Applied Thermal Engineering 30 (2010) 2386–2395

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Comparing different control strategies for indoor thermal comfort aimed at the evaluation of the energy cost of quality of building

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A R T I C L E   I N F O

Article history:
Received 16 March 2009
Accepted 11 June 2010
Available online 1 July 2010

Keywords:
Fuzzy logic
Indoor thermal comfort
Energy saving
HVAC system controller
PID controller

A B S T R A C T

The rapid improvement in the standard of living requires more detailed and sophisticated methods of evaluating comfort conditions. But, maintaining thermal comfort conditions in confined environments may require complex regulation procedures and the proper management of heating, ventilating and air conditioning (HVAC) systems. In turn, the requirements for indoor thermal comfort do not necessarily coincide with those of energy saving purposes, which in the last years are becoming a crucial issue owing to the enactment of the European Energy Performance of Buildings Directive (EPBD).

The aim of this work is to compare different indoor control thermal comfort strategies in view of the evaluation of the energy cost of quality in buildings.

In particular, a new PID-fuzzy controller is presented and compared with a classic ON–OFF controller. The performances of the two controllers are quantified and compared by means of two cost functions that are based on the quadratic forms of the overall energy required by the thermal fluid and of the deviation from the preferred set point of the predicted mean vote (PMV). It is found that the application of the PID-fuzzy controller results in lower costs of energy input and lower deviation from set point of PMV.

1. Introduction

Although the indoor thermal comfort issues have been dealt with widely in scientific literature [1–7], it is now gaining a more and more rising attention among designers of heating, ventilating and air conditioning (HVAC) systems, particularly due to the enactment of the European Energy Performance of Buildings Directive (EPBD) [6]. This directive, in fact, besides promoting directly the energy performances of the buildings, the reduction of the conventional fuels consumption and the decrease in greenhouse gas emissions to the atmosphere, indirectly gives emphasis to measures and actions devoted to the increasing of the indoor performances [8,9], even affecting the energy demand of buildings. It is well known that the increasing demand for energy management in buildings prompts to the development of control methodologies that could improve energy efficiency of building-HVAC systems [10–13]. Nevertheless, the most of the conventional control strategies for indoor comfort, proposed up to now, are limited to ON–OFF and conventional proportional, integrative and derivate (PID) methods, which actually show some limitations. In the ON–OFF method, for example, the controlled variable swings continuously and thermal comfort is regulated only by the indoor temperature; the classical PID control, on the other hand, is not well suitable in following the disturbances and modifications induced to the indoor climate by the varying thermal requirements of different buildings.

Hence it follows the need for developing a control method which could improve the energy efficiency of building while, simultaneously, indoor comfort is maintained within acceptable limits.

Despite the general thought, the need for a more comfortable indoor environment and the need for energy saving purposes could not be always in conflict although, generally speaking, the improving of the indoor conditions could result in a greater consumption of energy.

At this regard, although some interesting works related to the artificial intelligence topics have shown that fuzzy systems and neural networks can simultaneously control both requirements, in this way contributing to reduction of energy consumption and guarantying acceptable indoor comfort conditions [14–18], we need to better matching the purposes of the energy saving and of the indoor thermal conditions for people. In other words, we must

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doi:10.1016/j.applthermaleng.2010.06.008

Table 1
Seven-point thermal sensation scale [3].

+3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

dispose of effective and simple tools of analysis that contemporary take into account both requirements in the building and HVAC design process.

In this aim, we will present a comparison between the classic control strategies (ON–OFF controller) and a PID-fuzzy controller: having in mind the energy cost related with the achievement of indoor thermal comfort conditions, we will adopt a couple of *cost functions*, as suggested by Ardheali et al. [17], that is the penalty associated with the deviation from the optimal comfort set point of the selected comfort index, and the penalty associated with the energy consumption for heating purposes.

2. Indexes adopted for evaluating the performance of HVAC control systems

The analysis of the HVAC control is not a recent task: several studies and standards have been produced in order of assessing parameters and strategies on purpose [e.g.:[19,20]].

In the present section some indexes will be introduced to evaluate the performance of HVAC control systems: some of them aimed at computing the thermal comfort performance and other at computing the energy performance; these parameters are based on the work of Ardehali et al. [17], and on the EN 15251 standard [8].

2.1. Indexes of thermal comfort performance

The most widely used index for the evaluation of indoor thermal conditions in moderate environments is the well known Predicted Mean Vote (PMV) originally introduced by Fanger [1]. The PMV is refers to "*the mean value of the votes of a large group of persons on the 7-point thermal sensation scale, based on the heat balance of the human body*" [3]. In this paper, the PMV index is utilized by authors as overall index of the global thermal comfort conditions.

A neutral thermal balance is achieved when the internal heat production in the body is equal to the loss of heat to the environment. In a moderate environment, the human thermoregulatory system automatically attempts to modify skin temperature and sweat secretion in order to maintain heat balance. As it is well known, PMV depends on two personal parameters (metabolic rate, M, and clothing thermal resistance, I_{cl}), and on four environmental parameters (air temperature, θ_a, mean radiant temperature, θ_r, air velocity, v_a, and relative humidity of air, RH) [3,7].

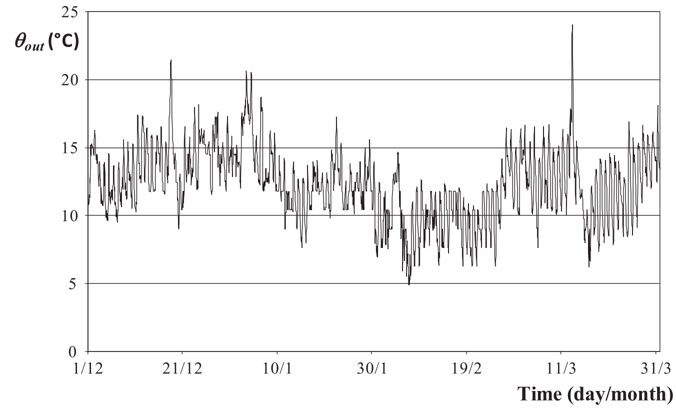

Fig. 1. Behaviour of the outdoor air temperature in a winter day.

The neutrality of the thermal sensation (corresponding to thermal comfort conditions for people) is given by a PMV value equal to zero; positive values mark a sensation of warmth, while negative values signal a sensation of cold. The Table 1 reports the complete seven-points sensation scale.

Such linguistic definition of thermal sensations (that is votes provided by people), along with the usual verbal gradations, like "more or less warm" or "more or less cold", suggests adoption of fuzzy control systems for the design of a controller which is able to suitably drive an HVAC equipment, by maintaining PMV values close to zero.

Ardheali et al. [17] suggest to define a "comfort cost function", J_{sp}, which allows to evaluate the penalty for indoor air temperature deviation from a desired set point. Following this approach, we introduce here an index that measures the deviation of the actual value of PMV (PMV_{act}) from a desired set point of PMV (PMV_{ref}). This index, that represents the first comfort index assumed in the present study, I_1^c, through the observation time (T), is expressed as (assuming the PMV_{ref} equal to zero):

$$I_1^c = \int_0^T \left(\mathrm{PMV_{act}} - \mathrm{PMV_{ref}}\right)^2 \mathrm{d}t = \int_0^T (\mathrm{PMV_{act}})^2 \mathrm{d}t \quad (1)$$

The quadratic form of this cost function, that amplifies the deviations, points out the importance of maintaining comfort conditions for the system.

Actually, a second comfort index can be usefully introduced. In fact, the standard EN 15251 [8] suggests PPD (Predicted Percentage of Dissatisfied people) weighted criteria (Annex F – Method C) to evaluate the general long term thermal comfort conditions. This standard introduces a weighting factor, wf, depending on the ratio between the PPD referring to the actual value of PMV (PPD_{act}) and the PPD referring to the limit value of PMV (PPD_{ref}). That is:

$$wf = \frac{\mathrm{PPD_{act}}}{\mathrm{PPD_{ref}}} \quad (2)$$

Table 2
Adopted values of thermo-physical characteristics of building and HVAC system.

Building envelope	Total heated volume $V = 271$ m^3	Overall Heat Transmittance $H_T = 160$ W/K	
Indoor air	Specific heat $c_a = 1012$ J/kg K	Density $\rho_a = 1.204$ kg/m^3	
Warming carrier of the heating system (water)	Temperatures in the heating season $\theta_{f,in} = 75$ °C $\theta_{f,out} = 65$ °C	Specific heat $c_f = 4186$ J/kg K	Range of the maximum flow rate $\dot{m}_{max} = 0.03 \div 0.18$ kg/s