A FUZZY CONTROL ADAPTED BY A NEURAL NETWORK TO MAINTAIN A DWELLING WITHIN THERMAL COMFORT

B. Egilegor, J.P. Uribe, G. Arregi, E. Pradilla, L. Susperregi
Artificial Intelligence and Energy Departments
IKERLAN Applied Research Centre
20500 Mondragon. Gipuzkoa. Spain
e-mail: begilegor@ikerlan.es

ABSTRACT

This paper presents the results of a neuro fuzzy control setting the fan-coils air flow rate of three zones of a dwelling to improve the comfort. The zones temperature and humidity are the input variables from which the value of Fanger's thermal comfort index PMV (predicted mean vote) is calculated and used as comfort variable. The TRNSYS simulation program has been used to simulate the building under different weather conditions. Under winter conditions in the heating mode hot water circulates through the fan coils and under summer conditions in the cooling mode, chilled water.

INTRODUCTION

A recent study in Sweden [1] found that children's allergic reaction to dust is correlated with excessive indoor humidity. The apparent reason is that dust mite population increase significantly at indoor relative humidity levels above 60%. But the conventional control systems do not attempt to control the humidity level. The conventional controls of the hydronic systems in our country usually maintain the temperature in a set point fixed by the users. The purpose of this study is to improve this control to maintain not only the temperature but also the humidity within the comfort zone whenever the system can do it taking into account its limitations.

The chosen hydronic system is not specifically designed to control the humidity. The zone air circulates through the fan coils and it is heated or cooled depending on the temperature of the water flowing in the fan coils. If the system is running in refrigeration mode cold water flows through the fan coils. Then the air is cooled and its humidity level will reduce if the coil surface temperature goes below the air dew-point. The capacity of the system to refrigerate the water depends mainly on the outdoor dry bulb temperature. Then the latent heat ratio of the indoor fan coils can not controlled.

The air conditioning system when is in refrigeration mode cools the air and reduces its humidity level in an undetermined ratio. In heating mode the air temperature increase but its absolute humidity level does not change.

The control tries to optimise the value of the PMV [12] index tuning zone temperature according to the humidity level. To achieve this we have implemented a neural-fuzzy control system.

The simulation and the control program have been run in two different computers. The information between the building and the control is exchanged via a data acquisition card. It was decided to communicate both computers via a data acquisition card in order to simulate reality as close as possible.

The simulation program sends the temperature and humidity of the three zones and the outdoor conditions to the control computer. The control program reads those temperatures and humidities and calculates the PMV as defined by Fanger. The fuzzy module of the control program sets the air flow rate of the fan coils as a function of PMV index and its mean rate of increase. These control signals are sent to the data acquisition card where the simulation program reads them. Afterwards the next simulation step will be executed. This process is repeated until the end of simulation.

The simulations have been performed with different values of the fuzzy control parameters; different offset applied to fuzzy antecedents. A neural network is trained using these simulations results in order to choose the optimum offset in each situation to improve the control performance. The neural network learns to tune the fuzzy control off-line. Thereafter, the control uses these tuning procedures on-line to optimise the control.

Several runs of computer model of a dwelling have been used to train a neural network which adapts the fuzzy control used to maintain the dwelling thermal comfort level for different climatic conditions.

The implemented fuzzy and neuro fuzzy control are as simple as possible because they are intended to be installed in a 8K ROM microprocessor.

We have connected the control computer to a real system but we have not got the results yet.

DWELLING AND HVAC DESCRIPTION

HVAC system is a hydronic one with a compact boiler for heating and water chiller for cooling. This plant can cool and heat the water but not simultaneously. The cool or hot water circulate through three fan coils to air condition the dwelling's three zones. The fans of those fan-coils have three air flow rates which are controlled by a neuro-fuzzy control.

The TRNSYS v13.1 [13] simulation program has been used to simulate the three zones of the dwelling, the water loop, the three fan coils, the chiller plant and the boiler. Also we have included two subroutines more to transfer the temperatures and humidities of the zones to the acquisition data card and to read the control signals (the air flow rates of the fan coils) from the data acquisition card. The simulation time step is 0.01 hour (36 seconds) but the communication between the two computers happens every 0.1 hour (6 minutes).

Three zones with different characteristics have been simulated using Trnsys TYPE 56 unit. The three fan-coils, using the TYPE 52 unit and the chiller, using a subroutine created by us. The boiler has been simulated by TYPE 6 unit. We have developed two new TYPEs to output the thermal conditions of the zones to the data acquisition card and to read the control signals from it. The simulation block diagram is shown in Fig.1.

Since we have also installed a real system in three zones of our company we have used its characteristics to make the simulation model. The characteristic of these zones are the following:

The floor area of the three zones is: 21 m^2, 23 m^2 and 13 m^2. Each one has a south oriented exterior wall (U = 0.658 $W/m^{2o}C$). The floor, the roof and the other interior walls of the zones are considered adiabatic. Each zone has 6 m^2 of single glazed window. The transmittance of windows is reduced in the summer because of the use of blinds to avoid direct solar radiation. The internal gains are null. We have simulated a humidity generation in two zones supposing an occupation of a person in 24 hours. The infiltration was assumed to be 0.3 air changes per hour.

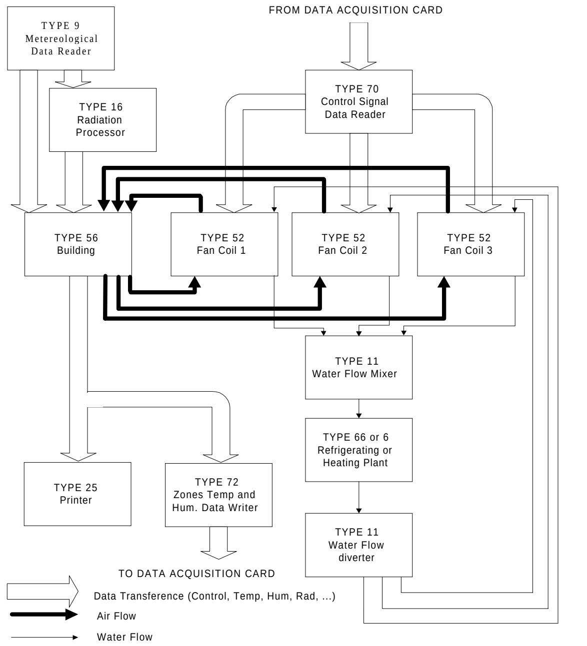

Fig 1. Simulation block diagram.

Two different fan coils have been simulated (type 1 fan coil were used in zone 1 and 3; and second type fan coil in zone 2). Both of them with three air flow rates. Its characteristic are summed up in table 1.

Table 1. Characteristics of fan coils used in the simulations

		FAN-COIL 1	FAN-COIL 2
Air flow rate	max	150	400
(l/hr)	med	125	300
	min	100	200
Refrigeration power	max	593	1100
(kCal/hr)	med	535	973
	min	467	798
Heating power	max	1358	3303
(kCal/hr)	med	1150	2636
	min	932	1844
Water flow (l/hr)		175	175

Conditions:	Cooling	Heating
Air in	T= 24ºC Hr=50%	T= 21ºC
Water in	T= 7ºC	T= 60ºC

These fan coils are not specifically designed to control the humidity. The air circulates through the fan coils and it is heated or cooled depending on the temperature of the water flowing in the fan coils. When the air is cooled its humidity level will reduce if the coil surface temperature goes below the air dew-point.

The chiller has a condenser with a heat exchanger efficiency of 0.6, an evaporator with an efficiency of 0.38 and a compressor. We have used the FLUIDS subroutine [14] to simulate the properties of the refrigerant R-22 to determine working conditions of the chiller when it is running. It has a refrigerating capacity of 3011 kCal/hr (water input temp = 12ºC; outdoor temp = 35ºC; water flow = 525 litres/hr; air flow = 1800 m^3/hr). It has a thermostatic control that acts depending on the return water temperature. If this temperature is less than 7ºC the chiller is off and if it is higher than 13ºC is on.

The boiler has a maximum heating capacity of 20000 kCal/hr and its set temperature is 60ºC. It is a modulating boiler. In other words, the outlet water temperature is maintained at its set point unless the heating requirement is higher than 20000kCal/hr. In such case the boiler heats the water using its maximum capacity.

WEATHER DATA

Three different summer and winter climatic data sets have been used to simulate the control performance. For winter a very cold set (Winter climate 1), a moderately cold (Winter climate 2) and a warmer one (Winter climate 3) have been used. For the summer a moderately hot and humid set (Summer climate 1), a moderately hot and less humid one (Summer climate 2) and a hot and very humid one (Summer climate 3) have been used. The general characteristic of the data sets used are shown in table 2.

Table 2. General characteristic of weather data used in the simulations.

		SOLAR RAD (KJ/m^2)	TEMP (ºC)	ABS. HUM. (Kg//Kg)
WINTER CLIMATE 1	mean	153	-4.54	0.00265
	max	661	0.29	0.00383
	min	0	-7.40	0.00203
WINTER CLIMATE 2	mean	343	0.31	0.00333
	max	1321	5.29	0.00408
	min	55	-2.40	0.00302
WINTER CLIMATE 3	mean	380	9.31	0.00587
	max	1521	14.29	0.00626
	min	0	6.60	0.00547
SUMMER CLIMATE 1	mean	936	25.59	0.01245
	max	2870	35.65	0.01384
	min	0	17.33	0.01076
SUMMER CLIMATE 2	mean	1145	23.85	0.00939
	max	3159	31.00	0.01106
	min	0	16.00	0.00799
SUMMER CLIMATE 3	mean	1057	27.09	0.01759
	max	3333	31.00	0.01957
	min	0	24.40	0.01638

CONTROL DESCRIPTION

A fuzzy control of the thermal comfort was used. Afterwards this control was adapted using a neural network to improve the control performance in different rooms and climatic conditions.

A fuzzy system with a PID control structure has been chosen because any control surface of a conventional PID can be implemented by fuzzy control methods using product-sum-gravity algorithm [3]. Due to the wide working conditions (outdoor temperature and humidity, zones sizes, internal gains...) and its dependence on time a self tuning system in a real time is necessary. Offset and scale factors can be used as tuning parameters [6]. In this case offset has been used and the use of scale factors as tuning parameters have been left for a future work. Because of the non-linearity of the system tuning a PID control (a linear control law) is hard and its more difficult to ensure its stability. However with the fuzzy system as it could be derived in a non-linear control surface the tuning is easier [2,5] and it does not create so much stability problems [8].

The control program, implemented in C language, reads the signals (outdoor temperature and humidity and zone temperatures and humidities) sent by simulation computer. The control program calculates the PMV index value for each zone with these data. The activity level of occupants and the air velocity are supposed constants (M = 75 w and v = 0.1 m/sec). The radiant temperature is supposed equal to the air temperature. This means that the walls and the window panes are at the temperature of the air. PMV index has been calculated supposing 0.5 clo of clothing insulation for the cooling mode and 1.5 clo for the heating mode.

In each simulation time step the control program calculates PMV index increments using the PMV values of each zone in the previous simulation time step and the value of present one. The PMV error value and its increments are used as inputs for the fuzzy module. The control program calls the fuzzy module which calculates required air flow rates for the zones fan coils. The outputs of the fuzzy module (the changes of air flow rates) are sent to the simulation computer to start the next simulation time step.

We have also implemented a conventional thermostatic control of temperature to compare the results obtained with the ones obtained with neuro-fuzzy control. When the thermostatic control is running the control program also calculates the PMV error and its increments but they are calculated only to be compared with the ones obtained by fuzzy and neuro-fuzzy controls. The thermostatic control does not use the PMV value to set the air flow rate.

In the heating mode only two air flow rates have been used. It has been assumed that the maximum air flow rate can produce discomfort due to created draught.

THERMOSTATIC CONTROL

This control sets the air flow rate of the fan coils depending on the temperature of the zones. It has been chosen as set temperatures 24ºC for refrigeration mode and 21ºC for the heating. The reason is because with the supposed clothing insulation and with 50% of relative humidity the PMV index has a zero value. The thermostatic control maintains the desired temperatures in the zones but depending on the humidity level the PMV index values could not be the best ones.

FUZZY

In fuzzy logic the parameters belongs to categories which are not exactly defined: a parameter belongs to a category in a higher or lower grade. One of the fuzzy logic advantages is that data can be expressed by linguistic variables.

The fuzzy module of the control has been implemented using the CUBICALC program [15].

The antecedents used in this fuzzy control are the PMV index error (desired PMV index value – current PMV index value) and its increments from one simulation time step to the next ("FzErrFng" and "FzIncFng") with 3 adjectives (zero, negative and positive).

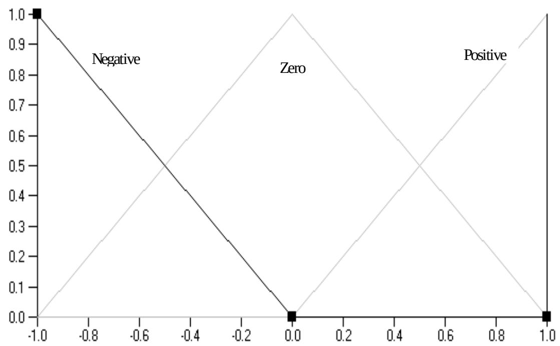

Fig 2. "*FzErrFng*" called antecedent adjectives (represents the PMV index error)

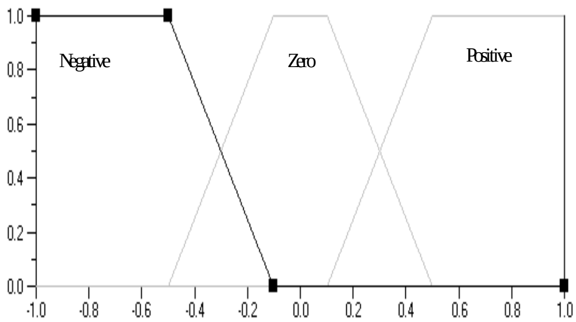

Fig 3. "*FzIncFng*" antecedent adjectives (represents the PMV increment from one simulation time step to the next).

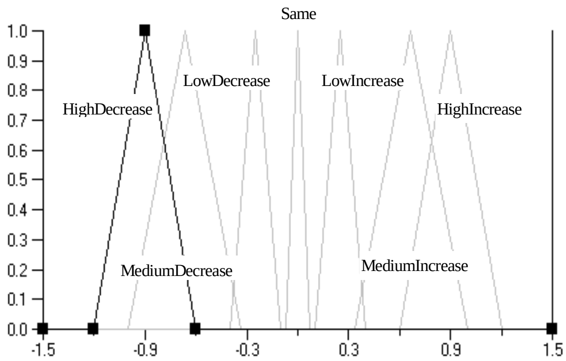

Fig 4. Adjectives of the consequent. It is the variation of fan-coils air flow rate (called *"FzAirInt"*).

The control is defined with 9 rules:

FzErrFng / *FzIncFng*	NEGATIVE	ZERO	POSITIVE
NEGATIVE	*Decrease*	*Increase*	*HighIncrease*
ZERO	*MediumDecr*	*Same*	*MediumInc*
POSITIVE	*HighDecrease*	*Decrease*	*Increase*

The rules represented in the table should be read in this way:

If *FzErrFng* is NEGATIVE and *FzIncFng* is NEGATIVE then *FzAirInt Decrease*

This means that if the PMV index value is negative (is greater than the desired value) and its increment is negative (its value is decreasing) then the control should decrease the air flow rate of the fan coil. Remember that these rules are for the heating mode. In refrigeration mode the rules are symmetrical.

The control implemented is a fuzzy PI.

The classic PID control is defined by the error, its increments and its rates of integration in the following way [3,4]:

$$e(n) = r(n) - y(n)$$

$$\Delta e(n) = e(n) - e(n-1)$$

$$u(n) = K_P \cdot e(n) + K_D \cdot \Delta e(n) + K_I \cdot \sum_{m=0}^{n} e(m)$$

The increment of the output signal is:

$$\Delta u(n) = u(n) - u(n-1)$$

$$\Delta u(n) = K_P \cdot \Delta e(n) + K_D \cdot \Delta^2 e(n) + K_I \cdot e(n)$$

In a classic PI would be:

$$\Delta u(n) = K_P \cdot \Delta e(n) + K_I \cdot e(n)$$

Then in the fuzzy PI control the antecedents are *e(n)* and *Δe(n)* and the fuzzy output is *Δu(n)* (the air flow rate change).

The inference used is "max-prod": This means that the scalation has been done multiplying the output fuzzy set by the value of the rule activation. Although the height of the triangle changes, the general shape does not. Moreover it means that the combination of rule outputs has been done calculating the maximum of scaled fuzzy sets. The fuzzy program computes the "envelope" surrounding all the output sets. Fig. 5 shows graphically the inference method used.

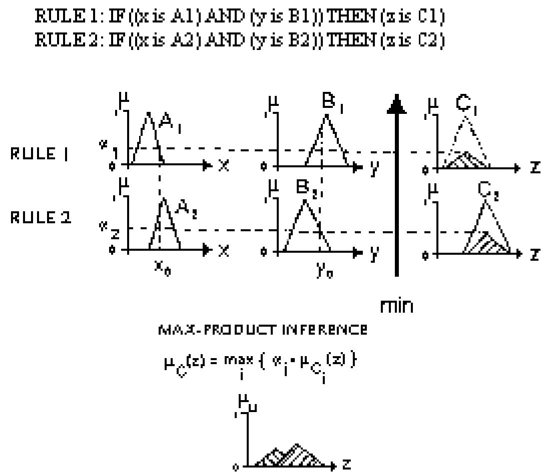

Fig 5. Graphical representation of the inference method used: "max-product" inference.

Defuzzyfication reduces the output fuzzy set produced in the rule combination step to a single value. In this case it has been made by calculating the centroid of the output fuzzy set graph. The centroid is the point at which an object of uniform density balances. It uses all the information present in the waveform and represents a good summary of the waveform in a single number.

The increment or decrement of the air flow rate is the control output. The resultant fan coil air flow rate is the previous air flow rate summed to the new air flow rate variation required by the fuzzy output. In this way the integral part of the control is defined.

NEURAL NETWORK:

The neural network (NN) solves the problems using the generalisation mechanism: for similar inputs a supervised NN produces similar outputs. The structure of NN is based on human brain: they have some processing elements similar to human neurones which are linked with several connections. NN is a technique to simulate the learning process and information retention and storage of the human brain [6,7].

NN performance in training:

An offset of PMV error antecedents (an offset of *FzErrFng* called antecedent) has been used as the adaptative parameter. Several simulations with different offsets have been run. The results of these simulations are used to train the NN.

The NN inputs are: the PMV index mean value of the day before (represents the thermal situation of the zone the day before), the offset applied the day before, the PMV index mean value of the current day (represents the thermal situation of the zone the current day) and PMV Index increment.

The NN output is: The change of the adaptative parameter from one day to the next (in other words, the change of the offset to be applied).

The NN learns to associate for a change in the offset a change of the PMV index mean value from one day to the next in each determined situation.

The offset reduces the stational error, that means that helps improve the integral part of the control.

Before the training process some data had to be eliminated because they shown system saturations. The saturations that appeared were the following:

- The air flow rate of fan coils is the maximum and the system needs more air flow rate.
- The fan coil is not running and the system needs less air flow rate.

Once these data were eliminated the NN was trained.

After the NN have learnt it was introduced in the control program loop. The NN performance on-line is the following:

At simulated midnight the NN is called and the whole day data are transferred to it. The desirable comfort index value is also transferred to the NN. Knowing these data the NN determinates the optimum increase of the adaptative parameter to obtain the desirable conditions in the following day (the optimum PMV index value; the one which is nearest to 0). The NN is called twice at simulated midnight: in one call the NN provides the increase of the adaptative parameter for the day and in the second call the increase of the adaptative parameter to be applied at night.

The NN characteristics:

A multilayer NN with a hidden layer. Its structure is of the direct flow type (feed-forward) and its learning is of the supervised type. The weights are tuned by backpropagation procedure. The input layer has 4 neurones, the hidden layer has 5 neurones and the output layer has 1 neurone. “Neural Networks” software has been used to build the NN [16].

RESULTS AND CONCLUSIONS

Three simulations have been run to compare the results: the first, with a thermostatic control (Winter set point temperature = 21ºC; Summer set point temperature = 24ºC with a 2 degrees dead band), the second, with the fuzzy control without the neural network and the third, the same fuzzy control but tuned by the neural network.

Comparing the PMV mean values and their standard deviations obtained from the three different controls (thermostatic, fuzzy and neuro-fuzzy) it has seen that the major improvement was obtained by fuzzy control. The neural network adjusts slightly these results. Tables 3 and 4 show the PMV mean values and its standard deviations obtained with the three type of controls for different climatic conditions in winter and in summer in the simulated three zones.

Table 3. The PMV index mean value and its standard deviation obtained with thermostatic, fuzzy and neuro-fuzzy controls in different winter climatic conditions in three zones.

WINTER	**CLIMATE 1**	Z1	Z2	Z3
THERM	MEAN	0.495	0.496	0.304
	DEV	0.289	0.530	0.441
FUZZY	MEAN	-0.070	0.294	0.021
	DEV	0.325	0.505	0.420
NEURO	MEAN	-0.038	0.088	-0.011
	DEV	0.309	0.501	0.409
WINTER	**CLIMATE 2**	Z1	Z2	Z3
THERM	MEAN	0.510	0.551	0.444
	DEV	0.362	0.492	0.445
FUZZY	MEAN	0.051	0.315	0.206
	DEV	0.318	0.435	0.398
NEURO	MEAN	-0.001	0.095	0.066
	DEV	0.331	0.426	0.423
WINTER	**CLIMATE 3**	Z1	Z2	Z3
THERM	MEAN	0.881	1.140	1.077
	DEV	0.592	0.666	0.839
FUZZY	MEAN	0.683	0.853	0.863
	DEV	0.618	0.665	0.866
NEURO	MEAN	0.468	0.647	0.698
	DEV	0.627	0.705	0.918

Table 4. The PMV index mean value and its standard deviation obtained with thermostatic, fuzzy and neuro-fuzzy controls in different summer climatic conditions in three zones.

SUMMER	**CLIMATE 1**	Z1	Z2	Z3
THERM	MEAN	0.107	0.295	0.155
	DEV	0.198	0.258	0.215
FUZZY	MEAN	-0.086	-0.046	-0.027
	DEV	0.228	0.145	0.131
NEURO	MEAN	-0.054	-0.011	-0.005
	DEV	0.277	0.137	0.120
SUMMER	**CLIMATE 2**	Z1	Z2	Z3
THERM	MEAN	-0.035	0.160	0.023
	DEV	0.200	0.227	0.220
FUZZY	MEAN	-0.127	-0.088	-0.068
	DEV	0.256	0.132	0.141
NEURO	MEAN	-0.136	-0.040	-0.045
	DEV	0.339	0.133	0.138
SUMMER	**CLIMATE 3**	Z1	Z2	Z3
THERM	MEAN	0.372	0.601	0.523
	DEV	0.351	0.354	0.423
FUZZY	MEAN	-0.015	-0.063	-0.025
	DEV	0.139	0.166	0.149
NEURO	MEAN	-0.003	-0.016	-0.006
	DEV	0.141	0.162	0.145

It has been observed that in winter the mean values are improved between 50% and 90% depending on the zone and the climate but the standard deviations are similar. This means that the PMV mean values are closer to the zero value but its oscillations have the same amplitude. Fig 6 shows the instantaneous values of PMV index for a simulated day of zone 3 in climate 2. It can be seen that fuzzy and neuro-fuzzy controllers heats the air according to the humidity level to reach the zero value of PMV. The thermostatic controller as it has not this information obtains worse PMV values.

For the summer results we can say that in climate 2 the results obtained with thermostatic control are so good that neuro-fuzzy control does not improve them. In climates 1 and 3 the PMV mean values are improved between 50% and 90% and its standard deviations are improved between 40% and 60% in zones 1 and 3. Fig 7 shows the instantaneous values of the PMV index for a simulated day of zone 3 in climate 3.

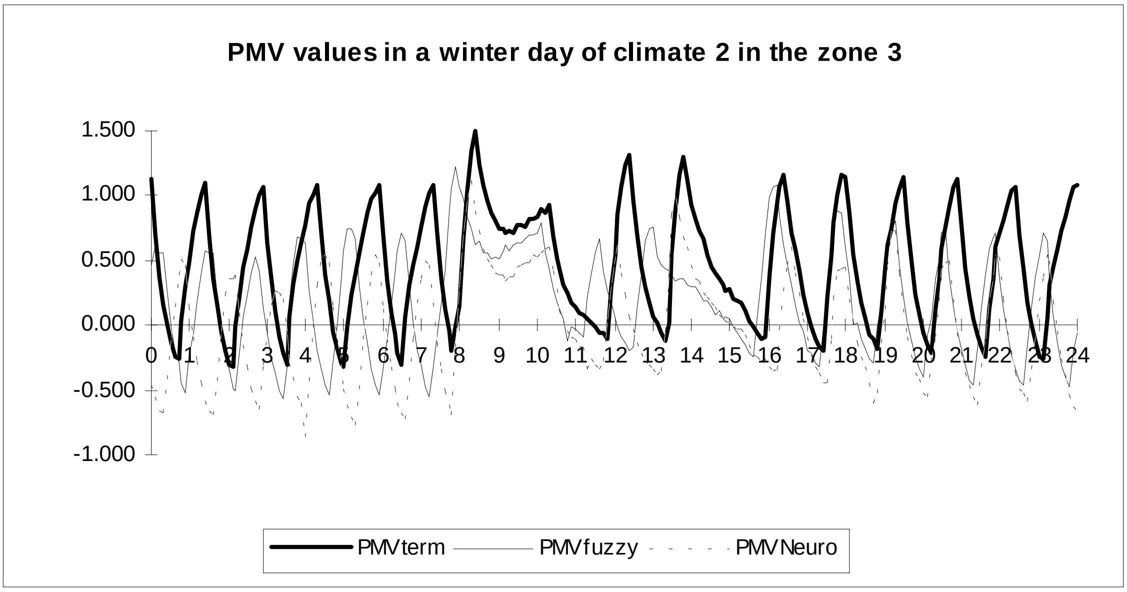

Fig 6. Instantaneous values of the PMV index for a simulated winter day of zone 3 in climate 2 with different controls: thermostatic, fuzzy and neuro-fuzzy.

The advantage of the fuzzy control is that it takes into account the humidity level of the zones. Although the system is not able to modify the humidity level as desired it adjusts the air flow level in a compromise solution for temperature and humidity to obtain the optimum PMV index mean value. If the system had the possibility to increase the humidity in the refrigeration mode and to change it (increase or decrease) in the heating mode the fuzzy control would obtain better results. But this is a limitation of the selected system.

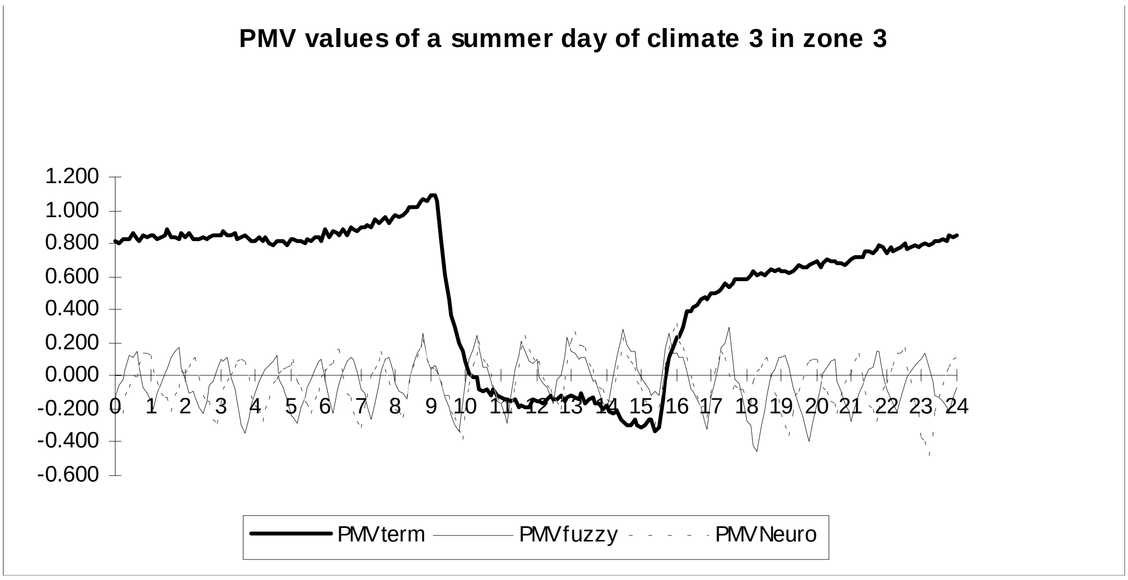

Fig 7. Instantaneous values of the PMV index for a simulated summer day of zone 3 in climate 3 with different controls: thermostatic, fuzzy and neuro-fuzzy.

Another limitation found is that although the output of the fuzzy control is an analogic signal the fan coils have three discrete air flow rates. Then, although the control is asking for a bit higher air flow rate the system does not increase it until it reaches the next one.

Also, it has been seen that the results obtained with thermostatic control in general are quite good and probably if the dead band used had been less than 2 degrees the results would improved (In the zone 1 and 3, in summer climate 2 are even better than the results obtained with the other controls).

The neural network adjusts the fuzzy control and the results obtained are better, nevertheless the improvements are not spectacular. It has been seen that it is able to learn the performance of the system. It should be remarked that although the neural network is quite simple (only 4 inputs with 5 neurones in the hidden layer and only one output) it is able to learn how to improve the control system. It can be predicted that if it had had more parameters to adapt probably the adjustment would have been better. In future work scale factors could be used as adaptative parameters to improve the proportional part of the control.

The possible parameters to be included could be the outside air flow rate and the air flow velocity. These could have been include as variables in PMV calculation and as parameters in the control. Introducing more variables the system complication will increase but the results could be improved.

Another analysis to be done would be the inclusion internal heat gains in the simulated zones but we predicted that if the HVAC system had enough capacity the results would be similar.

We have installed a real system but for the moment we have not got results.

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NOMENCLATURE

U	wall thermal conductance
n	time instant
$e(n)$	objective function error
$r(n)$	target objective function value
$y(n)$	objective function value in n instant
$\Delta e(n)$	change rate of error
$u(n)$	control output
$\Delta u(n)$	change rate of control output
K_P	proportional gain
K_D	differential gain
K_I	integral gain