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Research Article

Dynamics, Simulation, and Control of a Batch Distillation Column using Labview

Naseer A. Habobi† and Sura M. Yaseen†*

†Department of Chemical Engineering, University of Al-Nahrin, Iraq

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Abstract

In this work, the dynamic behaviors of batch distillation introduced by using a step changes in the reflux and find the response of this test on the concentration of distillate methanol. And it has been recognized that first order plus dead time (FOPTD) represent the process dynamics of batch distillation. The operating strategies for batch distillation were studied methanol / water mixture, 30% mole of methanol and 70% mole of water. Batch distillation column with eight trays was operated and controlled in real time by using LabVIEW program; giving the temperatures data and finding the concentration of distilled methanol using an empirical temperature-composition relationship model. Zieglar-Nichols tuning rules were applied to determine the parameters of the implemented PID controller. It was found that k_p=1.93, T_i =2760 sec, and T_d = 690 sec. The comparisons of the designed PID controller with experimental work are included (according to rise time, percentage overshoot and settling time). MATLAB Simulink was used to simulate the system using PID controller.

Keywords: *Batch distillation, LabView, Real time control system*

1. Introduction

Batch distillation is one of the oldest liquid separation units that are used for producing high purity products and valuable specialized chemicals in small quantities. One of the principal advantages of using batch distillation is the flexibility. It means that one column can be designed to separate different mixtures with different compositions and specifications for final purity (H. Galindez, *et al* 1988; A. Klingberg, 2000). The other advantage of batch distillation is the lower capital cost and relative simplicity compared with larger continuous distillation columns. (S. Skogestad *et al* 1997)

Although batch distillation is known to be less energy efficient than its continuous counterpart, it has received renewed interests in recent years due to the flexibility it offers. In general to control on batch distillation process one of following progress can be applied:

1) Constant reflux: Reflux is set at a predetermined value that is maintained for the run. Since pot liquid composition is changing, instantaneous composition of the distillate also changes.
2) Varying reflux with constant overhead composition, the amount of flow rate of liquid returned to the column is constantly increased to maintain a constant distillate composition.
3) optimize the reflux in order to achieve the desired separation in a minimum of time or with a maximum thermodynamic efficiency. Complex operations may involve withdrawal of side streams, provision for inter condensers, addition of feeds to Another control method which is possible to trays and periodic charge addition to the pot. (Maira Mendes *et al* 2009).

Frattini *et. al.* 1997, developed a self-adjusting gain scheduling PI control method and used it to the control of a binary batch distillation column. This method reached the control goal by continuously adjusting the gain to higher value. Li and Wozny introduced an adaptive control strategy to follow the pre-defined optimal reflux-ratio profiles.

Monroy and Alvarez use a robust nonlinear control method to compensate modeling errors, and adjust the reflux ratio to control the composition of a batch distillation process. Up to now, although researchers around the world have put forward many advanced control strategies for the control of batch distillation process, most of these control strategy research only carried out theoretical investigation or simulation study, and few of them are applied to practical industry batch distillation process or tested by experiment. (ZhiyunZou *et al,* 2006)

Model predictive control (MPC) is also used in control strategy in the process industry.

*Corresponding author: **Sura M. Yaseen**

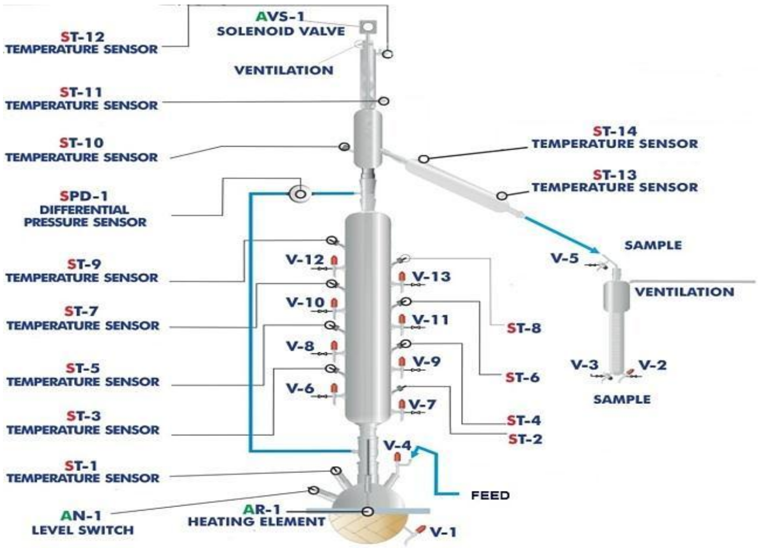

Fig.1 Process diagram and unit elements allocation of Temperature Sensor

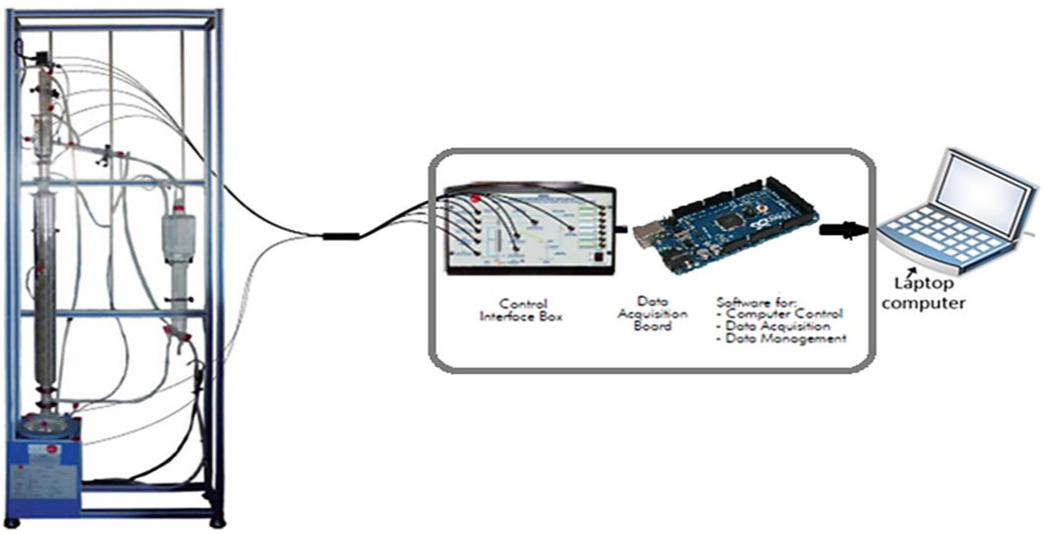

Fig.2 Computer Controlled Batch Distillation Unit

It's used for years in advanced industrial applications it is because accuracy also suitability for on-line control must be taken into account. First of all, the model must be accurate enough, capable of precise long-range prediction. An inaccurate model gives erroneous predictions which are likely to result in unacceptable control. Although classical linear MPC algorithms which use linear models give good or satisfactory results quite frequently, the majority of processes are nonlinear by nature. For such processes nonlinear MPC algorithms based on nonlinear models must be used (Maciej Lawry, 2011)

2. System Description

- The unit is basically composed by a boiler, a reflux system and a tank for the distillation.
- Binary system in which methanol/water mixture is used (feed = 1 liter).
- The steam of MVC goes to the head of the column is sent to a total condenser.
- Sieve Plates Column with 8 plates with one temperature taking and sample. The cooling water flow that crosses the condenser is regulated and indicated in a flow sensor.
- The pressure loss in the column can be measured with a pressure manometer.
- The temperatures of the system are measured by sensors placed in each stage measuring temperature of vapor liquid equilibrium as shown in Fig. 1.
- The system connected to computer controlled unit which is includes:

The unit + a Control Interface Box + an 2560 Mega Arduino board which was used as a Data Acquisition Board interfacewith 16 analog inputs and 10 Pulse Width Modulation (PWM) outputs to control on:

- The temperature of the heating element (boiler heater).
- The solenoid valve (reflux ratio).

- 2560 Mega Arduino was used because it is more accurate in connections between the temperature sensors and PC + Computer Control, Data Management Software Packages, for controlling the process and all parameters involved in the process.
- The temperature sensors (type J) of column is connected to Arduino Mega 2560 which is placed inside the Control Interface Box, as shown in Fig. 2.
- I/O USB single cable between the control interface box and computer
- Computer process was built using LABView including the front panel and block diagram as shown in Fig. 3
- Real time curves representation about system responses.
- Recording of all the process data and
- results in a file such as (Microsoft Word, xls, TXT)
- Graphic representation, in real time, of all the process/system responses.
- Both the boiler heater and solenoid valve values can be changed at any time allowing the analysis about curves and responses of the whole process.
- All the outputs relays controlling both boiler heater and solenoid valve and sensors values and their responses are displayed on only one screen in the computer.

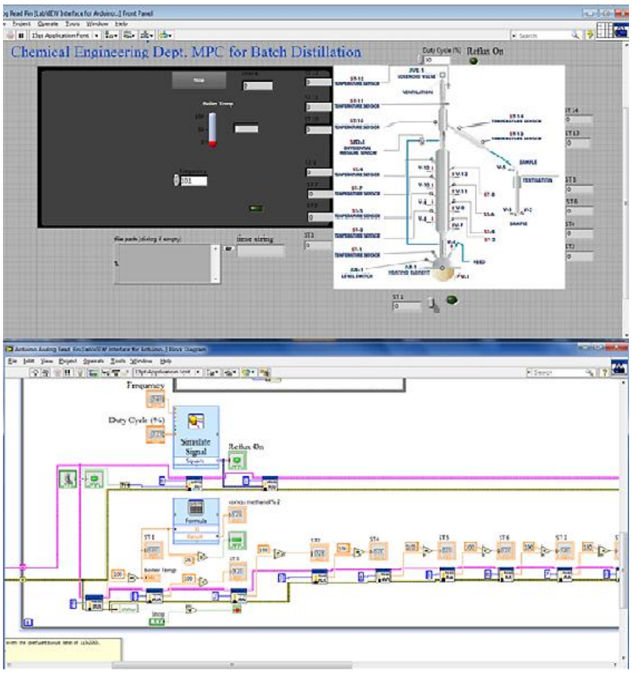

Fig.3 Front Panel & Block Diagram of LABView program

3. Experimental Work

All the feed of methanol-water is pumped into the still pot of the reboiler in one time before distillation. The reboiler is heated up and the flow-rate of steam is controlled by switched on relay by DAQ. The methanol vapor at the top of the column is cooled down by flowing through a cooling water condenser. The flow direction of the condensed methanol liquid is time-sharing controlled by an electric solenoid valve. Basic information about the experiment is summarized in Table 1.

4. Results and Discussion

The reflux ratio R remains constant in the whole process until the concentration of overhead goes down with time.

From Table 2, it is clear that the experiments which made at higher value of reflux ratio R= 100, permit to obtain the maximum recovery of pure methanol, Next figure also illustrates the relation of concentration of distillate methanol with all reflux ratio ranges.

Table 2 the experimental results for batch distillation constant reflux ratio

R%	x concentration
20	0.15333
40	0.2389
60	0.48708
80	0.6706
100	0.9477

4.1 Variable Reflux

The constructed controller made by LabVIEW program is implemented with the batch distillation system to control the distillate concentration. This is achieved by changing the reflux ratio as manipulating variable to control on temperature which is represent a (concentration) of the distillate (top plate).

4.1.1 Dynamic behavior for implemented model

It is necessary to identify model parameters from experimental data. The simplest approach involves Introducing a step test into the process and recording the response of the process. Then step changes of variable reflux ratio are applied 20-40, 40-60, 60-80, and 80-100. The response of the top distillate concentration is shown in Fig. 5.

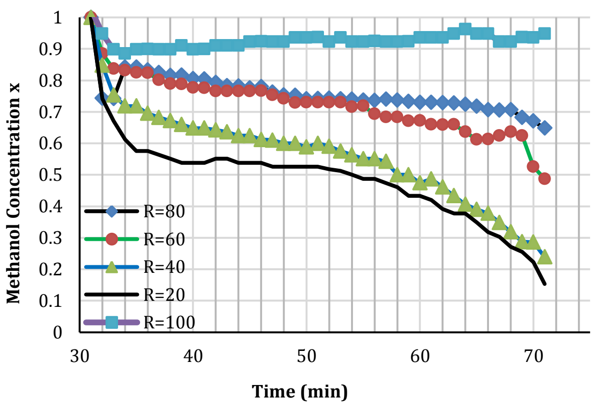

Fig.4 Experimental results with a constant reflux ratio

It has been recognized that a first order may in general represent process dynamics of batch distillation. The calculations are carried further to estimate the steady state in and the process time constant and time delay.

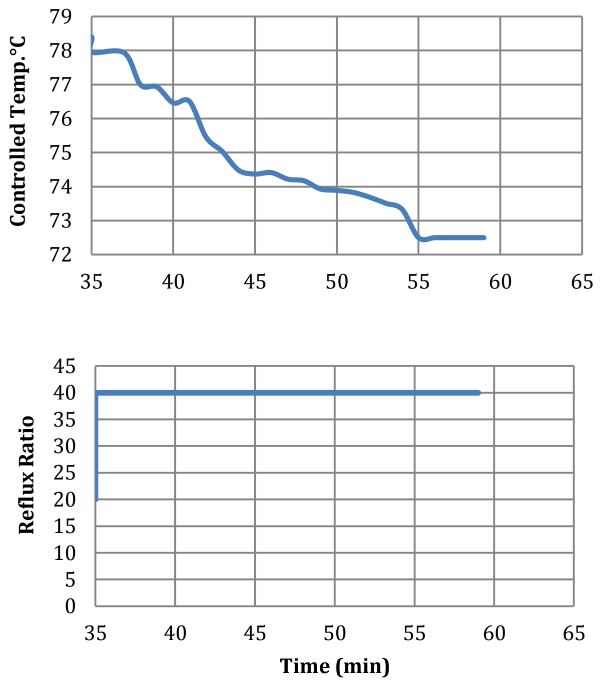

Fig. 5 The response of the top distillate temperature to step change for manipulating reflux ratio 20-40

Fig. 6 shows the open-loop test for the four step changes in manipulating variable reflux ratio from 20 to 100.

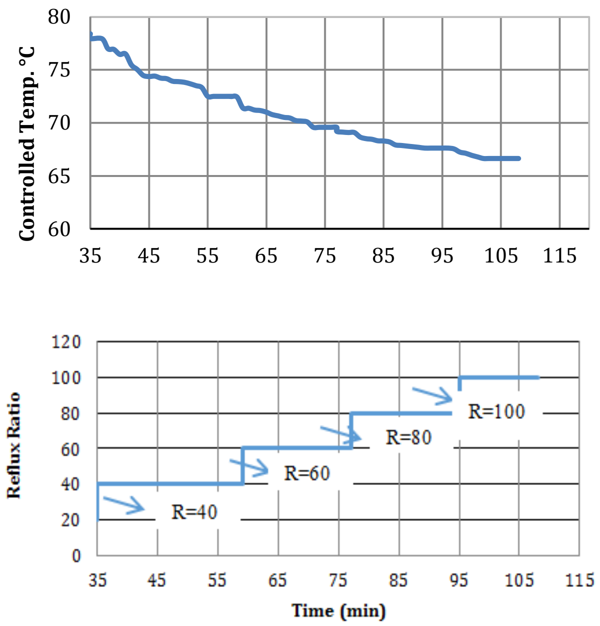

Fig.6 Open-loop test for the four step changes in manipulating variable reflux ratio from 20-40, 40-60, 60-80, and 80-100

Using the experimental data in Fig. 6, transfer function and PID controller are designed to maintain composition specifications for the distillate product taking the reflux flow rate as manipulated variable. (Dale E.Seborg, 2004; Katsuhiko Ogata, 2010)

4.1.2 First order model

The response for the outlet temperature to step change showing in Fig. 5 can recognize that a first order plus time delay (FOPDT) may in general represent process dynamic of the batch distillation and by drawing a tangent line to a process variable PV (controlled temperature) and using controller output CV can calculate the gain, time constant and time delay (Naseer A. Habobi, 2010) the process parameter we get it as following.

$$K = \frac{steady\ state\ change\ in\ the\ measured\ process\ variable\ \Delta\, y}{steady\ state\ change\ in\ the\ controller\ output\ \Delta\, u} \quad (1)$$

$$K = \frac{78-72.5}{(\ 40-20\ )\%} = 0.055\ °C\ /\% \quad (2)$$

and

Time delay L= 23 min (1380 sec)

Time constant $\tau = y_{max} - (\Delta y \times 0.63)$ (3)
τ=78-(5.5 ×0.63) = 75.035
this value represented on Fig. 5.2 and can read time constant value which is =37 min
τ=37 min (2220 sec)
Now the transfer function of the first order plus dead time (FOPDT) can be deduced as follow:

$$G\ (s) = \frac{K}{\tau s+1} e^{-tl\, s} \quad (4)$$

$$G\ (s) = \frac{0.055}{2220\ s+1} e^{-\ 1380\ s} \quad (5)$$

4.1.3 Initial Estimation for PID Controller parameters

Ziegler Nickols tuning method can be considered as one of the earliest closed loop tuning method. This method requires the value of the plant parameters obtained to be keyed into the formula. Ziegler and Nickols have developed PID tuning methods back in the early forties based on open loop tests and also based on closed loop test, which may be their most widely known achievement.

The open loop method allows calculating PID parameters from the process parameters. The procedure as follows:

- Step 1: Make an open loop plant test(e.g a step test)
- Step 2: Determine the process parameters: process gain, dead time, time constant. (As illustrate above).
- Step 3: Calculate the parameters using table 3 (Ahmad Athif, 2008)

4.2 PID Controller Design

The design of a controller requires specification of the parameters: proportional gain (K_p), integral time constant (T_i), and derivative time constant (T_d). There is crucial problem to tune properly the gains of PID controllers because many industrial plants are often burdened with the characteristics such as high order, time delays and nonlinearities. Ziegler-Nichols open loop tuning method is used to find the optimal PID parameters. The optimal parameters obtained for the reflux ratios are applicable over the entire useful range (20 to 100) which is represents 20% to 40% from the controller output. (Katsuhiko Ogata, 2010)

Table 3 Ziegler–Nichols Tuning Rule Based on Step Response of Plant

	K_p	T_i	T_d
PID Controller	1.2 × τ/L	2L	0.5 L

So the estimation of PID parameters became as follow:
K_p= 37/23 = 1.93
T_i=2 × 1380 = 2760 sec
T_d= 0.5 × 1380 = 690 sec

To verify the PID parameters, MATLAB-SIMULINK is used to simulate the system Fig. 7 Show the block diagram, and Fig. 8 shows the scope curve. (Dale E.Seborg, 2004)

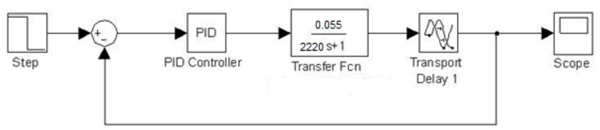

Fig.7 Simulation of close loop PID control using MATLAB- Simulink

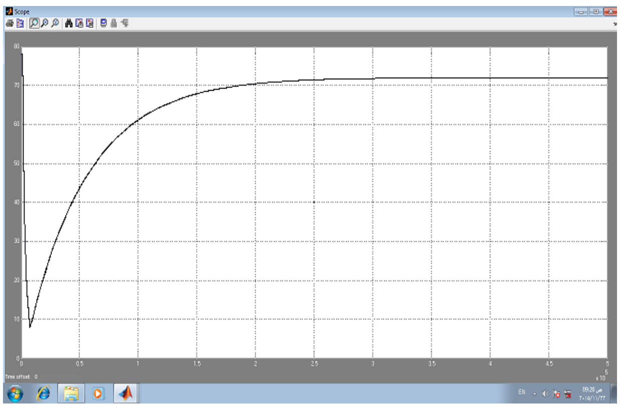

Fig. 8 The Scope view by MATLAB- Simulink

4.2.1 Response Experimental Results with PID Controller

To study the performance of the controller The experimental data which is correspond to the manipulating variable reflux ratio changes 20-40, 40-60, 60-80, and 80-100 are compares with the process model of PID controller. Fig. 9 showed response for close loop control process for 20-40 reflux ratio with PID controller.

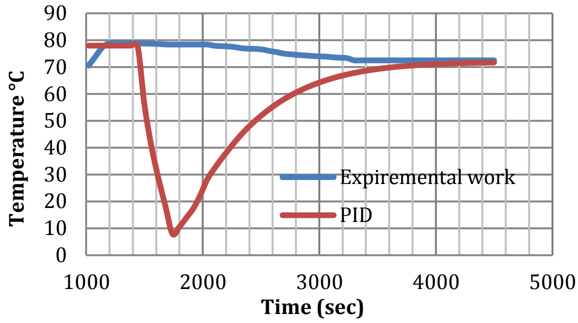

Fig. 9 Response for the open loop control temperature for 20 to 40 reflux ratio with PID controller

The unit-step response of this system can be obtained with MATLAB and the resulting unit-step response curve is shown in Fig. 10.

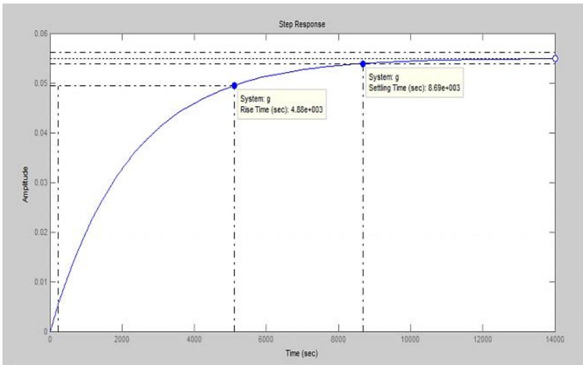

Fig.10 Unit step response of the implemented system with PID controller

From Fig. 10 and by using MATLAB following parameters are obtained:

- Rise Time: 4.8774×10^3
- Settling Time: 8.6848×10^3
- Settling Min: 0.0497
- Settling Max: 0.0550
- Overshoot: 0

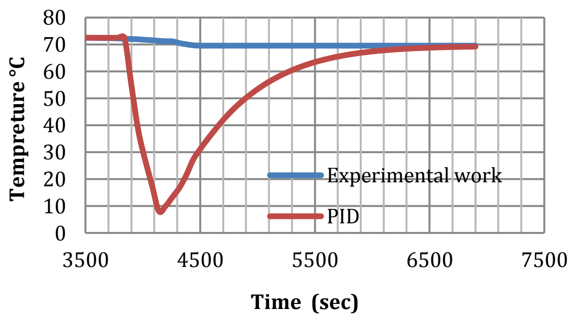

Fig.11 Response for the open loop control temperature for 40 to 60 reflux ratio with PID

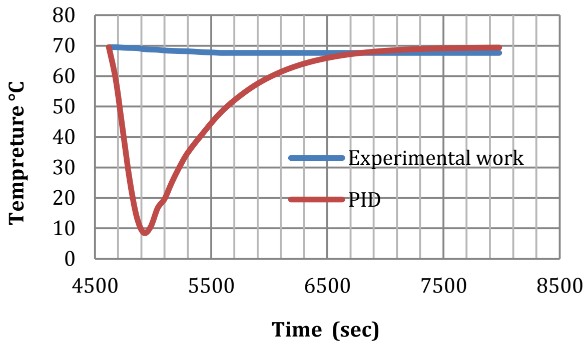

Fig. 12 Response for the open loop control temperature for 60 to 80 reflux ratio with PID

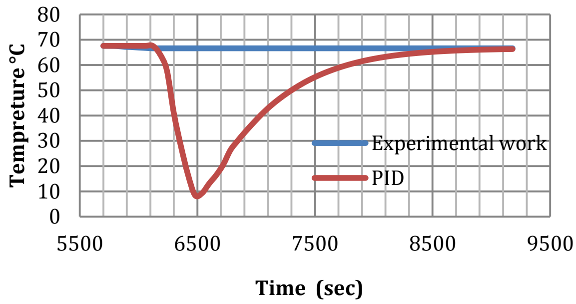

Fig. 13 Response for the open loop control temperature for 80 to 100 reflux ratio with PID

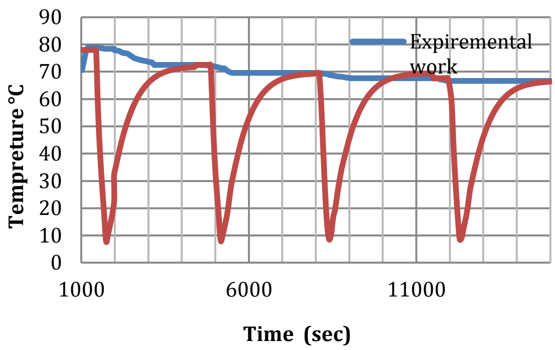

Fig. 14 Response for the close loop control process for 20 – 100 Reflux ratio for experimental work with PID controller

The data obtained from the MATLAB for PID controller and experimental data is summarized in Table 4 to compare the performance of each case. It is noted that experimental results have a faster rise time compared to PID and need less time to achieve the set point value. Experimental results showed also less in settling time compared with PID controller both cases give zero percent overshoot

Table 4 The performance of PID and experimental work

	PID controller	Experimental work
Rise time t_r	4.8774×10^3sec	1140 sec
Settling time t_s	8.6848×10^3sec	3300 sec
Over shoot %	0	0

Figures 11-13 showed, respectively, the experimental data that correspond to reflux ratio changes 40-60, 60-80 and 80-100 with PID controller. And final Fig. 14 represents the complete controlled range from 20 – 100 reflux ratio.

Conclusions

Batch Distillation is highly nonlinear process; therefore modeled using two point method to identify the process which is first order plus dead time (FOPTD) and by using Ziegler-Nichols method to estimate the controller parameter and tuned by MATLAB Simulink to give PID controller, PID controller has sensitive proportional gain. LABView was programming on PC to control on distillation column and compared with proposed PID controller; actually the comparisons are made between the process performance (rise time, percentage overshoot, and settling time).

From the present work carried out to study the optimal operation for batch distillation in different control strategies the following conclusions are obtained:

1- At constant reflux operation, it was found that increasing reflux ratio will increase the distillate concentration but it will be at the expense of the experiment time and power consumption.

2- Studying the dynamic behavior by introducing a step test into the process and recording the response. It has been recognized that first order plus dead time (FOPTD) may represent process dynamics of batch distillation. The transfer function was found to be:

$$G\ (s) = \frac{0.055}{2220\ s + 1} e^{-\ 1380\ s}$$

3- Zieglar-Nichols tuning rules were applied to determine the parameters of the implemented PID controller. It was found that:

K_p= 1.93

T_i=2760 sec

T_d= 690 sec

4- MATLAB Simulink was used to simulate the system using PID controller, flowing data are obtain

Rise Time: 4.8774×10^3sec

Settling Time: 8.6848×10^3sec

Overshoot: 0

5-By comparing the experimental work result obtained by control with LabView with Simulink of PID controller result obtained in Table 4 showed that: the experimental results have a faster rise time compared to PID and need less time to achieve the set point value. Experimental results showed also less in settling time compared with PID controller. And it's obvious that rise time for experimental work less than PID controller by 3737 sec.

Table 5 the experimental results for batch distillation variable reflux ratio

R%	Temp.	x concentration	Duration
0-20	78	0.6694	16min
20 -40	72.5	0.8011	25 min
40- 60	69.58	0.8727	18 min
60- 80	67.62	0.92234	16 min
80-100	66.64	0.9478	7 min

From above table we can obtain the average concentration at 66 min approximate 1 hour and it was equal to 0.8859

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