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The Dynamic Behavior and Control of the Methanol-Toluene Distillation Column

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A B S T R A C T

In this study, the dynamic behavior for two control methods of the distillation column for the separation of methanol and toluene mixture are studied. The experimental responses of temperature in each tray of distillation column for step changes in set point of reboiler, reflux ratio, and feed weight fraction are obtained. This is based on a derived mathematical model. Simulink simulator of the distillation column is used to implement the PID and fuzzy logic control methods. The comparison between the two controllers is done for step changes in set point, feed flow rate, feed weight fraction, and liquid reflux. The controller performance is measured depending on the mean square error and integral square error. The results show that the performance of the fuzzy controller is better than of the PID controller in fast access to the desired value and to cancelling the disturbances.

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السلوك الديناميكي والسيطرة على برج التقطير لمزيج ميثانول - تولوين

الخلاصة

تناول البحث دراسة السلوك الديناميكي لبرج التقطير وتم تطبيق طريقتين للسيطرة على عملية فصل الميثانول والتولوين. وتم الحصول عمليا على استجابات لدرجة الحرارة في كل صينيه من البرج لعدد من الاضطرابات الدرجية في معدل درجة حرارة الغلاية ونسبة السائل الراجع والكسر الوزني للمادة المغذية. تمت عملية المحاكاة لبرج التقطير اعتمادا على الموديل الرياضي المشتق حيث تم تطبيقه على طريقتين السيطرة من نوع تناسبي-تكاملي-تفاضلي والضبابية. تمت المقارنة بين الطريقتين لعدد من الاضطرابات في القيمة المرغوبة وتركيز ومعدل جريان القيم ومعدل جريان السائل الراجع. وتم قياس اداء المسيطر بواسطة كل من معدل مربع الخطأ وتكامل مربع الخطأ. وبينت النتائج إن المسيطر الضبابي أفضل وأكثر كفاءة من المسيطرات التقليدية من خلال سرعة الوصول إلى القيمة المرغوبة وإلغاء الاضطرابات.

1. INTRODUCTION

The main objectives of the distillation control are maintaining the product purity, constraint satisfaction, and energy reduction. It has a major impact upon the product quality, energy usage, and plant throughput of these industries. It consumes enormous amounts of energy, both, in terms of cooling and heating requirements. It contributes to more reduction in the operating costs reach more 50%. Energy requirements may be reduced significantly due to an improved operation. This is achieved, not only through optimal column design, but also to, in addition, a control system which is able to maintain the optimal conditions. Distillation control is a challenging endeavor to the inherent nonlinearity of distillation, multivariable interaction, the non-stationary behavior, and the severity of disturbance. Kano et al. [1] successfully applied a predicative inferential control through predicting the concentrations by controlling the process of the direct measurement of the variables instead of the concentration current appreciations. They proved that this method is effective and it is able to offer a good performance for most disturbances. On the other hand, Jana [2] suggested using a nonlinear adaptive control system for binary system distillation column and test the performance on adaptation under primary error and heterogeneous disturbances. They compared it with PI control. The results showed that the response velocity and access to the required value are obtained in a less time. Filetia et al. [3] developed a computerized algorithms of the fuzzy logic control and implementing an experimental, in distillation equipment for a mixture separation which consists a hexane and

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Nomenclature

A_{12}, A_{21}	coefficients of van laar model
A_i, B_i	coefficients of Antoine equation
B	bottom flow rate, (kg/hr)
C	heat specific capacity, (kJ/kg.℃)
D	distillate flow rate, (kg/min)
F	feed flow rate, (kg/min)
H	enthalpy, (kJ/kg.℃)
I	tray number
ISE	integral square error
Kc	proportional gain, (mA/ °C)
L	liquid flow rate on tray, (kg/hr)
LT	amount liquid reflux to column
M	liquid holdup, (kg)
MSE	Mean Square Error
PID	Proportional-Integrai-Derivative
NF	Feed zone
QC	heat of condenser, (kw)
QR	heat of reboiler, (kw)
P	total pressure, (kN/m^2)
P^{sat}	saturation pressure, (kN/m^2)
R	reflux ratio
T	time, (min)
T	temperature, (°C)
V	vapor flow rate, (kg/min)
x	liquid weight fraction, (kg/kg)
Z_f	weight fraction of feed, (kg/kg)
γ_i	activity coefficient

heptane. They arranged a fuzzy logic controller by changing the gain and the association function the for input and output variables. The results, which are compared with PID controller, showed that the fuzzy logic give a better performance than PID controller. El-garhy et al. [4] proposed a particle swarm optimization for estimating the ideality values of the steady-state elements. The simulation results showed a high accuracy and less mathematical burden in reducing the intersection. Canete et al. [5] developed a method for connecting Simulink program for simulating a dynamic distillation column with program (Lab view). The developed system is applied on a distillation column for separating a binary mixture which consists a methanol and propanol by PID controllers. The results showed that this method can be used in controlling and investigating a good performance. Duraid and Mohammed [6] applied a fuzzy logic controller for a continuous binary distillation tray column for an ethanol-water mixture separation. They designed the fuzzy logic controller according to a logic rules depending on a fuzzy sets and experimental works using a Matlab program. They concluded that the fuzzy controller is better than the PID controller because it has a fast access to the desired value and cancelling the disturbances. Duraid and Maha [7] designed a fuzzy logic controller for a continuous stirred tank reactor. The simulation study was done using a Matlab and they concluded that the fuzzy controller give the best performance in comparison with conventional control system. Duraid and Ahlam [8] designed a neural network controller of a batch packed distillation column for separating four systems; acetic acid-water, acetone-water, ethanol-water and benzene-toluene mixtures. The controller was designed using a Matlab program. This is used to control the top product temperature in the column. They concluded that the neural network gives better response than PID controller.

The objective of this study is to investigate the dynamic behavior of the distillation column and the modified dynamic model of a distillation process of the methanol - toluene mixture, then, applying it to a PID and fuzzy logic controllers.

2. MATHEMATICAL MODELING

The simulation is based on the mathematical model of a distillation column using mass and energy balance. The mass balance of the distillation column can be written as:

$$\text{Mass rate in} - \text{Mass rate out} = \text{Mass Accumulation} \qquad (1)$$

-Mass balance on tray (i) depending on Eq. (1) and can be written as:

$$\frac{dM_i}{dt} = L_{i+1} - L_i + V_{i-1} - V_i \qquad (2)$$

where *M*, *L*, *V* are Liquid holdup, Liquid flow rate and Vapor flow rate of tray respectively.

-Mass balance on feed tray number (NF) depends on Eq. (1) and can be written as:

$$\frac{dM_{nf}}{dt} = \frac{dM_{NF}}{dt} + F \qquad (3)$$

where *F* is the feed flowrate.

- Mass balance on the reboiler tray number (1) depends on Eq. (1) and can be written as:

$$\frac{dM_1}{dt} = L_2 - V_1 - B \qquad (4)$$

where *B* is the bottom flow rate.

-Mass balance on condensation tray (NT) depends on Eq. (1) and can be written as:

$$\frac{dM_{NT}}{dt} = V_{NT-1} - LT - D \qquad (5)$$

where *D* is the top product of the flow rate.

-Energy balance about the column tower-

$$Heat\ rate\ in - Heat\ rate\ out = Heat\ Accumulation \qquad (6)$$

-Energy balance on tray (i) depends on Eq. (6) and can be written as:

$$c_i \frac{M_1 d(T_1)}{dt} = c_{i+1}L_{i+1}T_{i+1} - c_{i-1}L_{i-1}T_{i-1} - c_i V_i T_i \qquad (7)$$

where *C* and *T* are the specific heat capacity and temperature respectively.

-Energy balance about the reboiler depends on Eq. (6) and can be written as:

$$\mathrm{C_1} \frac{\mathrm{M_1 d(T_1)}}{\mathrm{dt}} = \mathrm{C_1(L_2T_2 - BT_1) - H_1^V V_1 + QR} \qquad (8)$$

where *H* and *QR* are: enthalpy and heat reboiler respectively.

-Energy balance on condensation depends on Eq. (6) and can be written as:

$$c_{NT}\frac{M_{NT}d(T_{NT})}{dt} = c_{NT}V_{NT-1}(T_{NT-1}-T_{NT}) - H^{V}_{NT-1}V_{NT-1} - Q_C \quad (9)$$

where QC is the condenser heat.

-Vapor Liquid Equilibrium (VLE) Calculations

In the modeling of the distillation column operation, one the compositions of the liquid and vapor mixtures must be estimated in equilibrium. The equilibrium temperature and the composition of the vapor phase, at equilibrium, with the liquid phase is represented by

-Calculating the vapor concentration using Eq. (10)

$$y_i = \frac{x_i\gamma_i P_i^{sat.}}{P} \quad (10)$$

where P, P^{sat} and γ are total pressure, saturation pressure, and activity coefficient.

-Calculating the activity of a species liquid which computed by using the Van Laar model using Eqs. (11) and (12).

$$\ln\gamma_i = \frac{A12}{\left[1+\frac{A12}{A21}\frac{xi}{(1-xi)}\right]^2} \quad (11)$$

$$\ln\gamma_j = \frac{A21}{\left[1+\frac{A21}{A12}\frac{(1-xi)}{xi}\right]^2} \quad (12)$$

-Calculating the temperature in each tray using Antoine Eq. (13):

$$Ti = \frac{Bi}{Ai - \ln Pisat.} \quad (13)$$

3. EXPERIMENTAL WORK

The continuous distillation unit consists eight bubble cup trays with temperature sensors and samples intakes on each tray as shown in Fig. 1. The internal diameter and the height are 0.05 m and 1 m, respectively. The feeding tank capacity is 10 liters. This liquid quantity is used to ensure a continuous liquid feeding to the system with preheating to the specified temperature using a pump of a maximum flow of 3.8 L/min. The condenser is a straight tube. A reboiler capacity is 2 liters and it is supplied with an adjustable electric blanket of maximum power 500 W. The column has capital an intake at its both ends for load loss measurement through a pressure sensor. The condenser has two temperature sensor intakes. It is provided with a multifunction controller card for data acquisition through the PC and graphic environment to visualize, automatically and register all the system variables. A flow meter for cooling water measurement of 0 to 3.5 L/min is used. A methanol-toluene system is used which is non-ideal and it has azeotropes at 63.5℃ and 72.38 wt%.

4. SIMULATION WORK

The mathematical model that derived for the distillation depending on the mass and heat balance. This developed model consists a differential and algebraic equations that are validated by using a parameter sensitivities method that using data that collected from the industrial plant. The simulation work55 showed qualitatively acceptable behavior for all systems as shown in Figs. 2 and 3. The simulation work was designed depending on the developed model after entering all the values of the parameters for the studied system.

4.1. Fuzzy Logic Controller

The fuzzy logic controller becomes an important method in the control process. This method discovers one of the most important research areas by involving fuzzy set theory. The contributors are concern with the analysis and design of the fuzzy control process. The different types of models include, fuzzy reasoning models, fuzzy expert systems, and genetic algorithms, Mendel [9]. The fuzzy system is based on the knowledge of an expert in the process. The fuzzy system uses the human reasoning that has been designed into membership functions, fuzzy rules, and rules [10]. Fuzzy control uses the principles of fuzzy logic that based on an adopted decision to achieve the control tasks. The decision making approach is typically based on the inference rule. A fuzzy rule in the knowledge base of the control task, generally is a linguistic relationship. The membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1, as shown in Figs. 4 and 5. The five triangular membership functions are used for the input and output signals which are zero, big and small in negative and positive ranges. The final step in building of the fuzzy logic system is the fuzzy variables conversion which are processed by the fuzzy logic rules in order to gain the real values. This process is called (Defuzzification) because it compares the fuzzy groups its self to give a true indication then it uses the events of a certain acting. The final value of each variable is a single number of those gathering fuzzy aggregates to a certain extent from the outside after shows to give value (single output). Describing a group of five levels of inputs depending takes five acts following: PB: Positive Big act.PS: Positive Small act. Z: Zero act. NS: Negative Small act. NB: Negative Big act. Several methods are used including the method shown in the center of gravity and Bisector and middle of maximum ... etc. The center of gravity is the most important one. It is the simplest and most widely used. And it works as follows: if fuzzy levels (PB, PS ... .NB) function that its membership be $\mu 1$, $\mu 2$ values.

4.2. Fuzzy Control Rules

Fuzzy control rules depend on the expert of the process. The rules that expressed by a logical statement such as IF – THEN. This statement depends on man's knowledge in different actual application. A fuzzy statement associates a described condition by using a linguistic variables and fuzzy sets to an output or a conclusion. The IF part is mainly used to capture the knowledge by using the elastic conditions, and the THEN part can be utilized to give a conclusion or output in the linguistic variable form. This IF-THEN rule is widely used by the fuzzy inference system to compute the matching degree between the input data matches and rule condition of a rule. Fig. 6 shows the defuzzifier sets.

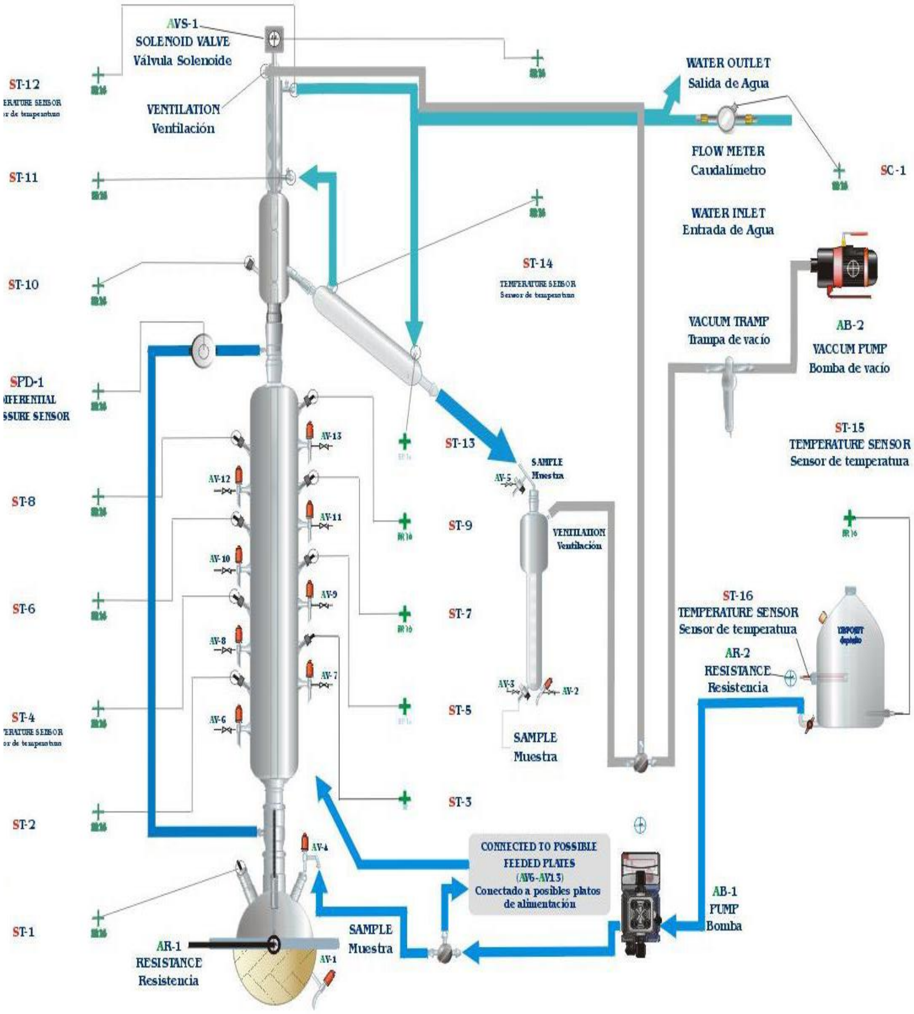

Fig. 1. Schematic diagram of the distillation unit.

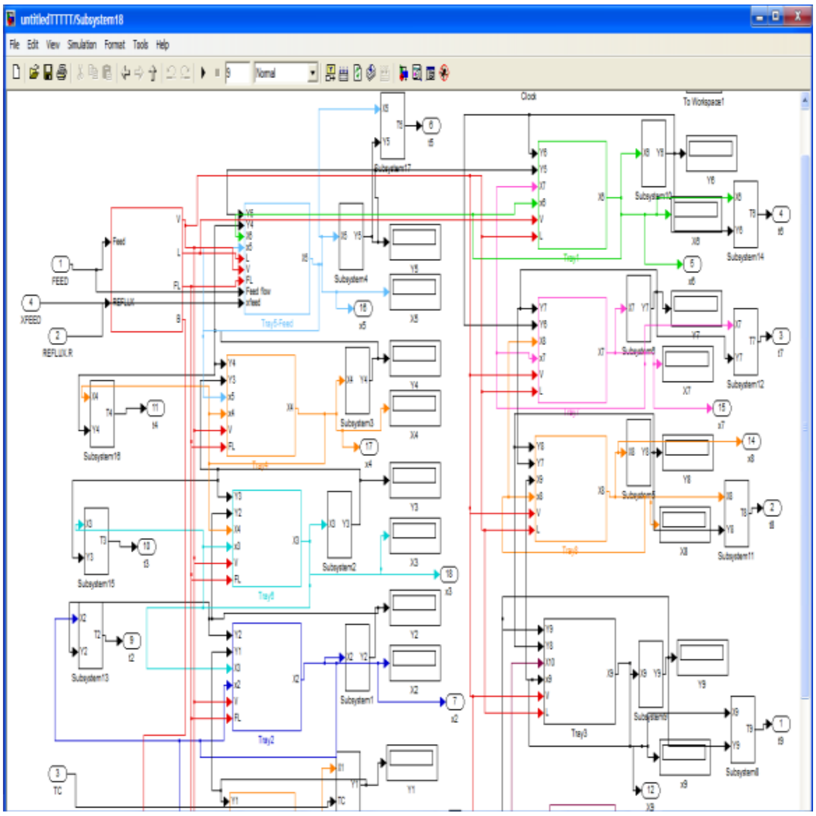

Fig. 2. A detailed mathematical representation model of the distillation tower.

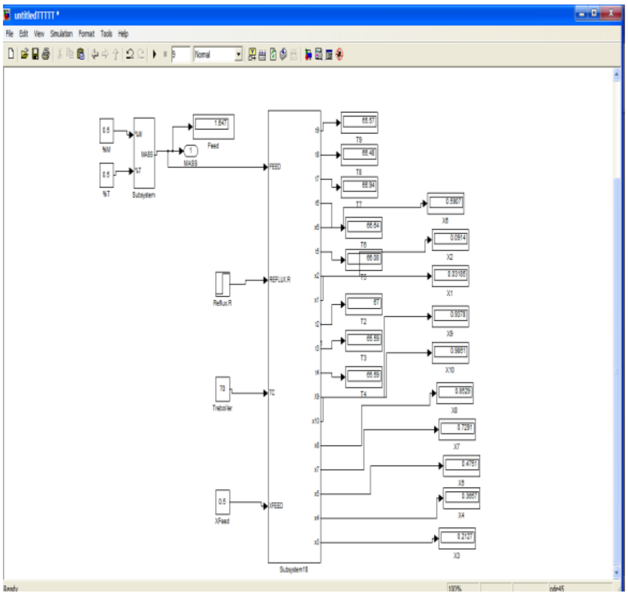

Fig. 3. Mathematical representation model of the total distillation tower.

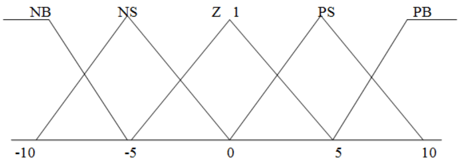

Fig. 4. Membership functions of the inputs.

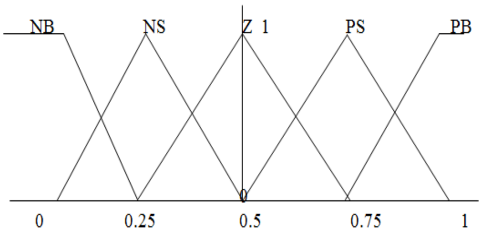

Fig. 5. Membership functions of the output.

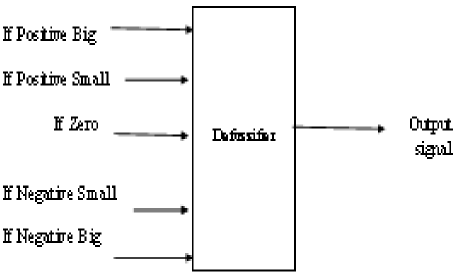

Fig. 6. Defuzzifier sets.

4.3. Fuzzy Controller Design

The used method for the controlled fuzzy design is described as follow;

1- Selection an appropriate measure of the error and the rate of change in the error L≤ (Ei) ≤ L . -L≤ (CEi) ≤ L (-L, L) represents the positive and negative ends of the full extent error and change rate of at the same moment.

2- Calculate the error and rate change:

$$E_i = \text{measured value} - \text{setpoint} \qquad (14)$$

$$CE_i = \text{instnt error} - \text{previous error} \qquad (15)$$

3- The triangular membership function is chosen for the number of rows to describe all the linguistic values.

4- Definition of the sub-totals of the fuzzy error and change rate in the error abroad and act. PB: Positive Big act.PS: Positive Small act. Z: Zero act. NS: Negative Small act. NB : Negative Big act.

5- The fuzzy sets are selected logically. Such as (IF E_i is PB and CE_i is NB THEN output is Z). The action is the framework that can be translated with groups aid to conduct fuzzy follows. Table 1 illustrates the fuzzy rules that controlling the distillation tower.

6- Choosing a particular style of Defuzzification is the aim of clarification in Mamdani type which produces a brief output.

7- The fuzzy control program uses Matlab / Simulink for the purpose of controlling fuzzy programming. This work uses two control systems; first, top temperature control with the use of bottom rate in tower as a manipulated variable, as shown in Fig. 7. Second, top temperature control with the use of the reflux ratio as a manipulated variable, as shown in Fig. 8.

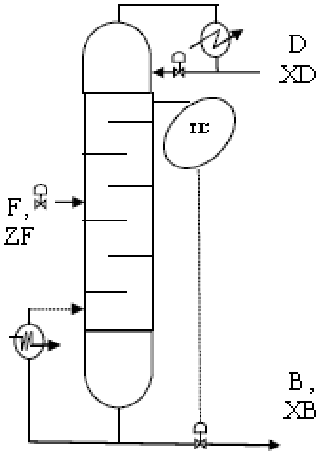

Fig. 7. Control system (1).

Table 1
The fuzzy rules that controlling the distillation tower.

CE \ E	PEB	PES	ZE	NES	NEB
PCB	PUB	PUB	PUB	PUS	ZU
PCS	PUB	PUS	PUS	ZU	NUS
ZC	PUB	PUS	ZU	NUS	NUB
NCS	PUS	ZU	NUS	NUB	NUB
NCB	ZU	NUS	NUB	NUB	NUB

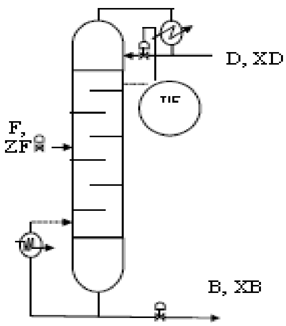

Fig. 8. Control system (2).

5. RESULTS AND DISCUSSION

5.1. Dynamic Behavior of the Open-loop System

The effects of the step change in the reflux ratio is 20% to 50% at reboiler temperature 70℃ and this shown in Figs. 9 and 10. Figs. 11 and 12 show the effect of the step change in the reflux ratio from 20% to 50% at reboiler temperature 85℃. These figures show that the reflux ratio is more effective for high temperature that other parameters, especially, on trays of rectification section because the vapor after passing through the condenser losses the most part of its heat and convert to the liquid. The reflux ratio represents a part of this liquid. The temperature of this liquid is less than the column temperature. This effect decreases gradually with the other trays that are far from the top because the temperature of this reflux liquid will increase whenever the liquid is flow down to the bottom end of the tower so that the effect of the reflux ratio in the trays of the stripping section is less than the temperature of the trays in the rectification section. The comparison between Figs. 9 and 10 with Figs. 11 and 12 shows that the effect of the reflux ratio decreases by increasing the reboiler temperature. The reflux ratio in Figs. 9 and 10 is more effective than that in Figs. 11 and 12 because the reboiler temperature in Figs. 9 and 10 is 70℃ while in Figs. 11 and 12 it is 85℃. The high value of the reboiler temperature increases the vapor in the top and then it increases the temperature value.

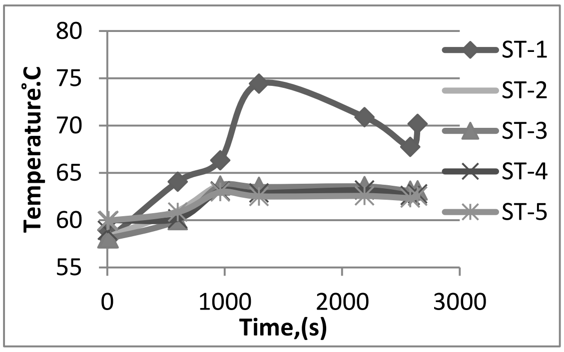

Fig. 9. The temperature response to the step change at reflux ratio 20% to 50% to temperature of trays 1,2,3,4 and 5 at reboiler temperature 70℃.

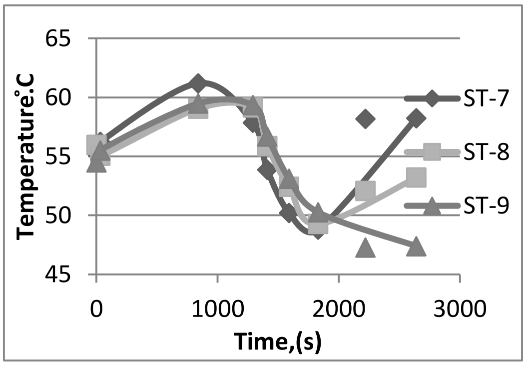

Fig. 10. The temperature response to the step change in the reflux ratio 20% to 50% to temperature of trays 7,8 and 9 at reboiler temperature 70℃.

The results of the experimental work showed that the step change in the reflux ratio is more effect on the behavior of distillation tower than the feed concentration and the reboiler temperature. The effect of step change in the feed concentration, reflux ratio and set point reboiler temperature in the experimental work are shown in the Figs. 13 to 16. The temperature responses of the experimental work at each tray of step change with weight fraction are 0.75 to 0.8 and reflux ratio of 0.5 on the reboiler temperature 70℃, Figs. 13 and 14 show the trays responses.

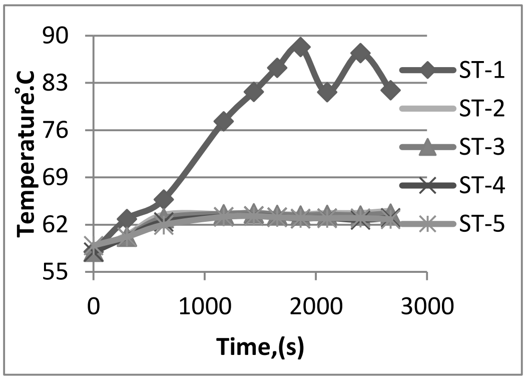

Fig. 11. The temperature response to the step change for the reflux ratios 20% to 50% to temperature of trays 1,2,3,4 and 5 at the reboiler temperature 85℃.

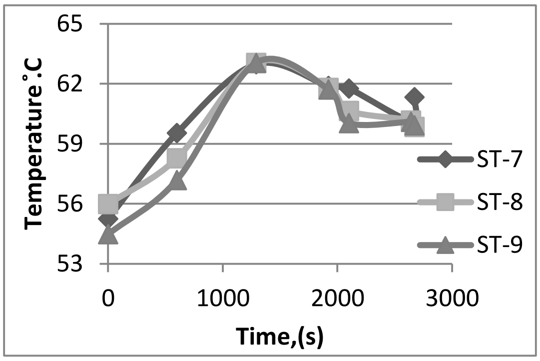

Fig. 12. The temperature response to the step change for the reflux ratios 20% to 50% to temperature of trays 7,8 and 9 at the reboiler temperature 85℃.

The behavior of the column is still effected by the increase of the feed concentration. The step change in weight fraction of feed represents more disturbances effecting the column behavior. The feed concentration causes an increase in the concentration of the light component in the mixture and a decreases in the boiling point temperature of the reboiler mixture. The increase in concentration feed causes a notable increase of vapor rising up to the top and also increasing the trays temperature.

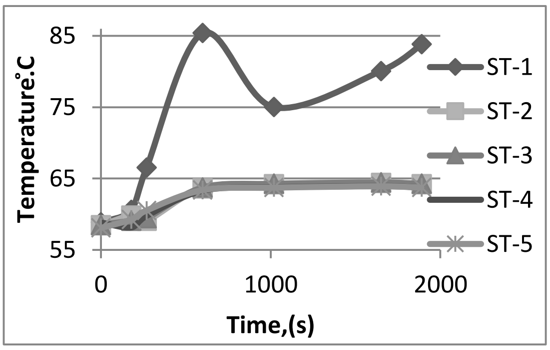

Fig. 13. The response of the temperature at step change in feed concentration 75% to 80% on temperature of trays 1,2,3,4 and 5 at reboiler temperature 85℃.

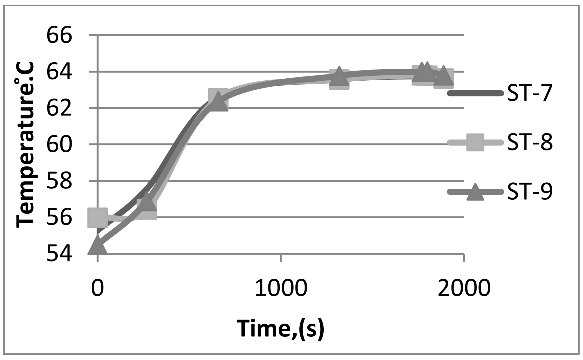

Fig. 14. The response of the temperature at step change in feed concentration 75% to 80% on temperature of trays 7,8 and 9 at reboiler temperature 85℃.

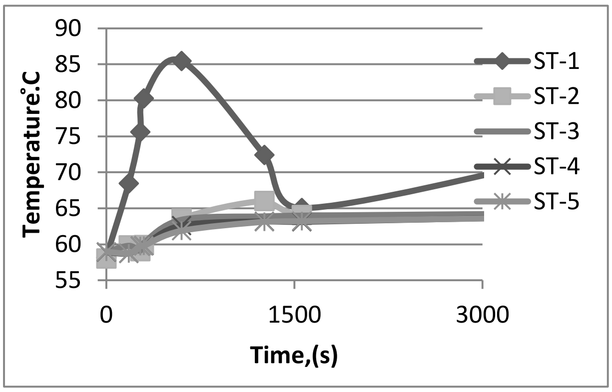

Fig. 15. The response of the temperature at step change in the set point of the reboiler temperature for the range 85 to 70℃ on temperature of trays 1,2,3,4 and 5.

There is a little influence on the temperature of trays 2,3,4,5 because their location is under the feeding position and the feed temperature is about 60℃. There is a clear effect of the feed concentration of light component on the trays in the rectification section because increasing the amount of the rising vapor to the top causes an increases of the notable temperature of these trays. The step change of the rates reboiler temperature from 85 to 70℃. Figs. 15 and 16 show that the step change in the set point of the reboiler temperature affects the temperature of trays in the rectification section more than trays in the stripping section. The disturbance in the reboiler temperature rates from 85℃ to 70℃ and leads to a decrease in the vapor rising to the top and decreases the temperature of the rectification trays. Additionally, the reflux ratio leads to a clear decrease in temperature of the trays that are near the top. These figures also show that the temperature in the

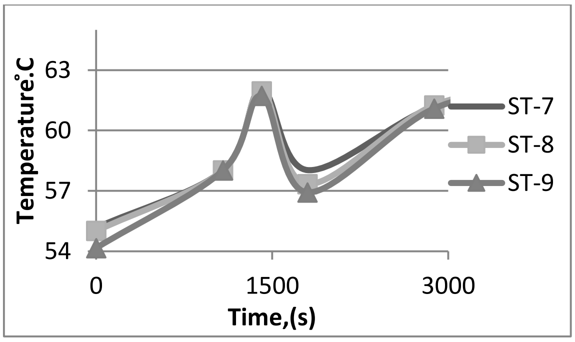

Fig. 16. The temperature response at step change in set point of the reboiler temperature rates from 85 to 70℃ for temperature of the trays 7,8 and 9.

stripping section decreases and returns to the first state because these trays are less effected by the vapor because these trays are located under feed trays. This, in turn, leads to decreasing the effect of temperature and vapor so that the effect is less on trays in the stripping section. Table (2) shows the layout of the runs for the experimental dynamics of the distillation tower**.**

5.2. Simulation of the Controller Methods

The comparison between the response of the top temperature between PID and the fuzzy controls are shown in Figs. 17 to 20. The results showed that the fuzzy logic controller is better and faster than PID in regarding the required value. The fuzzy is based on the logical functions which give out action with the input error. PID controls act gradually with time. The fuzzy controller keeps ISE between the two limits of 0.002064879 to 2.37226×10^{-6}. The PID controller action is very aggressive and unstable, therefore, it showed a large deviation in the set point. However, the fuzzy controller performance under the same conditions is better than and smooth.

Table 2
The layout of the experiment runs for dynamics distillation.

Run No.	Reboiler Temp., ℃	Weight Fraction %	Reflux Ratio %	Notes
1	70	75 to 80	50	Step change in weight fraction
2	75	75 to 80	50	Step change in weight fraction
3	70 to 75	75	50	Step change in reboiler temperat ure
4	70 to 75	80	50	Step change in reboiler temperat ure
5	75	80	50 to 80	Step change in reflux ratio
6	70	75	50 to 80	Step change in reflux ratio
7	70	80	50 to 80	Step change in reflux ratio

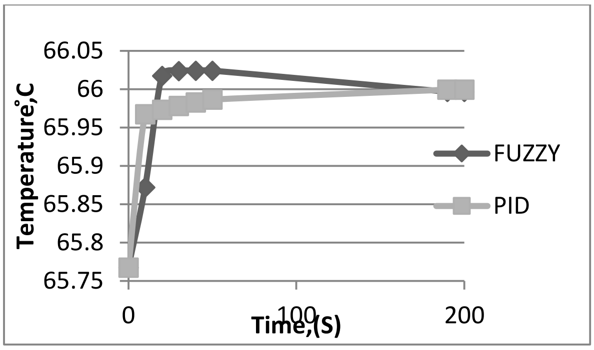

Fig. 17. The comparison between the response of PID and Fuzzy Logic control at step change in feed flow rates1.647 to 2 kg/hr for control system 1.

Figs. 21 to 23 show a good response of the two systems and small difference between them in responses to get the required value. The fuzzy results showed that when considering the reflux liquid as a manipulated variable it gave a better response than the bottom rate. The results showed good agreement between the two types.

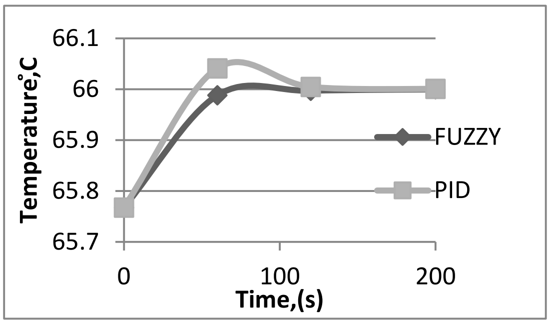

Fig. 18. The comparison between the response of PID and Fuzzy Logic control at step change in weight fraction of feed is from 0.75 to 0.8 for control system 1.

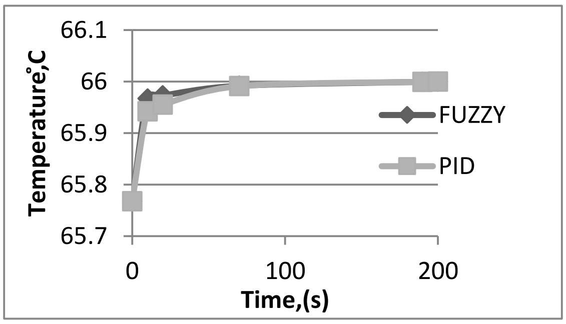

Fig. 19. The comparison between the response of PID and fuzzy logic control at step change in reboiler temperature from 70 to 75℃ for control system 1.

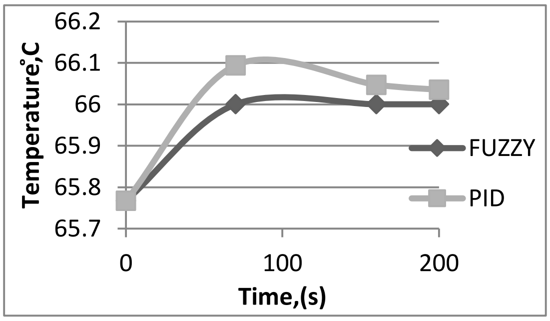

Fig. 20. The comparison between the response of PID and fuzzy logic control at step change in weight fraction of feed rates from 0.75 to 0.8 for control system 2.

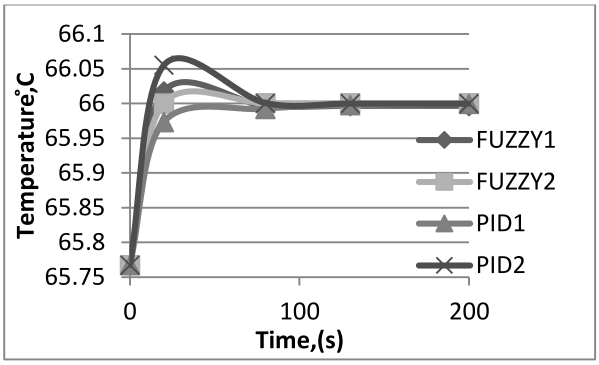

Fig. 21. The comparison between the response of the control systems at step change of the feed flow from 1.647 to 2 kg/hr.

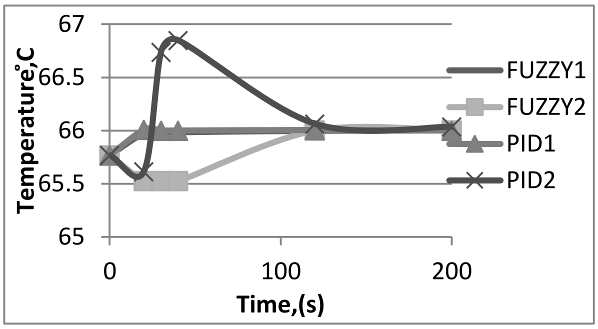

Fig. 22. The comparison between the response of control systems at step change in feed weight fraction from 0.7 to 0.8

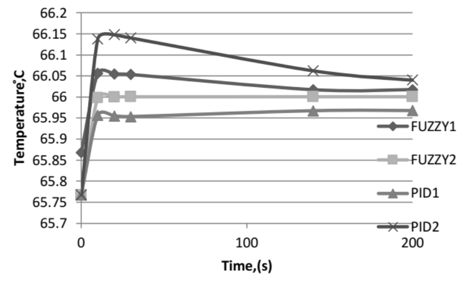

Fig. 23. Comparison between the response of the control systems at step change of the top temperature from 65 to 66℃.

6. CONCLUSIONS

Studying dynamic behavior of the distillation column showed that the effective variables on the distillation column are the feed weight fraction, reboiler temperature and the tower liquid reflux ratio. The reflux ratio is more effective than the other variables. The modified dynamic model for the distillation column gives better results and faster response than those gained from the experimental response of the tower because it theoretically depends on the solution of the equations. Fuzzy controller is better than the PID controller through its fast access to the desired value and cancelling the disturbances. The comparison showed clear difference through the curve of the response and the values of the mean square error and the integral square error. The comparison between the two control systems is seen in the bottom rate and the amount of the liquid reflux as a manipulated variable that used to control the top temperature. It basically, shows that there is a small difference between them.

Table 3
Simulation runs of PID and fuzzy control methods.

Run No.	Variables	Value	Control System	Mean Square Error		Integral Square Error	
				PID	**Fuzzy**	**PID**	**Fuzzy**
1	Feed flow rate	1.647 to 2	1	1.7×10^{-5}	1.1×10^{-5}	0.0003	0.0002
2	Weight Fraction of Feed (xf)	0.3 to 0.5	1	2×10^{-5}	1.7×10^{-5}	0.0004	0.0003
3	Reflux Ratio	0.6 to 0.8	1	0.0008	2×10^{-5}	0.017	0.0004
4	Temperature of reboiler	70 to 75	1	2.17878×10^{-5}	1.5×10^{-5}	0.0004	0.0003
5	Top temperature	65 to 66	1	9×10^{-5}	1.2×10^{-5}	0.002	0.0002
6	Feed flow rate	1.647 to 2	2	1×10^{-7}	5×10^{-6}	0.0001	2×10^{-6}
7	Weight Fraction of Feed (xf)	0.3 to 0.5	2	9×10^{-5}	0.0007	0.01	0.002
8	Temperature of reboiler	70 to 75	2	0.0002	5×10^{-6}	0.005	0.0001
9	Top temperature	65 to 66	2	0.0002	5×10^{-6}	0.005	0.0001

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