the controversy reflected in the research associated with the PMV model is related to the model's poor performance in predicting occupant thermal comfort ratings in buildings without central thermal control systems (free-running or naturally ventilated buildings in warm conditions. The introduction of the adapted thermal comfort model addresses this problem (Brager and deDear,1998; deDear and Brager, 2002).

3.8 Model Imbalance

The thermal comfort model uses a scale that is symmetrical around the so-called neutral thermal state. However, the human physiological response and individual control options are quite different for environments rated as too warm and too cool. Human physiological responses to the thermal environment are not symmetrical above and below the neutral temperature where the body is neither sweating and vasodilating to shed heat to the environment or shivering and reducing blood circulation to the skin and possibly cutting off circulation to the limbs to conserve heat in cold conditions.

In warm environments (or during strenuous exercise), human physiology provides the sweating response and increased blood flow to the skin to maintain thermally neutral core temperatures. “[S]ecretion and evaporation of sweat is the main factor in the dissipation of heat from the skin.” The evaporation rate increases as wind speed increases and humidity decreases. As wind speed decreases or humidity increases, sweating increases. Thus the body is in a dynamic relationship with its environment. Evaporative losses are larger than convective losses....” (Brunt, 1945).

In the case of extreme heat and extreme cold, the body's “sensors, ”warning systems and response systems are very different Extreme heat and extreme cold a trigger different and not necessarily opposite reactions. Milder heat or cold responses are mediated through changes in blood flow to the skin (vasodilation or vasoconstriction) and sweating.

3.9 Time matters

The ASHRAE Standard includes an equation for calculation of the average activity level during occupancy of a space to account for the distribution of activity levels over time. Typically design is based on assuming an activity level that is characteristic of the use for which the space is intended. It does not account for the fact that people first entering a space are generally at a higher metabolic rate than when at an office workstation, conference room table, or classroom desk. Occupants' previous activities may include walking, exercising, riding a bicycle, eating, etc.

Office workers and students in classrooms do not generally spend the entire time they are present at the lower activity level generally associated with the space. For example, office workers take breaks, to the coffee or refreshment space or to the toilet, walk to

communicate with a co-worker or to make copies or retrieve paper mail or supplies, etc. Thus, the actual metabolic rates characteristic of the office population is likely somewhat higher than that associated with the assumed sedentary activity level of the standard. (Goto, 2002). The actual average metabolic for an individual will depend on their activities in the time period preceding their entering the space of interest and during the time spent in the space. The metabolic rate will normally decline after entering an office or classroom, the average value misses the effect of the transitional time and process (Goto, 2002). Clearly someone who has been exercising or eating immediately before entering the space will be at an elevated metabolic level for some period of time after entering the space. The amount of time it takes to shift from the previous met level to the one characteristic of the activity level in the space may be a small (<0.1) or large (>0.4) fraction of the time spent in the space. The larger the ratio of the two met levels, the more important its impact on an individual's average met level while in the space.

3.10 Adjustment and improvement of the model

Research has focused on reducing the uncertainty of some of the model's parameters, particularly the environmental parameters, while the greatest uncertainty tends to be associated with the occupant variables, activity levels and clothing insulation values (van Hoof, 2008). van Hoof found deviations from the expected calculation of PPD based on PMV were large in the ASHRAE database of thermal comfort field studies (2008). One can try to adjust the variables and make other refinements to the model to account for the discrepancies found by many of the researchers reviewed in Charles (2003), and in van Hoof (2008), and Kim and deDear (2013), and summarized in Kim and deDear in their Table 1.

3.11 Interactions with air quality

The combination of indoor air quality (IAQ) and thermal conditions strongly affect the perceptions of occupants, according to Humphreys and Nicol (2003). They reported that "The physical variables that seemed likely directly to affect the perception of air quality were air temperature, relative humidity, and air movement." Thus, three of the four physical environmental factors in the PMV equation are important to the perception of IAQ. Since ASHRAE Standard 62.1-2013, Ventilation for Acceptable Indoor Air Quality (2013c), defines thermal conditions as being out of the scope of the standard, and Standard 55-2013 (2013b) defines indoor air quality as being out of the scope of the thermal comfort standard, these two standards intentionally ignore an important interaction that affects overall satisfaction of building occupants.

Zhang et al found perceived air quality closely correlated with thermal comfort in the range of temperatures from 18 to 30 °C. (Zhang et al, 2013)

4 Discussion of the construct of (thermal) comfort

A focus on the construct itself is rare within the vast literature on thermal comfort. But the choice between two definitions makes a large difference for energy and environmental policy: . "[O]ne that comfort is a universally definable state of affairs, the other that it is a socio-cultural achievement." (Chappells and Shove, 2005).

Cain (2002) discussed the construct of Comfort in his Plenary Lecture at Indoor Air 2002 and suggested how the conversation about thermal comfort could be improved with a more thoughtful construct. Cain made a case for reconsideration of the construct "comfort" and provides some criteria for the development of a more robust guideline or standard for use by building designers.

According to Cain, we must consider the following with respect to the thermal comfort construct:

- “1) Comfort is a construct that exists in our thinking and cannot be measured directly.
- 2) Assessment of a construct requires more than one expression (outcome variable) for valid measurement.
- 3) A model of a phenomenon, such as comfort, may productively view and assess interaction between constructs.
- 4) Thinking about the interaction and manifestation of constructs encourages development of hypotheses, the engines of scientific progress.
- 5) There exists statistical methodology to test models of relations between constructs.
- 6) The new models can move research beyond the intuitive model of comfort.” (Cain, 2002).

“Thermal comfort” drives design, construction and operation of modern buildings in industrialized economies. Because of the very large fraction of total building energy consumption attributable to thermal conditioning, the standards for thermal comfort are primary drivers of design and, therefore construction. Beyond that, they provide the basis for operations in terms of available options to the occupant and operator/facility manager. The construct depends strongly on subjective responses to the thermal environment based on human physiology and individual physical, psychological, and perceptual responses to the indoor environment. The focus during building design is on meeting the requirements of codes, standards and guidelines for thermal comfort and energy consumption. An important question is whether there will be continued imposition of the model on more and more geographical regions and an accompanying increase in the use of centrally-controlled mechanical systems with air conditioning. The environmental consequences of such a trend are of substantial concern. (Cain, 2002; Chappells and Shove, 2005).

The construct itself is viewed differently by different groups or stakeholders (Chappells and Shove, 2005).

Human physiology is not oriented toward maintaining thermal comfort but is oriented toward maintaining the core body temperature within a fairly narrow range of the normal temperature at basal metabolic rates. There is an imbalance in the model which is based on the 7-point subjective rating scale that is symmetrical on the high and low sides to represent thermal condition satisfaction on the warm and cool sides of “neutral.”

The foundation for the construct is poorly defined (vague?) and badly out-of-date. The construct’s underlying implicit and explicit assumptions are not supported by the

available data and are not relevant for most of the Earth's population. The standards and technologies used to implement the delivery of thermal comfort in buildings ignore the complexity of the human response (*e.g.*, user control and passive means for control and natural ventilation are not given their appropriate place in the construct or its manifestations as standards and guidelines). The dominant design solutions in buildings in industrialized economies and the standards that constrain them ignore the unsustainability of the relevant standards, codes, and practices .typical designs are not meeting the requirements within the resource limitations of planetary boundaries.

Step by step, the mechanism of human thermal adaptation has been discovered to include psychological adaptation, physiological adaptation, and physical factors. Anticipated control (or perceived control) plays an important role in psychological adaptation. Beyond the outdoor climate, long-term indoor thermal experience is a crucial factor for physiological adaptation as well. (Zhu et al 2016.)

4.1 Standards vs design

Humphreys and Nicol (2003) examined the use of "...ISO 7730 (predicted mean vote) to predict the thermal sensations of people in buildings." They used the ASHRAE database of field studies to examine the accuracy of predictions based on the PMV model used in ISO7730 and ASHRAE Standard 55-2013. They found that there are "...underlying biases in relation to all contributing variables, and a further bias related to outdoor temperature. These biases often combine to produce a substantial bias in PMV. In surveys of individual buildings, PMV often differs markedly and systematically from the actual mean vote, both for naturally ventilated and for air-conditioned (AC) spaces. "

"The direction of the overall bias in PMV is such as to overestimate (by a factor not much short of two) the main subjective warmth of groups of people in warm environments. This has practical consequences for the operation of buildings, and can lead to the provision of unnecessary cooling." (Brager and deDear, 1998) "It also affects design decisions, because thermal simulations at the design stage might indicate, mistakenly, that a building would need cooling to maintain comfortable indoor conditions in summer" (Humphreys and Nicol, 2002, 683)

4.2 The role of stakeholders

Chappells and Shove (2005) pointed out that the construct has been developed by a very limited segment of the stakeholders, and that it should be re-examined by a broader group including architects, developers, building occupants, and regulators as well as representative of the affected industries, researchers, and engineers.

5 Conclusions

Is it time to re-evaluate the construct (with all the stakeholders) which implies that we know what thermal comfort is -- for everyone and everywhere?

What are the alternatives to the Thermal Comfort construct? Consider the following:

- Adoption of a model for thermal comfort control by centralized systems that enables a trade-off between reducing the dissatisfied occupants and keeping

GHG emissions within a small percentage (e.g., 5%) of the minimum achievable with the best available thermal conditions control technology.

- Requiring maximum use of passive thermal conditions control prior to the use of energy from combustion or nuclear power. This could involve natural ventilation for cooling, passive solar heating, maximum use of economizer cycle ventilation system design and control, and maximum freedom for occupants to choose their clothing for personal comfort.

Some scholars have built their careers on analysis based on the thermal comfort model. One is led to ask: why does the scholarly community resist challenging the model and accepting that it might be the time to shift from efforts to refine the model and that it may be time to develop a new model?

PMV can be seriously misleading when used to predict the mean comfort votes of groups of people in everyday conditions in buildings, particularly in warm environments. The revision of ISO 7730 should note the limitations of PMV for use in buildings, and give a range of applicability in line with the empirical findings.

The biases in PMV affect PPD which can be very misleading when used to predict the extent of thermal dissatisfaction among people in everyday conditions in buildings. Although PMV is capable of modifications to greatly improve the validity of its predictions..." (Humphreys and Nicol 2002), an engineering approach is unlikely to eliminate all inaccuracies and is not sustainable from a global perspective.

Designers cannot control occupant behavior which produces large uncertainty in the model. Behavior can overwhelm the indoor factor measurements or estimates in their impact on the PMV and PPD. By enabling occupants to make small adjustments in their environment, the unpredictability can be removed as an obstacle to a higher fraction of satisfied occupants. Occupant behavior must be fully incorporated in any revision of the existing model or development of a new thermal comfort model.

Larger societal and environmental concerns suggest that alternatives to the standardization of thermal comfort should be seriously considered. The future of indoor environmental quality and thermal comfort may rely more heavily on the occupant to control the environment to reduce thermal discomfort and to improve occupant satisfaction.

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