Centnerova, L. & Hensen, J.L.M. (2001).
Energy and indoor temperature consequences of adaptive thermal comfort standards.
Proceedings of the 4th international conference on indoor climate of buildings, pp. 391-402.
Bratislava: Slovak society for environmental Technology.

Energy and indoor temperature consequences of adaptive thermal comfort standards

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Abstract

The intent of the presented study was to quantify the implications for energy demand of indoor temperature requirements based on a proposed adaptive thermal comfort standard (7) relative to a more traditional thermal comfort approach. The study focuses on a typical office situation in a moderate climate such as in The Netherlands or in the Czech Republic.

Keywords:

thermal comfort, adaptation, energy demand, computer simulation

INTRODUCTION

Thermal comfort can be defined as that condition of mind, which expresses satisfaction with the thermal environment (1). The main criteria for thermal comfort for the human body as a whole can be divided to A) environmental parameters: air temperature, radiant temperature, humidity, air velocity and B) personal parameters: clothing and activity. In addition there are other environmental parameters that can cause local thermal discomfort such as draught, a high vertical temperature difference between head and ankles or too high radiant temperature asymmetry.

TRADITIONAL VS. ADAPTIVE THERMAL COMFORT MODELS

Current comfort standards such as ISO/EN 7730 (1) and ANSI/ASHRAE 55-92 (2) are based on a more or less static model of human thermal comfort. The physiological and psychological response to the thermal environment is basically the same throughout the year. The only thing that changes is clothing and this results in different preferred temperatures in winter and in summer. Although ISO/EN 7730 presents a generic model according to Fanger (3), which will probably also be included in the upcoming revision of ANSI/ASHRAE 55 (4), in common usage the standards divide recommended comfort requirements into two categories: winter (heating season) and summer (cooling season) with parameters such as in Tables 1 and 2.

Table 1. Recommended operative temperature levels predicting an acceptable thermal sensation for 90 % of the occupants during light, mainly sedentary activity with other environmental parameters within specified limits according to ISO/EN 7730 (1)

Season	Clothing insulation (clo)	Activity level (met)	Optimum operative temperature (^{0}C)	Operative temperature range (^{0}C)
Winter	1.0	1.2	22	20 - 24
Summer	0.5	1.2	24.5	23 - 26

Table 2. Optimum and acceptable ranges of operative temperature for people during light, primarily sedentary activity, 50 % relative humidity and mean air speed ≤ 0.15 $m.s^{-1}$ according to ANSI/ASHRAE 55-1992 (2)

Season	Typical clothing	Clothing insulation (clo)	Activity level (met)	Optimum operative temperature (^0C)	Operative temperature range (^0C)
Winter	heavy slacks, long-sleeve shirt and sweater	0.9	1.2	22	20 – 23.5
Summer	light slacks, short-sleeve shirt	0.5	1.2	24.5	23 – 26
	Minimal	0.05	1.0	27	26 – 29

Experience shows that the most important factor determining human thermal comfort is the general feeling of warmth. “Get the warmth right and only then worry about any remaining causes of discomfort. They may well have disappeared”, according to McIntyre (5). The optimum operative temperature for comfort is a function of metabolic rate and clothing insulation. It is possible to predict the activity level of people in a particular environment and subsequently their metabolic rate. It is however very difficult to predict what people will wear. People usually change clothing according to outside temperatures; i.e. people choose clothes more for outdoor than for indoor climate. In practice, women are able and tend to adapt (the insulation level of) their clothing more to the outside temperature than men (4). And in addition to this, individual people are different not only in choosing their clothes but in thermal responses and thermal adaptation to the environment as well.

Adaptive thermal comfort model

According to the adaptive hypothesis of De Dear and Brager (6, 7, 13, 14), contextual factors and past thermal history modify building occupants’ thermal expectations and preferences. One of the predicted consequences is that people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones. This is contrary to the static assumptions underlying the current ASHRAE comfort standard (2).

De Dear and Brager published in (7) a draft proposal for a thermal comfort standard that would – unlike (1) and (2) - take thermal adaptation into account. They make a distinction between two types of buildings: 1) buildings with centralised (i.e. centrally controlled) HVAC (heating, ventilation and air-conditioning) and 2) buildings with natural ventilation. The reason for this distinction appears to be that people have different expectations in these two types of buildings. When people have a possibility to control their environment (for example just being able to open a window) they are more easily thermally satisfied than when they perceive not to have control. In addition there might be higher room air speeds in naturally ventilated buildings in warm periods. The result is apparently that in a building without centrally controlled HVAC the occupants will accept a wider range of operative temperature over the year.

In the adaptive comfort approach the optimum comfort temperature for buildings with centrally controlled HVAC systems is calculated from equation [1].

$$T_o = 22.6 + 0.04ET^* ......with.. -5 < ET^* < 33\,^{o}C \qquad [1]$$

The 90% acceptability range is between T_o – 1.2°C and T_o + 1.2°C

The adaptive model results are based on experimental findings in a large number of buildings in a range of climate zones. The static model's comfort temperature for each building was derived by inputting the buildings mean room air speed, relative humidity, clothing and activity level into the PMV model and then iterating for different operative temperature until PMV= 0.

In the adaptive comfort approach the optimum comfort temperature for buildings with natural ventilation is calculated from equation [2]. The static model's comfort temperature for each building was again derived as indicated above.

$$T_o = 18.9 + 0.255ET^* ......with..5 < ET^* < 33\,^{o}C \qquad [2]$$

The 90% acceptability range is between T_o – 2.5°C and T_o + 2.5°C

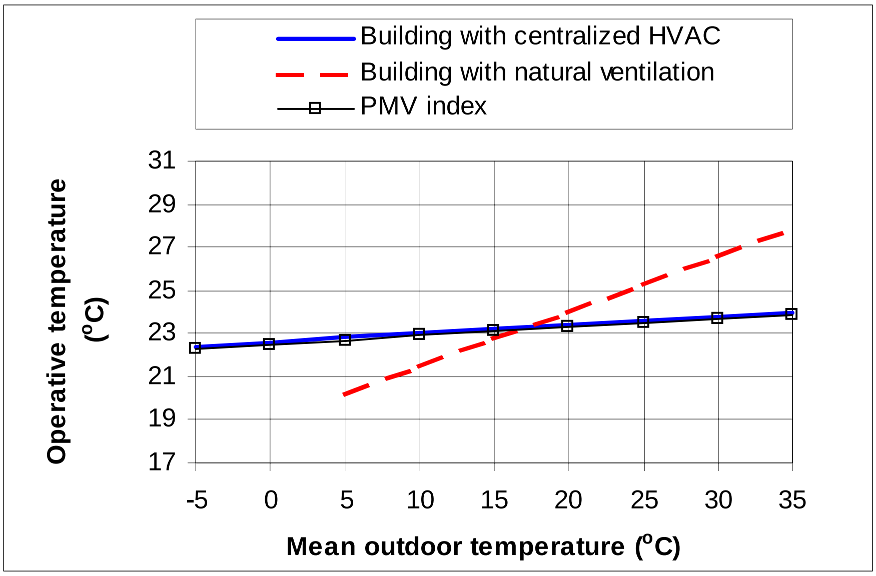

Figure 1. Optimal operative temperatures for buildings with centralised HVAC and with natural ventilation according to equations [1] and [2] and according to PMV.

COMPUTER MODELING AND SIMULATION

The objective of our current research was to predict energy demand implications by analysing the space heating and cooling energy demands of 'a standard office' using both concepts of thermal comfort. Currently the most powerful technique available for the analysis and design of complex systems (like buildings and their environment) is computer modeling and simulation. The current study made use of ESP-r (Environmental Systems Performance - research) (12), which is a transient energy simulation system, capable of modeling the energy and fluid flows within combined building and plant systems when constrained to conform to control actions.

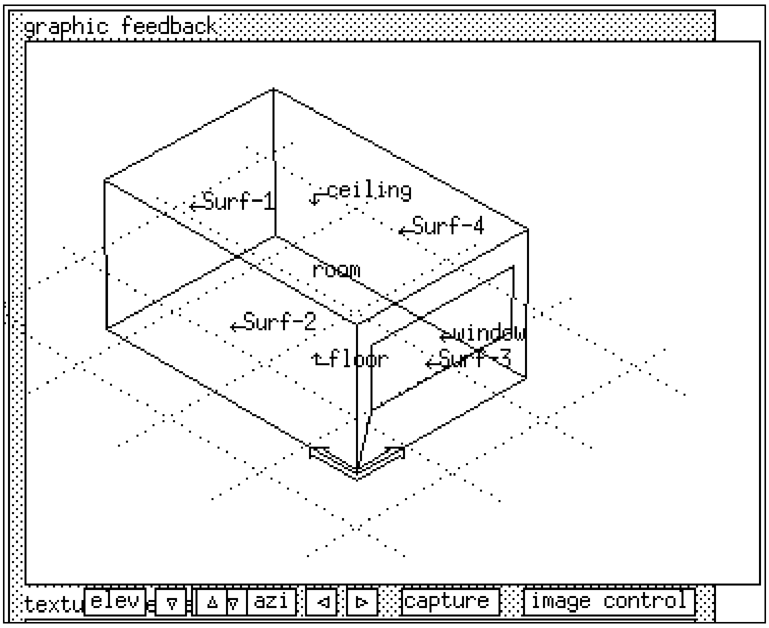

Figure 2. Model of test office used for simulations

Building model

The simulations were carried out for a "standard office" (11); a typical cellular office for two occupants as schematically shown in Figure 2. Further details of the office model are as follows.

3.5 x 5.4 x 2.7 m or floor area = 19.44 m^2 and volume = 52.5 m^3

Default orientation is window facing west. Other orientations were considered as well.

Constructions: external wall: U-value 0.39 W/m^2K

window: U-value 2.75 W/m^2K, transparency: 0.76

Activity: mainly sedentary

Internal gains: 2 people (total 140 W sensible plus 140 W latent)

equipment (300 W)

Occupancy: week days from 8 a.m. to 6 p.m.

Ventilation: fresh air supply by either natural or mechanical ventilation[1]

during occupancy hours: 1.2 ACH; i.e. 30 m^3/h/person (8.3 l/s/person)

when not occupied: 0.2 ACH

Outdoor climate: two moderate climate cases were considered:

- *Czech Republic (Prague)*: annual mean air temperature: 8.8°C
- *The Netherlands (Eindhoven)*: annual mean air temperature: 10.1°C

Required indoor temperature ranges

The required (or design) indoor temperature ranges are based on the thermal comfort approaches as described above. The numerical values of the indoor temperature mid points are summarised in Table 3. The temperature ranges for 90% acceptability for the Czech Republic are graphically shown in Figure 3. From this figure it is immediately clear that there are relatively large differences between the different required indoor temperature approaches.

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[1] In reality, the amount of fresh air supply will not be constant in natural ventilated buildings. However, since we wanted to focus on energy demand implications of different approaches to required indoor temperatures, variable infiltration and ventilation rates due to natural ventilation have not been taken into account.

Table 3. Monthly indoor temperature range mid points according to:

Month	ISO	The Netherlands			Czech Republic		
	T_i [1]	T_o	T_i [2]	T_i [3]	T_o	T_i [2]	T_i [3]
1	22.0	0.7	20.2	22.6	-1.5	20.2	22.5
2	22.0	3.4	20.2	22.7	2.5	20.2	22.7
3	22.0	2.8	20.2	22.7	4.3	20.2	22.8
4	22.0	8.5	21.1	22.9	9.3	21.3	23.0
5	22.0	13.9	22.4	23.2	13.9	22.4	23.2
6	24.5	15.3	22.8	23.2	17.1	23.3	23.3
7	24.5	16.4	23.1	23.3	17.5	23.4	23.3
8	24.5	16.0	23.0	23.2	17.1	23.3	23.3
9	22.0	14.0	22.5	23.2	15.4	22.8	23.2
10	22.0	8.1	21.0	22.9	9.5	21.3	23.0
11	22.0	6.6	20.6	22.9	4.5	20.2	22.8
12	22.0	2.2	20.2	22.7	-0.2	20.2	22.6

T_i [1] Static comfort model as in Table 1 and Table 2

T_i [2] Adaptive comfort model for buildings with natural ventilation according to Equation [2] and Figure 1

T_i [3] Adaptive comfort model for buildings with centrally controlled HVAC systems according to Equation [1] and Figure 1

T_o Monthly mean outdoor ET* or monthly mean outdoor dry bulb temperature which are practically almost the same in the current case (see section "outdoor ET* and solar radiation")

RESULTS

The following section presents our results in terms of energy demand for heating and cooling of a typical office. These results may alternatively be interpreted as indications for the time integrated degree of indoor conditions beyond the temperature limits of the respective comfort models should the office not have a heating or cooling system at all.

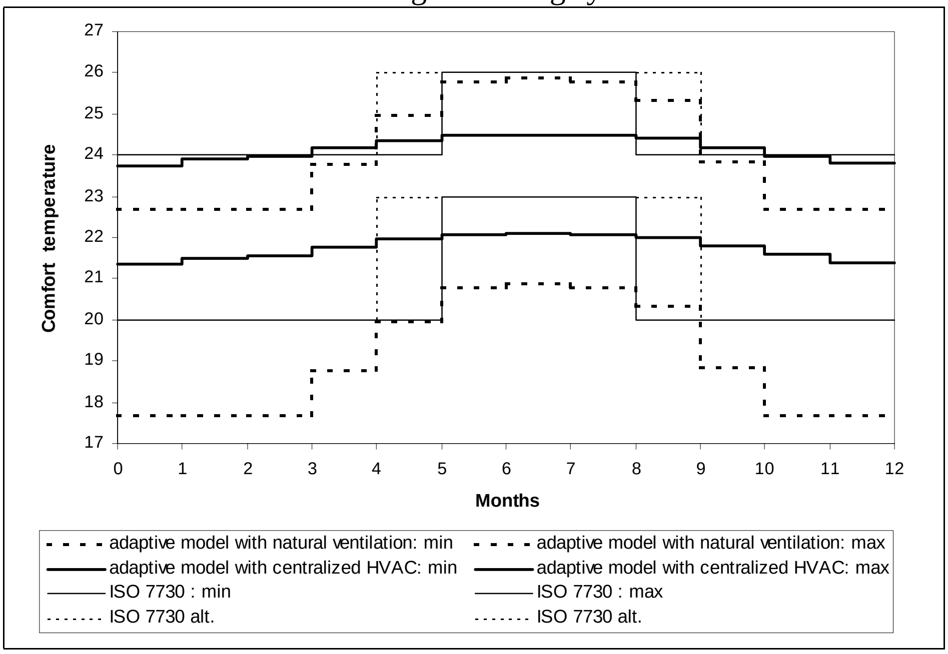

Figure 3. Required temperature ranges - according to the approaches in Table 3 - for 90% acceptability in the Czech Republic.

Table 4. Absolute and relative annual energy demand for heating and cooling of the office when facing different orientations (O) and for the 3 types of required indoor temperature ranges (Ti) as specified in Table 3.

O	T_i	The Netherlands				Czech Republic			
		Heating (kWh)	Cooling (kWh)	Total (kWh)	Total (%)	Heating (kWh)	Cooling (kWh)	Total (kWh)	Total (%)
N	1	586	134	720	100	541	232	773	100
	2	468	125	592	82	422	192	614	79
	3	761	164	925	129	704	260	964	125
E	1	547	309	856	100	450	512	962	100
	2	430	280	710	83	342	456	798	83
	3	709	341	1050	123	582	527	1109	115
S	1	389	430	819	100	365	607	972	100
	2	430	287	717	87	270	541	811	83
	3	534	452	986	120	478	609	1087	112
W	1	464	600	1064	100	415	882	1297	100
	2	355	565	920	87	321	813	1134	88
	3	611	607	1218	115	530	888	1418	109

Table 4 summarises the absolute and relative total annual energy demands for heating and cooling of the office for two different geographical locations, facing different orientations, and for the various required indoor temperature ranges.

Since the required temperatures during the heating season would be the lowest for case 2 (the adaptive comfort approach for naturally ventilated buildings) - see Figure 3, it comes no surprise that the energy demand for heating would be the lowest for this case.
The lowest temperatures during cooling season are for case 3 (the adaptive comfort approach for buildings with centrally controlled HVAC systems) – see Figure 3, but energy demand for cooling is almost the same for cases 1 and 3. The reason why this happened can be seen in Figure 4. There is considerable amount of cooling energy needed in May and September when these months are treated as heating season (which is according to the current standards).

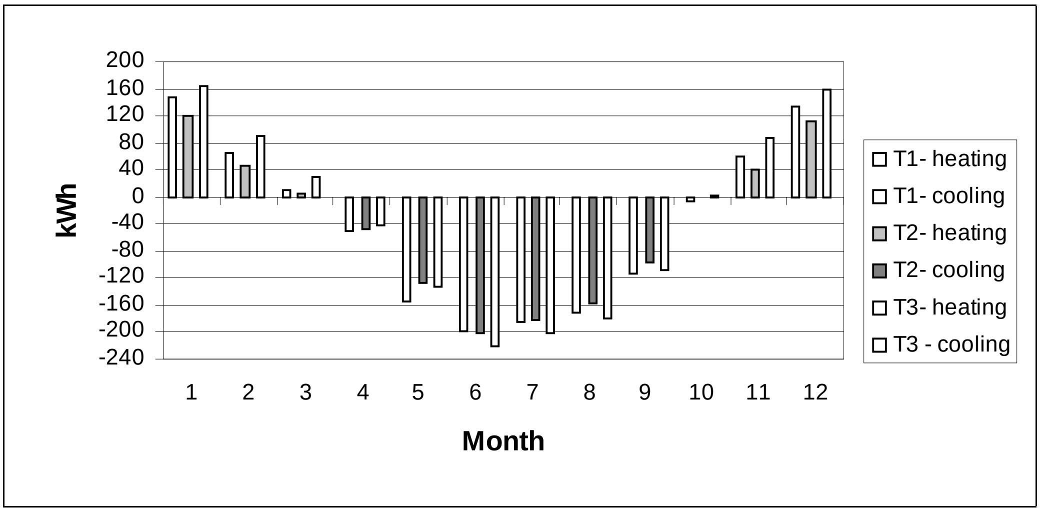

Figure 4. Monthly energy demand for heating and cooling for the office facing west and located in the Czech Republic.

DISCUSSION

During the work summarised above some questions and issues were encountered which are briefly discussed below.

Outdoor ET* and solar radiation

It is very problematic to speak about outdoor ET* when it doesn't contain solar radiation. ET* is primarily an index used by researchers, and that practitioners would be more likely to use the adaptive comfort model if the meteorological input data was a more familiar and accessible index. The adaptive comfort model was, therefore, reformulated in terms of mean monthly outdoor air temperature, defined simply as the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry bulb) temperatures for the month in question (14). This climate data is readily available and familiar to engineers.

Mean T_o based on daily or monthly mean values

In our current study, the required indoor temperature ranges according to the adaptive comfort approach were established per month; i.e. based on the monthly mean T_o. This also conforms to the current draft standard; see (14)). However, according to the originally proposed standard (7) it would be allowed to establish T_o on a daily basis. Figure 5 shows the difference for the required temperature range in The Netherlands during July of a climatic reference year. It is clear that if the daily approach would be used, the allowable indoor temperatures would be considerably higher during the warmer days, especially for buildings with natural ventilation. The underlying issue is of course whether the time constant of human thermal adaptation is in the order of one day or in the order of one month. It seems more reasonable to assume the former.

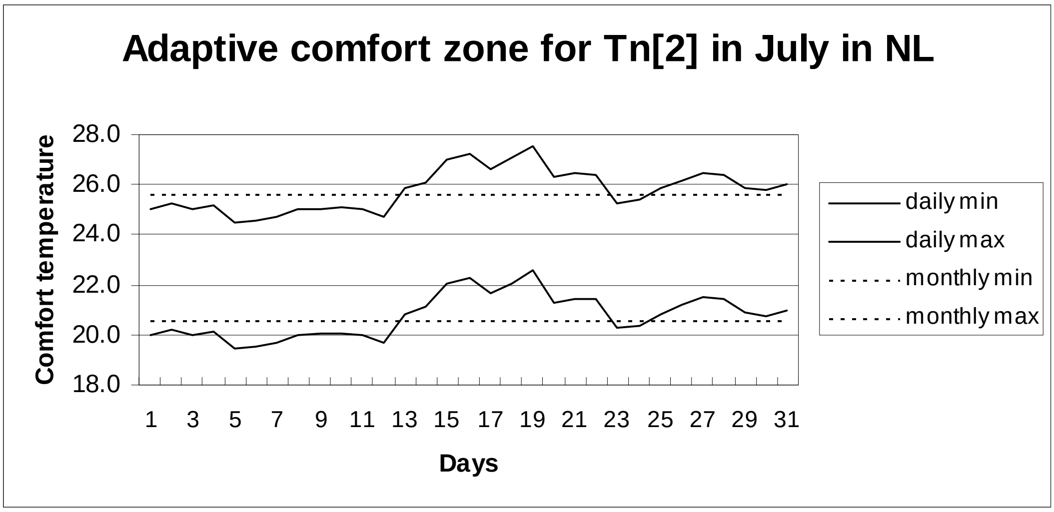

Figure 5. The required temperature range based on either daily or monthly mean outdoor temperatures according to the adaptive comfort approach for naturally ventilated buildings in The Netherlands during July.

Definition of building category

Finally there seems to be an issue in defining the two categories of building. The scope definitions in the originally proposed standard (7) state the following.

- Standard for buildings with centrally controlled
- Standard for naturally ventilated buildings

Many buildings in temperate climates have so-called mixed mode cooling systems. In some cases this means that either the mechanical cooling or the natural ventilation can be active at any point in time. In other cases these systems may work simultaneously. Very often these systems consist of centralised and local components and controls. Presumably these systems would mostly fall in the second category because the occupants have some form of control, however this is not immediately clear from the above scope definitions.

The current state is that the adaptive comfort approach will be included in Standard 55 as an option to be used only for the following conditions:

- naturally conditioned spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows
- spaces can have a heating system, but the method doesn't apply when it is in operation.
- spaces cannot have a mechanical cooling system
- spaces can have mechanical ventilation with unconditioned air
- occupants of spaces must be engaged in near sedentary activity (1-1.3 met), and must be able to freely adapt their clothing to the indoor and/or outdoor thermal conditions

CONCLUSIONS

As reported by Brager and De Dear (13, 14) the originally proposed (7) adaptive comfort model for buildings with centrally controlled HVAC systems is not relevant any longer. If it had been, then the indoor temperature requirements for The Netherlands and the Czech Republic would have been stricter – and the energy demand higher - than according to the current thermal comfort standard.
Using the originally proposed adaptive comfort standard (7) for buildings with natural ventilation would result in moderate climates such as in The Netherlands and in the Czech Republic in considerable lower energy demands for heating in comparison to the current thermal comfort standard. However, how realistic would it be to allow indoor temperatures down to 18°C operative temperature, which is the lower limit for 90 % acceptability when outside ET*≤ 5°C?

Based on monthly mean outdoor air temperatures in The Netherlands and the Czech Republic, the currently proposed adaptive thermal comfort standard for naturally ventilated buildings will be more strict than the current standard during the major part of the summer period. Since it will not be allowed to use the adaptive approach in case there is any mechanical cooling system, there will not be an energy penalty. It will, however, be easier for a designer to comply with the current standard thus making the adaptive comfort standard moot.

Based on the current work it may be concluded that for moderate climate countries such as The Netherlands and the Czech Republic there is no apparent reason for rushing to adopt the proposed adaptive thermal comfort standard in its current form.

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