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# Impact of different thermal comfort models on zero energy residential buildings in hot climate

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## ABSTRACT

The selection of a thermal comfort model for establishing indoor optimal hygrothermal conditions during the hot period has a major impact on energy consumption of Net Zero Energy Buildings in hot climates. The objective of this paper is to compare the influence of using different thermal comfort models for zero energy buildings in hot climates. The paper compares the impact of applying Fanger's model, Givoni's model, the ASHRAE 55 adaptive comfort model and the EN 15251 adaptive comfort model on energy consumption and comfort performance. Using both the building performance simulation tools ZEBO and EnergyPlus for energy simulation, an existing prototype of a residential apartment module is used to evaluate energy performance and thermal comfort in two parametric series. The first one is the result of coupling natural ventilation and mechanical cooling and the second one is guided coupling natural ventilation, mechanical cooling and ceiling fans. This study shows that the percentage of energy consumption difference meeting the comfort criteria according to ISO 7730 in comparison to EN 15251, ASHRAE 55 or Givoni's model varied up to 16%, 21% and 24.7%, respectively for the presented case study. More energy savings can be expected for buildings in hot climates with greater cooling demands.

## 1. Introduction

Net Zero Energy Buildings (NZEBs) aim to reduce at minimum, energy required for space cooling, space heating, (humidification and dehumidification if required), ventilation, lighting and, according to some definitions also appliances. By default NZEBs are grid connected and benefit from renewable energy sources such as direct solar radiation, wind and the earth's thermal storage capacity to balance their energy consumption annually.

However, using the words of the European standard EN 15251: "An energy declaration without a declaration related to the indoor environment makes no sense. There is therefore a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings" [1]. Thus, the specification about thermal comfort objectives that a building must achieve is a prerequisite for its design. Such objectives shall be explicitly included as an integral part of the definition of a zero energy building in hot climate and needs to be quantitatively defined through reliable and explicit methods for assessing the thermal comfort performance of a building. However, most energy efficiency research is conducted with cold climate in mind and the impact of the selection of different thermal comfort models for NZEBs in hot climates has been scarcely studied.

To date, a variety of thermal comfort models are available in the literature and standardization for moderate indoor environment such as Fanger's comfort model (also called rational or static model) [2], the European adaptive comfort model [1,3], the American adaptive comfort model [4], the Givoni's Building Bioclimatic Chart [5]. They provide the most likely thermal or hygrothermal conditions as individual objective values or zones on a psychrometric chart. These models deliver those conditions that should "statistically" minimize thermal discomfort perceived by typical occupants in a moderate environment and can be used for assessing how a given thermal or hygrothermal indoor condition is far from an optimal one. Thermal comfort models have been developed in the last four decades and have then included in standards, but their inclusion arrived in different periods: Fanger's

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*Abbreviations:* ASHRAE, American Society of HeatingRefrigerating and Air-Conditioning Engineers; BBCC, Building Bioclimatic Chart; BPS, Building Performance Simulation; CEN, European Committee for Standardization; DBT, Dry Bulb Temperature; DOE, Department of Energy; EPBD, Energy Performance Building Directive; HVAC, HeatingVentilation and Air Conditioning; IEA, International Energy Agency; nZEB, nearly Zero Energy Building; NZEB, net Zero Energy Building; PMV, Predicted Mean Vote; PPD, Predicted Percentage Dissatisfied ;.

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comfort model was first included in ANSI/ASHRAE 55 in 1982 [6] then in ISO 7730 in 1984 [7], the American adaptive model was added to a revision of ANSI/ASHRAE 55 in 2004 [8] and the European adaptive model has been included in EN 15251 in 2007 [1,9]. Furthermore, the adoption of standards on thermal comfort is globally voluntary. In fact, national legislations do not impose the adoption of a thermal comfort model to set objective conditions or the set-points of building energy systems, rather indicate reference temperature to be maintained during winter (and sometimes summer) and possibly an acceptability band around the reference value [10–15].

All standards on thermal comfort basically agree with suggesting the adoption of Fanger's model for mechanically heated and/or cooled buildings, while ANSI/ASHRAE 55 offers the possibility to use the American adaptive model in "naturally ventilated building" whether the "mean monthly outdoor air temperature" [1] falls into a given temperature domain ($10 \div 33.5\,^{\circ}$C), and EN 15251 allows the use of the European adaptive model in "buildings without mechanical cooling" whether the "exponentially weighted running mean of the daily outdoor air temperature" [9] falls into a given temperature domain ($10 \div 30\,^{\circ}$C). The Givoni's Building Bioclimatic Chart is not included in any standard, but it is often used in hot and tropical climate where applicability of adaptive models is limited [16–19].

In this paper, an extended study is performed on the effect of different thermal models on the energy performance of NZEB based on a previous study [20]. A brief description of main comfort models is proposed and their adoption in standardization is presented; then the impact of adopting different thermal comfort model on the design and energy consumption of net zero energy residential apartment module in hot climates is investigated by comparing optimal comfort temperatures drawn for a given hot climate and by assessing energy need for space cooling and heating.

The methodology used consists of screening the existing comfort models suitable in hot climates. The study includes an inventory of suitable comfort models that can be used as solutions for NZEBs. Then a typical base case building is selected for simulation analysis to examine the impact on thermal comfort and energy performance. The building energy use analysis is performed using the software ZEBO, an optimization engine, which guides EnergyPlus, a simulation engine, aiming to conduct global parametric analysis where the parameters are varied [21,22]. Finally, analysis of result provides guidance on the strategic design decision making for designing comfortable NZEBs in at least one hot climate.

This paper is organized into five sections. The first section identifies the research problem, objective and significance. The second section provides a review on the principles of thermal comfort followed by a literature review section on thermal comfort models. The third section summaries the thermal models in standards. The fourth section reports the results of a case study that investigates the impact of different thermal comfort models on energy consumption. The final section discusses and concludes the study outcomes, implications and limitation.

## 2. Review of thermal comfort in buildings

Fathy wrote: "People living in the hot, climates, are faced with a different problem: amplified ultraviolet rays that hit our concrete structures and rebound onto us in hot and humid weather conditions" [23]. In hot climates, it is always necessary to avoid sensible and latent heat gains in every possible way and to achieve thermal comfort conditions while minimizing energy consumption. This section reviews thermal comfort model for NZEBs in hot climates and list multiple model and systems solutions.

Thermal comfort is usually used to indicate whether an individual does not feel too hot or too cold with respect to a given thermal environment. It is a concept that attracted the attention of a number of scientists and doctors and it has been defined according to three main approaches: a physiological, a psychological and a rational (also called heat-balance-based) approach. According to the physiological approach, thermal perception of an individual is due to the entity of nervous impulses that start from thermal receptors in the skin and reach the hypothalamus. According to the psychological approach, thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" [24]. This definition is reported in the international standard ISO 7730 and a similar definition is also reported in the American standard ASHRAE 55, although the ASHRAE definition highlights the subjective character of such concept by adding to the previous definition the sentence "[...] and is assessed by subjective evaluation" [25]. According to the last approach, thermal sensation is related to the heat balance of the human body and thermal comfort is that condition when heat flows leaving the human body balance those incoming and the skin temperature and the sweat rate are within specified ranges depending on metabolic activity [26]. Therefore, the term thermal comfort is, in general, used to provide information about the thermal state of an individual within a given thermal environment.

### 2.1. Thermal comfort semantic, parameters and evaluation scales

Thermal comfort is viewed as a state of mind where occupants are satisfied with their surrounding thermal environment and desire neither a warmer nor a cooler condition [2]. According to the Fanger's approach, six primary factors affecting thermal sensation are either environmental or personal parameters; these factors are: air temperature, mean radiant temperature, air velocity, humidity, metabolic rate and clothing [27]. All these six factors are time dependent, but thermal comfort is just assessed by assuming steady-state conditions. Since previous exposure or activity can affect thermal comfort perception for about 1 h [28], thermal comfort requirement are not addressed to temporary visitors of a space. Moreover, thermal comfort models do not typically apply to sleeping or bed rest, even if Lin and Deng [29] proposed a modified version of Fanger's comfort model extended to sleeping thermal environments.

Researchers have shown that other contributing parameters include climate change with time, building and its services, and occupants' perception [3,30,31]. Due to biological variance beyond occupants and psychological phenomena, neither perfect conditions nor well defined thermal comfort boundary settings exist, but rather a thermal comfort zone with a band of operative temperatures that satisfy the highest percentage of occupants [32,33]. Humphreys found the best representation to predict occupants' thermal comfort, had to be derived from field studies [34]. Using field survey questionnaires with synchronized records of parameters about the thermal indoor and outdoor environments and clothing level and metabolic activity of occupants, researchers also collected and analyzed information about people's thermal satisfaction, preference and attitude to changes [32]. According to the literature, the evaluation of the personal thermal state is suggested through a series of guidelines with three scales [27,35]:

(1) A scale of perception of the personal thermal state with seven degrees and two poles: from 'Cold' to 'Hot' with a central point of neutrality that corresponds to the absence of hot and cold,
(2) An evaluative scale with four degrees and one pole: present affective assessment from 'Comfort' to 'Discomfort',