



System Identification of 4*4 Multivariable Distillation Column

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Abstract

Distillation columns are among the most critical units in chemical processes, especially in oil refineries. This research aims to develop a mathematical model for a nonlinear multicomponent naphtha distillation column using real experimental data. The naphtha distillation column used in this research consists of a column with a diameter of 2.2 m and a height of 16.6 m, containing 20 trays of type (valve tray). The process currently operates in Al-Dora Refinery as part of the Midland Refinery Company in eastern Baghdad, Iraq. Four manipulated variables (reflux flow rate, reboiler heat duty, light compound fraction in the feed, and feed flow rate) were tested for their impact on four control variables (light compound fraction in the top product, light compound fraction in the bottom product, amount of top product, and amount of bottom product). A 4x4 transfer function is produced by representing the obtained dynamic models for the variables under study using various second-order models (having different damping factors) with dead time

Keywords: MIMO Systems, Modeling of Distillation Column, System Identification.

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1. Introduction

Petroleum refineries are large and highly complex industrial systems composed of a wide range of interconnected units, including separation units, processing and conversion units, utility systems, and storage facilities. Among these operations, distillation is regarded as one of the most critical unit operations in the petroleum refining industry. It serves as the primary method for separating crude oil into various fractions according to their boiling point differences, thereby providing essential feedstocks for downstream refining and conversion processes [1], [2] and [3]. This process takes place in large distillation columns that operate under different conditions depending on the type of feed and quality of desired products. The separation relies on differences in boiling points of petroleum compounds. Crude oil or petroleum fractions are separated into a group of more useful compounds or products [3], [4] and [5]. Dynamics and control of distillation columns are considered one of the most difficult concepts due to the non-linearity of the process and the large interactions that occur in the control loops, in addition to the presence of large time delays. The system used to control the distillation column is called a multiple input and output (MIMO) system [6], [7] and [8]. The interactions among the control loops, and the decoupling are a significant in the performance of the control loops [9] and [10]. In recent years, there has been a substantial increase in interest in the monitoring, control, and optimization of industrial processes, with particular emphasis on distillation column control. This growing attention is driven by the need to improve product quality, energy efficiency, and operational

stability. Consequently, advanced control strategies have been widely developed and implemented to enhance the dynamic performance and robustness of distillation column operations [11] and [12]. To accomplish this task, the dynamic behavior must be understood. Experimental studies are essential for understanding the underlying thermodynamic and transport phenomena, validating theoretical models, optimizing process conditions, and linking the process inputs with the outputs using empirical mathematical models. Many models have been developed to describe the unsteady state of distillation columns based on this knowledge. While computational simulations are widely used, they must be validated with experimental data to ensure accuracy and reliability [13], [14] and [15]. Fundamental modeling, empirical modeling, and hybrid modeling are the three categories into which distillation column modeling is frequently divided. The empirical modeling builds the relationship between the input and the output by using the input and output data from the column's operation. This approach reduces processing and eliminates the requirement to comprehend the inner dynamics of the column. However, in order to use this method, experiments should be conducted on a real column. This approach makes use of the benefits of the other two, but to do so, it requires a well-structured model, where we must choose which aspects of the model to use empirical data and which to employ fundamental techniques [16], [17], [18] and [19]. Analysis of the most current nonlinear modeling applications in continuous distillation columns was conducted by Abdulla et al. [18]. The study focuses on hybrid models that can capitalize on the advantages of both the

fundamental and empirical models. The empirical model has been favored in industry due to its simplicity when compared to the fundamental model. S. Skogestad made a comprehensive critical review of the literature related to the control and dynamics of distillation columns. Due to the difficulty of solving differential equations and the lack of references to solve the model equations accurately, he made some simplifications to the models. These simplifications included the three fields of energy balance, vapor dynamics, and liquid flow dynamics. The response is greatly affected by the liquid dynamics [20]. The vapor constant and liquid hydraulic time are very important parameters for the dynamic model of distillation columns [21]. A mathematical model is proposed to find the variables that interact with each other in a vacuum distillation unit. This model is used to create a multivariable predictive model [22]. Wahid and Adi proposed a mathematical model for a distillation column for a binary system (benzene and toluene) used in multivariable control systems [23]. A laboratory distillation column used to separate methanol and water was characterized. A state-space model of the column was created [24]. This work aimed to develop an experimental mathematical model for a multi-input, multi-output distillation column (MIMO). The process currently operates in Al-Dora Refinery as a part of the Midland Refinery Company in eastern Baghdad, Iraq. The column with a diameter of 2.2 m and a height of 16.6 m, containing 20 trays of type (valve tray), is utilized to separate a multicomponent petroleum mixture into two cuts.

2. Process description or Theory

The distillation column of type LV-configuration is used. The L-V structure, also called the energy balance structure. In this structure, the liquid flow rate (L) and the vapor flow rate (V) are the control inputs that are used to maintain the products' output concentrations (X_d) and (X_b) despite the disturbance of the feed flow (F) and the feed concentration (X_f) [25]. A simple continuous distillation column for two products is shown in Fig. 1. The distillation column used in this research consists of a column with a diameter of 2.2 m and a height of 16.6 m, containing 20 trays of type (valve tray). The process currently operates in Al-Dora Refinery as a part of the Midland Refinery Company in eastern Baghdad, Iraq. The overhead vapors are completely condensed in the air cooler condenser, and the reboiler at the bottom of the column provides the energy required for the process. The feedstock, consisting of a multicomponent mixture, enters the column at the feed tray (13) as a saturated liquid ($q=1$). This tray divides the column into a rectifying section and a stripping section. The feedstock consists of a pseudo-binary mixture of light naphtha (pentane, hexane, and their isomers) and heavy naphtha (heptane, octane, nonane, and decane with their isomers). Four manipulated variables (reflux flow rate, reboiler heat duty, light compound fraction in the feed, and feed flow rate) were tested for their impact on four control variables (light compound fraction in the top products, light compound fraction in the bottom product, amount of top product, and amount of bottom product).

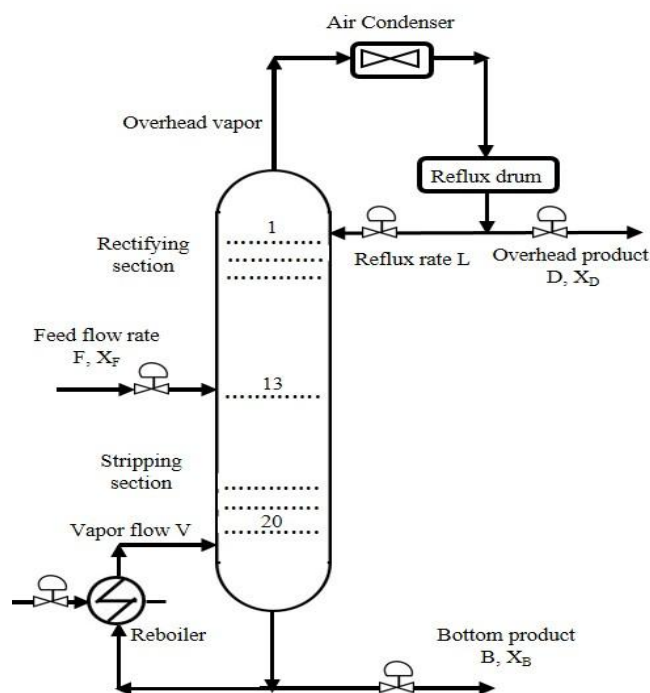


Figure 1. A simple continuous distillation column

The operating conditions and steady-state data for the naphtha separation distillation column are listed in Table 1. We need to figure out how the different variables in the naphtha separation distillation column affect each other. To do this, run a model test on each control variable to get the process reaction curve (PRC). This shows how the control variables (CVs) (outputs) change when the single manipulated variable (MV) (input) changes. The four manipulated variables that affected the four control variables listed in Table 2. The temperature of the top and bottom of the distillation column were used as an indicator of the fraction of light compounds, (X_d) and (X_b), respectively. A relationship was found in the form of a curve linking the temperature and the percentage of light components at the top of the column and the bottom of the column. The gas chromatography technique was used to analyze the top and bottom products at different temperatures. The percentage of each component in the mixture was found. Therefore, altering the four MVs independently will result in 16 process reaction curves (PRCs).

Table 1. Steady-state data for naphtha separation distillation column

Variable	Feed	Top Product	Bottom Product
Flow Rate (kg/h)	54000	19500	34500
Light Compound Fraction (wt%)	41.05	87.71	14.5
Heavy Compound Fraction (wt%)	58.11	11.56	84.6
Other Compounds	0.84	0.73	0.9
Temperature (°C)	102	100	130

Table 2. Control variables (CV) and manipulated variable (MV)

Control Variables (CV)	Manipulated Variable (MV)
Light Compound Fraction in Top Product (X_d) (wt%)	Reflux flow Rate (kg/h)
Light Compound Fraction in Bottom Product (X_b) (wt%)	Reboiler Heat Duty
Top Product (D) (kg/h)	Light Compound Fraction in Feed (X_f) (wt%)
Bottom Product (B) (kg/h)	Feed flow rate (kg/h)

3. Experimental Work

System identification is done by step-changing one manipulated variable (MV) while holding the other variables constant and recording the change in the controlled variables (CVs) over time. The multivariable model specifications are based on the process reaction curve (PRC). The steady-state gain (k), time constant (τ), and time delay (θ) are calculated based on time domain response [6], [26], [27] and [28].

$$K = \frac{y(\infty) - y(0)}{u} \quad \dots(1)$$

Where y is the controlled variable (output) and u is a known magnitude of input.

Time delay (θ) is the time at which a change in the controlled variable begins to appear.

The time constant (τ) for first order is the time for 63.2% response.

For the underdamped second-order ($0 < \varepsilon < 1$), there are many terms to consider.

Peak time (t_p) is the time to achieve maximum peak or first overshoot

$$t_p = \frac{\pi\tau}{\sqrt{1-\varepsilon^2}} \quad \dots(2)$$

Normalized maximum overshoot (M_p) is the difference between the output value at peak time and the steady-state value

$$M_p = \frac{y(tp) - y(\infty)}{y(\infty)} \quad \dots(3)$$

$$M_p = \exp\left(-\frac{\pi\varepsilon}{\sqrt{1-\varepsilon^2}}\right) \quad \dots(4)$$

For overdamped Second-order Systems ($\varepsilon > 1$), according to the procedure in [26]

$$G(s) = \frac{y_s}{u_s} = \frac{k(\tau_2 s + 1)}{(\tau_1 s + 1)^2} \quad \tau_1 \neq \tau_2 \quad \dots(5)$$

For a unit step of the manipulated variable

$$y_s = k\left[\frac{1}{s} - \frac{\tau_1}{\tau_1 s + 1} - \frac{\tau_1 - \tau_2}{\tau_1^2} \frac{\tau_1^2}{(\tau_1 s + 1)^2}\right] \quad \dots(6)$$

$$y_t = k\left[1 - e^{-t/\tau_1} + \frac{\tau_1 - \tau_2}{\tau_1^2} e^{-t/\tau_1}\right] \quad \dots(7)$$

By taking two points from the time domain ($t_1, y(t_1)$) and ($2t_1, y(2t_1)$) and substituting them into (7), then τ_1 and τ_2 are known. By repeating this calculation values for other points like ($t_2, y(t_2)$) and ($2t_2, y(2t_2)$) and take the average of τ_1 and τ_2 ,

For this form

$$G(s) = \frac{y_s}{u_s} = \frac{k(\tau_3 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad \tau_1 < \tau_2, \tau_3 \neq \tau_1, \tau_3 \neq \tau_2 \quad \dots(8)$$

$$y_t = k\left[1 + \frac{\tau_3 - \tau_1}{\tau_1 - \tau_2} e^{-t/\tau_1} - \frac{\tau_3 - \tau_2}{\tau_1 - \tau_2} e^{-t/\tau_2}\right] \quad \dots(9)$$

$$\begin{bmatrix} X_D \\ X_B \\ D \\ B \end{bmatrix} = \begin{bmatrix} \frac{22.08e^{-16s}}{(196s+1)} & \frac{-0.6e^{-60s}}{(142s+1)(176s+1)} & \frac{16.89e^{-100s}}{(255s+1)(310s+1)} & \frac{0.75e^{-110s}}{(116s+1)(254s+1)} \\ \frac{3.336e^{-120s}}{(135s+1)(280s+1)} & \frac{-2.025e^{-40s}}{(230s+1)^2} & \frac{10e^{-120s}}{(310s+1)^2} & \frac{0.949e^{-30s}}{(266s+1)^2} \\ \frac{-3.1e^{-25s}}{(172s+1)(290s+1)} & \frac{0.22e^{-80s}}{(57600s^2+211s+1)} & \frac{21.2e^{-120s}}{(216s+1)^2} & \frac{0.2294e^{-60s}}{(33124s^2+159.9s+1)} \\ \frac{3.2e^{-120s}}{(27225s^2+177s+1)} & \frac{-0.15e^{-90s}}{(30625s^2+219.5s+1)} & \frac{-21.1e^{-120s}}{(242s+1)(315s+1)} & \frac{0.7765e^{-30s}}{(17956s^2+117.7s+1)} \end{bmatrix} \begin{bmatrix} R \\ Q_R \\ X_f \\ F \end{bmatrix} \quad \dots(10)$$

The detailed findings of the above matrix are as follows:

3.1. The Effect of Reflux Flow Rate.

A positive step change of 50% in the reflux flow rate causes a reduction in the top temperature of the distillation column, which subsequently decreases the concentration of heavy components (C7+) in the overhead distillate. As a result, both the proportion of heavy compounds and the total distillate flow rate are reduced. Consequently, the fraction of light components in the distillate (X_d) increases from 87.71% to 96.2%, as illustrated in Fig. 2. Moreover, with the increase in reflux flow and after a certain time delay, the temperature at the bottom of the column decreases, allowing a greater fraction of light components to remain in the bottom product as illustrated in Fig. 3. Accordingly, the fraction of light compounds in the bottom stream increases from 14.5 to 15.9, accompanied by an increase in the bottom product flow rate. These observations are consistent with the results reported in the literature [20], [29], and [30]. In addition, Figs. 4 and 5 demonstrate a decrease in the distillate flow rate (D) and a corresponding increase in the bottom flow rate (B), respectively, as discussed above.

3.2. The Effect of Heat Duty of Reboiler

A positive step change of 50% in the hot fluid flow rate to the reboiler was applied to increase the thermal energy supplied to the system. The dynamic responses of the controlled variables were then monitored, as illustrated in Figs. 6–9. The increased heat input raises the temperature at the top of the column, resulting in a higher

concentration of heavy components in the distillate. Consequently, the distillate flow rate increases, while the mole fraction of light components in the distillate decreases from 87.71% to 85.2%. Conversely, the increased thermal energy elevates the temperature at the bottom of the column, enhancing the vaporization of light components from the bottom section. This effect leads to a reduction in both the light component fraction (14.5% to 6%) and the overall flow rate of the bottom product. These results are consistent with previously reported findings in the literature [20], [29], and [28].

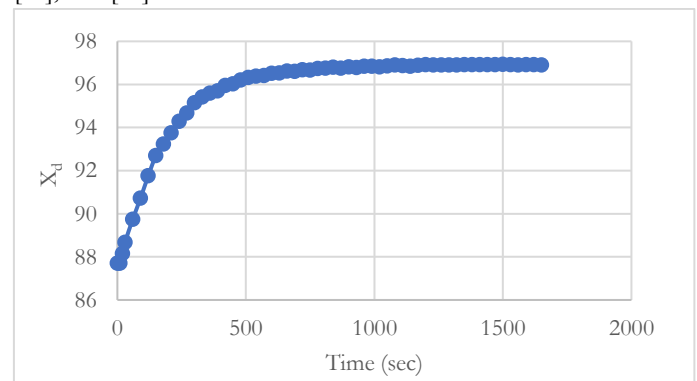


Figure 2. The Response of the Light Compound Fraction in the Top Product (X_d) to (+50%) Step Change in Reflux Flow Rate (R).

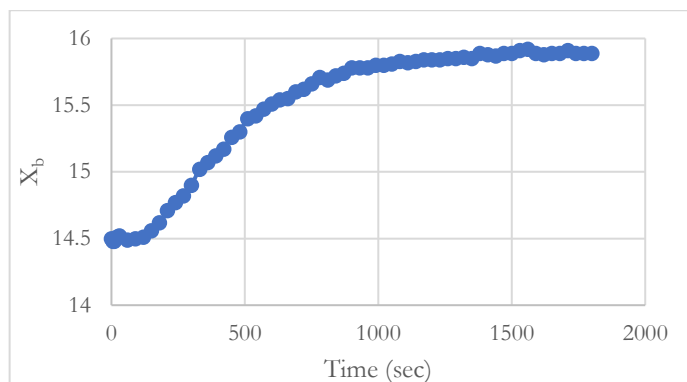


Figure 3. The Response of the Light Compound Fraction in the Bottom Product (X_b) to (+50%) Step Change in Reflux Flow Rate (R).

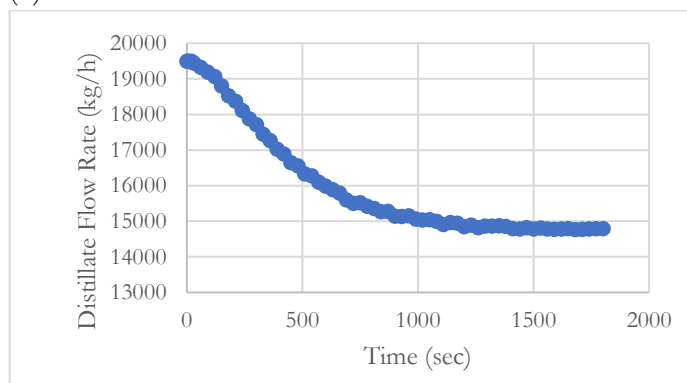


Figure 4. The Response of the Distillate Flow Rate (D) to (+50%) Step Change in Reflux Flow Rate (R).

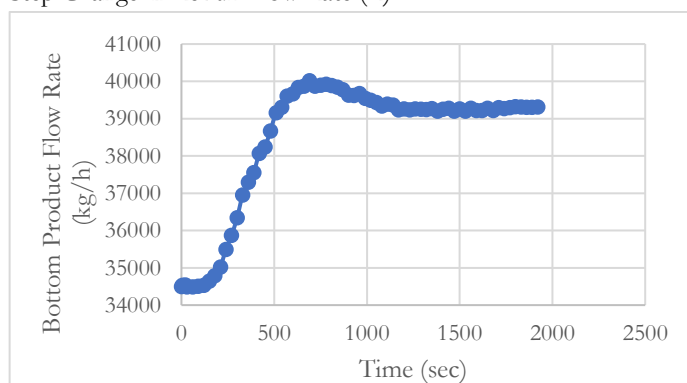


Figure 5. The Response of the Bottom Flow Rate (B) to a (+50%) Step Change in Reflux Flow Rate (R).

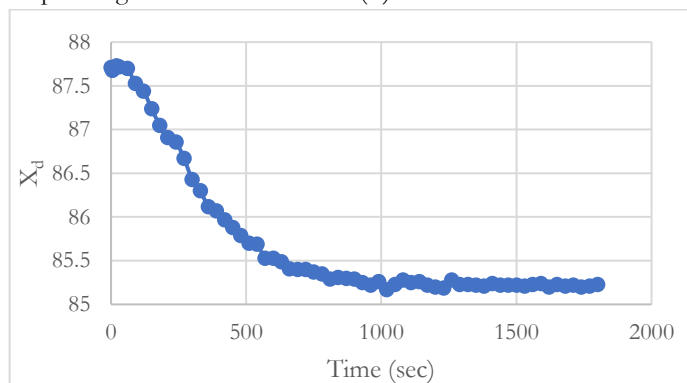


Figure 6. The Response of the Light Compound Fraction in the Top Product (X_d) to (+50%) Step Change in Heat Duty of Reboiler.

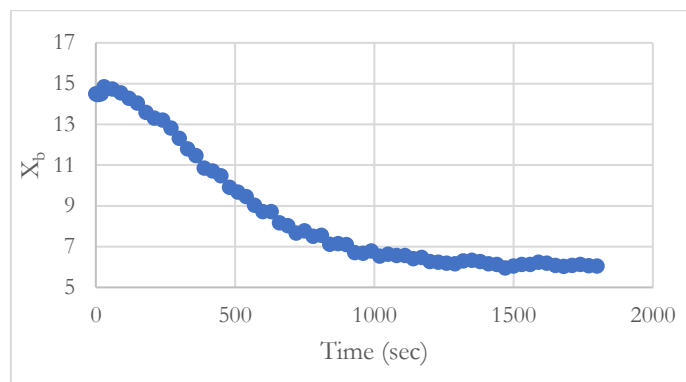


Figure 7. The Response of the Light Compound Fraction in the Bottom Product (X_b) to (+50%) Step Change in Heat Duty of Reboiler.

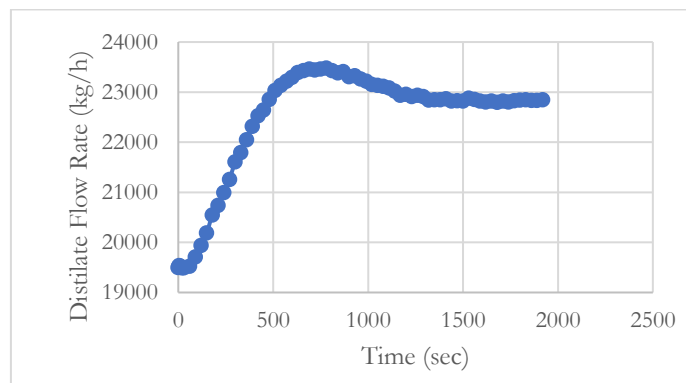


Figure 8. The Response of the Distillate Flow Rate (D) to (+50%) Step Change in Heat Duty of Reboiler.

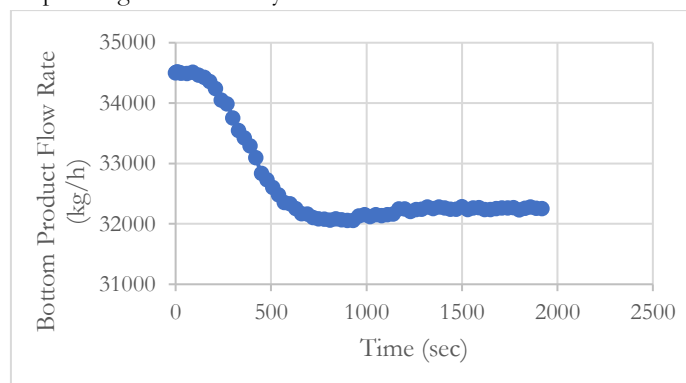


Figure 9. The Response of the Bottom Flow Rate (B) to a (+50%) Step Change in Heat Duty of Reboiler.

3.3. The Effect of the Light Compound Fraction in the Feed (X_f)

A step change in the light component fraction of the feed (X_f) was introduced to examine its effect on column behavior. An increase in X_f led to a higher concentration of light components in the upper section of the column. These lighter components absorb heat, resulting in a slight reduction in the vapor temperature. Under constant reflux conditions, the top temperature of the column decreases, which reduces the concentration of heavy components and consequently increases the fraction of light components in the distillate (87.71% to 89.25%), as shown in Fig. 10. In addition, the increased vapor flow contributes to an increase in the distillate flow rate, as illustrated in Fig. 12. These results are consistent with previous studies reported in [17], [29] and [31]. Furthermore, the

reduction in temperature and the downward flow of material leads to a slight decrease in the temperature of the lower section of the column. This behavior increases the fraction of light components in the bottom product (X_b) from 14.5% to 15.4%), while simultaneously reducing the bottom product flow rate, as shown in Figs. 11 and 13, respectively.

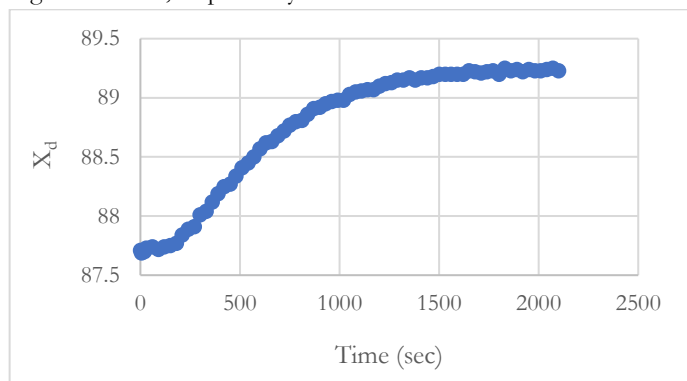


Figure 10. The Response of the Light Compound Fraction in the Top Product (X_d) to a (+25%) Step Change in the light Compound Fraction in the Feed (X_f).

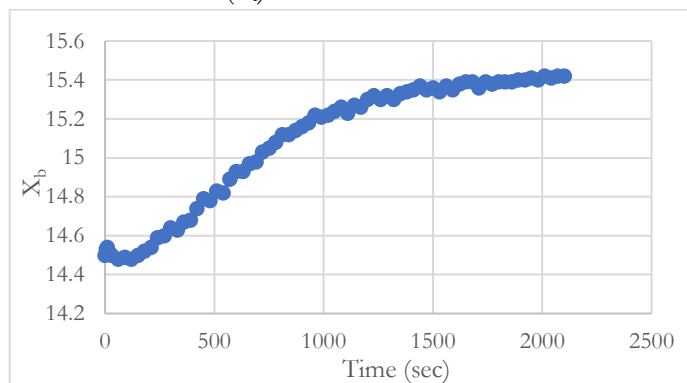


Figure 11. The Response of the Light Compound Fraction in the Bottom Product (X_b) to (+25%) Step Change in the light Compound Fraction in the Feed (X_f).

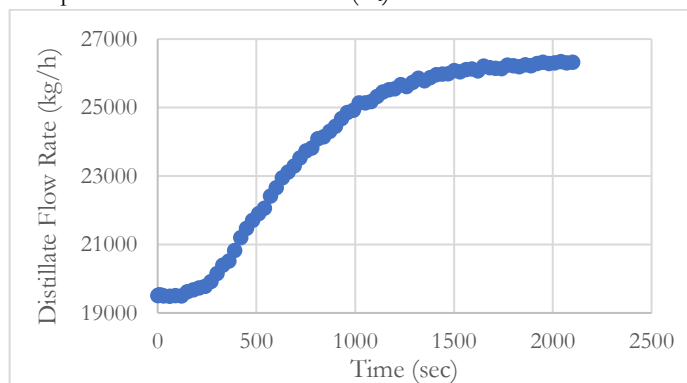


Figure 12. The Response of the Distillate Flow Rate (D) to (+25%) Step Change in the light Compound Fraction in the Feed (X_f).

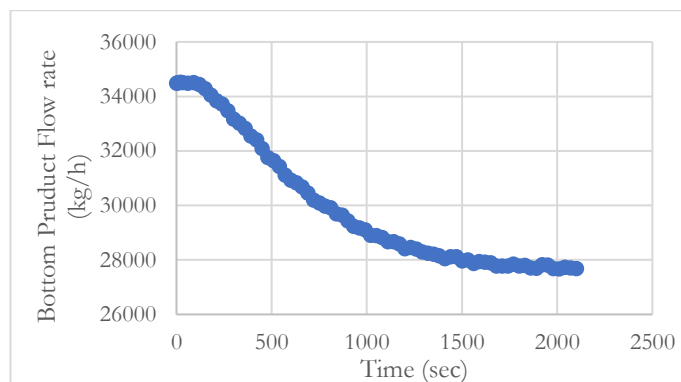


Figure 13. The Response of the Bottom Flow Rate (B) to (+25%) Step Change in the light Compound Fraction in the Feed (X_f).

3.4. The Effect of Distillation Column Feed

Figures 14–17 illustrate a noticeable increase in the fractions of light components in both the distillate (X_d) and bottom product (X_b), as well as increases in the distillate (D) and bottom (B) flow rates, resulting from a positive step change of 31% in the feed flow rate to the distillation column. This behavior can be attributed to the increase in feed flow under constant reflux and reboiler heat input, which leads to reductions in the temperatures at both the top and bottom sections of the column. The lower top temperature decreases the concentration of heavy components (C7+) in the overhead product, thereby increasing the proportion of light components in the distillate from 87.71% to 91.1%. Similarly, the reduced temperature at the bottom of the column allows a portion of the light components to remain in the bottom product, resulting in an increased light component fraction from 14.5% to 18.6%. In addition, the higher feed rate directly contributes to increased flow rates of both the distillate and bottom products. These results are in good agreement with the findings reported in [29] and [31].

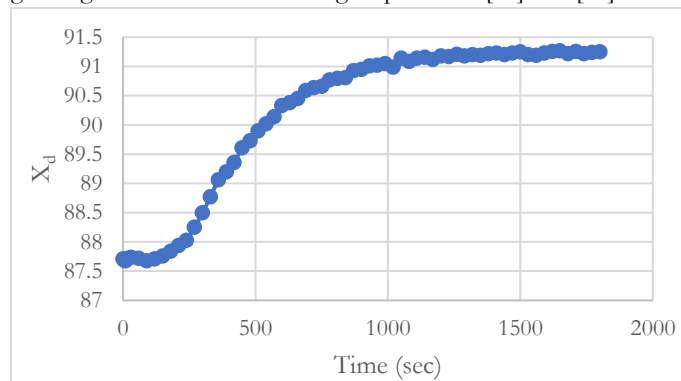


Figure 14. The response of the light compound fraction in the top product (X_d) to a (+31%) step change in the distillation column feed (F).

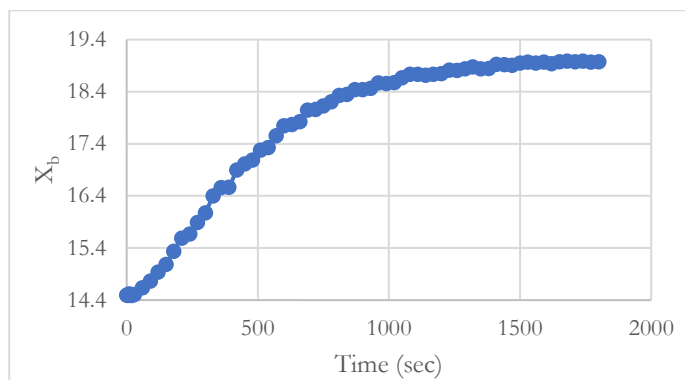


Figure 15. The response of the light compound fraction in the bottom product (X_b) to a (+31%) step change in the distillation column feed (F).

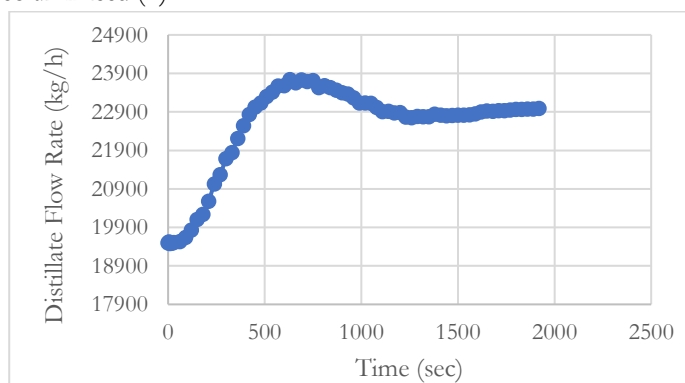


Figure 16. The response of the distillate flow rate (D) to a (+31%) step change in the distillation column feed (F).

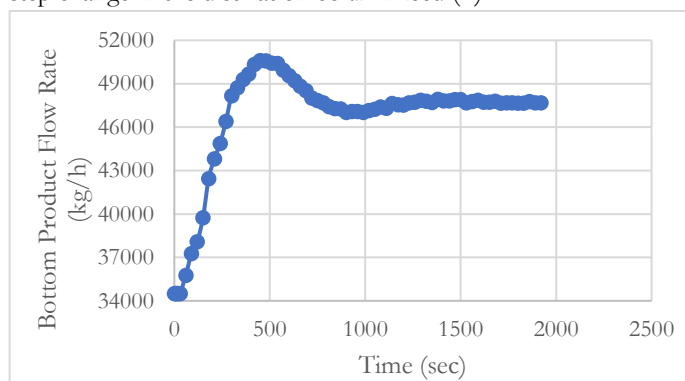


Figure 17. The response of the Bottom Flow Rate (B) to a (+31%) step change in the distillation column feed (F).

4. Conclusion

Based on the LV control setup, a dynamic model of a multicomponent naphtha distillation column with multiple inputs and multiple outputs (MIMO) is created in this work. Equation (10) describes the empirical model as 4×4 matrix with 16 transfer functions, the majority of which are of second order. The dynamic relationship between a particular manipulated variable and its matching controlled variable is described by each transfer function.

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