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The Dynamic Behavior and Control of Methanol-Toluene Distillation Column

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Abstract

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 were obtained. Based on a derived mathematical model, the Simulink simulator of the distillation column is used to implement the PID and fuzzy logic control methods. The Comparison between two controllers is done for step changes in set point, feed flow rate, feed weight fraction and liquid reflux. The controller performance is measured by using mean square error and integral square error. The results showed that the performance of the fuzzy controller is the best than the PID controller in fast access to the desired value and cancelling the disturbances.

Keywords: Dynamic Behavior, fuzzy logic controller, distillation column, PID controller, methanol-toluene.

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.

الكلمات الدالة: السلوك الديناميكي، مسيطر المنطق الضبابي، برج التقطير، مسيطر تناسبي-تكاملي-تفاضلي، ميثانول-تولوين.

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.̊C)
D: Distillate flow rate, (kg/min)
F : Feed flow rate, (kg/min)
H : Enthalpy, (kJ/kg.̊C)
i : Tray number
ISE: Integral square error
Kc : Proportional gain, (mA/ ºC)
L : Liquid flow rate on tray, (kg/hr)
LT : Amount liquid reflux to column
M : Liquid holdup, (kg)

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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, (^{o}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

Introduction

The main objectives of distillation control are maintaining 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 can contribute to more than 50% of plant operating costs. The energy requirement may be reduced significantly through improved operations. This is achieved not only through optimal column design, but requires, in addition, a control system which is able to maintain the optimal conditions. Distillation control is a challenging endeavor due to the inherent nonlinearity of distillation, multivariable interaction, the non-stationary behavior and the severity of disturbance. Kano et al. [1] applied predicative inferential control through predicting the concentrations by controlling the process of measuring the variables directly instead of the current appreciations of concentration. They proved that this method is effective and it was able to offer good performance for most disturbances. Jana [2] suggested nonlinear adaptive control system for binary system distillation column and testing performance on adaptation under primary error and heterogeneous disturbances. They compared it with PI control. The results showed that the velocity of the response and access to the required value in less time. Filetia et al. [3] developed computerized algorithms of the fuzzy logic control and implement experimental in distillation equipment for separation a mixture consists of hexane and heptane. They arranged fuzzy logic controller by changing the gain and the association function for input and output variables. The results compared with PID controller and showed that fuzzy logic gave better performance than PID controller. El-garhy et al. 4] proposed a particle swarm optimization for estimation the ideality values of the steady- state elements. The simulation results showed high accuracy and less burden mathematical in reducing the intersection. Canete et al. [5] developed a method for connecting program Simulink for simulation distillation column dynamic with program (Lab view). The developed system applied on distillation column for separation a binary mixture consists of methanol and propanol by PID Controllers. The results showed that this method can use in controlling and investigating with good performance. Duraid and Mohammed [6] applied fuzzy logic controller for a continuous binary distillation tray column for separation ethanol-water mixture. They designed the fuzzy logic controller according to some of logic rules depending on fuzzy sets and experimental works by using Matlab program. They concluded that the fuzzy controller is better than PID controller through fast access to the desired value and cancelling the disturbances. Duraid and Maha [7] designed the fuzzy logic controller for a continuous stirred tank reactor. The simulation study was done by using MATLAB. They concluded that fuzzy controller gave the best performance with compared with conventional control system. Duraid and Ahlam [8] designed a neural network controller of a batch packed distillation column for separation four systems; acetic acid-water, acetone-water, ethanol-water and benzene-toluene mixtures. The controller was designed by using "MATLAB" program and applied 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 studying the dynamic behavior of distillation column and modified dynamic model of distillation process of a methanol - toluene mixture consists of and then applying PID and fuzzy logic controllers.

Mathematical Modeling

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

Mass rate in – Mass rate out = Mass Accumulation (1)

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

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

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

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

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

Where F is feed flowrate.

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

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

where B is bottom flow rate.

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

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

where D is top product flow rate.
-Energy balance about column tower-

Heat rate in – Heat rate out = Heat Accumulation (6)

-Energy balance on tray (i) depending on Equation (6) and can be written as:

$$c_i \frac{M_1 d(T_1)}{dt} =$$

$$c_{i+1}L_{i+1}T_{i+1} - c_i L_i T_i + c_{i-1}V_{i-1}T_{i-1} - c_i V_i T_i \quad (7)$$

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

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

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

where H and QR are enthalpy and heat reboiler respectively.

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

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

where QC is heat of condenser.

-Vapor Liquid Equilibrium (VLE) Calculations

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

-Calculate vapor concentration by 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.

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

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

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

-Calculate the temperature in each tray by using Antoine Eq. :

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

Experimental Work

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

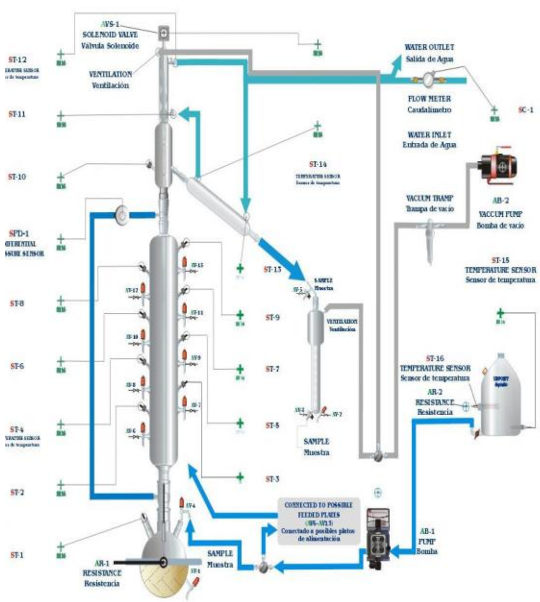

Fig. 1. Schematic diagram of the distillation unit.

Simulation Work

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

Fuzzy Logic Controller

Fuzzy logic controller becomes an important method in process control. This method discovers one of the most research areas by involving fuzzy set theory. The contributors concern with the analysis and design of 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 of 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 based decision making to achieve the control tasks. The decision making approach is typically based on rule of inference. A fuzzy rule in the knowledge base of the control task is generally a linguistic relation. 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 one input and output signals which are zero, big and small in negative and positive ranges. The final step in building a fuzzy logic system is the conversion of fuzzy variables processed fuzzy logic rules to real values again, and this process is called (Defuzzification) because it compares fuzzy groups to give a true indication then used the events of a certain act. The final value of overseas each variable is a single number to those gathering fuzzy aggregates to be a certain extent from the outside after the shows to give value (single output). Described 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. There are several methods used including the method shown in the center of gravity and Bisector and middle of maximum ... etc. The center of gravity the most important ways, the simplest and most widely used and works as follows: If fuzzy levels (PB, PS ... .NB) function that her membership be µ1, µ2 values.

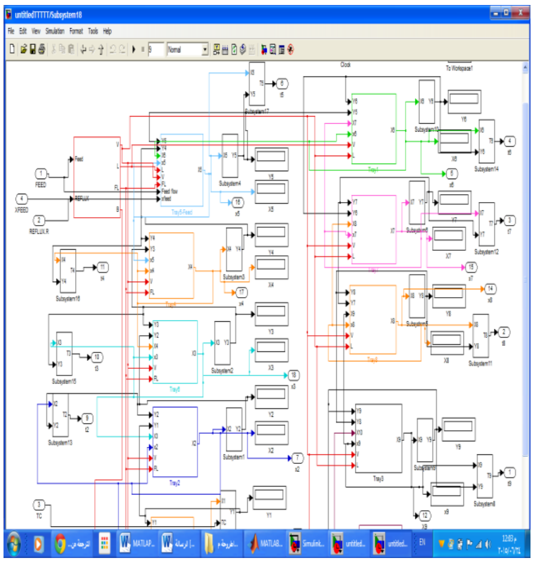

Fig. 2. Model detailed mathematical representation of the distillation tower.

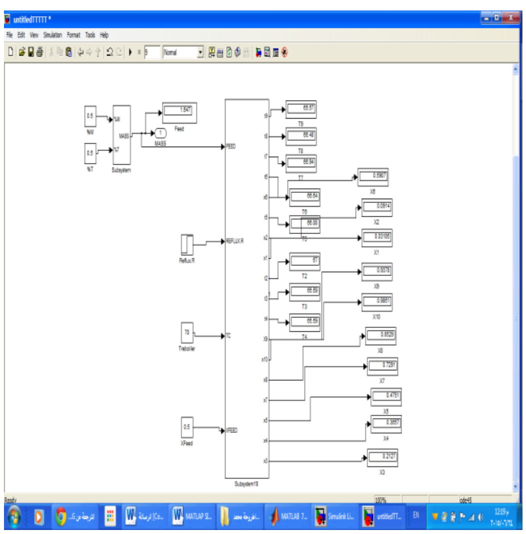

Fig. 3. Model mathematical representation of the total distillation tower.

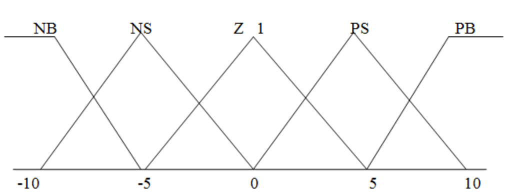

Fig. 4. Membership functions for inputs.

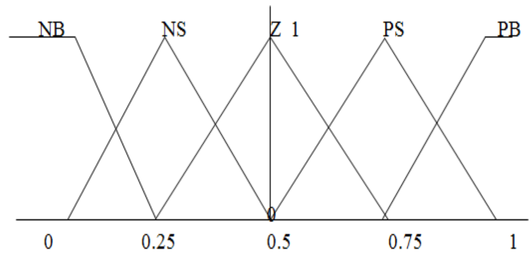

Fig. 5. Membership functions for output.

Fuzzy Control Rules

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

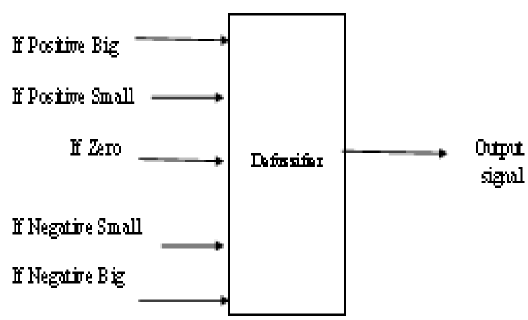

Fig. 6. Defuzzifier sets.

Design Fuzzy Controller

The method followed for the design of a controlled fuzzy can be described as the following;

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

2- Calculate the error and rate change in error: E_i = measured value – setpoint .(14) CE_i = instant error– previous error. (15)

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

4- Definition sub-totals for error fuzzy and rate of change 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 framework can be translated with aid groups to conduct fuzzy follows.. The Table (1) illustrates the fuzzy rules controlling the distillation tower.

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

7- The using of fuzzy control program where used in this work program MATLAB / Simulink for the purpose of controlling fuzzy programming. This work is uses two control systems first, control the top temperature with use the bottom rate in tower as manipulated variable. As shown in Fig. (7). Second, control the top temperature with use the reflux ratio as manipulated variables. As shown in Fig. (8).

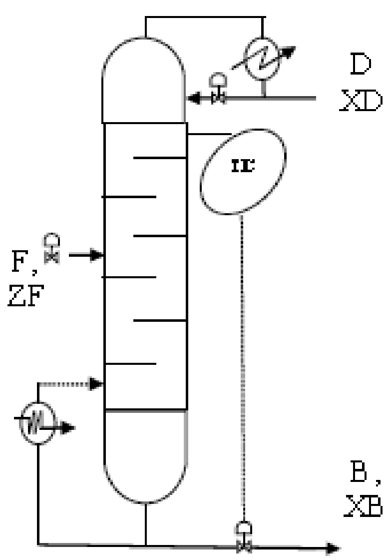

Fig. 7. Control system (1).

Table 1: The fuzzy rules 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

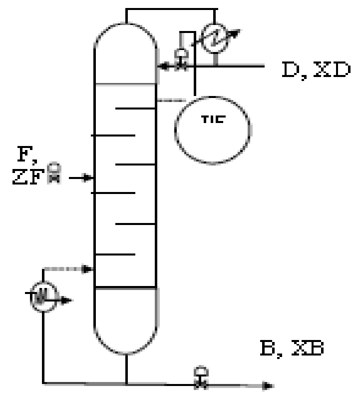

Fig. 8. Control system (2).

Results and Discussion

Dynamic Behavior of Open-loop System

The effects of step change in reflux ratio from 20% to 50% at reboiler temperature 70℃ are shown in Figs. (9) and (10). Figures (11) and (12) show the effect of step change in reflux ratio from 20% to 50% at reboiler temperature 85℃. These figures show that reflux ratio more effect on temperature from other parameters especially on trays of rectification section because the vapor after pass through condenser loss more part of the heat and convert to the liquid. The reflux ratio represents part of this liquid. The temperature of this liquid is less than the temperature of the column. This effect decreases gradually with the other trays that far from the top because the temperature of this reflux liquid will increase whenever the liquid down to the bottom of the tower so that be the effect of the reflux ratio in the trays in the stripping section less than in trays in the rectification section. The comparison of Figs. (9) and (10) with Figs. (11) and (12) show that the effect of reflux ratio decreases with increasing the temperature of the reboiler . The reflux ratio in Figs. (9) and (10) more effect on temperature than in Figs. (11) and (12) because the reboiler temperature in Figs. (9) and (10) is 70℃ while in Figs. (11) and (12) the reboiler temperature is 85℃. The high temperature of the reboiler leads to increase the vapor up to the top and then increasing the temperature.

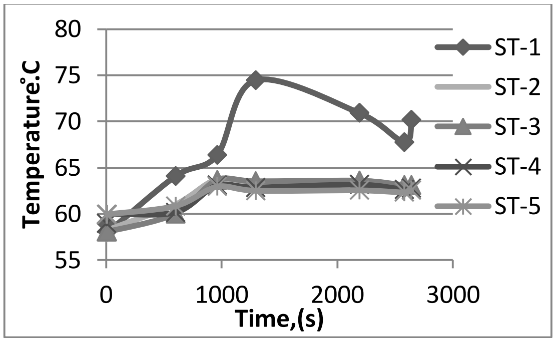

Fig. 9. The response of temperature at step change in reflux ratio from 20% to 50% on temperature of trays 1,2,3,4 and 5. At reboiler temperature 70℃.

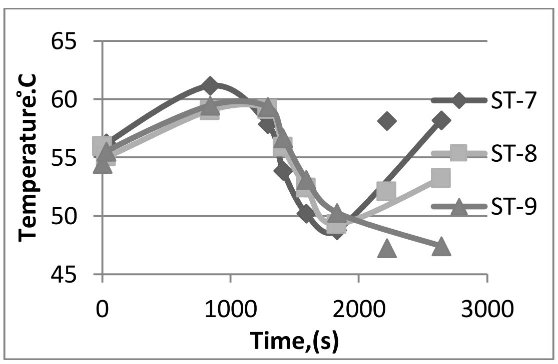

Fig. 10. The response of temperature at step change in reflux ratio from 20% to 50% on temperature of trays 7,8 and 9 at reboiler temperature 70℃.

The results of the experimental work showed that the step change in reflux ratio more effect on the behavior of distillation tower than concentration of the feed and reboiler temperature. The effect of step change in 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 from 0.75 to 0.8 and reflux ratio of 0.5 and Reboiler temperature 70℃. Figs. (13) to (14) show the responses of the trays

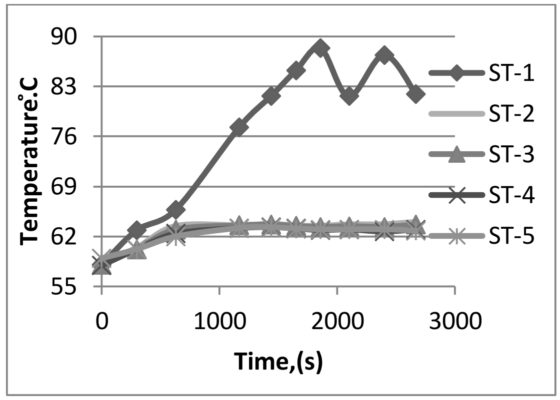

Fig. 11. The response of temperature at step change in reflux ratio from 20% to 50% on temperature of trays 1,2,3,4 and 5 at reboiler temperature 85℃.

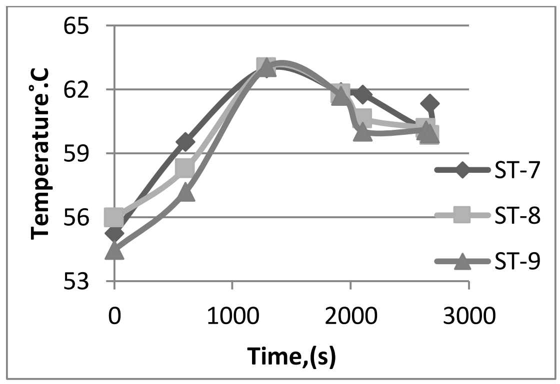

Fig. 12. The response of temperature at step change in reflux ratio from 20% to 50% on temperature of trays 7,8 and 9 at reboiler temperature 85℃.

temperature. The behavior of the column is still affected by increasing the concentration of the feed. The step change in weight fraction of feed represents more disturbances effects on the behavior of column. The concentration of feed causes increasing in concentration of the light component in the mixture and decreases the boiling point temperature for the mixture in reboiler. The increasing in feed concentration causes increasing the vapor rising to the top and increasing temperature of trays. There is a small effect on temperature of trays 2,3,4,5 because the location of these trays is under the feed and the temperature of the feed is about

60℃. There is a clear effect of increasing the feed concentration of light component on the trays in the rectification section because increasing the amount of rising vapor to the top causes increasing the temperature of these trays. The step change temperature in reboiler from 85 to 70℃. Figures (15) and (16) show that the step change in set point reboiler temperature effect on temperature of trays in the rectification section more than trays in the stripping section. The disturbance in reboiler temperature from 85℃ to 70℃ leads to decrease the vapor which rising to the top and decrease the temperature of the rectification trays. Additionally, the reflux ratio leads to decrease the temperature of the trays that near the top. These figures also show that the temperature in stripping section decreasing and return to the first state because these trays be less effect with vapor because this trays location under feed trays and that lead to decreasing the effect of temperature and vapor so that the effect is small on trays in the stripping section. Table (2) shows the layout of the runs for the experimental dynamics of the distillation tower.

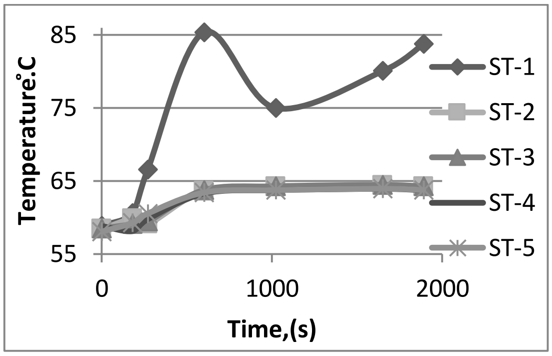

Fig. 13. The response of temperature at step change in concentration of feed from 75% to 80% on temperature of trays 1,2,3,4 and 5.At reboiler temperature 85℃

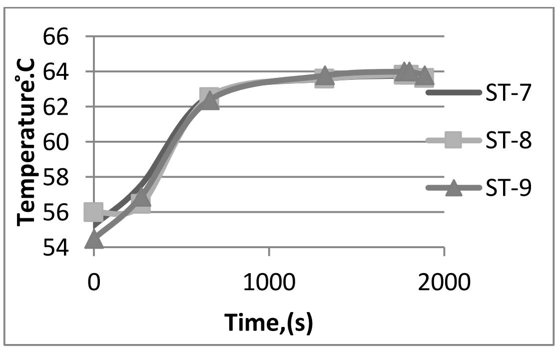

Fig. 14. The response of temperature at step change in concentration of feed from 75% to 80% on temperature of trays 7,8 and 9. At reboiler temperature 85℃.

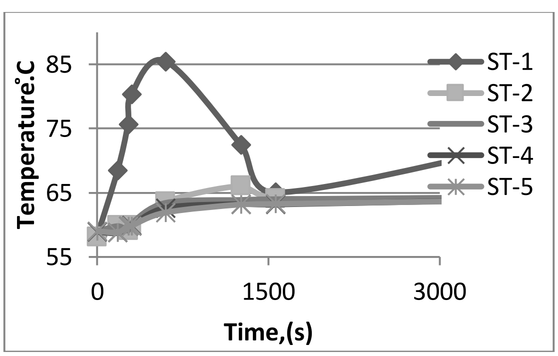

Fig. 15. The response of temperature at step change in set point reboiler temperature from 85 to 70℃ on temperature of trays 1,2,3,4 and 5.

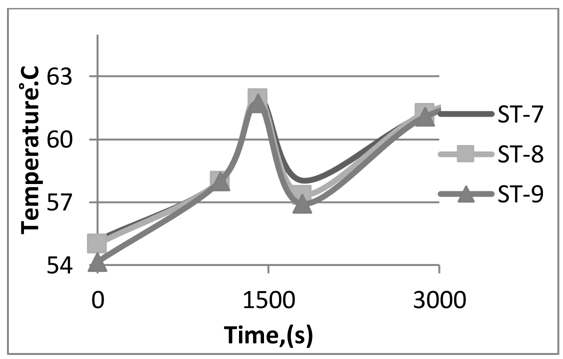

Fig. 16. The response of temperature at step change in set point reboiler temperature from 85 to 70℃ on temperature of trays 7,8 and 9

Simulation of controller methods

The comparison of the response of the top temperature between PID and fuzzy controls are shown in the Figs. (17) to (20). The results showed that the fuzzy logic controller best and faster than PID in getting the required value in shorter time. The fuzzy build on logical functions which give out action with the input error. PID control act gradually with time. The fuzzy controller keep ISE between the limit 0.002064879 to 2.37226*10^{-6}. The PID controller action is very aggressive and unstable, so it was observed a large deviation in set point. However, the fuzzy controller performance under the same conditions is better and smooth.

Table 2: The layout of the experimental runs for dynamics of the 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 temperature
4	70 to 75	80	50	Step change in reboiler temperature
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

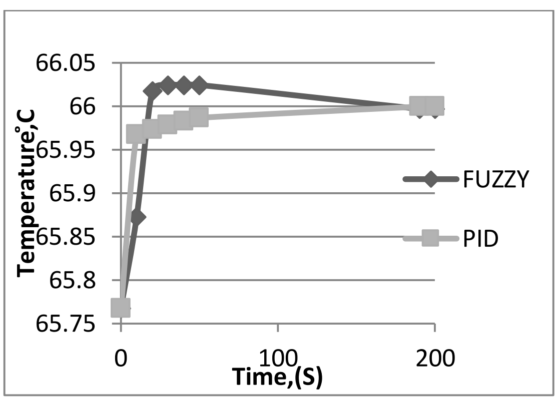

Fig. 17. Comparison between the response of PID and Fuzzy Logic control at step change in feed flow from 1.647 to 2 kg/hr for control system 1.

Figures (21) to (23) show a good response of two systems and small different between them in the response in getting the required value. The fuzzy results showed that when considering the reflux liquid as manipulated variable gave best response than the bottom rate. The results showed good agreement between the two types.

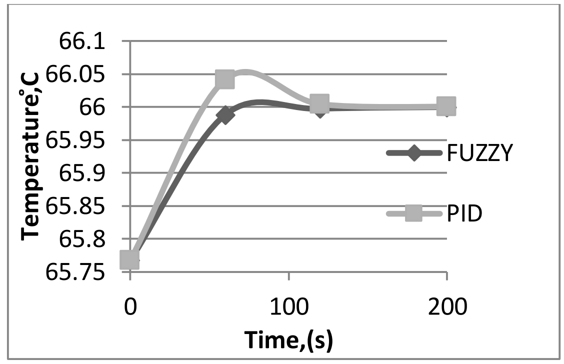

Fig. 18. Comparison between the response of PID and Fuzzy Logic control at step change in weight fraction of feed from 0.75 to 0.8 for control system 1.

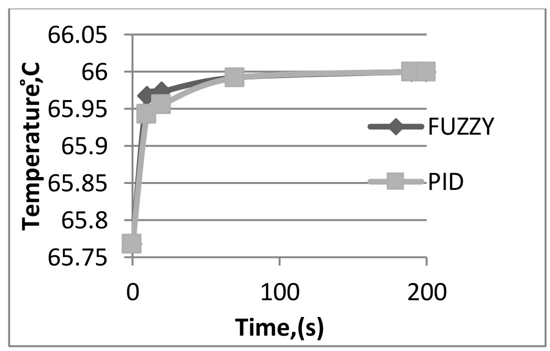

Fig. 19. Comparison between the response of PID and fuzzy logic control at step change in reboiler temperature from 70 to 75 ̊C for control system 1.

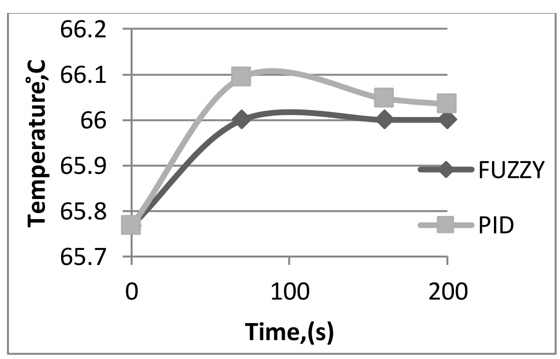

Fig. 20. Comparison between the response of PID and fuzzy logic control at step change in weight fraction of feed from 0.75 to 0.8for control system 2.

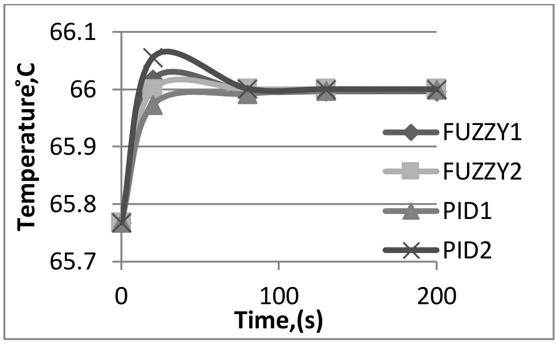

Fig. 21. Comparison between the response of control systems at step change feed flow from 1.647 to 2 kg/hr.

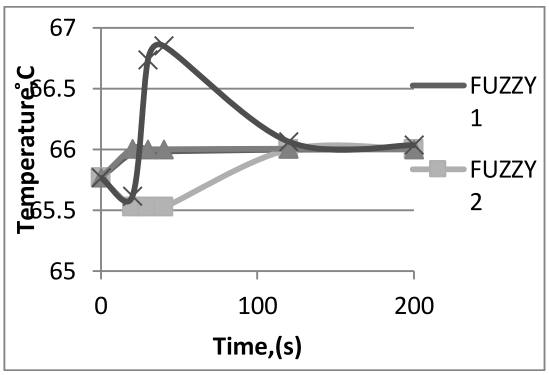

Fig. 22. Comparison between the response of control systems at step change weight fraction of feed from 0.7 to 0.8

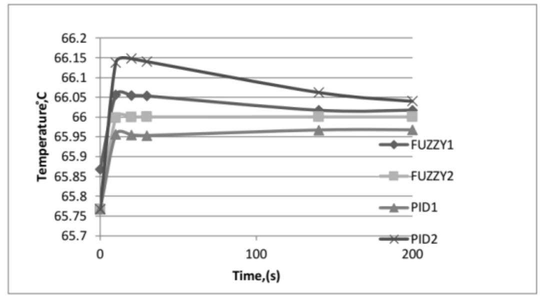

Fig. 23. Comparison between the response of control systems at step change of top temperature from 65 to 66 ̊C.

Conclusion

The studying of the dynamic behavior of distillation column showed that the effective variables on distillation column are feed weight fraction, reboiler temperature and ratio of liquid reflux to tower. The reflux ratio more effect of other variables than the feed weight fraction. The modified dynamic modeling for distillation column give good results and fast response from the experimental response of tower because this depending on solution of the equations theoretically. Fuzzy controller is best than the PID controller through fast access to the desired value and cancelling the disturbances. The comparison showed that clear difference through the curve of the

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

response and the values of mean square error and integral square error. The comparison between the two control systems are bottom rate and amount of liquid reflux as manipulated variables to control the top temperature show that there is a small difference between them.

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