Thermal Comfort in Offices – Natural Ventilation vs. Air Conditioning

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Abstract

Based on both subjective and objective data, a study was carried out in order to identify differences in the perception of thermal comfort of office workers in naturally ventilated and air-conditioned buildings. The analysis of the interviews shows that occupants of naturally ventilated office buildings are significantly more satisfied with their thermal environment than occupants in air-conditioned buildings. Several perceived parameters influence thermal comfort: lighting, draughts, temperature variations, acoustics, olfactory quality, glare and perceived control as well as for air which is perceived as stale and dry. The impact of these parameters depends on the type of ventilation and the perception of the indoor temperature (hot or cool). The closest agreement between predictions and subjective perception of thermal comfort for air-conditioned offices is achieved by Mayer's modification of the PMV-Model. For naturally ventilated offices the ASHRAE approach shows the best match.

Keywords

thermal comfort, adaptive, ventilation, field study, standards

1. Introduction

At present a lack of guidelines for the design of thermal comfort in naturally ventilated office buildings leads to uncertainty when planning such buildings in Germany. An analysis was carried out in order to identify differences in the perception of thermal comfort of office workers in naturally ventilated and air-conditioned buildings and to find out if existing approaches for assessing thermal comfort in mechanically ventilated buildings are also valid for natural ventilation.

2. Thermal comfort models

Relevant literature comprises four major approaches. On the one hand there is the PMV-Model of Fanger (ISO 7730) and its modification by Mayer 1998. Both approaches determine the Predicted Mean Vote (PMV) in dependence on the momentary air and radiant temperatures, air velocity, relative humidity, metabolism and clothing insulation value. Both authors calculate Predicted Percentage of Dissatisfied Persons as a function of PMV. On the other hand there are two adaptive approaches: a Dutch guideline (Boerstra et al. 2003) and the ASHRAE approach (de Dear et al. 1997). Contrary to the PMV-Model the adaptive models relate the indoor comfort temperature to mean outside temperature.

The PMV-PPD-Model of Fanger (ISO 7730) was modified by Mayer 1998. Mayer investigated the relation between PMV and PPD by asking not only for thermal sensation but also for preference. He found that a vote of slightly cool (-1) is already regarded as uncomfortable. His modification of the PMV-PPD relation is shown in Fig. 1 in addition to Fanger's relation. According to Mayer the minimum percentage dissatisfied can be reached at a PMV of +0.4. This means that a thermal environment which is slightly warmer then neutral is regarded as comfortable. The minimum percentage dissatisfied is 16% which is much higher than Fanger's minimum of 5%.

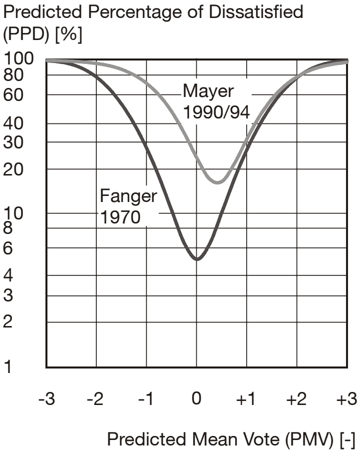

Fig. 1 Predicted percentage of dissatisfied (PPD) in dependence on the predicted mean vote (PMV) according to Fanger (ISO 7730) and Mayer 1998.

Fig 2 shows the comfort temperatures for office work in the adaptive models in comparison with the former German standard DIN 1946-2 (for mechanically ventilated buildings) and ISO 7730, category C. The reference outside temperatures of the adaptive models and DIN 1946-2 are different. The comfort temperature according to DIN 1946-2 depends on the momentary outside temperature. Last year DIN 1946-2 was replaced by DIN EN 13779 which refers to ISO 7730. Thus the PMV-model is mandatory for both naturally and mechanically ventilated buildings in Germany. The upper temperature limits of ASHRAE Standard 55 and the Dutch guideline are identical. In comparison, the upper temperature limit of DIN 1946-2 is 4°C lower. The maximum allowed temperature of DIN 1946-2 in summer lies within the comfort zone of ISO 7730, category C, summer conditions. The lower limits of ASHRAE Standard 55 and the Dutch guideline have a different slope. The Dutch guideline refers to the lower limit of the ASHRAE Rep. 884 (de Dear et al 1997) for air-conditioned buildings.

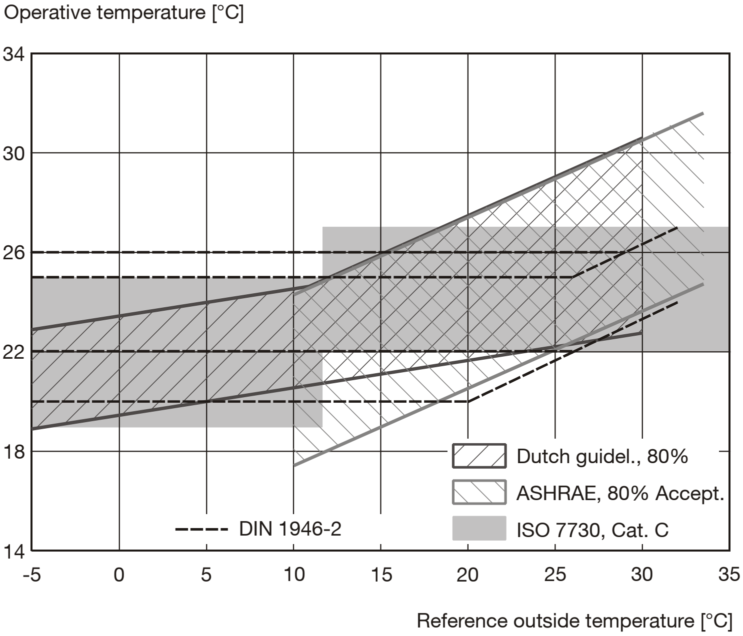

Fig. 2 Comparison of different indoor temperature limits for naturally ventilated buildings in dependence on the reference outside temperature with the temperature limits from German DIN 1946-2 and ISO 7730.

Fig. 3 shows the resulting comfort temperature according to the different standards for outside temperatures measured in Munich city centre in the hot summer of 2003. The Dutch approach allows the temperature to rise to just above 30°C (assuming 80% acceptance). Reference temperature is the running mean outside temperature. ASHRAE Standard 55 provides an upper limit of just below 30°C. Since DIN 1946-2 is not valid at outside temperatures above 32 °C (extrapolation is not permitted) the curve of maximum allowed temperature in the example is partly undefined (dashed line). DIN 1946-2 gives a 3 to 5 K lower maximum temperature than both adaptive approaches. Naturally ventilated buildings cannot provide indoor temperatures of about 25 or 27 °C if the running mean outside temperature rises above 30°C for a long period.

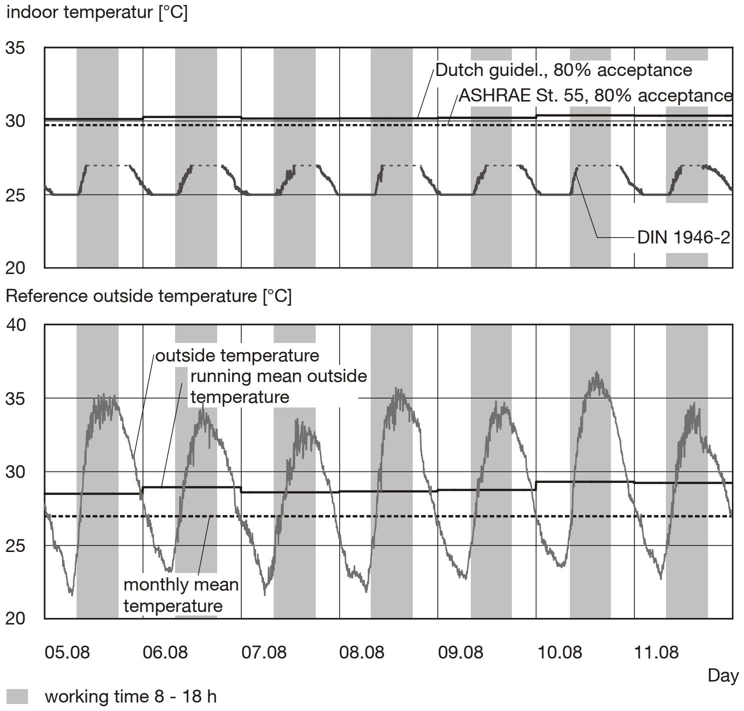

Fig. 3 Maximum allowed indoor temperature for a naturally ventilated office. Outside temperatures were measured during the hot summer in Munich, city centre. The upper graph shows the maximum allowed indoor temperature, the lower graph the corresponding reference outside temperature.

3. Material

The analysis is based on both subjective data from interviews as well as on objective data from physical measurements. It includes data collected in 14 German office buildings from the ProKlimA-Study (Bischof et al. 2003). The data were collected between 1995 and 1998. 6 of the buildings are naturally ventilated, 8 of them have air-conditioning systems. At the first investigation of the 14 buildings 4500 persons were interviewed. At the second investigation 1500 persons in these buildings were interviewed again and indoor climate parameters were measured.

The investigated buildings were built between 1900 and 1995. 41% of the subjects work in office buildings with natural ventilation. 22% and 37% of the work places are located in buildings with partial air-conditioning and full air-conditioning respectively. Windows are sealed at 87% of the work places in buildings with air-conditioning. 55% of the subjects are employed by public services and 45% work for private businesses. The mean value of the proportion of glazed façade is 41% for the naturally ventilated buildings. For buildings with mechanical ventilation the proportion is about 10 per cent higher. Mechanically ventilated buildings have low thermal mass in contrast to naturally ventilated buildings which have intermediate thermal mass. None of the buildings has a construction with high thermal mass.

4. Satisfaction with thermal conditions

The analysis of the interviews shows that occupants of naturally ventilated office buildings are significantly more satisfied with their thermal environment than occupants of air-conditioned buildings. Whereas 34% and 54% respectively of the occupants in buildings with partial air-conditioning and full air-conditioning regard the indoor temperature as slightly or very uncomfortable, only 20% of the occupants in naturally ventilated buildings assess the indoor temperature as slightly or very uncomfortable.

Fig. 4 shows for each of the investigated buildings the percentage of occupants who where satisfied with indoor temperature. The mean value of satisfaction for all buildings is 61%. In air-conditioned buildings only 50% of the occupants are satisfied whereas in naturally ventilated buildings 77% of the occupants are satisfied with indoor temperature.

In mechanically ventilated offices with an air heating system the percentage satisfied is 45%. In offices with radiators 60% of the occupants are satisfied with the temperature. Sealed windows result in only 40% satisfaction. In offices with openable windows satisfaction increases to 62% (Table 1).

Satisfaction with other indoor environmental parameters was requested also. The occupants in naturally ventilated offices are much more satisfied with all parameters (lighting, humidity, ventilation, noise, air movement) with the exception of olfactory load. This is the parameter which occupants in offices with mechanical ventilation rate more positively. The most remarkable differences in the ratings were found for satisfaction with ventilation, humidity, indoor temperature and air movement.

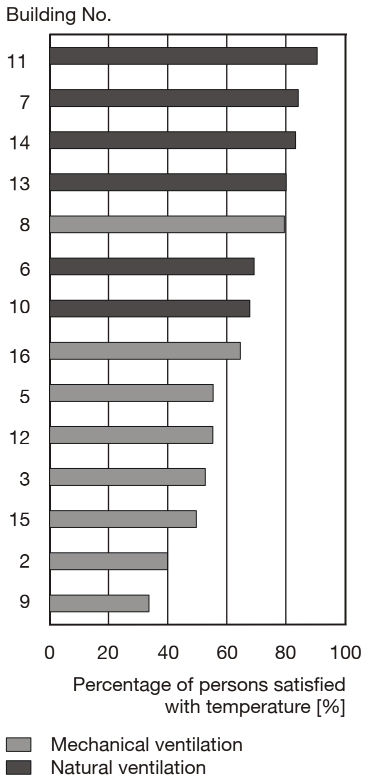

Fig. 4 Percentage of persons satisfied with indoor temperature for each building (n = 4400).

Table 1 Percentage of occupants satisfied with indoor temperature in mechanically ventilated buildings.

Mechanical ventilation and		Total n	Satisfied %
Heating system	Radiators	834	60
	Air heating system	1746	45
Windows	Sealed	1444	40
	Openable	1170	62

5. Parameters influencing thermal comfort

A review of relevant literature showed that interactions between thermal comfort and several parameters can be assumed. These parameters can be divided into three groups:

- Architectural parameters and parameters concerning the heating and ventilation system
- Psychosocial parameters
- Perception of other indoor climate parameters

Architectural parameters and parameters concerning the heating and ventilation system

The following architectural parameters and parameters concerning the heating and ventilation system show a strong connection with thermal comfort:

- Type of ventilation (natural or mechanical)
- Type of air-conditioning system (natural ventilation, partial air-conditioning, full air-conditioning)
- Type of heating and cooling system
- Position of air supply and extract
- Humidification of supply air
- Percentage of glazed area of the façade
- Solar gain value of the façade
- Type of windows (sealed, openable)
- Construction type (low – medium thermal storage properties)
- Perceived control over indoor environment

At the same time, parameters such as the type of heating or cooling system and the construction type have a strong connection with the type of ventilation and air-conditioning system respectively. Therefore only the type of ventilation / air-conditioning was used for further multivariate statistical analysis.

An important parameter which is influenced mainly by the ventilation system is perceived control. This parameter does not describe whether a room is equipped, or not, with objective control facilities like thermostats; perceived control describes to what extent occupants feel they have control over their indoor environment. There were two questions in the questionnaire which asked for perceived control: relating to indoor temperature and air movement. 57% and 51% of all occupants perceive they have control over indoor temperature and air movement respectively.

Regardless of the type of ventilation, 85% of all persons wish to have control over their indoor climate. In naturally ventilated offices 87% of persons feel they have control over the indoor temperature. The percentage of the same group in partially air-conditioned buildings is half as much (46%). In air-conditioned buildings the value is even lower (36%). In naturally ventilated offices the proportion of occupants perceiving they have control over air movement is just as high as for indoor temperature. In buildings with air-conditioning and sealed windows this proportion is only 7%.

The variables perceived control over temperature and air movement respectively were combined into a new variable “perceived control”. Those persons who answered that they have control over both temperature and air movement have a perceived control of 1. Persons who answered both “no control” have a perceived control of zero.

Fig. 5 shows the mean value of perceived control for each building. The mean value of perceived control in air-conditioned buildings is 0.32. It is significantly lower than the value for buildings with natural ventilation (0.87).

An exception is building no. 8 with a mean of 0.77. This value is quite comparable to those for naturally ventilated buildings. Building no. 8 has a partial air-conditioning system and openable windows with a glazed façade area of 25%. The air flows from air inlet in the floor to the outlet in the ceiling. The building does not have a cooling unit in the ventilation system and is heated with radiators. The maintenance of the ventilation system of the building was rated as very good.

There are two buildings with very low mean values of perceived control (2 and 9). The percentage of persons satisfied with temperature was also the lowest in these buildings. The buildings have sealed windows. The ventilation system is a mixed flow system which is also used for heating. Building 2 has air inlets and outlets in the ceiling. Building 9 has air inlets in the balustrade (induction unit) for areas close to the façade. Areas farther from the façade are ventilated via air inlets and outlets in the ceiling.

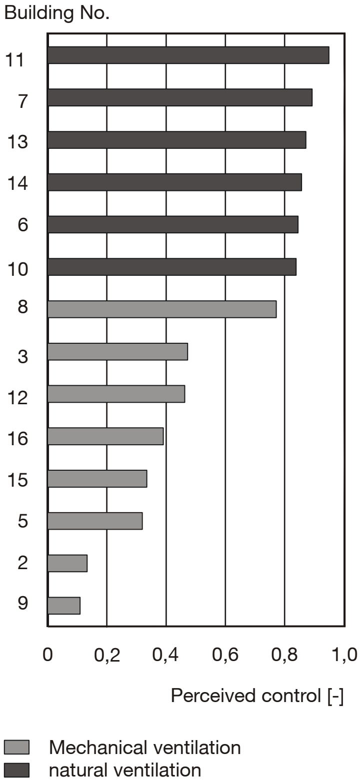

Fig. 5 Mean value of perceived control for each of the investigated buildings. Naturally ventilated buildings: Mean = 0.87; Mechanically ventilated buildings Mean = 0.32. (n = 4492).

Whereas 81% of the occupants in building 12 feel they have control over indoor temperature, only 12% of the same occupants think they have control over the air movement. The windows of the building are sealed. The building’s ventilation system consists of induction units with air supply on the bottom of the unit. The mean value of perceived control is 0.23 in buildings with an air heating system and 0.51 in buildings with radiators (Table 2). Buildings with sealed windows have a mean value of perceived control of 0.19. The value increases up to 0.48 in mechanically ventilated buildings with openable windows.

Table 2 Mean value of perceived control in mechanically ventilated buildings.

Mechanical ventilation and		Perceived control		
		n	Mean	SD
Heating system	Radiators	846	0.51	0.43
	Air heating system	1799	0.23	0.33
Air inlet - outlet	Ceiling – ceiling	715	0.21	0.37
	Floor – ceiling (Building 8)	287	0.71	0.38
	Balustrade (Induction unit)	1091	0.25	0.35
	bottom - ceiling	552	0.39	0.34

Analyzing the coefficient of contingency of perceived control and satisfaction with indoor temperature gives a strong significant connection ($n = 4343$, $CC_{corr} = 0.56$, $p < 0.001$).

Psychosocial parameters

The relation between psychsocial parameters as follows and thermal comfort was investigated:

- Sex(confounder)
- Age (confounder)
- Education
- “Sick building syndrome” case
- Hypersensation to warmth or cold (confounder)
- Job satisfaction
- Life satisfaction
- Work-related strain
- General strain

For psychosocial parameters such as job satisfaction, work-related and general strain, life satisfaction and education, only weak coefficients of contingency were determined. This is contrary to the results of Cena and de Dear 1998, who found a strong significant relation between job satisfaction and satisfaction with indoor temperature. Further investigation seems to be required.

The results of the present investigation indicate that the link between thermal sensation and thermal comfort is, in contrast to the Sick-Building-Syndrome (SBS), less sensitive to psychosocial influences. The parameters sex, age and hypersensitivity to warmth or cold were considered as potential confounders in the advanced statistical analysis.

Perception of other indoor climate parameters

The questionnaire used in the ProKlimA-Study contains a module which asks for the perception of indoor climate parameters. It includes ratings of 15 indoor climate parameters including thermal sensation and thermal comfort. The contingency analysis showed strong relations between some of the variables. For further analysis the 13 variables (excluding thermal sensation and comfort) were reduced to 6 new factors using factor analysis.

The following condensed factors were developed:

- Acoustical quality:
  loud – quiet; many – few distracting noises; low – high sound absorption
- olfactory quality:
  unpleasant – pleasant odours; pleasant-smelling – foul-smelling, high – low olfactory load
- Lighting conditions:
  good – bad illumination; light – dark
- Condition of air:
  dry – humid air; fresh – stale air
- Draught/ variability of temperature:
  varying – stable temperature; weak – strong air movement
- Glare: glaring vs. non-glaring light

The above mentioned potentially influencing variables were reduced to a few important variables during a logistic regression procedure. The impact of the variables on thermal comfort depends on the type of ventilation and perception of the indoor environment temperature (hot or cold). For each of the important variables so called odds ratios were determined. The odds ratio (OR) describes the change of the chance of feeling uncomfortably cool or warm in dependence on an influence variable.

Two examples explain the results: An environment which is perceived as loud or distracting increases the chance of feeling uncomfortably warm with an OR of 2 compared with an environment which is quiet and not distracting. The risk of persons feeling uncomfortably cool is 2 or 3.5 times higher in naturally or mechanically ventilated buildings respectively, when the persons are exposed to draughts or variability of temperature at the same time. In the case of lighting conditions perceived as bad, the chance of feeling uncomfortably cool rises, with an OR of 3. Also a medium to low olfactory quality as well as air which is perceived as stale and dry can influence the feeling of discomfort. Further investigations are required to support these results.

6. Validity of thermal comfort models

The validity of existing methods for assessing and predicting thermal comfort in offices is investigated. The PMV-PPD relation of Fanger and it's modification by Mayer were compared to results from approximately 4400 interviews. Data were subdivided into three types of ventilation: natural ventilation, partial air-conditioning and full air-conditioning (Fig. 6). On the "warm" side of the diagram a divergence between natural ventilation and air-conditioning can be noticed. For full air-conditioning, Mayer's distribution shows the closest agreement ($p = 0.0001$) with the interview-based distribution, but statistically both distributions are still different (level of significance = 0.05). Fanger's distribution does not give a good prediction for any of the ventilation types (all $p < 1*10^{-15}$).

Looking at the percentage dissatisfied in the categories of thermal sensation (cold to hot), the proportion is much lower for naturally ventilated buildings especially for warm (13%) and hot (32%) than for mechanically ventilated buildings (warm: 38%, hot: 82%). Only one of the naturally ventilated buildings was investigated in summer. Therefore it is reasonable to question whether the season influenced the result or not. Fig. 7 show the comparison of percentage dissatisfied for building no. 6, which was investigated in summer, and the other naturally ventilated buildings. Only slight differences can be seen.

The next step was to make up two groups: occupants with no control over their thermal environment (perceived control = 0) and occupants with perceived control of 1 (Fig. 8). None of the approaches, Fanger or Mayer, gives a good prediction of the distribution for "perceived control = 1" (both $p < 1* 10^{-72}$). But Mayer's distribution matches very well the distribution for a perceived control of 0 ($p = 0.11$). Fanger's PMV-PPD relation seems to be inappropriate.

The distribution of the percentage of dissatisfied occupants with a perceived control of 0 is quite similar to that of full air-conditioning. The distribution of perceived control of 1 is comparable to that of natural ventilation. As pointed out earlier, these person groups are identical to a large extent.

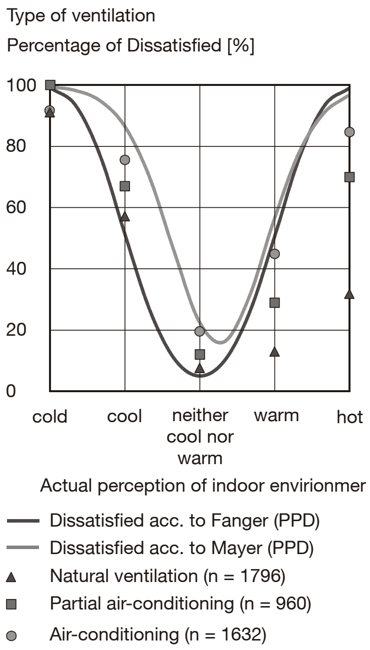

Fig. 6 Percentage of dissatisfied in dependence on the perception of the indoor climate (cold to hot) and the type of ventilation. Predictive distributions according to Fanger (ISO 7730) and Mayer 1998 are also shown.

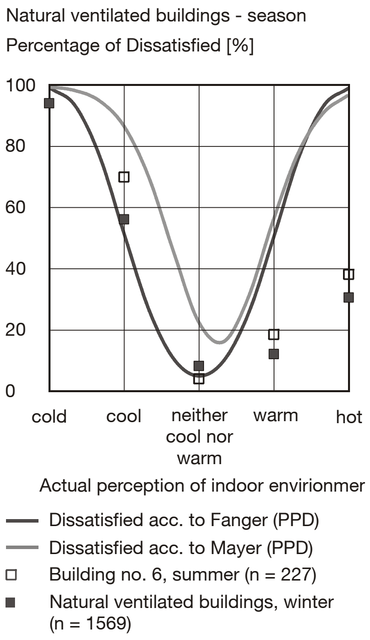

Fig. 7 Percentage of dissatisfied in dependence on the perception of the indoor climate (cold to hot) for all naturally ventilated buildings and building no. 6, which was investigated in summer.

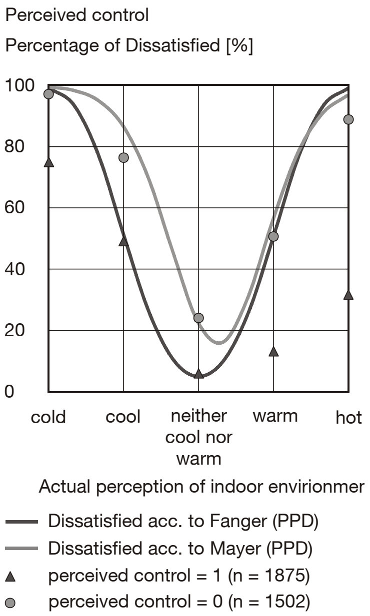

Fig. 8 Percentage of dissatisfied in dependence on the perception of the indoor climate (cold to hot) and perceived control. Predictive distributions according to Fanger (ISO 7730) and Mayer 1998 are also shown.

On the basis of data from approximately 1500 interviews and the related measurements it was examined how well the four approaches (see Section 2) can predict the indoor comfort temperature. Activity, clothing insulation (including the effect of a chair), air and radiant temperature, air velocity and humidity were deduced from the measurements. The indoor comfort temperature was calculated:

- according to Fanger with a PMV = 0 (ISO 7730)
- according to Mayer with a PMV = 0.4 (Mayer 1998)

and for the two adaptive models:

- the ASHRAE approach (ASHRAE St. 55, de Dear and Brager 2002) and
- the Dutch approach (Boerstra et al. 2003).

The adaptive models are different for naturally ventilated and mechanically ventilated buildings.

Predicted comfort temperatures where compared with measured temperature for all persons who were satisfied with their indoor temperature. Fig. 9 and 10 show the frequency distributions of the difference between predicted indoor comfort temperature and measured temperature as well as the mean value of the distributions. If the mean value of the distribution is close to zero, then there is a good agreement between predicted comfort temperature and measured temperature.

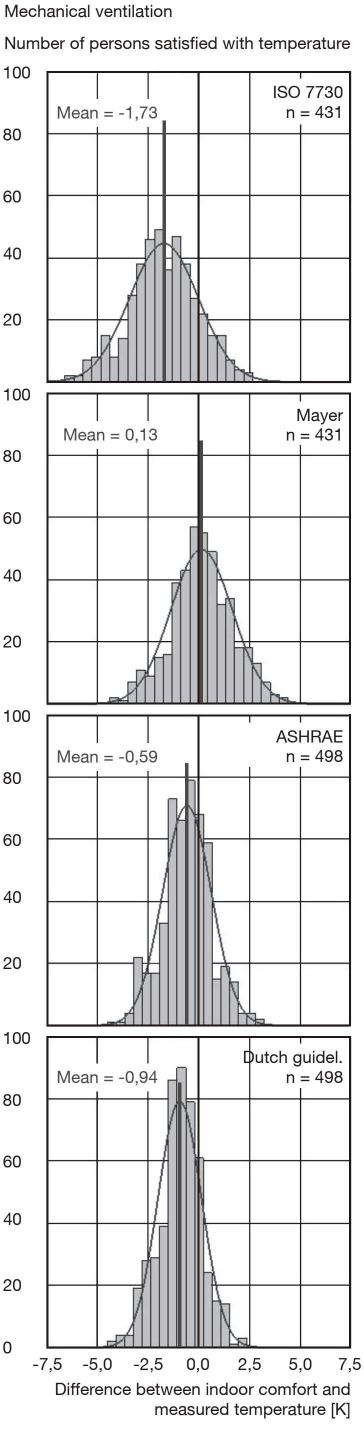

Fig. 9 (left): Comparison of predicted comfort temperature with measured temperatures for mechanically ventilated work places which where classified as "comfortable" by office workers. Predicted comfort temperatures were determined according to Fanger (ISO 7730), Mayer 1998, ASHRAE (ASHRAE St. 55, de Dear and Brager 2002) and the Dutch guideline (Boerstra et al. 2003).

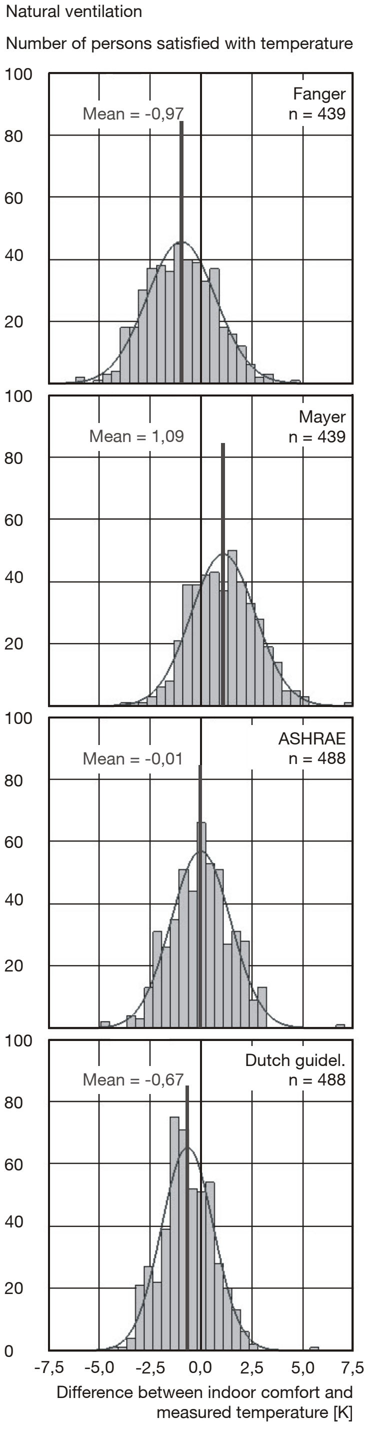

Fig. 10 (right): Comparison of predicted comfort temperature with measured temperatures for naturally ventilated work places which where classified as "comfortable" by office workers. Predicted comfort temperatures were determined according to Fanger (ISO 7730), Mayer 1998, ASHRAE (ASHRAE St. 55, de Dear and Brager 2002) and the Dutch guideline (Boerstra et al. 2003).

Fig. 9 shows the results for mechanically ventilated offices. From the statistical test it can derived that there is a difference between predicted and measured comfort temperature for both adaptive models and Fanger's PMV-PPD model (all $p < 0.001$). Obviously the approach of Mayer gives the best prediction out of the four approaches. Looking at the result statistically, there is still a difference between prediction and measurement ($p = 0.077$, level of significance $\alpha = 0.10$).

For naturally ventilated buildings the statistical test detects differences between predicted comfort temperatures and measured comfort temperature for both PMV-PPD models and the Dutch approach (all $p < 0.001$) (Fig. 10). The method according to ASHRAE Standard 55 and de Dear and Brager 2002 gives good agreement (p = 0.838).

7. Conclusion

So far, Fanger's PMV-Model is the standard method for assessing thermal comfort in Germany and Europe. The results demonstrate that new guidelines for assessing and planning thermal comfort in office buildings are required for both natural ventilation and air-conditioning.

Several perceived parameters influence thermal comfort: lighting, draughts, temperature variations, acoustics, olfactory quality, glare and perceived control as well as for air which is perceived as stale and dry. The impact of these parameters depends on the type of ventilation and the perception of the indoor environment temperature (hot or cool).

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