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Design of a fuzzy set environment comfort system

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Abstract

This paper presents the design of a fuzzy reasoning expert system for the achievement of thermal and visual comfort in buildings. This system does not demand the precise mathematical model of the building to achieve the control law but uses high-level control variables such as thermal and visual comfort. The powerful interactions of the passive components and of the comfort subjectivity match with the application of the fuzzy control theory entirely. Mathematical models are presented, where the actions of the actuators are applied. The design of the rule base is described and, finally, the system is evaluated by using extensive, worst-case, simulation results.

Keywords: Thermal comfort; Visual comfort; Fuzzy control theory; Expert system

1. Introduction

The problem of workspace and living-space environment comfort condition regulation has attracted considerable attention over the past few years. A wide range of solutions has been applied, ranging from simple thermostat control to sophisticated adaptive optimal controllers. The achievement of suitable indoor climate environmental conditions contributes to the normal psychophysiological state and improvement of the productivity of the people. These conditions depend on the parameters of the visual and thermal comfort. People-participation in the formation and definition of comfort is very important, since 'comfort' is a rather fuzzy concept itself.

A widely accepted mathematical representation of thermal comfort is the PMV (predictive mean vote) index [1]. This index is a real number and comfort conditions are achieved if it lies in the [−0.5, +0.5] range, the 'comfort range'. Since comfort is a fuzzy concept, the comfort range is a fuzzy range, rather than a crisply defined comfort zone. Consequently all classical techniques, including adaptive optimal controllers, requiring a crisp determination of the comfort conditions, are not suitable for handling this problem. Actually the fuzziness is not eliminated with these techniques, it is simply obscured into the mathematical formulation of the problem. With classical techniques, strict mathematics is applied only after the process model is defined. However, the model definition is mainly an intuitive process, since the full mathematical models involved are too complicated to implement. Consequently a model simplification invariably takes place, which adds fuzziness in the whole mathematical solution that follows.

The fuzzy modeling process is the main reason why no single optimal solution has been determined yet, as is clearly demonstrated by the results achieved within the CEC-sponsored PASTOR project, which has led to different 'optimal solutions', each having its strong points [2,3]. These control systems are:

(1) the passive building control system of TU Delft (Delft University of Technology);

(2) the control system of CSTB-EMP (Centre Scientifique et Technique du Batiment, Ecole des Mines de Paris);

(3) the control system of NAPAC-Armines (Centre d'énergique).

Advanced techniques are applied in these approaches, such as adaptive modelling, optimization, weather prediction and adaptive control. The control system of TU Delft and the CSTB-EMP system use (a) a data acquisition system from meteorological stations and local controllers, (b) an adaptive model of the room, and (c) the weather predictor. The design of NAPAC-Armines is a sophisticated room thermostat with solar

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gain control as part of a home dashboard. This system has no weather predictor. The solar gain is controlled by the awning.

The utilization of the optimal control theory achieves the determination of the optimal control law of the auxiliary heating by minimizing a performance index which includes (a) the cost of the energy consumed and (b) the thermal discomfort [4–6]. The minimization is achieved by application of the technique of the minimum principle of Pontryagin [7–9]. The use of a second actuator (passive element) complicates the solution of optimization mathematically with the net result that the derived solution is complex and expensive to implement. The benefits of optimal control depend strongly on the type of building and the heating system that is implemented [10], i.e., low thermal inertia buildings with a lot of glazing and direct solar gains, or higher thermal inertia buildings with less glazing, less solar gains and good insulation. Heavy internal structure and heat distribution through the floors and ceilings give a strong thermal inertia to the system.

The present paper investigates a new approach to the problem. The system model mathematics are disregarded and an expert system, with an embedded knowledge base is implemented. This system aims to make the correct decisions about which actuator to use, according to environmental measurements made in real time [11]. Since comfort is a fuzzy concept, the new system employs fuzzy reasoning in its inference engine. Also it is capable of handling complicated arrangements, such as multispace buildings, variable user requirements, etc., by extending the rule base. Evidently the system is not optimal in the mathematical sense, but can be made to operate 'satisfactorily' if the rules are properly chosen [11,12]. This paper presents such a system and demonstrates the process by which a meaningful set of rules can be obtained. It should be noted however that there is no single meaningful set of rules; the aim is to determine one that keeps the environmental conditions within the comfort zone and minimizes the usage of auxiliary energy at the same time. The process starts with analysis of the thermal and visual comfort concepts, the analysis of the system operation and, by trial and error, elimination of non-applicable rules.

This paper is organized as follows. In the subsequent section, the thermal and visual comfort indices as fuzzy variables are presented. Section 3 describes the mathematical models, which are used in the simulator. Section 4 develops the fuzzy control system and gives the fuzzy control rules. Section 5 presents the simulation results and discussion about the new way to control environmental conditions. Finally, the last Section gives the conclusions and a summary of the characteristics of the proposed system.

2. Thermal and visual comfort variables

The ASHRAE Standard 55-81 gives a psychrometric chart, that defines the winter and summer comfort zones (Fig. 1). The comfort zone of the Standard 55-81 sets effective temperature limits of 20 °C and 23 °C for winter and 23 °C and 26 °C for summer. The upper and lower limits of the comfort zone are bounded by lines of constant dew point temperature with 2 °C as the lower limit and 17 °C as the upper limit [13].

Thermal comfort is expressed by the thermal index PMV which ranges between the seven points of the psychophysical scale (from −3 (cold) through 0 (neutral) to +3 (hot)). Thermal-comfort-influencing variables are classified in two categories:

(a) personal-dependent variables such as activity (metabolism) and thermal resistance of clothing;

(b) environmental-dependent variables such as air temperature, mean radiant temperature, relative air speed and air humidity.

Fanger introduced another index known as the predicted percentage of dissatisfied (PPD) to predict the percentage of persons that can be dissatisfied. PMV and PPD are related through a one-to-one correspondence. This index must be less than 10%, therefore the PMV can vary from the optimum condition (thermal neutral) ±0.5 units ($-0.5 < \text{PMV} < +0.5$).

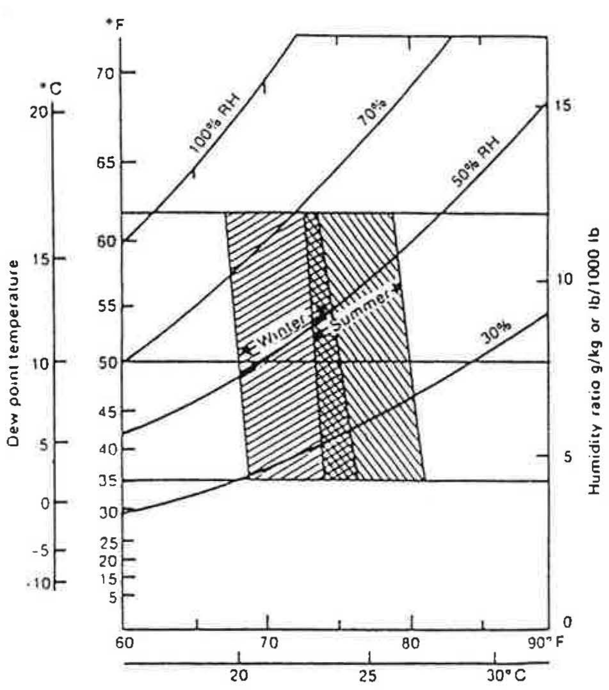

Fig. 1. Summer and winter comfort zones, as shown in ASHRAE Standard 55-81.

The above definitions regard thermal comfort as a zone rather than as a single point in the psychrometric chart. Also the comfort zone does not have crisp limits and, consequently, thermal comfort is easily represented by a fuzzy set. The control of the fuzzy variable PMV gives the capability of comfort verification. The thermal comfort index PMV can be considered as a new indoor climate high-level performance variable and its regulation results indirectly in the regulation of the environmental variables.

Visual comfort is achieved if proper lighting conditions exist at the user position. Lighting can be either natural or artificial. The present paper assumes that natural lighting enters the room by the window directly from the sky vault, possibly from the sun, or indirectly from reflections at the ground or nearby reflecting surfaces (e.g., buildings). The user is located in the centre of the room facing the window. International recommendations for the level of illuminance for visual comfort exist for different types of operations and different types of working environments [14].

Daylighting is an important energy conversion area, where energy savings (due to artificial lighting savings) and visual comfort can be achieved at the same time. Visual discomfort arises from improper lighting conditions, creating glare and contrast problems. Inadequate natural lighting requires the use of additional artificial lighting. Any strong light source, particularly the sun and the sky vault, may cause glare, if they are within the optical field of the observer. Glare is quantified by a daylight glare index (DGI), depending mainly on the window luminance and the reflections within the room. Glare caused by direct view of the sky is considered to be acceptable if the glare index at a particular point in the room does not exceed the recommended level for the particular operation. Glare control is achieved by shading devices, such as horizontal (or vertical) venetian blinds, translucent curtains, etc. [15]. The control of these devices can be either manual or mechanical with automatic regulators, or a combination of both manual and mechanical regulators.

3. Mathematical models

3.1. Indoor temperature model

Inside room air temperature is controlled by a number of factors as the heat flux coming into the room through walls ($\dot{Q}_{con}$), windows and roof, air infiltration ($\dot{Q}_{inf}$) and ventilation, internal heat gain ($\dot{Q}_{int}$) and auxiliary heating or cooling. The energy balance equation for the room air temperature T_a is written as:

$$m_a c_a \, dT_a/dt = \dot{Q}_{con} + \dot{Q}_w + \dot{Q}_{inf} + \dot{Q}_{int} + \dot{Q}_{vent} \pm \dot{Q}_{aux}$$

3.1.1. Heat flux through the window

To calculate the net heat gain through the window an assumption is made that the heat capacity and the absorptivity of window glass is negligible and $\dot{Q}_w$ is written as:

$$\dot{Q}_w = A_w \tau_{gl} D I_w - h_w (T_a - T_{amb})$$

where τ_{gl} is the transmissivity of glass, D is the window shading, computed from the visual comfort fuzzy reasoning system, I_w is the total amount of solar radiation that reaches the window, h_w is the window glass conductance (W/m^2 °C).

3.1.2. Auxiliary heating

In this study electric auxiliary heating is used for the space heating. The power supply can be varied continuously from 0 to 100% capacity, as described in the following equation:

$$\dot{Q}_{aux} = \dot{Q}_{max} x_r$$

where $\dot{Q}_{max}$ is the maximum power supply and x_r is the fraction of capacity. The designed fuzzy control system can be easily adapted for any heating or cooling systems.

3.1.3. Heat transfer due to ventilation

The ventilation heat flow is caused by natural ventilation. This is caused by opening the windows. The heat flow is given in the following equations:

$$\dot{Q}_{vent} = \rho c \Phi_v (T_{amb} - T_a)$$

$$A_{eff} = A_w \sin\left(\frac{\text{AW.180}}{n}\right)$$

$$V_{eff} = (10^{-3} \times v_w{}^2 + 1.12 \times 10^{-3} \Delta T + 0.01)^{0.5}$$

$$\Phi_v = A_{eff} V_{eff}$$

where

ρ is the air density,

c is the specific heat capacity of air,

Φ_v is the natural ventilation airflow (m^3/s),

A_{eff} is effective slice area (m^2) of the window,

A_w is the window area,

AW is the window opening angle (°) regulated from the fuzzy control system,

V_{eff} is the average effective air velocity (m/s), and

v_w is the outdoor air velocity.

The mathematical models that calculate the outdoor parameters (temperature (T_{amb}), relative humidity (RH), humidity ratio (x_0), wind speed (v_w)) and the corresponding indoor parameters are presented in Ref. [16]. The mathematical expressions of the outdoor and indoor illumination (ILL) and the calculation of the glare index DGI are analysed in an earlier paper, see Ref. [15]. The solar radiation is computed by the solrad code [17].

Table 1
Linguistic terms of the fuzzy sets PMV, T_{amb}, AW, AH, AC

PMW		T_{amb}/AW		AH/AC	
VN	very negative	S	small	VB	very big
NB	negative big	VB	very big	PB	positive big
NS	negative small	B	big	PM	positive medium
BNM	below negative medium	M	medium	PS	positive small
NM	negative medium			S	small
OK	satisfactory			VS	very small
				VVS	very very small

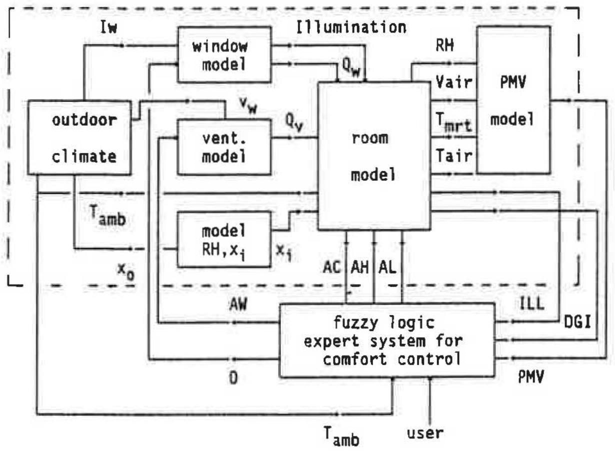

Fig. 2. General structure of the simulator.

3.2. *The simulator*

The interconnection of the models is shown schematically in Fig. 2. This simulator is designed mainly to test the fuzzy system and consists of the following modules: outdoor climate model, the window model, the room model, the indoor relative humidity model and the PMV model. The fuzzy system is connected with the simulator as if the simulator was a real building with actuators and sensors.

In the simulation, the time step is one minute. The outdoor climate model calculates the outdoor variables and this information is passed to the fuzzy system and to the building model together with the variables PMV, ILL, DGI, which are also inputs to the fuzzy system. The fuzzy system processes the information to calculate new actuator positions.

4. Design of the fuzzy logic expert system

4.1. *System architecture*

The fuzzy logic expert system consists of two fuzzy control subsystems, used for thermal comfort and visual comfort respectively. There is a powerful interaction between the thermal and visual comfort variables, since the use of shading for illumination affects the solar gain and consequently PMV.

The thermal comfort fuzzy system retains thermal comfort control within user-defined limits. PMV and outdoor temperature are the system inputs, as is shown in Fig. 2. Auxiliary heating (AH), the auxiliary cooling (AC) and ventilation window opening angle (AW) settings are the system outputs. These outputs, which are deterministic signals, drive the process actuators. The auxiliary heating and cooling systems give a proportion of the power to the physical system. The output AW determines the opening angle of the ventilation window. Outdoor temperature has been selected as a system input because it affects the natural ventilation and the PMV simultaneously.

Three major functional blocks are used for the fuzzy system: fuzzification (FF), inference engine (IE) and defuzzification (DF) (Fig. 3). The actual quantization levels and the membership functions are determined largely in an *ad hoc* manner and based on insights in the nature of the underlying nonfuzzy variables and the control problems at hand.

The design of the fuzzy control system starts with establishing certain quantization levels for PMV, T_{amb}, AC, AH, AW along with membership functions corresponding to these quantization levels (Table 1). This process defines the appropriate fuzzy sets to be the basis for applying fuzzy logic. They serve as linguistic values to be assigned, respectively, to the fuzzy variables. Triangular membership functions are used, because they lead to very tractable systems, except for the comfort zone where the PMV membership function has trapezoid shape (Fig. 4).

The fuzzification block transforms a real signal into the appropriate fuzzy set. Because the control system is a multivariable complex fuzzy system, the inference method used is based on the decomposition of multivariable control rules [18]. This inference engine leads

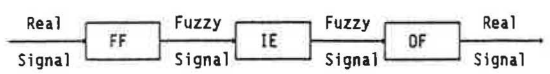

Fig. 3. Functional blocks for the fuzzy control system.

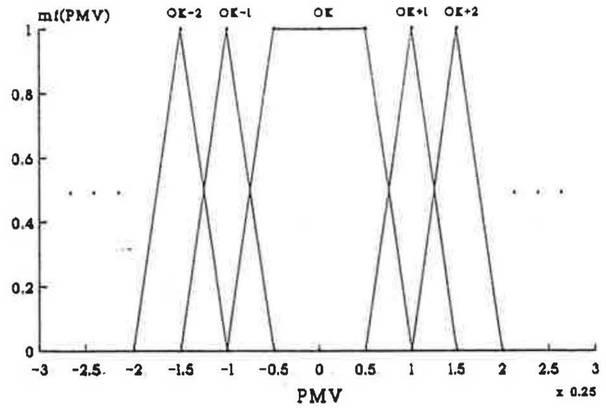

Fig. 4. Quantization of the input (PMV) space into fuzzy regions and the corresponding membership functions.

Table 2
Thermal comfort fuzzy rules

1.	if	PMV VN	& Tamb S	then AH VB	& AC OFF	& AW OFF
2.	if	PMV NB	& Tamb S	then AH PB	& AC OFF	& AW OFF
3.	if	PMV NS	& Tamb S	then AH PM	& AC OFF	& AW OFF
4.	if	PMV BNM	& Tamb S	then AH PS	& AC OFF	& AW OFF
5.	if	PMV NM	& Tamb S	then AH S	& AC OFF	& AW OFF
6.	if	PMV OK-3	& Tamb S	then AH VS	& AC OFF	& AW OFF
7.	if	PMV OK-2	& Tamb S	then AH VVS	& AC OFF	& AW OFF
8.	if	PMV OK-1	& Tamb S	then AH BOFF	& AC OFF	& AW OFF
9.	if	PMV OK-1	& Tamb S	then AH OFF	& AC OFF	& AW OFF
10.	if	PMV OK+3	& Tamb VB	then AH OFF	& AC PM	& AW OFF
11.	if	PMV OK+3	& Tamb B	then AH OFF	& AC S	& AW OFF
12.	if	PMV OK+2	& Tamb VB	then AH OFF	& AC S	& AW OFF
13.	if	PMV OK+2	& Tamb B	then AH OFF	& AC S	& AW OFF
14.	if	PMV OK+1	& Tamb VB	then AH OFF	& AC VS	& AW OFF
15.	if	PMV OK+1	& Tamb B	then AH OFF	& AC BOFF	& AW OFF
16.	if	PMV OK	& Tamb VB	then AH OFF	& AC BOFF	& AW OFF
17.	if	PMV OK	& Tamb B	then AH OFF	& AC BOFF	& AW OFF
18.	if	PMV OK	& Tamb M1	then AH OFF	& AC OFF	& AW ON
19.	if	PMV OK	& Tamb B	then AH OFF	& AC OFF	& AW OFF
20.	if	PMV OK+1	& Tamb M2	then AH OFF	& AC BOFF	& AW OFF
21.	if	PMV OK+3	& Tamb M2	then AH OFF	& AC PS	& AW OFF
22.	if	PMV OK+1	& Tamb M1	then AH OFF	& AC OFF	& AW ON
23.	if	PMV OK+2	& Tamb M1	then AH OFF	& AC OFF	& AW M
24.	if	PMV OK+2	& Tamb M2	then AH OFF	& AC VS	& AW OFF
25.	if	PMV OK-1	& Tamb M1	then AH OFF	& AC OFF	& AW S

Table 3
Fuzzy decision table for thermal comfort

Rules	AH (W)	AW (°)	AC (W)
1	1720	1.5	233
2	1600	1.26	233
3	1400	0.69	233
4	1200	0.69	233
5	916	0.69	233
6	800	0.69	233
7	555	0.69	233
8	433	10.8	233
9	269	10.8	233
10	233	0.69	967
11	233	0.69	927
12	233	0.69	850
13	233	0.69	833
14	233	0.69	645
15	233	0.69	590
16	233	0.69	525
17	233	0.69	489
18	233	15.00	516
19	233	15.00	547
20	233	0.69	645
21	233	0.69	870
22	233	19.20	600
23	233	17.78	744
24	233	15.00	745
25	233	11.50	414

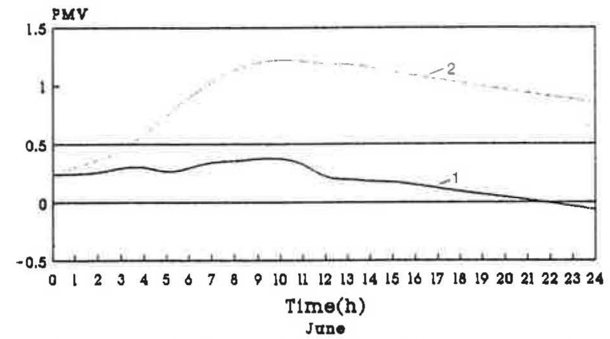

Fig. 5. PMV vs. time for a single day (June). Curve 1—PMV with fuzzy control; (b) curve 2—PMV without control. The PMV is found in the comfort zone according to ASHRAE.

to a fast, flexible and unified computer implementation algorithm. The last functional block of the fuzzy controller is a defuzzifying process that produces a real signal from the fuzzy variable. This is essentially the reverse operation of the fuzzifying process. The center of area (COA) method is used [19].

4.2. *Fuzzy logic system rules*

The fuzzy control subsystem of thermal comfort uses two inputs PMV and T_{amb} which correspond to 13 and 5 linguistic variables respectively. These variables generate a maximum number of 65 rules. This number of

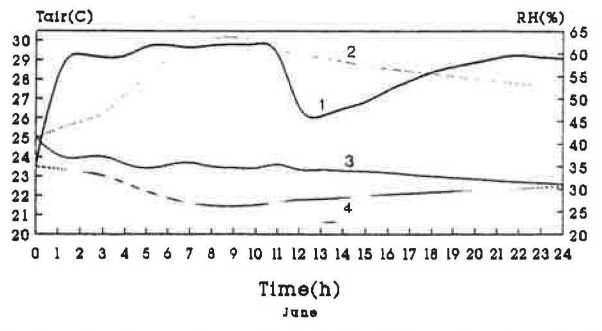

Fig. 6. Indoor temperature and relative humidity vs. time for a single day (June). Curves 3 and 2 – temperature with and without PMV control; curves 1 and 4 – relative humidity with and without PMV control. The variables T_{amb} and RH are found in the comfort zone according to ASHRAE. 3 – controlled T_{air}, 1 – uncontrolled T_{air}, 3 – controlled RH, 4 – uncontrolled RH.

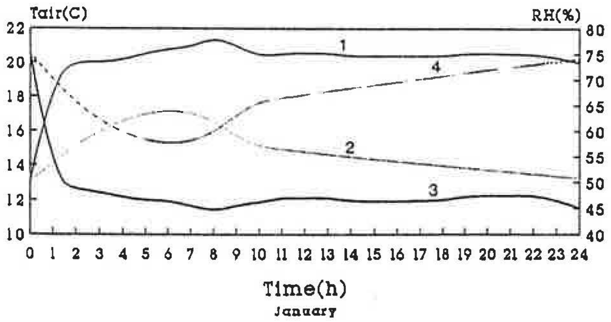

Fig. 7. Indoor temperature and relative humidity vs. time for a single day (January). Curves 1 and 2 – temperature with and without PMV control; curves 3 and 4 – relative humidity with and without PMV control. The variables T_{amb} and RH are found in the comfort zone according to ASHRAE. 1 – controlled T_{air}, 2 – uncontrolled T_{air}, 3 – controlled RH, 4 – uncontrolled RH.

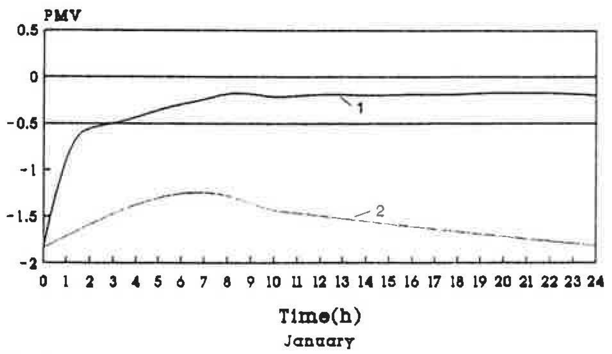

Fig. 8. PMV vs. time for a single day (January) Curve 1 – PMV with fuzzy control; curve 2 – PMV without control. The PMV is found in the comfort zone according to ASHRAE. 1 – controlled PMV, 2 – uncontrolled PMV.

rules is reduced to 25, since there are rules that correspond to 'not applicable' conditions [12]. The visual comfort rule set is developed in detail in the paper [15]. The applicable thermal comfort rules are given in Table 2.

The results of the fuzzy control rules are shown in the fuzzy decision table, Table 3. The number 233 as indicated on Table 3 corresponds to the condition OFF of the actuators AH, AC.

5. Simulation results and discussion

Simulation results for two extreme climatological seasons (January and June) are investigated. For both seasons the PMVdes = 0 (desired), met = 1.2 (metabolic rate) has been used whilst clo = 1 and clo = 0.5 is used for January and June respectively (clo = clothing unit).

The PMV in June is shown in Fig. 5. The uncontrolled PMV is out of the comfort zone and decreases in the afternoon. The fuzzy system maintains the PMV index in the comfort zone and particularly in the −0.2 to +0.2 range. During the night there is further PMV degradation, mainly owing to natural ventilation. The indirect temperature control and the relative humidity are shown in Figs. 6 and 7. These variables are maintained within the ASHRAE comfort zones.

The PMV in January is shown in Fig. 8. The unregulated thermal comfort index is always below −0.5, i.e., outside the nominal comfort zone. The fuzzy system increases PMV, keeping it within the comfort zone. During the night the PMV is constant because there is no cooling. The natural ventilation operates mainly during the night and the morning, to remove the additional thermal load. Natural ventilation is essential to achieve thermal comfort with least energy expediture [16].

Natural ventilation contributes to the control of the relative humidity and the air velocity determinative. Increase of indoor air velocity by means of passive cooling results in the reduction of PMV. Therefore, the outdoor air velocity is an important parameter, affecting natural ventilation [11].

6. Conclusions

The main conclusions from this study may be summarized as follows:

- The concepts of thermal and visual comfort are used as fuzzy control variables instead of using them as simple performance indices.
- The fuzzy rule system does not require a particular process model.
- The user participates in the formation of the comfort in the living or working space. The user introduces his/her activity, a typical clothing ensemble and the desired thermal comfort level.
- The actuators used are the auxiliary heating and cooling, the ventilation window, the shading device and the artificial lighting.

- The thermal comfort rules give very good results in both extreme climatological seasons, where the maximum and minimum illumination and temperature values occur.
- The cost is low, since the system can be realized with commercially available components and equipment [11].
- The control of thermal comfort leads to indirect control of the indoor temperature and the relative humidity. The width of the oscillation is low and does not generate thermal discomfort.

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