Indoor Air 2008; 18: 182–201
www.blackwellpublishing.com/ina
Printed in Singapore.

INDOOR AIR
doi:10.1111/j.1600-0668.2007.00516.x

Forty years of Fanger's model of thermal comfort: comfort for all?

Abstract The predicted mean vote (PMV) model of thermal comfort, created by Fanger in the late 1960s, is used worldwide to assess thermal comfort. Fanger based his model on college-aged students for use in invariant environmental conditions in air-conditioned buildings in moderate thermal climate zones. Environmental engineering practice calls for a predictive method that is applicable to all types of people in any kind of building in every climate zone. In this publication, existing support and criticism, as well as modifications to the PMV model are discussed in light of the requirements by environmental engineering practice in the 21st century in order to move from a predicted mean vote to comfort for all. Improved prediction of thermal comfort can be achieved through improving the validity of the PMV model, better specification of the model's input parameters, and accounting for outdoor thermal conditions and special groups. The application range of the PMV model can be enlarged, for instance, by using the model to assess the effects of the thermal environment on productivity and behavior, and interactions with other indoor environmental parameters, and the use of information and communication technologies. Even with such modifications to thermal comfort evaluation, thermal comfort for all can only be achieved when occupants have effective control over their own thermal environment.

J. van Hoof
Faculty Chair of Demand Driven Care, Faculty of Health Care, Hogeschool Utrecht, Utrecht, The Netherlands, Faculty of Architecture, Building and Planning, Technische Universiteit Eindhoven, Eindhoven, The Netherlands

Key words: Thermal comfort; PMV model; Validity; Adaptive; Personal control.

J. van Hoof
Lectoraat Vraaggestuurde Zorg
Faculteit Gezondheidszorg
Hogeschool Utrecht
Bolognalaan 101
3584 CJ Utrecht
The Netherlands
Tel.: +31 30 2585268
Fax: +31 30 2540608
e-mail: joost.vanhoof@hu.nl

Received for review 20 May 2007. Accepted for publication 30 December 2007.

Practical Implications

The paper treats the assessment of thermal comfort using the PMV model of Fanger, and deals with the strengths and limitations of this model. Readers are made familiar to some opportunities for use in the 21st-century information society.

Introduction

Thermal comfort contributes to overall satisfaction, well-being and performance. Comfort is an important parameter in the building design process as modern man spends most of the day indoors. In the 1970s and 1980s, the development and usage of energy balance models of the human body came within the focus of human biometeorology (Höppe, 1997). The most important contributor was P.O. Fanger (1934–2006), who created a predictive model for general, or whole-body, thermal comfort during the second half of the 1960s from laboratory and climate chamber research. In that period, environmental techniques were improving, wealth increased and workers wanted the best indoor environment, while at the same time offices were growing larger (McIntyre, 1984). 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 (Fanger, 1967). It provided a solution for predicting the optimum temperature for a group in, for instance, an open plan office, which could be provided by architects and engineers (McIntyre, 1984). This new predicted mean vote (PMV) model has become the internationally accepted model for describing the predicted mean thermal perception of building occupants.

Fanger (1970) 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. PMV is based on Fanger's comfort equation (Fanger, 1967). The satisfaction of the comfort equation is a condition for optimal thermal comfort of a large group of people, or, when most of this group experiences thermal neutrality, and no local discomfort exists. Based on PMV, the predicted percentage of dissatisfied (PPD) can be determined

$$\mathrm{PPD} = 100 - 95 \times e^{(-0.03353\times \mathrm{PMV}^4 - 0.2179\times \mathrm{PMV}^2)} \quad (1)$$

(Equation 1). Fanger foresaw applications for the comfort equation in thermostats, the design of life support systems, work units and in relation to meteorology. For application in environmental engineering, PMV was needed to assess a given room climate in terms of deviations from an optimum thermal situation. This became of great importance after the oil crisis, when the focus of research abandoned the central optimum, and began to explore the edges of comfort, searching for how cold or warm it could get before getting uncomfortable (McIntyre, 1984). The PMV model has since been the basis of numerous studies and experiments worldwide. As with any model, it has been subject to criticism and support.

The PMV model applies to healthy adult people and cannot, without corrections, be applied to children, older adults and the disabled. The model has been globally applied for almost 40 years throughout all building types, although Fanger was quite clear that his PMV model was intended for application by the heating, ventilation and air-conditioning (HVAC) industry in the creation of artificial climates in controlled spaces (de Dear and Brager, 2002; Fanger, 1970). Fanger's PMV model is adopted by many (inter)national standards and guidelines, for instance, ISO 7730, ASHRAE Standard 55, and CEN CR 1752, for providing an index of thermal comfort, and, even after the latest rounds of thermal comfort standard revisions, is still the official tool to evaluate thermal comfort, although a new adaptive model developed in the 1990s by Brager and de Dear was incorporated alongside the PMV model as an optional method.

Given the passing away of Fanger in September 2006, numerous (field) validation studies on thermal comfort, the emergence of adaptive thermal comfort models and the ever growing need and search for improved comfort for all building occupants, it is time to give consideration to Fanger's contribution, or legacy, to the world thermal comfort research, and to explore what his model might bring us in the near future. The central goal of this article is to provide an overview of the developments in thermal comfort practice since the introduction of the PMV model by Fanger in 1970. It explores the meaning and potential of the PMV model by literature research for past and present use, and future application by, indoor air scientists, environmental engineers, and the HVAC industry. Fanger's elaborate work in the field of indoor air quality (Fanger, 2004a, 2006) is not part of the scope of this paper. The objectives of this publication, which have been chosen in accordance with questions from engineering practice, are to: (i) summarize criticism regarding the PMV model and its input parameters, and (ii) the validity of the model, while at the same time, (iii) extending its application domain, and (iv) improving individual comfort.

Literature review

The literature search was divided into several categories: (i) studies regarding the validity of the PMV model, (ii) studies regarding the model's input parameters, (iii) studies regarding the application of the model in relation to building type and climate, (iv) the use of the PMV model for special groups, (v) studies regarding the new applications of the model, and (vi) individualized thermal comfort.

Electronic databases of scientific publications that were searched include ScienceDirect, PubMed, and Web of Science. Also, selected journals were searched for relevant articles: Building and Environment, Energy and Buildings, International Journal of Biometeorology, ASHRAE Transactions, Indoor Air, Proceedings of Indoor Air and Healthy Buildings. The university libraries of Eindhoven and Delft were also browsed for non-digitally available books and dissertations. Articles providing relevant background information were also taken into account.

Basis of the PMV model

The human body produces heat, exchanges heat with the environment, and loses heat by diffusion and evaporation of body liquids. During normal activities these processes result in an average core body temperature of approximately 37°C (Prek, 2005). The body's temperature control system tries to maintain these temperatures even when thermal disturbances occur. The human body should meet a number of conditions in order to perceive thermal comfort. According to Fanger (1970), these requirements for steady-state thermal comfort are: (i) the body is in heat balance, (ii) mean skin temperature and sweat rate, influencing this heat balance, are within certain limits, and (iii) no local discomfort exists. Local discomfort to be avoided includes draughts, radiant asymmetry, or temperature gradients. Moreover, high frequency of temperature fluctuation should be minimized as well. In order to describe these physical processes, Fanger derived his comfort equation (Fanger, 1967) based on college-age students exposed to steady-state conditions in a climate chamber for a 3-h period in winter at sea level (1,013 hPa) while wearing standardized clothing and performing standardized activities, for use within temperate climate zones (Fanger, 1970). Although the comfort equation may probably be applied in the tropics as well, Fanger (1970) stated this needed further research. Also, there were no reliable corrections available for extreme climate conditions.

For practical applications, in which subjects do not feel neutral, an extension of the comfort equation was needed. By combining data (n = 1396) from various studies, Fanger expanded his comfort equation into the current PMV model. This thermal sensation index predicts the mean thermal sensation vote for a large group of persons and indicates the deviation from presumed 'optimal' thermal comfort, i.e., thermoneutrality. Results of the PMV model are expressed on the 7-point ASHRAE scale of thermal sensation. The central three categories of this scale are labeled 'slightly cool,' 'neutral,' and 'slightly warm.' It is generally accepted that a person with a thermal sensation in one of these three categories considers his environment acceptable, and that someone voting in one of the four outer categories is dissatisfied with his thermal environment (McIntyre, 1984).

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 velocity and relative humidity are measured, and activity level and clothing insulation are estimated using tables. Activity level is measured in terms of metabolic rate, or met units, and clothing insulation in clo units (Gagge et al., 1941). To insure a comfortable indoor environment, PMV should be kept 0 with a tolerance of ± 0.5 scale units (ISO, 2005a). In his dissertation, Fanger stated that the PMV model was derived in laboratory settings and should therefore be used with care for PMV values below -2 and above $+2$. Especially on the hot side, Fanger foresaw significant errors.

Criticism of the PMV 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. The model's validity and application range were subject to study. Many studies have given support to the PMV model while others showed discrepancies (Benton et al., 1990). Criticism involves various aspects, for instance, the model as a whole, its geographic application range, application in various types of buildings, and the model's input parameters.

Validation

The process of validation of PMV for everyday use requires the results of many field studies, covering indoor environmental conditions found in buildings across the world. An early field validation by Howell and Kennedy (1979) showed that PMV and PPD provide 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 modal comfort is somewhat closer to the cooler-than-normal position. Croome et al. (1993) suggest that the PMV model underestimates thermal impressions and undervalues the swings of these impressions, due to the assumption of steady-state laboratory conditions in the derivation of the model, an oversimplification of metabolic rates, and the sensitivity of PMV to clo-values. When deriving his model, Fanger considered his test persons to be dissatisfied if they judged the thermal environment as cold, cool, warm, or hot, or out of the range of -2 to $+2$ on the ASHRAE 7-point scale of thermal sensation. However, data referred to by Fanger show that discomfort already arises in somewhat cooler and warmer than neutral conditions, and gradually increases.

Results of the PMV model are interpreted as what a hypothetical 'average' person will feel, or as the average response of large group of people experiencing the same conditions. The model was designed to predict the latter. Within a large group, optimal thermal conditions are likely to vary between individuals by up to 1.15 K according to Fanger and Langkilde (1975), or up to 1.0 scale unit (on the ASHRAE 7-point scale of thermal sensation) according to Humphreys and Nicol (2002). Fountain et al. (1996) stated that individual differences are frequently greater than 1.0 scale unit when people are exposed to the same environment (inter-individual variance). In addition, how a person feels in the same environment from day-to-day can also vary on the order of 1.0 scale value (intra-individual variance). This corresponds to approximately 3 K; the full width of the comfort zone in either summer or winter (Fountain et al., 1996). Therefore, it is impossible to exactly predict thermal comfort for individuals, and that is the reason the comfort zone is as wide as it is, and why it is unreasonable to expect all people to be satisfied within a centrally controlled environment, even when the thermal conditions meet current standards.

A validation by Humphreys and Nicol (2002) based on a meta-analysis of data from the ASHRAE RP-884 database (de Dear et al., 1997), showed that PMV was a valid index. It predicted thermal sensation within 0.11 ± 0.01 scale units of the observed votes. When separate database samples were analyzed, 33 out of a total of 41 samples showed evidence of bias in PMV, often exceeding 0.25 scale units, and reaching as much as 1.0 scale unit. Humphreys and Nicol (2002) found that the more thermal conditions moved away from neutral, the larger the bias. PMV is only reliable between -0.5 and 0.5, unlike the range of validity stated by Fanger and given in ISO 7730

(−2.0 < PMV < 2.0). This makes the PMV model seem unrealistic for application in field settings.

Researchers have compared the results of the PMV model against the votes of subjects (actual mean vote, AMV) on the ASHRAE 7-point scale of thermal sensation. Doherty and Arens (1988) reviewed climate chamber studies and found that there were discrepancies between predicted and actual thermal sensation as large as 1.3 scale units. A comparison of the actual and PMVs by Parsons (2002) showed that the PMVs predicted AMVs within 0.5 of a scale value for neutral and warm conditions. However, in slightly cool to cool conditions subjects were between neutral and slightly cool, and hence, warmer than predicted. Parsons concluded that changes in thermal comfort responses in neutral and slightly warm environments are small and unlikely to be of practical significance. Kähkönen (1991) assessed thermal comfort in 17 enterprises at 129 work sites in shops, stores, and offices. The estimated PMV indicated that the thermal environment was too warm, and in fact, the calculated PMVs were usually lower than the estimated ones. In a previous study by Kähkönen and Ilmarinen (1989) in 13 shops and stores, workers were asked to rate their subjective thermal sensations (n = 96). No correlation was found between calculated PMV and subjective ratings.

Various researchers found a different relationship between PMV and PPD than the one described by Fanger (Figure 1). Araújo and Araújo (1999) found a PPD of 47.5% corresponding to a PMV of 0.0 based on an assessment (n = 1866 votes, mean clo 0.6, naturally ventilated) carried out in secondary school buildings and a university in Brazil

$$\mathrm{PPD} = 100 - 52.5 \times e^{-(0.03353 \times \mathrm{PMV}^4 + 0.2179 \times \mathrm{PMV}^2)} \quad (2)$$

(Equation 2). Korean climate chamber research by Yoon et al. (1999) found a minimum PPD of 18% matching with a PMV of −0.8

$$\mathrm{PPD} = 11.37 \times \mathrm{PMV}^2 + 18.34 \times \mathrm{PMV} + 24.42 \quad (3)$$

(Equation 3) (n = 40 students, mean clo 0.4, summer, mean met 1.2). People involved in the study preferred cooler temperatures. A German study by Mayer (1997) based on approximately 100 subjects found a minimum PPD of 16% instead of 5%, corresponding to a PMV of 0.5 instead of 0.0

$$\mathrm{PPD} = 100 - 84.3 \times e^{[0.01(\mathrm{PMV}-0.4)^4 + 0.5479(\mathrm{PMV}-0.4)^2]} \quad (4)$$

(Equation 4). There is a shift in the curve to the warm side and to higher PPD for the cold side. de Paula Xavier and Roberto (2000) produced a thermal sensation index S

$$S = 0.219 t_0 + 0.012 \times RH - 0.547 v_a - 5.83 \quad (5)$$

(Equation 5) similar to PMV, through field studies in a school in Brazil (> 1200 votes). This thermal sensation index corresponds to a PPD I

$$I = 18.94 S^2 - 0.24 S + 25.41 \quad (6)$$

(Equation 6). If the thermal sensation index is neutral, the PPD is 25.4%. The different outcomes of these studies may be due to the building ventilation type (natural ventilation/field study vs. air-conditioning/climate chamber), and the small number of subjects that may have a large inter-individual spread in thermal preferences. The studies mentioned do illustrate that the outcomes of the PMV model should be used with caution, as errors may occur when using this large-group model for small samples.

Field validations of the PMV model have raised discussions on the validity and reliability of the model for use in real-world settings. Large discrepancies were found between outcomes of the PMV model and

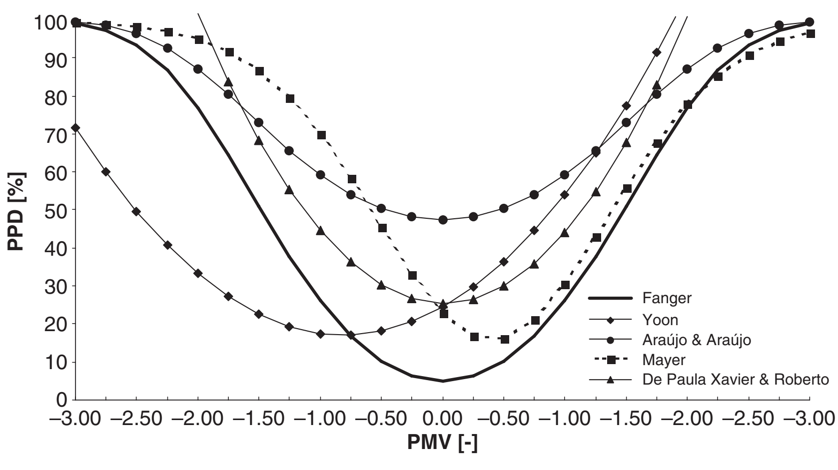

Fig. 1 Relationship between predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) and other thermal sensation indices

comfort votes of subjects. Also, various researchers found a different relationship between thermal votes and dissatisfaction than the one described by Fanger, in smaller climate chamber and field studies.

Thermoneutrality vs. preferred thermal sensation

The PMV model is based on the concept of thermoneutrality, and PMV expresses how warm or cool occupants perceive the thermal environment. This thermal sensation is a measure of how occupants perceive a certain thermal condition. Other measures such as thermal satisfaction, thermal acceptability, thermal comfort, and thermal preference, also deal with the appropriateness of a given thermal condition. Values ranging from −1 to 1 on the ASHRAE scale of thermal sensation are often considered to reflect satisfaction with a given thermal environment. However, direct measures of thermal satisfaction and acceptability are not incorporated in the current PMV model. Thermal neutrality does not necessarily have to correspond to the desired or preferred thermal sensation, for instance, when people like it slightly warm (Humphreys and Hancock, 2007). In addition, Fountain et al. (1996) mentioned two fundamental assumptions that need further discussion: (i) optimum temperature corresponds to a 'neutral' thermal sensation, and (ii) the notion of 'acceptability' is associated with specific thermal sensations on the ASHRAE 7-point scale of thermal sensation. It is suggested that thermal sensation cannot be assumed to be the equivalent of evaluative measures mentioned above, and that the PMV model requires a critical interpretation and application (Fountain et al., 1996). These considerations are supported by other studies (Table 1).

Various field and climate chamber studies showed differences between both neutral and preferred temperatures, as well as differences between field and climate chamber research. In a review by Humphreys (1994), the observed neutral temperatures in eight climate chamber studies were between 0.8 K lower and 3 K higher than predicted by the PMV model. In a combined field (n = 497) and climate chamber (n = 455) study in the UK (season and building ventilation type unknown), Williams (1995) found that people preferred lower temperatures. Field data showed a 2.5 K difference between the air temperature at which people felt most comfortable and that predicted using PMV, whereas the climate chamber only gave a 0.5 K difference compared to PMV. In a review of field studies in air-conditioned and naturally ventilated buildings, Brager and de Dear (1998) found that the observed and predicted neutral temperatures were overestimated by as much as 2.1 K (Melbourne, summer), and underestimated by up to 3.4 K (Bangkok, time of year not mentioned); both extremes in naturally ventilated buildings.

Various studies from Asia on neutral and preferred temperatures found that these temperatures were often higher than based on the PMV model, and found considerable between-subjects differences (Table 2). For instance, Humphreys (1994) provides an overview of mainly Asian studies on this matter, and mentions that one study on Malays in London and Malaysia had a difference in neutral temperature as large as 3 K.

Table 1 Selection of studies showing that thermal comfort does not only occur around thermal neutrality

Reference	Location	Setting	Time of year	Subjects	Results
Schiller (1990)	San Francisco Bay Area, USA	Field	Winter and summer 1987	304 subjects (187 females, 117 males) in 10 office buildings (2342 visits)	People generally felt warmer than predicted more often than they felt cooler, in both seasons. 22% (winter) and 15% (summer) of people voting +2 and +3 on a 7-point scale of thermal sensation stated to be moderately to very comfortable on a 6-point scale of thermal comfort. At the same time, 17% (winter) and 34% (summer) of people voting −2 and −3 stated to be moderately to very comfortable too
Busch (1990, 1992)	Bangkok, Thailand	Field	Hot season and wet season 1988	Over 1,100 Thai office workers in AC and NV buildings	36% of people voting neutral preferred to feel warmer or cooler
Brager et al. (1994)	Various countries	Review of field studies	Summers and winters	Office workers	Of occupants voting in the outer categories of the thermal sensation scale (−3,−2,+2,+3), 0 to 50% preferred no change to their thermal environment. Also, of occupants voting in the same outer categories (−3,−2,+2,+3, other studies reviewed), 3–66% were comfortable
Paciuk and Becker (2002)	Haifa, Israel	Field	Summer	117 AC and NV owner-occupied dwellings	Of residents of NV homes, voting between −1 and +1 (on the 7-point scale of thermal sensation), about 47% were not comfortable (as rated on a 5-point thermal comfort scale). In AC homes, the majority of dwellers voted to be comfortable (81%), although thermal votes ranged from −1 to +3 on the 7-point scale

AC, air-conditioned; NV, naturally ventilated.

Table 2 Overview of studies from Asia on neutral and preferred temperatures

Reference	Location	Setting	Time of year	Subjects	Results
de Dear et al. (1991)	Singapore	Climate chamber	–	16 male and 16 female Asian college-age subjects	The preferred temperature was 25.4 ± 1.2°C. The preferred thermal sensation was closer to neutral than to slightly cool. Not significantly different from samples from colder climates
Ishii et al. (1993)	Japan	Experimental room	Summer 1991–1992	College-age students (n = 926)	Under warmer conditions (PMV > 0.7) the actual percentage of dissatisfied is higher than the PPD for Japanese subjects. This suggests that Japanese perceive a cool environment as less comfortable, and a warm environment as less uncomfortable, than Westerners do
Kimura et al. (1994)	Tokyo, Japan	Climate chamber	Summer	College-age persons (n = 172): 50% male, 50% female	Japanese subjects transpired less and had lower skin wettedness than American counterparts, even at higher temperature and relative humidity
Karyono (1995)	Jakarta, Indonesia	Field	–	Indonesian office workers (n = 596)	The actual neutral temperature was 26.7°C, which is 1.2 K higher than provided by the PMV model. People preferred slightly warmer temperatures
Ahmed et al. (1990)	Dhaka, Bangladesh	Field data, calculations	Year round	Occupants using electric fans in summer (no air-conditioning)	Neutral temperatures ranged from 18.0°C in January to 26.8°C in August. The comfort zone stretches from 16.0 to 28.8°C. These figures show agreement with the PMV model for lightly clothed people and high air velocities
Chan et al. (1998)	Hong Kong Island and Kowloon, Hong Kong	Field	Summer and winter	Office workers in 13 buildings. Summer: (n = 1198), winter: (n = 975)	The preferred temperature was 22.5°C, which is 1 K lower than the neutral temperature. Neutral and preferred temperatures are lower than those found in other studies in the tropics
Sassa et al. (1999)	Nara, Japan	Climate chamber	Summer 1995	Healthy college-age females (n = 29)	The preferred air temperature of lightly clothed female subjects ranged from 23.6 to 30.8°C (27 ± 2.0°C)
Yoon et al. (1999)	South Korea	Climate chamber	Summer	Male and female university students (n = 40)	The preferred operative temperature was 25.7°C, which is 0.9 K lower than specified in ASHRAE Standard 55
Nakano et al. (2002)	Tokyo, Japan	Field	All four seasons (1997–1998)	Multinational office workers (n = 406); 60% Japanese (97 male, 161 female) and 40% non-domestic (125 male, 23 female)	The neutral temperature of Japanese women was 25.2°C (Japanese men 23.4°C), while the neutral temperature of European and North-American men was 22.1°C under the same conditions. This is a 3.1 K difference
Wang et al. (2003)	Harbin, China	Field	Winter 2000–2001	120 participants in residential districts (61 females, 59 males)	The neutral operative temperature was 21.5°C, whereas the preferred operative temperature was 21.9°C, indicating that people want it slightly warmer

In a normally distributed population, about 95% of neutral temperatures of subjects will be within the range of four times the standard deviation (Wyon, 1994). Wyon (1994) further stated that in the derivation of the PMV model this range was 6.4 K, whereas a French study found a 10.4 K range, and an American study even a 13.6 K range. Wyon (1994) continues by stating that 'when individual variation is so large, […] the practical value of estimating group mean neutral temperatures is very limited. It is more important to provide the practical means for individuals to adjust their own heat loss, than to try to guess what the collective average of their individually preferred temperatures might be.'

Differences found between field and climate chamber research are explained by the greater variation in occupants' clothing patterns in real buildings, compared to the standard uniforms used in laboratory studies. Too high estimations by the PMV model might be found in erroneous values for metabolism and clothing insulation during the derivation of the comfort equation. Fanger's test persons wore the KSU clothing combination, of which the insulation was estimated at 0.6 clo. According to Nishi et al. (1975), this turned out to be only 0.32. A wrong estimation in clothing insulation, however, cannot be the only explanation.

In conclusion, (i) thermal neutrality is not necessarily ideal for a significant number of people, and (ii) preferences for non-neutral thermal sensations are common, very asymmetrically around neutrality, and in several cases are influenced by season. Also, (iii) 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.

Differences among building types

At present, the PMV model is applied globally throughout every type of building. However, the model was developed from laboratory studies, and the effects of building type were not considered. 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 or hybrid buildings (de Dear et al., 1997). 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 (de Dear, 2004). This is reflected by numerous studies, which showed that the neutral temperature observed in air-conditioned buildings differs from that observed in naturally ventilated buildings in the same climatic context (Table 3).

de Dear et al. (1997) showed that occupants of air-conditioned buildings are twice as sensitive to temperature changes as those of naturally ventilated buildings. In contrast, Humphreys and Nicol (2002) found no difference between the accuracy of the predicted responses in air-conditioned and free-running buildings because of noticeable variations in thermal environments of the buildings. PMV provides larger accuracy in terms of the average preferences for air-conditioned buildings due to narrower bandwidths of the thermal environment. It is wrong to assume that the use of PMV is without exception correct when used for people in air-conditioned buildings (Humphreys and Nicol, 2002). According to de Dear and Brager (1998), the PMV model is not applicable to naturally ventilated buildings, because it only partly accounts for thermal adaptation to the indoor environment. Or, as stated by de Dear (2004), the PMV model has lost much of its predictive ability in naturally ventilated buildings. Therefore, a model of adaptive thermal comfort has been proposed for free-running buildings, which relates the neutral temperature indoors to the monthly average temperature outdoors (de Dear and Brager, 1998). This model is incorporated into ASHRAE (2004) Standard 55 as an optional method, applicable in naturally ventilated office buildings for people engaged in sedentary activity, when 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 (de Dear et al., 1997; Humphreys and Nicol, 2002). In temperate climate zones, the comfort zones of adaptive models and the PMV model are largely superimposed over one another (van Hoof and Hensen, 2007). An adaptive model proposed earlier for fully air-conditioned buildings has not been included in the ASHRAE Standard.

Fanger and Toftum (2002) see the exclusion of the six input parameters of PMV that have an impact on the human heat balance as an obvious weakness of the adaptive model. Although the PMV model is often referred to as a 'static' model, it turns out to be an adaptive model as it accounts for behavioral adjustments and fully explains adaptation occurring in air-conditioned buildings (de Dear and Brager, 2002). Fanger (2004b) expressed some thoughts on the linguistic problems concerning the term 'adaptive'. "Adaptation should be a process of machines adapting to human requirements and ergonomics, not the adaptation of humans to technology."

Although the PMV model is still applied throughout every type of building all across the globe, it was found that (i) for naturally ventilated buildings the indoor temperature regarded as most comfortable increases significantly in warmer climatic contexts, and decreases in colder climate zones, and that (ii) the neutral temperature observed in air-conditioned buildings differs from that observed in naturally ventilated buildings in the same climatic context. This led to the

Table 3 Overview of studies showing that the neutral temperature observed in air-conditioned (AC) and naturally ventilated (NV) buildings differs from each other in the same climatic context

Reference	Location	Setting	Time of year	Subjects	Results
de Dear and Auliciems (1985)	Brisbane and Melbourne, Australia	Field	Summer	Occupants of air-conditioned and free-running office buildings (n = 2242)	Differences in neutral temperatures were 1.7 K and −1.3 K between AC and NV buildings in Brisbane and Melbourne in summer
Schiller (1990)	San Francisco Bay Area, USA	Field	Winter and summer 1987	304 subjects (187 females, 117 males) in 10 office buildings (2342 visits)	In winter, the measured neutral temperature (ET*) was 22.0°C, vs. 24.4°C predicted by PMV. In summer, the measured neutral temperature (ET*) was 22.6°C, vs. 25.0°C predicted by PMV. In both seasons, there was a 2.4 K difference between measurements and predictions
Busch (1990, 1992)	Bangkok, Thailand	Field	Hot season and wet season 1988	Over 1,100 Thai office workers in AC and NV buildings	For both seasons, temperatures at which people expressed optimal comfort had a slightly broader bandwidth in NV office buildings compared to AC buildings. In NV buildings, the PMV model underestimated neutral temperatures by 3.5 K, while in AC building it overestimated by 0.5 K. The upper limits for thermal comfort in both types of office buildings were higher than stated in standards
Fan et al. (1993)	Wuxi, China	Field	All year round	10 students (5 males, 5 females), in residential buildings and a school	People prefer different thermal conditions during long-term exposure without space heating or cooling than based on thermal comfort standards. Local young people accepted operative temperatures of 10–12°C in winter
Oseland (1996)	UK	Field	Winter and summer	Winter: (n = 935 questionnaires) + 6,050 half-day questionnaires. Summer: (n = 5,037 questionnaires), in 4 NV and 4 AC buildings	In NV offices, the neutral temperature was 1.3 to 2.2 K (winter-summer) lower than in AC buildings. At the same time, there were only minor differences between dress code and activity levels. Discrepancies of up to 4 K were found between the observed neutral temperatures in NV buildings and those predicted by the PMV model
Ealiwa et al. (1999)	Ghadames, Libya	Field	Summer 1997–1998	Residents (n = 60) of NV (50%) and mechanically (50%) ventilated dwellings	Occupants were comfortable at temperatures to 35.6°C in traditional buildings compared to 30.0°C in AC buildings. The PMV model failed to predict comfort temperatures adequately
Nicol et al. (1999)	Karachi, Multan, Quetta, Islamabad, Peshawar, and Saidu Sharif, Pakistan	Field (2 studies)	(1) Longitudinal in summer and winter, and (2) transverse with monthly surveys over a year	Both residential and commercial buildings. (n = 36 subjects, n = 4927 questionnaires). Study 2: (n = 846 subjects, n = 7,112 data sets)	PMV tended to overestimate the impact of high indoor temperatures especially in summertime conditions, overemphasizing the need for air-conditioning. There was generally little discomfort at indoor globe temperatures between 20 and 30°C
van der Linden et al. (2002)	the Netherlands	Field	Summer (≤ 1990)	Samples from 29 AC buildings, 32 with individual temperature control, of which 21 with natural and 11 mechanical ventilation. Number of subjects not mentioned	Occupants of NV and mechanically ventilated buildings experienced the indoor climate as being warmer than in AC buildings, even though the percentage of dissatisfied (PD) is lower in the first two buildings (PD 25%, AMV 0.5/PD 41%, AMV 1.0) than in air-conditioned buildings (PD 42%, AMV 0.5/PD 49%, AMV 1.0)
Heidari and Sharples (2002)	Ilam, Iran	Field	Hot summer and cold winter 1998, and whole year 1999	Occupants of NV buildings. Hot summer (n = 513), Cold winter (n = 378), whole year (n = 30 people, n = 3819 questionnaires)	The neutral temperature during the hot summer in the short-term study was 28.4°C, and 26.7°C for the long-term study. The neutral temperature during the cold winter in the short-term study was 20.8°C, and 21.2°C for the long-term study. People in NV buildings were comfortable at indoor higher temperatures than recommended by standards
Feriadi and Hien (2003)	Samples from Singapore and Indonesia	Field data, simulations	Rainy and dry seasons (2000–2002)	Singapore (n = 538), Indonesia (n = 525)	PMV model has discrepancies for NV buildings in the tropics in terms of tolerance and perception of thermal comfort, which is due to lexical uncertainty of the ASHRAE 7-point scale of thermal sensation. People in the tropics may have another perception of the meaning of the word 'warm' than people from temperate maritime climates. In tropical conditions it fails to give accurate information about the temperatures people find comfortable

Table 3 (Continued)

Reference	Location	Setting	Time of year	Subjects	Results
Fato et al. (2004), Conte and Fato (2000)	Bari, Italy	Field	Summer (1995, 1999), and winter (1996, 2000)	University students. Sample size: 423 in 1995, 1034 in 1996, 250 in 1999, and 133 in 2000. Building type (two modes): AC in winter, NV in summer	Neutral temperatures were 24.4°C in summer 1995, 26.3°C in summer 1999, 20.7°C in winter 1996, and 20.6°C in winter 2000. Occupants of NV buildings (summer) regarded a 3.3 K and 2.1 K bandwidth to be acceptable compared to 3.6 K in AC buildings (winter)
Yamtraipat et al. (2005)	Thailand (Chiang Mai, Bangkok & Mahasarakham, Prachuabkirikhan)	Field	August 2001	Users of AC buildings in private and public sectors (n = 1520)	The neutral temperature of people with a post-graduate education level was the lowest around 25.3°C, while that of the other groups (graduate and scholar) was higher at 26.0°C. For people with air-conditioning home, the difference between neutral temperature of every education level is rather small (0.3 K). However, for the other group (no air-conditioning), the difference of 0.9 K is larger. People with higher educational degrees are found to prefer lower indoor temperature compared to the less-educated

development of a model of adaptive thermal comfort, which is now an optional method alongside the PMV model for application to naturally ventilated buildings.

Improving the PMV model

Many researchers have tried to find ways to optimize the use of the PMV model, for instance, by improving the model and enlarging its application domain. Improving the original PMV model is twofold; first, by correcting or adjusting the model itself, second by introducing methods to increasing the accuracy of the model's input parameters.

Adjusting the model

The ability to incorporate expectation into the evaluation of thermal comfort is an area where the heat balance models offer no information. The difference does not lie in physiology but in expectation (Fountain et al., 1996). Fanger and Toftum (2002) acknowledged some of the limitations of the PMV model, as Fanger already did in his 1970 dissertation, and proposed an extension to free-running buildings in warm climates by introducing two correction factors. First, factor '**e**' should be introduced to account for expectancy of the occupants depending on previous thermal experiences. This factor is to be multiplied with PMV to reach the mean thermal sensation vote of the occupants. Based on professional judgment, **e** varies between 1 and 0.5 (1 for buildings with HVAC, for buildings without HVAC **e** is assumed to depend on the annual duration of the warm weather, and if these buildings can be compared with other buildings with HVAC in the region) (Table 4). The second factor is a reduced activity level, as it is slowed down unconsciously by people feeling warm as a form of adaptation. The new extension predicts the actual votes well, and it 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 with direct impact on the human heat balance.

Humphreys and Nicol (2002) provide a statistical method named PMV_{new}, which is illustrative only, and is not recommended for using as a replacement index

Table 4 Expectancy factors in relation to building classification and expectation (Fanger and Toftum, 2002)

Expectation	Building classification	Expectancy factor e
High	Non-HVAC in regions where HVAC buildings are common. Warm periods occurring briefly during summer season	0.9–1.0
Moderate	Non-HVAC in regions with some HVAC buildings. Warm summer season	0.7–0.9
Low	Non-HVAC in regions with few HVAC buildings. Warm weather during all seasons	0.5–0.7

$$\mathrm{PMV}_{\mathrm{new}} = 0.8(\mathrm{PMV} - D_{\mathrm{PMV}}) \tag{7}$$

$$D_{\mathrm{PMV}} = -4.03 + 0.0949T_0 + 0.00584 \times RH + 1.201(MI_{\mathrm{cl}}) + 0.000838T_{\mathrm{out}}^2 \tag{8}$$

(Equations 7 and 8). They state that the appropriate method to revise the PMV model would be to revise its psychophysical and physiological construction, rather than to make empirical statistical adjustments. The revised PMV has a reduced bias against all the contributing variables and the ranges of validity are greatly extended. The bias against $\mathrm{PMV}_{\mathrm{new}}$ itself is much less than the PMV, extending the range of application about three-fold, though it is still unsatisfactory in cold environments. Holmér (2004) stated that for use in moderately cold and cold environments, the basic comfort criteria may also apply, but the complex heat transfer through multilayer clothing should be considered in a more adequate way. A modified PMV model was proposed by modification of the sweating criteria and some of the heat transfer equations. The suggested criteria provide more realistic and reliable prediction of heat balance and conditions for comfort in colder environments.

Gagge et al. (1986) proposed PMV* for any dry or humid environment by replacing operative temperature in Fanger's comfort equation by standard effective temperature (SET*). Two classic indices of temperature sensation and warm discomfort (PMV and DISC) are combined as generalized index PMV*, which is directly related to new effective temperature (ET*). PMV* is responsive to thermal stress caused by heat load, as well as to the physiological heat strain caused by changing humidity of the environment and by changing vapor pressure permeability properties of clothing worn. Gagge's PMV* model has been used in a limited number of studies, for instance, by Prianto and Depecker (2003). Unfortunately, the modification is unjust because Gagge and colleagues assumed that Fanger used different comfort criteria for cold and heat, instead of one. Also, Prek (2005) made a comparison between exergy consumption and the expected level of thermal comfort. Since this analysis used the two-node model and special attention was given to heat and mass transfer, a new PMV index (PMV*) was used. This model can be used for any dry or humid environment by replacing the operative temperature in Fanger's comfort equation with rational ET*. According to Prek, this modification represents an improvement as it includes the physiologic heat strain caused by the relative humidity and vapor permeability properties of clothing.

The calculation of PMV is complicated as it is nonlinear and iterative. Sherman (1985) proposed a model based on Fanger's original work to calculate PMV without iteration, by linearizing the radiation exchange terms, simplifying the convection coefficient, and using dew-point temperature. Sherman indicated that these simplifications should not affect the precision of PMV only when the occupants are near the comfort zone. Federspiel (1992) proposed another thermal sensation index V, which is a modification of the PMV index. He simplified the derivation by supposing that radiative exchange and heat transfer coefficient are linear, assuming that bodily heat production and clothing insulation are constant, and that the occupants are in a thermally neutral condition. V is a linearly parameterized function of the four environmental variables and becomes nonlinear when activity level or clothing insulation is changed, which is a limitation to the applicability of the model.

Another method for adjusting the current PMV model is through fuzzy logics, for instance, by Feriadi and Hien (2003). Hamdi et al. (1999) proposed a fuzzy thermal sensation index based on the original work of Fanger that can be used in feedback HVAC control applications with online calibration and without requiring any simplification. The difference between PMV and fuzzy PMV values was found to be lower than 0.05 for any state of the six input parameters, which indicates high precision of the proposed fuzzy PMV model.

Although many modifications to the original PMV model have been proposed and tested to date, none of these developments have yet found widespread application in environmental engineering practice. The most promising application is the extension of the PMV model to free-running buildings in warm climates by Fanger and Toftum (2002), which incorporates expectation into the evaluation of thermal comfort. Engineering practice has not yet come up with practical methods to use the extension.

The PMV model's input parameters

For an appropriate use of the PMV model, the parameters involved in the calculation of PMV need to be within certain limits (Table 5) according to ISO 7730. The validity intervals stated in this standard contribute largely to the biases in PMV (Humphreys and Nicol, 2002). Bandwidths of comfort parameters matching correct PMV are narrower than that stated in ISO 7730. The current intervals are too large, and near the extremes there is not sufficient data to confirm the validity. However, fortunately the PMV model has a bias-free range of conditions (Humphreys and Nicol, 2002). In tropical areas air temperatures frequently rise above 30°C, and air velocities in excess of 1 m/s are seen. In Jakarta, for instance, the maximum average air temperature is 33°C (Karyono, 2000). In case of naturally ventilated buildings, the PMV model cannot be used without error according to ISO 7730. Similar situations are found for architecture in deserts and vernacular buildings in cold climate zones.

Table 5 Validity intervals for PMV input parameters, taken and adapted from ISO 7730 (ISO, 2005a) and Humphreys and Nicol (2002)

Parameter	ISO 7730 (ISO, 2005a)	Humphreys and Nicol (2002) PMV free from bias if	Comment
Clothing insulation	0–2 clo (0–0.310 m^2K/W)	$0.3 < I_{cl} < 1.2$ 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	0.8–4 met (46–232 W/m^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'		$M \cdot I_{cl} < 1.2$ units of met·clo	Serious bias at 2 units
Air temperature	10–30°C		Overestimation warmth sensation $t_o > 27$°C. At higher temperatures bias becomes severe. Upper limit t_o approx. 35°C in ISO 7730
Mean radiant temperature	10–40°C		
Vapor pressure or relative humidity	0–2.7 kPa or 30–70%	RH < 60%	Suggested bias becomes important if $p_a > 2.2$ kPa
Air velocity	0–1 m/s	$v_a < 0.2$ m/s	Overestimation warmth sensation $v_a > 0.2$ m/s. Underestimation cooling effect increased v_a

Uncertainty in thermal comfort predictions and measurements of physical parameters has also been investigated by de Wit (2001). Error can also be found when instruments are malfunctioning or have not been calibrated correctly. Early thermal comfort research made use of instruments with wider ranges of error than instruments used today, particularly instruments measuring air velocity. Many studies used simple sets of instruments, often measuring on one position in a room. Uncertainty remains as to whether the indoor climate measured was representative for the room or building as a whole. ISO 7726 (ISO, 1998) prescribes that PMV shall be assessed on a height of 0.6 m for sedentary activity. This height is actually indicative, as body length differs per individual and not all chairs are of the same dimensions. Variations in heights can contribute to small variations in PMV, which are largely negligible. In climate chamber settings, physical and personal parameters can be controlled for more easily. In field setting, all variables tend to show greater variation. These differences might be the key contributor to discrepancies found between PMV and AMV. According to Fanger (1994), 'it is essential that all four environmental factors are properly measured and that a careful estimation is made of the activity and clothing,' when making a fair comparison. 'Poor input data will provide a poor prediction.'

de Dear and Brager (1998) claimed that the accuracy of the PMV model is not as good as that of the adaptive model, as some of its input parameters are not accurately specified. Activity level and clothing insulation are the two main variables that affect the uncertainty of the PMV index (Chamra et al., 2003), and are likely to contribute to differences between actual and predicted thermal sensations. Because PMV is much more sensitive to air velocity, metabolism and clothing insulation than for air or radiant temperature, estimations with some deviation can lead to large differences in PMV and thus considerable misinterpretations. In field studies, it is not possible to accurately determine clothing insulation. Therefore, some researchers specify an average clothing value for the total research population, even though there are inter-individual differences, while others make use of elaborate garment tables for better group averages or for individual calculations. The calculated clothing insulation differs by as much as 20% depending on the source of the tables and algorithms commonly used (Brager et al., 1994). Fanger claims this is due to the diversity of methods used to estimate clo-values (de Dear and Brager, 1998). In field settings, there is always some body movement increasing air velocity, particularly in non-sedentary activity. Some studies involving thermal manikins suggest that body movement has a very limited impact on clothing insulation (Olesen and Nielsen, 1984; Olesen et al., 1982). Other studies using humans suggested that there are effects of body movement (Chang et al., 1988; Vogt et al., 1984). The clo-value is reduced by increased air movement (Kimura and Tanabe, 1993), which can be as much as 25% (Tanabe et al., 1993). Havenith et al. (2002) showed that effects of body motion and air movement on clothing insulation are so big that they should be accounted for in comfort models to be physically accurate. However, effects on dry heat exchange are small for stationary, light work at low air movement. Also, algorithms for convective heat exchange in prediction models should be reconsidered. Other factors that might contribute to deviations in clo-values are body posture, material/fabric and cut, and – often omitted – the amount of chair insulation, which depends on geometry and material. McCullough et al. (1994) showed that an additional value of 0.15 clo needs to be added to one's total clothing insulation for the impact of a chair. CEN Report 1752 (CEN, 1998) mentions an additional 0.1–0.3 clo for chairs. A good example of the impact of omitting the thermal insulation posed by chairs is the aforementioned study by Brager et al. (1994). Data from the Californian offices were reanalyzed, accounting for an extra chair insulation of 0.15 clo. Also, adjustments were made based on recent clothing insulation tables (an additional 0.1 clo). The results of the new analysis showed a better correspondence between AMV and PMV.

For precise comfort assessments, a precise measure of activity level or metabolic rate is needed. In field studies, measuring physiologic parameters can be invasive and time-consuming tasks. As with clothing insulation, activity level is often equal for a group as a whole. According to Havenith et al. (2002), the methods for determining metabolic rate provided in ISO 8996 (ISO, 2004) do not provide sufficient accuracy to classify buildings to within 0.3 PMV scale units. In order to improve metabolic rate estimation based on ISO 8996, more data and detail are needed for activities with a metabolic rate below 2 met units. According to Goto et al. (2002), the metabolic rate is influenced by a person's body mass, blood flow, and fitness. Wyon (1975) found that performing mental tasks can increase activity levels up to 1.3 met units, while Humphreys (1994) states that the vigor with which certain activities are carried out can affect met values. Rowe (2001) conducted a study involving 144 occupants filling out activity checklists ($n = 1{,}627$). The mean activity level was 1.2 met units, with inter-individual and over-time differences ranging from 1.0 to 1.9 met.

Errors in clothing insulation and activity level are found to contribute to the inaccuracy of PMV, particularly in field studies. As differences between AMV and PMV are larger than could reasonably be attributed to these errors, other factors are probably involved as well. As comment on de Dear and Brager (1998), Fanger says: 'A careful assessment of an "average" building occupant's metabolic rate could be in error as much as plus or minus 0.3 met units and that what researchers might rate as a "typical office task" 1.2 met is in fact a "siesta" 0.9 met in certain parts of the world. In view of this enormous difficulty in getting the PMV-inputs right, we feel that [...] an adaptive model is probably not such a bad thing after all...'

For an appropriate use of the PMV model, the parameters involved in the calculation of PMV need to be within certain limits, but the bandwidths of comfort parameters are subject to discussion. The quality of predictions and evaluations also depends on the accuracy of input parameters, especially clothing insulation and activity level, and measurements. Wrong estimations of clothing insulation and activity level may even be contributing to the inaccuracy of PMV, particularly in field studies.

Extensions to the application domain

The current PMV model is used for assessing and predicting thermal comfort in indoor spaces, often offices with presumably stable thermal conditions. New insight is gained for application in semi-outdoor environments and in transient thermal conditions, as well as on interaction between various indoor environmental parameters and the use of the PMV model for non-office workers, such as older adults. Moreover, the model holds interesting promises for other applications, such as in a control strategy for optimizing productivity and in relation to environmental psychological factors. The latter also play a major role in offering modes for individualized thermal comfort.

The PMV model for (semi-)outdoor use. Potter and de Dear (2000) asked themselves a question: 'Why do holiday makers deliberately seek out thermal environments, that would rate "off the scale" if they were encountered indoors?' In their investigation of outdoor scenarios, the researchers found that outdoor neutral temperatures were about 3 K higher than for indoor spaces. Indoor and outdoor thermal sensations are perceived in a different manner.

Current comfort standards do not clearly address transitional spaces, locations where the physical environment bridges between the interior and exterior environment. Outdoor situations are not included either. When designing the PMV model, it was never intended for use in such spaces. Clothing insulation is generally higher in transitional spaces, as people are often traveling to another destination and dress for the outdoor weather. Field research from Thailand on transitional spaces by Jitkhajornwanich et al. (1998) showed that the neutral temperature was 27.1°C while the thermal acceptability was between 25.5 and 31.5°C, whereas the expected neutral temperature, based on the PMV model, was 26.7°C. Chun et al. (2004) found that the PMV model cannot be used for thermal comfort predictions in transitional spaces, because of unstable and dynamic physical conditions and met values. This is especially true for outdoor pavilions, where PMV often travels out of the validity range of $-2 < \text{PMV} < +2$. These two studies from Asia suggest that PMV cannot be used as an evaluative parameter in semi-outdoor spaces.

Thermal sensation outdoors is perceived differently from that of indoors. This implies that models for indoor thermal comfort are not applicable to the outdoor settings (Höppe, 2002). By parameterization of the complex radiation fluxes outdoors, Fanger's comfort equation became a universally acceptable model, which is used today under the name of Klima-Michel-Modell (Höppe, 1997). Various similar efforts have been undertaken by various researchers worldwide.

Transient thermal conditions. In practice, the indoor environment is often characterized by transient or spatially non-uniform thermal conditions. Fanger (1970) stated that his model was valid only for invariant conditions – constant environmental values. Thermal conditions in buildings are seldom steady, due to the interaction between building structure, climate, occupancy, and HVAC system (Hensen, 1990). Transient conditions in the indoor environment include periodic variations, ramps, and drifts. In his dissertation, Fanger mentioned that unhealthy shock effects may be found in air-conditioned spaces when people move from hot to cold.

According to Goto et al. (2002), steady-state models for the prediction of thermal sensation seem to be applicable after approximately 15 min of constant activity. Climate chamber research by Iwamoto and Yoneki (1999), comparing thermal sensation at the start of a low humidity air-conditioning system and domestic air conditioner from subjects' votes ($n = 104$), showed that soon after starting the air-conditioning, subjects did not feel so hot as indicated by PMV. Such research sets limits to the application of the PMV model, which is designed for use in artificial indoor environments, in which occupants do not necessarily have to be involved in constant activity. Currently, much investigation is carried out on transient thermal conditions, and how such conditions impact the applicability of the PMV model. New research can contribute to a proper assessment of thermal comfort in non–steady-state conditions, for which PMV was not developed according to Fanger.

Interactions. Thermal comfort has been widely investigated and standardized. In practice, overall comfort also originates from other physical parameters such as odor, lighting, and noise. Little research has been carried out on the combined effects and interactions between these different parameters. In 2004, de Dear stated that it has not been possible to assess how dissatisfactions from multiple sources are combined. It is unknown whether the dissatisfaction resulting from general thermal discomfort is additive with the percentages of those who are dissatisfied because of local discomforts, or whether the total dissatisfied may be less than the sum of the individual percentages.

A study by Pellerin and Candas (2002) on the combined effects of noise and temperature showed that females accepted noisier environments than males, suggesting that thermal comfort is more dominant for women. Noise may alter thermal pleasantness in warm conditions. Nagano and Horikoshi (2005) studied the combined effects of operative temperature and noise ($n = 22$). Results showed that both sound and temperature affected the sensation of one another. Alm et al. (1999) studied temperature, air quality, and sound pressure level as a whole and showed that out of 27 different combinations rising temperature is the most dominant factor in thermal discomfort. A difference of 1 K has the same effect on thermal perception as a difference in sound pressure level of 3.8 dB(A) or a difference in air pollution of 7 decipol at 26°C. The only significant interaction was the one between temperature and desired air quality. The perception of indoor air quality is improved when temperatures are cooler, and therefore, ventilation rates can be decreased by lowering the indoor temperature (de Dear and Brager, 2002). Elevated air speeds also have a positive influence. Within the occupied zone it could mean that thermal comfort can be achieved at higher temperatures, while simultaneously improving perceived air quality. More research on the combined effects of indoor air quality and thermal comfort was conducted by Fang et al. (2000). The higher the air's enthalpy, the staler the air is perceived. In short, people prefer rather dry and cool air (Fanger, 2001). Santos and Gunnarsen (1999) studied the interaction between thermal comfort, sound, view, and daylight, and showed that a decrease in the operative temperature of 1 K has the same effect on total comfort as an increase in 0.5 m^2 of window surface area or a decrease in the sound level of 7 dB(A). Kim and Jeong (2002) studied the effects of different levels of illumination below 1,000 lx on temperature regulation of humans ($n = 7$). The subjects preferred heavier clothing and showed stronger vasoconstriction in the upper limbs in dim light.

In case of healthy persons, building occupants balance the good features against the bad to reach their overall assessment of the indoor environment (Humphreys, 2005). 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 (Humphreys, 2005).

Results of interaction studies lead to a better understanding of the influence of the total indoor environment on occupants, and may one day lead to an integration of aspects of the PMV model with other indoor environmental parameters as people try to quantify overall comfort.

Gender, age, and disablement. In the 1960s, Fanger carried out a series of experiments to investigate the effects of inter-individual differences. From these studies, Fanger (1970) concluded that the neutral temperature of a large group of people was independent of age, body size, menstrual cycle, time of day, color and crowding of the room, gender, race, or national geographic location. The current PMV model does not account for groups other than students and people in sedentary activity, as the model was derived based on tests with approximately 1,300 students. Real buildings involve much larger and diverse samples of real occupants as opposed to college-age subjects (de Dear, 2004). In his experiments, Fanger (1970) found that women were more sensitive to fluctuations in optimum temperature than men. A comparison of the actual and PMVs by Parsons (2002) showed that for cool conditions (PMV = −2.0), females tended to be significantly cooler ($P < 0.05$) than males, and the responses of the females were close to the PMVs. Also, Nakano et al. (2002) found differences in neutral temperature between males and females (Table 2). Fanger (1970) concluded that women are more sensitive to deviations than men. Parsons concluded that for identical clothing and activity, there are few gender differences in thermal comfort responses for neutral and slightly warm conditions, although females tend to be cooler than males in cool conditions.

In a study by Karjalainen (2007), gender differences in thermal comfort were examined by a quantitative interview survey ($n = 3094$), and by controlled experiments. Females were less satisfied with room temperatures, preferred higher room temperatures, and felt both uncomfortably cold and uncomfortably hot more often than males.

Thermal comfort is not only important in work settings. In our ageing society, the voice of older adults is growing ever louder and there is a tendency of creating a more fitting building stock to accommodate this group of people. This is also expressed in the desire for excellent indoor environments, which offer thermal comfort in compliance with physical needs.

Fanger (1970) validated his model for older adults by carrying out experiments involving 128 older subjects to study the influence of age and aging. Some scientists, most of them from Japan, have since repeated studies on the effects of aging on comfort sensation. Most studies confirm that in principle older adults do not perceive comfort differently from younger groups. However, older adults have a lower activity level and basal metabolism, resulting in a preference of higher ambient temperature (Havenith, 2001; van Hoof and Hensen, 2006). These differences may also result from differences in clothing between the age groups.

Physically disabled persons respond as predicted by the PMV model, although the range of responses for physically disabled is much greater than that of healthy people at PMVs of −1.5 and 0 (Webb and Parsons, 1998). Multiple sclerosis patients are shown to have larger actual PPD than based on Fanger's PPD, and the preferred environment (PMV = 0) is slightly warmer than 23°C. Further work is needed to qualify whether preferred environments match that of PMV +1 and PMV −1 and to identify whether any of the factors such as age, duration of disability, and medication affect the actual mean vote (Webb et al., 1999). According to Haghighat et al. (1999), physically handicapped persons demonstrate thermoregulatory abnormalities in the affected portion of their bodies. Measured thermal sensations for physically handicapped persons were found to have no general tendencies. In 2002, Parsons stated that there are few group differences between thermal comfort requirements of people with and without physical disabilities. However, there is a greater necessity to consider individual requirements for people with a physical disability.

The technical specification ISO/TS 14415 (ISO, 2005b) deals with thermal comfort requirements of people with special needs and impairments. However, this technical specification is far from complete, as so few studies have been conducted in the field. More research is needed on the requirements of particularly vulnerable groups of older adults, such as those with dementia, who are hypothesized to perceive their thermal environment differently because of atrophy of their brain tissue, and who are unable to express the need for cooler or warmer conditions. Similarly, people with psychiatric impairments may respond differently to the thermal environment.

A promising new application of the PMV model for use for older adults is relating (extreme) climatic conditions to increased mortality rates in summer (Luscuere and Borst, 2002). National governments in Europe are stressing the importance of air-conditioning as a protective measure, but the impact on thermal comfort and preferences remain unclear. In nursing homes, the PMV model could be used for determining comfort of all occupants, mortality/morbidity risk resulting from heat and cold, and even productivity level of nursing staff in relation to the thermal conditions.

Besides the aged and aging, more research is needed on infants and children, who have a different metabolism and posture, especially in light of studies of the indoor environment in daycare centers and primary schools in relation to well-being and school productivity.

Productivity and the role of environmental psychology. The application range of the PMV model can be enlarged, for instance, for the prediction of productivity in relation to the thermal climate. Productivity on the work floor is affected by indoor environmental parameters, including noise and thermal discomfort. Kosonen and Tan (2003 and 2004) made a PMV-based productivity model to estimate the effects of different thermal conditions on productivity, as task-related performance is correlated with the human perception of thermal environment. The theoretical optimal productivity 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 (PL) in thinking and 26% in typing. The mathematical expressions of PL for typing and thinking tasks in offices (boundary constraints: PMV −0.21 and PMV + 1.28), are given by

$$\begin{aligned}PL_{\text{typing task}} = {} & -60.543 \times PMV^6 + 198.41 \\ & \times PMV^5 - 183.75 \times PMV^4 - 8.1178 \\ & \times PMV^3 + 50.24 \times PMV^2 + 32.123 \\ & \times PMV + 4.8988\end{aligned} \tag{9}$$

$$\begin{aligned}PL_{\text{thinking}} = {} & 1.5928 \times PMV^5 - 1.5526 \times PMV^4 \\ & - 10.401 \times PMV^3 + 19.226 \times PMV^2 \\ & + 13.389 \times PMV + 1.873\end{aligned} \tag{10}$$

(Equations 9 and 10). More studies have been carried out on the influence of thermal comfort and the indoor environment on productivity that promise interesting field of application for the PMV model in the near future.

The perception of thermal comfort is closely related to environmental psychology. The important role of environmental psychology has been discussed earlier by Heijs and Stringer (1987) and de Dear (2004). For the integrity of person–environment relationships to be preserved, thermal comfort research must be conducted within natural contexts (de Dear, 2004). In air-conditioned settings, the occupant is regarded as a passive recipient of the thermal stimuli presented by their environment, with the latter being assessed subjectively against very specific expectations of what such an environment should be like (de Dear, 2004). A field study by Howell and Stramler (1981) on the role of cognitive psychological variables (n = 260) found that there was a substantial impact of cognitive variables on thermal sensation judgments. The most important determinant of perceived comfort was, perhaps not surprisingly, perceived temperature. Rohles (1980) found that adding wood paneling, carpets, comfortable furniture and soft lights, without any changes in thermal parameters in a climate chamber, made people feel warmer. Even providing information (both true and false) could influence feelings of warmth and comfort. In winter, people preferred warm temperatures to cold temperatures, while in summer the opposite situation was found.

Other psychological factors related to thermal climate are manifold. Anderson et al. (1996) reported effects of extreme temperatures on arousal, cognition, and affect. High temperatures increase levels of aggression. Simister and Cooper (2005) reported evidence that violent crime rates vary from month to month in a seasonal pattern, and this evidence is consistent with the hypothesis that the seasonal pattern is caused by temperature. This seasonal pattern might be due to the side effects of stress hormones, which the body generates to cope with thermal stress.

Perhaps, input from environmental psychology can one day be combined with the PMV model, as a means to quantify the thermal environment, to predict the level of arousal and aggression, for instance, in hospitals, jails, or police offices.

Individual control. It is generally believed that most comfort standards specify conditions that provide comfort for everybody. The PMV model is often applied bearing this idea in mind. Unfortunately, fulfilling the criteria does not mean 100% acceptability because of individual differences in preferred temperature. 'When the building is later constructed and occupied, it is sometimes believed that the building should be operated strictly according to [such criteria]. This was never the intention. The standard should be a servant, not a master' (Fanger, 1994). Selection of an acceptable PPD often depends on economy and technical feasibility (Fanger, 1984, 2001; Olesen et al., 2001). In practice this means 'quite a number of dissatisfied persons' (if the thermal climate is maintained in compliance with the international standards, there will be up to 10% dissatisfied people due to whole-body discomfort), 'while few seem to be ready to characterize the indoor environment as outstanding' (Fanger, 2001).

Individual differences in comfort temperature are so large that it would be a historical mistake to develop new models and standards focusing on guaranteeing thermal comfort for a group as a whole (Wyon, 1994). In air-conditioned environments, the occupants are not expected to attenuate it, or their responses to it, in any significant way. There is no need for prescriptive standards if individual control over the thermal climate is provided, allowing all occupants to be satisfied (Fanger, 2001; Fountain et al., 1996), for instance, by being able to slightly adjust temperature at the workplace level. 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' (McIntyre, 1984).

Palonen et al. (1993) recommended that a temperature range of 20–24°C without individual temperature control is too wide a range from the point of thermal comfort. Room temperature should stay between 21 and 23°C if no control is available. The best solution is an individual temperature control that gives the possibility to adjust the room temperature at 22 ± 2°C. In rooms with conventional mixing of ventilation air, the air should be kept at a moderately low temperature that corresponds to the coolest temperature preferred by any of the occupants (Fanger, 2001). All other occupants should have access to additional personalized local heating to obtain their own preferred operative temperature. These small heating flows should be provided by radiation or conduction in order to keep the air for inhalation cool (Fanger, 2001). Individual thermal control by air movement should be avoided because of the risk of draught (Fanger, 2001). In a study investigating the use of thermostats, Karjalainen (2007) concluded that even though females were more critical of their thermal environments, males used thermostats in households more often than females. 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? More research is needed on means to individualize thermal comfort. Having control over the environment is a very effective way to limit negative health effects of stress, as one can use external coping strategies (Vroon, 1990). Providing all kinds of pseudo solutions, for instance, imitation thermostats, may have a positive effect in the beginning, but can have serious counterproductive effects some time later, as occupants feel not taken seriously (Vroon, 1990). A negative placebo effect (*nocebo* effect) can emerge resulting in a further increase in dissatisfaction with the environment (Vroon, 1990). In line with these statements, attention needs to be paid to the nature of building structures in relation to preferred fast gratification. Changes to the indoor temperature depend both on the system of heating and cooling available, and the thermal mass of the structure. In thermal activation of building parts, changes in temperature may be slow. Thermostat control may not have an immediate effect and therefore lead to more dissatisfaction and complaints.

The PMV model can be used for providing a basic thermal environment that meets the preferences of a group of people. On an individual level, people should be equipped with simple means to control the direct thermal environment in order to maximize satisfaction and comfort.

ICT and thermal comfort. The emergence of information and communication technologies (ICT) in building services engineering will lead to the development of real-time thermostats that incorporate software based on the comfort equation and the PMV model. Such systems will be at the basis of environmental systems that control the indoor climate, and offer means for controlling local environments to individual needs and in relation to the thermal conditions in adjacent spaces. Personal user profiles, based on a one's preferred temperature, and one's sensitivity to deviations on the lower and warmer side, may be incorporated in time to control the overall indoor climate. The speed at which local environments can be adapted to these needs will be essential in the success of individualized solutions. The introduction and development of these systems will undoubtedly be closely linked to energy conservation and management. Fanger (2006) stated that compromises are needed between energy conservation and best possible indoor environments. New developments in the field of indoor air quality may provide room for simultaneous energy savings. According to de Dear and Brager (2002), a more integrative view of optimizing the indoor environment, energy consumption, and productivity is needed. Based on building automation and advances in sensor technology, we will see the monitoring and control of the indoor environment of offices in relation to achieving optimal conditions for maximum productivity. In other types of buildings, other psychophysiological parameters may be coupled to the PMV model when controlling the indoor environment. Also, the previously described modified PMV models may be used for computerized control strategies.

The current use of building performance simulation tools providing iso-PMV lines as output are an example of misuse of ICT, as PMV is not the property of a single point in space, but rather a whole-body sensation. The increasing important of ICT solutions means that for complex and detailed simulations, new multi-segmental models of human physiology and thermal comfort are increasingly used, for instance, models by Fiala et al. (2001) and Huizenga et al. (2001). These models are based on earlier work by Gagge and Stolwijk (see Gagge et al. (1971) for an example of their occasional collaborations) from the 1980s, and represent the body as a sum of separate body parts. These models can describe local effects due to non-uniform environments and/or non-uniform clothing coverage. Although they have found little application outside of the laboratory, the new models are able to deal with real-world thermal complexities, and may therefore gain importance.

Conclusions

After almost 40 years of practical experience with the PMV model, the foundation of the model and its use, particularly in air-conditioned buildings, are growing ever more solid. In four decades, numerous studies have been conducted on thermal comfort in both field settings and in climate chambers. These studies have provided valuable insight into the principles on which the PMV model is based.

Thermal neutrality is not necessarily the ideal thermal condition as preferences for non-neutral thermal sensations are common. At the same time, very low and very high PMV values do not necessarily reflect discomfort for a substantial number of persons.

The PMV model is applied throughout every type of building all across the globe and its use is prescribed in thermal comfort standards. However, it was found that for naturally ventilated buildings the indoor temperature regarded as most comfortable increases significantly in warmer climatic contexts, and decreases in colder climate zones. This important milestone in thermal comfort research led to the development of an adaptive comfort model. The support for the PMV model is still larger than that for this adaptive model, which was expressed by the latest round of standard revisions that only included the adaptive model as an optional method in very restricted conditions.

Many researchers have tried to improve the PMV model, and enlarge its application domain. Improvements can be made by correcting or adjusting the model itself, or by introducing methods to increasing the accuracy of the model's input parameters. Although many modifications to the original PMV model have been proposed and tested to date, none of these developments have yet found widespread application in environmental engineering practice. The accuracy of the PMV model and the quality of its predictions gain in strength when users are able to more precisely determine the model's input parameters, particularly clothing and activity levels. This requires more sophisticated tables and tools for use in daily practice, and in case of office settings, should also provide accurate data on the insulation of various types of chairs.

The current PMV model is used for assessing and predicting thermal comfort in indoor spaces, often offices. The model, however, holds interesting promises for other applications that go beyond the original scope, such as optimizing productivity. Thermal comfort plays a major role among other indoor environmental parameters. The exact interactions between these parameters are not yet fully understood, and subject of many studies, as are transient thermal conditions. Also, groups other than college-age students and occupants of office buildings need to be studied in terms of thermal preferences.

There is a tendency, influenced by the emancipation of building occupants and energy conservation, to set the general indoor climate in accordance with requirement of the PMV model, while on an individual level, people are equipped with simple means to control the direct thermal environment. The development of individualized thermal comfort in work spaces takes place simultaneously with the computerization of the work floor. In the near future, the thermal environment may be set in compliance with personal preferences stored in an automated user profile that allows for further personal fine-tuning, energy conservation, and coupling with other indoor environmental parameters.

Fanger's PMV model is almost 40 years old and still used as the number one method for evaluating thermal comfort. Even the incorporation of an adaptive model in AHSRAE Standard 55 did little harm to the status of the PMV model, as it is still recognized as valid for all buildings types. The quality of the outcomes of the PMV model is as good as that of its input parameters specified by the model's user. The many input parameters of the comfort equation make PMV an index with great potential for the computerized 21st century in which occupants have increased demands regarding the indoor environment. In combination with means for individual control, engineers should be able to create indoor environments that provide nearly 100% acceptability and comfort to all, based on the work of Fanger.

References

Ahmed, Z.N., Howarth, A.T. and Zunde, J.M. (1990) Thermal comfort studies and applications for Dhaka, *Build. Serv. Eng. Res. Technol.*, **11**, 105–108.

Alm, O., Witterseh, T., Clausen, G., Toftum, J. and Fanger, P.O. (1999) The impact on human perception of simultaneous exposure to thermal load, low-frequency ventilation noise and indoor air pollution. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 5, Edinburgh, 270–275.

Anderson, C.A., Anderson, K.B. and Deuser, W.E. (1996) Examining an affective aggression framework: weapon and temperature effects on aggressive thoughts, affect, and attitudes, *Pers. Soc. Psychol. Bull.*, **22**, 366–367.

Araújo, V.M.D. and Araújo, E.H.S. (1999) The applicability of ISO 7730 for the assessment of the thermal conditions of users of the buildings in Natal-Brazil. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 2, Edinburgh, 148–153.

ASHRAE (2004) *Thermal Environmental Conditions for Human Occupancy*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE Standard 55-2004).

Benton, C.C., Bauman, F.S. and Fountain, M.E. (1990) A field measurement system for the study of thermal comfort, *ASHRAE Trans.*, **96**, 623–633.

Brager, G.S. and de Dear, R.J. (1998) Thermal adaptation in the built environment: a literature review, *Energy Build.*, **27**, 83–96.

Brager, G.S., Fountain, M.E., Benton, C.C., Arens, E.A. and Bauman, F.S. (1994) A comparison of methods for assessing thermal sensation and acceptability in the field. In: Oseland, N.A. and Humphreys, M.A. (eds) *Proceedings Thermal Comfort, Past, Present and Future*, Garston, 17–39.

Busch, J.F. (1990) Thermal responses to the Thai office environment, *ASHRAE Trans.*, **96**, 859–872.

Busch, J.F. (1992) A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand, *Energy Build.*, **18**, 235–249.

CEN (1998) *Ventilation for Buildings: Design Criteria for the Indoor Environment*, Brussels, European Committee for Standardization (Technical report CR 1752).

Chamra, L.M., Steele, W.G. and Huynh, K. (2003) The uncertainty associated with thermal comfort, *ASHRAE Trans.*, **109**, 356–365.

Chan, D.W.T., Burnett, J., de Dear, R.J. and Ng, S.C.H. (1998) A large-scale survey of thermal comfort in office premises in Hong Kong, *ASHRAE Trans.*, **104**, 1172–1180.

Chang, S.K.W., Arens, E. and Gonzalez, R.R. (1988) Determination of the effect of walking on the forced convection heat

transfer coefficient using an articulated manikin, *ASHRAE Trans.*, **94**, 71–82.
Chun, C., Kwok, A. and Tamura, A. (2004) Thermal comfort in transitional spaces – basic concepts: literature review and trial measurement, *Build. Environ.*, **39**, 1187–1192.
Conte, E. and Fato, I. (2000) Thermal comfort in mixed mode buildings. In: Seppänen, O. and Säteri, J. (eds) *Proceedings of Healthy Buildings 2000*, Vol. 2, Espoo, 581–586.
Croome, D.J., Gan, G. and Awbi, H.B. (1993) Thermal comfort and air quality in offices. In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (eds) *Proceedings of Indoor Air* '93, Vol. 6, Helsinki, 37–42.
de Dear, R. (2004) Thermal comfort in practice, *Indoor Air*, **14**, s32–s39.
de Dear, R.J. and Auliciems, A. (1985) Validation of the predicted mean vote model of thermal comfort in six Australian field studies, *ASHRAE Trans.*, **91**, 452–468.
de Dear, R.J. and Brager, G.S. (1998) Developing an adaptive model of thermal comfort and preference, *ASHRAE Trans.*, **104**, 145–167.
de Dear, R.J. and Brager, G.S. (2002) Thermal comfort in naturally ventilated buildings, revisions to ASHRAE Standard 55, *Energy Build.*, **34**, 549–561.
de Dear, R.J., Leow, K.G. and Ameen, A. (1991) Thermal comfort in the humid tropics – part I, climate chamber experiments on temperature preferences in Singapore, *ASHRAE Trans.*, **97**, 874–879.
de Dear, R.J., Brager, G.S. and Cooper, D. (1997) *Developing an Adaptive Model of Thermal Comfort and Preference*, Final Report ASHRAE RP- 884, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers.
Doherty, T.J. and Arens, E. (1988) Evaluation of the physiological bases of thermal comfort models, *ASHRAE Trans.*, **94**, 1371–1385.
Ealiwa, M.A., Taki, A.H., Howarth, A.T. and Seden, M.R. (1999) Field investigation of thermal comfort in both naturally and mechanically ventilated buildings in Ghadames, Libya. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 2, Edinburgh, 166–171.
Fan, Y., Lang, S. and Xu, W. (1993) Field study on acceptable thermal conditions for residential buildings in transition zone of China. In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (eds) *Proceedings of Indoor Air* '93, Vol. 6, Helsinki, 109–114.
Fang, L., Clausen, G. and Fanger, P.O. (2000) Temperature and humidity: important factors for perception of air quality and for ventilation requirements, *ASHRAE Trans.*, **100**, 503–510.
Fanger, P.O. (1967) Calculation of thermal comfort: introduction of a basic comfort equation, *ASHRAE Trans.*, **73**, III.4.1–III.4.20.
Fanger, P.O. (1970) *Thermal Comfort*, Copenhagen, Danish Technical Press.
Fanger, P.O. (1984) The philosophy behind a comfort standard. In: Berglund, B., Lindvall, T. and Sundell, J. (eds) *Proceedings of Indoor Air* '84, Vol. 1, Stockholm, 91–98.
Fanger, P.O. (1994) How to apply models predicting thermal sensation and discomfort in practice. In: Oseland, N.A. and Humphreys, M.A. (eds) *Proceedings Thermal Comfort, Past, Present and Future*, Garston, 11–17.
Fanger, P.O. (2001) Human requirements in future air-conditioned environments, *Int. J. Refrigeration*, **24**, 148–153.
Fanger, P.O. (2004a) Curriculum vitae, *Indoor Air*, **14**, s12–s17.
Fanger, P.O. (2004b) *Oral communication*, Eindhoven, Technische Universiteit Eindhoven, June 10 2004.
Fanger, P.O. (2006) What is IAQ?, *Indoor Air*, **16**, 328–334.
Fanger, P.O. and Langkilde, G. (1975) Interindividual differences in ambient temperatures preferred by seated persons, *ASHRAE Trans.*, **81**, 140–147.
Fanger, P.O. and Toftum, J. (2002) Extension of the PMV model to non-air-conditioned buildings in warm climates, *Energy Build.*, **34**, 533–536.
Fato, I., Martellotta, F. and Chiancarella, C. (2004) Thermal comfort in the climatic conditions of Southern Italy, *ASHRAE Trans.*, **110**, 578–593.
Federspiel, C.C. (1992) *User-adaptable and Minimum-Power Thermal Comfort Control*, Cambridge MIT (Dissertation).
Feriadi, H. and Hien, W.N. (2003) Modelling thermal comfort for tropics using fuzzy logic. In: Hensen, J.L.M. and Augenbroe, G. (eds) *Proceedings Building Simulation 2003*, Vol. 1, Eindhoven, 323–330.
Fiala, D., Lomas, K.J. and Stohrer, M. (2001) Computer prediction of human thermoregulation and temperature responses to a wide range of environmental conditions, *Int. J. Biometeorol.*, **45**, 143–159.
Fountain, M.E., Brager, G.S. and de Dear, R.J. (1996) Expectations of indoor climate control, *Energy Build.*, **24**, 179–182.
Gagge, A.P., Burton, A.C. and Bazett, H.C. (1941) A practical system of units for the description of the heat exchange of man with his environment, *Science*, **94**, 428–430.
Gagge, A.P., Stolwijk, J.A.J. and Nishi, Y. (1971) An effective temperature scale based on a simple model of human physiological regulatory response, *ASHRAE Trans.*, **77**, 247–262.
Gagge, A.P., Fobelets, A.P. and Berglund, L.G. (1986) A standard predictive index of human response to the thermal environment, *ASHRAE Trans.*, **92**, 709–731.
Goto, T., Toftum, J., de Dear, R. and Fanger, P.O. (2002) Thermal sensation and comfort with transient metabolic rates, In: Levin, H. (ed.) *Proceedings of Indoor Air* '02, Vol. 1, Monterey, 1038–1043.
Haghighat, F., Donnini, G., Megri, A.C. and Giorgi, G. (1999) Prediction of thermal perception of disabled persons vs measurement. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '999, Vol. 2, Edinburgh, 113–118.
Hamdi, M., Lachiver, G. and Michaud, F. (1999) A new predictive thermal sensation index of human response, *Energy Build.*, **29**, 167–178.
Havenith, G. (2001) Temperature regulation and technology, *Gerontechnology*, **1**, 41–49.
Havenith, G., Holmér, I. and Parsons, K. (2002) Personal factors in thermal comfort assessment: clothing properties and metabolic heat production, *Energy Build.*, **34**, 581–591.
Heidari, S. and Sharples, S. (2002) A comparative analysis of short-term and long-term thermal comfort surveys in Iran, *Energy Build.*, **34**, 607–614.
Heijs, W. and Stringer, P. (1987) Comfort as a property of the dwelling: a conceptual analysis, *Neth. J. Housing Environ. Res.*, **2**, 331–356.
Hensen, J.L.M. (1990) Literature review on thermal comfort in transient conditions, *Build. Environ.*, **25**, 309–316.
Holmér, I. (2004) Cold but comfortable? Application of comfort criteria to cold environments, *Indoor Air*, **14**, 27–31.
van Hoof, J. and Hensen, J.L.M. (2006) Thermal comfort and older adults, *Gerontechnology*, **4**, 223–228.
van Hoof, J. and Hensen, J.L.M. (2007) Quantifying of relevance of adaptive thermal comfort models in moderate thermal climate zones, *Build. Environ.*, **42**, 156–170.
Höppe, P. (1997) Aspects of human biometeorology in past, present and future, *Int. J. Biometeorol.*, **40**, 19–23.
Höppe, P. (2002) Different aspects of assessing indoor and outdoor thermal comfort, *Energy Build.*, **34**, 661–665.
Howell, W.C. and Kennedy, P.A. (1979) Field validation of the Fanger thermal comfort model, *Hum. Factors*, **21**, 229–239.
Howell, W.C. and Stramler, C.S. (1981) The contribution of psychological variables to the prediction of thermal comfort judgments in real world settings, *ASHRAE Trans.*, **87**, 609–621.
Huizenga, C., Hui, Z. and Arens, E. (2001) A model of human physiology and comfort for assessing complex thermal environments, *Build. Environ.*, **36**, 691–699.
Humphreys, M.A. (1994) Field studies and climate chamber experiments in thermal

comfort research. In: Oseland, N.A. and Humphreys, M.A. (eds) *Proceedings Thermal Comfort, Past, Present and Future*, Garston, 52–72.

Humphreys, M.A. (2005) Quantifying occupant comfort: are combined indices of the indoor environment practicable?, *Build. Res. Inf.*, **33**, 317–325.

Humphreys, M.A. and Hancock, M. (2007) Do people like to feel 'neutral'?: exploring the variation of the desired thermal sensation on the ASHRAE scale", *Energy Build.*, **39**, 867–874.

Humphreys, M.A. and Nicol, J.F. (2002) The validity of ISO-PMV for predicting comfort votes in every-day thermal environments, *Energy Build.*, **34**, 667–684.

Ishii, A., Iwamoto, S., Sakai, E., Katayama, T. and Tsutsumi, J. (1993) The effect of humidity reduction on thermal sensations. In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (eds) *Proceedings of Indoor Air* '93, Vol. 6, Helsinki, 115–120.

ISO (1998) *Ergonomics of the Thermal Environment – Instruments for Measuring Physical Quantities*, Geneva, International Organization for Standardization (ISO 7726).

ISO (2004) *Ergonomics of the Thermal Environment – Determination of Metabolic Rate*, Geneva, International Organization for Standardization (ISO 8996).

ISO (2005a) *Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*, Geneva, International Organization for Standardization (ISO 7730).

ISO (2005b) *Ergonomics of the Thermal Environment – Application of International Standards to People with Special Requirements*, Geneva, International Organization for Standardization (Technical Specification ISO/TS 14415).

Iwamoto, S. and Yoneki, T. (1999) Indoor thermal environment in transient condition. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 2, Edinburgh, 178–183.

Jitkhajornwanich, K., Pitts, A.C., Malama, A. and Sharples, S. (1998) Thermal comfort in transitional spaces in the cool season of Bangkok, *ASHRAE Trans.*, **104**, 1181–1193.

Kähkönen, E. (1991) Draught, radiant temperature asymmetry and air temperature – a comparison between measured and estimated thermal parameters, *Indoor Air*, **1**, 439–447.

Kähkönen, E. and Ilmarinen, R. (1989) Assessing indoor thermal climate – a critical discussion. *Environ. Int.*, **15**, 531–535.

Karjalainen, S. (2007) Gender differences in thermal comfort and use of thermostats in everyday thermal environments, *Build. Environ.*, **42**, 1594–1603.

Karyono, T.H. (1995) Higher PMV causes higher energy consumption in air-conditioned buildings, a case study in Jakarta Indonesia. In: Nicol, J.F., Humphreys, M.A., Sykes, O. and Roaf, S. (eds) *Standards for Thermal Comfort, Indoor Air Temperature Standards for the 21st Century*, London, Chapman & Hall, 219–226.

Karyono, T.H. (2000) Report on thermal comfort and building energy studies in Jakarta-Indonesia, *Build. Environ.*, **35**, 77–90.

Kim, S.H. and Jeong, W.S. (2002) Influence of illumination on autonomic thermoregulation and choice of clothing, *Int. J. Biometeorol.*, **46**, 141–144.

Kimura, K. and Tanabe, S. (1993) Recommended air velocity against combinations of temperature and humidity for sedentary occupants in summer clothing. In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (eds) *Proceedings of Indoor Air* '93, Vol. 6, Helsinki, 61–66.

Kimura, K., Tanabe, S. and Iwata, T. (1994) Climate chamber studies for hot and humid regions. In: Oseland, N.A. and Humphreys, M.A. (eds) *Proceedings Thermal Comfort, Past, Present and Future*, Garston, 88–105.

Kosonen, R. and Tan, F. (2003) PMV-derived productivity model as a tool to assess productivity loss. In: Tham, K.W., Sekhar, S.C. and Cheong, K.W.D. (eds) *Proceedings of Healthy Buildings 2003*, Vol. 1, Singapore, 749–754.

Kosonen, R. and Tan, F. (2004) Assessment of productivity loss in air-conditioned buildings using PMV, *Energy Build.*, **36**, 987–993.

van der Linden, A.C., Boerstra, A.C., Raue, A.K. and Kurvers, S.R. (2002) Thermal indoor climate building response characterized by human comfort response, *Energy Build.*, **23**, 737–744.

Luscuere, P.G. and Borst, V. (2002) Air-conditioning in nursing homes till death do us part? In: Levin, H. (ed.) *Proceedings of Indoor Air* '02, Vol. 1, Monterey, 1032–1037.

Mayer, E. (1997) A new correlation between predicted mean votes (PMV) and predicted percentages of dissatisfied (PPD). In: Woods, J.E., Grimsrud, D.T. and Boschi, N. (eds) *Proceedings of Healthy Buildings/IAQ* '97, Vol. 2, Washington, 189–194.

McCullough, E., Olesen, B.W. and Hong, S. (1994) Thermal insulation provided by chairs, *ASHRAE Trans.*, **100**, 795–802.

McIntyre, D.A. (1984) Evaluation of thermal discomfort. In: Berglund, B., Lindvall, T. and Sundell, J. (eds) *Proceedings of Indoor Air* '84, Vol. 1, Stockholm, 147–158.

Nagano, K. and Horikoshi, T. (2005) New comfort index during combined conditions of moderate low ambient temperature and traffic noise, *Energy Build.*, **37**, 287–294.

Nakano, J., Tanabe, S. and Kimura, K. (2002) Differences in perception of indoor environment between Japanese and non-Japanese workers, *Energy Build.*, **34**, 615–621.

Nicol, J.F., Raja, I.A., Allaudin, A. and Jamy, G.N. (1999) Climatic variations in comfortable temperatures, the Pakistan projects, *Energy Build.*, **30**, 261–279.

Nishi, Y., Gonzalez, R.R. and Gagge, A.P. (1975) Direct measurement of clothing heat transfer properties during sensible and insensible heat exchange with thermal environment, *ASHRAE Trans.*, **81**, 183–199.

Olesen, B.W. and Nielsen, R. (1984) A comparison of the thermal insulation measured on a thermal manikin and on human subjects. In: Berglund, B., Lindvall, T. and Sundell, J. (eds) *Proceedings of Indoor Air* '84, Vol. 5, Stockholm, 315–320.

Olesen, B.W., Sliwinski, E., Madsen, T.L. and Fanger, P.O. (1982) The effect of posture and activity on the thermal insulation of clothing: measurement by a moveable thermal manikin, *ASHRAE Trans.*, **88**, 791–805.

Olesen, B.W., de Dear, R.J. and Brager, G.S. (2001) Status and new developments in indoor thermal environmental standards, *J. Hum. Environ. Syst.*, **5**, 1–12.

Oseland, N.A. (1996) Thermal comfort in naturally ventilated versus air-conditioned offices. In: Yoshizawa, S., Kimura, K., Ikeda, K., Tanabe, S. and Iwata, T. (eds) *Proceedings of Indoor Air* '96, Vol. 1, Tokyo, 215–220.

Paciuk, M. and Becker, R. (2002) Predicted vs. recorded summer thermal responses in air-conditioned and naturally ventilated dwellings in Israel. In: Levin, H. (ed.) *Proceedings of Indoor Air* '02, Vol. 5, Monterey, 104–109.

Palonen, J., Reinikainen, L.M. and Jaakola, J.J.K. (1993) The effects of air temperature and relative humidity on thermal comfort in the office environment. In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (eds) *Proceedings of Indoor Air* '93, Vol. 6, Helsinki, 43–48.

Parsons, K.C. (2002) The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort, *Energy Build.*, **34**, 593–599.

de Paula Xavier, A.A. and Roberto, L. (2000) Indices of thermal comfort developed from field survey in Brazil, *ASHRAE Trans.*, **106**, 45–58.

Pellerin, N. and Candas, V. (2002) Combined effects of temperature and noise on human discomfort, *Physiol. Behav.*, **78**, 99–106.

Potter, J.C. and de Dear, R.J. (2000) Field study to calibrate outdoor thermal comfort index. In: de Dear, R.J., Kalma, J.D., Oke, T.R. and Auliciems, A. (eds)

Biometeorology and urban climatology at the turn of the millennium, Geneva, World Meteorological Organization, 315–320.
Prek, M. (2005) Thermodynamic analysis of human heat and mass transfer and their impact on thermal comfort, *Int. J. Heat Mass Transfer*, **48**, 731–739.
Prianto, E. and Depecker, P. (2003) Optimizing of architectural design elements in tropical humid region with thermal comfort approach, *Energy Build.*, **35**, 273–280.
Rohles, F.H. (1980) Temperature or temperament: a psychologist looks at thermal comfort, *ASHRAE Trans.*, **86**, 541–551.
Rowe, D.M. (2001) Activity rates and thermal comfort of office occupants in Sydney, *J. Thermal Biol.*, **26**, 415–418.
Santos, A.M.B. and Gunnarsen, L. (1999) Optimizing linked pairs of indoor climate parameters. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 3, Edinburgh, 191–196.
Sassa, N., Kubo, H., Isoda, N. and Yanase, T. (1999) The individual differences of preferred air temperature at the direct determination and exposure to established air temperature. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 1, Edinburgh, 638–643.
Schiller, G.E. (1990) A comparison of measured and predicted comfort in office buildings, *ASHRAE Trans.*, **96**, 609–622.
Sherman, M. (1985) A simplified model of thermal comfort, *Energy Build.*, **8**, 37–50.
Simister, J. and Cooper, C. (2005) Thermal stress in the U.S.A.: effects on violence and on employee behaviour, *Stress Health*, **21**, 3–15.
Tanabe, S., Hasebe, Y. and Kimura, K. (1993) Reduction of clo value with increased air movement. In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (eds) *Proceedings of Indoor Air* '93, Vol. 6, Helsinki, 139–144.
Vogt, J.J., Meyer, J.P., Sagot, J.C. and Candas, V. (1984) Basic, effective and resultant clothing insulations, *ASHRAE Trans.*, **90**, 1091–1098.
Vroon, P.A. (1990) *Psychologische aspecten van ziekmakende gebouwen*, Utrecht, Rijksuniversiteit Utrecht (in Dutch).
Wang, Z.-J., Wang, G. and Lian, L.-M. (2003) A field study of the thermal environment in residential buildings in Harbin, *ASHRAE Trans.*, **109**, 350–355.
Webb, L.H. and Parsons, K.C. (1998) Case studies of thermal comfort for people with physical disabilities, *ASHRAE Trans.*, **104**, 883–895.
Webb, L.H., Parsons, K.C. and Hodder, S.G. (1999) Thermal comfort requirements. A study of people with multiple sclerosis, *ASHRAE Trans.*, **105**, 648–660.
Williams, R.N. (1995) A field investigation of thermal comfort, environmental satisfaction and perceived control levels in UK office buildings. In: Maroni, M. (ed.) *Proceedings of Healthy Buildings* '95, Vol. 3, Milan, 1181–1186.
de Wit, M.S. (2001) *Uncertainty in Predictions of Thermal Comfort in Buildings*, Delft, Technische Universiteit Delft (Dissertation).
Wyon, D.P. (1975) The mental performance of subjects clothed for comfort of two different temperatures, *Ergonomics*, **18**, 359–374.
Wyon, D.P. (1994) Assessment of human thermal requirements in the thermal comfort region. In: Oseland, N.A. and Humphreys, M.A. (eds) *Proceedings Thermal Comfort, Past, Present and Future*, Garston, 144–156.
Yamtraipat, N., Khedari, J. and Hirunlabh, J. (2005) Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level, *Solar Energy*, **78**, 504–517.
Yoon, D.W., Sohn, J.Y. and Cho, K.H. (1999) The comparison on the thermal comfort sensation between the results of questionnaire survey and the calculation of the PMV values. In: Raw, G., Aizlewood, C. and Warren, P. (eds) *Proceedings of Indoor Air* '99, Vol. 2, Edinburgh, 137–141.