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Adaptive comfort: Analysis and application of the main indices

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A R T I C L E I N F O

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A B S T R A C T

Active climatization is currently one of the main causes of energy use in buildings. Since it aims at providing indoor environmental conditions that are comfortable for most of the building occupants, the way these conditions are determined is very important in the framework of energy optimization.

Indoor comfort conditions are conventionally expressed in terms of steady temperature levels (e.g. 20–26 °C). Differently, the adaptive approach determines temperature levels that are unsteady and follow the variability of the outdoor climate.

Even if this alternative approach has proven to be very effective in providing mitigated indoor temperatures, agreement about its formulation and its practical application is still lacking.

In this paper some of the available formulations of the adaptive approach are described and adopted to determine comfort temperatures for three different Italian climatic contexts. Moreover, the discomfort levels for a case-study room are estimated, by the means of a dynamic building energy simulation model, according to both the conventional and the adaptive approaches.

1. Introduction

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment [1]. Actually, building users simply relate thermal conditions to the air temperature levels, regulated by managing the set-points of the climatization systems with subsequent effects on energy consumption.

In order to assess the quality of thermal environments in detail, the main international standards regarding the determination of the indoor comfort conditions [1–3] refer to the work of Fanger [4]. The heat balance of occupants staying in an indoor environment is defined in [4] in terms of personal and environmental parameters affecting the heat exchanges between the human body and the room. In order to clarify the related physics equation, the resulting heat exchange values were later connected to the 7-points thermal sensation scale [1] by collecting the responses of more than 1000 people to different environmental conditions provided inside a climatic chamber. As a result the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indices were defined: in these indices the ideal state for the occupants, called “neutrality”, corresponds to the thermal equilibrium with the indoor environment (equivalence of inward and outward heat flows).

In standards [1–3] the Fanger equation is however used to determine (according to conventional clothing level and standard air humidity and velocity) allowable reference ranges of operative temperature for different building uses, which correspond to different activity levels.

Several studies pointed out some flaws in this approach. First of all, in climatic chamber tests human beings are considered as passive “sensors” detecting the environmental conditions, that do not interact with the room in any way: this situation is very peculiar and deeply different from what happens in most of real buildings. Moreover, another important observation deals with the choice of equating comfort to the neutrality of heat exchanges between the body and the environment: the definition of ideal thermal environment as the neutral one is based on a very deterministic approach, which does not take into account the psychological and cultural aspects of comfort and can therefore be questioned [5].

For these reasons, alternative studies were carried out analysing the occupants’ sensation and preference inside actual buildings, and brought to the development of another method to assess the indoor thermal conditions: the adaptive approach.

During the last decades, several of such field studies were conducted, with different specific purposes and results, bringing to different formulations of the adaptive approach: this paper describes the main characteristics of the available adaptive indices and compares their application to the Italian context.

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Nomenclature

T_{co}	indoor comfort operative temperature [°C]
$T_{ext,ref}$	outdoor reference temperature [°C]
T_{rm}	running mean temperature [°C]
T_{dm}	daily mean temperature [°C]
v_a	air velocity [m/s]
Subscripts	
n	present day

2. The adaptive approach

From the 1970s, field studies on environmental conditions and comfort determination inside real buildings started taking place, and results pointed out important differences between the PMV/PPD predictions and the actual thermal sensation/preference expressed by the building occupants [6].

Considering the results of these studies, an alternative approach to the definition of "comfortable environmental conditions" was developed. The main assumptions of this theory, called "adaptive" [7–9], regard:

- the ability of human beings to adapt themselves to the environmental conditions (through conscious or unconscious changes in their metabolic rate or clothing level) and to interact with the environment in order to adapt it to their needs (through available environmental controls);
- the influence of thermal experience on the occupants' expectations regarding the indoor conditions, which can be short-term, due to the recent weather, or long-term, related to the general climate they are used to.

The huge amount of data collected in these studies [10,11] allowed a statistical analysis which, among all the considered environmental parameters, revealed a direct correlation between the indoor comfort temperature and the outdoor one that is commonly expressed by the adaptive approach founding equation

$$T_{co} = a \cdot T_{ext,ref} + b \tag{1}$$

where a is the slope of the function and b is its y-intercept, both statistically derived by the analysis of the collected data.

As already introduced, several adaptive indices have been developed during the last decades: the following sections analyse the elements characterizing the various formulations.

2.1. a and b values

The main difference between the applications of the adaptive approach is in the equation itself, which, as previously mentioned, is derived by the statistical analysis of extensive field studies. According to the assumptions of the related study and to the obtained results, both the slope (a) and the y-intercept (b) of the equation change: the slope value, in particular, represents the correlation between T_{co} and the $T_{ext,ref}$, in other words the "adaptiveness" of the equation.

2.2. Outdoor reference temperature

The *outdoor reference temperature* ($T_{ext,ref}$) is the only independent variable of the adaptive equation, and the way it is determined is very important in defining the kind of thermal experience taken into account in the index. Among the adaptive approach applications, two main kinds of temperature are considered: the monthly average one (T_{mm}) and the running mean one (T_{rm}).

The monthly average temperature (T_{mm}) was the first one to be used. Since it is based on the historical series of air temperatures in a specific location, it represents a typical climate and is therefore connected to the occupants' long-term experience.

During the 1990s, Nicol and Humphreys [9,12] suggested the use of a progressive value for the outdoor temperature, following the assumption that exponentially weighted average data would allow a higher reliability in the relationship between indoor and outdoor temperature. The running mean temperature (T_{rm}) was therefore introduced in the adaptive equation. In its general expression, T_{rm} is an average of the mean daily temperatures of a certain number of days immediately before the analysed one, weighted according to their time distance:

$$T_{rm,n} = (1-\alpha) \cdot \left(T_{dm,n-1} + \alpha \cdot T_{dm,n-2} + \alpha^2 \cdot T_{dm,n-3} + \alpha^3 \cdot T_{dm,n-4} + \dots\right) \tag{2}$$

where α is a reference constant value, ranging between 0 and 1 (recommended 0.8).

Being based on the recent daily temperature data, the running mean temperature is connected to the occupants' short-term experience.

2.3. Acceptability range amplitude

There is a limited interval of temperatures around the ideal comfort one (T_{co}, calculated by the means of Eq. (1)) that can be considered as comfortable according to a specific quality level. These intervals are called "acceptability ranges" and are defined through successive temperature thresholds.

In the available indices, the ranges amplitude is usually defined by the means of constant values deriving from the statistical analysis of the field studies results. In one case [12], however, a different approach was adopted, with a variable interval width calculated according to the comfort temperature value: the resulting correlation reveals a range of temperatures comfortable for the occupants that becomes narrower as the outdoor condition becomes warmer.

2.4. Applicability

Due to its assumptions, the adaptive approach has some applicability limitations, that are still a matter of discussion.

First of all some indices adopt a climatic restriction, according to the fact that the adaptation dynamics usually refer to warm conditions. In fact the adaptive mitigation strategies, that are based on interactions with the external climate variability, are not equally effective considering the harshness of cold conditions. Most of the field studies were therefore conducted considering only warm climates and/or the warm season and some of the adaptive equations can be applied only in these contexts.

Moreover, it was verified that the adaptation dynamics have different importance whether considering "naturally ventilated buildings", with manually operable windows and without active system, or "HVAC buildings" equipped with sealed facades and mechanical ventilation: different equations have been consistently derived.

Actually most of real buildings, particularly in Europe, do not clearly fall into one of the two categories but lie somewhere in-between (e.g. conditioned buildings with operable windows, hybrid ventilated buildings, etc.). Some indices (e.g. [1] and [3])