Adaptive thermal comfort explained by PMV

Citation for published version (APA):
Linden, van der, W., Loomans, M. G. L. C., & Hensen, J. L. M. (2008). Adaptive thermal comfort explained by PMV. In P. Strøm-Tejsen, BW. Olesen, P. Wargocki, D. Zukowska, & J. Toftum (Eds.), *Indoor Air 2008: Proceedings of the 11th International Conference on Indoor Air Quality and Climate* (pp. 8pp.-). Technical University of Denmark.

Document status and date:
Published: 01/01/2008

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

Linden, W. van der, Loomans, M.G.L.C. & Hensen, J.L.M. (2008).
Adaptive thermal comfort explained by PMV.
In Strøm-Tejsen, P, Olesen, BW, Wargocki, P, Zukowska, D & Toftum, J (Eds.), Indoor Air 2008: Proceedings of the 11th International Conference on Indoor Air Quality and Climate, p.8. Copenhagen: International Centre for Indoor Environment and Energy, Technical University of Denmark.

Adaptive thermal comfort explained by PMV

Willemijne van der Linden, Marcel Loomans* and Jan Hensen

Eindhoven University of Technology, Department of Architecture Building and Planning, Unit Building Physics and Systems, The Netherlands.

**Corresponding email: M.G.L.C.Loomans@tue.nl*

SUMMARY

Predicted Mean Vote (PMV) is a well known example of a thermal comfort performance indicator. Alternative indicators have gained interest over the last decade. Developments are found in higher resolution indicators, applying, e.g. thermo-physiological models. The adaptive thermal comfort approach (ATC), applying the indoor operative temperature in relation to the outdoor air temperature as the main performance indicator, represents an example of a less complex indicator. A clear advantage of the latter is the relative simple comfort assessment in use and the perceptibility of the indicator. However, the heat balance approach has a larger flexibility and a wider applicability.

In this paper the linkage between PMV and ATC is elaborated on by investigating the search space for PMV input parameters in relation to the ATC assessment. The results show that for a moderate maritime outdoor climate as in The Netherlands the PMV-approach is well able to explain the results derived from the ATC approach.

KEYWORDS

Thermal Comfort, Adaptive Thermal comfort, PMV, Comparison Dutch climate

INTRODUCTION

Functional requirements and the related performance requirements and performance indicators for those requirements, are the key-points in the design of buildings. They are also the key-points in the assessment of building designs. To agree with the performance based building approach this assessment should be possible in the design and in the use phase.

With respect to thermal comfort, the Predicted Mean Vote (PMV; Predicted Percentage of Dissatisfied [PPD]) is a well known and widely used example of a performance indicator (Fanger, 1970). Alternative comfort related indicators however have gained interest over the last decade. Developments are found in higher resolution indicators, applying, e.g. thermo-physiological models. This is still ongoing research. The adaptive thermal comfort approach (ATC), applying the indoor operative temperature in relation to the (running mean) outdoor air temperature as the main performance indicator, represents an example of a less complex (lower resolution) performance indicator. This approach responds to the differences found between PMV/PPD assessment and actual thermal comfort response for specific type of buildings (mainly non-air-conditioned) in warm climates.

At this moment the ATC approach has obtained a place in newly issued guidelines and standards such as CEN (2007) and ASHRAE (2004). In these references application of the ATC approach is optional for naturally conditioned spaces. For mechanically conditioned spaces the PMV/PPD model should be used. Also for moderate climates as in The Netherlands a specific guideline (ISSO 2004) has been issued that allows application of the adaptive approach. In the latter some specific changes were made with respect to the calculation of the running mean outdoor temperature and specifically also with respect to the building categorisation for which the adaptive approach may be used (van der Linden et al. 2006).

Application of the ATC approach has clear advantages over the PMV/PPD approach. It allows for a relative simple comfort assessment for buildings in use and can be communicated straightforwardly to building users. On the other hand the ATC approach currently only can be applied for office type of indoor environments with including related average conditions for metabolic rate, clothing, etc. It therefore is less flexible and limited in its application range compared to the PMV/PPD approach. Furthermore, an extension of the PMV/PPD model brings in a correction for non-air-conditioned buildings in warm climates (Fanger and Toftum, 2002). This correction is introduced through an expectancy factor. This factor is multiplied with the PMV-value to obtain the actual mean thermal sensation vote of occupants of a non-air-conditioned building in a warm climate. The expectancy factor is maximum 1.0 for air-conditioned buildings and minimum 0.5 for non-air-conditioned buildings if the weather is warm all year or most of the year.

Van Hoof and Hensen (2007) already discussed the energy reduction potential of the ATC approach as proposed by van der Linden et al. (2006). They conclude that a 10% reduction is possible for naturally conditioned buildings or buildings with a high degree of occupant control (Type Alpha buildings). However, for buildings with centrally controlled HVAC systems (Type Beta buildings) a 10% increase in energy use was found for heating.

This paper wants to discuss the applicability of the PMV/PPD approach in comparison to the by van der Linden et al. proposed ATC approach for a moderate outdoor climate as found in The Netherlands. It does so by linking PMV/PPD and ATC through Figure 1. This graph presents the maximum allowed band width for the indoor operative temperature, for a specified acceptance level, as a function of the running mean outdoor temperature ($T_{e,ref}$). This

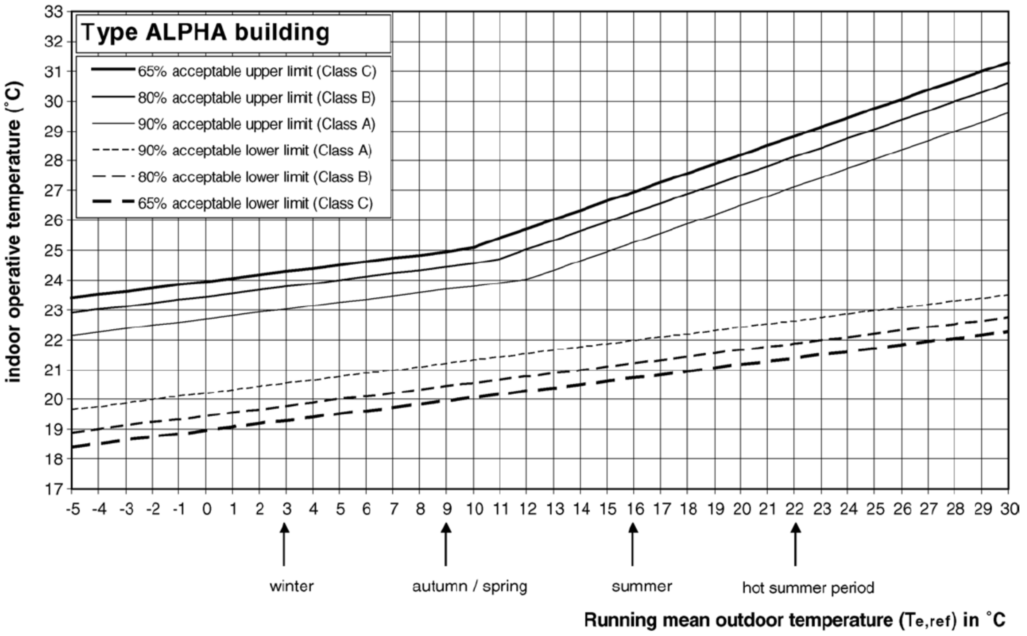


Figure 1. Maximum allowed indoor operative temperature range for a specified acceptance level, as a function of the running mean outdoor temperature ($T_{e,ref}$), for a building or indoor climate categorised as type Alpha (taken from: van der Linden et al. (2006)).

graph is valid for a building or indoor climate that can be categorised as type Alpha and has been taken from (van der Linden et al. 2006). By combining the two approaches it may be possible to get the best-of-both-worlds.

METHODS

The link between PMV/PPD and ATC shown in Figure 1 is through the indoor operative temperature and the percentage of acceptance of the indoor environment. The search space for the PMV/PPD approach than is focussed on the parameters for obtaining the specific PMV/PPD-value:

- Metabolic rate (M [met])
- Thermal resistance of clothing (I_{clo} [clo])
- Air temperature (T [ºC])
- Mean radiant temperature (T_{mrt} [ºC])
- Relative air velocity (v [m/s])
- Relative humidity (RH [%])

To reduce the search space, the following assumptions have been made: the relative air velocity is assumed low (0.10 – 0.20 m/s); the relative humidity is fixed (winter 40% - summer 70%); the air temperature and mean radiant temperature are equal.

In a first step the search space is investigated for two typical points on the x-axis of the graph in Figure 1, indicated by ‘winter’ and ‘hot summer period’, at an acceptance rate of 80% (PMV set at ±0.84). This investigation allows for an overview of the parameter ranges, specifically, for the metabolic rate and the thermal resistance of clothing that are allowed according to the PMV/PPD approach for the investigated temperature range set by the ATC approach.

In a second step the search space is reduced by applying available information on the thermal resistance of clothing as a function of the outdoor temperature and further assumptions on the typical air velocity and relative humidity. With this step it is possible to draw lines in the same graph as shown in Figure 1. Also in this case the acceptance rate is set at 80%.

For the relation between the clothing thermal resistance and the outdoor temperature information as presented by De Carli et al. (2007) was used. An example graph from this reference is shown in Figure 2. The relation for the mean Clo value has been applied.

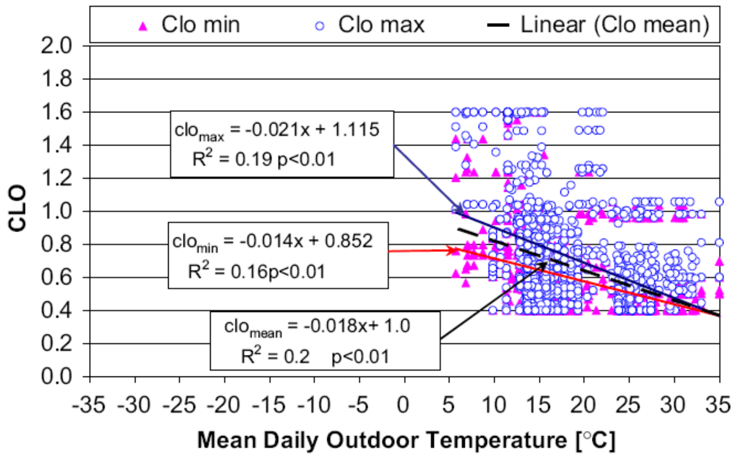


Figure 2. Clothing resistance as function of the mean daily outdoor temperature for naturally ventilated buildings (De Carli et al., 2007).

For the humidity and air velocity information is derived from ISO 7730 (2005). Below 26ºC sensitivity to the humidity is limited. Nevertheless, as outdoor humidity levels change different values are assumed for winter and summer. A similar assumption is made for the air velocity, applying somewhat higher values for the summer.

The expectancy factor is included as an additional compensation for the maximum acceptable PMV value in a hot summer period. For The Netherlands the expectation is assumed high as generally warm summer periods only occur briefly and there is a high rate of air-conditioned office buildings. Based on these assumptions the expectancy factor is estimated at 0.9 (as minimum).

Finally, the results of the second step are used to compare with results from a recent survey in the Netherlands (Kurvers et al. 2008).

RESULTS

Figure 3 presents the solutions within the search space for the metabolic rate (M) and the clothing resistance (I_{clo}). The values for M and I_{clo} adhere to the in the ATC approach allowed temperature range for an acceptance rate of 80% (see Figure 1). Results are shown for the 'winter period' and the 'hot summer period' ('×' refers to the upper temperature range and '○' to the lower one). In this case the relative humidity has been fixed to 40% and 70% respectively and results are shown for an air velocity of 0.1 m/s and 0.2 m/s.

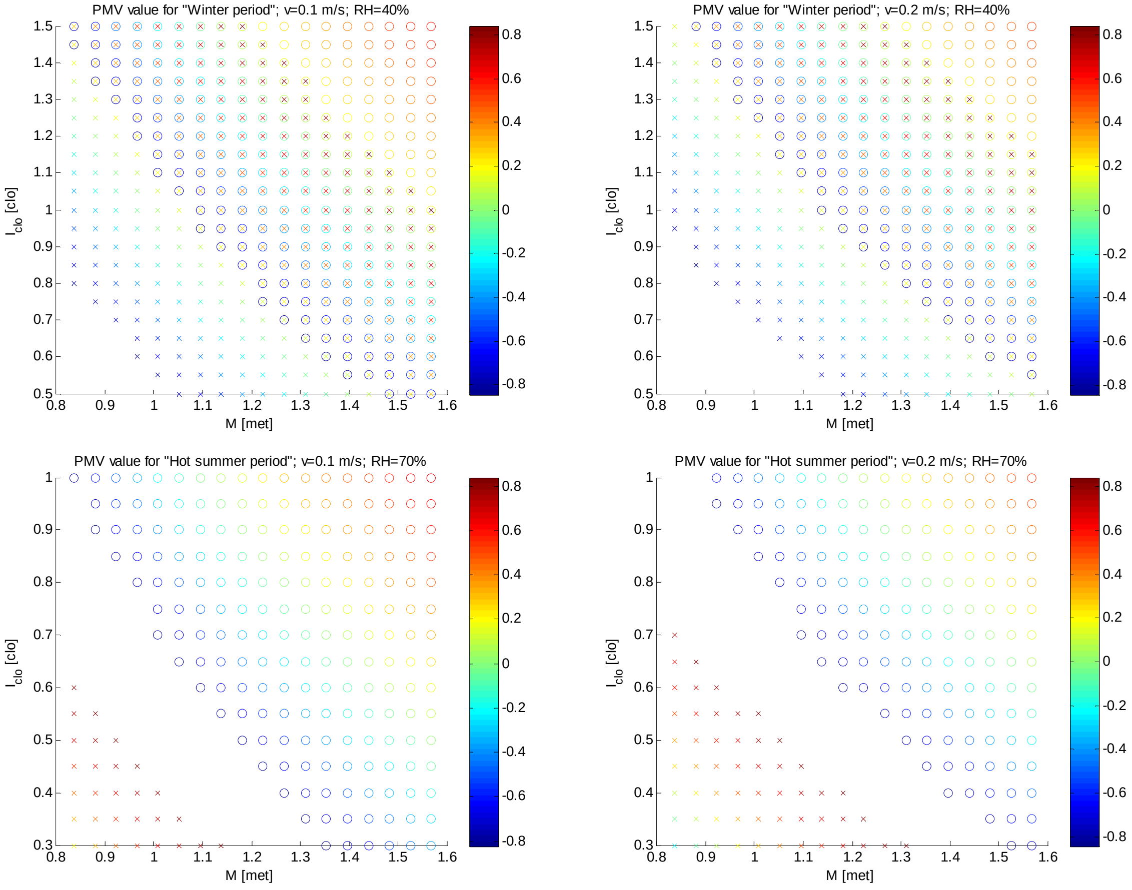


Figure 3. Solutions within the search space for the metabolic rate (M) and the clothing resistance (I_{clo}) for the in the ATC approach allowed temperature range for an acceptance rate of 80%, according to Figure 1. Conditions for the presented solutions are shown in the sub-graph titles.

In Table 1 results are presented for the second approach. Values are determined for the indicated positions in Figure 1 ('winter', 'autumn/spring', 'summer', 'hot summer period'). Furthermore, results are shown in which the expectancy factor is included (only 'hot summer period'). Based on a maximum PMV of +0.84, application of an expectancy factor of 0.9 allows for a PMV-value of +0.93. In Figure 4 the results for T_{op} are included in the graph.

Table 1. Allowed indoor operative temperature range (T_{op}) for PMV = ±0.84, at a metabolic rate of 1.0 met and for specified parameter values. $T_{op,exp}$ is the operative temperature range with expectancy factor of 0.9 included.

Season	$T_{e,ref}$ [ºC]	I_{clo} [clo]	RH [%]	v [m/s]	T_{op} [ºC]	$T_{op, exp}$ [ºC]
Winter	3	0.95	40	0.1	20.8 – 26.8	
Spring/ autumn	9	0.84	54	0.15	21.8 – 27.1	
Summer	16	0.71	70	0.2	22.8 – 27.4	
Hot summer period	22	0.60	70	0.25	23.9 – 28.0	23.9 – 28.3

Table 2. Allowed indoor operative temperature range (T_{op}) for PMV = ±0.84, at a metabolic rate of 1.2 met and for specified parameter values. $T_{op,exp}$ is the operative temperature range with expectancy factor of 0.9 included.

Season	$T_{e,ref}$ [ºC]	I_{clo} [clo]	RH [%]	v [m/s]	T_{op} [ºC]	$T_{op, exp}$ [ºC]
Winter	3	0.95	40	0.1	18.3 – 25.8	
Spring/ autumn	9	0.84	54	0.15	19.5 – 26.1	
Summer	16	0.71	70	0.2	20.8 – 26.5	
Hot summer period	22	0.60	70	0.25	22.1 – 27.2	22.1 – 27.5

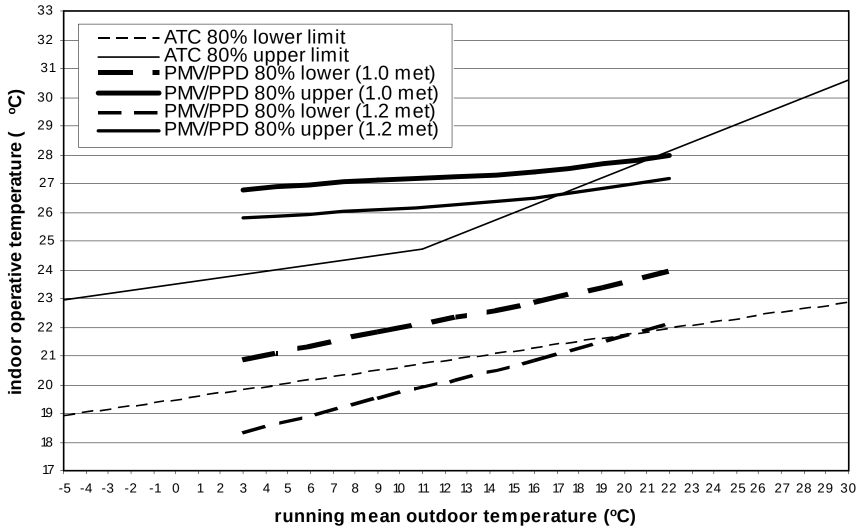


Figure 4. Comparison of the 80% acceptability rating for the ATC approach and the PMV/PPD approach considering the in Table 1 and 2 indicated conditions.

DISCUSSION

The results from the first method (Figure 3) show that the allowed range for metabolic rate and clothing resistance is large. For the ‘winter period’ an overlap is found for the range for both parameters, limiting the total band width. For the ‘hot summer period’ parameter values do not overlap for the lower and upper indoor operative temperature levels. The results indicate that for a wide range of parameter values the identified operative temperatures can be reached without neglecting the satisfaction rate derived from the PMV-value.

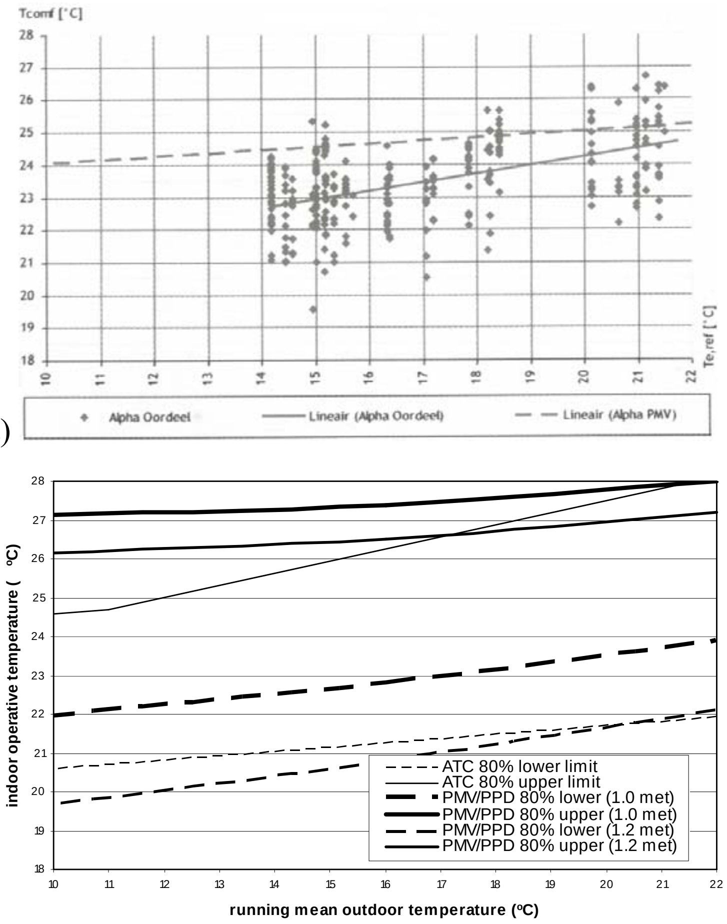
These results indicate that the acceptance of the indoor operative temperature range as defined by ATC can be explained largely by applying realistic parameter values. However, the results do not allow a good comparison with the temperature values shown in Figure 1.

The result from the second method provides this comparison (Figure 4). It shows that for the running mean outdoor temperature range as found in The Netherlands (‘winter’ to ‘hot summer period’) the PMV/PPD approach can explain the ATC data to a large extent.

The lines for the minimum required temperature level are somewhat higher than the ATC line at M = 1.0 met. For a metabolic rate of 1.2 met, however, lower temperatures are allowed. For the maximum temperature values in winter time PMV/PPD allowance is much wider, however in this case usually the minimum value is of interest. For the summer period ($T_{e,ref}$ = 16ºC) the PMV/PPD allowance for the indoor temperature is still wider. Only at hot summer periods as found in The Netherlands ($T_{e,ref}$ in the order 22ºC) the ATC criteria become less strict compared to the PMV/PPD approach. Figure 4 shows that the effect of the actual metabolic rate on the allowed indoor temperature however is significant, which is in line with the comment made by Fanger and Toftum (2002). The effect of the expectancy factor for the identified situation in the Netherlands and the temperature range is limited.

In a recent study by Kurvers et al. (2008) a field study was performed in the Netherlands to investigate, amongst others, possible improvements to ISSO (2004). Part of this study contained of an investigation in several buildings that were assessed as so-called Alpha buildings. Figure 5a presents an example result for one of these buildings for the comfort temperature as a function of the outdoor reference temperature. The comfort temperature is the measured operative temperature for which the occupants voted -1, 0 or +1 on the ASHRAE-thermal sensation scale and indicated no preference for another temperature. In the study also information was collected on the thermal resistance of the clothing (0.67 ± 0.10 clo; for all investigated buildings) and the metabolic rate (1.24 ± 0.14 met; for all investigated buildings).

Figure 5b presents a zoomed in result of Figure 4 with similar axis as Figure 5a. From the comparison it is clear that with an 80% acceptability rate for PMV/PPD (similar as to ATC) the results can be explained.



a)

b)

Figure 5. a) results from a field study by Kurvers et al. (2008) for a so-called Alpha building, b) Zoomed in result of Figure 4 for the axis shown in Figure 5a.

CONCLUSION

Following the results and discussion described above it is stated that application of the PMV/PPD approach and the ATC approach do not result in a different estimation of the thermal indoor environment for a moderate outdoor thermal environment as found in The Netherlands. The advantage of the use of the ATC method is its straightforward conception of the information. The PMV/PPD approach however has a much wider applicability.

If more detailed information such as shown in Figure 2 would become available this would allow a linkage between PMV/PPD and the outdoor and indoor temperature as shown in Figure 1. In that way the advantage of the ATC approach could be included in the PMV/PPD approach, bearing in mind that the current information for the ATC approach was obtained for office type of environments.

REFERENCES

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

CEN. 2007. EN 15251:2007, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: European Committee for standardization.

De Carli, M., Olesen, B.W., Zarrella, A., Zecchin, R. 2007. People's clothing behaviour according to external weather and indoor environment. *Building and Environment*, 42, 3965-3973.

Fanger P.O. 1970. *Thermal Comfort*. Copenhagen: Danish Technical Press.

Fanger, P.O. and Toftum, J. 2002. Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and Buildings*, 34, 533-536.

Hoof, J. van and Hensen, J.L.M. 2007. Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones. *Building and Environment*, 42, 156-170.

Kurvers, S.R., van Beek, M. Eijdems, H.H.E.W. et al. 2008. Adaptief thermisch comfort in de praktijk. *TVVL Magazine*, 1/2008, 18-25.

Linden, A.C. van der, Boerstra, A.C., Raue, A.K., Kurvers, S.R. and Dear, R.J. de. 2006. Adaptive temperature limits: A new guideline in The Netherlands A new approach for the assessment of building performance with respect to thermal indoor climate. *Energy and Buildings*, 38, 8-17.

ISSO. 2004. Thermische Behaaglijkheid; eisen voor de binnentemperatuur in gebouwen. Publication 74, Rotterdam: ISSO.