Fuzzy control of a biomass-fired and solar-powered fluidized bed prototype as a residential cogeneration system

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Abstract: - A fuzzy PI controller is proposed as an alternative to a PI traditional controller for regulation and control of a small-scale fluidized bed cogeneration system driven by two renewable energy sources: direct solar and biomass combustion. The design of the fuzzy logic controller, with Sugeno inference method, was based on the knowledge of the most relevant continuity diagrams of the process model, characterized by nonlinearity and parameter variability. The simulation results show that the PI fuzzy logic controller delivers a better performance, in terms of robustness and response speed, compared to a traditional PI controller. It is proved that the use of PI fuzzy controllers is a recommendable choice for control of nonlinear processes with parameters varying in time.

Key-Words: - Fuzzy control, PI (proportional integrative) controller, FBC (fluidized bed combustor), continuity diagram, Stirling engine, energy balance.

1 Introduction

The difficult task of modeling and controlling complex and nonlinear systems is well known. If a relatively accurate model of a dynamic system can be developed, it is often too complex to use it directly in controller development. Many conventional control design techniques in fact require restrictive assumptions (e.g., linearity), not only for the plant model, but also for control design. Traditional controllers are not able to perform very effectively when the systems to be controlled are characterized by high nonlinearity and parameter uncertainty. It is true that a PID (Proportional-Integral-Derivative) controller may be tuned to be effective at certain conditions, but a change in the value of some system parameters may also destabilize the whole control system, making ineffective the PID controller action. Many non-linear systems are in fact characterized by dynamics that can be strongly dependent on one or more parameters and their operative conditions turn out stable or acceptable only if the values of these parameters remain within a limited range. If the system parameters go out of this range, then the equilibrium point becomes unstable. To handle these unexpected events (e.g., changes in the system parameters) it is necessary to develop robust controllers such as fuzzy logic controllers. The design of a fuzzy controller is usually based on heuristics; however, because of their underlying fuzzyness, the fuzzy controllers are characterized by a high degree of clearness and robustness.

Fuzzy logic controllers (FLCs) have been reported to be successfully used for a number of complex and nonlinear processes (that are difficult to model analytically) [2] and are usually built up using fuzzy sets and fuzzy logic [3], [4]. The list includes cement kilns [5], subway trains [6], process heat exchangers, blast furnaces [7]. Obtaining an optimal set of fuzzy sets and rules is not an easy task. The tedious fuzzy tuning exercise requires time, experience, and skills of the operator. Recently, some intelligent techniques were considered for the task of tuning the fuzzy set [8].

This paper presents the control of a new small-scale fluidized bed cogeneration system driven by two renewable sources: direct sun energy (thermodynamic solar) and biomass thermal-chemical power (indirect sun energy) [1]. The dynamic model of the above unit, although very simple, is characterized by nonlinearity and parameters changing in time.

2 System description

2.1 FBC

The system considered is a bubbling fluidized bed prototype (FBC) that uses two renewable energy sources: biomass firing (indirect solar energy) and direct solar heating (thermodynamic solar) [9, 10]. The fluidized bed acts as a solar receiver, through the direct irradiation of bed solids by means of a concentrated solar radiation.

A Stirling engine, which is integrated into the fluidized bed, converts part of thermal energy into electricity. The large and unconditioned availability of the solar energy, especially in tropical and subtropical regions and the possibility to reduce the consumption of biomass, supports the integration of the Concentrated Solar Power (CSP). This source of energy allows obtaining fuel flexibility, low emissions and optimal operating conditions for the Stirling engine (SE) unit as well. A representation of the whole system is schematized in Fig.1. It consists of a solar collector (a mirror for the capture and concentration of the solar radiation); a FBC (used as: concentrated solar energy receiver, heat exchanger with the head of the SE and biomass combustor); a SE (to convert the heat collected in the FBC into mechanical and then electrical power); and a waste heat exchanger (to recover the unused low enthalpy heat). The maximum thermal/electric power is about 20 kW.

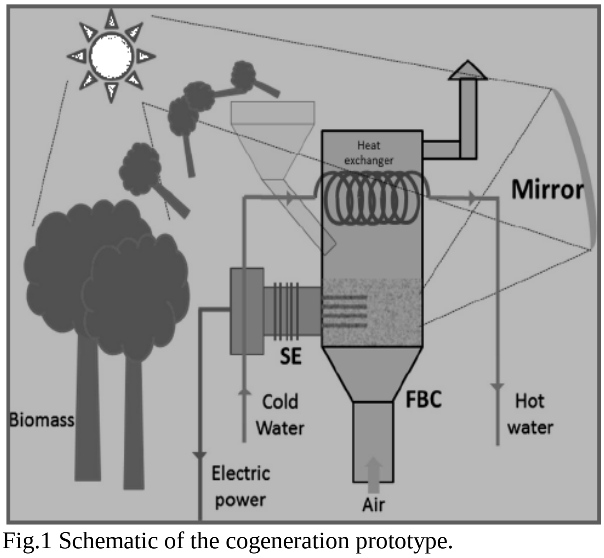

Fig.1 Schematic of the cogeneration prototype.

In Fig. 2 a flow diagram of the principal energy fluxes is shown. The fluidization is obtained, as usual, by air flow blowing from the bottom of a vessel where a certain amount of granular material, like sand, is loaded over an air distributor. This allows all particles and the gas phase to carry out efficient mass and heat transfer in the bed.

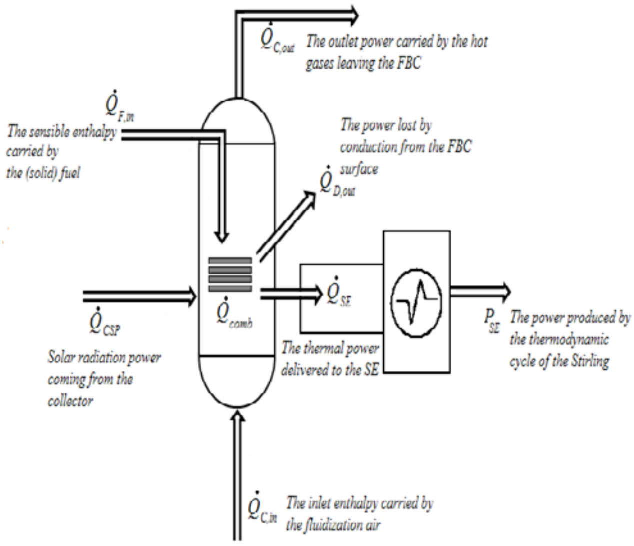

Fig.2. Flow diagram of the system with the indication of the control volume for the energy balance with the accounted energy fluxes.

2.2 Model of FBC

A simple model has been adopted by slightly modifying that developed by Angrisani et al. [1]. The model considers the direct coupling of a solar energy source and a heat sink (through the SE hot exchanger) in the bed of a FBC and is derived from an analysis of energy fluxes among the several system components. Inside the FBC the temperature can be assumed uniform in space. Several models are proposed in the literature to estimate fundamental design parameters for a FBC. This approach is described in [11] and [12], and it is here adopted by the authors to determine the performance of the system. The various flux contributions to the energy balance are shown schematically in Fig. 2. The energy balance is written assuming the FBC working as a pseudo-homogeneous, perfectly stirred reactor including both solid-phase and gas-phase. With this assumption it is possible to assume only a single temperature for both solid- and gas-phase. The dynamic energy balance is:

$$\frac{dT}{dt} = \frac{1}{m_s c_s}\left[\dot{Q}_{C,in} + \dot{Q}_{F,in} + \dot{Q}_{CSP} + \dot{Q}_{SE} + \dot{Q}_{C,out} + \dot{Q}_{D,out} + \dot{Q}_{comb}\right]$$

(1)

The main energy fluxes, per unit time, in (eq.1) are the following:

the inlet enthalpy carried by the fluidization air, assumed as an ideal gas:

$$\dot{Q}_{C,in} = \dot{m}_{C,in} \cdot c_p(T_{in}) \cdot T_{in} \quad (2)$$

the sensible enthalpy carried by the (solid) fuel entering the fluidized bed:

$$\dot{Q}_{F,in} = \dot{m}_F \cdot c_{pF}(T_{Fin}) \cdot T_{Fin} \quad (3)$$

the solar radiation power coming from the collector:

$$\dot{Q}_{CSP} = \eta_{CSP} \cdot I_S \cdot A_S \quad (4)$$

(where η_{CSP} is the global efficiency achieved in the process of collection and transmission to the fluidized bed of the solar power at irradiance I_S, adopting a mirror corresponding to a capture surface with area A_S);

the thermal power delivered to the Sterling engine: $\dot{Q}_{SE}$ It is considered a disturbance from the viewpoint of the control system, because it is highly dependent on weather conditions (it reaches its maximum value during a sunny day, but it may decrease during a cloudy day, down to a limiting value of zero);

the outlet power carried by the hot gases leaving the fluidized bed combustor, including both fluidization air and combustion gases:

$$\dot{Q}_{C,out} = -\dot{m}_{out} \cdot c_p(T) \cdot T \quad (5)$$

where $\dot{m}_{out} = \dot{m}_{C,in} + \dot{m}_F$;

the power lost by dispersion to the outside environment through the FBC walls:

$$\dot{Q}_{D,out} = -\alpha \cdot \dot{Q}_{comb} \quad (6)$$

where α is a parameter expressing a proportionality factor;

the thermal released by biomass combustion

$$\dot{Q}_{comb} = \eta_c \cdot \dot{m}_F \cdot \Delta H_F \quad (7)$$

where η_c is the in-bed combustion efficiency, $\dot{m}_F$ the mass feed rate of fuel, and ΔH_F the lower heating value of the fuel.

A large fraction of combustion enthalpy is released in the bed under usual operation, while the remainder fraction is released in the freeboard.

Table 1. Operating variables of the FBC

Air excess [-]	0.3
T_{in} Inlet gas temperature [K]	300
T_{Fin} biomass inlet temperature [K]	300
$\dot{m}_F$ Biomass feed rate [kg/h]	1 - 4
ΔH_F Lower heating value of biomass [J/kg]	18.24E+06
Air/Fuel stoichiometric ratio[kg/kg]	5.5814
m_s Total mass of bed particles [kg]	30 - 40
$\dot{Q}_{C,o}$ The outlet power carried by the hot gases leaving the FB, including both fluidization air and combustion gas [W]	5000 - 10000

Table 2. Parameter values of the FBC mathematical model

η_c biomass combustion efficiency	0.95
η_{CSP} global collector efficiency	0.75 – 0.85
I_S solar irradiance at the latitude of Naples [W/m^2]	500 - 1000
α parameter of thermal dispersion to the environment	0.05 – 0.15
C_p Specific heat of air / flue gas at constant pressure [J/(kg K)]	9.460168275862069e+02 + 0.213095448275862·T +3.099045517241379e-05·T^2
C_{ps} Specific heat of solids forming the fluidized bed [J/(kg K)]	800
ρ_s Density of bed solid particles [kg/m^3]	2600
C_{pf} specific heat of biomass [J/(kg K)]	1000 - 1500

In the model (eq. 1), the heating of the bed due to heat released in the freeboard region is not considered. Further, the in-bed combustion efficiency is taken as η_c=0.95, this value being reasonable on account of the amount of heat released in the bed as a function of the actual FBC conditions [13].

3 Problem Formulation

3.1 PID control

It is well known that traditional controllers such as PI or PID lend themselves to the construction of feedback linearization control. The PID control is actually more used than fuzzy control. It is an intuitive control and its actions depend on the current controller error (proportional term), the time history of the error (the integral term), and a time variation of the value of the error (the derivative term). The applicability of PID controllers is wide (they work well for a large class of processes) also in those cases where a process model is not always available and in addition there are many effective tuning rules. However there are many cases where the process is highly nonlinear and is necessary to consider a control characterized by nonlinearity as well. The controller nonlinearity in fact can be designed so as to compensate for process

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nonlinearities. The main advantage of fuzzy PID or fuzzy PI control is that of combining the advantages of ordinary linear PID or PI control with the possibility to introduce nonlinearities in the control law.

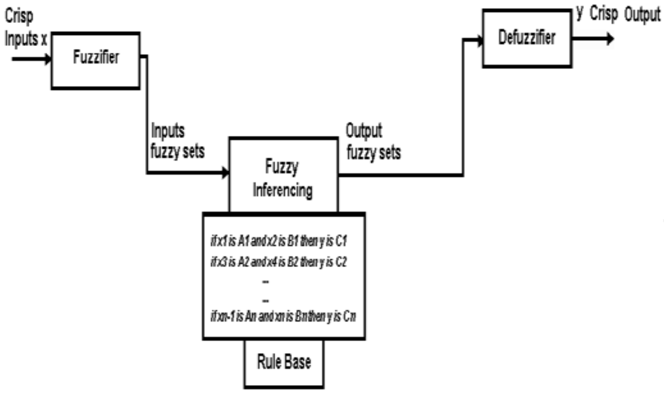

Fig. 3. Fuzzy logic system.

3.2. Fuzzy logic system

Four main components characterize the fuzzy controller (as shown in Fig.3) and they are: a) the fuzzification (fuzzifier block), necessary to modify the inputs to be interpreted in the rule base, fuzzifying the crisp inputs (by membership functions that derive the membership grades of the crisp inputs); b) the inference mechanism (fuzzy inferencing block), to evaluate which controls at the current time are relevant and then to decide consecutively what input (output of the fuzzy logic system) must be sent to the plant; c) the rule base (expressed in the form *if-then*) where is contained all the knowledge of the control process; d) the defuzzification (defuzzifier block), to convert the conclusions of the inference mechanism into the inputs (as crisp value) to the plant. The last block is fundamental because the resulting fuzzy set must be converted to a single number in order to form a control signal to the plant.

The input measurements are evaluated according to the premise of the rules. Each premise produces a membership grade expressing just the degree of membership of the premise. Generally the rule base is constructed so as to represent a human expert in the loop. Each rule has this form: *if* the behavior of the plant output is this *and* the reference input (set point) of the plant is this, *then* the plant input (the manipulation variable) should be this value.

It is necessary to load a whole set of *if-then* rules in to the rule-base and once the inference strategy has been chosen the system is ready to be tested. Fuzzy systems allow a flexible categorization of a domain of interest. Membership functions and rules are therefore the heart of fuzzy logic and the right choice of them influences all the system behavior.

The rule base formalism is intuitive and easy to understand, in each rule there is a local process knowledge and is described how the control signal should be selected for certain input signals.

3.3. FBC control

There are examples for control of FBCs in literature: Vamvuka et al. [14] proposed control methods for mitigating biomass ash- related problems in fluidized beds; an innovative bed temperature-oriented modeling and a robust control of a circulating fluidized bed combustor were proposed by Aboozar et al. [15]; a control system for an oxy-fuel combustion fluidized bed with flue gas recirculation was developed by Guedea et al. [16]; the control of NOx and N2O in pressurized fluidized-bed combustion was proposed by Yong Lu et al. [17]. The emission control measurements and devices to comply environmental regulations for a biomass fluidized bed combustion were discussed by Stefan [18].

In this paper the proposed control scheme is that of a simple feedback (Fig.4). The controlled variable is the bed temperature T and the manipulated variable is the fuel feed rate $\dot{m}_F$ (Fuel_in). The inputs of fuzzy logic controller are represented by the error and the integral of the error.

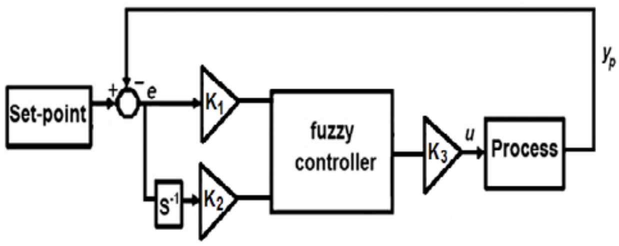

Fig. 4. Diagram block for the PI fuzzy control system.

The scale factors at the entrance of fuzzy controller adjust the error and the integral of the error values to the range of the input fuzzy sets. Before designing the controller, the diagrams solutions and dynamics of the open loop system were analyzed to make a diagnosis of the system. This first step is very important to understand the dependence of the system from variable and parameter values. The software used was Matlab®, integrated with Simulink toolbox and Matcont, this latter for the numerical study of a continuation or bifurcation on the continuous and discrete parameterized dynamical systems.

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4 Problem Solution

4.2 Dynamics and solution diagrams

4.2.1 Open loop simulation

In the next figures the dependence of the system bed temperature from $\dot{m}_F$ (Fuel_in), i.e., the manipulation variable in the control system, is analyzed.

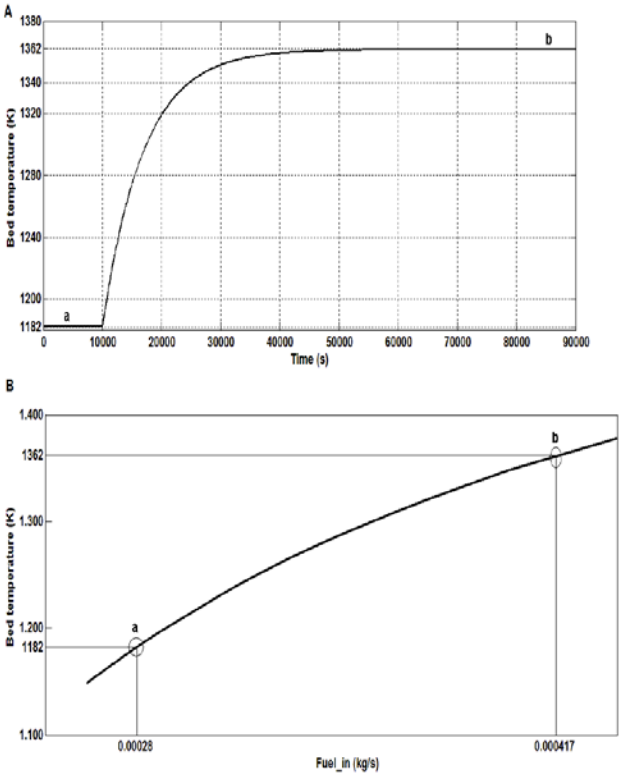

Fig. 5 – A) Time trajectory of the system bed temperature T (K), for Fuel_in value step change from a) 0.00028 to b) 0.000417 kg/s at fixed values of csp_irradiance = 750 W/m^2 and Q_{SE} = -9000 W. -
- B) Solution diagram of bed temperature T (K) vs Fuel_in (kg/s). The diagram shows the equilibrium point in correspondence of (a) Fuel_in = 0.00028 kg/s and bed temperature T =1182 K and b) Fuel_in = 0.000417 kg/s and Bed temperature T =1362 K (b), at fixed values of csp_irradiance = 750 W/m^2 and Q_{SE} = -9000 W.

Table 3- Contributions of the various terms in the energy balance
(Fuel_in = 0.000417 kg/s, csp_irradiance = 750 W/m^2 and Q_{SE} = -9000 W).

Qcin [W] 914.20	Qcsp [W] 7312.5	Qcomb [W] 7225.8	Q_{SE} [W] -9000
Qcout [W] -5525	Qrout [W] -1083.9	QFin [W] 156.38	

In Fig 5a and 5b the time trajectory and the solution diagram of the system bed temperature are respectively shown for Fuel_in value step change from a) 0.00028 to b) 0.000417 kg/s at fixed values of csp_irradiance = 750 W/m^2 and Q_{SE} = -9000 W. The contributions of the various terms in the energy balance in correspondence of the new steady state are shown in Table 3. It easy to note that in input the incoming solar heat and the chemical energy released from the fuel prevail, while in output the heat transferred to the Stirling engine prevails. It should be noted that under the conditions of Table 3, the values of solar irradiance I_s and power transferred to the Stirling engine have been fixed in the calculation. Obviously, being at steady state, the energy balance, which contributes to the terms listed in Table 3, closes to zero. The above trend is confirmed by Fig. 6 that shows the temperature of the bed as a result of the step change in Fuel_in from 0.00028 to 0.000417 kg/s at 10000 s, at fixed csp_irradiance = 750 W/m^2, for three different values of the load to the Stirling engine, e.g., Q_{SE} = -10000, -9000 and -8000 W, respectively.

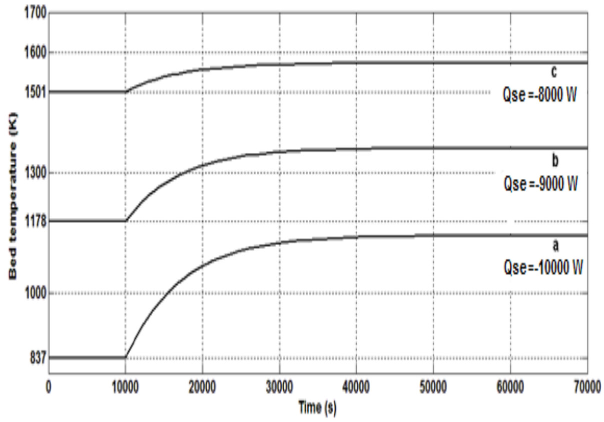

Fig. 6 Time trajectory of the system bed temperature T (K), for a step change in Fuel_in from 0.00028 to 0.000417 kg/s at 10000 s, at fixed csp_irradiance = 750 W/m^2, for different Q_{SE} values: a) Q_{SE} = -10000 W; b) Q_{SE} = -9000 W; c) Q_{SE}= -8000 W.

To optimize the control system it is necessary to delineate the different stability regions in the system and to study the effect of some operating parameters on the dynamics. The Fig.7a shows time trajectory of the system bed temperature (K), for csp_irradiance step change from c) 750 W/m^2 to a) 0 W/m^2 (cloudy day); b) 300 W/m^2; d) 1000 W/m^2 (sunny day) at fixed Qse = -8000 W and Fuel_in = 0.0006 kg/s. Obviously, the characteristics of the dynamic response of the system do not change. The settling time is in fact always of the order of 20000 s. The Fig. 7B shows the corresponding solution diagram of the bed temperature. It shows the locus of equilibrium points as a function of biomass feed rate $\dot{m}_F$ (Fuel_in) for a variation of csp_irradiance as a parameter.

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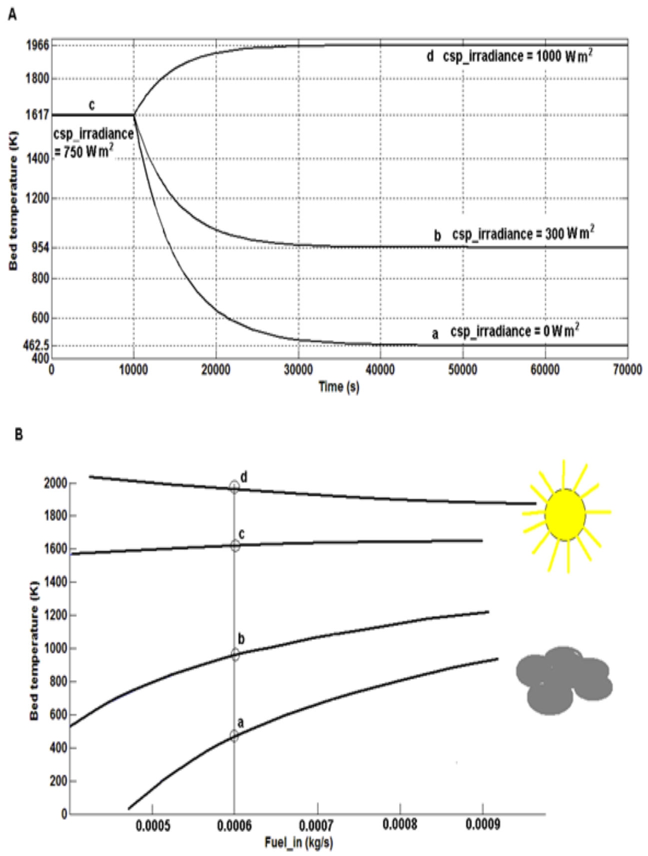

Fig. 7 – A) Time trajectory of the system bed temperature T (K) for csp_irradiance step change from c) 750 W/m^2 to a) 0 W/m^2; b) 300 W/m^2; d) 1000 W/m^2 at fixed Qse = -8000 W and Fuel_in = 0.0006 kg/s. - B) Solution diagram of bed temperature T (K) vs Fuel_in (kg/s). The diagram shows the equilibrium point in correspondence of Fuel_in = 0.0006 kg/s for different values of the disturbance: a) csp_irradiance = 0 W/m^2; b) 300 W/m^2; c) 750 W/m^2; d) 1000 W/m^2, at fixed value Q_{se}= -8000 W.

It easy to note that a decrease in the value of csp irradiance has unfavorable consequences on system bed temperature. This can lead to the shutdown of the FBC. Therefore, an effective control action is necessary to handle these contingencies.

5 Design, simulation and results

5.2 PI control and nonlinear PI fuzzy control

The transfer function of the PID controller is:

$$G_{PID} = K_c\left(1+\tau_D s+\frac{1}{\tau_I s}\right)$$

where K_c is the controller gain, τ_D is the *derivative time* e τ_I is the integral time or *reset time*). In this case only a PI controller was considered, because the derivative action contribution is negligible.

Tuning of the controller, i.e., the final adjustment of its parameters, is a topic extensively discussed in the literature. Nevertheless, the controller tuning is done, in most cases, manually "on the field" (trials and errors). In the present case the authors used a method based on the minimization of an objective function as the index IAE as obtained by simulation of the controlled system. This method led to the determination of the following values for the parameters of the PI controller:

$K_c = 12$ (control gain)

$\tau_I = 0.008$ s (integral time)

It was also tried to reach a compromise on a response of the controlled system that eliminates the offset in reasonable time and allows reducing the problem of overshooting as much as possible.

Regarding the non-linear fuzzy controller, the values of fuzzy set parameters, the rule base developed by the authors and its characteristics are reported in Tables 4, 5 and 6, respectively.

Table 4. Fuzzy sets for the error and the integral of the error.

Error	Gaussian membership functions
Negative	[42.46 -100]
Zero	[42.46 0]
Positive	[42.46 100]
Integral of the error	Triangular membership function
Negative’	[-200 -100 -20]
Zero’	[-100 0 100]
Positive	[20 100 200]
Output (crisp values)	[-200 -100 0 100 200]

Table 5. Rule base of nonlinear fuzzy controller

Error / Int Error	Negative	Zero	Positive
Negative’	-200	-100	0
Zero’	-100	0	100
Positive’	0	100	200

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Table 6. Fuzzy Controller characteristics

NumInputs	2
NumOutputs	1
NumRules	9
AndMethod	prod
OrMethod	probor
ImpMethod	prod
AggMethod	sum
DefuzzMethod	wtaver

The performance of the first fuzzy controller built following the method of Jantzen [8] is very similar to that of the PI controller and, for this reason, it has not been reported in the following simulations. Such a controller is in fact linear, as seen from the surface of the rules shown in Fig. 8A. By suitably modifying the fuzzy sets of the first and second input, it was possible to obtain a non-linear PI fuzzy controller (Nonlinear FLC) characterized by high-performance (Fig. 8B).

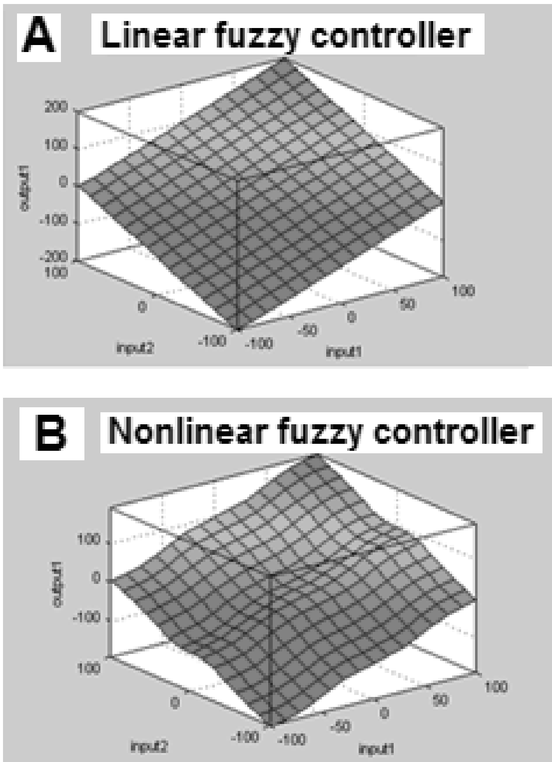

Fig. 8. Rule surface for linear fuzzy controller (A) and nonlinear fuzzy controller (B).

The following Fig. 9 shows the input, output and Sugeno fuzzy inference system that has been implemented into the adopted non-linear fuzzy controller.

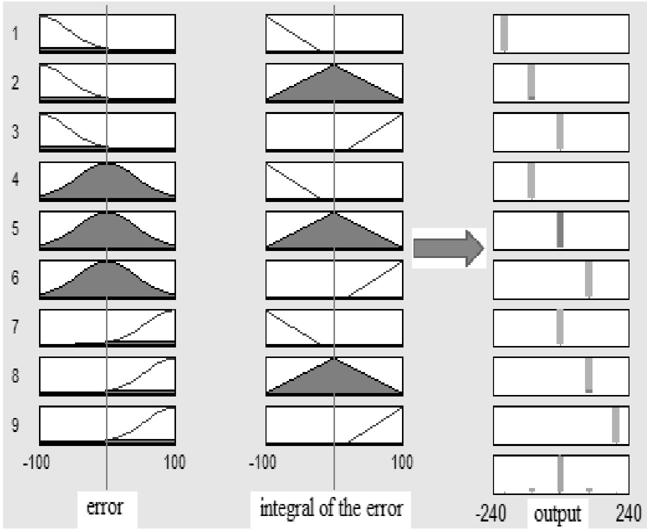

Fig. 9. Input, output and Sugeno fuzzy inference system for nonlinear fuzzy controller.

5.2 Closed loop simulation

5.2.1 Servo control

The time trajectory of the system bed temperature (K), for set point value step change from 1177 K to 1160 K at fixed values of Q_{SE}= -8000 W and csp_irradiance = 750 W/m^2 at t = 1000 s is shown in Fig. 10A. It is easy to note that only with nonlinear fuzzy controller it is possible to reach the new set point value and remain on it, without falling below this value and then approaching it after a long time. Only with a zoom shown in Fig. 10B it is possible to note the small overshooting of the fuzzy control system. In Fig. 11 the time trajectory of the system bed temperature (K) is shown, for a positive set point value change, i.e., precisely from 1177 K to 1220 K at fixed values of Q_{SE} = -8000 W and csp_irradiance = 750 W/m^2 at t = 1000 s. What is shown in Fig.11 confirms the previous result. The system controlled by either the nonlinear fuzzy controller or the traditional PI controller shows an overshoot; however, while the system controlled by PI controller crosses this value and falls below it , the system controlled by fuzzy controller reaches the new set point value and remain on it just at its second crossing point, showing to be more efficient and faster. In Fig 12 the time trajectory of the system bed temperature (K) is reported, for a set point value random variation at fixed value of Q_{SE} = -8000 W and csp_irradiance = 750 W/m^2.

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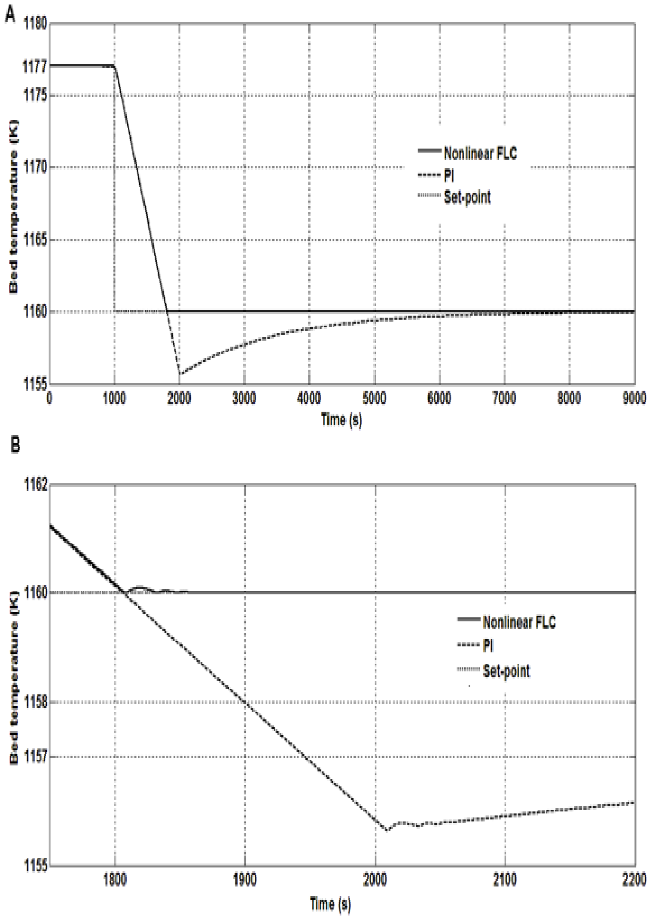

Fig. 10 - A) Time trajectory of the system bed temperature T (K), for set point value step change from 1177 a 1160 K at t= 1000 s, at fixed values of Qse = -8000 W and csp_irradiance = 750 W/m^2. - B) Zoom of Fig. 10A

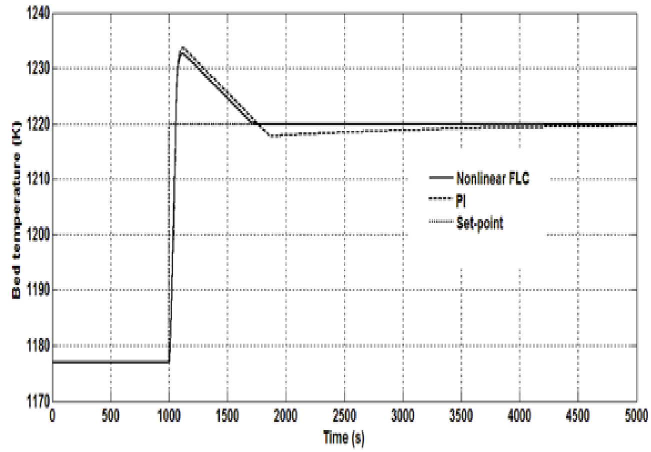

Fig. 11 - Time trajectory of the system bed temperature T (K), for set point value step change from 1177 to 1220 K at t= 1000 s, at fixed values of Q_{SE} = -8000 W and csp_irradiance = 750 W/m^2.

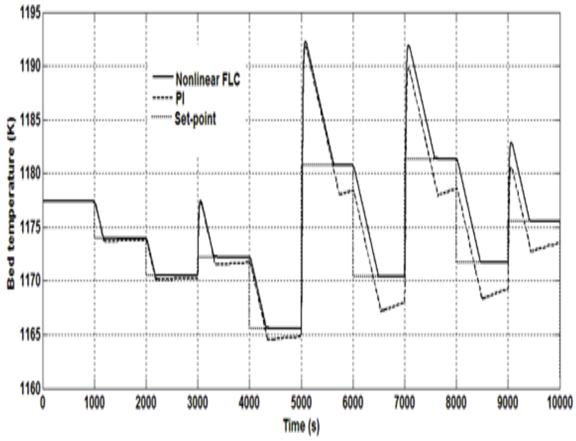

Fig. 12 - Time trajectory of the system bed temperature T (K), for set point value random variation at fixed value of Q_{SE} = -8000 W and csp_irradiance = 750 W/m^2.

Also in this case the results confirm the better performance of the fuzzy control, both for positive and negative step change. Only with fuzzy control the system can reach and settle to the new set point value before the set point changes randomly its value further.

5.2.2 Regulatory control

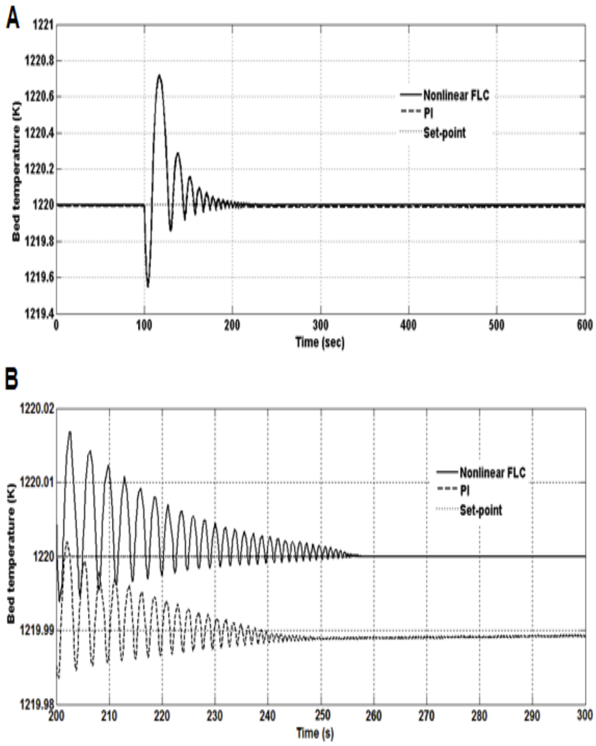

Fig. 13 - A) Time trajectory of the system bed temperature (K), for csp_irradiance (disturb) value step change from 750 to 0 W/m^2 at t= 1000 s, at fixed value of Q_{SE} = -8000 W.
- B) Zoom of Fig. 13 A.

In the last Fig. 13 the closed loop performance of nonlinear fuzzy control and traditional PI control are compared by changing the parameter csp_irradiance value, from 750 to 0 W/m^2, as if during the operation of the system, at some point, the solar energy collector becomes unable to absorb more energy (clouds obscure the sun), for fixed value of Q_{SE} = -8000 W at t = 100 s. Although the dynamics are much faster than the previous cases, it is possible to note that nonlinear controller FLC is a bit faster than the PI to reach the set-point due to the disturbance step in csp_irradiance.

6 Conclusions

- A feedback control system has been conceived, tuned and simulated for a cogeneration system driven by two renewable energy sources: direct solar and biomass combustion. In the simulations the system bed temperature was considered as the controller variable, while the irradiance as a disturbance and the biomass feed rate as the control variable (manipulation variable).
- Two different approaches were chosen for the choice and the development of controllers, the first conducted to a traditional PI controller, the second to a more advanced nonlinear fuzzy controller.
- The nonlinear FLC is performing much better than the traditional PI controller in terms of response oscillation, set point following, velocity and reject of disturb action.

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