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MODELLING AND SIMULATION OF FUZZY CONTROL IN AIR CONDITIONING SYSTEMS

Felipe Nascimento Silva
Paulo Marcos de Aguiar
Paulo Roberto Barbosa
Instituto Federal de Educação, Ciência e Tecnologia de São Paulo (IFSP) – *Campus* São Paulo
nsilva.felipe@gmail.com; aguiarpma@gmail.com; barbosapr@gmail.com

Abstract. *The temperature control of a closed environment presents a significant role in productivity, whether arising from human labor or the operation of electronic and/or mechanical devices. The ideal is an environment with thermal comfort and air quality that promotes intellectual and/or physical activities. Considering the electronic and/or mechanical devices, the temperature control seeks to provide ideal environments for the operation, reducing failure rates resulting from overheating. This work is inserted in the context of models that describe an air conditioning operation with constant air volume inflated to environment. The system configuration must access controllable parameters, such as the necessary air flow to maintain the room temperature constant, and temperature variations due to the thermal load variation or disorders that might occur in the environment. Through modeling parameters obtained in literature, this paper proposes the development of a fuzzy logic controller, considering its feature of easily in the treatment of several variables. The system configuration simulated was inspired in the air conditioning system installed at the ambulatory of Clinics Hospital of Faculty of Medicine - University of São Paulo. The proposed controller has multiple inputs and multiple outputs (MIMO), where the inputs are the temperature of the zone to be controlled, the outside temperature and also the temperature set by the user to the environment. The controller outputs are used to control the valves for hot water, cold water (for the system of coils) and adjust the air renewal. Preliminary results show the suitability of the proposed methodology for controlling the environment temperature, encouraging further studies. The main advantage of the proposed control technology is its versatility in environments where temperature conditions present many variations. Furthermore the controlled system demonstrated faster responses to disturbance and a better performance when compared with PID conventional technique clearing a path for practical applications*.

Keywords: *fuzzy control, air conditioning, modeling, temperature control*

1. INTRODUCTION

The environment temperature control has been emerged as necessary to safety work standards and equipments specification. Everyday, the costs and care of companies and condominium administrators with the heating, ventilation and air conditioning system (HVAC) of closed environments are increasing, aims the thermal comfort, air quality and a better conditions to machine's operation. Data presented by the Valor Econômico (2012), a Brazilian newspaper, shows that the number of HVAC units sold in 2011 it reached 3,2 million units while in 2009 registered the sale of 1,4 million devices.

The thermal comfort for a human can be described as the condition where the body loses the same quantity of heat produced by metabolism to the environment, without any thermoregulatory mechanism. Although this process is a natural way to control the body's temperature, represents an extra effort, causing falls in the work potential (Frota & Schiffer, 1988).

The thermal environment, according Brager & Dear (2001) is composed of the following parameters:

- Air temperature, which have an effect on the heat exchange by convection;
- Mean radiant temperature (walls and surfaces temperatures) which have an effect on the heat exchange by radiation;
- Relative air speed, which have an effect on the heat exchange in the convection;
- Vapor pressure of the environment or humidity, which have an effect on the heat exchange by respiration and by evaporation of water and sweat.

The Indoor Air Quality (IAQ) is an important index, because a lot of pollutants – among them, carbon monoxide, carbon dioxide, ammonia, sulfur oxide and nitrogen – are produced inside buildings by construction materials based on organics solvents, cleaning material, mold, mildew, also by human metabolism and man activities, such as cooking or washing and drying. These pollutants endanger the health and work performance of users (Carmo & Prado, 1999) and compromise the air quality of the environment.

It is known that inappropriate temperatures of an environment is detrimental to the operation of machines and equipments, exposing them to high temperatures unnecessarily. According to Felix (2006), extrinsic failures of systems or electronic components are usually related to mechanical loads, thermal or chemical.

From these goals, Xu *et al* (2007) proposed a model based on an optimized strategy for ventilation control based on a system of air-conditioning multipoint with variable air volume (VAV). The model objective was, by monitoring of the concentration of carbon dioxide (CO_2) in the air, to control of thermal comfort as well as avoiding sudden temperature changes with the change of the thermal load, determined by the number of occupants in a room. The authors succeeded in the experimental part, but the authors assert that the use of an algorithm or fuzzy neural algorithm can optimize the results, as the model depends on setting parameters experimentally obtained and inserted in the plant by hand.

Yang *et al* (2011) evaluated four strategies for the control of air-conditioning in buildings with VAV. The authors, in all strategies studied, used a linear control in inlet and outlet air valves, obtained by linear sensing (such as CO_2 and pressure) and reached the conclusion that each of the four strategies presented improvements in a different aspect, justified from which variable environment monitors, was executed the control, which had a set-point. The difficulty was to get the off-set of all variables with a single model, without to affect the other variables.

Ginestet *et al* (2010), a year earlier proposed a simpler model for VAV control "adjustable", analyzing the impact on energy consumption and air quality. The idea was to use a MIMO control – Multiple Input Multiple Output – that relates easily multiple input variables and output simultaneously. The main difficulty was to try relate the flow rate of air to air quality, where there a linearization process that required the adjustment of many control variables. Successfully, the authors observed that the control method monovariable from a Proportional Integral controller – PI – was satisfactory but did not have a great capacity for adaptation and adjustment, that would be necessary if the system suffers some change. The multivariable PI controller presented a result within the standard expected by the governing rules of comfort and air quality, and easily adaptation to changes on the system, but significantly increase of energy. The authors suggested further studies and research about the subject, with use of computer simulation and greater depth in other important items in the control systems.

The Fuzzy Logic came to assist in developing techniques to do the control of HVAC systems (Heating, Ventilation and Air-Conditioning) that provides thermal comfort and air quality with Rajagopalan *et al* (2008), which published an experimental analysis an air conditioning system controlled by fuzzy logic. The authors proposed an HVAC system where fuzzy logic is applied to the control of refrigerant through the system, replacing the thermostatic expansion valves. The system was tested with ventilation constant environment, with controlled ventilation by demand and the demand controlled ventilation with the economic cycle. According to the authors in their conclusions, the analysis results with the proposed control systems proved promising, with high rate of thermal comfort, air quality and energy saving, competitive enough compared to current systems of air-conditioning, leaving although many studies and applications in Fuzzy Logic area.

Given the high number of variables to be observed in an HVAC control system this paper proposes the use of Fuzzy Logic to build a controller that will have its performance simulated on a hybrid model proposed by Villani (2000) in their study of ambulatory of Clinics Hospital of Faculty of Medicine – University of São Paulo. The expectation is that the simulations confirm the reliability of fuzzy logic systems compared to traditional methods of control.

Fuzzy Logic can briefly be understood as an extension of boolean logic that allows intermediate values, it comprising mainly statistical concepts and in the use of this logic inference is used in intelligent systems to generate controllers capable of evaluating variables can not be quantified, as the thermal sensation and control through its output quantifiable variables, such as the actuation of a valve or an alarm level (Yenikomochian, 2011).

Rajagopalan *et al* (2008) conducted an experimental analysis of an HVAC system with a fuzzy logic controller and their conclusions they observed the capacity development of the application of Fuzzy Logic as the results indicated that the Fuzzy logic controlled systems reached satisfactory ranks of response, keeping the temperature and humidity within acceptable levels and beyond, saving more energy. However, the conditions of testing and the results do not show the behavior of the proposed system in situations where the variations of the parameters of the controller can be very dynamic, such as for example the continuous change of the thermal load within an environment represented by entry and exit of many people.

2. METHODOLOGY

The model proposed by Villani (2000) is the result of a thorough analysis of the HVAC system in order to treat it as a system of continuous variables (SVC) and system of discrete event (SED) simultaneously. Explaining in synthesis, a SVC system's main characteristic is the continuity in time, where physical phenomena are prime example, modeled and controlled through differential equations. In SED system, there is a system in which certain dynamics events do not directly linked to the time, making hard the modeling from differential equations. In this context, an HVAC system can be a hybrid between these two systems, since many of its operating characteristics are based and are altered by time, and many other changes are discrete bases such as, for example, a light lamp, opening and closing of a door or window, which alter the properties of the thermal load of the system instantly, without relying on a sliding scale based on time. For this hybrid system modeling, the author used Petri nets and obtained satisfactory results in their simulations.

Figure 1 shows the steps taken and those to be made in this research and simulation of this work, according to the methodology proposed by Gil (2002):

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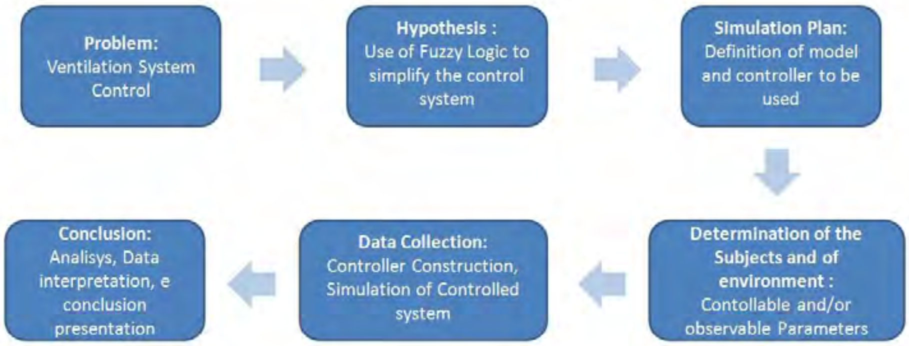

Figure 1. Methodology step detail

2.1 Work model definition

The model adopted for this research work is divided into two parts: modeling of air conditioning system and environment modeling. The air conditioning system is shown in Fig. 2:

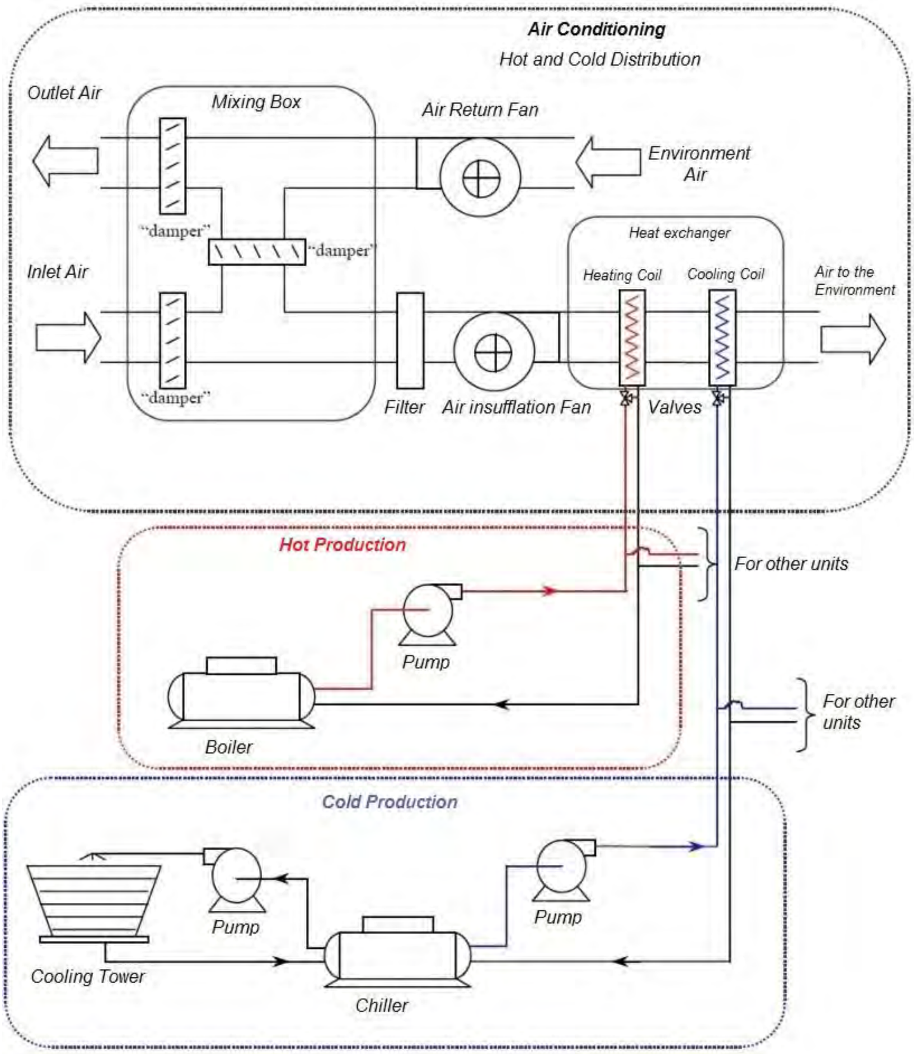

Figure 2. Simplified Scheme of an Air Conditioning System (Villani, 2000).

The air conditioning system basically consists of three main systems with distinct functions, the first being the hot production, the second is cold production and the third is responsible for distribution of cold, hot or both through the air conditioning (Carrier, 1950; McQuiston & Parker, 1994; Stocker, 1985).

For the cold production, the chiller cools a fluid, usually a liquid or gas coolant, which is pumped to the heat exchanger where it receives heat from the air and cools it, then generating cold air to the environment.

The hot production is made by warmer, called boiler, heating a fluid – usually water – which is then pumped to the heat exchanger for heating the air to the environment.

In the air conditioning system, there is a mixture of air that is drawn from the environment, through fans, and the air from the outside atmosphere. This process occurs in the mixing box and after this step the air conditioning flows to the conditioning, where it is filtered, heated or cooled, and finally returned to the environment air.

The chilled water supplied to the system has a temperature of 7 ºC and the hot water reaches 75 ºC. Table 1 shows some requirements for different hospital temperature environments, defined by Brazilian Standards.

Table 1. Basic requeriments for some hospital environments (Normas, 1985).

Room	Tmin (°C)	Tmax (°C)	% Humidity	N.Changes
Surgical Center	19	24	45-60	25
Offices	20	26	40-60	6
Laboratories	20	26	40-60	6
Circulation Areas	20	26	40-60	4

2.2 Assembly, parameters identification and simulation of the model and controller

For this study, the model of air condition system present in Villani (2000) was used as the basis for the assembly plant in MATLAB©-SIMULINK© simulation. Only a few parameters of the air conditioning system will be observed and controlled, while for simulation purposes, the values of flow and systems of hot and cooling production will be constant, due to the purpose is not to intervene in the heating and cooling of water.

Figure 3 identifies the points where the fuzzy controller will act in the control of air exchange (exchange of environment air by the air from the outside) and control water flow to the coils:

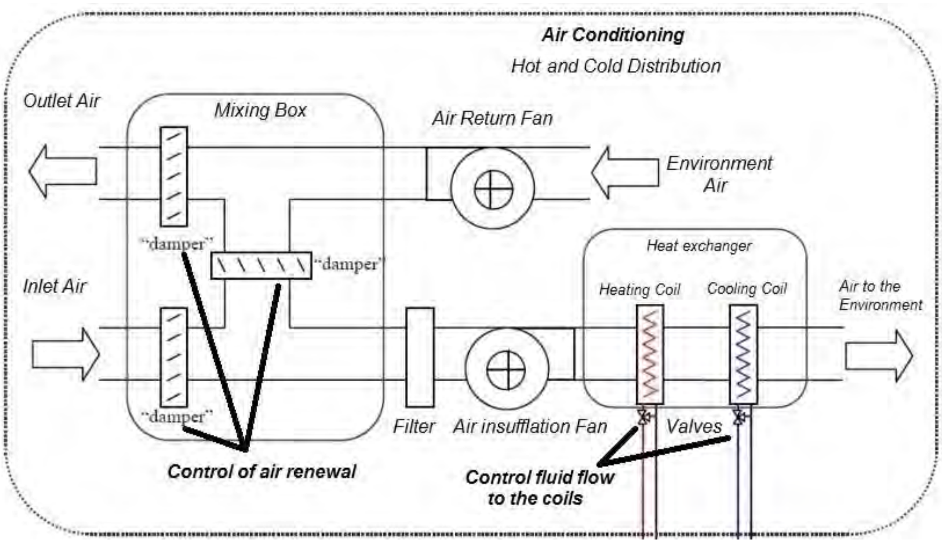

Figure 3. Controlled points of the system.

The controller inputs are: the environment temperature and the outside environment temperature.

2.2.1 Plant system and simulation of the system without controller

From the differential equations given in Villani (2000), were assembled various sub-systems that comprise the air conditioning system, according to Figure 4:

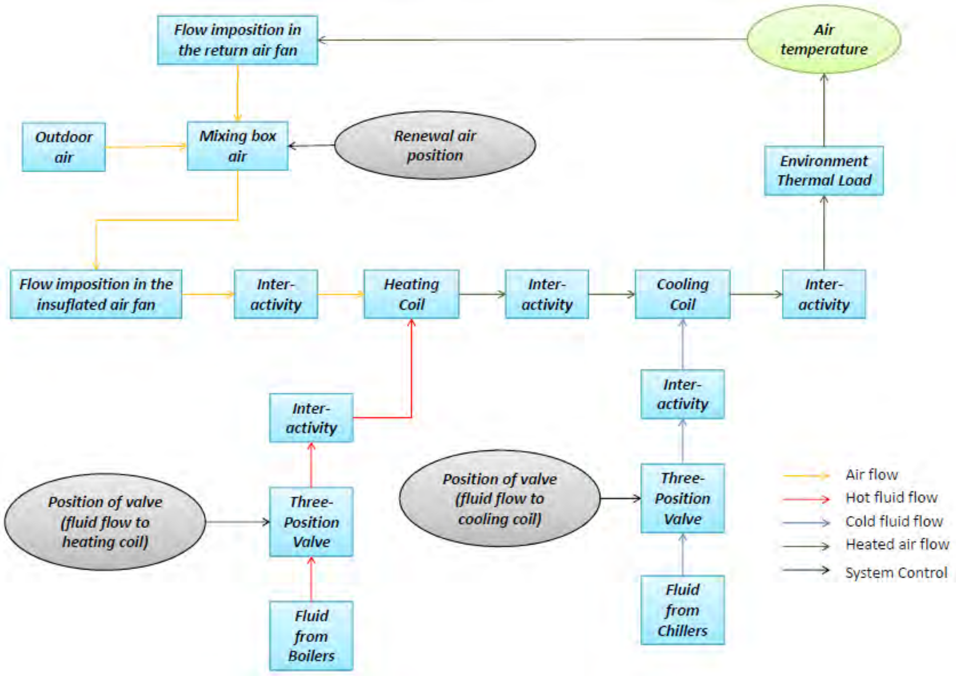

Figure 4. Air conditioning system, modeled in SIMULINK©, represented by flowchart.

For the system described above, the constants for the simulation, such as density and specific heat of water and air were acquired through bibliographic study for solving the heat transfer equations. Other constants operations, such as maximum flow of air and fluid flow to the coils were obtained from datasheet equipments (SALSBURY, 1996; ASHRAE, 2009; VILLANI, 2000; HOLMES, 1982; YORK, 2013). The table 2, above, shows some constants used for this study:

Table 2. Some constants used for model simulation.

Constant	Description	Value	Unit (SI)
Fans	Fan Air Flow	0,7	m³/s
Temperature Conditions	Initial Temperature	0	°C
	External Temperature	25	°C
	Fluid from Chillers	7	°C
	Fluid from Boilers	75	°C
Valves Operation	Valve Positions	0,01	-
	Exponencial Constant	2,75	-
	Valve leak Constant	0	-
	Maximum fluid flow to coils	0,00068	m³/s
Heat Exchanger Coils	Air Density	1,2928	kg/m³
	Water Density	1.000	kg/m³
	Air Constant	5.000	$W.kg^{-0,8}.s^{0,8}$
	Water Constant	10.000	$W.kg^{-0,8}.s^{0,8}$
	Water Specific Heat	4.144,14	J/(kg.k)
	Air Specific Heat	1.004,64	J/(kg.k)
Environment Parameters	Air Volume of Environment	500	m³
	Total Thermal Load	2000	W
	Air Density	1,2928	kg/m³
	Air Specific Heat	1.004,64	J/(kg.k)
Time	Delay in addition of thermal load	180	s
	Delay response of Heat Exchanger	300	s

The model is not intended for accuracy of the temperature and time, but the approximate description of system behavior. The scope of this study did not require a dynamic model that describes the air conditioning system with a high level of accuracy, but only about a model that describes the heat exchange between the environment and the air from air conditioning system.

At the simulations, the system inputs have been set manually controllable without dynamic fit with a renewal rate of 40%, fluid flow valves for the coils adjusted to allow the flow of 50% of the total, which for this plant is 0.00068 m^3/s, initial temperature of 0 ºC, external temperature equal to 25 ºC, chilled water supplied to the coil 7 ºC and supplied hot water at 75 ºC.

The proposed model was simulated and presented the behavior described in Figure 5, for the environment temperature, considering the purposes of this research.

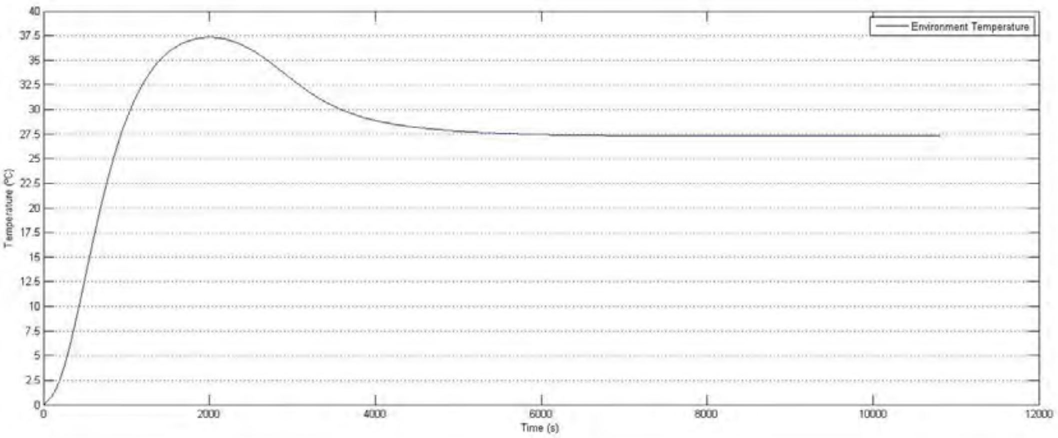

Figure 5. System simulation without control result.

2.2.2 Fuzzy Controller

As seen in the result of Figure 5, the model had a peak value before reaching the temperature stability, near the thermal equilibrium value. The Fuzzy controller, initially, must to avoid it, controlling the system to obtain the desired temperature, without high and low peaks before to reach stability, in a preset value.

For these conditions, using the Fuzzy toolbox presents in the MATLAB©, the following fuzzy controller is designed to start the simulations with the controlled plant, as shown in Figure 6:

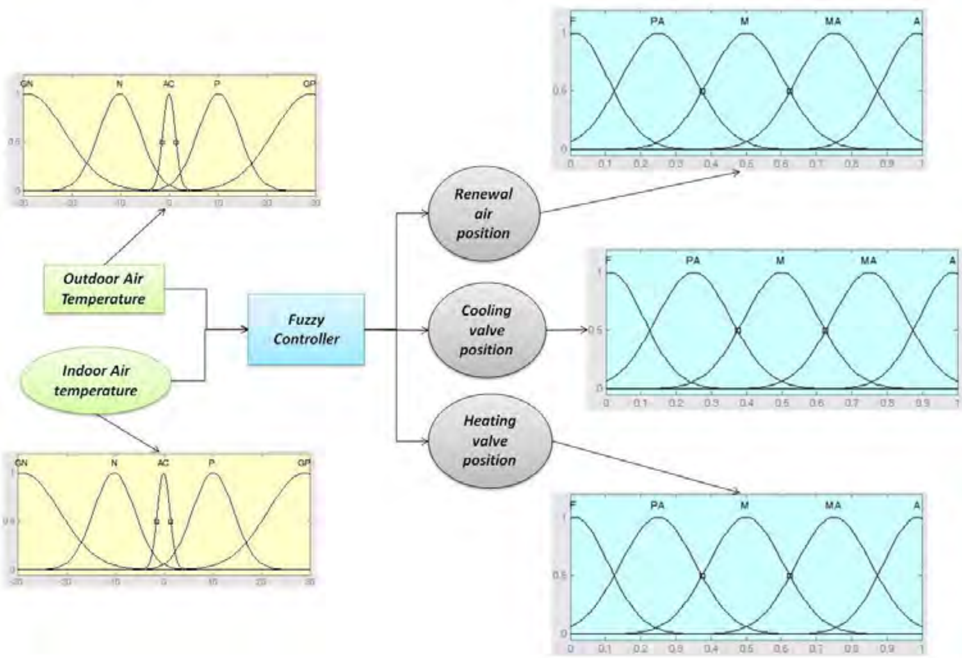

Figure 6. Fuzzy Controller and the membership functions.

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The membership functions were chosen after several simulations, where each round of simulation the functions were redefined (in type and quantity) to get better results, as less oscillation and faster response. The input variable (observable points of the system) of this controller is “Offset”, difference between indoor air and offset temperatures; and “Offsetext”, difference between outdoor air and offset temperature. The output variables (Controlled points of the system) are the position of control valves of fluid flow to the coils and renewal valve of air mixing box, all of them vary between zero to one.

The details of this membership function are:

- Input variables: Offset and Offsetext
    - GN: High Negative difference (between -30 ºC to -10 ºC);
    - N: Negative difference (between -20 ºC to 0 ºC);
    - AC: ACceptable difference (between -5 ºC to 5 ºC);
    - P: Positive difference (between 0 ºC to 20 ºC);
    - GP: High Positive difference (between 10 ºC to 30 ºC);
- Output variables: Cooling, Heating and Renewal valves
    - F: Closed (for positions between 0 to 0.3);
    - PA: Few Closed (for positions between 0 to 0.5);
    - M: Half closed (for positions between 0.25 to 0.75);
    - MA: Very Open (for positions between 0.5 to 1.0);
    - A: Open (for positions between 0.7 to 1.0);

The memberships functions chosen to represent the level of relevance of the input variables are to be sigmoidal according to Mendel (1995) and Ross (2004), generally used based on choice and experience of an expert in the field, besides having the advantage to model a system with smooth transition between their values. During the development of this research, the tests of the model without control shows that smalls variations of heating valve causes an increase in ambient temperature quickly, while variations in the cooling valve have an slow response time of the system. The examples of some inference rules were estimated as shown in Figure 7:

1. If (Offset is GN) then (Valvulaquente is F)(Valvulafria is A) (1)
4. If (Offset is AC) then (Valvulaquente is F)(Valvulafria is F) (1)
7. If (Offset is GP) then (Valvulaquente is A)(Valvulafria is F) (1)
26. If (Offsetext is GN) and (Offset is AC) then (Renovação is F) (1)
27. If (Offsetext is MN) and (Offset is AC) then (Renovação is F) (1)
28. If (Offsetext is MP) and (Offset is AC) then (Renovação is F) (1)
29. If (Offsetext is GP) and (Offset is AC) then (Renovação is F) (1)

Figure 7. Fuzzy Controller Inference rules.

The rule number 1, demonstrates that for environment temperatures between 10 °C to 30 °C above the desired temperature, the valve of heating coil must be totally closed and the valve of cooling coil fully open, so that the environment can be cooling more quickly.

The rule number 7 shows that for environment temperatures between 10 °C to 30 °C below the desired temperature, should occur otherwise rule 1, so that the environment air heats up quickly.

The rules number 4, 26, 27, 28 and 29 indicates that the controller should close the coils valves and the air renewal valve (if the outdoor temperature is not close to the desired temperature environment) to avoid heating or cooling air environment, because the temperature is at an acceptable level, between -5 °C to 5 °C.

2.2.3 Plant system and simulation of the system with Fuzzy controller:

The system with Fuzzy controller, mounted according to Figure 8, had as initial conditions and the same constant specified in clause 2.2.1 and 23 ºC as desired temperature by the user and result in the graph of Figure 9:

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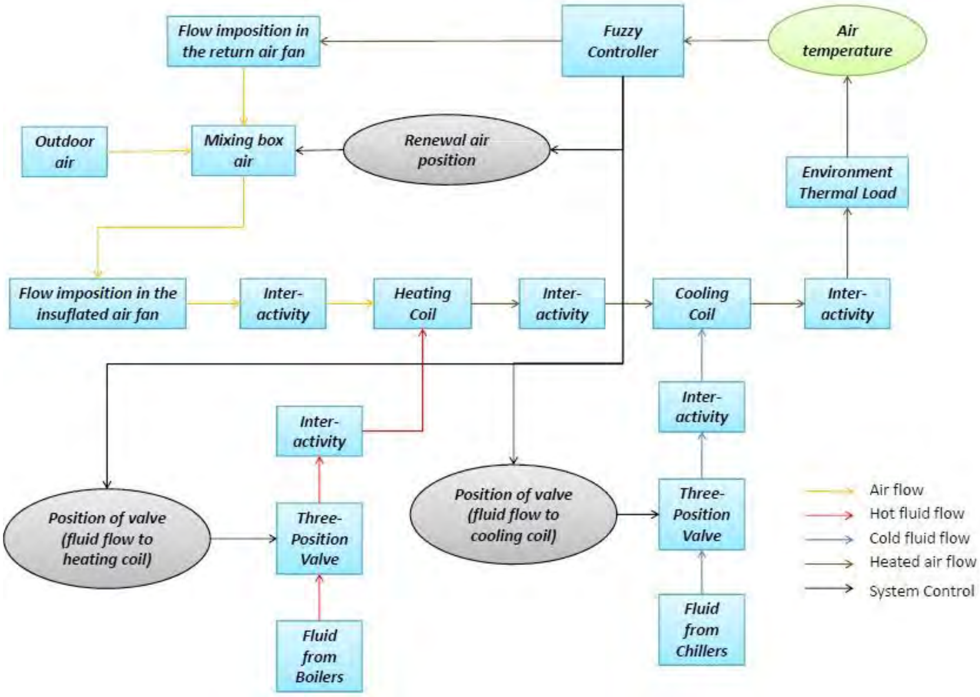

Figure 8. System with Fuzzy Controller flowchart.

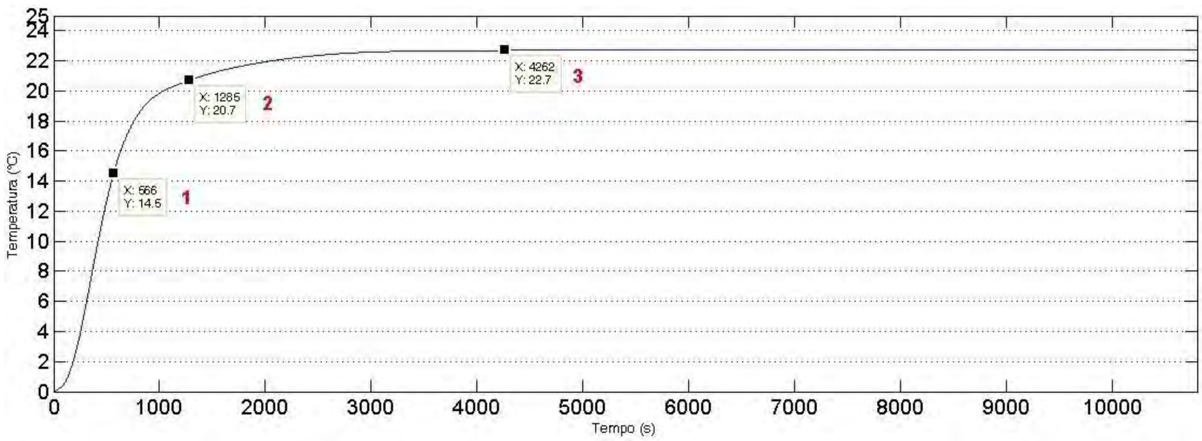

Figure 9. System simulation with Fuzzy Control result.

Given the result of Figure 9, observes a value of 63% (time response) for desired temperature reached primarily after 10 minutes (600 seconds) the start of simulation, following by 90% of value after 22 minutes and established in 22,7 ºC after 1 hour and 11 minutes. The regime value has an error of 1.30 % in relation to the desired temperature (23 ºC). Although this, Oliveira *et al* (2010) argue that for environments subject to intellectual activities and that demanding constant attention, citing for example, control rooms, living rooms or development project analysis, among others, are recommend effective temperatures between 20 ºC to 23 ºC, a variation of 3 ºC.

The proposed controller showed less variation (about 0.3 ºC) and, despite being set to the maximum recommended to a comfortable environment, not extrapolated to 23 ºC during the simulation, proving its effectiveness without variations in thermal load.

3. COMPARISON WITH PID CONTROLLED SYSTEM RESULTS

The choice to perform the fuzzy controller comparision with a classic controller action Proportional, Integral, Derivative (PID), was made by the fact of the latter being one of the most widely used controllers in the control area (FACCIN, 2004).

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It was inserted into the plant three PID controllers that perform the valve control of heating, cooling and renewal. As the scope of this work is not to describe how to build a PID controller, we used the auto-tuning PID parameters of MATLAB-Simulink ®. The feature automatically calculates the parameters P, I and D according to the model in order to present the best possible fit. The settings of the PID parameters of the controllers are shown in Table 3:

Table 3. PID parameters.

Renewal			**Heating**			**Cooling**		
P	**I**	**D**	**P**	**I**	**D**	**P**	**I**	**D**
-2,36111	-0,00198	-669,584	0,02117	0,000083	0,5983	-0,08329	-0,00033	-2,35415

The comparison between PID and fuzzy controllers are shown in Figure 10:

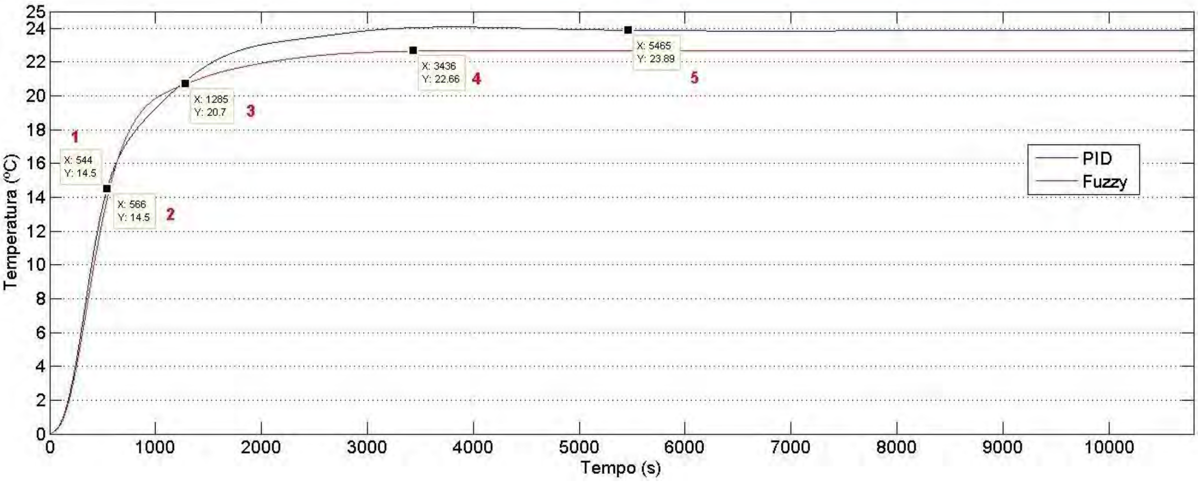

Figure 10. PID and Fuzzy comparison.

As shown in Figure 10 the fuzzy controller presented a closed response of the PID controller, whereas the PID controller had a response time 22 seconds faster than the fuzzy controller (point 1 – PID, point 2 - fuzzy), the time where the simulations have reached 90% of the system set point were equal (point 3) and the fuzzy controller achieved a lower permanent error, 1.47% versus 3.87% of the PID controller to the temperature set point (23 ºC). For this simulation, it can be considered that the fuzzy controller showed better results than PID, considering the permanent error of both controllers.

4. CONCLUSIONS AND FUTURE WORK

The results indicated that the model attend the purposes of the research, by presenting unstable results (temperature values above the expected value) at the beginning of the simulation and after reaching thermal equilibrium without any kind of control, as expected.

After implementation of the fuzzy controller, the results met the expectations, because with a simple set of rules there was an improvement in the response of the system, which did not show temperatures above stipulated by the user and hit accurately the value specified. In comparison with classical PID controller, the results obtained indicates the viability of fuzzy controller use.

For the next steps, the controller should be tested with the variation of thermal load on the environment and changing of others model parameters.

The next objective of this work aimed at proving the effectiveness of the control systems that suffer from disturbances such as entry or exit of people in the environment, start-up of equipment, also by situations where the initial temperature of environment is greater than off-set desired, to reinforce the idea of robustness of fuzzy controllers.

It is believed that this work can open a new approach to air conditioning controllers, to conclude that is possible to control an air conditioning system through changes of few system controllable parameters. A recommended future work is the use of the fuzzy controller developed in this research with computer software or neural network to an automatic adjust of the membership functions or inference rules, to adapt the controller for different environments.

The final objective of this research seeks to validate a simpler way to control and observe an air conditioning system, saving effort and often time in creating software and hardware, capable of controlling a system, which despite having vital importance nowadays, does not require a control almost instantaneous, because the temperature variation in the environment is not as fast.

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