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The impact of indoor thermal conditions, system controls and building types on the building energy demand

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Abstract

It is possible to evaluate the energy demand as well as the parameters related to indoor thermal comfort through building energy simulation tools. Since energy demand for heating and cooling is directly affected by the required level of thermal comfort, the investigation of the mutual relationship between thermal comfort and energy demand (and therefore operating costs) is of the foremost importance both to define the benchmarks for energy service contracts and to calibrate the energy labelling according to European Directive 2002/92/CE. The connection between indoor thermal comfort conditions and energy demand for both heating and cooling has been analyzed in this work with reference to a set of validation tests (office buildings) derived from a European draft standard. Once a range of required acceptable indoor operative temperatures had been fixed in accordance with Fanger's theory (e.g. $-0.5 < \mathrm{PMV} < -0.5$), the effective hourly comfort conditions and the energy consumptions were estimated through dynamic simulations. The same approach was then used to quantify the energy demand when the range of acceptable indoor operative temperatures was fixed in accordance with de Dear's adaptive comfort theory.

Keywords: Energy demand; Indoor environmental quality; Thermal comfort; Building energy simulation

1. Introduction

In recent years, there has been a growing interest in the evaluation of the energy demand for building heating and cooling. This is certainly due to the many research activities that arose after European Directive 2002/91/CE [1], concerning the energy performance of buildings, was issued. As the Directive underlines, the assessment of the energy demand for the climatic control of a building can only be dealt with if the level of the indoor environmental comfort is clearly defined: the building energy performance index must be shown together with an indoor environment comfort quality index. This is due to the fact that a reduction in the energy demand can also lead to a decease in the comfort level; on the contrary, it is clear that a higher energy demand should be foreseen for an increase in the comfort level demand, as the system and plant technologies are equal [2].

Some studies have been carried out in order to associate the concept of building energy performance to the concept of building comfort level [3–5] because both these concepts have to be expressed to globally qualify the performance of a building. The required level of microclimatic quality in fact has a direct effect on the building energy consumption [6,7].

The classification and certification of indoor environment quality is the subject of the CEN (European Committee for Standardization) draft standard prEN15251 [8]. The scope of this standard [9] is to specify not only how to establish indoor environmental input parameters for building system design and how to perform energy calculations, but also to describe methods for the long term evaluation of the indoor environment as a result of calculations or measurements. This allows the indoor environment to be classified in three categories, identified as A, B and C. Category A corresponds to the highest level of expectation concerning indoor comfort and therefore the highest number of satisfied people. A critical review of all of the contents of this standard can be found in [10].

In general, indoor environmental quality and its relationship with energy consumption can be analysed by focusing on the possible use of mechanical, natural or hybrid strategies for microclimatic control [11].

The possible strategies depend on both the expectations and the behaviour of the users [12] (i.e. opening or closing the

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Nomenclature

I_{clo}	clothing insulation
M	metabolic rate
PMV	Predicted Mean Vote (simulation output)
PMV*	Predicted Mean Vote (simulation input)
PPD	Predicted Percentage of Dissatisfied
Q_p	primary energy
RH	air relative humidity
t_e	monthly mean outdoor dry bulb temperature
$t_{e,i}$	monthly mean outdoor dry bulb temperature profile
t_{op}	operative temperature
$t_{op,i}$	operative temperature profile
$\tilde{t}_{op,i}$	theoretical operative temperature profile
Δt_e	annual monthly mean outdoor dry bulb range
Δt_{op}	annual operative temperature range
TSENS	thermal sensation vote (Pierce model)
TSV	thermal sensation vote (KSU model)
v_a	air velocity

windows by occupants for natural ventilation or free cooling). They also depend on the availability of ‘‘natural energy sources’’ to be used for the microclimatic control (i.e., the number of hours during a year when the outdoor air temperature is suitable for free cooling). In a sustainable environmental oriented approach, once the obtained thermal comfort level has been fixed, the use of natural resources has to be maximised in order to keep the energy demand for the microclimatic control at the lowest value.

Recent studies have pointed out that, in not fully mechanically controlled buildings, the expectations of the users concerning the thermal environment allow the interval of acceptable temperatures to be wider than that obtained from Fanger’s theory based on the PMV index [13] and centred on slightly different values. These studies belong to the results of the research carried out by de Dear and Brager, that are referred to as the ‘‘adaptive comfort theory’’ [14], which takes into account adaptive adjustment mechanisms (physiological, psychological or behavioural adjustment) induced by outside weather conditions that people can activate to modify their perception of thermal comfort. In this sense, it should be pointed out that the relationship between environmental quality and energy consumption is greatly influenced by ‘‘microclimatic control’’ strategies, that is, the HVAC control system, and the occupants’ use of space.

Since adaptive thermal comfort takes into account the possibility of an individual control, a distinction between different types of buildings must be made. de Dear and Brager have distinguished between ‘‘buildings with centralized HVAC’’ and ‘‘buildings with natural ventilation’’ [14]. This distinction is however quite impractical to apply to the vast majority of buildings, that are characterized by different envelopes, HVAC systems and user destinations. The authors of new Dutch guidelines for thermal comfort in buildings, including de Dear, have proposed a more useful distinction between two building climate types of office space named ‘‘alpha’’ and ‘‘beta’’ [15]. A flow chart has been made available to determine the type of building according to the façade type (sealed or with operable windows), the number of operable windows per occupant, and the possibility of adjusting clothing to outdoor and indoor conditions. The operative temperatures determined by Brager and de Dear for naturally ventilated buildings have been assigned to ‘‘alpha’’ type buildings; the operative temperatures determined in accordance with Fanger’s theory for centrally air conditioned buildings have been assigned to ‘‘beta’’ type buildings.

A distinction between ‘‘fully mechanically controlled’’ (FC) office buildings, similar to the ‘‘beta’’ type building, and ‘‘not fully mechanically controlled’’ (NFC) office buildings, similar to the ‘‘alpha’’ type building has been adopted in this work according to the van der Linden et al. approach [15].

With reference to thermal environment quality, which is the subject of this study, the ‘‘management of the thermal environment’’ differs significantly for FC buildings and NFC buildings where some aspects of the microclimatic control are connected to the direct actions of the occupants. As previously mentioned, these different microclimatic control strategies are also linked to different approaches to evaluate thermal comfort:

- The traditional ‘‘static’’ Fanger approach [13], based on the PMV index, which defines small intervals of the acceptable temperatures and which well suits *fully mechanically controlled* buildings;
- the new ‘‘dynamic’’ adaptive comfort approach [14], which defines wider intervals of the acceptable temperatures and which well suits *not fully mechanically controlled* buildings.

It is important to remark that the Fanger approach can be considered partially adaptive because it takes into account behavioural adjustments in people (in particular the modification of the clothing level) and it coincides with the results of the de Dear and Brager studies on *fully mechanically controlled* buildings. On the contrary, the de Dear and Brager research highlighted that, in naturally ventilated buildings, the traditional Fanger approach does not fully characterize the thermal response of the occupants, as they can activate adaptive adjustment mechanisms that lead to wider acceptable comfort temperature ranges.

2. Purpose of the work

According to this scenario, the study here presented deals with the relationship between building energy demand and the indoor thermal environment comfort level. The energy demand related to different comfort levels, expressed in terms of predicted mean vote (PMV), was calculated, for a case study consisting of a typical office room, by means of dynamic simulations and compared in terms of both heating/cooling energy and primary energy.