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Thermal comfort: research and practice

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1. ABSTRACT

Thermal comfort -the state of mind, which expresses satisfaction with the thermal environment- is an important aspect of the building design process as modern man spends most of the day indoors. This paper reviews the developments in indoor thermal comfort research and practice since the second half of the 1990s, and groups these developments around two main themes; (i) thermal comfort models and standards, and (ii) advances in computerization. Within the first theme, the PMV-model (Predicted Mean Vote), created by Fanger in the late 1960s is discussed in the light of the emergence of models of adaptive thermal comfort. The adaptive models are based on adaptive opportunities of occupants and are related to options of personal control of the indoor climate and psychology and performance. Both models have been considered in the latest round of thermal comfort standard revisions. The second theme focuses on the ever increasing role played by computerization in thermal comfort research and practice, including sophisticated multi-segmental modeling and building performance simulation, transient thermal conditions and interactions, thermal manikins.

2. INTRODUCTION

Thermal comfort is an important aspect of the building design process as modern man spends most of the day indoors. Thermal comfort is defined as 'the state of mind, which expresses satisfaction with the thermal environment' (1); a definition quickly comprehended, but hard to capture in physical parameters. There exist extensive modeling and standardization for thermal comfort, which depend both on physical and physiological parameters, as well as on psychology. The thermal environment itself can be described as the characteristics of the environment that affect the heat exchange between the human body and the environment. Thermal comfort research and practice is not a static field, in contrary, ever since the emergence of air-conditioning in the built environment the field has expanded. One of the highlights in research was the development of the PMV-model (Predicted Mean Vote) by Fanger in the late 1960s (2), which is used for evaluating indoor thermal comfort and forms the basis of present day thermal comfort standards. Other indices used are Gagge *et al.*'s (3) New Effective Temperature (ET*) and Standard New Effective

Temperature (SET*), as well as operative temperature.

Thermal comfort is a very interdisciplinary field of study, as it involves many aspects of various scientific fields: building sciences, physiology, and psychology, to name a few. This adds up to the complexity of the matter. Advances in computer technology have led to an increased and improved ability to evaluate and model complex physical and physiological conditions. This not only meant it became easier to solve the non-linear equations the PMV-model is based on, but also to carry out complex building performance simulations of buildings that were in their design phase in order to predict the comfort of future occupants.

This paper deals with developments in indoor thermal comfort research and practice since the second half of the 1990s, and groups these developments around two main themes; (i) thermal comfort models and standards, and (ii) advances in computerization.

Within the first theme, the most commonly used thermal comfort index, Predicted Mean Vote, and the underlying PMV-model, are discussed in the light of the emergence of models of adaptive thermal comfort. The PMV-model, which is the best known heat balance model, is often referred to as being a static model. The term 'constancy hypothesis' is also used in relation to heat balance models. Even though the application range of SET* is much wider than that of PMV (4), and despite its widespread use particularly in the United States, SET* is not treated further in this review. For a critical discussion on ET* and SET* see Michida and Sakoi (4). A second hypothesis that is gaining popularity in terms of practical applicability, occupant satisfaction and from an environmental perspective is the adaptive hypothesis, in which the perception of thermal comfort is related to outdoor weather conditions. The adaptive hypothesis has led to a number of closely-resembling models that have been considered for inclusion in the latest round of thermal comfort standard revisions. The adaptive models are based on adaptive opportunities of occupants and are related to the availability of options of personal control of the indoor climate as well as psychology and performance. This paper provides an overview of the basis of the two types of models, discusses their strengths and weaknesses, and shows how the two models are included in the main thermal comfort standards. The mean focus of this paper is on office work and office environments. Thermal comfort research of course is not limited to office environments alone. Some of the non-office environments studied include residential buildings (5-7), homes of older people (8,9), transportation including commercial airlines (10), places of worship (11,12), military field settings (13), health care settings (14) and (patient recording in) emergency rooms (15), including those with special needs as people with multiple sclerosis and persons with a disablement (16,17), schools (18-20), sleep environments (13,21), transitional spaces (22,23), and outdoor locations, for instance, in outdoor pedestrian zones and parks. As current comfort standards do not deal with outdoor thermal comfort (24), outdoor thermal comfort is not treated in this paper. Also, we briefly address the psychological and semantic aspects of thermal comfort, and the impact good indoor environments have on productivity and task performance in office settings. The need for thermostats and options for personal control of the thermal environment is clarified, also in relation to the adaptive models of thermal comfort.

The second theme focuses on the ever increasing role played by computerization in thermal comfort research and practice. The availability of improved building performance simulation tools and modeling using computers and sophisticated multi-segmental models of human physiology, and improved thermal manikins have their distinct impact in the field. Advances in computerization are linked to the development of alternative higher resolution thermal indicators that apply sophisticated thermophysiological models (25). Enhanced computer tools link thermal comfort needs to energy use, and help designers and engineers to create ideal environments for occupants. Such optimal environments do not only guarantee comfort but also contribute to work performance and productivity. Innovations in the field of thermal manikins find their way in a wide range of settings, and enable researchers to accurately study simulated human responses to the thermal environment without the use of actual subjects.

3. THERMAL COMFORT MODELS

3.1. The PMV-model

3.1.1. The model and its application

The PMV-model by Fanger is a predictive model for general, or whole-body, thermal comfort. The model was derived during the second half of the 1960s from laboratory studies and climate chamber research. With his work, Fanger wanted to present a method for use by heating and air-conditioning engineers to predict, for any type of activity and clothing, all those combinations of the thermal factors in the environment for which the largest possible percentage of a given group of people experience thermal comfort (26). The PMV-model is often referred to as a static or constancy model due to its construct. The human body produces heat, exchanges heat with the environment, and loses heat by diffusion and evaporation of body fluids. The body's temperature control system tries to maintain an average core body temperature of approximately 37 °C even when thermal disturbances occur. According to Fanger, the human body should meet a number of conditions (2). These requirements for steady-state thermal comfort are: (i) the body is in heat balance, (ii) mean skin temperature and sweat rate, influencing the heat balance, are within certain limits, and (iii) no local discomfort exists.

Fanger defined PMV as the index that predicts, or represents, the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environmental variables, activity and clothing levels (2). The PMV-model includes all the major variables influencing thermal sensation and quantifies the absolute and relative impact of six factors of which air temperature, mean radiant temperature, air

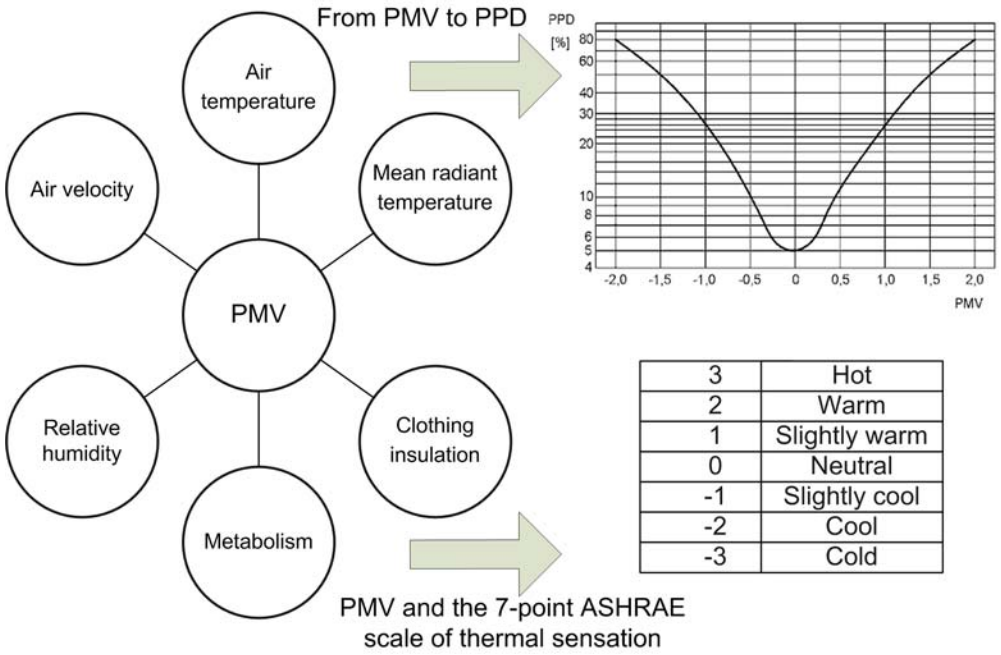

Figure 1. PMV, its input parameters, its relation to PPD, and its expression on the ASHRAE 7-point scale of thermal sensation.

velocity and relative humidity are measured, and activity level and clothing insulation are estimated with the use of tables (Figure 1). Activity level is measured in terms of metabolic rate, or met units, and clothing insulation in clo units (27). The PMV-model is often referred to as a static model, as it is based on a steady-state energy balance. It can not predict the exact response to a step change. However, the PMV-model is not as static as is often suggested, as one can use different parameters as input for the model, i.e., different values of activity level and clothing insulation. This however may have consequences to the reliability of the overall assessment of comfort.

The PMV-model is based on Fanger's comfort equation. The satisfaction of this equation is a condition for optimal thermal comfort of a large group of people. PMV predicts the mean thermal sensation vote for a large group of persons and indicates the deviation from presumed 'optimal' thermal comfort or thermoneutrality. Results of the model are expressed on the 7-point ASHRAE scale of thermal sensation (Figure 1). The central three categories of this scale are labeled 'slightly cool', 'neutral', and 'slightly warm', which match an acceptable sensation. Based on PMV, the Predicted Percentage of Dissatisfied (PPD) can be determined (Figure 1).

Fanger derived his comfort equation for use within temperate climate zones. Although this equation may probably be applied in the tropics as well, Fanger stated such application needed further investigation (2). The PMV-model has been applied for almost 40 years throughout all building types all over the world, even though the model was intended for application by the HVAC (heating, ventilation, and air conditioning) industry in the creation of artificial climates in controlled spaces (2,28). According to international standards, PMV should be kept 0 with a tolerance of ±0.5 scale units in order to ensure a comfortable indoor environment (29).

3.1.2. Validity of the model

Since the introduction of the PMV-model, numerous studies on thermal comfort in both real life situations and in climate chambers have been conducted. Many of these studies proved the strength of the PMV-model, while others led to criticism to the model as a whole, its geographical application range, application in various types of buildings, and the model's input parameters (30). According to some of the studies reviewed by van Hoof, the PMV-model provides just a first approximation to the prediction of thermal comfort in 'natural' settings, the three middle categories of the ASHRAE 7-point scale of thermal sensation seem to be not entirely valid, and the PMV-model cannot properly deal with great between-individual differences in optimal thermal conditions (30). At the same time, there are many studies that confirm the validity of PMV for air-conditioned offices. Recently, a validation study by Tse *et al.* found that PMV accurately represented the average thermal sensation of occupants of air-conditioned offices, and that it was not affected by other human factors as body mass and health status (31). Also, Nasrollahi *et al.* have drawn the conclusion that PMV is valid index for use in Iranian air-conditioned buildings (32). Humphreys and Nicol conducted secondary analyses on existing databases containing world-wide thermal sensation data in order to evaluate the overall accuracy of PMV (33). Through the calculation of PMV for each particular occasion, Humphreys and Nicol subtracted the corresponding actual comfort vote from it. This process yielded 16,762 usable individual discrepancies, each of which was an unbiased

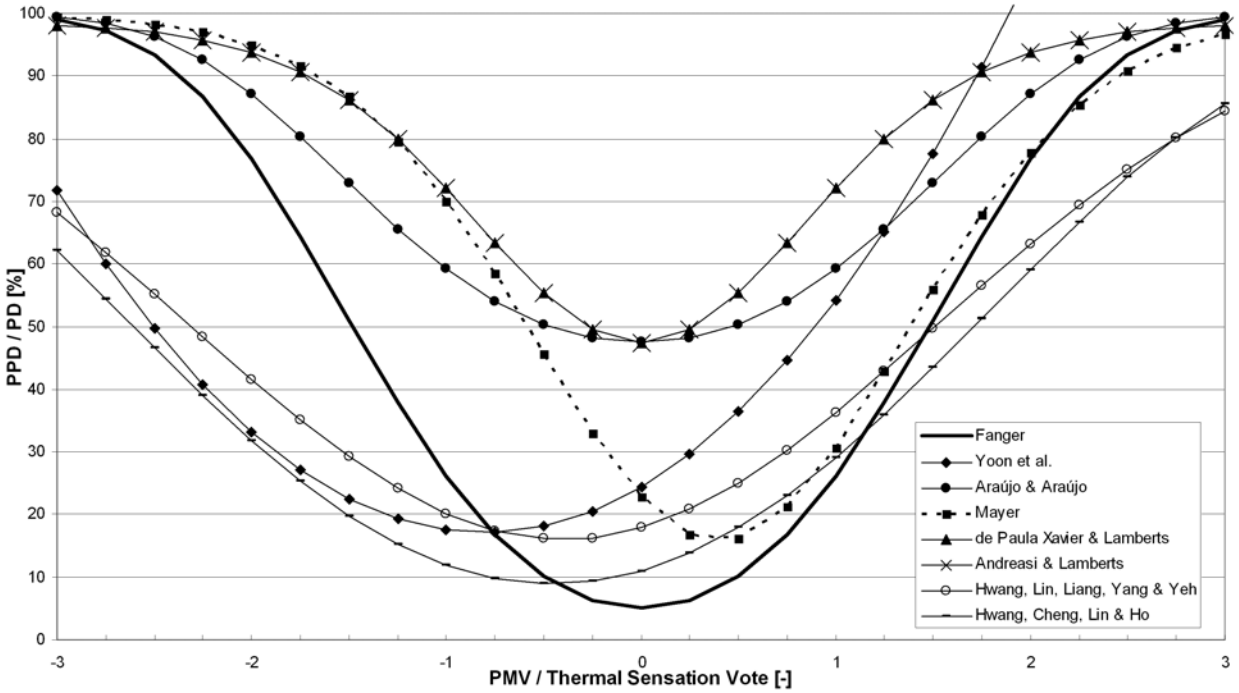

Figure 2. Relation between PMV and PPD, and other thermal sensation indices, as found by Fanger (2), Yoon *et al.* (35), Araújo and Araújo (36), Mayer (37), de Paula Xavier and Lamberts (38), Andreasi and Lamberts (39), and Hwang *et al.* (40,41). There is an overlap between the studies from Brazil (38,39).

but low precision estimate of the true discrepancy between PMV and the actual vote (33). All 16,762 discrepancies were pooled into a single distribution, which was closely normal, had a mean value of 0.11 scale units, and a standard deviation of 1.22 scale units. According to secondary analysis, the mean discrepancy indicated that the calculated value of PMV, for the data as a whole, is higher than the actual ASHRAE vote by 0.11±0.01 scale units. This bias was qualified by Humphreys and Nicol as being 'not large'. The analysis of results from the various buildings, climates, and seasons across the world showed that PMV is free from serious bias (33). When the separate database samples were analyzed in terms of predictive accuracy of PMV by file, 33 out of a total of 41 samples showed evidence of bias in PMV. For 31 of the 41 groups the mean discrepancy exceeded ±0.25 scale units, for 13 files it exceeded ±0.5 scale units, and for 5 it even exceeded ±1 scale unit. Humphreys and Nicol found that the more thermal conditions moved away from neutral, the larger the bias was (33). They concluded that PMV is only reliable between -0.5 and 0.5 scale units (i.e., the comfort zones stated in ISO 7730 (29)), which has severe implications for the use of the PMV-model in field settings.

Mochida and Sakoi have discussed the PMV-model by addressing the equation of evaporative heat loss from the skin surface, the equation of respiratory heat loss, the thermal load, and the model's application and use (34). They conclude that "in environments other than when PMV=0 and thermal equilibrium is achieved in a neutral physiological condition, PMV is closer to being an experimental index than to being a theoretical index based on thermal equilibrium. It can be said that [a range of conditions with still air, 0.6 clo] is the only range of application of PMV that is supported by experimental evidence."

Researchers have compared the outcomes of the PMV-model to the actual thermal sensation votes of subjects (actual mean vote, AMV). Differences were as much as 1.3 ASHRAE-scale units for climate chamber studies (30). Other studies have investigated the relation between PMV and PPD or Actual Percentage of Dissatisfied, for instance, Humphreys and Nicol (33), and have found a different relation than the one described by Fanger (2) (Figure 2). Even though some of these studies were carried out with a small number of subjects, they do indicate that the PMV-model should be applied with caution, since errors may occur when using this large-group model for small samples. Also, the data in Figure 2 were collected in East-Asia (35,40,41), South-America (36,38,39), and Germany (37), in both naturally ventilated buildings and climate chamber settings. Another issue that is being raised is whether the relation between PMV and PPD is entirely symmetric, both on the cooler and the warmer side (Figure 2). Also, Becker and Paciuk found that the symmetry of PPD around the optimum of thermoneutrality was not valid for residential buildings (42). Particularly on the warmer side, less people were dissatisfied than based on the PMV-PPD relation. It should be noted that the scatter (Figure 2) is very large, which may be due to the variability among different investigated

populations and/or the small size of samples. Also, Fanger's curve may probably be somewhat too steep, possibly reflecting problems in the definition of dissatisfied subjects.

Despite all the studies confirming the validity of the PMV-model, field studies have given momentum to discussions on the validity and reliability of the model for use in real world settings and on the global application of the PMV-model in all types of buildings.

3.1.3. Semantics and thermoneutrality as an ideal

According to the PMV-model, the optimal (most comfortable) thermal sensation is neutral. Apart from thermal sensations, there are other measures related to the perception of the thermal environment, including thermal satisfaction, thermal acceptability, thermal comfort, and thermal preference. These measures also indicate the appropriateness of a given thermal condition. Direct measures of thermal satisfaction and acceptability are not incorporated in the current PMV-model.

Researchers recognize the important role semantics and linguistics play in weather and (indoor) climate perception (43-46), as latent dimensions may exist that underlie people's use of adjectives, as well as systematic variations between different language groups and populations, and perhaps between different language writing systems. Pitts also found that conditions of thermal neutrality and comfort are significantly different for English-language respondents than for other language groups in his study (43). Consider this in combination with the fact that English is the lingua franca in science.

Humphreys and Hancock concluded that thermoneutrality does not necessarily correspond to the desired or preferred thermal sensation (47). For instance, when it is very warm outside, people prefer somewhat cool conditions over thermoneutrality or slightly warm. When it is very cold outside, people prefer slightly warm conditions. Thermoneutrality is thus not always the ideal. Butala and Muhič found that in a neutral thermal situation in air-conditioned buildings only a quarter of subjective evaluations indicated that people felt neutral too (48). This too was a reconfirmation of earlier statements made by Fountain *et al.*, who stated that the thermal sensation cannot be assumed to be the equivalent of the aforementioned evaluative measures, and that the PMV-model requires critical interpretation and application (49). These statements were supported by numerous field and climate chamber studies, which showed differences between both neutral and preferred temperatures, as well as differences between field and climate chamber research. These differences can be as large as 3 K. Overviews of such studies are given by van Hoof (30), Daghigh *et al.* (50), and Brager and de Dear (51). The studies mentioned above show that thermal neutrality is not always the ideal situation for occupants, as some prefer non-neutral thermal sensations (for instance, somewhat warm, slightly cool). These sensations may even be distributed asymmetrically around thermal neutrality (which may be related to findings shown in Figure 2), and may be affected by season. Furthermore, thermal sensations outside of the three central categories of the ASHRAE 7-point scale of thermal sensation do not necessarily reflect discomfort for a substantial number of persons. Von Grabe and Winter showed that people who are voting -2 and +2 on the ASHRAE 7-point scale of thermal sensation or beyond are not necessarily dissatisfied (52). Also, people who are voting between -1 and 1 are not necessarily satisfied with their thermal environment either (52).

3.1.4. Application in non-air conditioned buildings and extensions

As mentioned before, the PMV-model is applied throughout the world in all types of buildings. However, the model was developed from laboratory studies, and the effects of building type were not considered and neither were the influences of environmental psychology. Thermal comfort is the summation of not only technological and physiological aspects, but also social and psychological conditions. In a review study by Brager and de Dear of field studies in air-conditioned and naturally ventilated buildings, it was found that the observed and predicted neutral temperatures were overestimated by as much as 2.1 K, and underestimated by up to 3.4 K (51). Both these extremes were found for naturally ventilated buildings. According to de Dear and Brager, the PMV-model is not applicable to naturally ventilated buildings, because the model only partly accounts for thermal adaptation to the indoor environment (53). These research advances have led to the development of adaptive thermal comfort models, which are described in the section 3.2.

Despite all criticism, the PMV-model has many strengths. These strengths have led to the proposal of numerous modifications of the original model, though none of these developments have yet found wide-spread application in environmental engineering practice (30). One interesting extension of the PMV-model was proposed by Fanger and Toftum, which is an extension to free-running buildings in warm climates by incorporating expectation into the evaluation of thermal comfort, and by reducing the activity level in warm contexts (54). The PMV-model is actually a kind of adaptive model too since it accounts for behavioral adjustments and fully explains adaptation occurring in air-conditioned buildings (28). The new extension acknowledges the importance of expectations accounted for by the adaptive model, while at the same time not abandoning the current PMV-model's input parameters that impact the heat balance. Humphreys *et al.* conclude that the more complex the index (PMV, ET*, SET*), the lower the correlation with subjective warmth, suggesting that increasing the completeness of the index may actually introduce more error than it removes (55, cited in 45). A similar effort to combine the PMV-model and adaptive approaches was made by Yao *et al.* for the Chinese context (56).

3.2. Adaptive thermal comfort and personal control

3.2.1. Adaptation and thermal comfort

As stated before, our body maintains thermal equilibrium with the environment through a range of autonomous physiological thermoregulatory actions. Apart

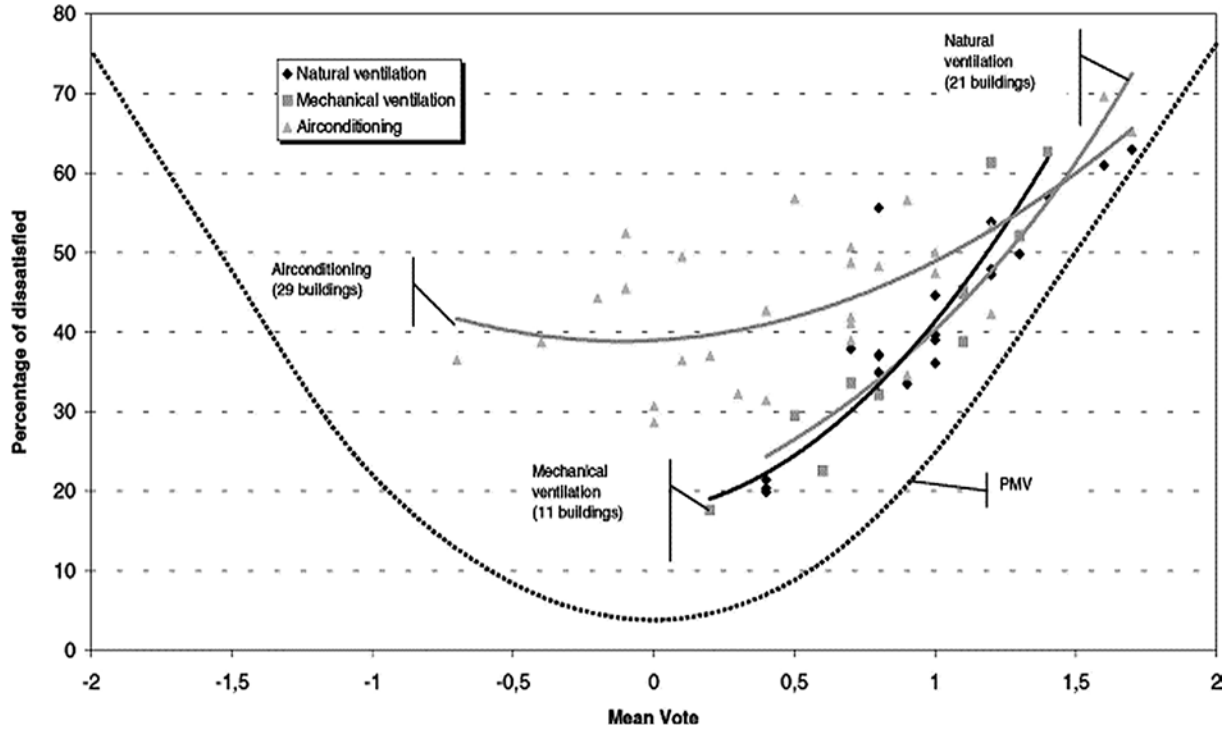

Figure 3. Relation between PMV and PPD in summer for air conditioned buildings (n=29), and buildings with natural (n=21) or mechanical (n=11) ventilation in the Netherlands (62).

from these actions, people have a wide range of strategies to adapt to indoor and outdoor thermal conditions. The hypothesis of adaptive thermal comfort predicts that contextual factors and past thermal history modify the occupant's thermal expectations and preferences (57). People in warm climate zones would prefer higher indoor temperatures than people living in cold climate zones, which is in contrast to the assumptions underlying comfort standards based on the PMV-model (57). Adaptation is defined as the gradual lessening of the human response to repeated environmental stimulation, and can be both behavioral (clothing, windows, ventilators), physiological (acclimatization) as well as psychological (expectation) (28,53,57).

In practice, differences in the perception of the thermal environment were found among occupants of naturally ventilated (also referred to as free-running), fully air-conditioned and mixed mode (hybrid) buildings (57). It was found that for naturally ventilated buildings the indoor temperature regarded as most comfortable increased significantly in warmer climatic contexts, and decreased in colder climate zones (58). This is reflected by numerous studies reviewed by van Hoof (30), including studies from the UK (59), Libya (60), Pakistan (61), the Netherlands (62) (Figure 3), Iran (63), Italy (64,65) and Thailand (66). These studies showed that the neutral temperature observed in air-conditioned buildings differs from that observed in naturally ventilated buildings in the same climatic context. De Dear *et al.* showed that occupants of fully air-conditioned buildings are twice as sensitive to changes in temperature as occupants of naturally conditioned buildings (56). Occupants of air-conditioned buildings tend to adapt less, and this makes their thermal sensation more sensitive to changes in temperature. They become finely tuned to the narrow range of comfort temperatures and develop high expectations for homogeneous, cool environments.

Wilhite describes such environments as 'comfort capsules', and air conditioning one of the tools involved in the 'homogenization of people', leading to 'thermal monotony', even though early air conditioning engineers made efforts to avoid designing monotonous thermal environments (67). Stoops mentions that the environment in modern buildings has little resemblance to the environment of the savannah in which the human species evolved (68). Stoops provides an example from physiology, and mentions that our cardiovascular and thermoregulatory systems are interrelated. "Increases in exercise levels that drive increased cardiovascular activity also increase metabolic heat output that must be balanced by the thermoregulatory system. However, unlike the cardiovascular system, there is no scientific recognition that the thermoregulatory system may itself require exercise for health. In fact, our entire effort in conditioning our living and working environments is to provide thermal conditions that minimize thermal discomfort. We therefore are intentionally minimizing the use of our thermoregulatory system with the way we build and condition our buildings (68)."

Occupants of naturally conditioned buildings turn out to be more active in thermoregulatory adaptation through changes in activity level and clothing (behavioral

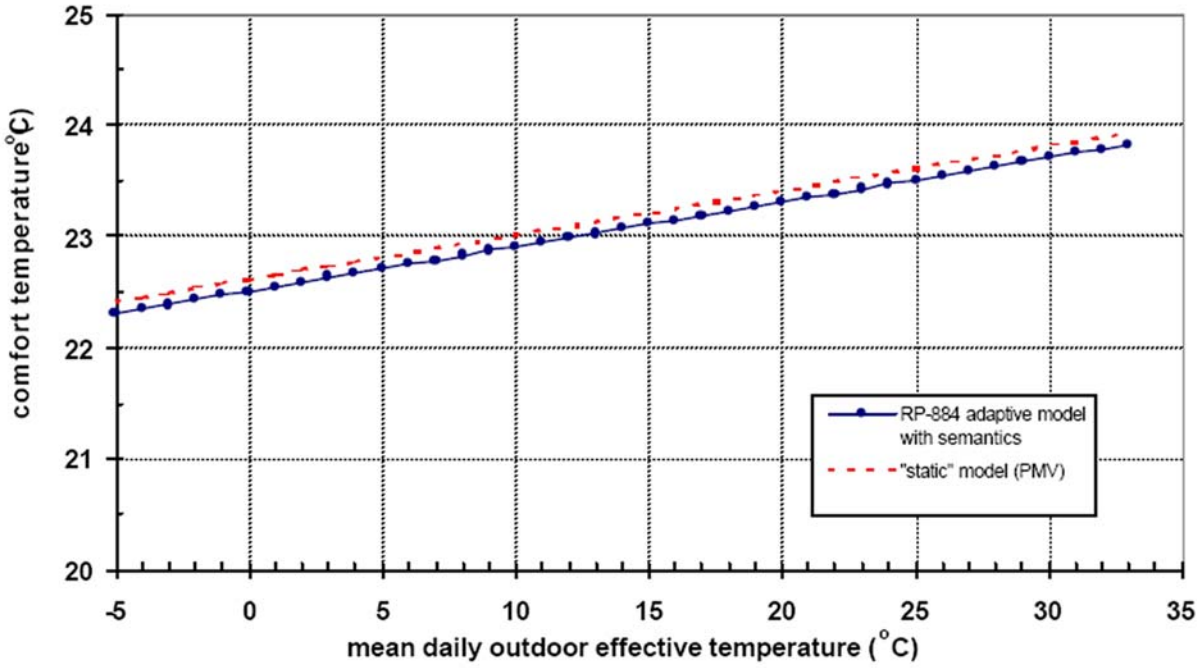

Figure 4. Comparison of the RP-884 adaptive model and the 'static' model (based on PMV predictions) for centrally-controlled buildings in terms of comfort temperatures (57).

adaptation), and appear more tolerant to a wider range of temperatures (psychological adaptation). A recent study from the UK by Yun *et al.* showed that in summer, the temperature of an office occupied by active window users can be up to 2.6 K lower than that of passive window users (69). Occupant control might lead to temperatures that vary from room to room within the same free-running building.

In short, the indoor temperature regarded as most comfortable increases significantly in warmer climatic contexts, and decreases in colder climate zones, due to adaptation. In a study from South-Korea and Japan by Chun *et al.*, it was found that the thermal history influenced indoor comfort experienced in identical climate chamber conditions (n=52), which form the basis of the PMV-model (70). The Yokohama subjects responded with cooler thermal sensations than Seoul subjects. It was also found that subjects who use air conditioning at home responded with warmer thermal sensations than the subjects who did not use air conditioning. At the same time, Olesen (71) raised the question if air conditioning at home affects the adaptation process of working in a naturally conditioned office? De Dear *et al.* proposed two models of adaptive thermal comfort, one for centrally controlled building that showed overlap with the PMV-model (Figure 4), and a second for naturally ventilated buildings (Figure 5) (56). The latter one has been incorporated in ANSI/ASHRAE Standard 55 in a modified version (Figure 6), and relates the comfort temperature indoors to the monthly average temperature outdoors. According to these models, past thermal history (the weather of the preceding days) modify the occupant's thermal expectations and preferences, including the choice of clothing.

Another recent project that investigated the adaptive hypothesis was the EU project Smart Controls and Thermal Comfort (SCATs) (72,73). This project aimed to reduce energy use by air conditioning systems by varying the indoor temperature in line with the outdoor temperature through the use of an 'adaptive algorithm'. Nicol and Humphreys mentioned before that a "low energy" standard which increases discomfort may be no more sustainable than one which encourages energy use because of the adaptive principle that occupants may well use energy to alleviate their discomfort (74). The project was carried out in 26 European offices in France, Greece Portugal, Sweden and the UK, many of which were naturally ventilated office buildings in free-running mode outside the heating season (45). A relationship between indoor comfort and outdoor climate was developed for free-running buildings (Figure 7), which is somewhat different from the method described in ANSI/ASHRAE Standard 55 (1).

The adaptive models derived by various researchers do not yield the same outcomes. For instance, Tablada *et al.* have calculated comfort temperatures using four adaptive models, which ranged from 26.8 °C to 28.2 °C, an interval of as much as 1.4 K (77). Also, differences in comfort temperatures can also be the result of the type of outdoor temperature parameter chosen for analysis. For the Netherlands, with its moderate climate, this difference can be as much as 3 K (78).

3.2.2. Adaptive opportunities and personal control

An important feature of the adaptive hypothesis is that people have means to individually control their thermal environment within the naturally ventilated building in

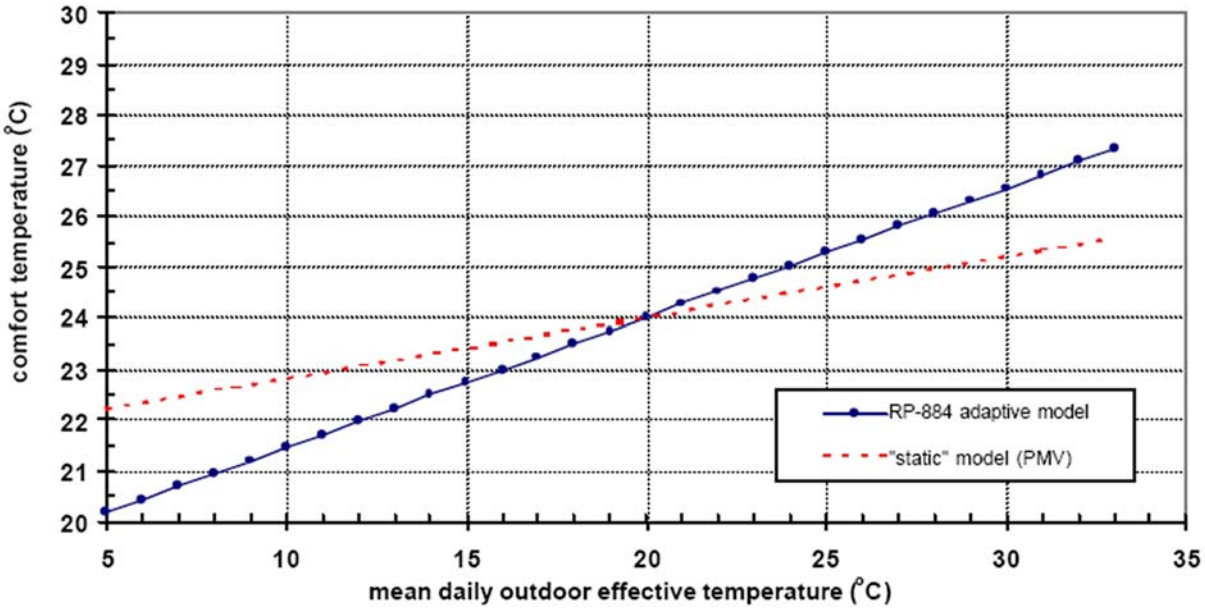

Figure 5. Comparison of the RP-884 adaptive model and the 'static' model (based on PMV predictions) applied to naturally ventilated buildings in terms of comfort temperatures (57).

free-running mode. Having control over the environment is a very effective way to limit the negative health effects of stress, since one can use external coping strategies (79). There is not such a strict need for prescriptive standards if individual control over the thermal climate is provided, allowing all occupants to be satisfied, for instance, by being able to slightly adjust temperature at the workplace level (49,80). The design ranges of the systems may be somewhat broader, whereas criteria for speed of the control action to have effect and controllability are desired. This requires systems designed for user involvement, both physical (individual temperature control), or "social, where the physical conditions are seen as a natural consequence of the situation, rather than arbitrarily imposed" (81). People become more tolerant of departures from thermoneutrality as a result of all indoor parameters, as people are to a certain extent responsible for the control of them.

One of these means is to adjust garment ensembles. The amount of clothing worn by people is significantly correlated with outdoor temperatures; the warmer, the fewer clothes people wear as long as they are free to choose the clothes they wish to wear (82). There are, however, differences between genders in adapting closing and garment ensembles worn. In offices with strict dress codes, this poses a problem to adaptive opportunities, and can lead to an increased need for energy. In the summer of 2005, the Ministry of Environment in Japan promoted "Cool Biz" fashion, where ties and jackets are not worn and comfort is maintained even at 28 °C (83). At the same time, "Warm Biz" fashion, where comfort is maintained at 20 °C, was also introduced in winter. Clothing can thus be reconsidered from an environmental standpoint (83). The potential of the adaptive model for reduced energy use, particularly in the tropics, and in relation to climate change, is discussed in various papers, including van Hoof and Hensen (78), Kwok and Rajkovich (84), and Toftum *et al.* (85).

Another means of adaptation runs via being able to close and open windows. Umemiya *et al.* studied this behavior for Japanese homes (n=10 apartments, with natural and mechanical cooling) and found that window opening is done most when the indoor temperature is about 5 K higher than the outdoor temperature in the cooling season (86). The ratio of the conditions when neither air conditioner nor window opening is used has a peak when indoor PMV is between 1.5 and 1.75 in the cooling season. Yun *et al.* found that there is a close connection between perceived control and actual control (with respect to window use), and that occupants with a high level of perceived control use their windows more frequently than others with a low level of perceived control (87). However, there might be a risk of draft by operating windows, depending on whether the windows are operated by the person in question or by a colleague. Without personal control, air movement limits are determined by predictions of draft discomfort. In a study by Toftum, it was found that when occupants are feeling warmer than neutral, at temperatures above 23 °C or at raised activity levels, people generally do not feel draft at air velocities typical for indoor environments (up to approximately 0.4 m/s) (88). In the higher temperature range, very high air velocities up to around 1.6 m/s were found to be acceptable at air temperatures around 30 °C, though they might be undesirable for other reasons. Many naturally ventilated buildings in Europe are in free-running mode around summer only. When assessing the indoor climate in naturally ventilated spaces in Brazil, Cândido *et al.* found that subjects preferred higher air velocities that even went

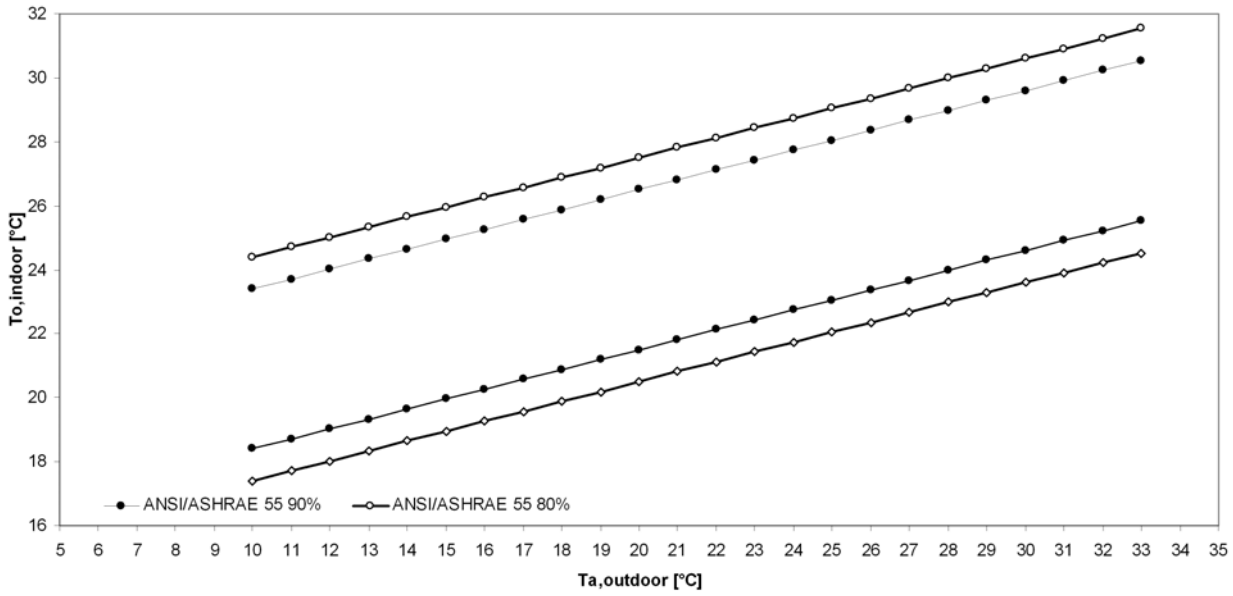

Figure 6. Optimum operative temperatures in naturally ventilated spaces as a function of prevailing outdoor temperature, as given in ANSI/ASHRAE Standard 55 (1).

beyond the 0.8 m/s limit prescribed by ANSI/ASHRAE Standard 55 (89).

The use of thermostats is not included as a means of adaptation in the current adaptive thermal comfort models, as it would mean that a building is -strictly speaking- not in a free-running mode. In a forum paper, Mithra (90) mentions a study by Huizenga *et al.* (91) that uses data comprising responses from 34,169 occupants in 215 buildings throughout North America and Finland. Respondents with access to a thermostat or an operable window were found to be more satisfied with workplace temperature. Of the subjects with access to thermostats 76% were satisfied, whereas only 56% of occupants without access to a thermostat were satisfied. For the case of access to an operable window, the ratio was 67% versus 57% satisfaction. These percentages become more important when looking at the number of people that have access to thermostats and operable windows. Only a mere 10% of occupants had access to a thermostat, and only 8% had access to an operable window. Occupants with portable heaters and fans had lower satisfaction than those without, as the presence of such devices might indicate a deficiency in the HVAC system of the buildings. The situation in residential situations might be slightly different. A study from Japan showed that when houses are poorly insulated and heating appliances are inadequate, staying in the only heated room as a means of behavioral thermoregulation increases (92). When even the warmth of the heated living room is inadequate, residents spend more time near heating appliances. Personal control and the voluntary character of exposure seem important. Mithra states that some workers have more limited means to adapt physically, but nevertheless do, for instance, by stacking books and papers in front of vents, dressing warm, opening doors that are marked 'keep closed', and by working at home when the office is going to be too hot (90). "Although workers are generally recipients of environmental conditions decided elsewhere, and their agency in the workplace is physically and socially limited, many are not passive about it (90)." Karjalainen and Koistinen conducted a study among 27 occupants of 13 offices in Finland on temperature control use (93). Temperature controls were often not used when people experienced thermal discomfort, as systems were installed without considering end-users, and interfaces turn out to be difficult to operate. In 2009, Karjalainen concluded that the perceived control over room temperature is remarkably low in Finnish offices (n=3,094 respondents) versus at home (94). Office occupants have fewer opportunities to control the thermal environment and deal worse with the thermostats. Karjalainen also found that even though females in Finland were more critical of their thermal environments, males used thermostats in households more often than females did (95). Would this mean that in office settings women are more reluctant to control their indoor environment and that men are more willing to operate technological means?

Thermal comfort however does not seem to be entirely dependent on building factors and options for personal control. Derksen *et al.* investigated the influence of some organizational and management characteristics on thermal comfort and related stress in office environments in the Netherlands (96). Through factor analysis they found that perceived thermal comfort correlated or was associated with (i) employees' stress, (ii) employees' over-commitment to work, and (iii) employees' perceived privacy. The managerial characteristics of an organization seem to influence thermal comfort as perceived by its employees. Further exploration of organizational and management characteristics lies outside the scope of this paper.

Table 1. Criteria for PMV, PPD and operative temperature for typical spaces.

Category	General comfort		Operative temperature range [°C]	
	PPD [%]	Predicted Mean Vote [-]	Winter [1.0 clo and 1.2 met]	Summer [0.5 clo and 1.2 met]
A	<6	-0.2<PMV<+0.2	21.0-23.0	23.5-25.5
B	<10	-0.5<PMV<+0.5	20.0-14.0	23.0-26.0
C	<15	-0.7<PMV<+0.7	19.0-25.0	22.0-27.0

Table 2. Applicability of the categories in the standard and their associated acceptable ranges of operative temperature around the adaptive comfort temperature in case of free-running building, or PMV in case of mechanically controlled buildings (76).

Category	Explanation	T_o [K]	PMV [-]
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	±2	±0.2
II	Normal expectation for new buildings and renovations	±3	±0.5
III	Moderate expectation (used for existing buildings)	±4	±0.7
IV	Values outside the criteria for the above categories (only acceptable for a limited period)		

Table 3. Validity intervals for PMV input parameters, taken and adapted from ISO 7730 and Humphreys and Nicol (29,33).

Parameter	ISO 7730	Humphreys and Nicol	
		PMV free from bias if:	Comment
Clothing insulation [I_{cl}]	0-2 clo (0-0.310 m^2KW^{-1})	0.3<I_{cl}<1.2 clo (chair included)	Overestimation of warmth of people in lighter and heavier clothing, serious bias when clothing is heavy. Little information exists for conditions when I_{cl}<0.2 clo
Activity level [M]	0.8-4 met (46-232 Wm^{-2})	M<1.4 met	Bias larger with increased activity. At 1.8 met overestimation sensation of warmth by 1 scale unit
'Hypothetical heat load' [M·I_{cl}]		M·I_{cl}<1.2 units of met·clo (about 10.8 K)	Serious bias at 2 units (about 18 K)
Air temperature [t_a]	10-30 °C		Overestimation warmth sensation t_o>27 °C[1]. At higher temperatures bias becomes severe. Upper limit t_o approximately 35 °C in ISO 7730. Data by Humphreys and Nicol do not indicate an unambiguous lower limit.
Mean radiant temperature [$\bar{t}_r$]	10-40 °C		
Vapor pressure [p_a] or relative humidity [RH]	0-2.7 kPa or 30-70%	RH<60%	Suggested bias becomes important if p_a>2.2 kPa
Air velocity [v_a]	0-1 ms^{-1}	v_a<0.2 ms^{-1}	Overestimation warmth sensation v_a>0.2 ms^{-1}. Underestimation cooling effect of increased v_a

[1] t_o = operative temperature, which is a function of air temperature, mean radiant function, and a weighing factor A that depends on air velocity. $t_o = At_a + (1-A)\bar{t}_r$; in which A=0.5 if v_a<0.2 ms^{-2}; A=0.6 if $0.2 \leq v_a < 0.6$ ms^{-2}; and A=0.7 if $0.6 \leq v_a < 1.0$ ms^{-2}.

4. THERMAL COMFORT STANDARDS

4.1. Standards and the PMV-model

In European countries ISO 7730 is the current standard for evaluating thermal comfort, together with EN 15251, which covers thermal comfort as well as other indoor environmental parameters (29,75). CR 1752 is a technical report on ventilation that deals with the quality of the indoor climate too (97). ANSI/ASHRAE Standard 55 is the standard in North America that deals with thermal comfort (1). These documents specify comfort zones in which a large percentage of occupants with given personal parameters will regard the environment as acceptable. An important issue of discussion during the latest round of standard revisions was the incorporation of an adaptive thermal comfort evaluation method. Such adaptive models have been introduced in ANSI/ASHRAE Standard 55 for the evaluation of the indoor environment in naturally conditioned buildings as well as in EN 15251.

The PMV-model, a method prescribed by ISO 7730 for evaluating general or whole-body thermal comfort, is also included in ANSI/ASHRAE Standard 55. ISO 7730 specifies three different levels of acceptability (classes) for general thermal comfort and local thermal discomfort parameters in compliance with CR 1752 (Table 1) (plus a fourth class that goes beyond the boundaries of Class C), and a similar schema has been proposed for ANSI/ASHRAE Standard 55. The background is that it may be desirable to establish different targets of thermal satisfaction (category A for 90% acceptability, B for 80% and C for 70%). These categories are an indicator of how close the indoor environment is controlled in relation to a certain set-point. Close control is regarded as "denoting a superior building" (76).

For an appropriate use of the PMV-model, the parameters involved in the calculation of PMV need to be within certain boundaries (Table 3). The bandwidths of these comfort parameters are subject to discussion. According to Humphreys and Nicol, the validity intervals stated in the international standard ISO 7730 contribute largely to the biases in PMV, and the bandwidths for valid use are much narrower (33). The quality of predictions and evaluations also depends on the accuracy of input parameters, especially the estimations of clothing insulation and activity level, and measurements. PMV is intrinsically more sensitive to air velocity, metabolism and clothing insulation than for air or radiant temperature, which can have serious consequences to the model's outcomes. Calculated clothing insulation can differ by as much as 20% depending on the source of common tables and algorithm (98). In addition, Havenith *et al.* state that standardized methods for determining the metabolic rate are insufficient to accurately classify buildings to within 0.3 PMV scale units (99).

Apart from the discussions on input parameter bandwidths, there is discussion on the class system (100). Arens *et al.* discuss the bandwidth of class A and/or I, and

Table 4. Recommended levels of acceptability for 3 classes of environment for local discomfort.

Category	**DR [%] (draft)**	**PD [%] to vertical air temperature difference**	**PD [%] to warm or cold floor**	**PD [%] to radiant temperature asymmetry**		
A	<15	<3	<10	<5		
B	<20	<5	<10	<5		
C	<25	<10	<15	<10		
Category	**Vertical air temperature difference [K]**	**Floor surface temperature [°C]**	**Radiant temperature asymmetry [K]**			
			Warm ceiling	Cool ceiling	Cool wall	Warm wall
A	<2	19-29	<5	<14	<10	<23
B	<3	19-29	<5	<14	<10	<23
C	<4	17-31	<7	<18	<13	<35

state that "a narrow range should presumably be preferable to the building occupants to justify its increased energy cost." There are unsolved questions on the widths at which temperature ranges are detected, preferred, and judged unacceptable by the occupants. Arens *et al.* ask themselves some very relevant questions (100): "If occupants were in individual rooms with individual thermostats which they could adjust according to their clothing [levels, activity levels], and personal preferences, would they control their temperature around a narrow band as in Class A, or would they control to a band more like Class B or C? If, rather than controlling the temperature themselves, it were controlled for them, would they really prefer Class A control to Class B control? Would they notice the difference?" A re-examination of three databases of occupant satisfaction in buildings showed that Class A does not to provide higher acceptability for occupants than class B and C environments. Arens *et al.* further conclude that the "theoretical basis of tight [PMV-based] building control is flawed. […] PMV itself may lack the precision needed to handle the fine distinctions needed for the three-class system of control. […] Class A as a category is unsupportable as a basis for environmental control in office buildings, given the energy costs of designing and controlling to its specifications (100)."

The new European Standard EN 15251 and its contents are described by Olesen *et al.* (101) and Olesen (102). This standard has a significant overlap with the previously mentioned standards for thermal comfort. The standard distinguishes between building types and spaces, due to variation in needs, activity levels, and clothing, that seem especially true for kindergartens and department stores. According to Nicol and Humphreys, EN 15251 uses a category system (using Roman numbers, not letters) that seeks to distance itself from the implication of closer control being superior (76) (Table 2).

4.2. Local discomfort, transient conditions and long-term evaluation in standards

It is not known how dissatisfaction due to local discomfort relates to whole-body thermal dissatisfaction. Therefore, the standards include diagrams showing the relation between the percentage of dissatisfied (PD) and various local comfort parameters (Table 4), as well as a diagram to estimate the air velocity required to offset an increase in temperature. In order to apply this diagram, it is essential that occupants have some degree of personal control over the air velocity for reasons of acceptability.

In real buildings, the indoor environment is often characterized by transient or spatially non-uniform conditions, including thermal conditions. Thermal conditions in buildings are seldom steady, due to the interaction between building structure, climate, occupancy, and HVAC system (103). Transient conditions in the indoor environment include periodic variations, step changes, ramps and drifts. The PMV-model is valid only for invariant conditions (2). According to Goto *et al.*, steady-state models (including PMV-model) for the prediction of thermal sensation seem to be applicable after approximately 15 minutes of constant activity (104). Zhang and Zhao found that under non-uniform conditions overall thermal acceptability and comfort were correlated closely, but not to overall thermal sensation due to non-uniformity (105). Many studies investigate human responses in non-uniform environments. ANSI/ASHRAE Standard 55 sets limits to temperature cycles depending on 3 categories of thermal acceptability. Non-cyclic temperature changes that last longer than 15 minutes will not be allowed to exceed 0.6 K/h. ISO 7730 does not include any transient criteria.

If criteria for good general thermal comfort have to be met 100% of occupancy time, even in extreme weather conditions, the heating and cooling capacities required would be prohibitive. Economic and environmental considerations lead to allowing thermal conditions to exceed the recommended ranges for a limited amount of time. For long-term evaluations -using computer simulation tools- ISO 7730 has incorporated weighted hours (WH). The WH criterion is similar to the method prescribed in directives of the Dutch Government Building Agency (62). The time during which PMV exceeds the comfort boundaries is weighted with a factor that is a function of PPD. This "weighted time" is then added for a characteristic working period during one year and is an overall index of indoor environmental quality. The method which is used in the Netherlands, however, has serious disadvantages in terms of communicating results to clients, building owners and architects.

4.3. Adaptive thermal comfort in standards and the relation to the PMV-model

ANSI/ASHRAE Standard 55 has incorporated a model of adaptive thermal comfort, called Adaptive Comfort Standard (ACS) (Figure 6) for occupant-controlled naturally ventilated buildings. The ACS prescribes a mean comfort zone band of 5 K for 90% acceptance, and another of 7 K for 80% acceptance, both centered around the optimum comfort temperature (T_{comf}) (Equation 1).

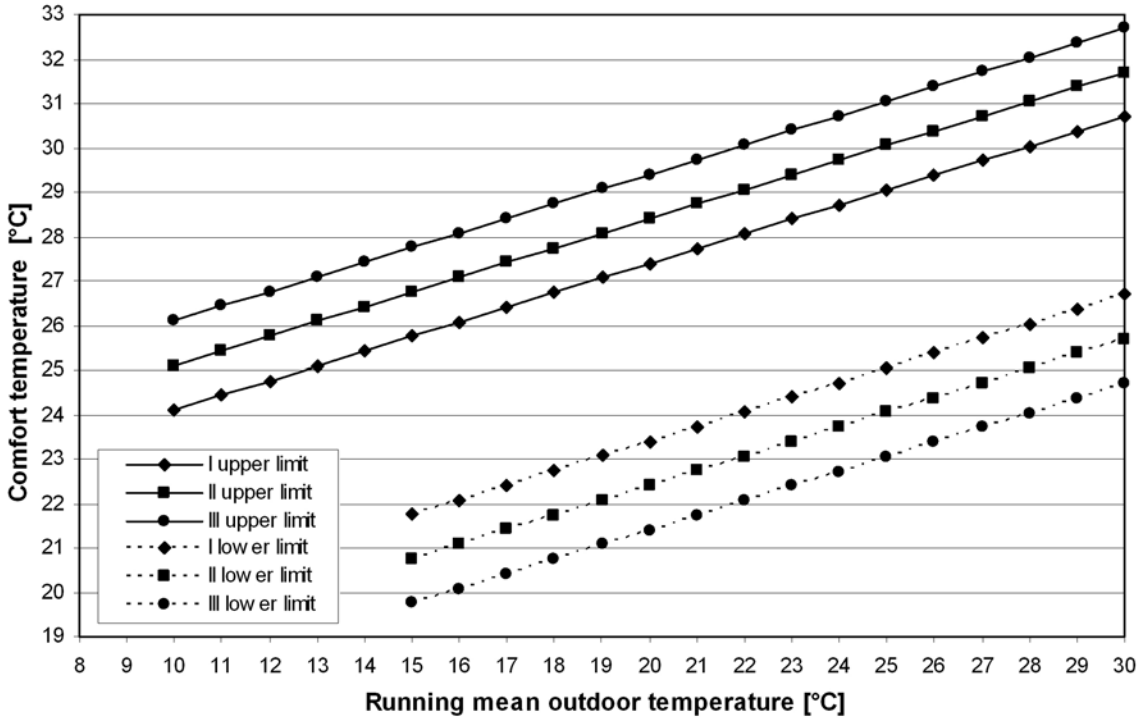

Figure 7. Design values for the upper and lower limits for operative temperature in free-running buildings for three categories of acceptability as a function of the running mean outdoor temperature as incorporated in Annexe A2 of EN 15251 (45,75,76).

$$T_{comf} = 17.8 + 0.31 T_{air,out} \quad (1)$$

The outdoor air temperature is based on a mean monthly outdoor temperature, in contrast to earlier models which were based on outdoor ET*. This model is incorporated into the standard as an optional method, applicable in naturally ventilated office buildings (not homes) for people engaged in near sedentary activity (1 to 1.3 met) who are able to freely adapt their clothing, when mean monthly outdoor temperatures are between 10 and 33 °C. Above 33 °C the only predictive tool available is the PMV-model, which is unreliable for predicting thermal responses of people in free-running buildings (33,57). There should be no mechanical cooling system in the space, although mechanical ventilation with unconditioned air may be utilized as long as operable windows are the primary means of regulating the indoor thermal environment. The ACS is not applicable for spaces with a heating system in operation. Although there has been much debate as to whether the ACS should be applicable to hybrid buildings, this type of buildings is excluded in the latest revision to ANSI/ASHRAE Standard 55. The research report by de Dear *et al.* contained a model for fully air-conditioned buildings (57) (Figure 4), but this model was not incorporated into ANSI/ASHRAE Standard 55. The standard recommends building consultants to assess local discomfort separately when necessary.

ISO 7730 has not incorporated any adaptive model, but allows the thermal indoor environment in naturally conditioned buildings with a high degree of personal control to be within the comfort limits of category C. Naturally ventilated office buildings that comply with the requirements for application of the ACS are small in number since most office buildings are equipped with some form of air-conditioning these days. It seems that the thermal comfort standards take this into account.

EN 15251 (Annexe A2) includes an adaptive comfort temperature model (Figure 7), which applies to all buildings that are being neither heated nor cooled mechanically (free-running), where people have access to operable windows and where one is relatively free to adjust clothing ensembles. This model relates neutral temperatures indoors to outdoor temperatures. Nicol and Humphreys see the arising of a conflict between the definition of comfort for free-running buildings, which is buildings-based, and that for mechanically cooled buildings (76).

The adaptive comfort models in both ANSI/ASHRAE Standard 55 and EN 15251 are conceptually similar, though several differences exist. These are described by Nicol and Humphreys (45). First of all, the databases for the derivation of the models are different (ASHRAE RP-884 versus SCATs). Second, the building classification differs. The ASHRAE chart applies only to naturally ventilated buildings, while the EN 15251 chart applies to any building in the free-running mode. Third, the derivation of the neutral temperature is different, which leads to deviations in neutral temperatures. Fourth, the outdoor temperature is defined differently (monthly mean outdoor air temperature versus a more realistic exponentially weighted running mean of the outdoor air

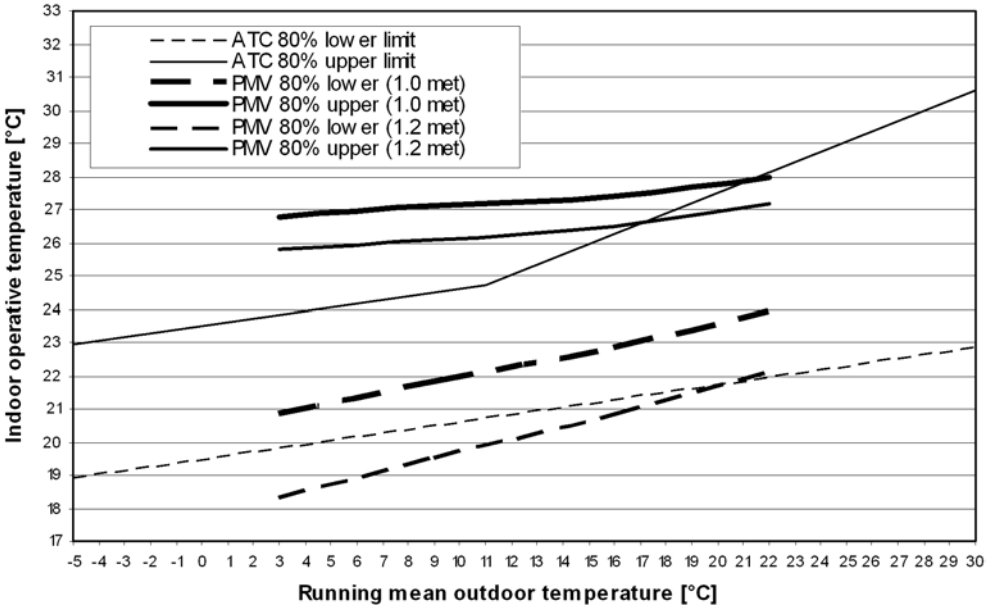

Figure 8. Comparison of the 80% acceptability rating for the Dutch adaptive model (ISSO 74 (78,106)) and PMV (relative v_a: 0.10-0.20 m/s, RH: winter 40%, summer 70%, $t_a = \bar{t}_r$, I_{cl}: winter 0.95 clo, spring/fall 0.84 clo, summer 0.71 clo and hot summer period 0.60 clo) (25).

temperature). An advantage of EN 15251 is that it relies on actual weather data which display more variability than do the historic monthly means (45).

Besides the international developments in the field of adaptive thermal comfort evaluation methods and standardization, there are also local initiatives. One example is the introduction of an adaptive guideline in the Netherlands, ISSO 74 (78,106). This Adaptive Temperature Limit method (ATL) should be used for evaluating design phase simulations as well as assessing existing buildings for regular activity and clothing levels, and is intended as a replacement method for the Dutch WH criterion. The PMV-model remains in use for situations with high metabolism or clothing insulation. The ATL method can be used only for office buildings and workspaces. It distinguishes between two different types of office buildings; type Alpha with a high degree of occupant control and type Beta with a low degree of occupant control.

In temperate climate zones, the comfort zones of the adaptive models and the PMV-model are to a large extent superimposed over one another (78). A great arithmetic advantage of adaptive models is their relative simplicity, compared to the PMV-model that requires six input parameters and iterative calculations. One of the great disadvantages of adaptive models is their application range, which is limited to offices and workspaces only. The PMV-model is applied throughout most types of buildings, although one might pose questions to the validity of such a wide application range. Van der Linden *et al.* mention their relative simplicity when carrying out assessments as an advantage of the adaptive models, as well as the perceptibility of the indicator, i.e., its straightforward conception of the information (25). At the same time, van der Linden *et al.* conclude that a heat balance approach has a larger flexibility and a wider applicability. In their study, van der Linden *et al.* elaborate the linkage between PMV and the adaptive model by investigating the search space for PMV input parameters in relation to the 'adaptive' assessment (25). The results show that for moderate maritime outdoor climates, PMV is well able to explain the results derived by using an adaptive model (Figure 8).

4.4. Interactions with other parameters

Overall comfort also originates from other environmental factors as odors/indoor air quality, lighting and noise levels. These interactions are not always understood in great detail, although CR 1752 and EN 15251 deal with all these aspects of the indoor environment separately, but not in an integrated manner. Experimentally, the effects of environmental conditions upon human capabilities have been studied most often through the imposition of a single stressor in isolation (107). Candas and Dufour state that while many studies have shown multi-sensory integration between touch, vision and hearing in different areas of the brain, few studies have highlighted multisensory regions in the cerebral cortex which involve thermal sensation (107).

Smaller studies investigated the combined effects of noise and temperature (108,109), temperature, air quality and sound pressure level (110), the perception of indoor air quality and enthalpy in relation to temperature (28,111), the interaction between thermal comfort, sound, view and daylight (112), and illumination and thermoregulation (113). Candas and Dufour reviewed a number of such

studies and conclude that "thermal components are very dominant factors in determining global comfort (107). One simply cannot avoid thermal stimuli, unlike stimulations by other sensory modalities (noise, light, odors)." Also, Candas and Dufour conclude that "vasodilatation under high illuminance or high temperature color environments may slightly lower core temperature, which may act on thermal comfort" (107).

Results of interaction studies have not yet led to an overall understanding of the impact of the total indoor environment on occupants, but provide just first steps. Hence, interactions are not within the focus of the standards.

In case of healthy persons, building occupants balance the good features against the bad to reach their overall assessment of the indoor environment (73). Not all aspects are equally important in this subjective averaging process, for instance, satisfaction with warmth and air quality is more important than satisfaction with the level of lighting or humidity. Moreover, the relative importance of the various aspects differ from country to country (in case of the importance of the contribution of air movement between France and Greece), making it impossible to develop an internationally valid index to rate office environments by means of a single number (73).

4.5. Health and comfort

HVAC systems and buildings with air conditioning are also within the focus of health studies, with the term Sick Building Syndrome as its best-known exponent. A review by Yu *et al.* mentions the increasing health problems associated with air conditioning systems and indoor air quality in buildings equipped with such systems (114). A study from Hong Kong by Wong *et al.* found that significantly higher levels of airborne bacteria and fungi were seen during non-office hours when the air conditioning system was shut down, and that levels of airborne bacteria and fungi are correlated with the thermal environmental parameters in some offices (115). Also, recirculation of a large fraction of air by many air conditioning systems limits ventilation and increases indoor pollution levels (116). Mendell and Mirer re-examined data from 95 U.S. office buildings and investigated relationships between building-related symptoms and thermal metrics constructed from real-time measurements (117). Findings suggest that less conditioning of buildings in both winter and summer may have unexpected health benefits. Health effects are also not within the scope of the standards, even though they form an ever increasing field of study and become important in daily engineering practice. After reevaluation of a large database composed of 1,272 responses, Toftum concludes that the degree of control over the indoor environment, as perceived by the occupants of a building, seems more important for the prevalence of adverse symptoms and building-related symptoms than the ventilation mode per se (118). This implies that even the latest advances in building controls should not compromise the occupants' perception of having some degree of control. According to Stoops, there is no real health-based physiological reason to condition the buildings in compliance with the abovementioned standards, as they are based on the assumption of minimizing discomfort (68). Stoops mentions that it is logical that buildings are conditioned in such a way that hypothermia and hyperthermia are avoided, and questions if current standards go too far in prescribing thermal conditions; limiting the thermal stimulation that people could actually need for long-term health (68). Even though there is no current scientific justification for the alternative scenario outlined by Stoops, it might be plausible from the perspective of evolutionary biology. Another point raised by Stoops is related to the character of current standards, which are mainly applied by the engineering community. This community accepts the existing standards because they are based on a physics-centered interpretation of physiology and the pure physics of thermal balance, even though applying such standards result in occasional problems (68). Focus should not be on the underlying physics, but on the occupants of actual buildings in all their variety. However, such a conclusion implies that clear and unequivocal recommendations in terms of thermal comfort needs cannot be drawn if large differences between occupants seem to exist. The concept of 'one solution fits all' does not seem to match with every day thermal comfort realities (68).

5. ADVANCES IN COMPUTERIZATION: MODELING AND PERFORMANCE

5.1. Computerization and simulation

Increased computational power, improvements to equipment and software, and the overall computerization of society have had an impact on thermal comfort research and practice. The dynamic thermal interaction between a building, and the HVAC systems which service it, is difficult to predict (119). Building performance simulation has developed over the last three decades to allow the simultaneous solution of the thermal and mass flow paths within buildings. This allows engineers to quantify the environment to which occupants are exposed during the design phase (120).

One of the possibilities that have come within reach are real-time thermostats that might be based on personal user profiles that include data on an individual's preferred temperature, and sensitivity to deviations on the lower and warmer side. Indoor climate control of the future should be pro-active, and intelligent systems should be able to predict the needs of occupants on a space-level, for instance, based on outdoor weather, temperature profiles in adjacent rooms, and the way a space is utilized. The introduction and development of new control systems will undoubtedly be closely linked to energy conservation, automated choice of energy sources and strategic (time) management. This view is shared by de Dear and Brager, who stress the need for a more integrative view of optimizing the indoor environment, energy consumption, and productivity (28).

Within building energy simulation two approaches to air flow modeling are extant: nodal networks and computational fluid dynamics (121). These approaches

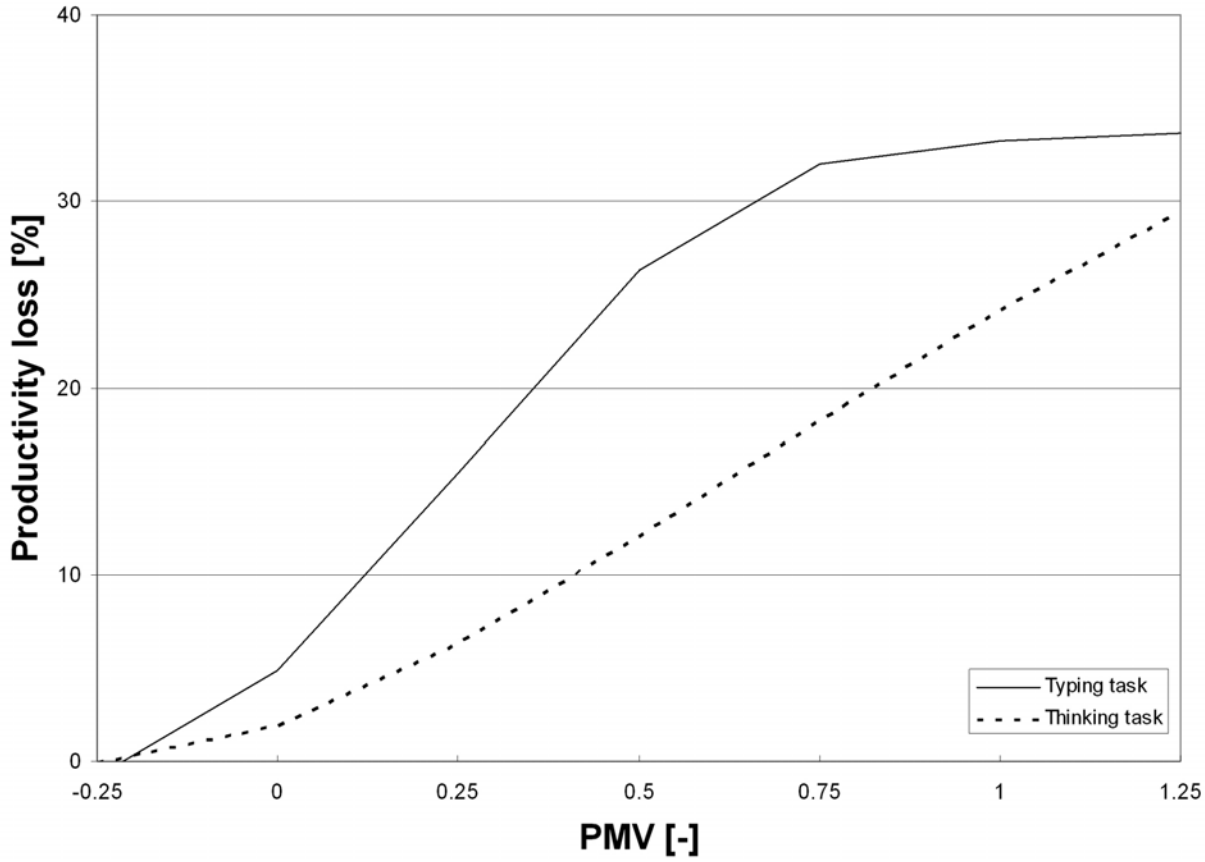

Figure 9. The correlation between PMV and productivity loss according to Kosonen and Tan (132).

should also include the dynamics of occupants in the building. Hoes *et al.* found that occupants have influence on the thermal environment due to one's presence and activities in the building, and due to one's control actions (122). The weight of user behavior on building performance increases, particularly for passive or free-running buildings. Current approaches to building performance assessment are found to be inadequate for buildings that have a known close interaction of the user with the building. According to Clarke *et al.*, it is increasingly accepted that occupants alter their environment to maintain a comfortable condition in accordance with the adaptive hypothesis (120). In order to enable design decision support, the control actions and the trigger events have to be understood and encoded into algorithms for inclusion in a predictive environment.

5.2. Task performance, productivity and the thermal environment

One of the factors that have come within reach of study by computer is the productivity of workers from improved performance, for instance, via the automated measuring the output of call-centers and office workers (typing tasks). Apart from human interaction and dynamic elements of the work environment (123), productivity on the work floor is also affected by indoor environmental parameters, of which excessive noise, lighting and thermal discomfort are the most important. Improved indoor environmental quality has a profound impact on performance, and this subject is thoroughly studied and reviewed (124-128). Humphreys and Nicol concluded that self-assessed productivity was significantly related to satisfaction with the various aspects of the office environment, while the relation with the measured physical conditions was indirect and weak (126). According to Leaman and Bordass, losses or gains of up to 15% of turnover in a typical office organization might be attributable to the design, management and use of the indoor environment (129). Fisk and Rosenfeld have estimated that the potential financial benefits of improving indoor environmental quality exceed costs by a factor of 18 to 47 (130). Seppänen and Fisk have shown that there are links between the improvements to the indoor environments and reduced medical care cost, reduced sick leave, better performance of work, lower turnover of employees, and lower costs of building maintenance due to fewer complaints (131).

Kosonen and Tan made a PMV-based productivity model used to estimate the effects of different thermal conditions on productivity (132,133) (Figure 9). The theoretical optimal productivity (task-related performance) occurs when the PMV value is -0.21 (around 24 °C). The normally accepted PMV value of +0.5 leads to

about 12% productivity loss in thinking tasks and 26% in typing tasks. The boundary constraints for the model are -0.21<PMV<1.28. Tse and So compared human productivity in an office with conventional set-point control and PMV-based control (134). The conventional control caused a significant reduction in human productivity, whereas the PMV-based control performed well. The authors recommend considering human productivity in the design of future air-conditioning control, which according to Tse and Chan could be based on real-time measurements via a distributed smart sensor network (135). Many studies on task performance were conducted in centrally-controlled buildings and climate chambers, whereas the relation between task performance and occupant-controlled buildings is studied in less detail. There seems to be a gap between the adaptive thermal comfort studies and productivity studies.

5.3. Multi-segmental models of human physiology

Also complex and detailed (high-resolution) simulation models of the human body are emerging as a result of increasing computational power. New multi-segmental models of human physiology and thermal comfort are increasingly used, for instance, models by Fiala *et al.* (136), Huizenga *et al.* (137), and Tanabe *et al.* (138). These models have their roots either in the Stolwijk (139) or the Wissler (140) models, and incorporate more detail including heat transfer within the body and between the body and its environment, as well as sweating, shivering and vasomotor capabilities. The human body is represented as a sum of separate body parts, and can be utilized to describe local effects due to non-uniform environments and/or non-uniform clothing coverage. They are foreseen to gain importance in terms of practical application.

Recent study of Rees *et al.* predicts the sensations of local thermal discomfort in the near-window region of a room using a detailed, multi-node dynamic IESD-Fiala model (141). Close to windows occupants may be directly exposed to both transmitted solar radiation and enhanced long wave radiation exchange due to window surfaces that are noticeably hotter or colder than other room surfaces. This model that enables simulation of the thermophysiological behavior of 59 human body sectors and the calculation of local skin temperatures and heat transfer rates was combined with recently developed models of local thermal comfort (142) and a detailed polygonal representation of the person. Calculations of long-wave, diffuse and direct short-wave radiation factors coupled with a thermal model showed that a local thermal comfort was achieved for only a small range of boundary conditions that lay within the global thermal comfort envelope and at the same time the predicted global thermal comfort was insensitive to the window surface temperature. This suggests that models that only predict global comfort without explicit representations of local discomfort will not reveal problematic environmental conditions in near wall regions.

5.4. Thermal manikins

The use of thermal manikins in research and design field is steadily growing and has significantly increased in recent years, which is seen from the number of manikins being manufactured and used, and in the number of publications containing thermal manikin applications. The first thermal manikins were one segmental and constructed for the purpose of clothing research but it was soon recognized that a heated thermal manikin could also be used for evaluation of microclimate conditions in closed environments, equipped with different HVAC systems.

In a thermally non-uniform environment, the assessment of the thermal environment using the conventional methods by measuring several physical parameters including air temperature and air velocity is inaccurate. The most important feature of multi-segmental thermal manikins from this aspect is the capability of providing accurate and repeatable simulation of human body heat exchanges over the surface in all directions, which makes them particularly useful in assessing thermally non-uniform environments.

Nowadays, thermal manikins become more and more multi-functional and provide a useful and valuable complement to direct measurements with human subjects. For conditions with complex and transient heat exchange, thermal manikins assure accurate and reliable values of whole-body and local heat exchange. They are used to determine heat transfer and thermal properties of clothing (143-146), heat transfer coefficients for the human body segments (147,148), to predict human responses to extreme or complex thermal conditions (149,150), to determine air movement around the human body in closed spaces (151,152), and for evaluation and assessment of the thermal environment (153).

Thermal manikins have been traditionally used for indoor climate research and this application has increased recently especially within the automobile industry and building sector. The increased use of manikin in indoor climate research has led to the development of a thermal manikin that can simulate breathing and has been successfully used to assess indoor air quality (154,155), including studying of the amount of re-inhaled exhaled air. At present breathing thermal manikins are used for the evaluation of occupants' thermal comfort and inhaled air quality in buildings and vehicles as well as for the optimization of performance of HVAC systems with the emphasis on personalized ventilation systems (156-158). However, existing breathing thermal manikins cannot be used for simulating human subjective and physiological responses to transient thermal environments (159).

A detailed simulation of heat exchange between human body and the environment requires a combination of sensible and latent heat transfer. The main mechanism for heat loss in warm environments is sweat evaporation that has a significant role in comparison to the convective, radiative and conductive heat transfer. A complete understanding of these mechanisms and their impact on thermal comfort is possible only with a simulation of human sweating, which provides valuable information about heat transfer by evaporation. For this reason different complex, sophisticated, multi-function thermal manikins

have been developed recently to study the interactions of the complex body-clothing-environment system. These manikins are able to simulate sweating or perspiration, a walking motion and human dynamic thermoregulatory responses over a wide range of environmental conditions.

One example of such a manikin is a one-segment movable sweating fabric manikin 'Walter' from Hong Kong, which is used to directly measure interactions of the surface heat and mass transfer from the human body under varying climatic conditions and walking speeds (160,161). Another thermal manikin, ADAM, that was a sort of a forerunner of a new generation of multi-segments sweating thermal manikins, was developed for the American National Renewable Energy Laboratory for comfort testing (162). It was primarily intended for vehicle climate comfort testing and has been validated only for steady-state conditions in the range of comfort-related temperatures. Validation has shown deviations in predicted core and skin surface temperature of up to 0.6 K and 4.2 K respectively (163), with even larger discrepancies of core temperature under transient conditions (164). Another example is the Swiss thermal manikin SAM, developed by Empa - Swiss Federal Laboratories for Materials Testing and Research for clothing research (165). SAM is a multi-sector thermophysiological human simulator, which consists of a sweating heated device coupled with the Fiala multi-node model of the human physiology and thermal comfort in order to simulate human dynamic thermoregulatory responses over a wide range of environmental conditions. Recent validation tests conducted for steady-state and, to some extent, transient conditions revealed a good agreement with the corresponding experimental results obtained for semi-nude subjects (166). Similar thermal manikin 'Newton', produced by Measurement Technology Northwest Company in the United States, is another example of multi-segments sweating thermal manikin. It is fully jointed and can simulate walking as well as almost any possible body pose and consist of up to 34 zones (167). State of the art in the field of thermal manikins shows that sophisticated multi-function thermal manikins are more or less capable of simulating accurately the dynamic overall thermal behavior for light and moderate transient conditions with some limitations in terms of clothing levels. Ongoing research is directed into improving existing human simulators that should respond to the transient thermal environment dynamically as real humans do.

6. CONCLUSION

The last twenty years have witnessed significant advances in the field of thermal comfort that build on the foundations laid the preceding century. The PMV-model that was derived in the 1960s is still prescribed by thermal comfort standards as the most important method to evaluate thermal comfort. The greatest advantage of the deterministic PMV-model is its wide application range. The emergence of models of adaptive thermal comfort stems from research from the 1990s and the first decade of the 21st century. Such models are on the threshold of wide-spread application. The current application range is still subject to debate, which leads to the risk of use beyond the application thresholds. The adaptive models pose advantages in terms of practical application and interpretation of results, and deal with human responses and adaptation in naturally ventilated settings. Personal control of the indoor climate and human performance have become important directions of study and practice. Unfortunately it is very rare that people have actual control over their environment, given that the whole issue of establishing objective criteria for comfort stems right from the extreme variability that human beings display when it comes to establishing thermal comfort. If each and everyone of use could freely adjust the air temperature and velocity, and/or his/her activity level or clothing there would be 'no' discomfort to begin with. The more control an individual has over the comfort-related parameters (both physical and behavioral), the more relaxation can be tolerated in standards. So it is not so much a matter of naturally versus artificially controlled environments but flexibility versus rigidity whether occupants are comfortable and satisfied.

The computerization of society has led to the emergence of sophisticated multi-segmental models of human physiology and computational fluid dynamics that can be used for improved thermal comfort predictions for laboratory purposes and the design of buildings. A great challenge to the use of thermophysiological models is to link the outcomes to the perception of thermal comfort. Whereas current thermal comfort standards mainly address low-resolution problems in office building, increased computational capacities will help solve high-resolution thermal comfort issues in both real-life and laboratory settings.

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