

A Novel Study of Upgrading Catalytic Reforming Unit by Improving Catalyst Regeneration Process to Enhance Aromatic Compounds, Hydrogen Production, and Hydrogen Purity

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Abstract

Catalytic reforming is a chemical process utilized in petroleum refineries to convert naphtha, typically having low octane ratings, into high octane liquid products, called reformates, which are components of high octane gasoline.

In this study, a mathematical model was developed for simulation of semi-regenerative catalytic reforming unit and the result of the proposed model was compared with the plant data to verify accuracy of the model. Then, an extra fixed bed reactor was added for upgrading the semi-regenerative process to cyclic process. The optimal condition of the cyclic process was calculated mathematically. The results show that the proposed configuration is capable to enhance the octane number, yield of product, hydrogen production rate, and hydrogen purity by 1.5%, 7.14%, 8.1%, and 13.2%, respectively. The modifications improve the performance in comparison with the current facilities. The results indicate that aromatic and hydrogen production and hydrogen purity improve in comparison with the semi-regenerative reformatting process. Due to the additional swing reactor, which is a spare one, each of the reactors must be removed for regeneration process and, then, be replaced with a rebuilt one.

Keywords

Catalytic naphtha reforming;
Modeling;
Octane number enhancement;
Hydrogen production;
Upgrade of semi-regenerative reformer.

1. Introduction

Catalytic reforming is a chemical process utilized in petroleum refineries to convert naphtha, typically having low octane ratings, into high octane liquid products, called reformates,

which are components of high octane gasoline. A reformat is an excellent gasoline blend stock, which has a high content of benzene, toluene, xylene (BTX) [1-3]. In addition, hydrogen as a desirable by-product is produced in this process [1-3]. Hydrogen will be a requisite energy source in the upcoming future. In the refineries, hydrogen is used for processing of crude oil into refined fuels, such as gasoline and diesel. According to the environmental protection law, sulfur and ni-

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trogen should be removed as a primary goal of refineries [4]. To achieve this goal, refineries use a large amount of hydrogen. Furthermore, heavy components are converted to more valuable fractions by hydrocracking technique [5-6]. Hence, attempts are made to enhance hydrogen production rate and its purity in refineries. Due to the importance of hydrotreating and hydrocracking techniques, studies should be focused on upgrading naphtha reforming processes, which supply a large quantity of required hydrogen for refineries. Pursuant to the nature of the reactions, reforming process also produces light ends gases, such as propane and butane [7]. In the last decade, due to its wider economic importance, researchers have focused to find new ways for upgrading naphtha reforming process. Rahimpour et al. presented novel reactor configurations to enhance reformate yield and hydrogen production [8-9]. Zahedi et al. [10] performed the steady state and dynamic simulation of a fixed bed reactor in the naphtha reforming process. Ramage et al. considered the effects of coke formation and deactivation of the catalyst on the catalytic reforming process [11]. Iranshahi et al. modeled a multi-stage naphtha reforming process using novel thermally coupled recuperative reactor to enhance aromatic production [12]. Also, many studies have been done on a new catalyst provision that has shown better resistance against sintering and coke deposition on catalyst. Benitez et al. and Boutzeloit et al. investigated the performance of catalytic reforming process by monometallic, bimetallic, and trimetallic catalysts [13-14]. Some researchers, such as Mazziari et al. and Sugimoto et al., have investigated the coke formation and regeneration of catalyst pending the catalytic reforming process [15-16].

The most commonly used types of catalytic reforming units have three reactors, each with a fixed bed of catalyst, and the catalyst is wholly regenerated in situ during routine catalyst regeneration shutdowns. A simplified schematic of the semi-regenerative catalytic reforming process is shown in Fig. 1.

Treated naphtha is pumped up to the reaction pressure and is joined by a stream of hydrogen-rich recycle gas in molar ratio of 3 to 8 (H_2/HC). The resulting liquid-gas mixture is preheated by flowing through a heat exchanger. The preheated feed mixture is then totally vaporized and heated to desired weight average inlet temperature

(WAIT) before the vaporized reactants enter the first reactor [17]. Specific properties of the feed are presented in Table 1. Dehydrogenation and isomerization are the main reactions that take place in the first reactor.

Table 1. Specifications of feed and product

TBP	Naphtha feed	Reformate
IBP	98	37
10%	110	70
30%	120	101
50%	129	122
70%	143	141
90%	158	164
FBP	170	188
Feed % Feed stock (Mol %)		
Paraffin		49
Naphthene		36
Aromatic		15

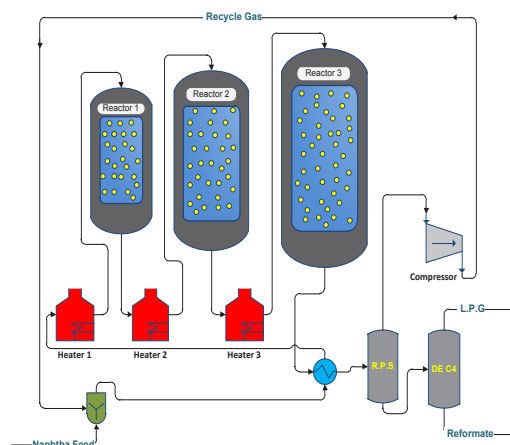


Figure 1. A schematic diagram of semi-regenerative catalytic reforming process

Since reforming reactions in the first reactor are predominantly endothermic, to maintain the required reaction temperature and the rate of reaction, the vaporized stream is reheated in the second fired heater before it flows through the second reactor. Dehydrogenation, isomerization, hydrocracking, and dehydrocyclization are the main reactions that take place in the second reactor. The temperature again decreases across the second reactor and the vaporized stream must again be reheated in the third fired heater before it flows through the third reactor. As the vaporized stream proceeds through the three reactors, the reaction rates decrease and, therefore, the reac-

tors become larger. Hydrocracking and dehydrocyclization are the main reactions that occur in this reactor. The product of the last reactor is separated into liquid and gas phases in reactor product separator (R.P.S). Table 2 shows the characterizations and operational conditions of naphtha reforming reactors. Catalytic reforming processes are commonly classified, according to the frequency and mode of catalyst regeneration, into (1) semi-regenerative, (2) cyclic, and (3) continuous.

Table 2. Reactors characterizations and conditions

Reactor			
Parameter	1 st	2 nd	3 rd
dis (wt %)	20.26	30	49.74
d (m)	1.524	1.676	1.981
Parameter	Numerical value	Unit	
Naphtha feed	56	m ³ /hr	
H ₂ /HC	4.8	-	
LHSV	1.92	hr ⁻¹	
WHSV	2.04	hr ⁻¹	
MW _{ave}	108.47	kg/mol	

A semi-regenerative catalytic reforming process usually has 3 or 4 reactors in series with a fixed bed catalyst system and operates continuously (cycle length) from 6 months to one year. During this period, the activity of the catalyst diminishes due to coke deposition, provoking a decrease in aromatic yield and in hydrogen purity [18-19]. The cyclic regenerative reformer operates under more severe process conditions than the semi-regenerative process does. In this process, apart from the catalytic reforming reactors, the cyclic regeneration process has an additional swing reactor, which is used when the fixed bed catalyst of any of the regular reactors needs regeneration. The reactor with the regenerated catalyst then becomes the spare reactor. By this, the reforming process maintains continuous operation. Therefore, the reforming operation can operate for a much longer period as a part of the catalyst is periodically regenerated using a swing reactor [18-19]. The deficiencies in cyclic regeneration reforming are solved by a low-pressure continuous regeneration process, which is characterized by high catalyst activity with reduced catalyst requirements, producing more uniform reformate of higher aromatic content and high hydrogen purity. Continuous regeneration typically consists of 3 to 4 radial flow reactors. This type of process uses moving bed reactor design, in which the re-

actors are stacked. The catalyst bed moves by gravity flow from top to bottom of the stacked reactors. The spent catalyst is withdrawn from the last reactor and sent to the top of the regenerator to burn off the coke. The transport of catalyst between reactors and regenerator is done by the gas lift method. For more information, a conceptual design for a radial flow reactor in the catalytic reforming process is given in Fig. 2.

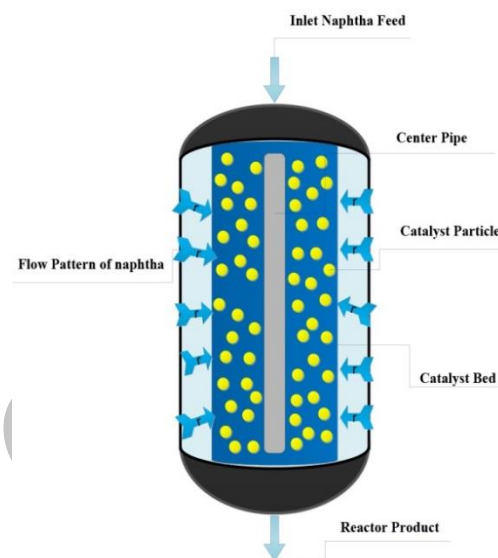


Figure 2. A conceptual design for radial flow reactor in catalytic reforming process

The semi-regenerative reforming process is described by operations at approximately low severity as restricted by certain operation conditions, naphtha quality, and catalyst management, which lengthen the cycle duration (cycle length) or, in other words, the time between catalyst regenerations. In the present study, the effects of temperature, pressure, space velocity, and hydrogen to hydrocarbon ratio have been investigated to enhance the octane number and yield of the products. Also, the effect of each parameter to decrease coke deposition in the catalyst surface area in the semi-regenerative naphtha reforming process has been investigated.

After that, it is proposed to add an extra fixed bed reactor to upgrade semi-regenerative process to cyclic process, and apply the best conditions to increase octane number, yield, and hydrogen production rate as well as its purity in this new configuration. In this work, the operating data of the Shiraz oil refinery were collected for two

years. After simulation of naphtha reforming unit using the Smith model, the results of the model were used for sensitivity analysis of the catalytic reforming unit.

2. Reaction Characterization

The commonly used catalytic reforming catalysts contain noble metals such as platinum and/or rhenium, which are very susceptible to poisoning by sulfur and nitrogen compounds. Specifications of conventional catalyst and catalyst bed are reported in Tables 3 and 4, respectively. Naphtha feedstock is always pre-processed in a desulfurization unit, which removes both the sulfur and the nitrogen compounds. Depending upon the type or version of catalytic reforming used as well as the desired reaction severity, the reaction conditions range from temperatures of about 495 to 525°C and from gauge pressures of about 5 to 45 atmospheres. Desirable and undesirable reactions are two categories of reaction involved in the naphtha reforming process [18]. Desirable reactions lead to a higher octane number and may also produce hydrogen.

Table 3. Typical properties of catalyst

Parameter	Value	Unit
d_p	1.2	mm
Pt	0.3	wt %
Re	0.4	wt %
S_a	220	m^2g^{-1}
P_v	0.6	cm^3g^{-1}
ρ_b	0.3	$Kg l^{-1}$
ϵ	0.36	-
S_{id}	0.58	Kg/L
D_{id}	0.68	Kg/L

Table 4. Specifications of catalyst bed of reactors

Reactor			
Parameter	1 st	2 nd	3 rd
A (m^2)	1.36	1.70	2.49
H (m)	4.35	5.11	5.87
V (m^3)	5.9	8.69	14.63
W (kg)	4148	6142	10185
L_d (Kg/m^3)	703	706.8	696.2
d_{cp} (mm)	420	420	420
d_b (mm)	1380	1530	1830

Dehydrogenation, dehydrocyclization and isomerization are desirable reactions. A principal de-

sirable reaction is dehydrogenation, because it produces aromatics that have high octane numbers and produce hydrogen. Dehydrocyclization is probably the most difficult reaction to promote in the naphtha reforming process. It predominantly takes place in the last reactor in the train. It involves dehydrogenation with a release of one mole of hydrogen, followed by a molecular rearrangement to form a naphthene and by the subsequent dehydrogenation of naphthene. The isomerization reaction is one in which the hydrocarbon formula remains the same, but the shape of the hydrocarbon molecule changes. In fact, a rearrangement takes place in the structure.

Undesirable reactions are the reactions that lead to decrease in octane number, yield, and hydrogen purity. They are the reactions that must be avoided. The breaking of C-C bond in reforming operation is called hydrocracking. Hydrocracking reaction breaks a Paraffin molecule into two molecules of lower molecular weight or opens the ring of a naphthene. The main effects of hydrocracking are decrease in hydrogen production, yield, and hydrogen purity and increase in light ends. Due to decrease in paraffins in reformate, it leads to increase in the aromatic concentration or, in other words, octane number. Hydrogenolysis has some similarities with hydrocracking in cleavage of bonds. Due to this undesirable reaction, paraffin compound breaks and methane or ethane is produced, resulting in reduced yield. Hydrodealkylation is the breakage of the branched radical of an aromatic ring, which consumes hydrogen and produces methane. The main effect of Hydrodealkylation is decrease in hydrogen production and yield. Alkylation is the addition of an Olefin molecule to an aromatic ring that leads to heavier molecules, which may increase the end point of the product and high tendency to form coke. Specifications of desirable reactions as well as undesirable reactions are described in Tables 5 and 6, respectively.

Deposited coke on the catalyst is a temporary poison, since its detrimental effect is reversible through regeneration. Due to coke formation, the active contact area of catalysts decreases and catalyst activity is reduced.

Table 5. Specifications of desirable reactions

Desirable reactions	Reaction type	Catalyst promoted function	Pressure condition to promote	Reaction rate
Naphthenes dehydrogenation	Highly endothermic	Metallic part	Low	Very fast
Paraffins isomerization	Slightly endothermic	Acidic part	No effect	Fast
Naphthenes isomerization	Slightly endothermic	Acidic part	No effect	Low
Dehydrocyclization	Endothermic	Both parts	Low	Very low
Dehydroisomerization	Endothermic	Both parts	Low	Low

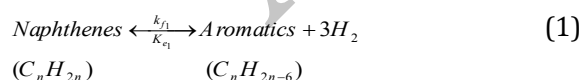
Table 6. Specifications of undesirable reactions

Undesirable reactions	Reaction Type	Catalyst Promoted Function	Pressure Condition to Promote	Reaction Rate
Hydrocracking	Exothermic	Both Parts	High	Low
Hydrogenolysis	Exothermic	Metallic	High	Low
Hydrodealkylation	Exothermic	Metallic	High	Low
Alkylation	Exothermic	Both Parts	High	Very low

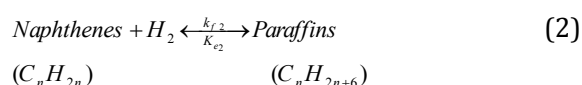
Coke formation is due to heavy unsaturated productions, such as polycyclic, which can be dehydrogenated. Since coke formation is inherently associated with the reforming reaction, there is no real way to avoid it. Coke will be reduced by a decrease in reactor temperature and an increase in hydrogen circulation. At low pressure, coking will increase.

In 1959, Smith proposed the first successful kinetic model for naphtha reforming process [20]. In this model, naphtha feed involved naphthenic, paraffinic, and aromatic compounds. Also, he introduced hydrogen and light ends in addition to his model. The reactions are as follows:

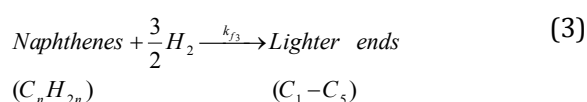
Dehydrogenation of naphthenes to aromatic



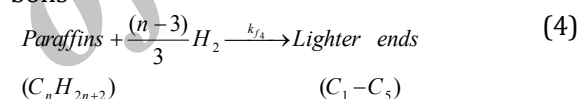
Dehydrocyclization of paraffins to naphthenes



Hydrocracking of naphthenes to lower hydrocarbons



Hydrocracking of paraffins to lower hydrocarbons



$$r_1 = \left(\frac{k_{f1}}{K_{e1}}\right)(k_{e1}p_n - p_a p_h^3) \quad (5)$$

$$r_2 = \left(\frac{k_{f2}}{K_{e2}}\right)(k_{e2}p_n p_h - p_p) \quad (6)$$

$$r_3 = \left(\frac{k_{f3}}{p_t}\right)p_n \quad (7)$$

$$r_3 = \left(\frac{k_{f4}}{p_t}\right)p_p \quad (8)$$

The rate constants and heat of reactions are listed in Table 7.

Table 7. Rate constants and heat of reactions for naphtha reforming

Rate* Constant	A	B	E	ΔH (298 k)
Kr1	9.87	23.21	36350	71038.06
Kr2	9.87	35.98	58550	-36953.33
Kr3	1	42.97	63800	-51939.31
Kr4	1	42.97	63800	-56597.54
Ke1	1.04×10 ⁻³	46.15	46045	-
Ke2	9.87	-7.12	8000	-

* $k = A \exp(B - (E/1.8T))$

3. Mathematical Modeling

A heterogeneous mathematical model is developed by assembling the mass and energy balance on the naphtha reforming system. The mass balance provides a variety of the concentrations and the energy balance provides the variation of temperature along the reactors. Also, one of the main functions in naphtha reforming is to consider the pressure drop through the catalyst bed. The Sabri Ergun pressure drop equation considered viscous changes as well as kinetic energy changes for a wide range of flow rates to account for the pressure drop through the reforming reactors [21-22]. In order to develop the mass and energy balance, the following assumptions are considered during the modeling step:

- 1) Axial dispersion of heat is neglected.
- 2) All the reactors work under adiabatic condition.
- 3) Ideal gas behavior is applicable.
- 4) Plug flow pattern is considered.

By considering component material balances as well as energy balance for a differential element 'dw' of the catalyst bed, the mass and energy balances are obtained as follows [24]:

Mass balance:

$$\frac{dF_i}{dw} + \sum_{j=1}^n \gamma_{i,j} r_j = \frac{\varepsilon}{\rho_b} \frac{d(c_i)}{dt} \quad (9)$$

Energy balance:

$$\frac{dT}{dt} = \frac{-\left(\sum_{i=1}^{n_c} F_i C_{p_i}\right) \frac{dT}{dw} + \sum_{j=1}^{n_r} r_j \left(\sum_{i=1}^{n_c} H_i \gamma_{i,j}\right)}{C_{p_{cat}} + \frac{\varepsilon}{\rho_b} \sum_{i=1}^{n_c} c_i C_{p_i}} \quad (10)$$

Ergun equation:

$$\frac{dP}{dw} = -\frac{G}{\rho d_p \varepsilon^3} \left(\frac{150(1-\varepsilon)\mu}{d_p} + 1.75 \right) \frac{1}{A_c \rho_c} \quad (11)$$

4. Results and Discussion

4.1. Model validation

The operating data of the Shiraz oil refinery were collected for two years. After simulation of naphtha reforming unit, the predicted results from the simulation were compared with plant

data and the ability of the model to predict the desired outputs was confirmed (Figs. 3 and 4).

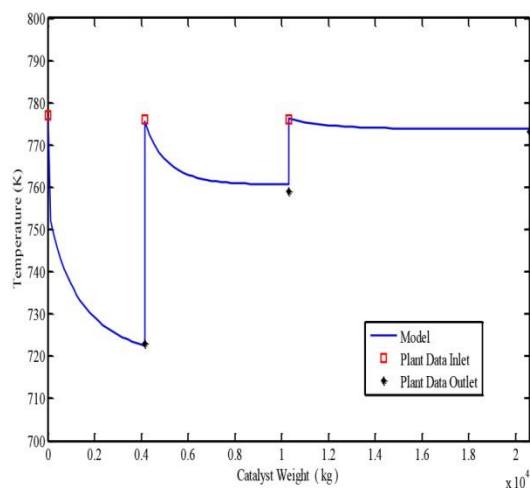


Figure 3. Temperature profile along the reactors; a comparison between Smith model and plant data for semi-regenerative reforming at 3000kPa

4.2. Effect of temperature on semi-regenerative process

Catalyst activity is directly proportional to the temperature of the reactor. The reaction temperature is the most important variable in catalytic reforming, since the product quality and yield are highly dependent on it. Since reformers are designed with 3 or more reactors in series and each reactor may contain a different quantity of catalyst, it is commonly accepted to consider the weighted average inlet temperature (WAIT) [25-27]. In a conventional semi-regenerative unit, the loss of activity of catalyst results in decrease in product octane number as well as reformate yield and recycle gas purity. The effect of WAIT on volume percent of naphthene, aromatic, and light ends production in reformate in reactors production is given in Fig. 5. In Fig. 5, the curves indicate that increasing the WAIT of the reactor leads to increase in conversion of the non-aromatic compounds in the feed to aromatic, although the hydrocracking reaction is more favored than the cyclization of paraffins.

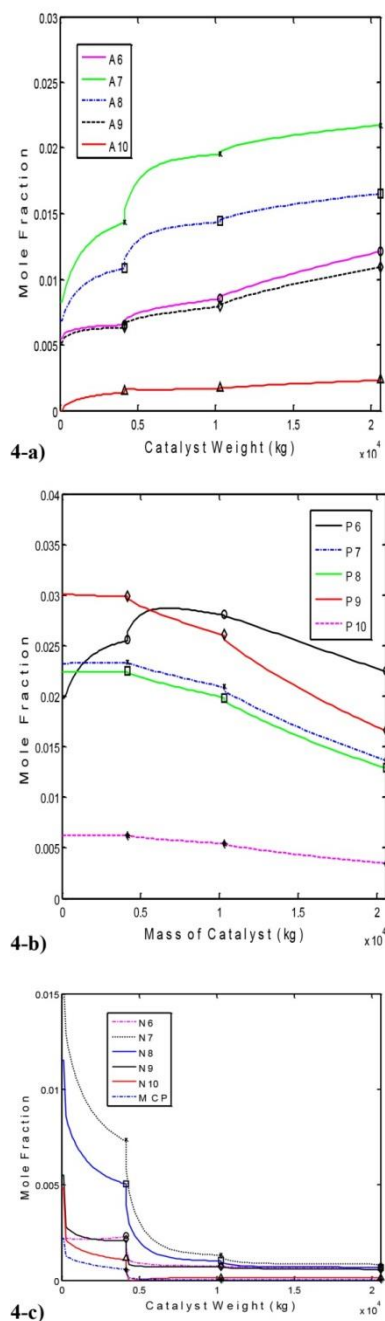


Figure 4. Concentration profiles of (a) paraffins, (b) aromatics, and (c) naphthenes along the reactor axis for fluid phase; a comparison between Smith Model (dash line) and actual data

By increase in light ends compounds, reformate yield and coke deposit increase. On the other hand, all reaction rates increase when operating at high temperature. Hydrocracking, which is not desirable in catalytic reforming, occurs to a greater extent at high temperatures. Therefore, to obtain high product quality and yield, it is

necessary to carefully control the hydrocracking and aromatization reactions. Reactor temperatures are monitored constantly to observe the extent of each of these reactions.

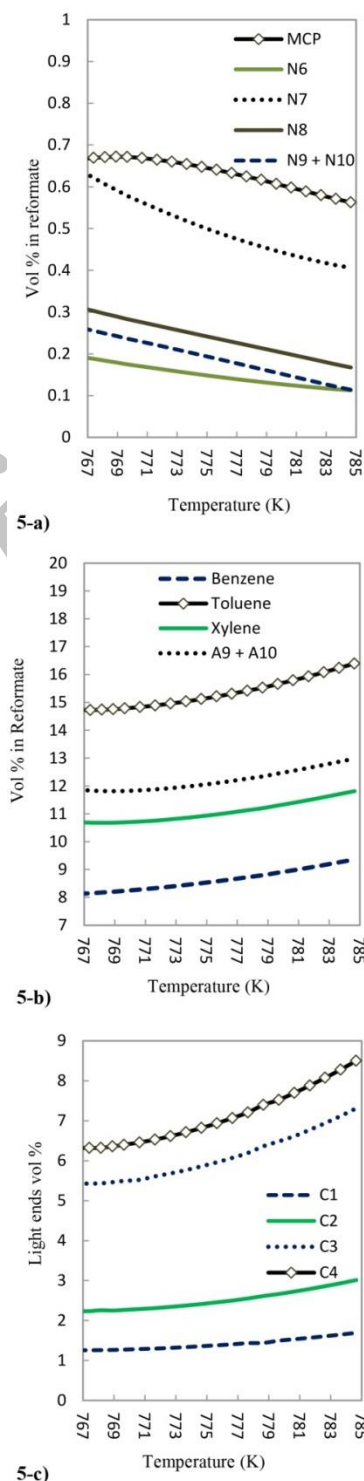


Figure 5. Effect of WAIT on volume percent of (a) naphthene production in reformate, (b) aromatic production in reformate, and (c) light ends in reactors production

4.3. Effect of pressure on semi-regenerative process

A reduction in the reactor pressure increases the hydrogen and reformate yield, decreases the required reactor temperature to achieve a constant product quality, and shortens the catalyst cycle by increasing the catalyst coking rate. Higher pressures cause higher rates of hydrocracking and more hydrocracking causes a loss of reformate yield for a given octane number [24-26]. The real incentive for reducing pressure in reformer reactors is more reformate yield with the added benefit of increased hydrogen. Fig. 6 represents the effect of pressure on R.O.N and yield in the naphtha reforming process. Due to catalyst distribution in the reactors, it is usually close to the inlet pressure of the last reactor.

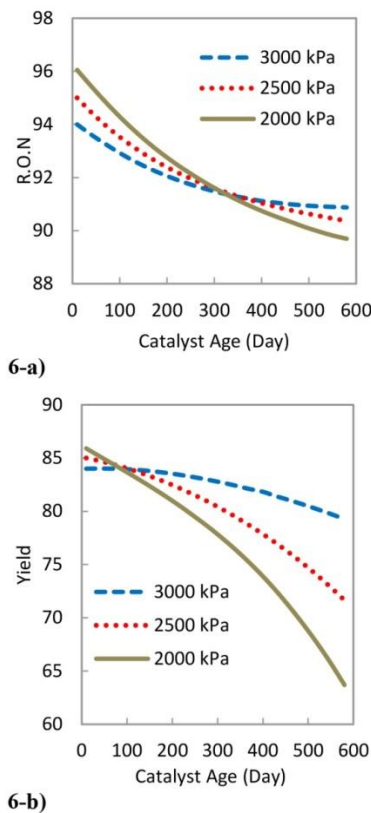


Figure 6. Profiles of (a) research octane number and (b) the yield of semi-regenerative reformer versus catalyst age in various pressures to investigate the effect of pressure in reforming process

Fig. 7 demonstrates the effect of pressure on coke deposition on catalyst for each reactor. By

these graphs, the amount of coke formation on catalyst at various pressures is illustrated. As it can be noticed, at lower pressures, coke deposition increases. The results of Fig. 6 and Fig. 7 show that it is better to keep the catalytic reforming unit at the lowest practical pressure if coke deposition on catalyst does not make any problem on reactor condition.

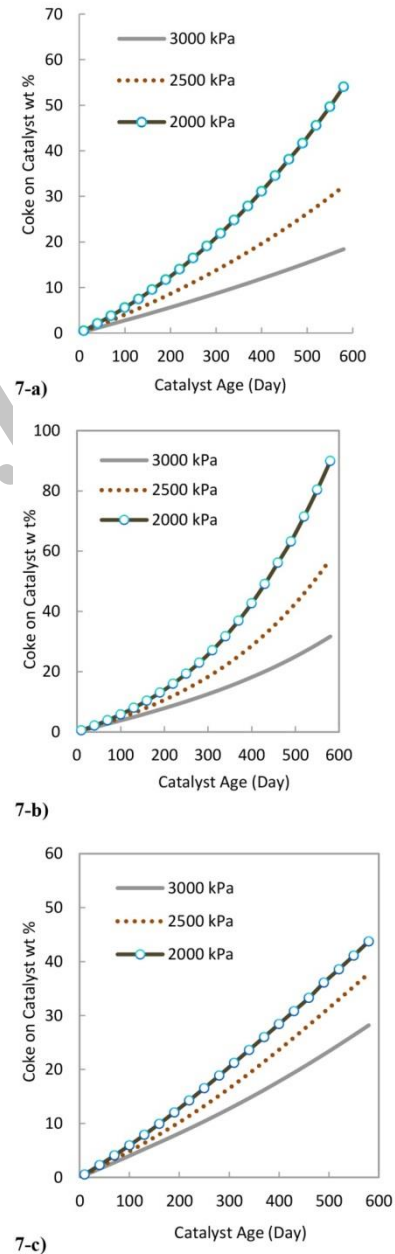


Figure 7. Profiles of coke deposit on the catalyst in (a) reactor 1, (b) reactor 2, and (c) reactor 3 versus catalyst age in various pressures to investigate the effect of pressure on coke formation on catalyst in reforming process

4.4. Effect of hydrogen to hydrocarbon ratio

The profile of coke deposit on the catalyst at each reactor in various H_2/HC ratios is illustrated in Fig. 8. Recycled hydrogen is necessary in the reformer operation for purposes of catalyst stability. The hydrogen reacts with coke precursors, removing them from the catalyst before they can form polycyclic aromatics, which ultimately deactivate the catalyst [27]. Increase in H_2/HC ratio causes increase in the hydrogen partial pressure and removes coke precursors from the metal sites. The global effect of this is increased catalyst life. In other words, the rate of coke formation on the catalyst and, thus, catalyst stability and life are functions of the H_2/HC ratio and hydrogen partial pressure present in the reactor system. The H_2/HC ratio has little influence on product quality or yield. Hydrogen partial pressure is set by an economic balance between the consumed energy by heaters, recycle gas, and cycle duration.

4.5. Effect of space velocity

Space velocity is an important variable, because it is interchangeable with reaction temperature and it relates to the length of time of contact with the catalyst; thus, it affects the severity of reforming. The residence time of the feed in the reactor is the inverse of the liquid hourly space velocity ($LHSV^{-1}$). The space velocity directly affects the kinetics of the reforming reactions. Decreasing the space velocity leads to increase in the residence time; hence, the higher the severity, which results in increase in octane number, the lower the reformate yield and the higher the coke deposit will be. The profiles of the research octane number and the yield profiles in various LHSVs to investigate the effect of LHSV in reforming process are given in Figs. 9(a) and 9(b), respectively. Also, the effect of process variables is gathered in Table 8.

A schematic diagram of the cyclic naphtha reforming process is illustrated in Fig. 10. In this configuration, for upgrading the semi-regenerative process, an extra fixed bed reactor is used with the same size as the third reactor. The flexibility of the proposed configuration allows refinery to operate at lower pressure and temperature, which results in gaining higher yield, hydrogen production, and hydrogen purity.

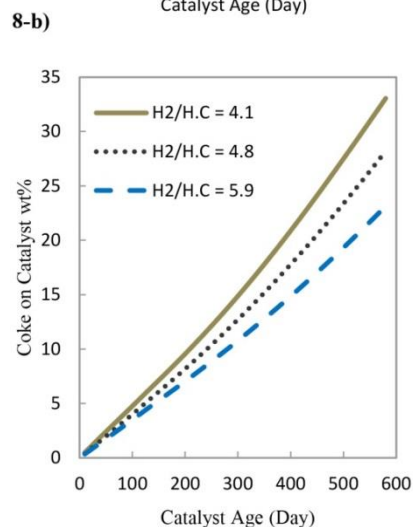
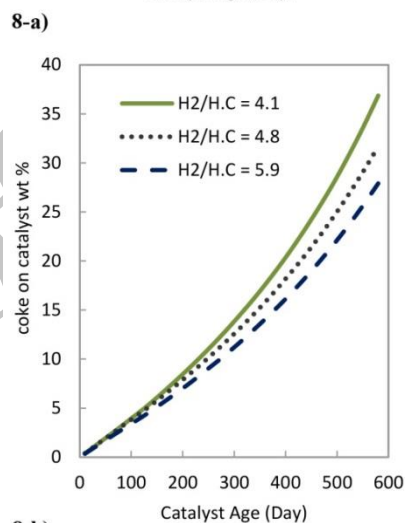
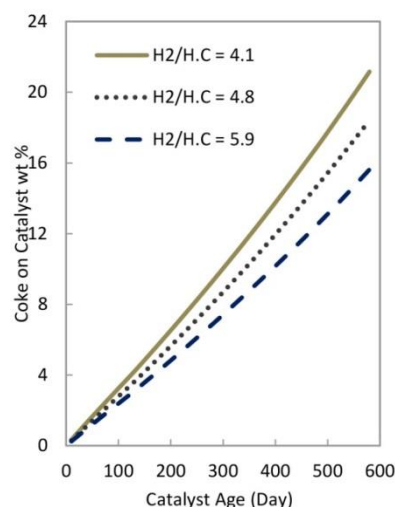


Figure 8. Profiles of coke deposit on the catalyst in (a) reactor 1, (b) reactor 2, and (c) reactor 3 versus catalyst age in various $H_2/H.C$ rates to investigate the effect of H_2/HC on coke formation on catalyst in reforming process

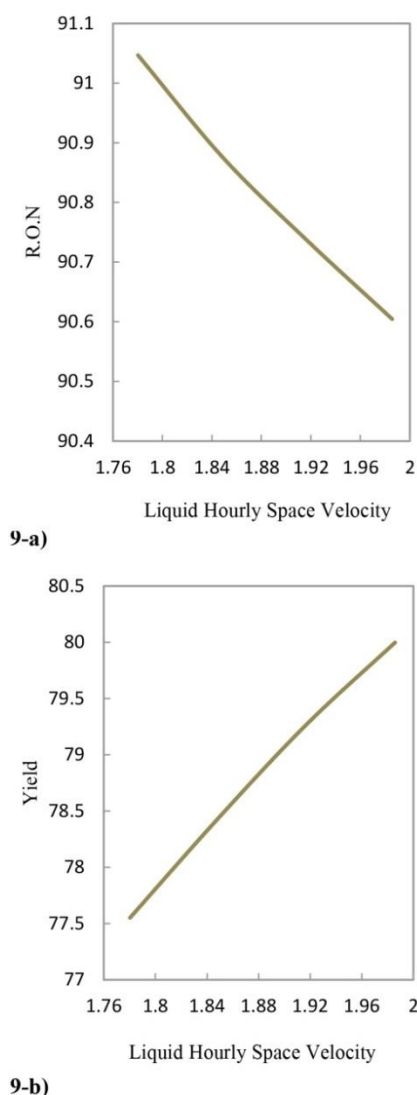


Figure 9. Profiles of (a) research octane number and (b) the yield of reformate in various LHSVs to investigate the effect of LHSV in reforming process

Table 8. Effect of process variables on naphtha reforming

Increases	RON	Reforming yield	Coke deposit
P	Decreased	Decreased	Decreased
T	Increases	Decreased	Increases
Space velocity	Decreased	Increases	Decreased
H ₂ /HC ratio	Negligible	Negligible	Decreases

4.6. Proposed configuration (cyclic)

Semi-regenerative process is characterized by continuous operation over long periods with decrease in catalyst activity, selectivity, and sta-

bility. Fig. 11 represents the research octane number and yield of product for semi-regenerative reformer and the proposed configuration (cyclic).

The semi-regenerative process is a conventional reforming process that continuously operates over a period of typically up to two years. As it is shown in Fig. 11, due to the reduction in activity of catalyst in semi-regenerative reforming during the cycle, the research octane number and yield of aromatic drop by lapse. The proposed configuration is capable to enhance the octane number and yield of reformate.

Hydrogen purity and hydrogen production profiles are illustrated in Fig. 12. Due to the adverse effect of undesirable reactions, such as hydrocracking, Hydrogenolysis, Hydrodealkylation, and alkylation, it is better to keep the naphtha reforming operation condition at lower pressure, instead of increasing WAIT during cycle length. Due to lower WAIT and pressure operating conditions in a cyclic process, the overall catalyst activity, conversion, and hydrogen purity changes with time are much less than those in the semi-regenerative process. The characterizations and operational conditions of proposed configuration are presented in Table 9. However, a difficulty in the proposed configuration is that reactor switching needs a complex process layout with higher safety precautions. An extra reactor lets the refinery to have one reactor out of operation for regeneration, while the reforming process continues in operation.

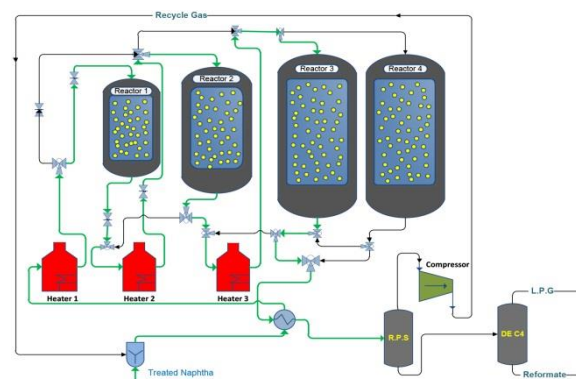
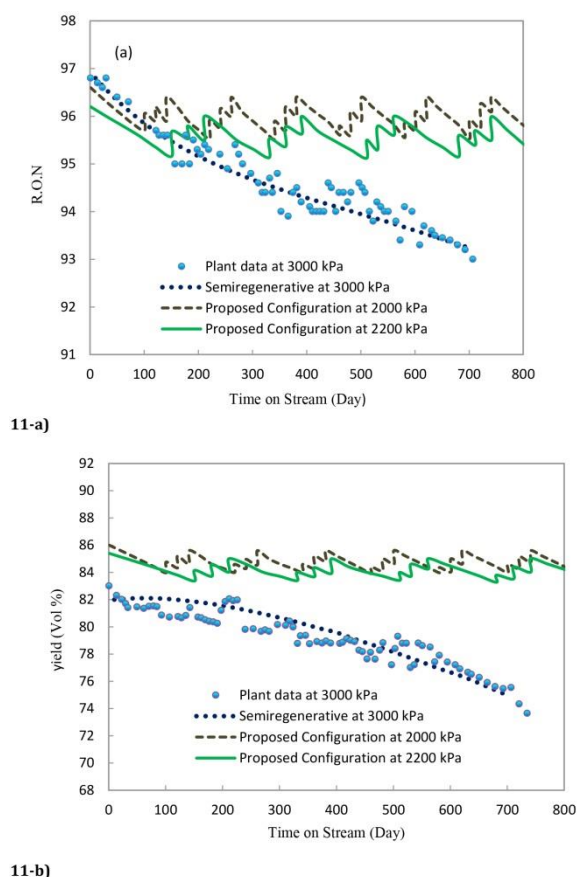
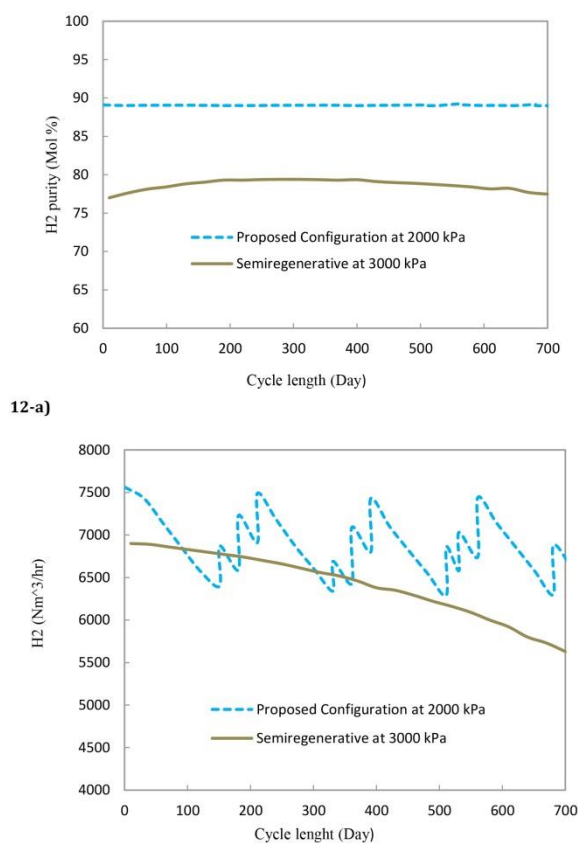


Figure 10. A schematic diagram of the cyclic naphtha reforming process



11-b)

Figure 11. Comparison of (a) the research octane number and (b) the yield of reformate versus catalyst age for case (1) plant data for semi-regenerative reforming at 3000kPa, case (2) semi-regenerative reforming at 3000kPa, case (3) the proposed configuration at constant WAIT (768K) and 2000kPa, and case (4) the proposed configuration at constant WAIT (768K) and 2200kPa



12-a)

12-b)

Figure 12. Profiles of (a) hydrogen purity and (b) hydrogen production versus cycle length. Comparison between case (1) semi-regenerative reforming at 3000kPa and case (2) the proposed configuration at constant WAIT (768K) and 2000kPa

Table 9. Specifications of feed and product

Case	Reactors in use	Day	RON	Yield	Case	Reactors in use	Day	RON	Yield
1	1,2,3	1	96.19995	85.39945	19	1,4,3	391	95.62786	83.91267
2	1,2,3	31	95.99199	85.01137	20	2,4,3	391	96.00035	84.99888
3	1,2,3	61	95.79356	84.61913	21	2,4,3	421	95.68741	84.41851
4	1,2,3	91	95.58762	84.21395	22	2,4,3	451	95.48691	84.03058
5	1,2,3	121	95.3508	83.79919	23	2,4,3	481	95.29818	83.72989
6	1,2,3	151	95.16205	83.37311	24	2,4,3	511	95.12138	83.41438
7	1,4,3	151	95.68272	84.1579	25	1,2,4	511	95.49962	83.99985
8	1,4,3	181	95.52693	83.71219	26	1,2,4	531	95.29529	83.70949
9	2,4,3	181	95.79961	84.59923	27	1,2,3	531	95.79404	84.61432
10	2,4,3	211	95.48829	84.01847	28	1,2,3	561	95.60038	84.24566
11	1,2,4	211	96.00068	85.00233	29	1,4,3	561	96.00052	85.01313
12	1,2,4	241	95.79223	84.61133	30	1,4,3	591	95.82118	84.59928
13	1,2,4	271	95.49684	84.01638	31	1,4,3	621	95.55181	84.17396
14	1,2,4	301	95.31092	83.71092	32	1,4,3	651	95.35153	83.73624
15	1,2,4	331	95.13434	83.3939	33	1,4,3	681	95.15086	83.27601
16	1,2,3	331	95.53104	84.00248	34	2,4,3	681	95.59991	83.80005
17	1,2,3	361	95.36215	83.67206	35	2,4,3	711	95.38998	83.51728
18	1,4,3	361	95.78109	84.36011	36	1,2,4	711	95.70036	84.40208

5. Conclusion

In order to enhance octane number, yield, hydrogen production, and hydrogen purity, a novel reactor configuration has been proposed for an old semi-regenerative catalytic naphtha reforming process. Due to approximately low severity in semi-regenerative reforming, such as trend towards a lower octane number, yield, hydrogen production, and hydrogen purity by the lapse, and due to coke deposition on catalyst, the reforming operation may be shut down, which leads to a huge economic damage. To avoid these problems, the effects of temperature, pressure, space velocity, and hydrogen to hydrocarbon ratios in semi-regenerative naphtha reforming process were investigated to assess each parameter in enhancing the octane number and yield of the product. Also, the effect of each of these parameters on the reduction in coke deposition on the catalyst surface area was studied. Finally, for converting semi-regenerative process to cyclic process, a fixed bed reactor was added to the semi-regenerative reforming process to increase the octane number, and the rates of yield and purity of hydrogen production in this new configuration. 1.5%, 7.14%, 8.1%, and 13.2% improvements in the octane number, yield of reformate, hydrogen production rate, and hydrogen purity were observed, respectively. The results indicated that aromatic and hydrogen production and hydrogen purity improved in comparison with the semi-regenerative reformatting process. Due to the additional swing reactor (which is a spare reactor), each of the reactors must be removed for regeneration process to be replaced with a rebuilt reactor.

Nomenclature

A	Area, m ²
d _p	Particle diameter, mm
S _a	Surface area, m ² gr ⁻¹
H ₂	Hydrogen, kmol/h
P _v	Total pore volume, cm ³ gr ⁻¹
k _{r1}	Forward rate constant for reaction (5), kmol h ⁻¹ kg cat ⁻¹ MPa ⁻¹
k _{r2}	Forward rate constant for reaction (6), kmol h ⁻¹ kg cat ⁻¹ MPa ⁻¹
k _{r3}	Forward rate constant for reaction (7), kmol h ⁻¹ kg cat ⁻¹ MPa ⁻¹
k _{r4}	Forward rate constant for reaction (8), kmol h ⁻¹ kg cat ⁻¹ MPa ⁻¹
k _{e1}	Equilibrium constant for reaction (5), MPa ³

k _{e2}	Equilibrium constant for reaction (6), MPa ³
P _i	Partial pressure of the ith component, kPa
P	Total pressure, kPa
T	Temperature of gas phase, °K
H	Height, m
V	Volume, m ³
W	Weight, kg
L _D	Loading density, kg/l
dis	Catalyst distribution, wt %
d _b	Bed diameter, mm
d	Reactor diameter, m

Greek Letters

ε	Void fraction of catalyst bed
ρ _b	Catalyst bulk density, kg m ⁻³
ΔH	Heat of reaction, kJ kmol ⁻¹ Hz

Subscript

a	Aromatic, -
h	Hydrogen, -
n	Naphthene, -
p	Paraffin, -

Abbreviations

IBP	Initial boiling point, °C
FBP	Final boiling point, °C
RON	Research octane number
WAIT	Weighted average inlet Temperature, °C
Pt	Platinum
Re	Rhenium

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