Decentralized Temperature Fuzzy Logic Control of a Passive Air Conditioning Unit

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Abstract—A closed loop fuzzy logic control (FLC) with a decentralized architecture has been applied to a passive air conditioning unit. The objective of the studied unit is to guarantee a microclimate with controlled temperature and relative humidity setpoints for crop growth chambers. As the process involves time-varying and distributed parameters, we propose the use of fuzzy logic to implement an expert rule based systems that care of different contexts of the air-conditioning temperature management. In the aim to get a local and global efficient performance, the proposed decentralized FLC architecture is applied on two principal subsystems which composed this global unit. A significant improvement in the system performance is observed on a wide range of operating point conditions.

I. INTRODUCTION

Research on greenhouse climate control has received attention during the last years because chamber cultivation has extended significantly in the last two decades [1], [2]. Thus greenhouse climate control became a tool used for crop yield manipulation which maximizes the entrepreneurial benefits. In traditional greenhouses, the fog systems are primarily used to decrease the temperature [22]. Other typical current technologies for temperature control are accomplished by different ways, such as fan ventilation, natural ventilation, evaporative cooling or shading [2], [9].

Among the proposed solutions, one founds heating, ventilating, and air-conditioning (HVAC) units which are used in environment control for living systems and for particularly growth chambers. Most of these units are usually composed of heating elements, a cooling system with a compressor and evaporator techniques [10], [11]. Some disadvantages of these systems include system failure, nozzle blockage, high energy consumption, or prohibitive maintenance costs. These have led us to investigate a simple and practical method of air-conditioning, with the objective of using this technology for greenhouse production.

The air-conditioning unit studied herein is passive and does not use the more typical compression system or absorption-refrigeration cycle [20]. The specificity of the system is to produce a variable microclimate with variable temperatures and moisture set-point values, without pollution rejection which presents ecological advantages.

Ones the objectives that optimise crop growth and development are defined, the control engineer must design and implement automatic control systems that make possible to obtain maximum crop yield at minimum production costs [8]. In this sense, control engineering has undergone a considerable development. Many control techniques are used in different fields, from the classic strategies as Proportional Integral Derivative (PID) control, to artificial intelligent (AI) like fuzzy control [14] [23], neural networks and genetic Algorithms, advanced control techniques as predictive control, adaptive control, robust control strategies, non linear and optimal control.

In industry automation, the PID controllers work properly just when the process under control is in stable condition, but they cannot ensure stable conditions in the following cases: presence of strong disturbances, presence of non-linearity behaviour, time-varying parameters of the process, or in the presence of dead time, because the classical controllers like PID controllers are based on a known analytical model of the controlled system. However in many situations, full knowledge is not available, yet control decisions still have to be made. In such situations, a reasonable idea is to find a human operator who is better in this kind of control, and translate his control experience into a precise formula [18][19]. The control experience is usually formulated in terms of natural language. It is the main idea of fuzzy logic control (FLC): to build a model of a human control expert who is capable of effecting control without the need to think in a complex mathematical model [15][24]. It is the case of our air conditioning unit where the differential equation model of this plant was developed in [17], and an aerodynamic study demonstrates that the system is more complex with distributed parameters [21].

The global air conditioning unit is a complex system because it is composed of three nonlinear HVAC subsystems [17]. Therefore the implementation of centralized fuzzy control strategy is cumbersome and decreases reliability. For these reasons, a typical local-loop control configuration for each subsystem of the air conditioning unit will be more efficient. For such control loops, fuzzy-PI controller is considered. The present study is focused on the temperature control for each single-input-output (SISO) non linear subsystem with multiple operating modes.

This paper proceeds as flow; in the section II the problem statement will be presented. In the next section the fuzzy-PID control theory is developed. Then in the last section, the real time implementation of the decentralized strategy and the experimental results are discussed.
II. PROBLEM STATEMENT

The unit is composed of two flows: a non-saturated flow (or dry duct) and a saturated flow (or humidified duct) [21]. As shown in “Fig. 1”, in the saturated air flow, fresh air is saturated in humidity after being heated by a coil resistor. Saturation operates at constant enthalpy [6], [7]. The saturation part consists of a closed system, including a pump, a water tank and cross-corrugated cellulosic pads of the type using in cooling. The suction pump carries water from the tank to the top of the pads. Once a steady state of saturation is reached, the pads contain a constant mass of water with a given temperature.

In the unsaturated air flow, fresh air is only heated by another coil resistor. Dry pads are included to provide pressure drop balance. The low speed of the air and of the water through the pads reduces the difference of pressure drop between the two streams.

And $q_1$, $q_2$ are the volumetric air-flow rates depending on the aperture position “Fig. 1”. The total volumetric air-flow rate $Q_{air}$ is given as:

$$Q_{air} = q_1 + q_2 = a(x)Q_{air} + (1-a(x))Q_{air}$$

A complete description of the physical behaviour for the two principal ducts is given through the following steps:

1) In the dry duct, the air temperature $T_{RDD}$ after the heater is considered to be equal to the air output temperature $T_{ODD}$.

The heat balance in the pads of the dry duct is given by the following equation

$$\frac{dT_{ODD}}{dt} = \frac{-\alpha(x)Q_{air}}{V_{mixer}} [T_{mixure} - T_{ODD}] + \frac{k_{RDD}}{\rho_{air} C_{air} V_{DD}} U_{DD}$$

with $T_{air \_intake}$ the intake air temperature (°C), $U_{DD}$ the applied voltage (V), proportional to the resistor heating in the dry duct, $k_{RDD}$ the proportionnal coefficient between the voltage and the heating-power (J/sV), $V_{DD}$ the volume of the dry duct (m$^3$).

And as there is no addition and nor extraction of water in the dry duct, the air intake moisture is conserved.

$$AH_{air \_intake} = AH_{RDD} = AH_{ODD}$$

Where $AH_{air \_intake}$, $AH_{RDD}$, $AH_{ODD}$, are respectively the absolute humidity of the air intake, and of the air after the heater of the dry duct and the absolute humidity of the air of the dry duct output (kg of water/kg of dry air).

2) In the humidified duct, the heat balance in the pads and in the heater, are respectively given by the following equations:

$$\frac{dT_{ODD}}{dt} = \frac{-1 - \alpha(x)Q_{air}}{V_{mixer}} [T_{ODD} - T_{ODD}] + \frac{h}{\rho_{air} C_{air} V_{pad}} [T_{RHD} - T_{water \_intake}]$$

+ $L_{f}(T_{water \_intake}) \frac{\rho_{water} h_{air} A_{pad}}{\rho_{air} C_{air} V_{pad}}$ $\times [AH_{sat}(T_{water \_intake}) - AH_{air \_intake}]$

$$\frac{dT_{RHD}}{dt} = \frac{-1 - \alpha(x)Q_{air}}{V_{RHD}} [T_{RHD} - T_{air \_intake}] + \frac{k_{RHD}}{\rho_{air} C_{air} V_{RHD}} U_{HD}$$

The proportional mixing of the two air flows is carried out by an aperture operated by a DC motor. Assuming that the two air flows are well mixed, a local climate can be easily produced in the growth chamber, according to the following thermodynamic equations:

$$\frac{dT_{mixure}}{dt} = \frac{-\alpha(x)Q_{air}}{V_{mixer}} [T_{mixure} - T_{ODD}] + \frac{1 - \alpha(x)}{V_{mixer}} [T_{mixure} - T_{ODD}]$$

where $T_{mixure}$ is the air temperature (°C) in the mixer, $T_{ODD}$ the air temperature (°C) after the dry duct, $T_{RHD}$ the temperature after the humidified duct (°C), $\alpha(x) \in [0;1]$ the volumetric air-flow percentage in the dry duct (%), $x$ the percentage of aperture opening (%), $Q_{air}$ the total volumetric air-flow rate (m$^3$/s), $\rho_{air}$ the air density (kg/m$^3$), $C_{air}$ the specific heat of air (J/kg °C), $V_{mixer}$ the volume of the air mixer.
where \( T_{RHD} \) is the air temperature (°C) after the heater of the humidified duct, \( T_{water\_intake} \) the intake water temperature after the pads of the humidified duct, \( U_{HD} \) the applied voltage (V), proportional to the heating in the humidified duct, \( AH_{sat}(T_{water\_intake}) \) the saturated absolute humidity at the temperature of water intake, \( k_{RHD} \) the proportional coefficient between the voltage and the heating-power (J/sV), \( \rho_{water} \) the water density (kg/m³), \( C_{water} \) the water specific heat (J/kg °C), \( V_{RHD} \) the heater chamber volume of the humidified duct (m³), \( V_{pad} \) the pads volume (m³), \( A_{pad} \) the pads exchange surface (m²), \( L_{v}(T_{water\_intake}) \) latent heat (J/kg of water) at the temperature of the intake water, \( h_{c} \) respectively the convective heat coefficient (J/m²s) and the mass-transfer coefficient (m³/m²s).

However, there is extra water flowing through the pads of humidified duct. Thus moisture (absolute humidity) balance is given by the following equation:

\[
dAH_{OHD} = \frac{(1-\alpha(x))Q_{Pad}}{V_{pad}} [AH_{OHD} - AH_{air\_intake}] + \frac{\rho_{water}h_{c}A_{pad}}{\rho_{air}V_{pad}} [AH_{air}(T_{water\_intake}) - AH_{air\_intake}]
\]

(7)

Where \( AH_{OHD} \) is the absolute humidity of the air of the humidified duct output (kg of water/kg of dry air).

The temperature and the relative humidity (%) are commonly measured air proprieties; they are highly coupled through the following non linear thermodynamic laws

\[
AH = \frac{0.622}{AP - SP(T)} \frac{SP(T) \cdot RH}{RH}
\]

(8)

With, AP the atmospheric pressure (N/m²) and \( SP(T) \) the saturation vapor pressure (N/m²), depending on the temperature and given by:

\[
SP(T) = 10^5 \frac{101325}{760} \frac{10^{(0.66+0.031 \cdot (T-1.285)10^{-4}T^2+2.939 \cdot 10^{-7}T^3)}}
\]

(9)

The physical models given above are complex and difficult to use for control objectives, especially the relative humidity. The air-flow measurements for the main aperture positions indicate a nonlinear relationship between the percentage of air-flow and the percentage of apertures positions [21].

In order to take into account these uncertainties and all this complexity, the intelligent control like a fuzzy logic strategy gives an opportunity to solve this type a of problem.

III. FUZZY-PI CONTROLLER DESIGN

The human creative capacity of inexact reasoning, uncertain or diffuse, contrasts with the computers and machines operation form, driven by binary logic. If these machines lose its ‘reasoning’ restrictions, they would become eventually intelligent, being able to reason by an inexact form. This form of reasoning is known as Fuzzy logic [3],[4],[23].

Fuzzy logic tries to incorporate the human way of thinking in computational systems. When this technique is applied to control loops, it’s usual to call it Fuzzy Control. This type of control is generally used with complex dynamic systems.

A fuzzy controller consists of the following major components depicted in “Fig. 2”.

The most of the measured data from the process sensors are numerical data. To allow a mathematical treatment of linguistic variables, it is necessary to transform measurements data into fuzzy sets. This step is the fuzzification.

The knowledge base stores the control rules and data base. This step provides the logic of the control law, through a series of “IF…THEN…” rules which operate on the linguistic descriptions of measured variables and produce linguistics descriptions of the control signal.

These rules are of the form:

“IF A is small and B is big THEN C is medium”

Here A, B are input variables (known data) and C is an output variable (data variable to be computed). The adjectives “small” in relation to A, “big” in relation to B and “medium” in relation to C are membership functions in this case.

The fuzzy inference simulates a human ability to make decisions using fuzzy logic and approximate reasoning. The procedure for obtaining the fuzzy output of such knowledge base consists of the following three steps: find the firing level of each of the rules; find the output of each of the rules; and aggregate the individual rule outputs to obtain the overall system output.

The output of the inference process is a fuzzy set, specifying a possibility distribution of control action. In the on-line control, a non-fuzzy (numerical) control action is usually required. The defuzzification inference converts fuzzy control output to a numerical control command.

Numerous methods of defuzzification have been proposed in literature [16]. The most commonly used method is the “centroid method”. It is expressed by:
\[ u^* = \frac{\mu(y) u dt}{\mu(y) dt} \quad (10) \]

With \( u^* \) is the numerical output value, \( \mu(y) \) is the membership function of the fuzzy sets.

The fuzzy control structure can be classified according to its application. One of the most popular fuzzy structures is based on error \( e(t) \) and on error increment \( \Delta e(t) \), constituting the basis of the fuzzy-PI and fuzzy-PD controllers, with \( u(t) \) and \( \Delta u(t) \) output control and output incremental control, respectively.

Fuzzy-PI controller is known to be more practical than fuzzy-PD controller, since it is difficult for the fuzzy-PD controller to remove the steady state error. The inertia of studied HVAC system leads to the use of Fuzzy-PI structure for the temperature regulation.

IV. APPLICATION TO THE PASSIVE AIR-CONDITIONING UNIT

Due to model complexity of the air-conditioning unit, the decentralized architecture was chosen in order to apply the thermodynamic cycle described by the psychometric air humid diagram given in “Fig.3”.

The rules used for the classical fuzzy-PI controller for both of sub-systems, have been obtained and optimized by trial and error for the given plant. “Fig. 5.(a), 5.(b), 7” and “Fig. 9.(a), 9.(b), 11” respectively show the input and output membership functions of both controllers.

In our case, for the temperature error and its derivative, three membership functions were used with a Gaussian functions, distributed throughout the whole input range.

Both controllers had one output with five distributed triangular membership functions, “Fig. 8, 13” which represents the change of heating voltage applied on each duct.

The rule base was composed by a typical Mamdani-type rule for inference of the fuzzy-PI controllers, according to the following model:

1. IF (Error is N) AND (delta-Error is N) THEN (delta-U is PB)
2. IF (Error is N) AND (delta-Error is Z) THEN (delta-U is P)
3. IF (Error is N) AND (delta-Error is P) THEN (delta-U is Z) (1)
4. IF (Error is Z) AND (delta-Error is N) THEN (delta-U is Z) (1)
5. IF (Error is Z) AND (delta-Error is Z) THEN (delta-U is Z) (1)
6. IF (Error is Z) AND (delta-Error is N) THEN (delta-U is N) (1)
7. IF (Error is P) AND (delta-Error is N) THEN (delta-U is Z) (1)
8. IF (Error is P) AND (delta-Error is Z) THEN (delta-U is N) (1)
9. IF (Error is P) AND (delta-Error is P) THEN (delta-U is NB) (1)

The inputs and outputs fuzzy sets were marked with the following labels: positive big (PB), positive (P), zero (Z), negative (N), negative big (NB)

The adopted defuzzification method, for fuzzy outputs \( \Delta u_1 \) and \( \Delta u_2 \), were based on the determination of the ‘center of gravity’.
Fig. 5. (a) Error fuzzy sets, (b) error variation-fuzzy sets of the dry duct-fuzzy controller

Fig. 6. Input-output relationship of the dry duct-fuzzy controller

Fig. 7. Voltage fuzzy sets of the dry duct-fuzzy controller

Fig. 8. Closed loop response of the dry duct temperature

“Fig.8” and “Fig.12” show a good performance for each temperature closed loop behavior. In the dry duct, it was observed a short response time with an accepted overshoot for the different positive and negative set points values, as represented in “Fig.8”.

Fig. 9. (a) Error fuzzy sets, (b) error variation-fuzzy sets of the humidified duct-fuzzy controller

Fig. 10. Input-output relationship of the humidified duct-fuzzy controller

Fig. 11. Voltage fuzzy sets of the humidified duct-fuzzy controller

Fig. 12. Closed loop response of the humidified duct temperature

In the humidified duct it was also observed a short response time but without overshoots “Fig.12”. Both of PI-controllers guaranteed a good accuracy in steady state. This precision is a result of a range reduction of the zero membership functions referring to the controller output.
The fuzzy-PI controller presented an efficient disturbance rejection caused by the outdoor temperature variation. Stability robustness was observed through elimination of the temperature overshoot for each flow rate variation, caused by the aperture commutation “Fig.8, 12”. This robustness was improved in most part by an adequate choice of small zero membership function of error-variation range, which increase the control sensitivity in spite of a speed output temperature variation.

The air mixture set point temperature was guaranteed indirectly “Fig.13”, as consequence to the two temperature accuracy at the upstream ducts “Fig.8, 12”, with an accepted precision, proving the feasibility of the proposed air humid thermodynamic strategy.

V. CONCLUSION

In this paper we have presented an application of the fuzzy-PI control of complex HVAC process. Stability is maintained with an adequate choosing of controller parameters values based on the expert knowledge and on the experiment behavior observations. The performances are maintained in spite of parameters system varying and disturbance rejection controller is able to reduce the effect of thermal loads thinks to the nonlinear proprieties of the fuzzy-PI regulator.

The choice of decentralized architecture presents a basic solution over the complexity of the centralized control strategies and guarantees a better robustness in spite the operating point variation.

A current study is on the supervision aspect, carrying out an adaptive control strategy of the fuzzy-PI parameters controller with an extension of the decentralized strategy for the relative humidity control.

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REFERENCES


