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FUZZY HYBRID AIR-CONDITIONING FOR THERMAL COMFORT AND ENERGY EFFICIENCY

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Abstract. *This paper describes the implementation of a Hybrid Air-Conditioning System which offers better thermal comfort with air renewal and especially with lower electric energy consumption. The system has been implemented in a meeting room in a Brazilian University. The system's operating modes and a short analysis of the results are presented. ON-OFF and PID SISO controllers were used to show, mainly, the energy potential of the concept. Latter a Fuzzy control have been used in spite of the non-linear MIMO interactions in the process. As actuators we have: fan, damper, water pump and compressor. We measure temperature and humidity in various points of the process. The achieved outcome was better thermal comfort as well as relevant electricity cost reduction (as much as 67% by dry weather). This environmentally clean and energy efficient system can be considered as an alternative to the mechanical vapor compression systems.*

Keywords: *fuzzy control, evaporative cooling, hybrid cooling, air-conditioning, automation*

1. INTRODUCTION

Electric energy consumption is growing continually by the constant addition of new technological devices and equipment. Electric energy consumption is directly connected to the efficient operation of the electric facilities, especially air-conditioning systems, Costelloe and Finn, 2007

Air-conditioning systems usually employ a compression system, using cooling gas in refrigerating circuits, which leads to higher energy consumption due to the power demand of the compressor. Recently this has been changed by evaporative cooling, especially useful in dry climate regions. Evaporative cooling consists in reducing air temperature by increasing the relative humidity, Heidarinejad, 2008.

Atmospheric air is a mixture of dry air and steam. In a given temperature and pressure condition, this mixture has a capacity to hold a maximum of steam (saturated air = 100% of RH-Relative Humidity). The air is usually unsaturated (RH<100%), and, therefore, able to absorb more humidity. The dryer the air (lower RH), the more vapor is feasible to be absorbed. However, it is necessary that the employed water changes from liquid to vapor phase to produce such absorption. This phase change demands an amount of energy which is withdrawn from the surroundings, here meaning the air, cooling it.

The air conditioning through evaporative cooling is an environment-friendly and energy-efficient method, which uses water as a working fluid and may represent a cheaper alternative to the conventional air-conditioning systems in many cases.

In section 2, we present principles, with a description of related researches developed in this area. Concepts dealing with evaporative cooling are described. Implementation with instrumentation are seen in Sector 3. Following section deals with control strategies. Results obtained with the implementation of hybrid air-conditioning system are depicted in section 4. Finally, section 6 presents the conclusions.

2. EVAPORATIVE COOLING

Evaporative cooling is a natural process consisting in reduction of air temperature and increasing its relative humidity through a simultaneous mechanism of heat and mass transfer between air and water. Pimenta and Castro (2004) present a theoretical approach to the basic working principles of a direct evaporative cooling system through contact control panels applied for thermal comfort, in addition to a mathematic model for heat and mass transfer in evaporative cooling.

The decision to use an evaporative cooling system depends on a detailed evaluation of the saved energy and the invested capital. Costelloe and Finn, 2003, show that a good evaluation requires detailed information about disposable cooling water generated through evaporation on every location. Detailed quantification of evaporative cooling taking south European cities is shown. These researcher also present research about experimental thermal effectiveness on indirect evaporative cooling testing equipment, designed for north Europe.

The use of different cooling systems in areas with varying climates is presented by Heidarinejad et al. (2008). The implementation of Direct Evaporative Cooling systems (DEC), Indirect Evaporative Cooling systems (IEC), and both

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cooling methods combined in Iranian cities are presented. Direct evaporative cooling system has been considered a fair alternative taking in account climate conditions and natural water resources. In Brazil, a study performed by Oliveira et al. (2009) shows that solutions differ according to regional climate features, being evaporative cooling the one with better results in semi-arid regions.

A cooling cycle is a closed system with flowing coolant keeping its evaporation continuously where cooling is requested, and then resuming to its original properties. The cooling cycle is basically made of a compressor, a condenser, an expansion valve, and evaporator.

Evaporative cooling is called when a means or object/item/article releases heat to vaporize water. Any article's evaporation is an endothermic process, i. e. it requires heat to take place. This heat transfer can be forced (when heat is provided) or induced (when conditions are created for the article to withdraw heat from the surroundings). A well known example of evaporative cooling is the Cooling Tower, where part of the water is induced to vaporize withdrawing heat from the remaining water, which cools because it delivers this heat.

The same principle is used in air evaporative cooling: the air delivers energy (heat) to evaporate water, resulting in a colder draft at the cooler output. Although not always perceptible, the evaporative cooling effects can be frequently noticeable, like when leaving a swimming pool (you leave the colder water and get in touch with the warmer air) and feeling the chill; when washing and shaking hands you feel them cooling up; when on a hot day there is a summer rain and you observe an almost immediate drop of temperature.

The evaporative air cooler has a ventilator drawing external air through a special evaporative panel, on which water circulates continually due a small pump. The evaporated water is replaced using a buoy, keeping a constant level in the reservoir. Usually the air cooler evaporative panel is framed with levels of high quality wavy porous kraft paper, impregnated with a resin which delivers rigidity and durability. The glued layers form blocks with a very large surface and little resistance to air flow. Figure 1 shows an evaporative cooling system scheme.

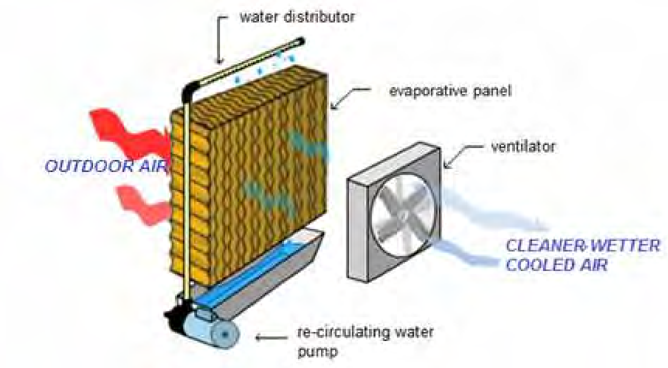

Figure 1. Direct evaporative cooling operating scheme

The result is an equipment of large efficiency, simple, which produces clean air of great quality, non-saturated, and cooled by up to 12º C under the outdoor air temperature, Lee et al., 2008, Heidarinejad et al., 2008.

The result is an equipment of large efficiency, compact, simple, durable, with little need of maintenance, which produces clean air of great quality, non-saturated, and cooled by up to 12º C under the outdoor air temperature.

Each design parameter of the evaporative cooling system has to be optimized. Ahmad et al, 2013, for example, have investigated the performance of a 5-ton capacity indirect evaporative cooler under controlled environmental conditions (43.9 ◦C dry-bulb temperature and 19.9% relative humidity) but for different air flow rates (631 to 2388 m3/h). The experimental results showed that the intake air energy efficiency ratio of the cooler varied from 7.1 to 55.1 depending on test conditions and air flow rate. At full fan speed, an average of 58.7% of the total water consumed by indirect evaporative cooler was evaporated. The results indicated that intake air energy efficiency ratio was directly proportional to the wet-bulb depression. The study emphasizes that indirect evaporative cooling is suitable for hot and dry climatic conditions. With a hybrid cooling system even more design parameters have to be considered in order to obtain optimal energy saving with comfort.

2.1 Recent works in hybrid evaporative cooling

In Heidarinejad et al, 2010, a ground-assisted hybrid evaporative cooling system in Tehran is discussed. A Ground Coupled Circuit (GCC) provides the necessary pre-cooling effects, enabling a Direct Evaporative Cooler (DEC) that cools the air even below its wet-bulb temperature. Simulation results revealed that the combination of GCC and DEC system could provide comfort condition whereas DEC alone did not. Based on the simulation results the cooling effectiveness of a hybrid system is more than 100%. This hybrid system can decrease the air temperature below the ambient wet-bulb temperature.

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Khalajzadeh et al. 2012, analyze an integrated thermal system using ground heat exchanger and indirect evaporative cooler in the summer conditions of Tehran,Iran. A ground-coupled circuit precools the entering air of an indirect evaporative cooler. This circuit includes four vertical ground heat exchangers which are arrayed in a series configuration. Simulation results reveal that the combination of the ground-coupled circuit and the indirect evaporative cooler can easily provide comfort conditions. Based on the results, the cooling effectiveness of this hybrid system is more than unity.

Hao et al. 2013, study the energy efficiency of an evaporative air-cooled chiller (EACC), composed of an evaporative air cooler and a conventional air-cooled chiller. A mathematical model is presented and a new index, increase of seasonal energy efficiency ratio (ISEER), was proposed to evaluate the energy saving potential of the evaporative air-cooled chiller. The energy saving potential of EACC was simulated by using the hourly weather data for four typical cities in China. Optimization results of the pad thickness in 31 main cities in China are presented. The maximum energy saving potential of EACC in China was found to be between 2.4% and 14.0% depending on the climatic condition. It is pointed out that it is necessary to determine optimal design parameters according to different climatic condition for maximum energy saving.

2.2 Evaporative system operation

Figure 2 presents a typical temperature reduction on a psychrometric chart using evaporative cooling. Displacement on the Wet-Bulb Temperature line from initial temperature T1 by 30ºC (RH by 30%) to T2 by 23.4ºC (RH by 60%) to be noticed on the red line.

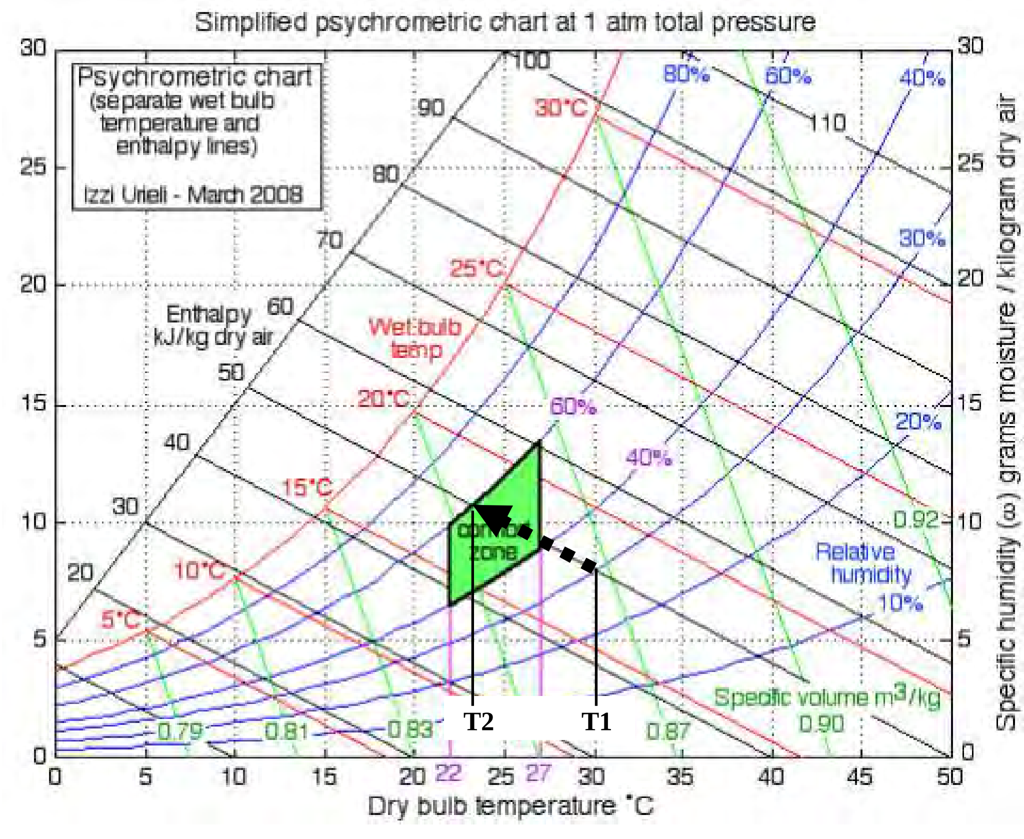

Figure 2. Temperature reduction using evaporative cooling (adapted).

3. HYBRID AIR-CONDITIONING SYSTEM

The Hybrid Air-Conditioning System has been developed and installed in the LARA meeting room with the purpose of better indoor air quality aiming energy efficiency, meaning that its operation has to provide better thermal comfort and consume less electric power compared to conventional systems.

The thermal load of the meeting room has been calculated as 6,090 kcal/h (7.08 kW). The following parameters for the hybrid system development and installation have been taken in account: One evaporative air-conditioner with approximately 1,059 m3/h flow was built; one split hi-wall of 18,000 BTU/h was used; the evaporative air-conditioner is the main device for cooling; if the air-conditioner can't reach the temperature, the split starts working, resulting in air

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return to the system to avoid loss of cold; the temperature in the room has to be 22,5 ºC, with 1ºC variation; ambient relative humidity has to be 60%, ± 5%. Figure 3 shows the developed hybrid air-conditioning system.

3.1 Design Specifications

The following specifications have been taken in account while designing the Hybrid Air-Conditioning System: assure adequate indoor air renewal in the conditioned environment, that is, a minimum of 27 m3/h/person (7.5 liters/s/person), thereby meeting the prescriptions of Norm 3523, August 28, 1998 - Brazilian Health Ministry; comply with the ABNT (Brazilian Association for Technical Standards) NBR (Brazilian Norm) 16401-2 (e.g, 22,5ºC to 25,5º ºC, rh 65% for Summer), Creder, 2000.

In the HYB operating mode we actuate on fan, water pump, compressor and damper. With the damper open (internal air circulation) we use the compressor in a conventional cooling mode. When the damper is closed external air is forced through the wet evaporative panel have – this is the evaporative operating mode.

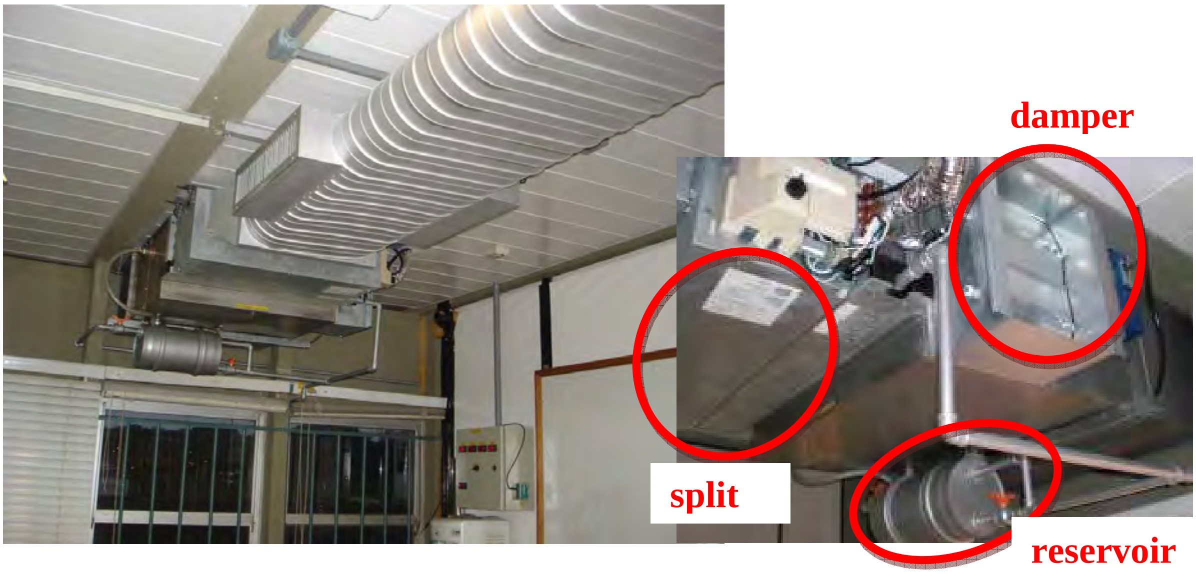

Figure 3. Hybrid air-conditioning system. Detail: split, damper and reservoir.

Figure 4 a schematic view of the implemented hybrid air-conditioning system. The sensors used in a ZieBee based wireless network are: SHT71 – temperature e humidity, DWYER 641 - anemometer, TY7321 – medium thermal radiation, WE300 – piranometer. In a former version wired sensors from Full Gauge have been used.

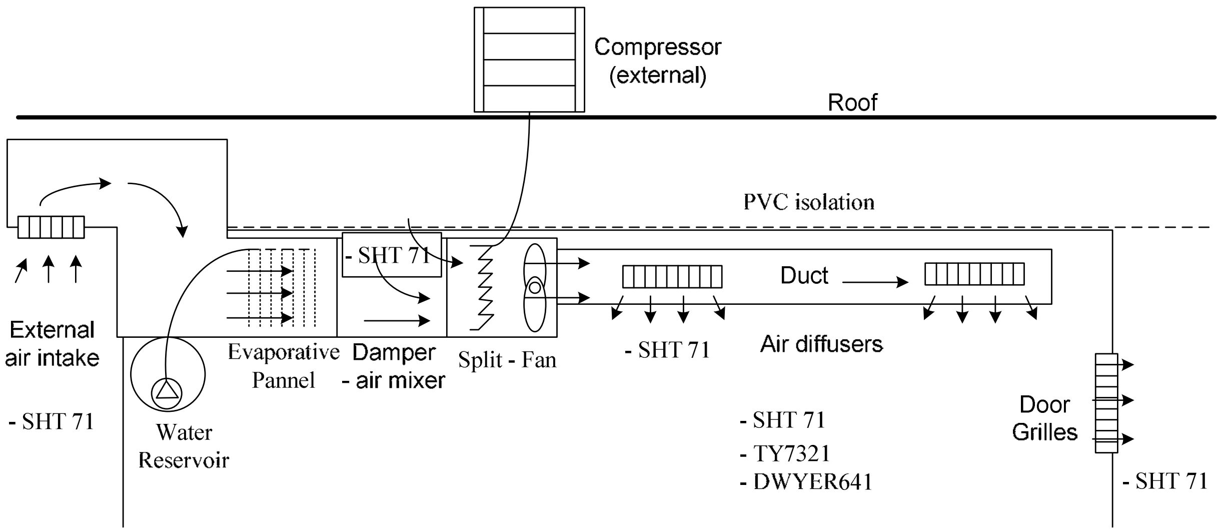

Figure 4. Scheme and sensors used in the hybrid air-conditioning system.

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3.2 Operating ranges

The following objectives have been taken in account while elaborating the Hybrid System Project: assure adequate indoor air renewal in the conditioned ambient, that is, a minimum of 27 m3/h/person (7.5 liters/s/person), thereby meeting the prescriptions of Ordinance 3523 from August 28, 1998 of the Brazilian Health Ministry; comply with the ABNT (Brazilian Association for Technical Standards) NBR (Brazilian Norm) 16401-2, which states the ambient parameters likely to produce acceptable thermal comfort for in at least 80% of the people, as shown in Table 1:

Table 1. Temperature and RH according to NBR 16401-2

Season	Operative Temperature	Relative Humidity
Summer	22,5 °C a 25,5 °C	65%
	23,0 °C a 26,0 °C	35%
Winter	21,0 °C a 23,5 °C	60%
	21,5 °C a 24,0 °C	30%

Other goals from the environment preservation point of view are as follows: to use less chilling gas, aiming reduction of Ozone Layer destructing substances, thus meeting the Montreal Protocol requirements; consume less electric energy within Environment Protection and Sustainable Development criteria, cooperating with the Montreal and Kyoto Protocols. Figure 6 features a the hybrid air-conditioning system installed in the meeting room of LAVSI.

The system was built by making adaptations on the split system, using its components, and designing a new electronic control project. The evaporative part was built using Cellulose from Munters manufacturer (Munters, 2008) and a water pump. A damper has been installed for partial air renewal and return when the system operates with the compressor turned on. It means that the damper opens only when the compressor is in operation, reducing energy consumption in this situation.

3.3 Operation modes

As seen in Table 2, the Hybrid System has five operating modes, which are:

Mode OFF: the whole system is turned off.
Mode VENT: the ventilation part is working.
Mode EVAP: the evaporative part is working.
Mode COOL: the cooling part is working.
Mode HYB: the whole system works automatically due to settled parameters.

Table 2 – Hybrid System Operating Modes

Operating Mode		State of the Equipment			
Symbol	**Description**	**Ventilator**	**Water pump**	**Compressor**	***Damper***
OFF	Turned off	Turned off	Turned off	Turned off	Turned off
VENT	Ventilation	Operating	Turned off	Turned off	Turned off
EVAP	Evaporative	Operating	Operating	Turned off	Turned off
COOL	Cooling	Operating	Turned off	Operating	Operating
HYB	Hybrid	Operating	Operating	Operating	Operating

The different operating modes here were used to characterize the cooling potential and energy demands in order to guide the hybrid operating scheme. Some experiments were run with PMV (Predicted Mean Vote) comfort norm, but later we focused on temperature and humidity, the most relevant parameters in our field of interest.

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4. CONTROL STRATEGIES

4.1 On-Off Control

Through the electronic temperature and humidity controller MT-531Ri plus, the interface CONV 32, and the Software Sitrad from Full Gauge Controls (FullGauge, 2007, FullGauge, 2008) it was possible to assess the controller data and store them in a computer. The On-Off controller (used in the first experiments) presents a 67.1% lower energy consumption in relation to the conventional split-compressor operation. For details, see Olmos Flores, 2009.

On-Off controllers are quite simple, but cannot guarantee that the middle vale of the set point is hold. The switching frequency is also dependent on the controlled process.

Olmos Flores, 2009, implemented separated On-Off controllers where temperature and humidity have independent hysteresis assigned. The water pump is activated at fixed time points. Despites it gave good energy savings no consistent joint optimization of the thermal and the humidity cycles were carried out.

4.2 PID Control

Using SHT71 as temperature and humidity sensor, ZigBit as wireless automation nodes, and MatLab/Simulink as computational platform, a PID controller was implemented, Such, 2009. It important to note that the air-conditioning apparatus, driven by 220 V, can only be turned on or off. The PID calculated actuator signal feeds a PWM modulation to drive the air conditioner. The PWM cycle was chosen of the order of 5 or more minutes so the respect the recovery time of the compressor.

4.3 Fuzzy Control

The many inputs of this distributed-parameter system and the complicated relations between temperature and humidity led to the implementation of fuzzy control in the hope that a air-conditioning expert could formulate rules that are effective for building air-conditioning.

A Fuzzy controller uses a rule (knowledge) basis, normally assigned by an expert, to combine them with new facts (entered by a user). A typical rule is like **<IF> premises <THEN> consequences**. The fuzzy inference machine produce new facts that act like the expert would be. The facts could be real world sensor or actuator signals, in which case fuzzyfication and defuzzification are in order. The fuzzy inference system is a non-linear mapping build on the basis of meaningful rules. A Fuzzy controller is thus a multi-dimensional non-linear controller where new rules, for specific operating points, can easily be added.

The fuzzy controller was implemented in Simulink using now ZigBee wireless sensors are shown in figure 3. PWM driven operation of the actuator (due to recovery time-off of the compressor) has been used. During the fuzzy control experiments the external medium temperature was 31.23°C and the measured energy consumption was 7.86KWh.

Our system has 5 inputs and 2 outputs, as seen in figure 5. For each signal e different partition of the domain space was used. For the temperature, finer slices around “0”, meaning, small error, was used. For the external temperature, we considered that values below 20ºC have no relevant influence on the fuzzy control strategy, as seen in figure 6. The non-linear character of the fuzzy controller can be seen in control surface shown in figure 7. An expert should be able to interpret the shape as was as suggest enhancement in the form of new/modified rules.

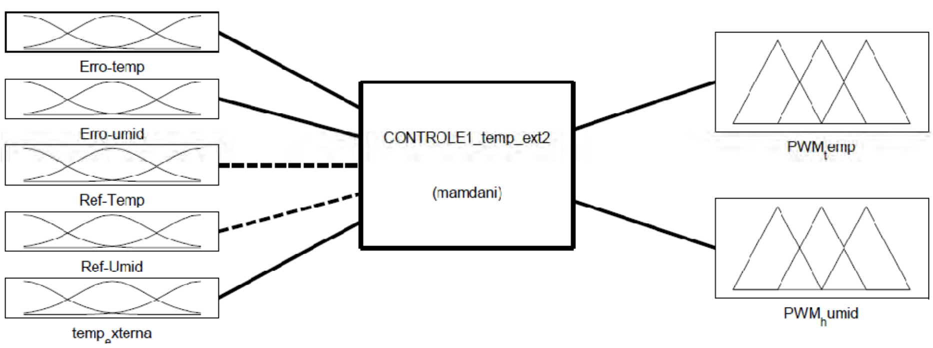

Figure 5. Fuzzy input and output signals used in the hybrid cooling sytem.

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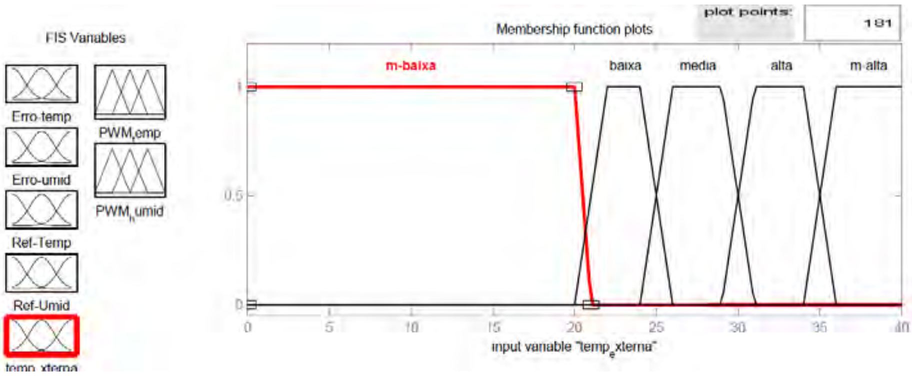

Figure 6. Fuzzy membership functions – illustrating example for the external temperature.

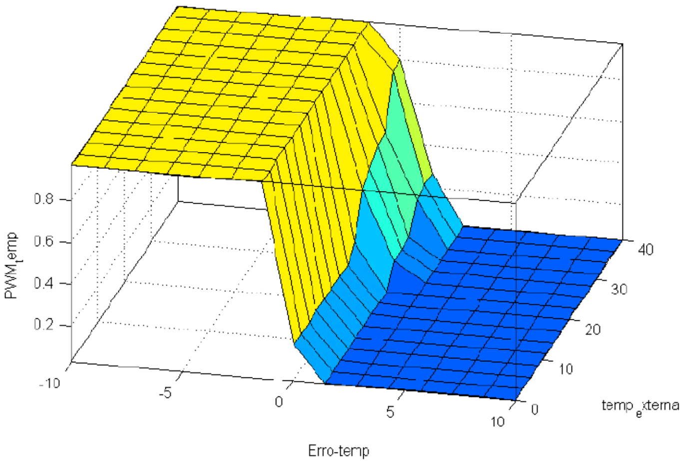

Figure 7. Example fuzzy control surface – temperature-PWM = f (temp-error, outside temperature).

The designed fuzzy rule basis, relating linguistic variables, are given by:

1. If (Erro-temp is ZERO) and (temp_externa is alta) then (PWM_temp is medio) (1)
2. If (Erro-temp is pouco_negativo) and (temp_externa is alta) then (PWM_temp is alto) (1)
3. If (Erro-temp is pouco_positivo) and (temp_externa is alta) then (PWM_temp is baixo) (1)
4. If (Erro-temp is positivo) then (PWM_temp is muito_baixo) (1)
5. If (Erro-temp is negativo) then (PWM_temp is muito_alto) (1)
6. If (Erro-umid is aceitavel) then (PWM_humid is muito_baixo) (1)
7. If (Erro-umid is positivo) then (PWM_humid is baixo) (1)
8. If (Erro-umid is muito_positivo) then (PWM_humid is medio) (1)
9. If (Erro-umid is negativo) then (PWM_humid is muito_baixo) (1)
10. If (Erro-umid is muito_negativo) then (PWM_humid is muito_baixo) (1)
11. If (Erro-temp is ZERO) and (temp_externa is baixa) then (PWM_temp is baixo) (1)
12. If (Erro-temp is pouco_negativo) and (temp_externa is baixa) then (PWM_temp is medio) (1)
13. If (Erro-temp is pouco_negativo) and (temp_externa is m-alta) then (PWM_temp is muito_alto) (1)
14. If (Erro-temp is pouco_negativo) and (temp_externa is media) then (PWM_temp is medio) (1)
15. If (Erro-temp is pouco_negativo) and (temp_externa is m-baixa) then (PWM_temp is baixo) (1)
16. If (Erro-temp is ZERO) and (temp_externa is m-baixa) then (PWM_temp is baixo) (1)
17. If (Erro-temp is ZERO) and (temp_externa is media) then (PWM_temp is medio) (1)
18. If (Erro-temp is ZERO) and (temp_externa is m-alta) then (PWM_temp is alto) (1)
19. If (Erro-temp is pouco_positivo) and (temp_externa is m-alta) then (PWM_temp is medio) (1)
20. If (Erro-temp is pouco_positivo) and (temp_externa is media) then (PWM_temp is baixo) (1)

4.4 Parameters

Figure 5 shows the LAVSI meeting room location. Taking in account that distribution, the thermal load of the meeting room has been calculated with a resulted of 6,090 kcal/h, which means 2.01 TR, 7.08 kW or 24,167 BTU/h.

The following parameters for the hybrid system development and installation have been taken in account: One evaporative air-conditioner with approximately 1,059 m3/h flow was built; one split hi-wall of 18,000 BTU/h was used; the evaporative air-conditioner is the main device for cooling; if the air-conditioner can't reach the temperature, the split stars working, resulting in air return to the system to avoid loss of cold; the temperature in the room has to be 22,5 ºC, with 1ºC variation; ambient relative humidity has to be of 60%, with 5% variation.

5. RESULTS

The Hybrid Air-Conditioning System designed and installed in the LAVSI meeting room enabled to perform different operating tests and data assessment. Therefore, the system was tested in five operating modes during a 24 hours time. Temperature and humidity graphics for the HYB (Hybrid) operating mode, which is one of the paper's case study, are presented hereafter, figure 8.

In this operating mode the ventilator, the water pump, and the compressor remain in activated due to the system's Set-points adjustments. In Table 3 the control parameters in HYB mode are displayed.

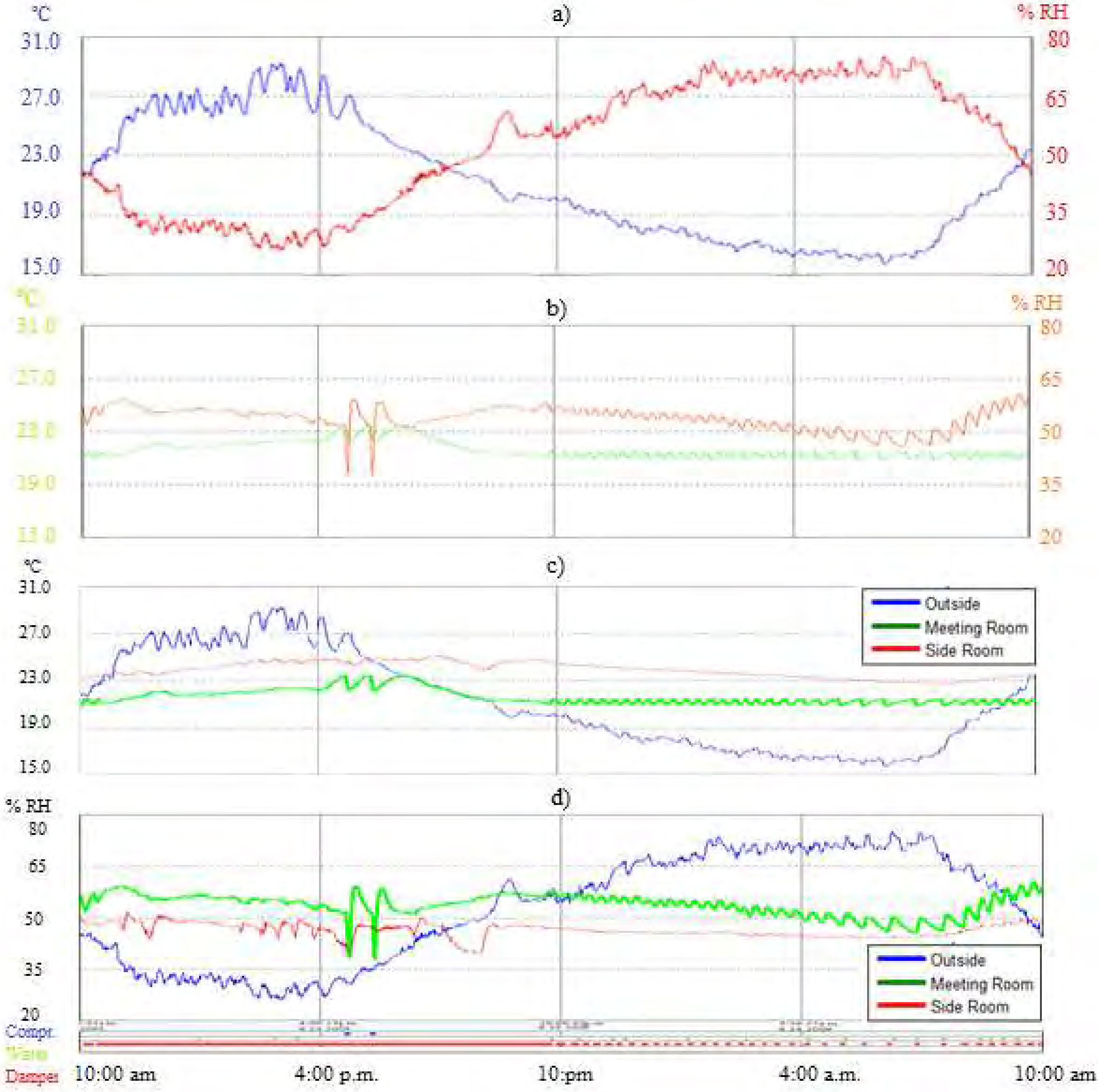

Figure 8 – On-Off hybrid cooling experiment of the LARA meetining room (HYB). a – outdoor temperature and humidity, b – meeting room temperature and humidicy, c – relevant temperatures, d) relevant humidities.

Table 3. HYB mode control parameters

Action	*Set-point 1*	*Set-point 2*	*Set-point 3*
	Compressor	**Water pump**	**Ventilator**
On	23,5 ºC	60 %	21,5 ºC
Off	22,5 ºC	65 %	21,0 ºC

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Through the electronic temperature and humidity controller MT-531Ri plus, the interface CONV 32, and the Software Sitrad from Full Gauge Controls (Full,, 2008) it was possible to assess the controller data and store them in a computer. The collected data are:

Ambient temperature: Minimum=20.8ºC; Maximum=23.5ºC; Average=21.6ºC
Humidity: Minimum=37.8% RH; Maximum=60.7% RH; Average=53.4% RH.
Electricity consumption = 1.95 kWh.

5.1 Ambient Temperature Analysis

Table 4 shows an analysis of the hybrid system temperature data of all operating modes throughout an individual 24-hours sampling time. The monitored and controlled environment temperature was that of the LAVSI meeting room.

Table 4. Data analysis of Thermal comfort (temperature)

Operating mode	Minimum temp.	Maximum temp.	Medium Temp.	Observations
OFF	22,5 ºC	25,9 ºC	24,5 ºC	High
VENT	21,0 ºC	26,1 ºC	23,3 ºC	High
EVAP	20,9 ºC	22,4 ºC	21,3 ºC	Normal
COOL	21,0 ºC	23,5 ºC	22,5 ºC	Normal
HYB	20,8 ºC	23,5 ºC	21,6 ºC	Normal

Table 4 features that in situations without cooling (system OFF or VENT) the ambient temperature at some times hits over 25.5ºC, which qualifies a thermal discomfort condition by high temperature for activities performed in the meeting room. In normal conditions with the remaining operating modes (EVAP, COOL, and HYB) based on obtained data, the situation is of thermal comfort.

5.2 Relative humidity analysis

Table 5 shows that in cases without cooling (system OFF or VENT) the ambient relative humidity falls under 30.0 %, which means a thermal discomfort situation by low air humidity. In normal conditions with the remaining modes (EVAP, COOL, and HYB), based on obtained data, the situation is of normal thermal comfort due to ambient relative humidity. Data also indicates that the monitored ambient presented best relative humidity conditions when the Hybrid System worked with the modes EVAP and HYB, i.e., with the evaporative component operating.

Table 5. Data analysis of Thermal comfort (relative humidity)

Operating mode	Minimum RH	Maximum RH	Medium RH	Observations
OFF	27,6%	46,5%	38,0%	Low
VENT	29,8%	51,0%	41,8%	Low
EVAP	45,7%	63,3%	53,6%	Normal
COOL	32,2%	61,1%	46,3%	Normal
HYB	37,8%	60,7%	53,4%	Normal

5.3 Energy Consumption Analysis

Table 6 displays data analysis of electric energy consumption of the hybrid system in all operation modes during a 24-hours individual sampling time. The recorded energy consumption refers to the total consumption of the equipment, including all components and electric and electronic devices.

It shows also that in mode OFF (turned off) there is a residual energy consumption, which is justified due to the system's measuring instruments' consumption. In mode COOL (cooling) there is high electric energy consumption, corresponding mainly to the compressor's consumption. In modes EVNT (ventilation), EVAP (evaporative), and HYB (hybrid=EVAP + REF) there is an electric consumption considered normal for the installed system.

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Considering the total electric energy consumption in mode REF as a reference or 100%, then, there is a consumption of 37.7% in mode VENT, 23.0% in mode EVAP, and 32.9% in mode HYB. By the data obtained in 120 hours of analysis, it is to conclude that the solely evaporative system (EVAP) presents a 77.0% lower energy consumption, and mode HYB 67.1% lower, both in relation to mode COOL, Figure 9.

Table 6. Data analysis of energy efficiency

Operating mode	**Ventilator operating time**	**Pump operating time**	**Compressor operating time**	**Total energy consumption**	**Observations**
6. (	**7. 00H0**	**8. 00H0**	**9. 00H0**	**10. (**	**11. V**
VENT	22h15m45s	00h00m00s	00h00m00s	**2,23 kWh**	Normal
EVAP	13h52m54s	00h29m42s	00h00m00s	**1,36 kWh**	Normal
COOL	22h58m08s	00h00m00s	01h49m57s	**5,92 kWh**	High
HYB	14h56m31s	00h28m40s	00h09m02s	**1,95 kWh**	Normal

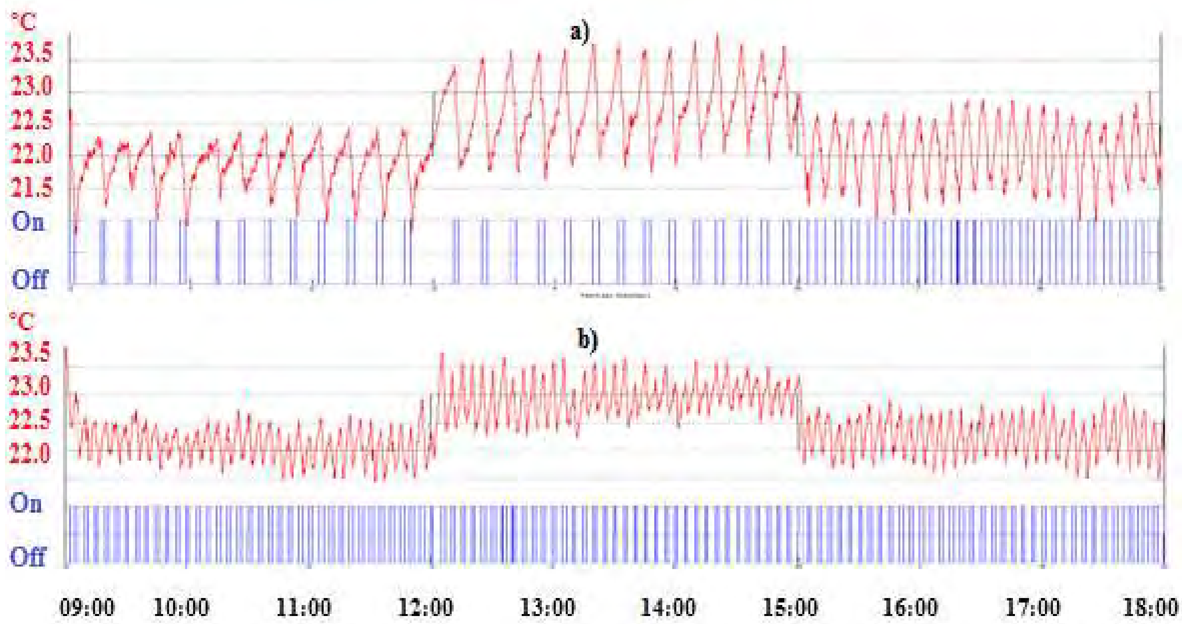

Figure 9. Meeting room temperature obtained using PWM modulated drive. (a) PID control. (b) Fuzzy control. Reference: square signal (22ºC - 23ºC).

Table 6. Energy measurement and external average temperature, PID Control.

	Energy (KWh)	Outside average temperature (°C)
Constant reference	8,8	25,93
Square reference	5,94	27,04

Table 7. Energy measurement and external average temperature, Fuzzy Control.

	Energy (KWh)	Outside average temperature (°C)
Constant reference	7,84	31,26
Square reference	6,37	29,26

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Figure 10 show a one hour detail of the Fuzzy control. It can be clearly seen that the chosen 5 minutes PWM period produce a rather smooth temperature swing. When the set point changes from 23ºC to 22ºC a larger pulse (duty cycle) is in order. In this picture the average temperature around 23.0 ºC fits better the set point than for 22.0ºC, showing that further tuning of the fuzzy rules are necessary. A more effective approach would be to use fuzzy-I (fuzzy with integral channel) controller that can better cope with steady state error than the fuzzy – P controller used here.

It is worth to mention that the fuzzy controller designed for a single operating point showed better results than the on-off or the PID controller in the sense that swing amplitude around the set point. Because finding appropriate rules for MIMO systems in a broader operating range is quite exhausting we emphasize the need to associate fuzzy with integral action.

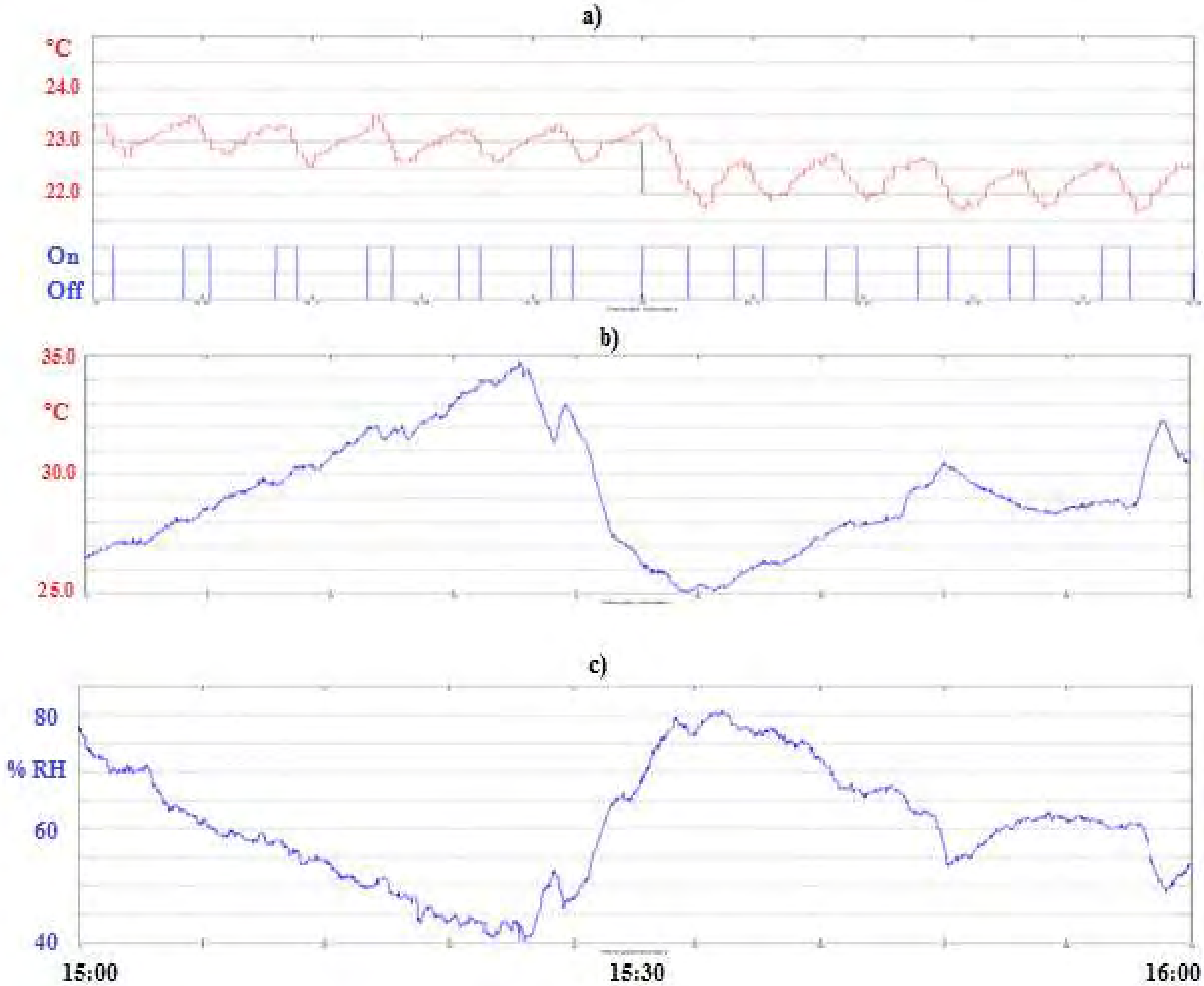

Figure 10. *Fuzzy* control of the room temperature. One hour zoom view.
a) temperature, set-point and actuator signals. b) External temperature, c)External Humidity.

6. CONCLUSIONS

The hybrid air-conditioning system implemented demonstrated that it is possible to obtain ratings close to those adequate to thermal comfort in conformity to Technical Standards requirements and a considerable reduction in electrical energy consumption.

Temperature decrease resulted through the evaporative cooling process depends mainly on the relative humidity of the incoming air. The lower the relative humidity, the higher the obtained decrease in temperature. Compared to conventional systems, we obtained electric energy saving of the order of 67% (measurements during dry season).

The PID controller implementation was difficult due to the rain season. The external variables have had great changes during a day period including torrential rain fall. The PWM used to drive the compressor is, by no means, the best way to work with air conditioners. Variable speed compressors are available. But, quite often, this is a cost question. To preserve the compressor a PWM basis period of 5 minutes was chosen. This value give rise to the observed temperature fluctuations. But, as a model of the process is used to design the PID controller, the result obtained is better than a simple on-off controller.

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The fuzzy controller was very hard to design due to number of membership functions used. A lot of trial and error was needed to obtain better results than that achieved by our PID. In this case, the rain also was a strong drawback to test the hybrid air-conditioning system. By rain the external temperature dropped more than 10ºC and the relative humidity approached 100%.

It is worth to mention that a related work (Ferreira Jr, 2009), using a conventional split air conditioner, also with PWM driving of the compressor, but in this case during the dry season in Brasília, give us that the fuzzy control can give as much as 20% energy saving, compared to on-off control. With the hybrid system much higher savings are expected. New tests are being carried out with the hybrid air conditioner.

The different operating modes used in this paper to characterize the cooling potential and energy demands were in order to guide the hybrid operating scheme. Later a simple fixed timing was tested for the water pump. Fixed hysteresis was used to switch between evaporative and conventional compressor mode. Further studies are in progress in order to obtain a wide-range dynamic model (in opposition to operating point linearization – "transfer function models") involving temperature and humidity models that allow to build really optimized controllers, like predictive controllers. Better process models by grey-box identification could also support more systematic designs. The predictive approach is particularly interesting because saturation and non-linear prediction models can easily be used.

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9. RESPONSIBILITY NOTICE

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