Modeling and Simulation for Integrating Four Reactors in the Continuous Catalytic Regeneration Reforming Process Using MATLAB

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Abstract: Modeling and simulation were developed of the continuous catalytic regeneration reforming process for integrating four reactors and studying the effecting operating parameters to improve the process performance. The process model included four reactors as stack and used to investigate the profiles of reformate composition products and research octane number. The main reactions that occur in reforming reactors included five reactions namely; dehydrogenation, dehydrocyclization, isomerization, hydrocracking and hydrodealkylation. The kinetic and thermodynamic parameters were estimated by the particle swarm optimization approach to monitor the process behavior. The expected results have been validated of the model simulation with comparison to data of actual plant, and average absolute deviation (AAD%) of two parameters; reformate composition and octane number reached 0.04% and 1.3%, respectively. This evaluation was a fair agreement and within the acceptable limit.

Keywords: Reactor model, kinetic model, simulation, MATLAB, CCRRP

1. Introduction

Mathematical modeling and simulation for an industrial process have mainly become important for providing opportunities to modify and improve the design process. The predicted behavior of the process through simulation will deliver a full understanding of monitoring the effecting operating parameters of the process. Improvement opportunities analyses of any current process to achieve the optimum operation often focuses on modifications of the important operating parameters of the process [1].

Catalytic reforming process represents the significant process that produces gasoline with high octane number in oil refineries. Catalytic reforming processes are generally categorized into three types
according to catalyst regeneration systems, namely (a) semi-regenerative catalytic reforming process (SRCRP), (b) cyclic regenerative catalytic reforming process (CRCRP) and (c) continuous catalytic regeneration reforming process (CCRRP). The difference of these processes depends on the shutdown of process in order to request the catalyst regeneration [2]. The catalytic reforming process included several reactions namely; dehydrogenation, dehydrocyclization, isomerization, hydrocracking, and hyrodealkylation of aromatics. Desired reactions are dehydrogenation, dehydrocyclization and isomerization reactions of hydrocarbons chains such as naphthenes and paraffins because they dominate the octane number and amount of hydrogen. While the hydrocracking is undesirable reactions because it breaks paraffins and hydrocarbons chains into the small chain for paraffins that produce low octane light gases (such as liquefied petroleum gas). In addition, the hydrocracking reaction consumes hydrogen which reduces the yield of reformate [3-5].

A kinetic model of this process based on lumped technique describes the kinetics of reactions and provides distinguish reactive groups of components. This approach reduces the complexity of reactions that occurs in catalytic reforming. For satisfying of demands of each classification of catalytic reforming processes, different components can be taken of considering in reactions network of the suggested kinetic model. Selective of pseudo components depends on the feed and catalyst properties. The kinetic model used to simulate the reformer reactors, which provides mathematical lumps of reactions. There a lot of previous research about the catalytic reforming process of all kinds has been studied by modeling and simulation. For example, one of the studies about modeling and simulating of catalytic reforming process was by Vathi and Chaudhuri in 1997. This study focused on proposed kinetic model containing 26 pseudo components for studying both profiles of concentration and temperature in reactor to provide process performance [6]. In 2000, Ancheya-Juárez and Villafuerte-Macias studied catalytic naphtha reactions and proposed kinetic model including 24-lumps for simulation of three reforming reactors in series [7]. Hu et al. (2003) proposed the kinetics-based mathematical model for monitoring of commercial catalytic reformers. The kinetic model includes 17-lumps to predict reaction temperature, concentration profiles and other parameters. This model has agreements of results between model predictions and plant [8]. Weifeng (2006) simulated and improved the industrial reforming process which was adapted for process profit of the plant. They suggested an 18-lump of reactions as a kinetic model to simulate the process. The obtained results were about 1000Yuan/h as profit of process [9].

There are some of the researches that studied simulation and analysis for reactors of the naphtha catalytic reforming process and focused on reformate composition profiles, which was by Alves et al.. The obtained results of modeled simulation were fair agreement with plant [10]. In 2009, Arani et al. proposed kinetic model containing 17-lumps with 15 reaction pathways and hydrocarbon range C6 to C8+. They focused on finding kinetic and thermodynamic parameters of process. The results are compared and validated with plant data [11]. Fazeli et al. (2009) simulated commercial naphtha catalytic reformer including three reactor fixed bed in series at the steady sate conditions using mathematical model. They proposed a kinetic model that includes 26-lumps with reaction network containing 47 reactions. The obtained results compared with actual data that it was a good agreement [12]. Hongjun et al. (2010) developed a kinetic model containing 27-lumps of catalytic naphtha reforming process to predict aromatic compositions. They carried out the validation of the model against commercial continuous reforming unit. The predicted results of the model display that good agreement of compositions at the outlet of the fourth reactor [13].

For the recent years about catalytic reforming process, in 2011, Saidi et al. studied simulation of continuous catalytic process set up formation of the model. They used the model consisting of 25-lumps with 12 reaction network for improving process performance. The simulation results were a good agreement of compositions at the outlet from reactors against CCR plant data [14]. At the same year, Shakoor analyzed and simulated of a semi regenerative naphtha catalytic reforming process. The kinetic model included 24-lumps with 71 reactions. The obtained results for this simulation of the process model were compared with the experimental data, and it showed a good fair agreement [15].
Weifeng et al (2013) simulated of continuous catalytic reformer and focused on the affected variables of operating conditions. The proposed kinetic model was included a 20-lumps for simulation of process. The obtained result of aromatics yield was 0.49% in weight averagely that is equivalent as profits of process approximately 5 million yuan/year [16]. In 2014, Ivanchina et al. applied the mathematical model for predicting operating parameters of catalytic reforming process. The results were indicated that the work with the optimal operating parameters will allow increasing product of the process with production costs at a fixed level [17]. Mohaddecy and Sadighi (2014) simulated and developed a semi-regenerative catalytic reforming process. They proposed the kinetic model including 9-lumped and 4 reactions. They compared the predicted variables such as exit temperatures of reactors, gasoline yield, hydrogen yield and octane number against plant data. The results indicated that there is agreement between the predicted variables and the actual [18]. Mohaddecy (2016) used catalytic fixed-bed process and for simulation he used approach of discrete lumping. The proposed model was consisting 21components with 21 reactions that represents feed and products. The results of the model simulation process are compared with the existing plant data [19]. Babaqi et al. (2018) developed the CCRRP via the mathematical model and simulation to identify the process parameters to improve the process performance. They used approach of the lumping that aimed to reduce the complexity reactions. The simulation results have been validated of the model by comparison with actual plant data and the evaluation of the process parameters was a fair agreement [20]. Yusuf t al. (2019) studied modeling and simulation of naphtha reforming reactions with sensitivity analysis using the gPROMS soft-ware. They used this model to monitor the behaviour of the temperature and concentrations of feed composition with respect to the changing heights of the reactors. The obtained results from this study were focused on the coke on catalyst and its relationship with production of aromatics, hydrogen yield, and lighter gases [21]. Dias et al. (2020) predicted the research octane number for quality gasoline. They used a real process data of a catalytic reforming process for comparing with the research octane number prediction. The results were found the more accurate for complex problem [22].

This work focused on the kinetic-reactor model and simulation based on integrating four reactors with studying the profiles of reformate and research octane number to enhance the process performance and to monitor the effecting behaviour of the process. The model was based on 36-lumps and 55-reactions and implemented by particle swarm optimization using MATLAB®.

2. Process Description
Continuous Catalytic Regeneration Reforming Process (CCRRP) is the modern process that uses reactors as side-by-side or stacked with a continuous catalyst regenerator and produces a high yield of octane gasoline and rich aromatic at low operating pressures. In the process, high octane value gasoline expresses the main product, but hydrogen gas is produced as a byproduct and other products such as liquefied petroleum gas and off-gas. The process comprises three sections namely: reaction with regenerator catalyst section, a compressor with re-contacts section, and a section of product separation. The prime target of this process is to enhance the low-octane to high-octane naphtha to mix engine fuel [23]. The process flow diagram of CCRRP is shown in Figure 1. Composition of naphtha feed and operation of reactors are represented in Table 1.
Figure 1: Process flow diagram of CCRMP

Table 1: Composition of naphtha feed and operation of reactors

| ID                                      | Feedstock (Mole fraction) |
|-----------------------------------------|---------------------------|
| Hydrogen (H2)                           | 0.66897                   |
| Light Gas (LG)                          | 0.05589                   |
| paraffinic hydrocarbons (FP)            | 0.11315                   |
| branched paraffinic hydrocarbons (FIP)  | 0.04726                   |
| naphthenic hydrocarbons (FAKCH)         | 0.07295                   |
| naphthenic hydrocarbons (FAKCP)         | 0.01318                   |
| aromatics (FA)                          | 0.04116                   |

Temperature for four reactors (K): 822
Weight of catalyst for four reactors (kg): 2750, 4550, 4800, 5925
Mole flow rate (kmol/h): 7060

3. Methodology
The current data were extracted from the actual process (CCRRP), and then the creation of kinetic and reactor models for predicting of the output products behavior. The particle swarm optimization technique was applied to estimate the kinetic and thermodynamic parameters. MATLAB® Software is used to achieve that task.

3.1 Kinetic model of the reactions
The reaction rate expresses reaction kinetics where the reactions are categorized as either reversible reactions or irreversible reactions. For paraffinic branched and naphthenic, reversible reactions occur in the reactions such as dehydrogenation, dehydrocyclization and isomerization. While irreversible
reactions occur in the reactions such as hydrocracking of paraffinic and paraffinic branched, and aromatics hydodealkylation [2, 24]. The reaction rate is expressed according to the type of reaction. All reactions occur as naphtha raw material within reactors and are expressed like a proposed network to provide an understanding of the model. The network model included 36-lumps and 55-reactions. The reaction kinetic model was provided in Table 2 according to the proposed model to Babaqi et al. [20].

**Table 2**: Types and rate equations of reactions in the kinetic model

| Type of Reaction                   | General Equation                                                                 | Rate Equations of reactions |
|-----------------------------------|----------------------------------------------------------------------------------|-----------------------------|
| **Dehydrogenation Reaction**      |                                                                                  |                             |
| (1) \( N_x + 2H_2 \rightarrow A_x \) where \( N_x \) is Alkylcyclopentane (AKCP) | \( r_{1, AKCH} = K_{1, AKCH}(P_{AKCH}P_{H_2}^2) \) |                             |
| (2) \( nP_x + H_2 \rightarrow iP_x \) where \( N_x \) is Alkylcyclopentane (AKCP) | \( r_{2, nP} = K_{2, nP}(P_{AKCP}P_{H_2}^2) \) |                             |
| **Dehydrocyclisation Reaction**   |                                                                                  |                             |
| (3) \( iP_x + H_2 \rightarrow nP_x \) where \( N_x \) is Alkylcyclohexane (AKCH) | \( r_{3, iP} = K_{3, iP}(P_{AKCH}P_{H_2}) \) |                             |
| (4) \( N_x + H_2 \rightarrow iP_x \) where \( N_x \) is Alkylcyclohexane (AKCH) | \( r_{4, nP} = K_{4, nP}(P_{AKCH}P_{H_2}) \) |                             |
| (5) \( N_x + H_2 \rightarrow iP_x \) where \( N_x \) is Alkylcyclohexane (AKCH) | \( r_{5, iP} = K_{5, iP}(P_{AKCH}P_{H_2}) \) |                             |
| (6) \( iP_x \rightarrow nP_x \) where \( iP_x \) is 2-Methyl Paraffin (iso-Paraffin) | \( r_{6, iP} = K_{6, iP}(P_{nP}P_{H_2}^2) \) |                             |
| **Isomerization Reaction**        |                                                                                  |                             |
| (7) \( N_x \rightarrow iP_x \) Or: AKCP \( \rightarrow AKCH \) where AKCP is Alkylcyclopentane and AKCH is Alkylcyclohexane  | \( r_{7, AKCP} = K_{7, AKCP}(P_{AKCP}P_{AKCH}) \) |                             |
| (8) \( nP_x + H_2 \rightarrow \frac{l}{m} \left( \sum_{i=1}^{x} P_i + P_{nP} \right) \) | \( r_{8, nP} = K_{8, nP}(P_{nP}P_{H_2}^2) \) |                             |
| (9) \( iP_x + H_2 \rightarrow \frac{l}{m} \left( \sum_{i=1}^{x} P_i + \sum_{n=1}^{x} P_n \right) \) | \( r_{9, iP} = K_{9, iP}(P_{iP}P_{H_2}) \) |                             |
| **Hydrocracking Reaction**        |                                                                                  |                             |
| (10) \( A_x \rightarrow A_x + P_n \) \( x = 7, 8, 9, 10 \) | \( r_{10, A} = K_{10, A}(P_{A}P_{H_2}) \) |                             |
3.2 Thermodynamic of reaction

As for the kinetic model, the thermodynamics of the reaction in the four reactors includes the chemical reaction rate. The Arrhenius equation defines the rate of a chemical reaction, and it was suggested by Svante Arrhenius in 1889, as in Equation (1) [25]:

\[ K_j = k_° e^{-\frac{E}{RT}} \]  

(1)

Where \( K_j \) represents constant of rate, \( k_° \) represents a frequency factor, \( E \) represents the activation energy, \( R \) represents the gas constant, and \( T \) represents the temperature.

3.3 Reactors model

To describe chemical reactions in this process, a plug flow reactor is selected. Creating a plug flow reactor model presupposes formation of appropriate equations via derivation such as material and energy balances, and pressure drop equation to supply a perfect understanding of reactions in reactors. Figure 2 illustrates the control volume and structure in the reactor model. The mathematical model of the reactor is developed based on the derivation of governing equations by control volume, according to some assumptions as follows [26]:

- Plug flow model with one dimension.
- Steady state.
- Radial flow direction is changing.
- Axial and radial dispersion are ignored.
- Axial flow direction is uniform and not changing.
- At high temperature, the ideal gas law is considered.
- Adiabatic system.
- Homogeneous catalyst moved axially.

Figure 2: Views and structure of the reactor model:
(a) Integrated four reactors (b) length-section of reactor (c) across-section of reactor (d) control volume of reactor
For every reactor, the mathematical model is developed based on the material equations that described the four reactors as shown in Equation 2. This eq. (2) used for the integrated four reactors as a stack to predict the behavior of the reactor in the process. This model as ordinary differential equations and that involved 28-dependent variables besides one independent variable, which can be solved by the 4th order Runge-Kutta method using MATLAB Software.

\[ \sum_{m=1}^{4} \left[ \frac{d(F_{xm})}{dw_m} = \sum_{j=1}^{r} r_{jm} \right], \quad x=1, 2, \ldots, x_n \text{ and } m=1 \text{ to } 4 \quad (2) \]

Where \( r_{jm} \) denotes rate of reaction \( j \) of component \( x \) in reactor \( m \) (kmol/kg h), \( F_{xm} \) denotes mole flowrate of component \( x \) in reactor \( m \) (kmol/h) and \( w_m \) denotes the catalyst weight in reactor \( m \) (kg).

### 3.4 Research octane number model

The research octane number of hydrocarbons was estimated by equations that illustrated in Table 3. For each pure component of the feedstock and products can be calculated by the polynomial equation (3). The calculation of hydrocarbon mixture can be estimated by equation (4).

#### Table 3: Research octane number equations of four reactors

| Research octane number model | Ref. |
|------------------------------|------|
| \( RON= A + B T + C T^2 + D T^3 + E T^4 \) | (3) [27] |
| \( RON= \sum_{x=1}^{n} RON_x y_x \) | (4) [28] |

### 3.5 Estimating the kinetic parameters based particle swarm optimization

The proposed model of four reactors in the CCRRP was validated by simulation and comparing of predicted results of the model with plant data. This simulation was carried out according to the operation conditions of the existing plant. The rate constants \( (K_j) \) were estimated in each reaction in the reactor that included two parameters namely; frequency factor \( (k_o) \) and activation energy \( (E) \). The initial values of these two parameters were taken for the guesswork from the literature [6].

The procedure for estimation of kinetic parameters in each reaction of components can be solved by finding the minimum error values between model results and plant data. From the law of Arrhenius, the activation energy and frequency factor are two unknown variables each rate constant \( (K_j) \) of the reaction in the reactors according to kinetic models. For each reactor of the process, it contains 110 unknown kinetic parameters, which will be determined using the objective function in Equation (5). This function will search the target for the desired convergence between expected values and plant data. Using the application of the particle swarm optimization, the sum of the average absolute deviation as a function of obtaining the desired convergence is used, which is expressed as follows:
Where $F_{l, actual}^x$ denotes molar flowrate of component (x) from the actual plant; $F_{l, model}^x$ denotes molar flowrate of component (x) from model; $r$ represents number of reactors, and $n$ represents number of components.

The structure of the problem algorithm to find the kinetic parameters of CCRRP via particle swarm optimization is shown in Figure 3. This started with initial guesses and then generated random values for the input parameters. After first adjusting the frequency, it follows the suitability assessment and operation of the process model which included calculations of thermodynamics and mass integration of four reactors, then the target function calculation. If the target function (OF) is less value global best, it is saved as the best value that updates location and speed. If it is not less value than global best, it will be rejected and the location and speed are updated accordingly. The target function will search for the minimum value using new random values for the input parameter values. These iterations will continue until it reaches the limit and then ends.

![Figure 3: Structure of an algorithm for estimating the parameters of kinetic model with the rate constants](image-url)
4. Results and Discussion

The suggested model has validated for four integrated CCRRP reactors, simulated the predicted results for four reactors were compared with plant data, focused on the profiles of the output composition (reformate) and the research octane number (RON) of four reactors. The solution of model for four integrating reactors was illustrated in Figure 4 that shows the objective function of minimum error versus iterations for obtaining the thermodynamic parameters of process simulation. It can be noted the optimum point to provide a minimum error at iteration 189.

![Objective function of minimum error vs. iterations for obtaining the thermodynamic parameters of process simulation](image)

**Figure 4**: Objective function of minimum error vs. iterations for obtaining the thermodynamic parameters of process simulation

The composition profiles results of the model were compared to actual plant data for the four reactors were shown in Figure 5. The composition of the products includes the average total of paraffinic hydrocarbons (FP), branched paraffinic hydrocarbons (FIP) naphthenic hydrocarbons (FAKCH and FAKCP) and aromatics (FA). From the Figure 5, it can be noted that sharply decrease in naphthenic hydrocarbons (AKCH) due to its consumption during the reaction. The concentration of AKCH decreases rapidly, mostly in the 1st reactor and more slowly in the others reactors. The reason is that the dehydrogenation reaction occurs very fast and considers endothermic, leading to a concentration reduction of the naphthenic and declining the reactor temperature. It can be seen that the aromatics concentration increases quickly during reaction, typically in the 1st reactor and more gradually in the others reactors. The reason again is the speed of the dehydrogenation reaction and that it is endothermic, leading to arise in the concentration of the aromatics compounds and a decrease in reactor temperature. The increasing aromatic is a result of the conversion of the alkyl cyclohexane compounds (AKCH) into aromatics compounds via dehydrogenation. This also leads to the increasing of the octane number of gasoline. To maintain the reactor temperature, there must be a heater after each reactor during endothermic reactions in the reforming process. Furthermore, it can be observed that the concentration of paraffinic hydrocarbons (P) decreases due to the fact that the dehydrocyclization reaction is endothermic also leading to a reduction in the temperature. The concentration of branched paraffinic hydrocarbons (IP) increases steadily because of the dehydrocyclisation and isomerisation reactions, especially in the 1st, 2nd, and 3rd reactors but is decreased in the fourth reactor due to the hydrocracking reaction. Next, the concentration of AKCP increases gradually due to dehydrocyclisation and isomerisation reactions.
It is noted that the results show good agreement between the simulated prediction and the plant data. The average absolute deviation (AAD) of the comparison between actual and predicted reached 0.0004 for the four reactors and was within acceptable limits. Thus, the mathematical model could be used to predict the behaviour of the process.

The other significant parameter is the research octane number (RON) in the catalytic reforming process. The octane number of reformate for the predicted model and plant data depending on calculated equations was investigated in shown Figure 6. It can be observed that feed naphtha has RON= 49.4 as entire to the reactors for upgrading of octane number into RON=76.32, according to the actual plant. While it can be seen that the predicted output model of octane number reached to RON=75.31 that indicated to the predicted model closed to the actual plant. The error of the comparison of the research octane number between the model and plant was around 1.3%.
5. Conclusion
The kinetics and reactor models development for integrated four reactors in the CCRRP was conducted to predict and improve the process performance. The model of the reactors includes a description of the most important reforming reactions of paraffinic compounds, paraffinic compounds branched, naphthenic compounds and aromatics, enclosing lumps at ranges of carbon number from C₆ to C₁₀. Multi-reactions network that contained 36 lumps and 55 reactions were investigated. The desired convergence of the process between expected outputs results and plant output was minimized via applying of particle swarm optimization. The predicted results of the reactor model are fair agreement by comparison to actual plant that reached the average absolute deviation (AAD%) for composition of reformate and octane number reached 0.04% and 1.3%, respectively. This was within acceptable limits; therefore the mathematical model could predict the required behaviour of the process.

Abbreviations and Acronyms

\( P_{nP_n} \): Partial pressure for component \( nPx \) or any component, kPa

\( nP_x \): Paraffinic hydrocarbons component (P)

\( iP_x \): Paraffinic hydrocarbons branched component (IP)

\( N_i \): Naphthenes, alkylcyclohexane (AKCH) component or alkylcyclopentane component (AKCP)

\( A_x \): Aromatic component, alkyl benzene (A)

\( K_j \): Rate constant, kmol/kg \_cat \_h kPa

\( k_o \): Frequency factor

\( E \): Activation energy (kJ/kmol)

\( T \): Temperature (K)

\( R \): Constant of gas (8.314 kJ/kmol K)

RON: Research octane number

Appendix A

The mass balance can be expressed of all components for one reactor as the net reaction by these equations, for example:

1- Paraffinic hydrocarbons (hexane component)

\[
\frac{dFnP_6}{dW} = -r_2(nP_6) + r_4(nP_6) + r_6(nP_6) + r_8(nP_6) + \sum_{x=7}^{10} r_8(C_6H_{14})_x + \sum_{x=7}^{9,10} r_9(C_6H_{14})_x
\]

2- Paraffinic hydrocarbons branched (isohexane component)

\[
\frac{dFiP_6}{dW} = -r_3(iP_6) + r_5(iP_6) + r_6(iP_6) + r_9(iP_6) + \sum_{x=7}^{10} r_9(C_6H_{14})_x
\]

3- Naphthenic hydrocarbons (Alkyl cyclohexane component & Alkyl cyclopentane component)

\[
\frac{dFAKCH_6}{dW} = -r_2(AKCH_6) + r_4(AKCH_6) + r_5(AKCH_6) + r_7(AKCH_6)
\]

\[
\frac{dFAKCP_6}{dW} = r_2(AKCP_6) + r_3(AKCP_6) + r_7(AKCP_6)
\]

4- Aromatics (benzene component)

\[
\frac{dFA_6}{dW} = r_1(A_6) + \sum_{x=7}^{10} r_10(A_6)_x
\]
References

[1] Babaqi, B.S., M.S. Takriff, N.T.A. Othman, and S.K. Kamarudin, Yield and energy optimization of the continuous catalytic regeneration reforming process based particle swarm optimization. Energy, 2020. 206: p. 118098.

[2] Babaqi, B.S., M.S. Takriff, S.K. Kamarudin, N.T.A. Othman, and M.M. Ba-Abbad, Comparison of Catalytic Reforming Processes for Process Integration Opportunities: Brief Review International Journal of Applied Engineering Research 2016. 11(19): p. 9984-9989

[3] George, J.A. and M.A. Abdullah, Catalytic naphtha reforming. Marcel Dekker, New York, 2004.

[4] Sadighi, S. and R.S. Mohaddecy, Simulation, Sensitivity Analysis and Optimization of an Industrial Continuous Catalytic Naphtha Reforming process. European Chemical Bulletin, 2013. 2(10): p. 777-781.

[5] Zahedi, G., S. Mohammazadeh, and G. Moradi, Enhancing gasoline production in an industrial catalytic-reforming unit using artificial neural networks. Energy & Fuels, 2008. 22(4): p. 2671-2677.

[6] Vathi, G.P. and K.K. Chaudhuri, Modelling and simulation of commercial catalytic naphtha reformers. The Canadian Journal of Chemical Engineering, 1997. 75(5): p. 930-937.

[7] Ancheyta-Juárez, J. and E. Villafuerte-Macias, Kinetic modeling of naphtha catalytic reforming reactions. Energy & Fuels, 2000. 14(5): p. 1032-1037.

[8] Hu, Y.-y., H.-y. Su, and J. Chu, Modeling and simulation of commercial catalytic reformers. Journal of Chemical Engineering of Chinese Universities, 2003. 17(4): p. 418-424.

[9] Weifeng, H., S. Hongye, H. Yongyou, and C. Jian, Modeling, simulation and optimization of a whole industrial catalytic naphtha reforming process on Aspen Plus platform. Chinese Journal of Chemical Engineering, 2006. 14(5): p. 584-591.

[10] Alves, R.M., F. Menten, W.S. Maejima, R. Guardani, and C. Nascimento. A study on naphtha catalytic reforming reactor simulation and analysis. in 18th European Symposium on Computer Aided Process Engineering, Bertrand Braunschweig and Xavier Jou-lia (Editors). 2008.

[11] Arani, H., M. Shirvani, K. Safdarian, and E. Dorostkar, Lumping procedure for a kinetic model of catalytic naphtha reforming. Brazilian Journal of Chemical Engineering, 2009. 26(4): p. 723-732.

[12] Fazeli, A., S. Fatemi, M. Mahdavian, and A. Ghaee, Mathematical modeling of an industrial naphtha reformer with three adiabatic reactors in series. Iranian Journal of Chemistry and Chemical Engineering (IJCCE), 2009. 28(3): p. 97-102.

[13] Hongjun, Z., S. Mingliang, W. Huixin, L. Zeji, and J. Hongbo, Modeling and simulation of moving bed reactor for catalytic naphtha reforming. Petroleum science and technology, 2010. 28(7): p. 667-676.

[14] Saidi, M., N. Mostoufi, and R. SotudehGharebagh, Modeling and simulation of continuous catalytic regeneration (CCR) process. International Journal of Applied Engineering Research, Dindigul, 2011. 2(1).

[15] Shakoor, Z.M., Catalytic reforming of heavy naphtha, analysis and simulation. Diyala Journal of Engineering Sciences, 2011. 4(2): p. 86-104.

[16] Weifeng, H., Z. Xiuqiang, H. Yanping, and J. Fengyue, Simulation, sensitivity analysis and optimization of a commercial continuous catalytic naphtha reformer. Information Technology Journal 2013. 12(19): p. 4953-4958.

[17] Ivanchina, E.D., E.S. Sharova, and I.V. Yakupova, Mathematical Modelling Method Application for Optimisation of Catalytic Reforming process. Procedia Chemistry, 2014. 10: p. 197-202.

[18] Mohaddecy, R.S. and S. Sadighi, Developing a Steady-state Kinetic Model for Industrial Scale Semi-Regenerative Catalytic Naphtha Reforming Process. Kemija u Industriji, 2014. 63: p. 149-154.

[19] Mohaddecy, S., Modeling catalytic naphtha reforming process using discrete lumping approach.
Indian Journal of Chemical Technology (IJCT), 2016. 21(5-6): p. 309-320.

[20] Babaqi, B.S., M.S. Takriff, S.K. Kamarudin, and N.T.A. Othman, Mathematical Modeling, Simulation, and Analysis for Predicting Improvement Opportunities in the Continuous Catalytic Regeneration Reforming Process. Chemical Engineering Research and Design, 2018. 132: p. 235-251.

[21] Yusuf, A.Z., Y.M. John, B.O. Aderemi, R. Patel, and I.M. Mujtaba, Modelling, simulation and sensitivity analysis of naphtha catalytic reforming reactions. Computers & Chemical Engineering, 2019. 130: p. 106531.

[22] Dias, T., R. Oliveira, P. Saraiva, and M.S. Reis, Predictive Analytics in the Petrochemical Industry: Research Octane Number (RON) forecasting and analysis in an Industrial Catalytic Reforming Unit. Computers & Chemical Engineering, 2020: p. 106912.

[23] Babaqi, B.S., M.S. Takriff, S.K. Kamarudin, N.T.A. Othman, and M.M. Ba-Abbad, Energy optimization for maximum energy saving with optimal modification in Continuous Catalytic Regeneration Reformer Process. Energy, 2017. 120: p. 774–784.

[24] Meyers, R.A., Handbook of petroleum refining processes. Third ed. Vol. 548. 2004: McGraw-Hill New York.

[25] Missen, R.W., C.A. Mims, and B.A. Saville, Introduction to chemical reaction engineering and kinetics. 1999: J. Wiley.

[26] Fogler, H.S., Elements of chemical reaction engineering. fourth ed. 2006 Pearson Education, Inc.

[27] Albahri, T.A., M.R. Riazi, and A.A. Alqattan, Octane number and aniline point of petroleum fuels. Fuel Chemistry Division Preprints 2002. 47(2): p. 710-711.

[28] Nikolaou, N., C. Papadopoulos, I. Gaglias, and K. Pitarakis, A new non-linear calculation method of isomerisation gasoline research octane number based on gas chromatographic data. Fuel, 2004. 83(4): p. 517-523.