Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v35i2.14775

High performance controller for drying processes

Camila Nicola Boeri*, Fernando Neto da Silva and Jorge Ferreira

Departamento de Engenharia Mecânica, Universidade de Aveiro, Campus Universitário de Santiago, 3810-183, Aveiro, Portugal.
**Author for correspondence. E-mail: camilaboeri@hotmail.com*

ABSTRACT. This paper proposes a high performance nonlinear fuzzy multi-input-multi-output controller for a drying control process. The highly nonlinear characteristics of drying processes make classical control theory unable to provide the same performance results as it does in more well behaved systems. Advanced control strategies may be used to design temperature, relative humidity and air velocity nonlinear tracking controllers to overcome its highly non-linear dynamics over the whole drying operating conditions. Open-loop experiments were carried out to collect experienced-based knowledge of the process. PID and Fuzzy logic (FLC) real-time-based controllers were designed to perform food drying tests and compared without controllers' retuning. Absolute errors reached by FLC-based controller were 3.71 and 3.93 times lower than PID for temperature and relative humidity, respectively.

Keywords: drying, Fuzzy logic controller, PID controller, relative humidity, temperature, air velocity.

Controlador de alta performance para processos de secagem

RESUMO. Este trabalho propõe um controlador difuso não-linear, de alto desempenho, para o controle do processo de secagem. As características altamente não-lineares dos processos de secagem tornam a teoria de controle clássica incapaz de fornecer os mesmos resultados de desempenho como acontece em sistemas lineares. Estratégias de controle avançado podem ser usadas para projetar controladores não-lineares de temperatura, umidade relativa e velocidade do ar, para superar a sua dinâmica não-linear ao longo de todas as condições operacionais de secagem. Foram realizados ensaios em malha aberta, na instalação experimental de secagem, a fim de conhecer a dinâmica do processo e obter dados para o projeto dos controladores. Foram projetados controladores em tempo real, utilizando-se o controle PID e o controle por Lógica Difusa (FLC,) para realizar testes de controle dos parâmetros de secagem, comparando-se as respostas de ambos os controladores. Os erros absolutos atingidos pelos controladores difusos foram 3,71 e 3,93 vezes menores que os obtidos pelo controle PID, para o controle de temperatura e umidade relativa do ar, respectivamente.

Palavras-chave: secagem, controlador difuso, controlador PID, umidade relativa, temperatura, velocidade do ar.

Introduction

Drying technology is the major energy consumer used in many industries, including food, agriculture, textile, biotechnology, mineral, pharmaceutical, pulp and paper, polymer, timber industries and others. Research interests on this matter is on the increase, mainly with regard to air conditioning systems, refrigeration systems, food processing (bovine blood, eggs, vegetable extract, tomato pulp, pulps of fruits, molasses, milk, corn starch, baker, sugar beet shreds, grain, among others), pharmaceuticals, bio-cell, mineral, painting, textile, tobacco, wood, paper industries and others. The correct drying procedures of a vast range of food products are crucial in energy minimization and minimal time of kiln residence without jeopardizing the final product's quality. However, drying may change the sensory characteristics and nutritional value of food and thus the intensity of these changes depends upon the conditions used in the drying process and for the specific characteristics of each product. Several parameters influence the time required to reduce the product's moisture content. The main external variables are air temperature, relative humidity and air velocity. Their control is highly complex due to their highly nonlinear dynamic: their multi-variability is strongly coupled and lagged, and there are a lot of factors which affect the rate drying, such as time, very slow dynamics, non-minimum phase, hidden time-constants in high frequencies, nature of feeding, gas-solid contact mode and others. Consequently, the above research field may lead towards the evolution of control techniques. Siettos et al. (1999) state that the dryer control is probably one of the less studied areas in process control. Dufour (2006) has found that most published studies about drying control are related to control regulations rather than to control optimization. The author's main goal was to attract attention of the scientific control communities about drying control problems.

The model predictive control (MPC) is one of the most used techniques in advanced drying control. Dufour et al. (2004) designed a MPC for experimental water painting that used a diffusion model leading to the knowledge of the drying characteristics. Yüzgeç et al. (2008) presented a neural-network-based MPC scheme for a bakery yeast drying process. A genetic-based search algorithm was used to find the optimal drying profile.

Drying process parameters are full of uncertainties. According to Gou et al. (2005), in complex plants, namely in drying technology, it is often impossible to formulate a physical and chemical model of the process, because heat and mass transfer phenomena, characterized by a complex mass and energy transfer, should be included. However, through fuzzy sets and rules, it is possible to model any nonlinear function and perform any nonlinear control action. Alvarez-López et al. (2005) designed a relative humidity's fuzzy controller for the drying of tobacco leaves. Taking error and the error rate as their inputs and 49 rules, their relative humidity errors is close to nil. A single Fuzzy Control of Mixed-Flow Grain Dryer was proposed by Liu et al. (2003). With 49 rules, error range of the final moisture content remained at 0.8%.

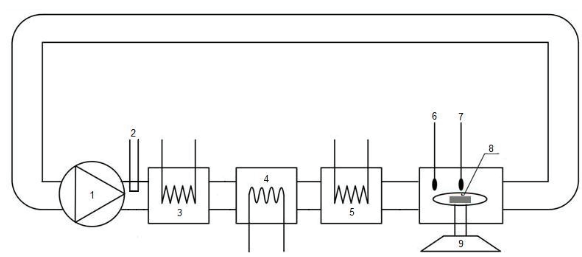
Atthajariyakul and Leephakpreeda (2006) investigated the design of hybrid schemes and found a systematic determination of optimal conditions for fluidized bed paddy drying. They then put forward an adaptive FLC to perform good quality and consume energy efficiency. Air temperature and recycled air percentage were controlled by only 6 rules. A learning algorithm and a gradient descent-based optimization to adapt to the FLC parameters were introduced. The authors achieved moisture content errors lower than 2.5%.

Current essay provides a nonlinear scheme for drying processes, composed of four fuzzy controllers: Fuzzy Dehumidifier Controller (FDC-PD), Fuzzy Humidifier Controller (FHRC-PD), Fuzzy Electrical Resistance Controller (FERC-PD) and Fuzzy Blower Controller (FBC-FD). The research's main aim is to discover the optimal conditions for codfish drying.

Material and methods

Experimental installation

The experimental installation is used for codfish drying, although it can be used to dry any kind of product within its technical specifications. It includes a centrifugal blower driven by a variable velocity AC motor which defines air velocity control within the drying chamber. The air is forced through electric heating resistances, allowing the rise of air temperature control. Steam at atmospheric pressure is used for humidification and a dehumidifier is employed for cooling and dehumidifying the air. The air velocity is measured by an air velocity transmitter (Omega, model FMA 1000). The air temperature and the relative humidity are measured by a digital thermo-hygrometer (Omega, model RH411). Figure 1 shows the scheme of the dryer in which all drying tests were performed.



(1 – centrifugal blower; 2 – humidifier; 3 – electrical resistances of 2 kW; 4 – dehumidifier; 5 – electrical resistances of 1 kW; 6 – air velocity transmitter; 7 – thermo-hygrometer; 8 – sample; 9 – digital balance).

Figure 1. Experimental installation scheme.

Hardware and software platforms

The control of the drying process is ensured by a computer card with the Matlab/Simulink® platform. Data acquisition is handled by a PCI-6025E card from National Instruments. Four 12-bit analog inputs were used to measure environment temperature, current temperature, relative humidity and air velocity within the dryer; two 12-bit analog outputs were used for output of the dehumidifier and centrifugal blower signals; and digital gateways were employed for electrical resistance and humidifier control signals. The PC is a Pentium with a dual core CPU featuring 2.25 GHz and 2 GB of RAM.

The Matlab/Simulink® environment was the development tool used to design all the control schemes. With Real-Time Windows Target, which allowed running Simulink program in real-time on the PC, and using Real-Time Workshop (RTW) 7.3 from Mathworks, C code was generated, compiled and put into real-time execution on the Windows-based PC. RTW target I/O device drivers support an interface between the control software and the instrumentation devices, performed through the PCI-6025E board.

Drying process dynamics

Drying tests were performed for the following operational conditions: drying air temperature comprising 15, 18, 20 and 23°C; drying air velocity comprising 1.5 and 2.5 m s^{-1}; relative humidity comprising 40, 45, 50, 55, 60, 65 and 70%. Drying air temperature rates should be around 20°C, whereas rates above 20 - 22°C will trigger the deterioration of the codfish. The constraints of the mechanical apparatus have constricted relative humidity rates always above 40%. The air velocity rates remained within the range for fish drying.

Knowledge on the drying process dynamics is always required to build up either numerical model-based controllers or experienced model-based controllers for the best control scheme. Nonlinearities were studied through a set of open-loop experiments, some of which provided in Figures 2 to 5.

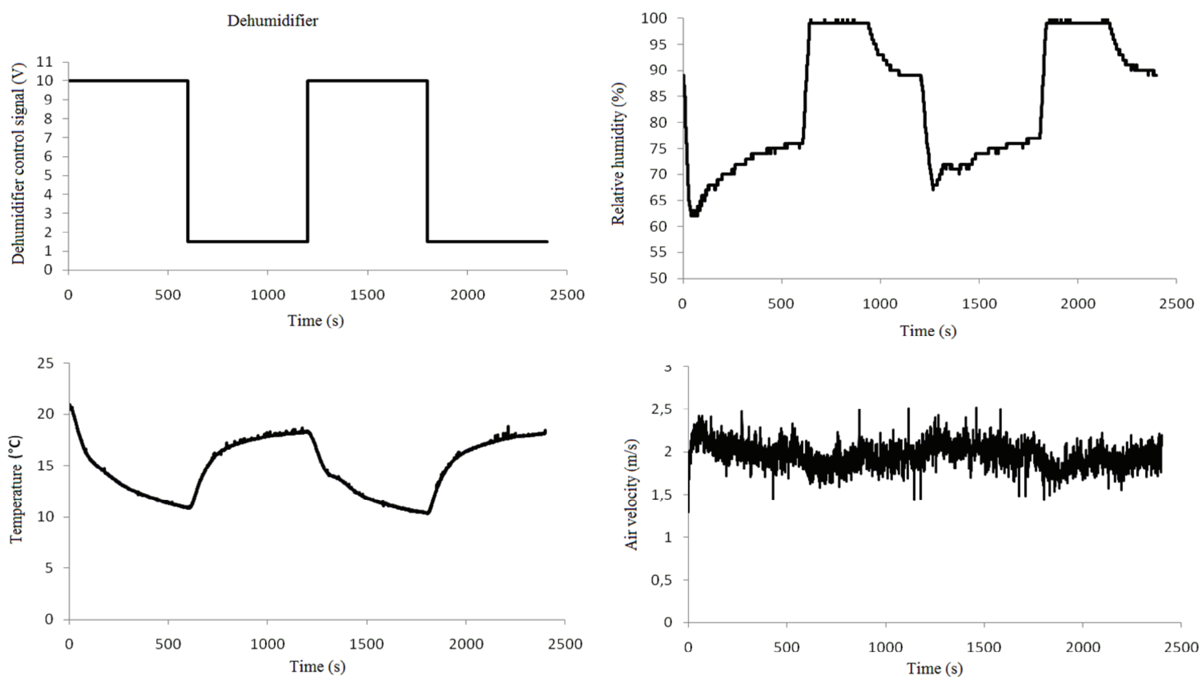


Figure 2. Dynamics of drying process parameters when dehumidifier control signal is changed.

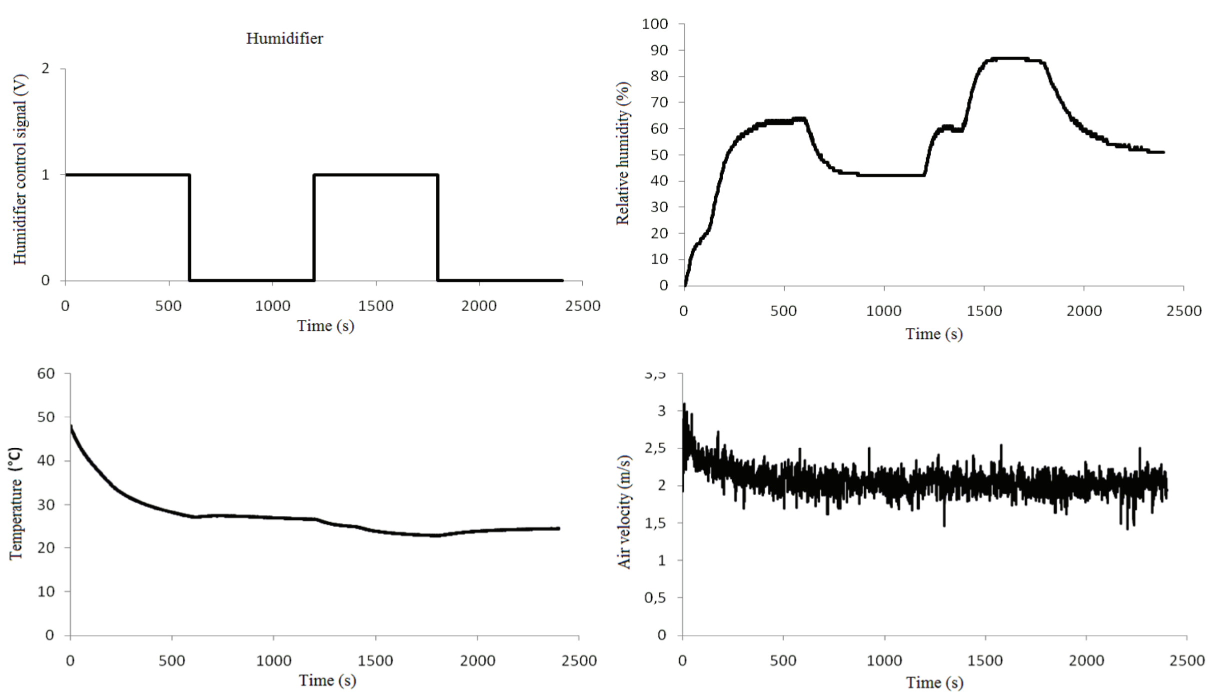


Figure 3. Dynamics of drying process parameters when humidifier control signal is changed.

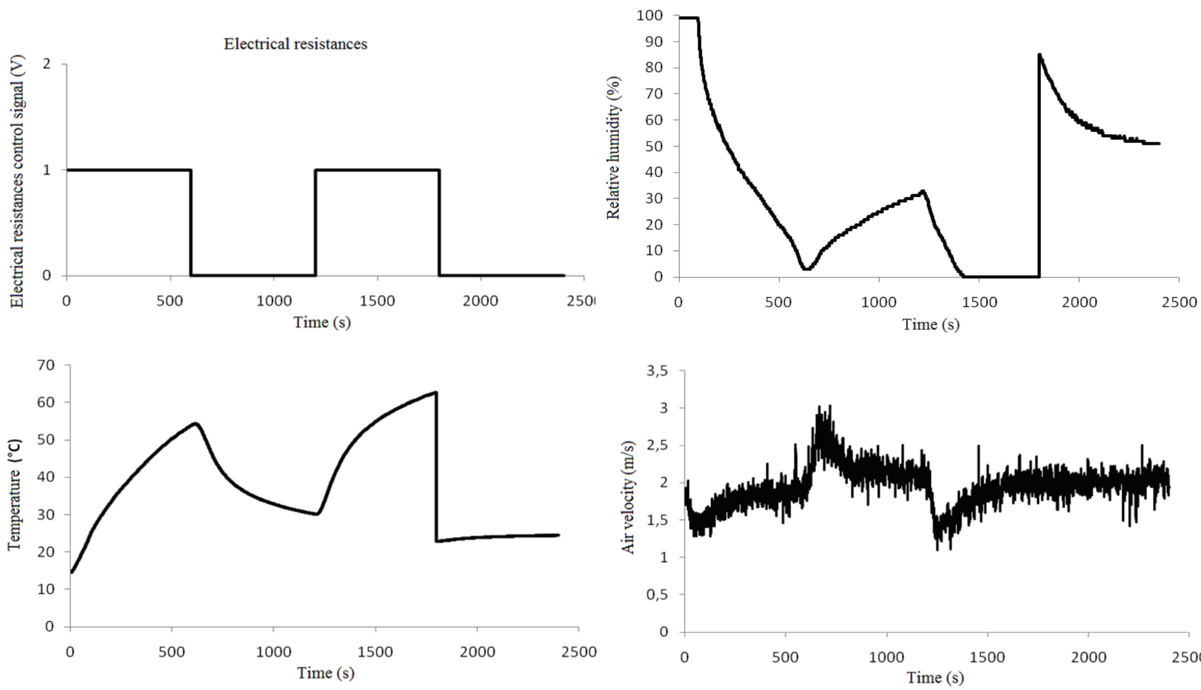


Figure 4. Dynamics of drying process parameters when the electrical resistances control signal is changed.

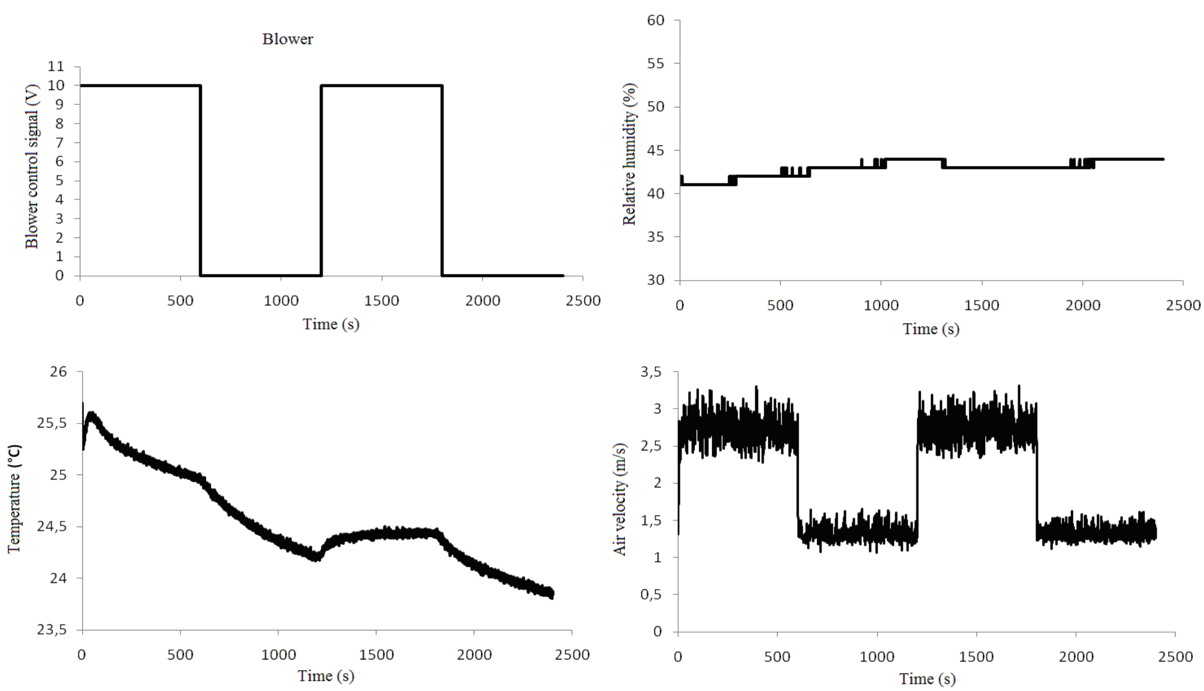


Figure 5. Dynamics of drying process parameters when the blower control signal is changed.

Controllers design

Overall-based Controllers

The overall drying controller was first designed using a PID control scheme (Figures 6 and 7), but was later upgraded to four fuzzy controllers: FDC-PD, FHRC-PD, FERC-PD and FBC-FD. The control system performance was not designed to be a function of any mathematical model accuracy and thus avoided hard issues on lower-order design models required by several control techniques. With regard to the design of the FLCs, the "mamdani" inference mechanism, the "minimum" implication, the "maximum" aggregation and the "COG" defuzzification methods were applied. Manual tuning was used to optimize the FLCs parameters.

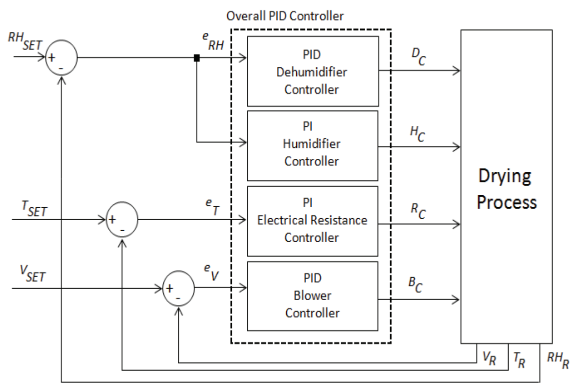


Figure 6. Overall PID-based controller.

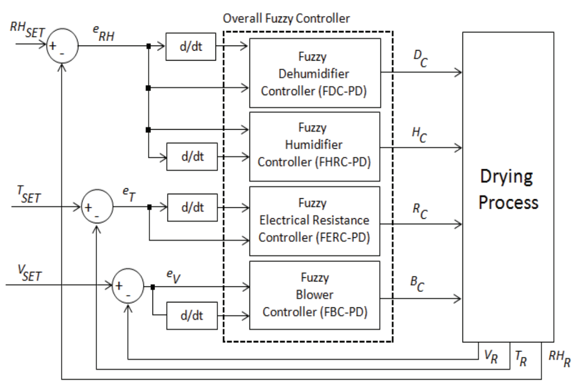


Figure 7. Overall Fuzzy Logic -based Controller.

PI-based Humidifier Controller

The PI Humidifier controller was designed as a control scheme as shown in Figure 8, and a control law identified by Equations 1 and 2 was applied. The windup phenomenon in the integral action is a hard issue in drying processes. Mainly due to its very slow dynamics, the introduction of an integral mechanism produces large integral control actions. Therefore, an anti-windup technique was designed to avoid a high increase in the integral action. Its parameters were found by manual tuning posterior to the application of the Ziegler-Nichols method (in fact, the maximum contribution of PID automatic tuning methods has only provided good initial estimations for an iterative-based approximation), which conducted to $K_P = 5$; $K_I = 0.1$; $K_{AW} = 5$. The lower and upper limits of the saturation block were set up at 10 and 0, respectively.

$$H_C(t) = K_p e_{RH}(t) + K_I f_{anti-windup}(K_{AW}, f_{AW}) \int_0^t e_{RH}(t)dt \quad (1)$$

$$f_{AW}(t) = \begin{cases} \dfrac{u_1(t)}{u_2(t)} & u_3(t) - H_C(t) > 0 \\ u_1(t) & u_3(t) - H_C(t) \le 0 \end{cases} \quad (2)$$

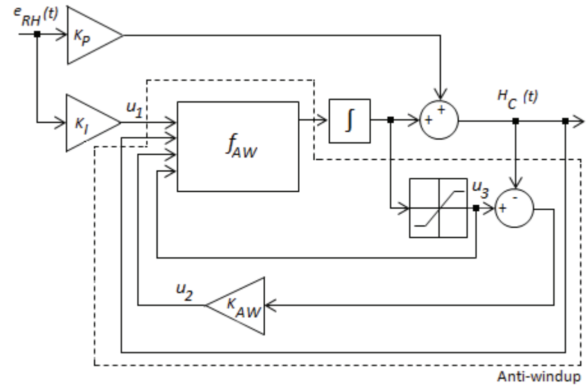


Figure 8. PID-based Humidifier Controller.

PID-based Dehumidifier Controller

As Figure 9 shows, the PID humidifier controller was also designed with an anti-windup mechanism. Equation 3 describes its control law and its parameters were found by applying the Ziegler-Nichols method, following a manual iterative optimization: $K_P = 5$; $K_I = 0.1$; $K_D = 0.001$; $N = 0.1$; $K_{AW} = 1$. The upper and lower limits of the saturation block were set up at -5 and 5, respectively.

$$D_C(s) = K_p e_{RH}(s) + \frac{K_I f_{anti-wind\ up}(K_{AW})}{s} e_{RH}(s) + \frac{sK_D N}{s+N} e_{RH}(s) \quad (3)$$

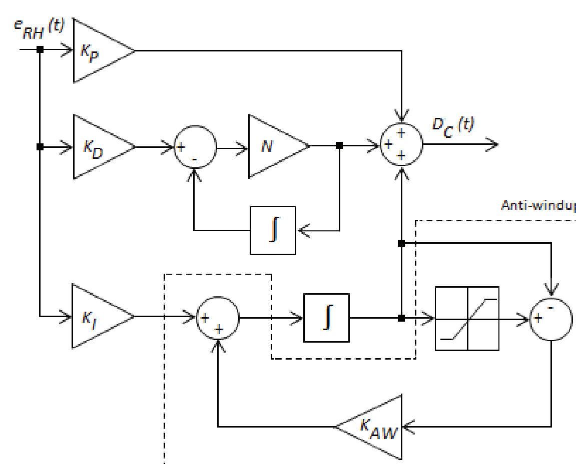


Figure 9. PID-based dehumidifier Controller.

PI-based Electrical Resistance Controller and PID-based Blower Controller

These controllers have the following control laws in time and frequency domains:

$$R_C(t) = K_P e_T(t) + K_I \int_0^t e_T(t)\,dt \quad (4)$$

$$B_C(s) = K_P e_V(s) + \frac{K_I}{s} e_V(s) + \frac{sK_D N}{s+N} e_V(s) \quad (5)$$

Parameters were found by the Ziegler-Nichols method; after a manual iterative optimization, $K_P (R_C) = 2$; $K_I (R_C) = 0.02$; $K_P (B_C) = 10$; $K_I (B_C) = 10$; $K_D (B_C) = 10$; $N = 0.1$ were obtained

Fuzzy Dehumidifier Controller (FDC-PD)

The FDC-PD controller obtains a non-linear action of current and future error by a FLC that defines the proportional and derivative mapping of relative humidity. Nineteen fuzzy sets and fifty-four rules designed the nonlinear behavior between the two inputs and the controller output. Equations 6 and 7 present its control law, whereas Figure 10 presents its control surface.

$$D_C(t) = K_{FDC} K_{FDC\_out} \quad (6)$$

$$K_{FDC} = f(K_{FDC\_in} e_{RH}(t), K_{dFDC\_in} de_{RH}(t)/dt) \quad (7)$$

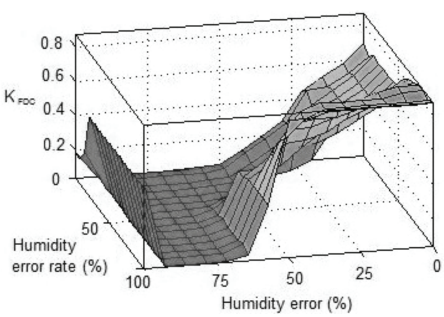


Figure10. FDC's control surface ($K_{FDC\_in} = 0.8$; $K_{dFDC\_in} = 0.005$; $K_{FDC\_out} = 10$).

Fuzzy Humidifier Controller (FHRC-PD)

The FHRC-PD controller performs a non-linear action of current and future error to map the relative humidity control action. Sixteen fuzzy sets and forty-five rules were designed to map inputs and output. Equations 8 and 9 present the FHRD-PD control law, and Figure 11 its control surface.

$$H_C(t) = K_{FHRC} K_{FHRC\_out} \quad (8)$$

$$K_{FHRC} = f(K_{FHRC\_in} e_{RH}(t), K_{dFHRC\_in} de_{RH}(t)/dt) \quad (9)$$

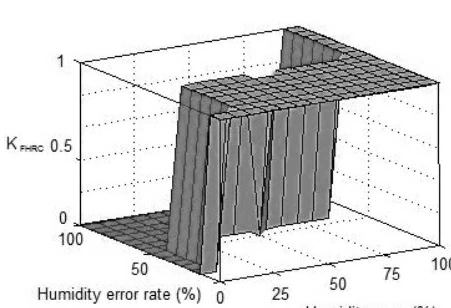


Figure 11. FHRC's control surface ($K_{FHRC\_in} = 0.8$; $K_{dFHRC\_in} = 0.005$; $K_{FHRC\_out} = 10$).

Fuzzy Electrical Resistance Controller (FERC-PD)

The controller defines the proportional and derivative action of air temperature. Eleven fuzzy sets and nine rules were designed to map its relationship between inputs and the output. Equations 10 and 11 present its control law and Figure 12 shows its control surface.

$$R_C(t) = K_{FERC} K_{FERC\_out} \quad (10)$$

$$K_{FERC} = f(K_{FERC\_in} e_T(t), K_{dFERC\_in} de_T(t)/dt) \quad (11)$$

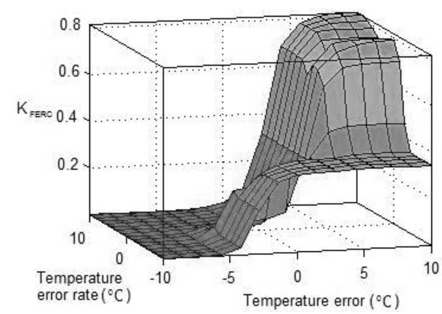


Figure 12. FERC's control surface ($K_{FERC\_in} = 2$; $K_{dFERC\_in} = 0.003$; $K_{FERC\_out} = 20$).

Fuzzy Blower Controller (FBC-PD

The controller is a nonlinear mapping of air velocity control action. Nine fuzzy sets and nine rules were used as parameters to characterize the behavior with current and future velocity error. Equations 12 and 13 present the FBC-PD control law, whereas Figure 13 provides the corresponding control surface.

$$B_C(t) = K_{FBC} K_{FBC\_out} \quad (12)$$

$$K_{FBC} = f(K_{FBC\_in} e_V(t), K_{dFBC\_in} de_V(t)/dt) \quad (13)$$

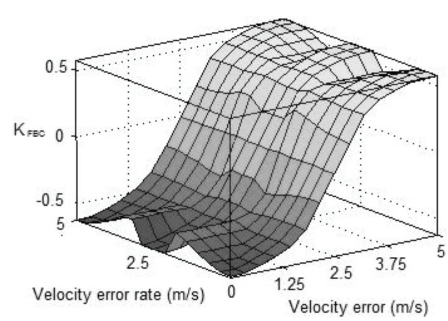


Figure 13. FBC's control surface ($K_{FBC\_in} = 0.3$; $K_{dFBC\_in} = 0.3$; $K_{FBC\_out} = 5$).

Results and discussion

Relative humidity and temperature tracking tasks

Figures 14 to 19 show the experimental results of MIMO-based PID and FLC controllers presented in the last section, without retuning their parameters.

The experiments were performed simultaneously by controlling the three parameters within the installation, that is, by the performance of the four controllers developed (humidifier, dehumidifier, electric resistances and centrifugal blower).

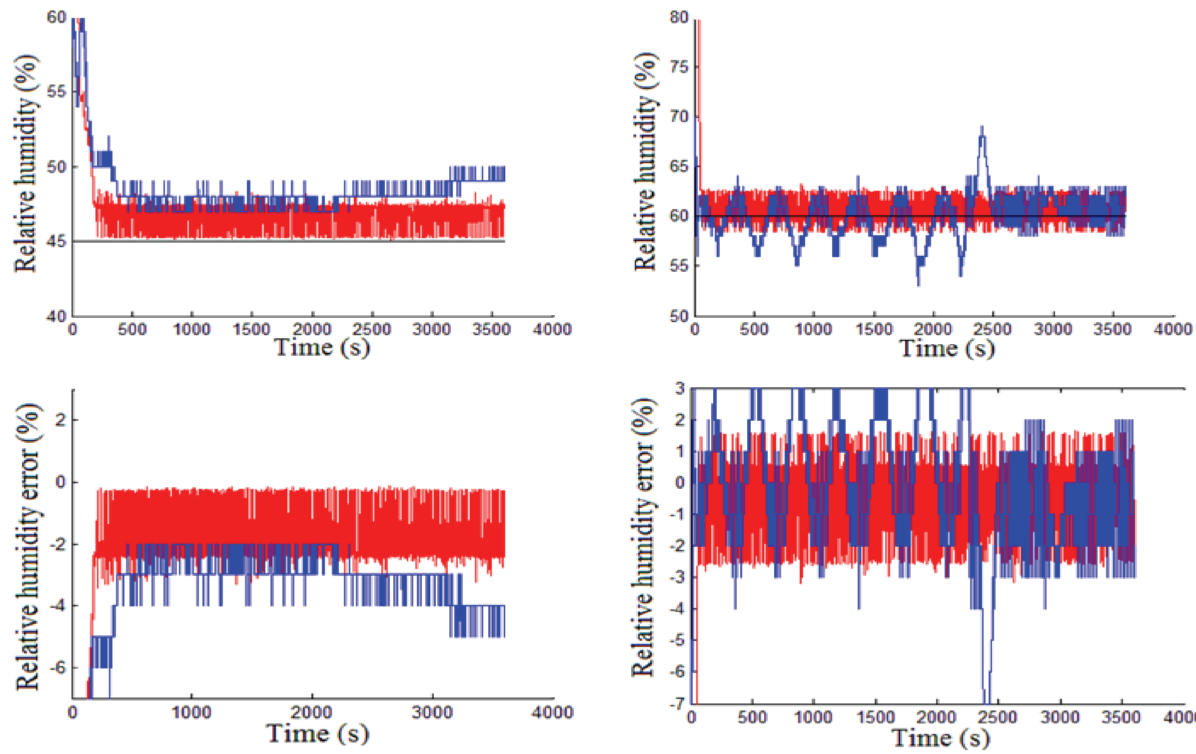


Figure 14. PID and FLC controllers' response to relative humidity control - experiment 1 (left) and 2 (right).

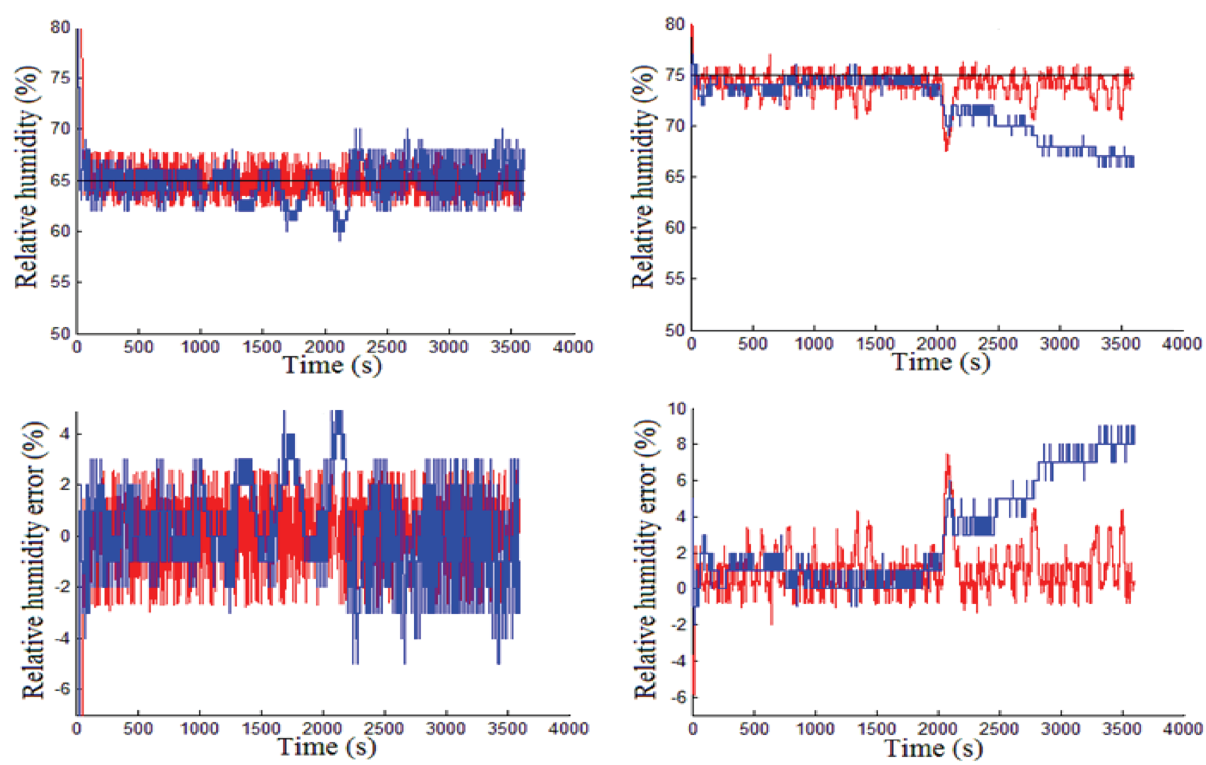


Figure 15. PID and FLC controllers' response to relative humidity control - experiment 3 (left) and 4 (right).

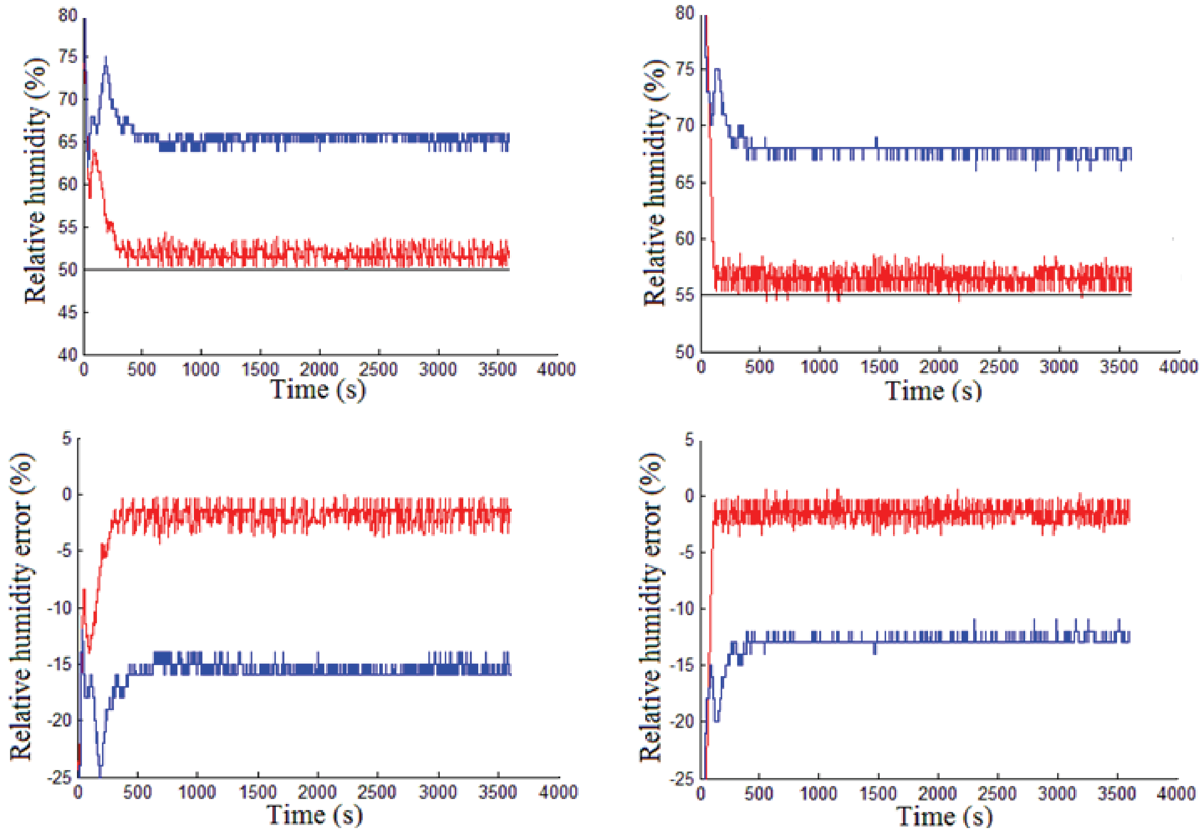


Figure 16. PID and FLC controllers' response to relative humidity control - experiment 5 (left) and 6 (right).

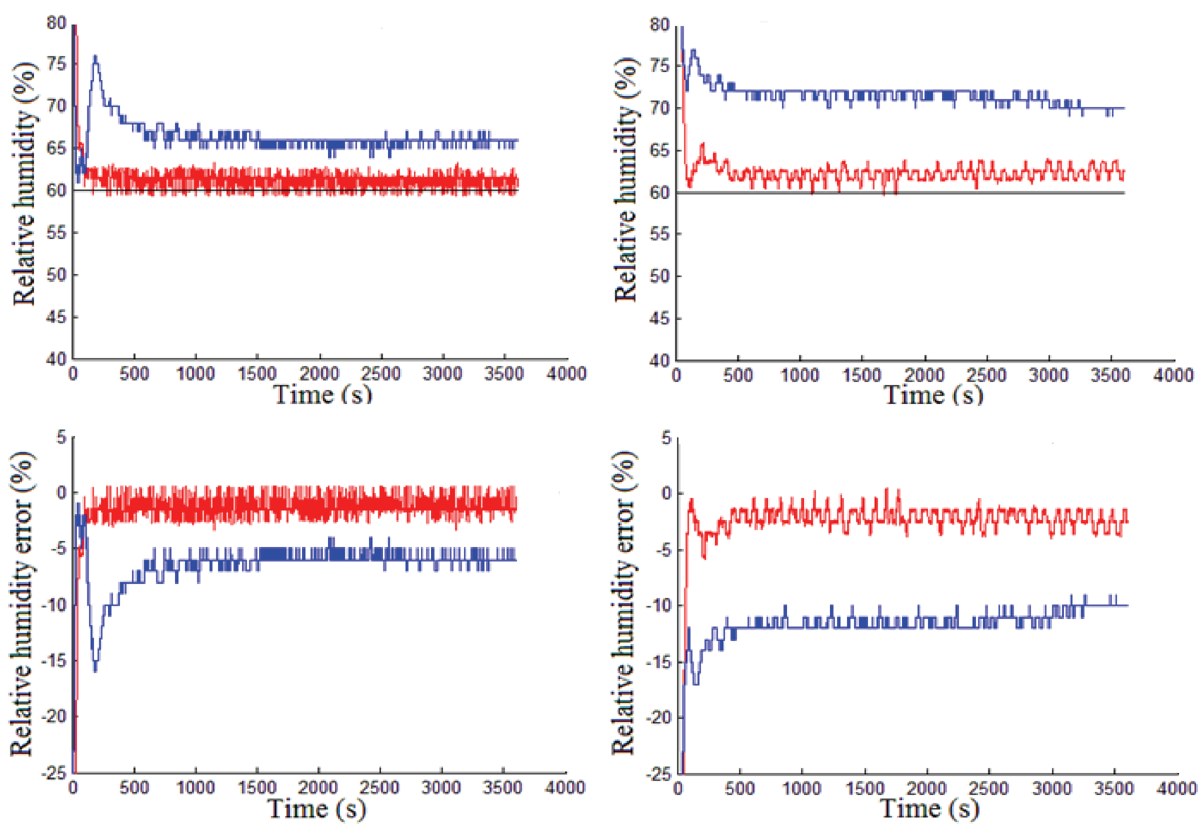


Figure 17. PID and FLC controllers' response to relative humidity control - experiment 7 (left) and 8 (right).

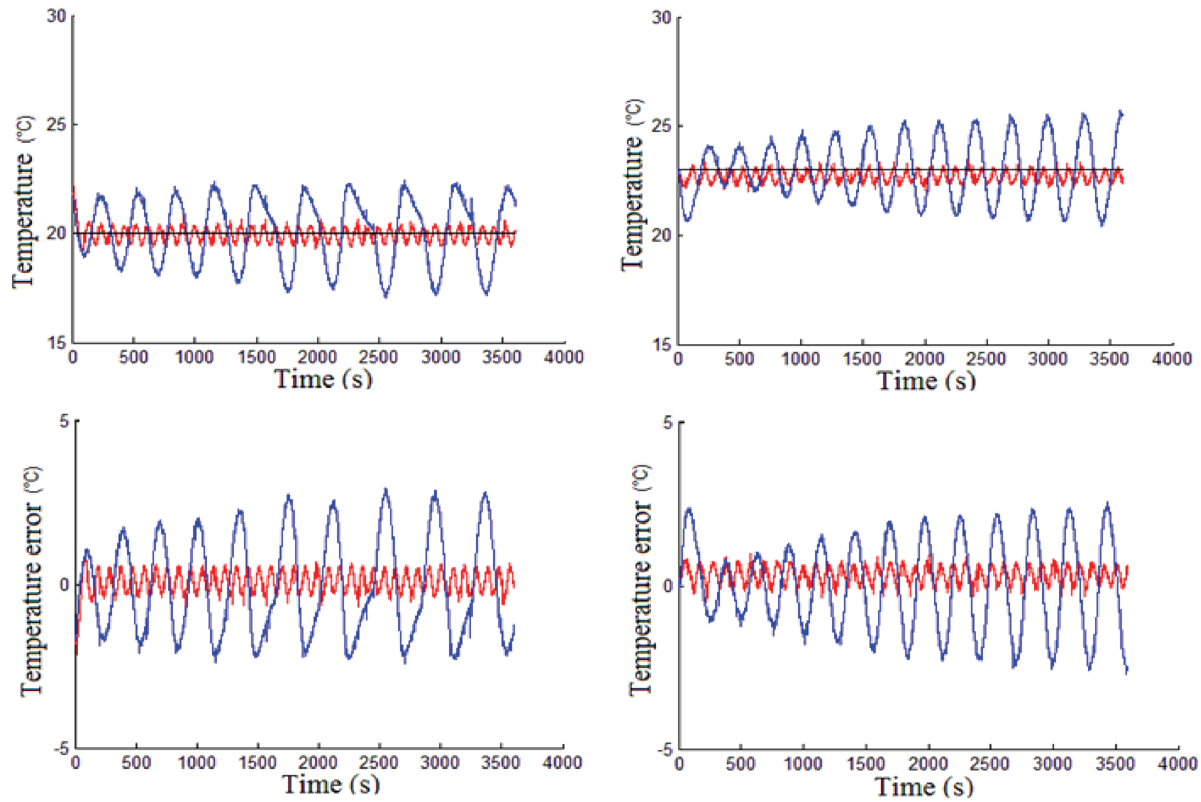


Figure 18. PID and FLC controllers' response to temperature control - experiment 1 (left) and 2 (right).

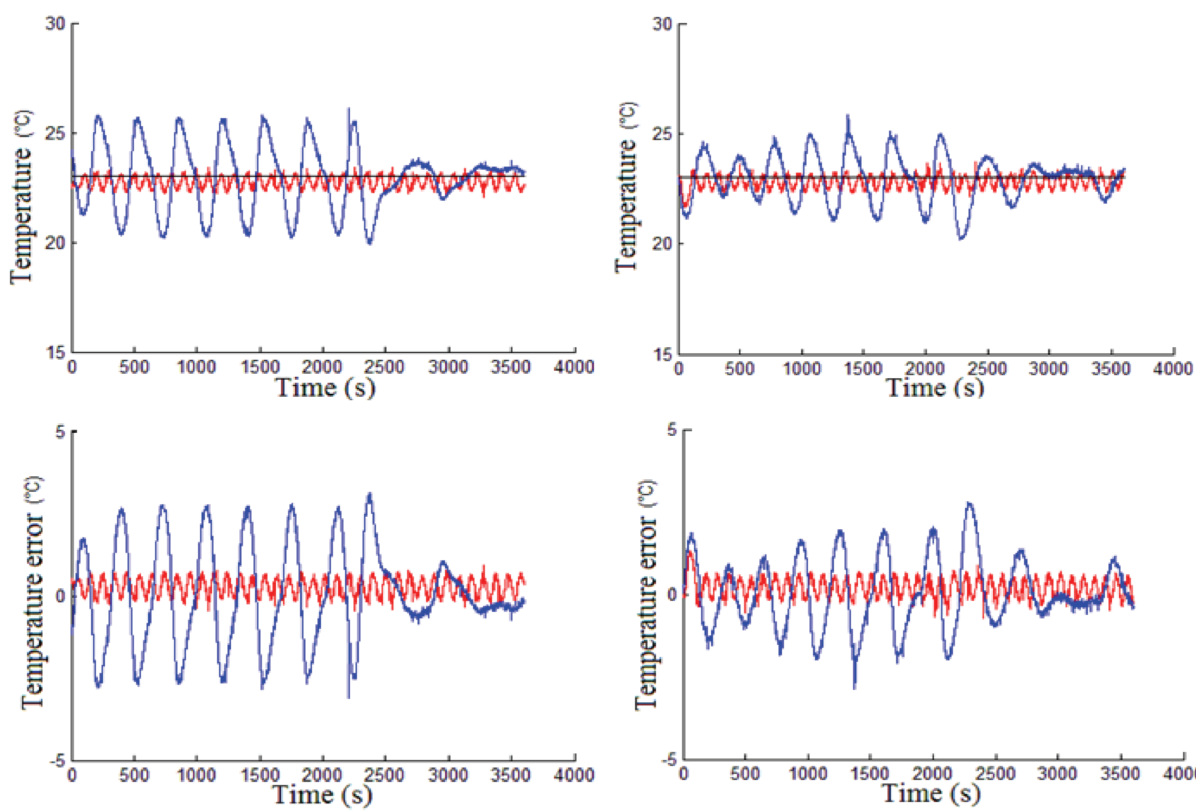


Figure 19. PID and FLC controllers' response to temperature control - experiment 3 (left) and 4 (right).

Figures 14 to 19 show that humidity and temperature control provided a better performance by the fuzzy logic-developed controller, for all analyzed conditions. These observations are confirmed by an analysis of errors in the results obtained for each controller, when compared to the desired rates in each experiment.

Controller performance analysis and discussion

Controllers' performance was analyzed through the absolute mean error (AME) and mean squared error (MSE). Tables 1 and 2 show numerically the results.

Results obtained from the fuzzy control were compared by a PID control. The analysis of these controllers showed better results for the fuzzy control: mean absolute errors were less than 2.79% for relative humidity control and 0.349°C for temperature control, respectively around 3.93 and 3.71 times lower than the experimental results found when the PID control was used.

Table 1. Controllers' response to relative humidity control.

Experiment	Criteria Evaluation (FLC | PID)	
	AME	MSE
1	1.84 | 3.25	5.37 | 13.32
2	1.10 | 1.73	1.70 | 5.16
3	1.22 | 2.94	3.34 | 16.77
4	2.49 | 16.15	14.54 | 265.47
5	2.33 | 13.51	32.27 | 192.53
6	1.72 | 6.66	15.01 | 49
7	2.79 | 11.93	26.33 | 151.78
8	2.28 | 5.83	18.68 | 44.33
Mean	1.97 | 7.75	14.66 | 92.29

In the case of relative humidity control, the rate of absolute mean error, by fuzzy controller, ranged between 1.10 and 2.79, whereas in the case of PID controller, the absolute mean error ranged between 1.73 and 16.15. The mean squared error ranged between 1.70 and 32.27 for the fuzzy control and from 5.16 to 265.47 for PID control.

Table 2. Controllers' response to temperature control.

Experiment	Criteria Evaluation (FLC | PID)	
	AME	MSE
1	0.289 | 1.355	0.126 | 2.339
2	0.349 | 1.201	0.176 | 1.909
3	0.319 | 1.218	0.149 | 2.271
4	0.293 | 0.86	0.131 | 1.138
Mean	.312 |1.159	0.146 | 1.914

In the case of temperature control, the rates obtained by fuzzy controller for absolute mean error ranged from 0.289 to 0.319, whereas in the case of PID controller, absolute mean error ranged between 0.86 and 1.355. The mean squared error ranged between 0.126 and 0.176 for the fuzzy control and ranged from 1.138 to 2.339 for PID control.

Conclusion

Current paper proposes high performance non-linear fuzzy controllers for real-time operation of a drying machine. PID and FLC-PD real-time-based controllers were designed, tested and compared for the control of relative humidity and temperature drying parameters. The overall FLC was composed of four fuzzy controllers: Fuzzy Dehumidifier Controller, Fuzzy Humidifier Controller, Fuzzy Electrical Resistances Controller and Fuzzy Blower Controller. Analysis of their performance revealed a better performance of the fuzzy logic controller: absolute mean errors were lower than 2.79% for relative humidity control and 0.349°C for temperature control, respectively about 3.93 and 3.71 times lower than the experimental results found by PID control. Despite a reasonable number of rules and fuzzy sets, high performance drying controllers were carried out, without taking into account the mathematical model of the drying process. Further, the authors would like to develop an automatic tuning algorithm to optimize fuzzy sets, rules and parameters of FLC controller by genetic-based search algorithms.

Nomenclature

AME	Absolute mean error	%
B_C	Blower control signal	V
D_C	Dehumidifier control signal	V
e_{RH}	Relative humidity error	%
e_T	Temperature error	°C
e_v	Air velocity error	$m\ s^{-1}$
FBC-PD	Fuzzy Blower Controller	-
FDC-PD	Fuzzy Dehumidifier Controller	-
FERC-PD	Fuzzy Electrical Resistance Controller	-
FHRC-PD	Fuzzy Humidifier Controller	-
H_C	Humidifier control signal	V
MSE	Mean squared error	%
R_C	Electrical resistances control signal	V
RH_R	Real relative humidity	%
RH_{SET}	Desired relative humidity	%
T_R	Real temperature	°C
T_{SET}	Desired temperature	°C
v_R	Real air velocity	$m\ s^{-1}$
v_{SET}	Desired air velocity	$m\ s^{-1}$

References

ALVAREZ-LÓPEZ, I.; LLANES-SANTIAGO, O.; VERDEGAY, J. L. Drying process of tobacco leaves by using a fuzzy controller. **Fuzzy Sets and Systems**, v. 150, n. 3, p. 493-506, 2005.

ATTHAJARIYAKUL, S.; LEEPHAKPREEDA, T. Fluidized bed paddy drying in optimal conditions via adaptive fuzzy logic control. **Journal of Food Engineering**, v. 75, n. 1, p. 104-114, 2006.

DUFOUR, P. Control engineering in drying technology: review and trends. **Drying Technology**, v. 24, n. 7, p. 889-904, 2006.

DUFOUR, P.; BLANC, D.; TOURÉ, Y.; LAURENT, P. Infrared drying process of an experimental water painting: model predictive control. **Drying Technology**, v. 22, n. 1, p. 269-284, 2004.

GOU, P.; COMAPOSADA, J.; SERRA, E.; COROMINAS, M.; POCH, M.; ARNAU, J. Fuzzy control system in drying process of fermented sausages. **Drying Technology**, v. 23, n. 9, p. 2055-2069, 2005.

LIU, H.; ZHANG, J.; TANG, X.; LU, Y. Fuzzy control of mixed-flow grain dryer. **Drying Technology**, v. 21, n. 5, p. 807-819, 2003.

SIETTOS, C. I.; KIRANOUDIS, C. T.; BAFAS, G. V. Advanced control strategies for fluidized bed dryers. **Drying Technology**, v. 17, n. 10, p. 2271-2291, 1999.

YÜZGEÇ, U.; BECERIKLI, Y.; TÜRKER, M. Dynamic neural-network-based model-predictive control of an industrial baker's yeast drying process. **IEEE Transactions on Neural Networks**, v. 19, n. 7, p. 1231-1242, 2008.

Received on September 16, 2011.
Accepted on March 2, 2012.