International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 5 Issue 11, November-2016

Decentralized Fuzzy Supervisory Control for Binary Distillation Column

Ibrahim El Khalil Mekki [1,2], Maarouf Saad [3], Bouhamida Mohamed [2]

[1] Institut de maintenance et de sécurité industrielle (IMSI), Université d'Oran 2 Mohamed Ben Ahmed, Oran, Algérie
[2] AVCIS laboratory, University of Science and Technology Mohamed Boudiaf (USTO-MB), Oran, Algeria
[3] Department of Electrical Engineering, École de technologie supérieure, Montreal, Canada

ABSTRACT

This paper proposes a decentralized fuzzy supervisory control approach to control the nonlinear multivariable distillation column in order to improve the performance of the classical proportional integral (PI) controller. An inverted decoupling may be good and efficient to overcome interaction between the two loops of regulations and time delay. Due to their simplicity, the decentralized PI and fuzzy logic control (FLC) are popular and successful controllers in industrial applications. One combines the two controllers to form a decentralized fuzzy supervisory control (FSC) to overcome the limitation of decentralized PI control in nonlinear systems using FLC as an adaptive controller. For this purpose, one chooses the control error e and its variation Δe as inputs. The outputs of the fuzzy logic controllers are used to vary the parameters of the decentralized PI controllers gains, namely K_P, K_I. To show the performance of the fuzzy supervisory control, a comparison is performed with the decentralized IMC-PI (Internal Model Control-Proportional Integral) controller. The FSC shows better results than the PI controller.

Keywords: Decentralized control, distillation column, fuzzy supervisory control, fuzzy logic controller, PI control.

NOMECLATURE

y_D	Overhead composition	s	Laplace transform variable
x_B	Bottom composition	$Yr1$	Overhead composition set point
L	Reflux flow rate	$Yr2$	Bottom composition set point
V	Steam flow rate	D_{12}	Non-interacting compensator to eliminate the effect of control of overhead composition on bottom composition
F	Feed flow rate	D_{21}	Non-interacting compensator to eliminate the effect of control of bottom composition on overhead composition

1. INTRODUCTION

Distillation column is an essential chemical process, used frequently for separation and purification of final useful products in different fractions of predefined concentration in a petroleum refinery by applying heating power (reboiler) and cooling power (condenser) during the cycles of operation.

This continuous process poses serious control problems; it's a difficult and an interesting problem at the same time, due to the following reasons: significant time delays, nonlinear multivariable system, and interaction between variables, disturbances and non-stationary behavior.

This process is also considered as being one of the most energy consuming processes [1].

For these reasons, improved distillation control is expected to have an important impact on energy efficiency and production quality. Decentralized and decoupling controls are the most popular control approaches in a real case [2]. Numerous control approaches have been presented in the literature for the distillation control tasks: Garrido et al. [3] have proposed a centralized PI regulators design with inverted decoupling. Morilla et al. [4] have proposed a control strategy, which is centralized, employs four proportional integral derivative (PID) controllers and two controllers with proportional delays and the designed decoupling network with integral action. A robust controller design for distillation column based on multi-objective optimization and genetic algorithms is proposed in Arvani et al. [5]. Benaskeur &

Desbiens [6] have proposed a backstepping based PID, neural network based estimator is developed for the estimation of methanol composition by the works of Singh et al. [7, 8]. Regina & Mija [9] proposed a comparative study between sliding mode and relay enhanced PI controllers.

Mekki et al. [10] proposed a comparative study of predictive multivariable control and decentralized control for a distillation column. Mekki [11] has proposed another comparative study of control design methods PI applied to a distillation column.

The use of fuzzy supervisory for the PID controllers, modifies on line tuning of PID parameters. To provide appropriate solutions, adjusting of the PID parameters on-line is carried out in the papers such as Dotoli et al. [12]; Zhao et al. [13]; Copeland & Rattan [14]. Comparing several techniques, one can say that the FSC is better than the PID controller [15-22] or proportional derivative (PD) results [23]. Tuning of fuzzy controller can give adequate results and realize improved performance than a classical PID controller when there are very difficult processes. When the PID controller may not be sufficient, the two controllers most widely used in industry are combined: the proportional integral (PI) and the fuzzy logic control (FLC). This combination of both controllers is referred as fuzzy supervisory PI controller. To reduce the existing interaction effects in the distillation column, the PI controller with a decoupling network will be added. The inverted decoupling is used, that combines the essential advantage of both the simplified and ideal decoupling methods [24].

A distillation process may be classified as binary or multi-component distillation. In this work, two regulators are applied to a continuous binary distillation column. The simulation results for different situations show the importance and the effectiveness of fuzzy supervisory control methodology for nonlinear dynamical processes. An important issue is the robustness of the controller. All the previously presented research works do not take into account the robustness test. To overcome this problem, this paper aims to improve the rise time, overshoot, settling time and permanently eliminates interactions with a robustness test. The comparative study presented in this paper requires the design and assessment of controllers for distillation column.

In this study, the two fuzzy supervisory controls have a form of two PI controllers; the PI parameters are adjusted via fuzzy controller based on the error and change of error as inputs to fuzzy logic control. The decoupled system combined with two fuzzy supervisory controls are presented for the Wood & Berry (WB) distillation column. The remainder of the paper is organized as follows. Section 2 presents the distillation column model. Section 3 explains the decentralized fuzzy-PI controller. In section 4, the simulation results are given and finally, section 5 gives some conclusions.

2. MODELING OF THE DISTILLATION COLUMN

The distillation is a technique that exploits the different volatility of the components of a liquid or vapor mixtures to separate and purify binary or multi-components feed. A model of lab-scale binary distillation column (Wood & Berry) has been used for separation of two components methanol/water mixture [25-28]. It contains a vertical column that has eight (8) trays mounted inside of it, equipped with a total condenser in the top of the column and a basket type reboiler in the bottom [25, 28].

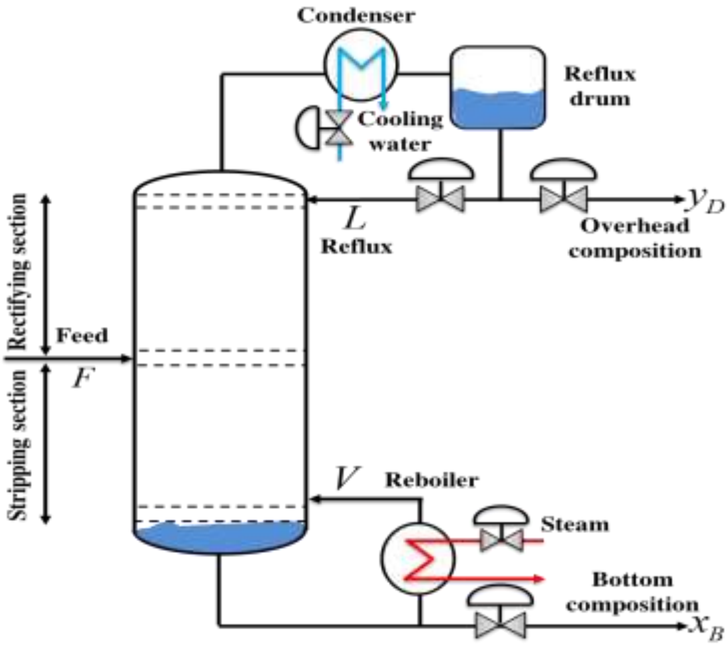


Fig 1: A diagram of binary distillation column

As it is shown in Fig. 1, the variation in the feed flow F is treated as a disturbance. The control variables are the compositions of methanol in the overhead and the bottom products. To make certain that the disturbance is negligible, the regulators of binary continuous distillation column change the liquid and vapor flow rate to keep the overhead and bottom concentrations at their desired values despite the variation in the feed flow [25, 28]. The distillation column has been adapted in this work to assess the proposed fuzzy supervisory control-decoupling scheme.

The transfer function matrix of the distillation process is given in Wood & Berry [28] and Sivakumar et al. [25] as follows:

$$Y(s) = G_P(s) \cdot U(s) + G_d(s) \cdot F(s) \tag{1}$$

Where: $Y = [y_D, x_B]$, $U = [L, V]$, and F are the vectors of outputs, controls, and disturbance respectively. G_P and G_d are the transfer function matrix of the process and the disturbance.

The two (2) manipulated variables are the reflux flow rate L and the steam flow rate V and the two (2) controlled variables are the overhead composition y_D and the bottom composition x_B. In a detailed form, the dynamics is given as follows:

$$\begin{bmatrix} y_D(s) \\ x_B(s) \end{bmatrix} = \begin{bmatrix} \dfrac{K_{11}}{\tau_{11} s+1} e^{-\theta_{11} s} & \dfrac{K_{12}}{\tau_{12} s+1} e^{-\theta_{12} s} \\ \dfrac{K_{21}}{\tau_{21} s+1} e^{-\theta_{21} s} & \dfrac{K_{22}}{\tau_{22} s+1} e^{-\theta_{22} s} \end{bmatrix} \cdot \begin{bmatrix} L(s) \\ V(s) \end{bmatrix} + \begin{bmatrix} \dfrac{K_{13}}{\tau_{13} s+1} e^{-\theta_{13} s} \\ \dfrac{K_{23}}{\tau_{23} s+1} e^{-\theta_{23} s} \end{bmatrix} \cdot F(s) \tag{2}$$

The process parameters of distillation column model are the gains $(K_{11}, K_{12}, K_{21}, K_{22}, K_{13}, K_{23})$, the time constants $(\tau_{11}, \tau_{12}, \tau_{21}, \tau_{22}, \tau_{13}, \tau_{23})$ and delays $(\theta_{11}, \theta_{12}, \theta_{21}, \theta_{22}, \theta_{13}, \theta_{23})$ of the system are in minutes.

3. DECENTRALIZED FUZZY-PI

A. Inverted decoupling multivariable process

The proportional integral (PI) controller is utilized together with an inverted decoupling as shown in Fig. 2. The decoupling control system is useful since the interactions in multivariable processes produce complications in keeping the required set points (in overhead, and bottom compositions) for all controlled variables for both set point's tracking and disturbances rejection [29].

By adding an inverted decoupling, the plant will be separated into two independent loops. As a result, the controllers will be able to control every single loop of the plant separately, in order to reduce the interaction between control loops and minimize the control workload on the feedback controllers [30].

To analyze the interaction and assess whether a system can be decoupled or not, several mathematical methods can be used including the relative gain array (RGA) method used in [31]. The selected inverted decoupling system configuration for distillation column for a two-input/two-output (TITO) is given in Wood and Berry (WB) [28] as:

$$\wedge = \begin{bmatrix} \dfrac{1}{1-\xi} & \dfrac{-\xi}{1-\xi} \\ \dfrac{-\xi}{1-\xi} & \dfrac{1}{1-\xi} \end{bmatrix} \tag{3}$$

For the distillation column system, the steady state gain matrix is obtained from the transfer function matrix by setting s=0, giving with:

$$\xi = \frac{K_{12} \cdot K_{21}}{K_{11} \cdot K_{22}} \tag{4}$$

B. Design of Fuzzy Supervisory controller

Due to nonlinearities in the dynamics, the Proportional, Integral, Derivative (PID) controller is not sufficient to give satisfactory results. However, an efficient control for nonlinear systems can be established by fuzzy logic controller (FLC) [21].

The fuzzy supervisory system works in a similar way to that of the FLC and adds an upper level of monitoring to the present system [15]. The design of FSC looks like the structure of PID controller. However, the controlled parameter of a PID depends on the output of the fuzzy controller [21, 32].

For this controller (FSC), one seeks to build a regulator able to learn the behavior of the PI controller. The block diagram of this method is shown in Fig. 2. Each fuzzy controller modifies the parameters of the PI controller, so the combination of these two regulators gives us a fuzzy supervisory control, based on the error and its variation such as in [33-35]. It also creates more appropriate solution to control binary distillation column.

The parameters of the two PI controllers used independently for the two control loops of the distillation column are normalized using the following linear transformation [36]:

$$\begin{cases} K'_{P\_i} = \dfrac{\left(K_{P\_i} - K_{P\_i\_\min}\right)}{\left(K_{P\_i\_\max} - K_{P\_i\_\min}\right)} \\ K'_{I\_i} = \dfrac{\left(K_{I\_i} - K_{I\_i\_\min}\right)}{\left(K_{I\_i\_\max} - K_{I\_i\_\min}\right)} \end{cases} \qquad i = 1, 2 \qquad (5)$$

Where: i is the number of the regulator. K_{P_i} and K_{I_i} are the proportional and integral gain parameters, respectively.

The inputs of the two fuzzy supervisory controllers are the error ei and the error change Δei, outputs are the normalized value of the proportional action K'_{P_i} and of the integral action K'_{I_i}.

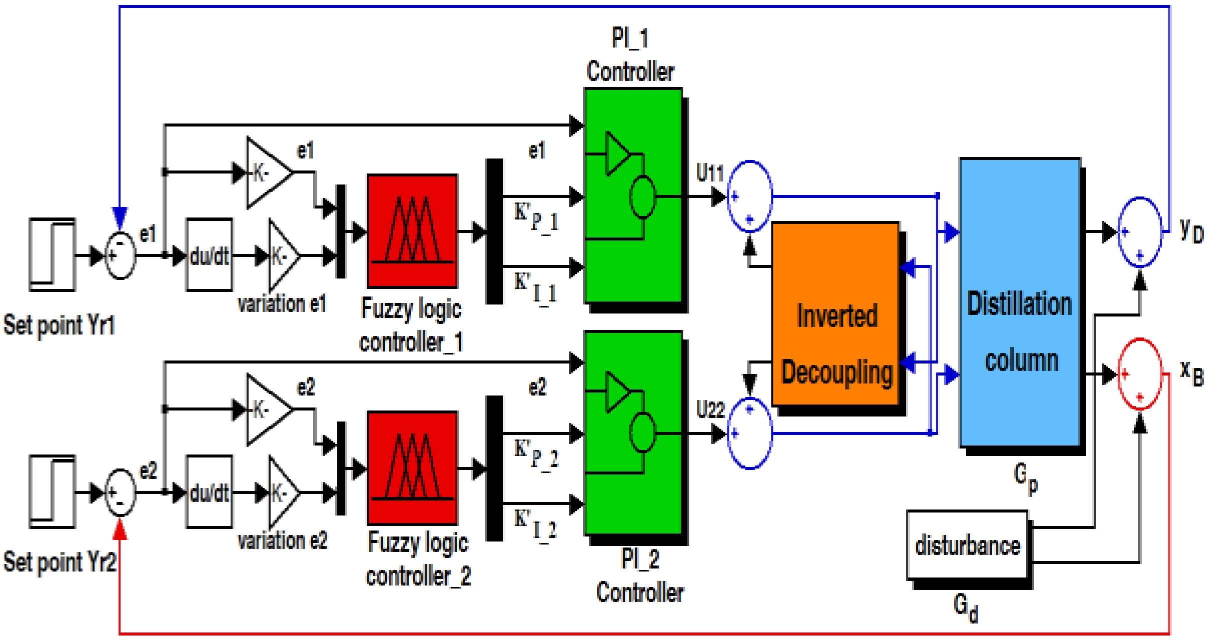


Fig 2: The fuzzy PI parameters tuner combined with inverted decoupling for distillation column model

Once the inverted decoupling is used, the two PI control each single loop of the distillation column separately. Figures 3 and 4, show the schematic diagram of the two PI controllers.

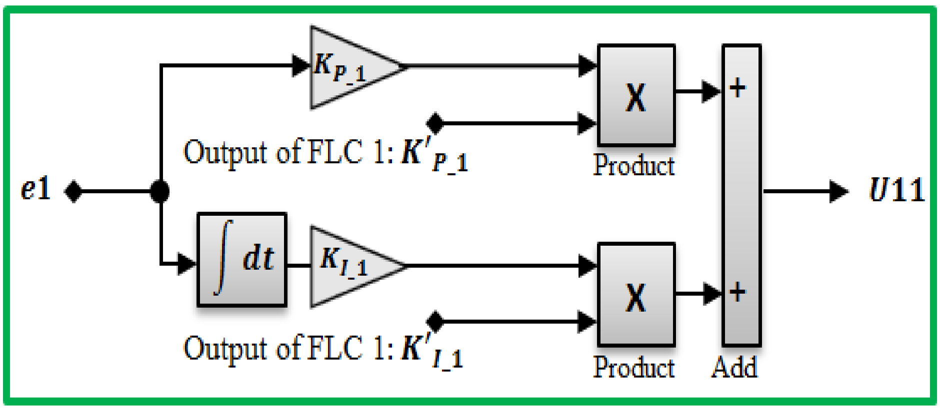


Fig3: Design of PI_1 controller

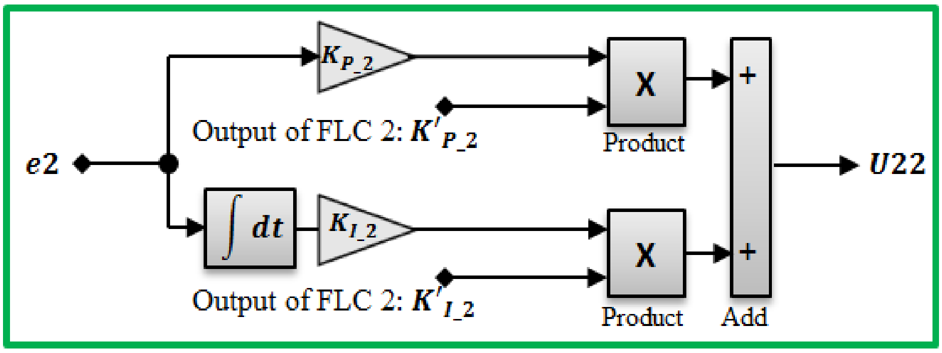


Fig 4: Design of PI_2 controller

The centroid defuzzification method is chosen and the precise value U is calculated as below:

$$U = \frac{\sum_{i=1}^{m} \mu(x_i) \cdot x_i}{\sum_{i=1}^{m} \mu(x_i)} \tag{6}$$

In which x_i indicates the control output of the ith linguistic variable, $\mu(x_i)$ is the output membership degree of the ith rule. In this study Mamdani's (max-min inference) method is used for the inference mechanism.

Once the values of (K'_{P_1}, K'_{I_1}) and (K'_{P_2}, K'_{I_2}) have obtained, the new settings of the two PI controllers are computed using relation (7):

$$\begin{cases} K_{P\_i} = (K_{P\_i\_\max} - K_{P\_i\_\min}) \cdot K'_{P\_i} + K_{P\_i\_\min} \\ K_{I\_i} = (K_{I\_i\_\max} - K_{I\_i\_\min}) \cdot K'_{I\_i} + K_{I\_i\_\min} \end{cases} \tag{7}$$

From the study of the behavior of the system, the control rules, which connect the outputs with the inputs, can be established.

4. SIMULATIONS RESULTS

The distillation column model is:

$$\begin{bmatrix} y_D(s) \\ x_B(s) \end{bmatrix} = \begin{bmatrix} \frac{12.8}{16.7s+1}e^{-s} & \frac{-18.9}{21s+1}e^{-3s} \\ \frac{6.6}{10.9s+1}e^{-7s} & \frac{-19.4}{14.4s+1}e^{-3s} \end{bmatrix} \cdot \begin{bmatrix} L(s) \\ V(s) \end{bmatrix} + \begin{bmatrix} \frac{3.8}{14.9s+1}e^{-8s} \\ \frac{4.9}{13.2s+1}e^{-3s} \end{bmatrix} \cdot F(s) \tag{8}$$

Table 1: Steady state values

Variable	Steady State value
y_D	96.25 mol% MeOH
x_B	0.5 mol% MeOH
L	1.95 lb/min
V	1.71 lb/min
F	2.45 lb/min

Equation (3); can be written as:

$$\wedge = \begin{bmatrix} \lambda & 1-\lambda \\ 1-\lambda & \lambda \end{bmatrix} \tag{9}$$

Where;

$$\lambda = \lambda_{11} = \frac{1}{1-\xi} \tag{10}$$

After applying numerical values, the RGA matrix of the distillation column becomes:

$$\wedge = \begin{bmatrix} 0.66 & 0.33 \\ 0.33 & 0.66 \end{bmatrix} \tag{11}$$

Since $\lambda_{11}= 0.66$ in this interval $0.5 \prec \lambda_{11} \prec 1$, the control and manipulated variables were paired $(y_D - L, \quad x_B - V)$. Then, it's possible to control the distillation process with single loop controllers.

Fig. 5 depicts a bloc diagram of a conventional decoupling scheme for a linear process with two (2) inputs L and V, two (2) outputs y_D and x_B with reference variables $U11$ and $U12$. The set of transfer functions G_{11}, G_{12}, G_{21} and G_{22} represent the transfer function matrix of distillation process G_P. Each transfer function of G_P is the first-order-plus-delay form.

In order to remove the influence of overhead and bottom compositions control affects; the two decouplers should be chosen as [11, 12]:

$$\begin{cases} D_{12}(s) = -\dfrac{18.9 \cdot (16.7\,s+1)}{12.8 \cdot (21\,s+1)} e^{-2s} \\ D_{21}(s) = -\dfrac{6.6 \cdot (14.4\,s+1)}{19.4 \cdot (10.9\,s+1)} e^{-4s} \end{cases} \tag{12}$$

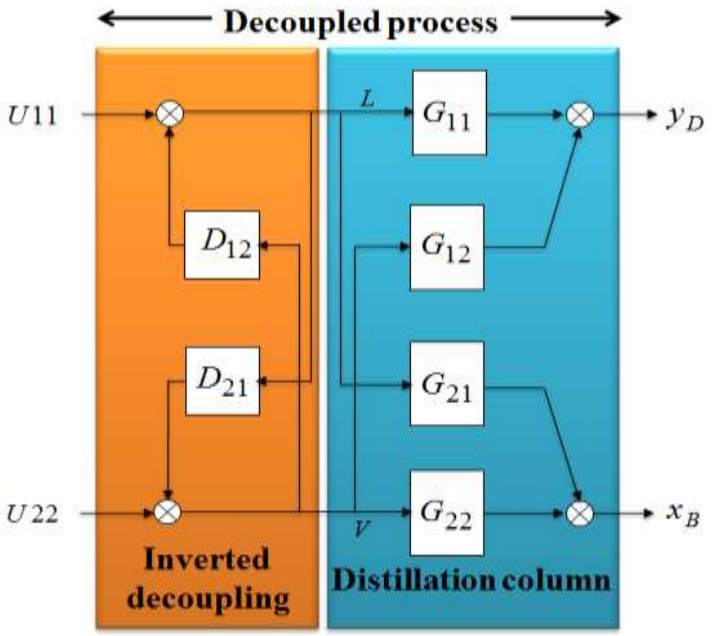


Fig 5: Decoupling process of binary distillation column model system

Then, assume the ranges of parameters in relation 7 are: $[K_{P\_i\_\min}, K_{P\_i\_\max}]$, $[K_{I\_i\_\min}, K_{I\_i\_\max}]$ respectively. The ranges of these parameters are determined by tests as: $K_{P\_1} \in [0-5]$, $K_{I\_1} \in [0-0.6]$, $K_{P\_2} \in [0-2]$, $K_{I\_2} \in [0-0.6]$

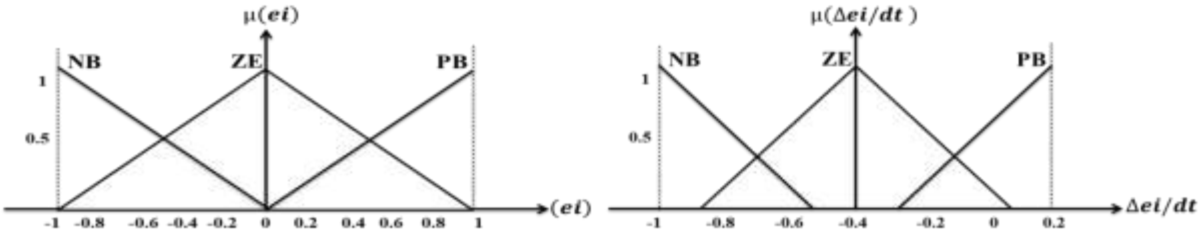
The triangular membership functions will be adopted for the FSC.

Membership functions for the first and second fuzzy controllers inputs ei and Δei are shown in Fig. 6. The fuzzy subsets of each input variable are determined along these lines: **NB**: negative big; **ZE**: zero; **PB**: positive big. The fuzzy subsets of the first output variables K'_{P_1}, K'_{P_2} are defined as: **NB**: Negative Big, **NS**: Negative Small, **PS**: Positive Small, **PB**: Positive Big.

The second output variables K'_{I_1}, K'_{I_2} are defined as: **PS**: positive small, **PB**: positive big.

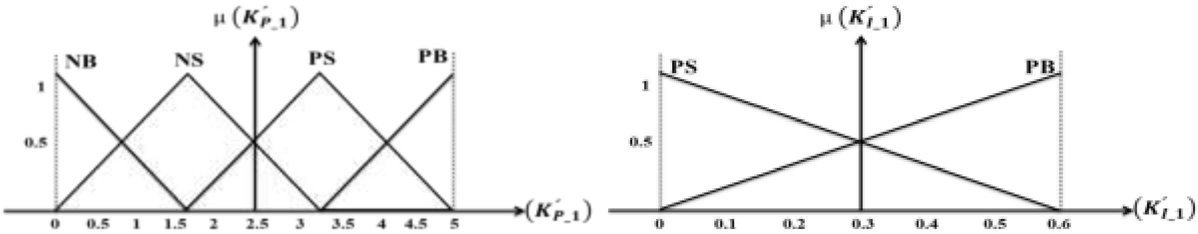
Membership functions for the first fuzzy controller outputs K'_{P_1} and K'_{I_1} are shown in Fig. 7.

Membership functions for the second fuzzy controller outputs K'_{P_2} and K'_{I_2} are shown in Fig. 8.



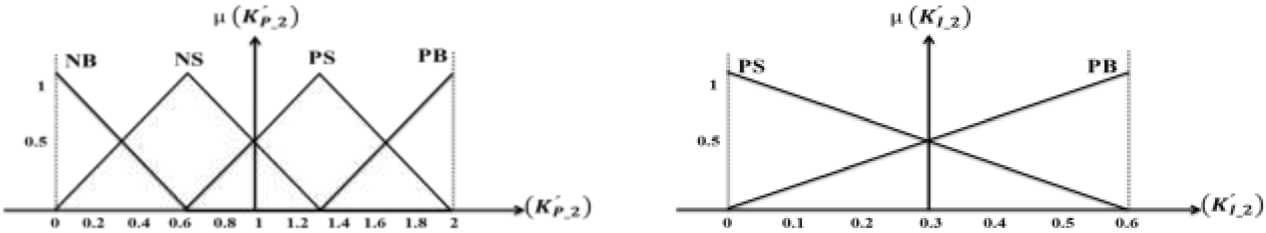
(a) (b)

Fig6: Membership functions of: (a) ei **, (b):** Δei



(a) (b)

Fig 7: Membership functions of: (a) K'_{P_1} **, (b)** K'_{I_1}



(a) (b)

Fig 8: Membership functions of: (a) K'_{P_2} **, (b)** K'_{I_2}

The tuning of PI gains should be judiciously obtained. The rule base for calculating the K'_{P_i} and K'_{I_i} gains are shown in Tables 2, 3 respectively.

The rules base of FSC are built from two inputs two outputs (TITO) fuzzy rules base and they have the forms:

If $e1$ is PB and $\Delta e1$ is ZE then K'_{P_1} is PB, & K'_{I_1} is PS.

If $e2$ is ZE and $\Delta e2$ is ZE then K'_{P_2} is PS, & K'_{I_2} is PB.

The rule base table of the FSC must be selected more precisely to ensure a system with settling, rise time faster than IMC-PI. For disturbance rejection, the FSC should be given lower IAE (Integral absolute error) and overshoot values than IMC-PI.

Table 2: Rule base of fuzzy controller: K'_{P_i}

K'_{P_i}		*ei*		
		NB	**ZE**	**PB**
Δei	**NG**	ZE	NS	ZE
	ZE	NB	PS	PB
	PB	ZE	PS	ZE

Table 3: Rule base of fuzzy controller: K'_{I_i}

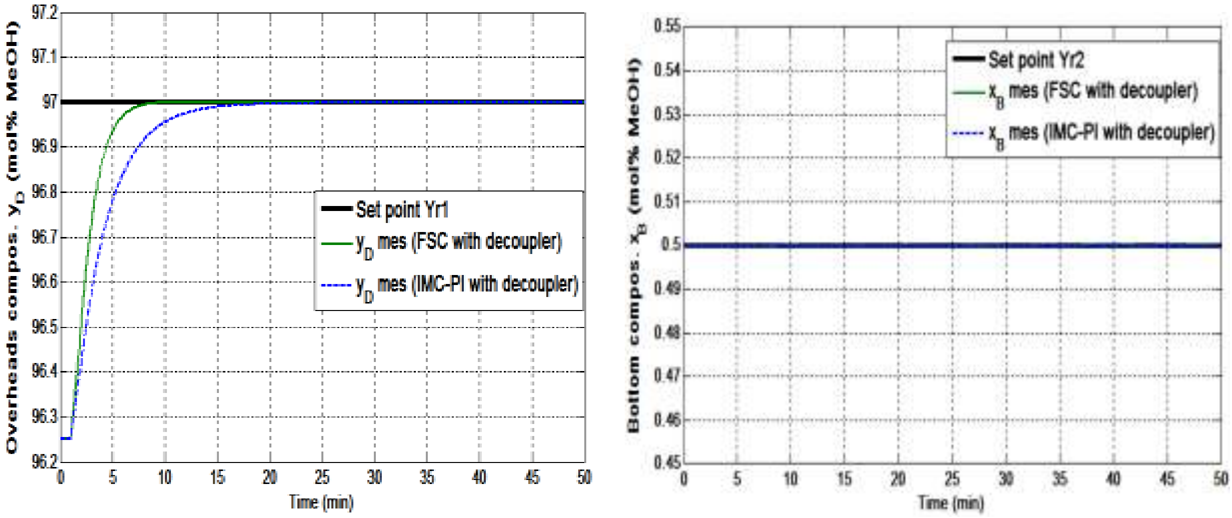
K'_{I_i}		*ei*		
		NB	**ZE**	**PB**
Δei	**NG**	ZE	PS	PB
	ZE	PS	PB	PS
	PB	PB	PS	PB

In this part, two cases are studied. In the first one, we compared between overhead and bottom compositions obtained using the IMC-PI used in [11, 12] and FSC controllers.
The system was simulated for different set points change without feed flow rate variable in the WB distillation column. Then, the previous controllers are used and only feed flow rate set point is changed to disturb the system.

A. Set point change simulation without disturbance

These set points change were already used in our paper [11]. In Fig. 9(a), the set point of the composition in the overhead composition $(Yr1)$ was changed to 0.75%, but the bottom composition $(Yr2)$ is fixed to 0.5 mol% methanol, as shown in the Fig. 9(b).

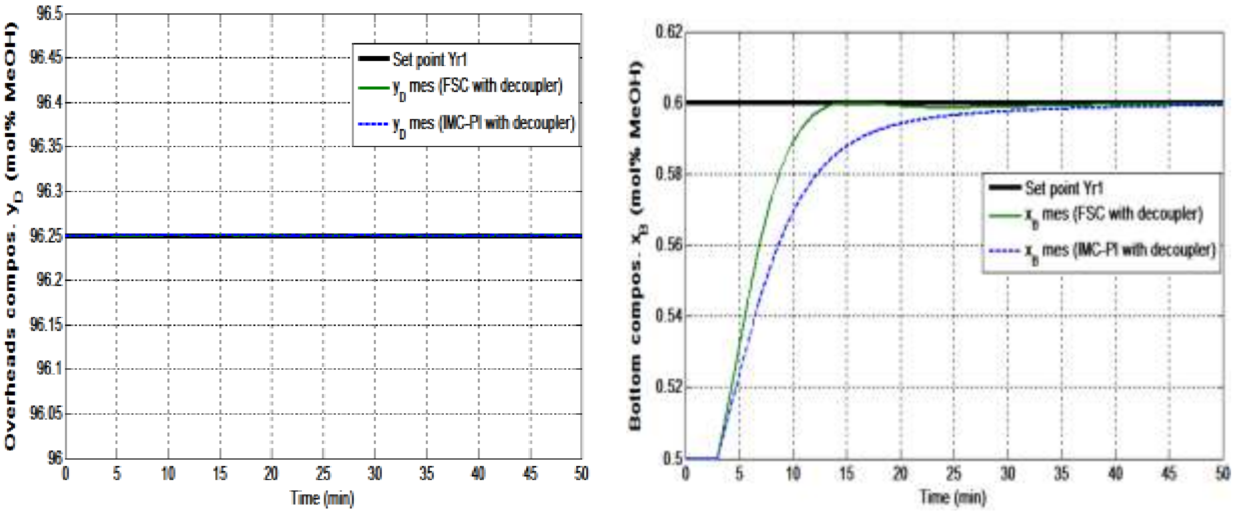
In Fig. 10(b), the set point of the composition in the bottom composition $(Yr2)$ is changed to 10%, but the overhead composition $(Yr1)$ is fixed to 96.25 mol% methanol, as shown in the Fig. 10(a).



(a) (b)

Fig 9: Simulation for a set point change in overhead from 96.25 to 97 mol% MeOH:

(a) overhead composition, (b) bottom composition



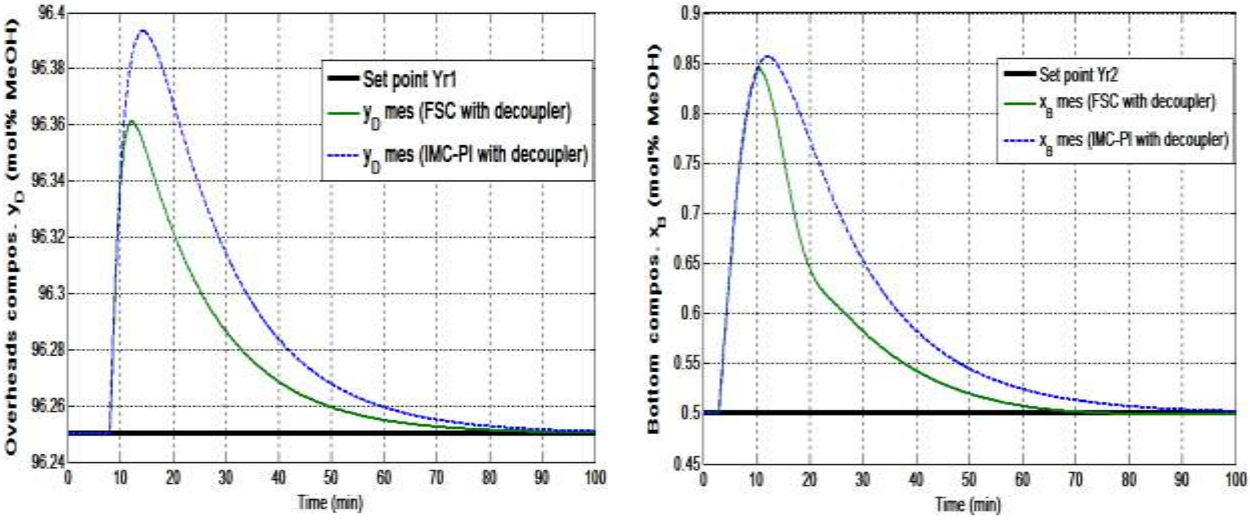
(a) (b)

Fig 10: Simulation for a set point change in bottom from 0.5 to 0.6 mol% MeOH:

(a) overhead composition, (b) bottom composition

B. Simulation with disturbance rejection

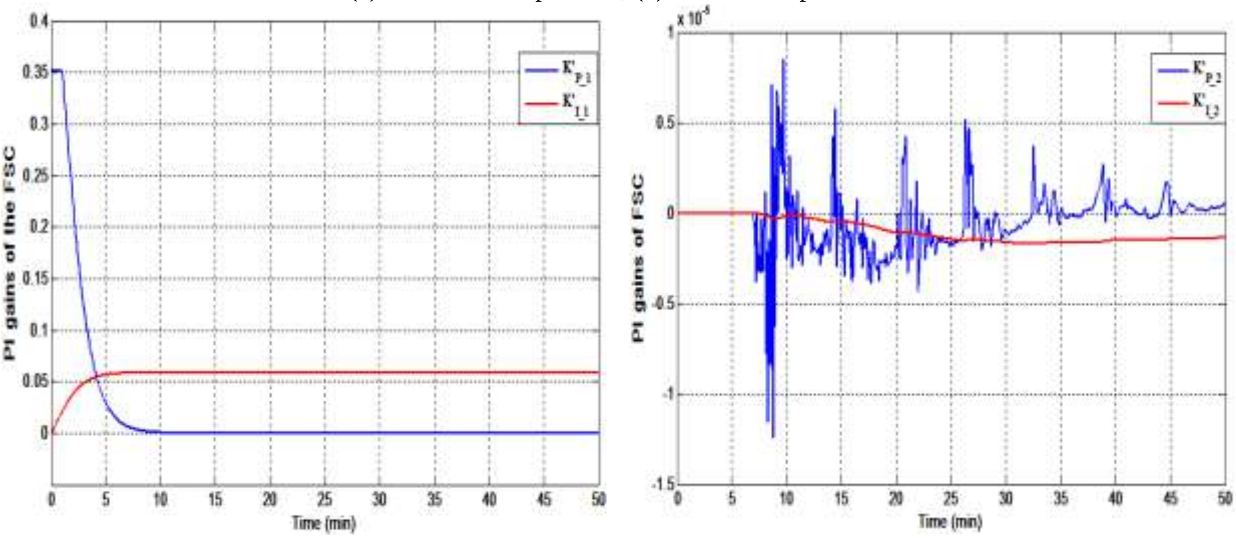
The feed flow rate F was modified of +8% to disturb the plant in order to test the controller's robustness. The simulation results shown in Figs. 11 have been executed to 0.2 lb/min increase in the feed flow rate. The same test has been carried out [11].



(a) (b)

Fig 11: Simulation disturbance rejection:

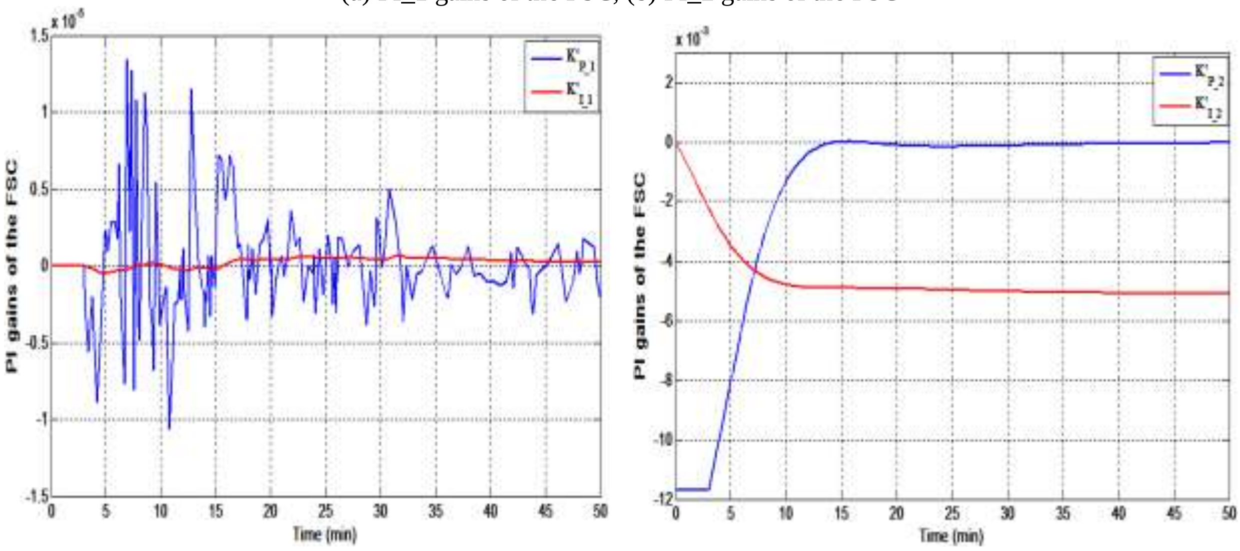
(a) overhead composition, (b) bottom composition



(a) (b)

Fig 12: The FSC controller increase set point from 96.25 to 97 mol% MeOH:

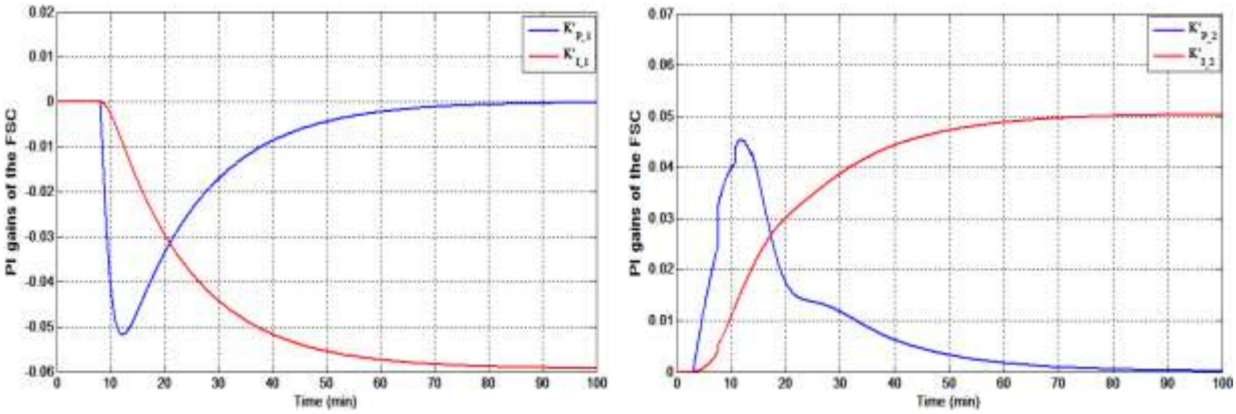
(a) PI_1 gains of the FSC, (b) PI_2 gains of the FSC



(a) (b)

Fig 13: The FSC controller increase set point from 0.5 to 0.6 mol% MeOH:

(a) PI_1 gains of the FSC, (b) PI_2 gains of the FSC



(a) (b)

Fig 14: The FSC controller disturbance rejection:

(a) PI_1 gains of the FSC, (b) PI_2 gains of the FSC

The decentralized fuzzy supervisory controller on the WB distillation column shows that the interactions between control loops are eliminated as illustrated in figures 9 to 11.

In these figures, the set point change of 0.75% in overhead composition and 10% in bottom composition, with a robustness test show improved results in simulations, with a small rise time, establishment time and disturbance rejection compared to IMC-PI controller.

Compared to the classical PI gains controller, figures 12 to 14 show the variations of the two PI gains $\left(K'_{P\_1}, K'_{I\_1}\right)$, $\left(K'_{P\_2}, K'_{I\_2}\right)$ during the operation using two fuzzy supervisory controls to improve the system responses both for set point tracking and disturbances rejection.

Therefore, the power supplied by the reboiler (heating) and the cooling power during the operation of the distillation was minimized by changes the two manipulated variables: reflux flow rate (L) and steam flow rate (V).

Table 4: Performance comparison

Set point change	**Controlled variable; with**		**Rise time (t_r)**	**Settling time (t_s)**	**IAE (disturbance rejection)**
$Yr1$	y_D	IMC-PI	6.9	10.58	3.287
		FSC	3.47	6	2.105
$Yr2$	x_B	IMC-PI	12.38	21.52	9.317
		FSC	6.56	11.75	6.774

As shown in figures 9 and 10, the outputs responses of the FSC have no peak overshoot and steady state error. The results confirm the effectiveness of the results obtained with FSC controller.

Thus the optimizations of the outputs are achieved and the performance assessment measures are compared with the rise time, settling time and IAE (disturbance rejection) values (see table 4). The results carried out by the fuzzy logic controls are better than tuning methods IMC-PI.

DISCUSSION AND CONCLUSION

The distillation column is a multivariable strongly coupled system with delay. A decoupling phase was used in order to reduce the interaction and the control workload on the feedback controllers. It’s necessary to have an optimal cost between the power supplied by the reboiler (heating) in the bottom of the column and the cooling power at the top of the column. The Fuzzy supervisory control proposed in this paper gives satisfactory results after the combination with inverted decoupling. The Fuzzy supervisory control simulation results of different set points show excellent results. They achieve very quickly the tracking of the measure to the desired value by changing online the initial control parameters on binary distillation column system and ensure good quality product and optimized energy.

REFERENCES

[1]. H. Truong, I. Ismail, and R. Razali, "Fundamental modeling and simulation of a binary continuous distillation column", in Intelligent and Advanced Systems (ICIAS), 2010 International Conference on, 2010, pp. 1-5.
[2]. [2] Z. Hu, D. Li, J. Wang, and F. Xue, "Analytical design of PID decoupling control for TITO processes with time delays", Journal of Computers, vol. 6, pp. 1064-1070, 2011.
[3]. J. Garrido, F. Vázquez, and F. Morilla, "Centralized inverted decoupling for TITO processes", in Emerging Technologies and Factory Automation (ETFA), 2010 IEEE Conference on, 2010, pp. 1-8.
[4]. F. Morilla, F. Vázquez, and J. Garrido, "Control centralizado PID 2x2 por desacoplo", XXVIII Jornadas de Automática, Huelva, 2007.
[5]. A. Arvani, M. Teshnehlab, and M. A. Sh, "Robust H∞ controller design for distillation column based on multi-objective optimization and genetic algorithms", in Industrial Electronics & Applications, 2009. ISIEA 2009. IEEE Symposium on, 2009, pp. 773-777.
[6]. A. Benaskeur and A. Desbiens, "Backstepping-Based PID DESIGN for TITO Decentralized Control", in Proceedings of the 10th Mediterranean Conference on Control and Automation-MED2002 Lisbon, 2002, p. 7.
[7]. V. Singh, I. Gupta, and H. Gupta, "ANN-based estimator for distillation using Levenberg–Marquardt approach", Engineering Applications of Artificial Intelligence, vol. 20, pp. 249-259, 2007.
[8]. A. K. Singh, B. Tyagi, and V. Kumar, "Application of feed forward and recurrent neural network topologies for the modeling and identification of binary distillation column", IETE Journal of Research, vol. 59, pp. 167-175, 2013.
[9]. P. Regina and S. Mija, "Comparative Study of Sliding Mode and Relay Enhanced PI Controllers for MIMO Systems", in Technological Developments in Education and Automation, ed: Springer, 2010, pp. 201-206.
[10]. I. Mekki, M. Bouhamida, and M. Benghanem, "Comparative Study of Predictive Multivariable Control and Decentralized Control for a Distillation Column", International Review of Automatic Control (IREACO), vol. 6, pp. 513-520, 2013.
[11]. I. MEKKI, "A Comparative Study of Control Design Methods PI Applied to a Distillation Column", Journal of Science and Advanced Technology, vol. 4, pp. 6-10, 2014.
[12]. M. Dotoli, B. Maione, and B. Turchiano, "Fuzzy-Supervised PID Control: Experimental Results", in the 1st European Symposium on Intelligent Technologies, 2001, pp. 31-35.
[13]. Z.-Y. Zhao, M. Tomizuka, and S. Isaka, "Fuzzy gain scheduling of PID controllers", in Control Applications, 1992., First IEEE Conference on, 1992, pp. 698-703.
[14]. R. P. Copeland and K. S. Rattan, "A fuzzy logic supervisor for PID control of unknown systems", in Intelligent Control, 1994., Proceedings of the 1994 IEEE International Symposium on, 1994, pp. 22-26.
[15]. L. Bergh, J. Yianatos, and C. Leiva, "Fuzzy supervisory control of flotation columns", Minerals Engineering, vol. 11, pp. 739-748, 1998.
[16]. L. Reznik, O. Ghanayem, and A. Bourmistrov, "PID plus fuzzy controller structures as a design base for industrial applications", Engineering applications of artificial intelligence, vol. 13, pp. 419-430, 2000.
[17]. F. Abdel-Hady and S. Abuelenin, "Design and simulation of a fuzzy-supervised PID controller for a magnetic levitation system", Studies in Informatics and Control, vol. 17, pp. 315-328, 2008.
[18]. G. Shabib, "Applications of Fuzzy Supervisory PID Controller to a Power System", International Journal of Control Science and Engineering, vol. 2, pp. 102-110, 2012.
[19]. A. Omar, T. Khedr, and A. Zalam, "Particle swarm optimization of fuzzy supervisory controller for nonlinear position control system", in Computer Engineering & Systems (ICCES), 2013 8th International Conference on, 2013, pp. 138-145.
[20]. M. A. Rashidifar, A. A. Rashidifar, and D. Ahmadi, "Modeling and Control of 5DOF Robot Arm Using Fuzzy Logic Supervisory Control", IAES International Journal of Robotics and Automation (IJRA), vol. 2, pp. 56-68, 2013.
[21]. M. A. Oleiwi and Z. A. Aljasem, "POSITION CONTROL FOR (PPDCV) USING PID & FUZZY SUPERVISORY CONTROLLER", Academic Research International, vol. 4, p. 110, 2013.
[22]. N. K. Jaiswal and V. Kumar, "Comparison between conventional pid and fuzzy pid supervisor for 3-dof scara type robot manipulator", in Electrical, Electronics and Computer Science (SCEECS), 2014 IEEE Students' Conference on, 2014, pp. 1-5.
[23]. E. M. Rowida, M. B. A. Halim, M. B. Elsayed, and A. T. Ali, "Systematic Design and Implementation of Decentralized Fuzzy-PD Controller for Robot Arm", vol. 1, pp. 8-14, 2013.
[24]. E. Gagnon, A. Pomerleau, and A. Desbiens, "Simplified, ideal or inverted decoupling?", ISA transactions, vol. 37, pp. 265-276, 1998.
[25]. R. Sivakumar, C. Sahana, and P. Savitha, "Design of ANFIS based Estimation and Control for MIMO Systems", International Journal of Engineering Research and Applications, vol. 2, pp. 2803-2809, 2012.
[26]. S. Javadi and J. Hosseini, "Control of binary distillation column using fuzzy PI controllers", in Proceedings of the 11th WSEAS international conference on Mathematical and computational methods in science and engineering, 2009, pp. 50-57.
[27]. S. Skogestad, "Dynamics and control of distillation columns: A tutorial introduction", Chemical Engineering Research and Design, vol. 75, pp. 539-562, 1997.
[28]. R. Wood and M. Berry, "Terminal composition control of a binary distillation column", Chemical Engineering Science, vol. 28, pp. 1707-1717, 1973.
[29]. I. M. Adel, I. Elamvazuthi, and N. H. H. B. M. Hanif, "Monitoring and controlling system for binary distillation column", in Research and Development (SCOReD), 2009 IEEE Student Conference on, 2009, pp. 453-456.
[30]. R. Garduno-Ramirez and K. Y. Lee, "Feasibility Analysis of Control-loop Interaction Compensation for a Fossil-Fuel Power Plant", in Power Plants and Power Systems Control 2003: A Proceedings Volume from the 5th IFAC Symposium, Seoul, South Korea, 15-19 September 2003, 2004, p. 331.
[31]. M. Ramzi, H. Youlal, and M. Haloua, "Continuous Time Identification and Decentralized PID Controller of an Aerothermic Process", International journal on smart sensing and intelligent systems, vol. 5, pp. 487-503, 2012.
[32]. D. Dulaidi, "Modeling and control of 6 DOF industrial robot using fuzzy logic controller", Universiti Tun Hussein Onn Malaysia, 2014.

[33]. Y. Yang, W.-G. Wang, D.-J. Yu, and G. Ding, "A fuzzy parameters adaptive PID controller design of digital positional servo system", in Machine Learning and Cybernetics, 2002. Proceedings. 2002 International Conference on, 2002, pp. 310-314.
[34]. A. Z. Alassar, I. M. Abuhadrous, and H. Elaydi, "Comparison between FLC and PID Controller for 5DOF robot arm", in Advanced Computer Control (ICACC), 2010 2nd International Conference on, 2010, pp. 277-281.
[35]. G. R. Kumar and M. C. V. Raja, "Comparison between FSC and PID Controller for 5DOF Robot Arm", International Journal of Emerging Trends in Electrical and Electronics (IJETEE–ISSN: 2320-9569) Vol, vol. 10, pp. 1-6, 2014.
[36]. H. Elaydi, I. A. Hardouss, and A. Alassar, "Supervisory Fuzzy Control for 5 DOF Robot Arm", International Journal of Science and Advanced Technology, vol. 2, pp. 1-6, 2012.