Towards Adaptive PMV/PPD Indices for European Climates…

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ABSTRACT

There are currently two main standards relative to indoor thermal comfort assessment (EN 15251 and ASHRAE-55). Both specify different criteria depending on whether the building is air conditioned or free ventilated. The analytic approach must be used as the comfort criteria for air conditioned buildings whereas it is possible to employ the adaptive approach for naturally conditioned buildings provided that they meet some requirements. This study aims at looking for a way to unify the different thermal comfort approaches. Unifying the metrics should have two main impacts in the purpose of moving towards more efficient buildings. The first one is to make air conditioned buildings more efficient by shifting to higher set points. The second one is to enhance the use of the adaptive theory during the design phase and stimulate the construction of free ventilated buildings. In a first step, the two standards, EN 15251 and ASHRAE-55, are presented and their consequences in terms of recommended temperatures are analyzed in the European context. It appears that there are significant differences between the standards regarding free running buildings and a first attempt to explain this difference is developed in this paper. At the end, this study proposes a possible method for unification that could satisfy defenders of both the adaptive and analytic approaches.

Introduction

The definition of summer comfort zones can bring about important consequences for buildings energy consumption: too stringent comfort rules will imply a generalization of air conditioning even if it is sometimes unnecessary whereas too wide comfort zones can lead individuals to feel uncomfortable and look for local (and often inefficient) solutions to improve their comfort. There are currently two main standards relative to indoor thermal comfort assessment: EN 15251 (ESO 2007) and ASHRAE-55 (ASHRAE 2004). Both specify different criteria depending on whether the building is air conditioned or free ventilated. The analytic approach must be used as comfort criteria for air conditioned buildings whereas it is possible to employ the adaptive approach for free-running buildings provided that they meet some requirements. This paper aims at studying the adaptive part of both standards (i.e., regarding free running buildings) and proposing a unified method of comfort assessment in order to go beyond the traditional opposition between defenders of the analytic approach and defenders of the adaptive approach. We think unifying the metrics should contribute to move towards more efficient buildings. On the one hand this should make air conditioned buildings more efficient by shifting to higher set point. On the other hand, we think that the use of the adaptive theory during the design phase is restrained because of two main problems: this theory is not generally accepted and is only presented as an optional method; displayed comfort temperatures are very high and can scare planners that want to avoid occupants' discontent (lawsuit…). As a result, a consensus on the adaptive comfort ranges along with lower displayed temperatures can stimulate the construction of free ventilated buildings by conducing building planners to use the adaptive theory

Presentation of the American (ASHRAE 55) and European (EN 15251) Standards Relative to Thermal Comfort

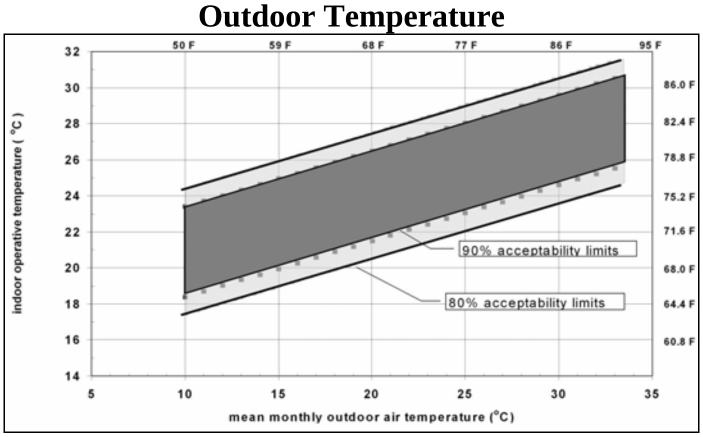
ASHRAE 55-2004

The purpose of ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy) is "to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within a space."

Comfort conditions for air-conditioning buildings according to ASHRAE 55-2004. For air conditioned buildings, this standard is mainly based on the PMV/PPD indices. The PMV ("Predicted Mean Vote") and the PPD (Predicted Percentage of Dissatisfied) were developed in Fanger 1970. In brief, these indices depend on six parameters: four regarding indoor climate (air temperature, mean radiant temperature, air velocity, relative humidity) and two concerning people (physical activity, clothing thermal resistance). A PMV equal to zero represents the optimum comfort when the thermal balance is null; this index can vary from –3 (cold) to 3 (hot). It is also possible to predict the reaction of individuals thanks to the PPD index, which aims at calculating the expected number of thermally dissatisfied people in a group according to the PMV. The recommended criterion in ASHRAE-55 is to limit the PMV to between –0.5 and 0.5 (i.e., a dissatisfaction rate of less than 10 %).

The American standard also proposes an adaptive model for naturally conditioned spaces where the thermal conditions of the space are regulated by the occupants through opening and closing of windows. The adaptive theory is based on field studies pointing out that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable by making adjustments to their clothing, activity, and posture as well as their thermal environment (Humphreys & Nicol 1998). Allowable indoor operative temperatures can be derived from the mean monthly outdoor temperature as shown in Figure 1. This temperature is the arithmetic average of the mean daily minimum and the mean daily maximum outdoor temperatures for the month in question. Two categories of indoor temperatures are defined, one for 80% acceptability (typical applications), another for 90% acceptability (when a higher standard of thermal comfort is desired).

Figure 1. Acceptable Indoor Operative Temperature According to the Mean Monthly Outdoor Temperature



Source: (ASHRAE, 2004)

EN 15251

The European standard EN 15251 specifies design values for the indoor environment, values to be used in energy calculations, and methods to check the specified indoor environment in the buildings. Three categories of buildings are defined in this standard according to the occupants' level of expectations - Category 1: high level of expectation (very sensitive and fragile persons), Category 2: Normal level of expectation, Category 3: an acceptable, moderate level of expectation (may be used for existing buildings) and the recommended criteria depend on them. This paper only discusses thermal comfort but a comprehensive description of this standard can be found in Olesen 2007.

Comfort conditions for air conditioned buildings according to EN 15251. This standard is quite similar to ASHRAE-55 since it is based on the PMV/PPD indices dicussed above. The recommended PMV/PPD criteria for each building category are summarized in Table 1.

Table 1. Recommended PMV/PPD **Criteria by Building Category**

Category	**Thermal State of the Body as a Whole**	
	Predicted Percentage of Dissatisfied [%]	Predicted Mean Vote
I	< 6	-0.2<PMV<0.2
II	< 10	-0.5<PMV<0.5
III	< 15	-0.7<PMV<0.7

Comfort conditions for some types of free running buildings according to EN 15251. The main novelty of this standard compared to EN ISO 7730 (ESO 2006) is the proposition of the adaptive approach as an optional method for free-running buildings. Thus, while one has to use the PMV and PPD indices as comfort criteria for air conditioned buildings, it is possible to employ the adaptive approach for free-running buildings provided that they meet some requirements (see below). However, this optional method slightly differs from the one developed for ASHRAE-55.

EN 15251 uses the results of the SCATs project (McCartney & Nicol 2002) to define the comfortable range of indoor temperature according to outdoor climatic conditions. Once again, the ranges depend on the building category and are more stringent for the Category I than for Category III (Figure 2). It must be kept in mind that this approach can be used only if free ventilated buildings meet some requirements:

- Occupants must have quasi-sedentary activities (between 1 and 1.3 met).
- Occupants must not have a strict clothing code so they can freely adapt their clothes.
- Rooms must be equipped with operable windows under the occupants' control.

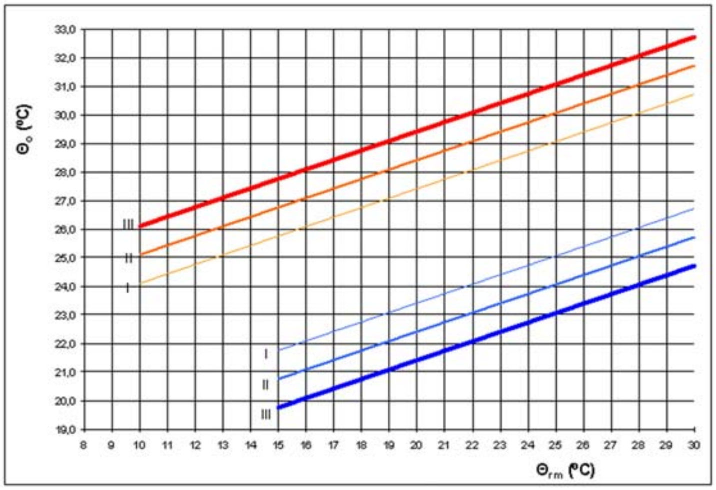
The acceptable indoor operative temperatures depend on a running mean outdoor temperature defined by Equation 1. This is an exponentially weighted running mean of the daily mean external air temperature. As the adaptive approach is partly justified by people's adaptation (clothing, activity), this average gives higher weightings on recent days. It is also possible to use Equation 2, which is a simplification of Equation 1.

$$\Theta_{rm} = (1-\alpha).[\Theta_{ed-1} + \alpha.\Theta_{ed-2} + \alpha^2.\Theta_{ed-3} + ...] \quad (1)$$

$$\Theta_{rm} = (1-\alpha).\Theta_{ed-1} + \alpha.\Theta_{rm-1} \quad (2)$$

where Θ_{rm} is the running mean temperature for today, Θ_{rm-1} is the running mean temperature for the previous day, Θ_{ed-1} is the daily mean external temperature for the previous day, Θ_{ed-2} the daily mean external temperature for the day before and so on. α is a constant between 0 and 1 and it is recommended to use 0.8 based on the SCATs project.

Figure 2. Acceptable Indoor Operative Temperature According to the Running Mean Outdoor Temperature (Equation 1)

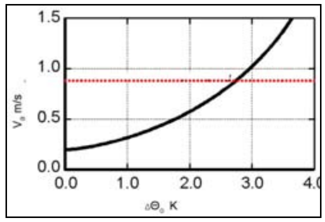


Source: ESO 2007

Contrary to the American standard in which comfort temperature ranges also account for people adaptation so it is not necessary to estimate the clothing values for the space and no humidity or air speed limits are required, EN 15251 introduces an allowance for air movement. This means that the upper limit of acceptable temperature can be raised when the air is moving in the room. Figure 3 gives the possible increase of temperature according to the provided air speed. According to the standard, this figure comes from EN ISO 7730 and is based on a theoretical calculation: the air speed increases in the amount necessary to maintain the same total heat transfer from the skin.

Figure 3 as presented in EN 15251 raises a problem for two reasons. The first reason is that EN ISO 7730, from which the figure comes, mentions that the reference point is 26°C (ESO 2006) and so it is less useful for temperature's above that. For instance when the acceptable indoor temperature is 32°C, it is not so obvious that increasing air speed will improve comfort since it is close to the skin temperature and air movement is likely to contribute to warm the occupant. A second reason is that the adaptive approach as proposed in this standard is based on results from the SCATs project (McCartney & Nicol 2002). The comfortable temperature ranges were worked out from field studies which means in real-life buildings where it was sometimes possible to use a comfort fan. Comfort fans are adaptive opportunities just as windows or clothes could be. This means that the possibility to use a comfort fan should be already included in the temperature range. As a result, this allowance for increased air speed will not be taken into account in what follows.

Figure 3. Allowance for Air Movement



Source: (ESO, 2007)

Comparison between the Adaptive Part of Both Comfort Standards (ASHRAE-55 and EN 15251)

Maximum Allowed Temperatures in the European Context

The comfortable temperatures defined by the two adaptive approaches presented in EN 15251 and ASHRAE 55 depend on the outdoor temperatures and, in order to compare them, it is necessary to take climatic data into account. Typical Meteorological year format that are derived from up to 18 years of hourly weather data have been used for 27 European cities.

For the first time, the moving averages have been figured out along with the monthly averages. This enables us to determine the maximum allowed temperatures over a typical year for both standards. It must be kept in mind that the maximum allowed temperature depends on the outdoor temperature and that this one is only allowed at a given moment over the year. The results are presented in Figure 4 for the 27 cities. It appears that the adaptive approach as defined in EN 15251 is the one that enables the highest temperatures. The difference between this approach and a temperature of 26°C ranges between 1.2°C in Dublin to 5.5°C in Seville. The adaptive approach as presented in ASHRAE 55 is more stringent since the difference between this approach and a temperature of 26°C ranges between 0°C in Dublin and 3.5°C in Athens. In terms of maximum allowed temperature, a main finding is also the significant difference between the two adaptive approaches (up to 2 °C). This difference would have been even more important if the allowance for air movement, which suggests a temperature increase up to 2.5 °C for air speed of 0.8 m/s, had been taken into account (Figure 3).

Long-Term Comparison in the European Context

To complete the comparison between the different approaches, a comparison over the long run has been carried out. This consists in calculating the number of hours during which the maximum allowed temperature will be higher than 26°C weighted by the number of degrees by which this temperature has been exceeded (degree hours). Assuming an office schedule of 8 hours a day (except during the weekend), the results are presented for the 27 cities in Figure 5. This is purely indicative since buildings that meet comfort criteria are not likely to be always at the maximum limit but to fluctuate between the lower and the upper comfort limits. Nevertheless, this calculation enables us to see if the differences previously noted also exist over a long-term assessment. Once again, the difference between the two adaptive approaches is significant; it appears that ASHRAE 55 is twice as stringent as EN 15 251. It also appears that the potential for reduction of cooling needs by applying adaptive standards in place of analytic ones varies significantly between the countries but turns out to be important..

Figure 4. Maximum Allowed Temperature for Different European Cities According to the Adaptive Approaches Developed in EN 15251 and ASHRAE-55 (80% Acceptability)

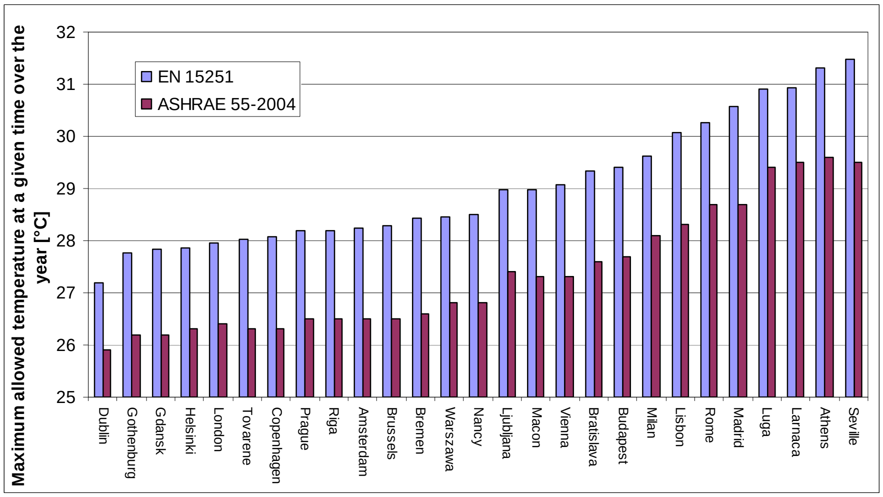
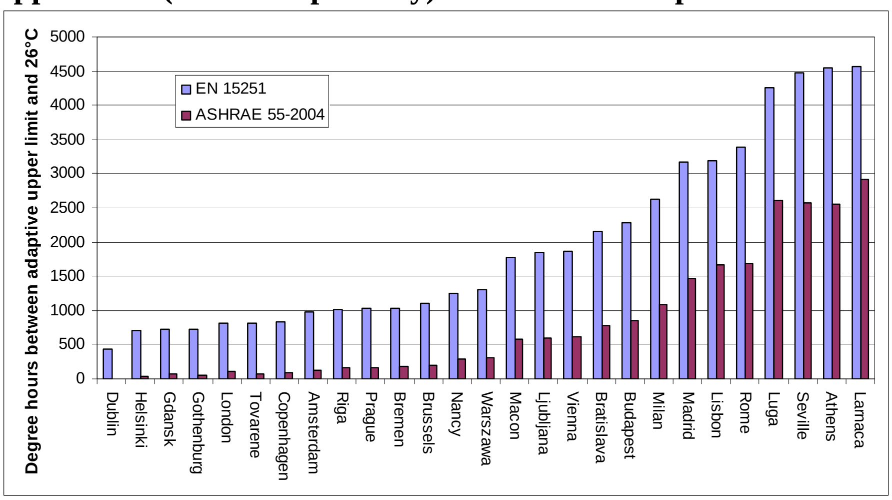


Figure 5. Degree Hours between the Upper Comfort Limits of the Two Adaptive Approaches (80% Acceptability) and a Fixed Temperature of 26°C



A Preliminary Attempt to Explain the Difference between the Two Adaptive Approaches Developed in ASHRAE-55 and EN 15251

It was shown in the previous section that the ASHRAE adaptive approach is more stringent than the European one. What can explain the differences between the two adaptive approaches? It seems impossible to find reliable causes in the differences in terms of adaptation. The ASHRAE adaptive standard is derived from surveys all around the world and since Europe is not among the warmest part of the world; it would be astonishing whether Europeans were among those who acclimatized better. In this section, the two methodologies that enabled the development of both adaptive standards have been studied in an attempt to explain the differences.

Basis of the ASHRAE Adaptive Approach

This subsection gives a short overview of the method used to develop the ASHRAE adaptive comfort standard (ACS), which has been comprehensively explained by de Dear & Brager 1998. According to the authors, the ACS is based on the analysis of 21,000 sets of raw data compiled from field studies in 160 buildings located on four continents in varied climatic zones. From these surveys, the authors carried out a statistical analysis of subjective thermal sensation votes within each building to define thermal neutrality, which is defined as the operative temperature found to correspond most closely with the scale's central vote of neutral. Thus, neutrality was calculated for each building by the following steps:

- The building's indoor operative temperature observations were binned into half-degree (K) increments and the bins' mean thermal sensation responses were calculated.
- A weighted linear regression model was fitted between mean thermal sensations and indoor operative temperature. Each building data point was weighted according to the number of questionnaires it represented. A statistical significance criterion was introduced to eliminate those buildings that had small sample sizes or that had uniformly cold or hot indoor temperature.
- Neutrality was derived by solving each building's regression model for a mean sensation of zero.

This methodology enabled the determination of a linear regression of the comfort temperatures (one comfort temperature per building) according to the mean outdoor temperatures.

Basis of the European Adaptive Theory

The European adaptive standard is based on the EU-funded SCATs project (McCartney & Nicol 2002), which aimed at developing an adaptive control algorithm as an alternative to fixed temperature set point controls within air conditioned buildings. Numerous comfort field studies have been carried out by Nicol and his team in five European countries: France, Greece, Portugal, Sweden, and UK. Then, the obtained databases were analyzed to ascertain the comfort temperatures at various outside conditions.

The first step consisted in determining an equation linking the comfort temperature to the comfort vote and the globe temperature at the time when the questionnaire was being filled. The authors suggested using Equation 3 stemming from the inspection of the ASHRAE database of thermal comfort field studies carried out by de Dear and Brager (de Dear & Brager, 1998).

$$CV = 0.5.T_G + h \quad (3),$$

where CV is the comfort vote from ASHRAE scale (1 to 7 correspond to –3 to 3 respectively with the PMV scale), T_G is the indoor globe temperature, and h is a constant.

Since the comfort temperature occurs at point 4 in this scale (i.e., the comfort vote is neutral), Equation 3 becomes Equation 4 and it is possible to derive Equation 5 from Equations 3 and 4. With this equation, the comfort temperature can be calculated for each response of the field surveys. Indeed, one can deduce the comfort temperature of an occupant knowing his comfort votes (ASHRAE scale) and the globe temperature when he was filling the questionnaire.

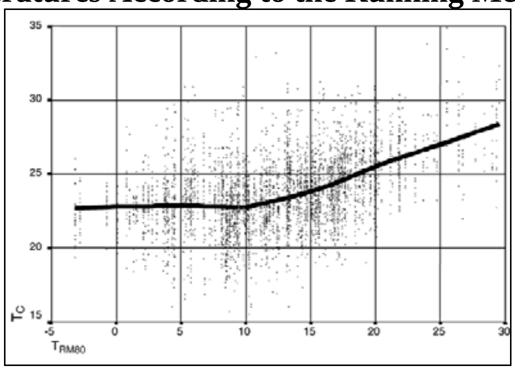
$$4 = 0.5.T_C + h \quad (4)$$

$T_C = T_G - 2(CV - 4)$ (5),

where T_C is the comfort temperature

Once all the comfort temperatures were calculated, the best correlation between them and outdoor climatic conditions was looked for. It appeared that the running mean outdoor temperature as defined in Equation 1 allowed the best correlation. All the calculated comfort temperatures and the regression line have been plotted according to the running mean outdoor temperature in Figure 6. The Lowess regression gave the equation linking the comfort temperature to the running mean outdoor temperature that was selected for the adaptive part of the EN 15251 standard.

Figure 6. Comfort Temperatures According to the Running Mean Outdoor Temperature



Source: McCartney & Nicol 2002

Can the Differences in Methodologies Imply Different Results?

Obviously the methodologies adopted to determine temperature ranges for the two standards are not identical. Roughly, the method used for ASHRAE determines a comfort temperature for each building of the survey and looks for a correlation between these comfort temperatures and outdoor climatic conditions. On the other hand, the European method calculates a comfort temperature from each occupant comfort vote and then looks for a correlation between these calculated temperatures and outdoor climatic conditions.

The causes that can explain the differences between the two approaches in terms of final results are numerous. One main cause could be the field surveys: uncertainties, and discrepancies regarding comfort votes and climatic conditions between the studied buildings. This study does not aim to give the only cause but tries to explore one of the possible reasons, which is the difference in applied methodologies.

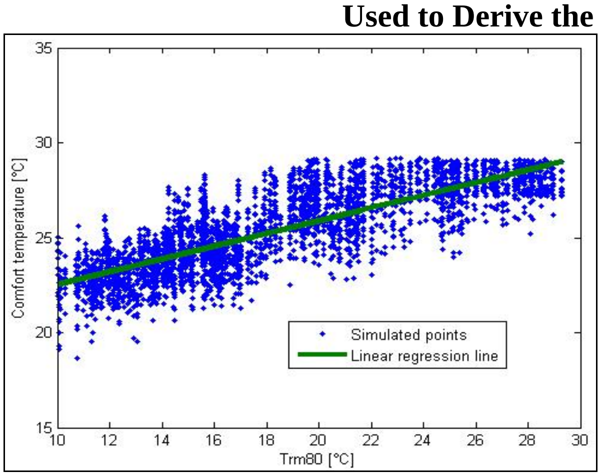
As no data from the field surveys were available, a method has been developed to access the three necessary values when dealing with adaptive comfort: the indoor globe temperatures, the outdoor temperatures, and the comfort votes. We chose to simulate a free running office building in three different climates (Dublin, Macon, and Seville). These simulations were led with the TRNSyS software by University of Athens and are described in Rivière 2007.

Having building simulation results, it remains to access the comfort votes of the occupants. A simple method was created that consisted of using the PMV index but allowing for some adaptive means. As previously explained, the PMV calculations depend on 6 parameters. In this case, the metabolic rate is set at 1.15 met and the relative humidity at 50% whereas ambient temperature and mean radiant temperature are provided by building simulations. Other remaining factors (air speed and clothing) are assumed to be directly under occupant action and the PMV is therefore optimized (i.e., as close to zero as possible) by playing on these two parameters. In summer, the lightest allowable clothing is 0.42 clo that corresponds to underpants, light shirts, light pants and light shoes (ESO 2006). Regarding airspeed, the maximum reachable value is set at 1 m/s, which corresponds to an opened windows or a fan at low speed. The obtained “optimized” PMV is then rounded up or down to the nearest integer, which is assumed to be the comfort vote of an occupant on a comfort scale from –3 to 3.

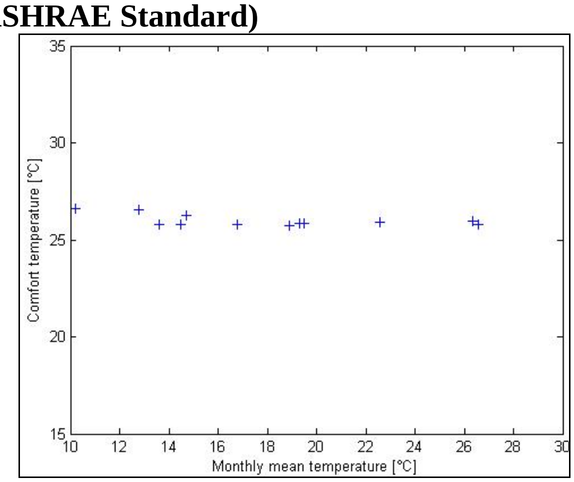
Thus, the indoor globe temperature, the outdoor temperature and a comfort vote are available at each simulation step. By applying Equation 5 as in the SCATs project, it becomes possible to calculate at each step the comfort temperature. All these temperatures are plotted according to the running mean temperature (Eq. 2) in Figure 7a. A linear regression is also displayed and this emphasizes a clear trend: the comfort temperature increases when the running mean increases. This result looks like the adaptive temperature ranges figured out within the SCATs project but does not have any legitimacy since this work is not based on field studies.

Another exercise consisted in applying the ASHRAE method previously presented to the same set of data. The comfort temperatures were calculated every month for each building. The comfort temperatures have been plotted according to the monthly mean temperature. It appears that the comfort temperature does not increase with the outdoor temperature (Figure 7b). Of course, as these results are not based on field studies, this does not suggest that the adaptive principle as defined in ASHRAE-55 is false. However, this enlightens the fact that, from the same set of data, the results provided by the two different methods completely differ.

Figure 7a). Comfort Temperatures According to the Running Mean Temperature (Method Used to Derive the European Standard)
Figure 7b). Comfort Temperatures According to the Monthly Mean Temperature (Method Used to Derive the ASHRAE Standard)



a)



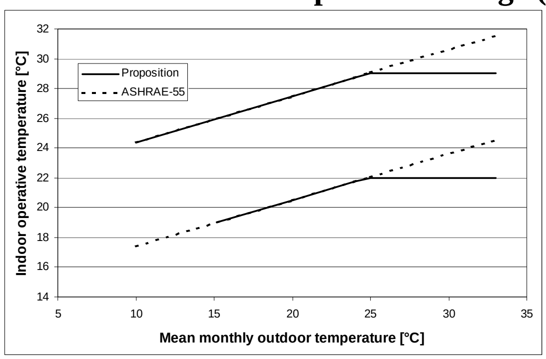
b)

A First Proposition to Unify the Evaluation of Summer Comfort

This section aims at reconciling the comfort evaluation in air conditioned buildings and in free ventilated ones, i.e., between the analytic theory and the adaptive one as defined in ASHRAE-55.

The proposition consists of considering the adaptive approach (as defined in ASHRAE-55) but with a maximum temperature that cannot be exceeded regardless of the outdoor climatic conditions. This limit is calculated with the PMV index including the adaptation possibilities available in the building. Clothing and air speed are considered as adaptation possibilities in a given building. A maximum airspeed of 1 m/s is taken into account as it is often recommended to not exceed this value for the PMV calculation even if comfort fans may provide higher airspeeds. A minimum allowed level of clothing of 0.42 is kept (underpants, light shirt, light pants, socks and shoes according to ESO 2006). No adaptation possibility is considered for the activity, which is kept at 1.15 met. According to the analytic approach, the maximum allowed indoor temperature is 29°C (for the second category of building according to EN 15251). The proposed comfortable range is given in Figure 8. This range should be accepted by the defenders of PMV/PPD indices since it is in agreement with these indices, provided that some adaptive means regarding clothing and air movement exists in the building. It remains to be studied if this comfort range could be adopted by defenders of the adaptive theory.

Figure 8. Proposition of Comfortable Temperature Range (80% Acceptability)



For this purpose, we looked at the extent to which different long-term indicators differ in "real life" for typical European cities. Four different acceptable zones were studied. The first one is based on the PMV index with default parameters as defined in EN 15251. This leads to an upper limit of 26°C. The second one is based on the adaptive range proposed in EN 15251 for naturally ventilated buildings of category II (80% acceptability – Figure 2). The third acceptable zone is based on the adaptive range proposed in ASHRAE 55 for free-running buildings and 80% acceptability (Figure 1). The fourth acceptable zone is the one proposed in this study (Figure 8). The two main methods to assess thermal comfort over the year are applied:

- Percentage outside range: the proportion of the occupied hours during which the temperature lies outside the acceptable zone.
- Degree hours criterion: the time during which the actual operative temperature exceeds the specified range during occupied hours is weighted by the number of degrees by which the range has been exceeded.

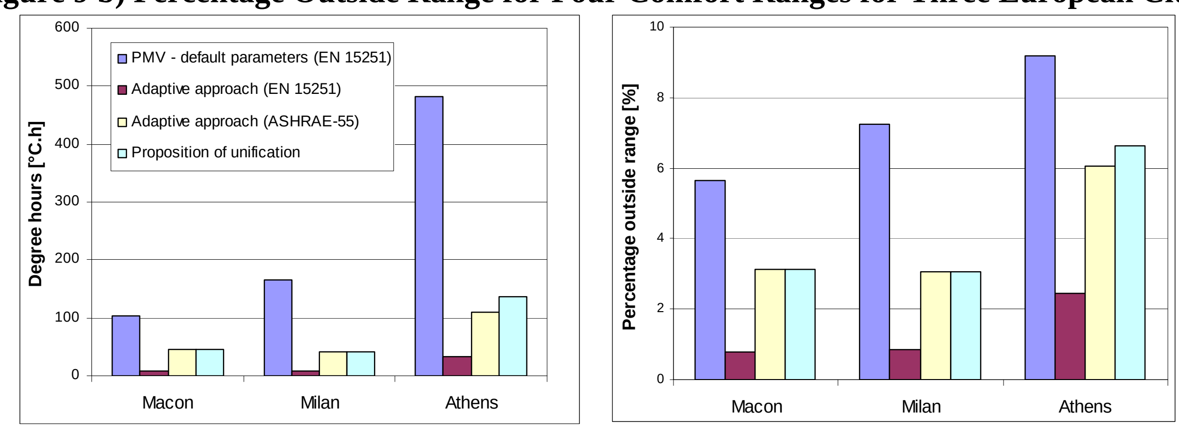
In order to access indoor climatic conditions over a full year, the office building whose characteristics have been already briefly presented in this paper (Table 4) was simulated in free running mode for three European cities (Milan [45°25N/9°16E], Macon [46°18N/4°49E], and Athens [37°54N/23°43E]). This enables us to calculate the eight long-term indices and to plot them in Figure 9a and b.

First of all, Figure 9 strengthens the fact that there is a gap between the adaptive and analytic approaches. Once again, the significant difference between the two adaptive standards (EN 15251 and ASHRAE-55) is highlighted. Regarding the proposition of comfortable temperature range, the difference between it and the ASHRAE adaptive standard depends on the period during which the monthly mean temperatures are higher than 25 °C. Indeed, the comfort ranges start to diverge from this temperature (Figure 8). As a result, the "warmer" the cities, the higher is the difference between the proposition and the ASHRAE adaptive standard. There will not be any difference for most of the European cities since even in Milan, which is a relatively "warm" climate, the proposed comfort range and the ASHRAE adaptive standard do not differ (Figure 9). Regarding the warmest European climates like Athens and Seville, the difference exists according to Figure 9a and b but remains low.

Except for the warmest European climates, there is no difference between long-term indices based on the proposed comfort range and the ASHRAE adaptive standard. This could contribute to the acceptance of this comfort range by defenders of the adaptive approach. Another advantage of this comfort range proposition is that the maximum allowed temperature depends on the adaptive possibilities of the building, which is very logical and could conduce builders and owners to strengthen the adaptation possibilities in buildings (satisfaction not only depends on indoor conditions, but also on occupants' ability to control their environment individually).

This study was a first attempt to determine a way to unify thermal comfort assessment. Additional works are obviously required and should focus on two main issues. The first one is to identify and quantify in a better way the main adaptation factors to be included in the maximum allowed temperature calculation (opening of windows, fans…). The second point is to evaluate in more detail the difference between the proposed comfort range and the ASHRAE adaptive standard, if possible by using results from field studies.

Figure 9 a) Degree Hours According to Four Comfort Ranges for Three European Cities
Figure 9 b) Percentage Outside Range for Four Comfort Ranges for Three European Cities



a) b)

Conclusions

This study aimed at looking for a way to unify the different thermal comfort approaches. The first step consisted of analyzing the two main standards related to thermal comfort assessment EN 15251 and ASHRAE-55. With the recent addition of adaptive standards as options for the comfort assessment of free ventilated buildings, these standards recommend different temperature ranges depending on whether the building is air conditioned or not. It appears that these adaptive standards which depend on outdoor climatic conditions significantly differ for European climates and a possible explanation regarding this difference is proposed in this paper. This would come from the methodology used to derive the standards but this needs to be confirmed by additional research notably on empirical data stemming from field surveys. Then, this study has shown that it should be possible to find a way to reconcile the adaptive and analytic approaches. This would consist in considering the adaptive approach (as defined in ASHRAE-55) while not allowing temperatures higher than a given limit calculated from the analytic theory but considering possible ways of adaptation. The main advantage is that this index could be adopted by defenders of both adaptive and analytic approaches since it is not in contradiction with PMV/PPD indices while remaining close to the ASHRAE adaptive standard in the European context. This should contribute to make air conditioned buildings more efficient by shifting to higher set points and to enhance the use of the adaptive theory during the design phase and therefore stimulate the construction of free ventilated buildings. Additional works are obviously required and should focus on two main issues: identifying and quantifying in a better way the main adaptation factors to be included in the maximum allowed temperature calculation and evaluating in more detail the difference between the proposed comfort range and the ASHRAE adaptive standard, if possible based on results from field studies.

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