Maximize the Gas Oil Yield from Delayed Coker Unit by Optimization Between Process Variables

Samy Nabil Mohamed[1*], Nadia Ali ElSayed[2], Saeed Mohamed Abdallah[3], Mohamed ElSokary[4]

[1]*EPROM Company, MIDOR Refinery, Ministry of Petroleum and Mineral Resources, Alexandria, 21934, Egypt*

[2,3]*Refining and Petrochemical Department, Faculty of Petroleum and Mining Engineering, Suez University, Suez 43512, Egypt*

[4]*Egyptian Petroleum Research Institute, Nasr City, Cairo 11759, Egypt*

Corresponding author*

Samy Nabil Mohamed

Email: sinm2@pme.suezuni.edu.eg

Tel: +201229533019

Abstract:

Today the oil market demands are calling for more gasoline and diesel products while having a problem of heavier crude oils with high density that becomes available over the lighter crudes in the last decades. The needs to heavy oil processing become the priority in all refineries. More sophisticated distillation, physical separation units and conversion units are required for heavy oil processing. One of the most important conversion units is the delayed coker unit which converts the heaviest and least desirable elements of crude bottoms, such as heavy sour vacuum residue into marketable products that is further processed to higher economic value products like jet fuel, gasoline and diesel fuel that highly demanded in the world markets. The products of the delayed coker process are sour fuel gas, Liquefied petroleum gas (LPG), naphtha (gasoline), light gas oil (LGO), heavy gas oil (HGO) and coke. Now it's the time to think on how to increase the liquid yields of gasoline and gas oil from delayed coker unit at the expense of coke formation. A simulation model has been built by using Aspen HYSYS to obtain results and to make an optimization for the process variables for the delayed coker unit while comparing them to the old design case to achieve the maximum gas oil yield while keeping process safety factors in our concerns.

Keywords: Delayed coker unit, Maximizing gas oil yield, Aspen HYSYS, Delayed coker unit optimization, Economic study.

1. Introduction:

Petroleum coke was first made by the pioneer oil refineries in Northwestern Pennsylvania in the 1860's.These primitive simple refineries boiled oil in small, iron stills to recover kerosene, a valuable and much needed luminescent. The stills were heated by wood or coal fires built underneath that heated and coked the oil near the bottom. After the vaporization was completed, the still was allowed to cool so the workmen could dig out the coke and tar before the next run. The use of single horizontal shell stills for distillation of the crude was used until the 1880's, with the process sometimes stopped before bottoms coked to produce heavy lubricating oil. Multiple stills were used to process more fractions by running the stills in series with the first still producing the coke. In the 1920's the tube furnace with distillation columns (bubble cap distillation trays patented by Koch ushered were being built with the bottoms from the distillation column going to wrought iron stills in which the total outside of the horizontal still was in direct contact with the flue gases. This produced the maximum amount of heavy gas oil. Some of these units were still in operation after World War II [1].

The origin of the vertical coke drum was probably from thermal cracking of gas oil for the production of gasoline and diesel fuel. From 1912 to 1935 the Burton process developed by Standard Oil at Whiting, Indiana converted gas oil to gasoline with the production of petroleum coke. Dubbs and other thermal cracking processes also produced petroleum coke [2].

Lack of an adequate supply of crude oil and the lack of a heavy oil market caused land-locked Middle American refineries to process the heavy fuel oil (atmospheric distillation bottoms and vacuum distillation bottoms) in a delayed coker to produce more gasoline and diesel fuel [3].

Delayed coking combined a number of the features and improvements from the development of the thermal cracking process. The use of pressure as well as heat for cracking and separating the heater from the coker and the use of two drums enabled the delayed coker to operate on a continuous basis. The number of cokers built before 1955 was small, with a surge in delayed coker construction between 1955 to 1975 at 6% per year and an 11% growth rate during the 1965 to 1970 period [4].

The savior delayed coker unit is a low-pressure thermal cracking process. It derives its name from the fact that the formation of coke takes place not in furnace tubes but it is delayed until it is laid down in the coke drums, where it can be accumulated and removed as a saleable product. During this thermal process the vacuum residue from vacuum crude distillation is heated in a furnace batch-wise that considered the cornerstone of the unit then confined in a reaction zone or coke drum under proper operating conditions of temperature and pressure until the unvaporized portion of the furnace effluent is converted to vapor and coke [5].

Delayed coker is an endothermic reaction, with the furnace supplying the necessary heat for the coker reactions to take place. The reactions in the delayed coker are complex and were firstly random take place without any studies or prediction about the resulting product yields. Today a lot of studies concerns about the

product yields from the delayed coker process with an equations or simulation cases you can target a proximity your coker product yields [6].

2. Material and methods:

2.1. Process description:

2.1.1. Fresh feed to the coker fractionator:

The fresh residue feed to the delayed coker unit is fed from hot vacuum unit residue and cold feed from storage. The two feed streams are then combined, preheated in heat exchangers and introduced to the bottom of the main fractionator at 290°C that acts as a surge drum for the coker furnace see figure (1) [7].

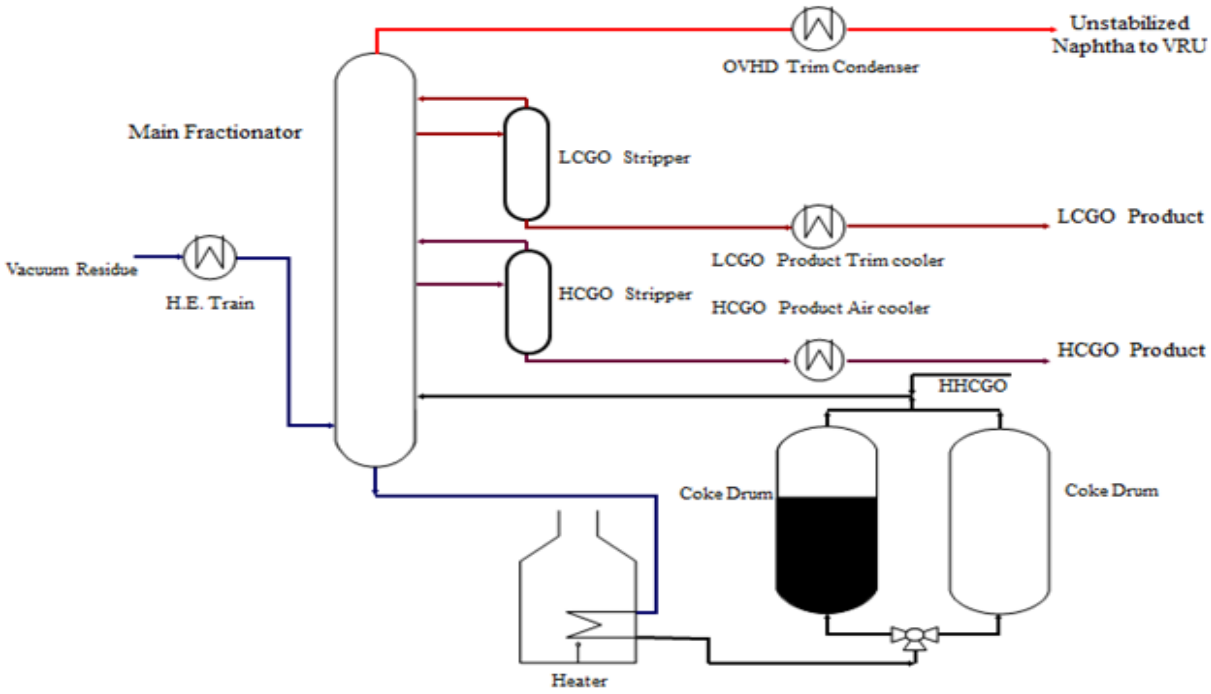


Figure 1: Delayed Coker Unit Distillation section simple process flow diagram

2.1.2. Coker furnace and coke drums:

The liquid which collects in the bottom of the fractionator flows from the bottom of the tower and pumped to the coker furnace. A recycle naphtha or middle distillate heavy gas oil stream might joins the main hydrocarbon stream just before entering the furnace cells. The blend mixture is then heated to the temperature required for the coker reaction (approximately 500° C) [8]. Each pass has a high pressure steam line that ties into it called the velocity steam. The velocity steam role is very important as it's used to increase velocity in each pass and reduce coker rate in the furnace see figure (1) [9]. Coke drum charge enters the bottom of one of the coke drums see figure (1). The cracking and condensation reactions start to take place inside the drum forming coke and lighter components that exit the top of the drum in a vapor state [10].

2.1.3 Fractionator section:

In the fractionator, the coke drum vapor introduced in the flash zone section. The vapor sprayed with heavy heavy gas oil (HHGO) or fresh feed vacuum residue. The spray condenses some of the flash zone gas oil which drops into the flash zone draw pan. From the flash zone draw pan, the Flash zone gas oil (FZGO) flows to the FZGO pump suction filters to remove the entrained coke from the coke drum to the main fractionator. The FZGO then introduced to the bottom of the fractionator as a recycle with the fresh feed vacuum residue [11].

Heavy gas oil (HGO) product drawn from tray is stripped with steam to adjust product flash point in the HGO stripper, before it is sent hot to the Hydrocracker unit or cold to storage see figure (1) [12].

LGO, drawn from tray, is sent to the LGO stripper where it is also stripped with steam before it is sent to storage or to the distillate Hydrotreater. Part of the LGO product stream is used as lean oil to the sponge oil absorber tower in the gas recovery unit (GRU) [13].

Unstabilized naphtha is produced at the top of the tower, separated in the fractionator overhead receiver and then is sent to the Gas Recovery Unit. The tower top temperature and pressure determine the endpoint of the naphtha [14].

2.2. Process variables:

The key process variables are [15]:

- Type of Feedstock
- Coke Drum Temperature
- Coke Drum Pressure
- Recycle ratio
- Fractionation Section

2.2.1. Type of feedstock:

As discussed in the process description, the crude source and type of charge stock have a major effect on the coke yield and quality. The Conradson carbon content of the feedstock is the predominant property determining the yield of coke: the higher the conradson carbon content of the feed, the higher the coke yield. The nature of the feedstock, that is its relative proportions of asphaltenes, resins, aromatics, and its impurities levels affect quality of the coke [16].

2.2.2. Coke drum temperature:

Coke drum temperature considered the second most effective variable in coker process after the type of feedstock it's adjusted by varying the coker heater transfer temperature which has an important effect on both the yield and quality of coke and liquid yields. Heater transfer temperatures should be maintained between 480°C and 500°C.

At lower temperatures, a tarry coke is produced with high VCM% and a significant increase in coke yield and gas plus gasoline. Within the temperature range discussed for a given feedstock, an increase in temperature will increase the gas oil yield instead of coke and gas plus gasoline [17].

2.2.3. Coke drum pressure:

The thermal cracking reactions in coker process are a function of time and temperature. The effect of the two variables is related. The drum pressure which determines the degree of vaporization inside the drum and the velocity through the heater can be used to vary the residence time inside the heater passes. By increasing the coke drum pressure, the residence time increased through the heater and also lowering the velocity of vapors inside the coke drums which allow more condensation reactions to occurs that lead to increase in coke yield with high VCM% and decrease in the liquid gas oil yields produced. The fractionator overhead receiver pressure controls the pressure of the coke drum. Changing in coke drum pressure has a low effect on delayed coker process product yields [18].

2.2.4. Recycle ratio:

Recycle ratio is one of the most important factors that effect on the delayed coker process yields. Increase the natural recycle ratio will result in reducing the heavy gas oil yield draw and lowering the total fresh feed drawn to the unit by taking up the unit capacity. Flash zone temperature where the coke drum vapors effluent enters the fractionation section is the most effective factor in recycle ratio flow rate and its temperature. A decrease in flash zone temperature will allow more condensation to occur firstly in the bottom of the fractionator, so increasing

the natural recycle flow rate and lowering its temperature. It's noticed that increasing in natural recycle or decrease in temperature will produce coke with a high HGI and lower coker liquid yields [19].

2.2.5. Fractionation section:

The main variables that affect in the Fractionation Section are the end point of each product cut (Naphtha, Light gas oil and heavy gas oil), Flash zone point, tower refluxes, pump around and side strippers steam flow rate. Change in any product end point could be achieved by adjusting the tray temperature by changing the pump around and reflux flow rates. For example increasing in LGO draw tray temperature will result in increasing the end point of LGO and increasing its yield while lowering in the HGO yield. So change in any variable in the fractionation section will effect on the other variables [20].

3. Case study:

To achieve the maximum benefits from the delayed coker unit we have to study each process variable effects on product yields while keep the key principles of process safety terms in front of our eyes.

This study for the process variables and its effects on the delayed coker unit product yields done using the Aspen HYSYS modeling and simulation technology tool.

3.1. Modeling and simulation for delayed coker unit:

Starting guide will cover the process of creating a delayed coker model, including setting up a heavy crude feed with a petroleum assay, configuring a delayed coker unit operation, calibrating the coker unit, and putting a recycle network together [21].

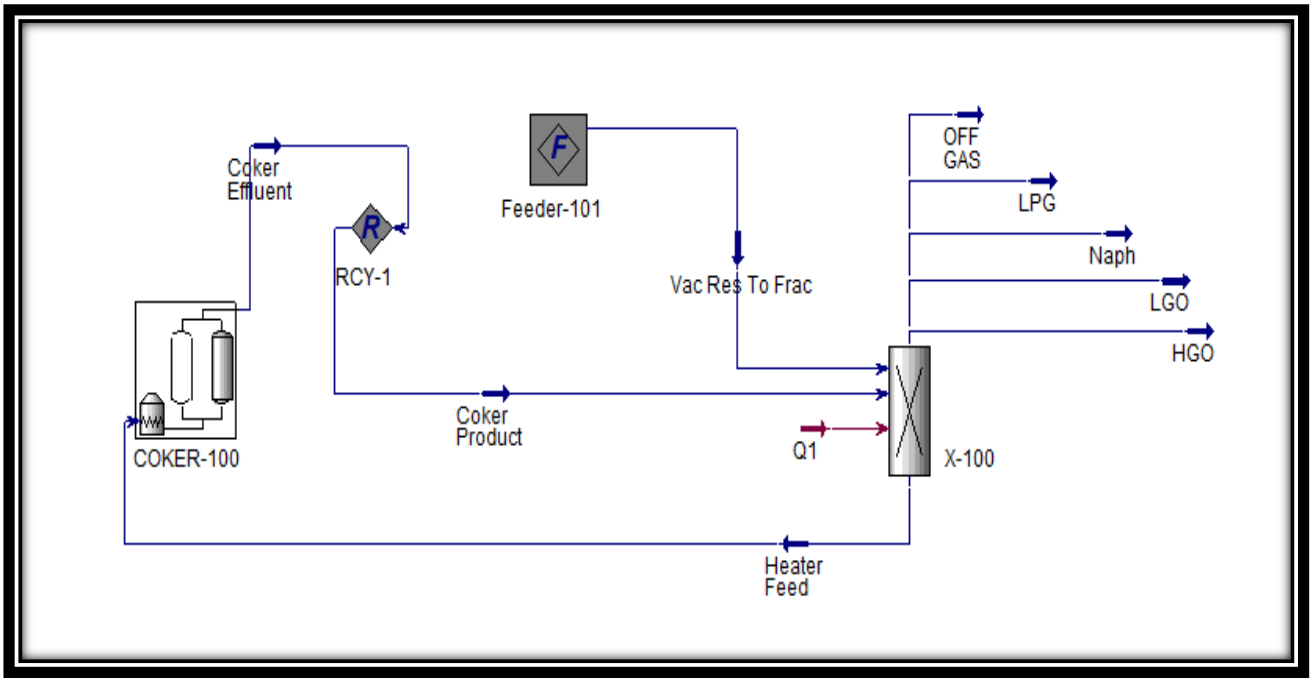


Figure 2: Completed flowsheet for a delayed coker process Combined Feed Ratio.

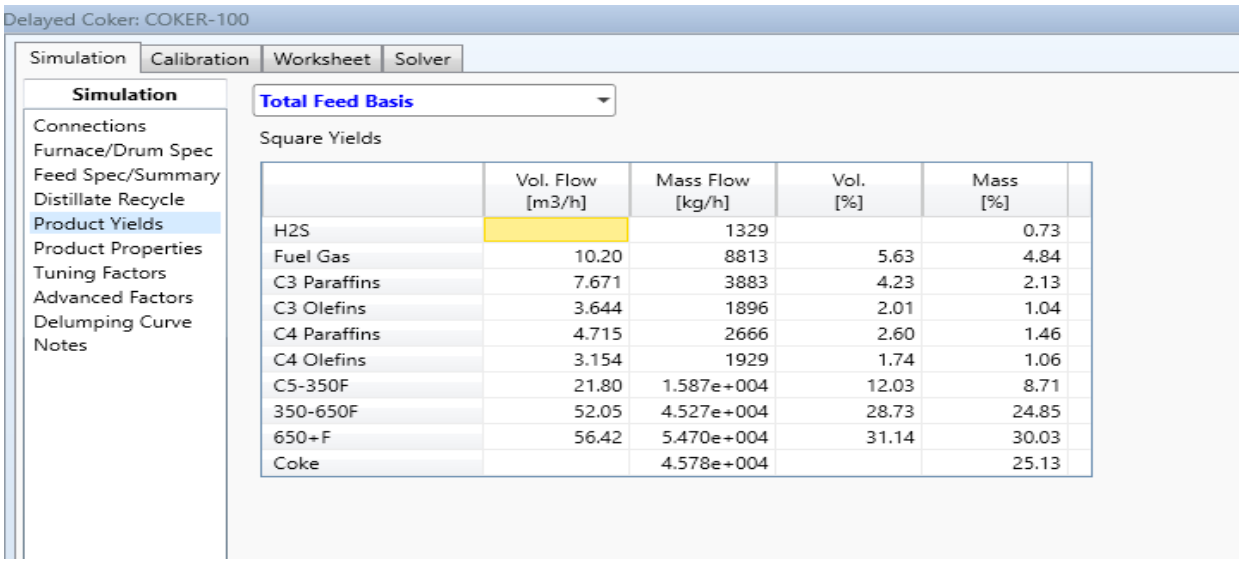
Now after finished the total modeling of the delayed coker unit see figure 2 we will start the optimization between process variables to maximize gas oil yield produced from delayed coker unit by studying the effect of changing in each variable on the coker product yields. We will start with entering the design condition based on the delayed coker unit at the Middle East oil refinery and find the results and log it.

Design condition:

By entering the design conditions that concerned on our study Drum outlet temperature, Drum pressure, Recycle ratio and Cycle time in the delayed coker complex and solve it see table 1. We will find the results as shown in figure 3.

Table 1: Design condition and results.

Drum Outlet Temp C	446	**Feed M3/hr**	156
Drum Press barg	1.034	**Gases + Naph Yield WT%**	19.99
Recycle WT%	20%	**Gas Oil Yield WT%**	54.88
Cycle Time hr	16	**Coke WT%**	25.13



	Vol. Flow [m3/h]	Mass Flow [kg/h]	Vol. [%]	Mass [%]
H2S		1329		0.73
Fuel Gas	10.20	8813	5.63	4.84
C3 Paraffins	7.671	3883	4.23	2.13
C3 Olefins	3.644	1896	2.01	1.04
C4 Paraffins	4.715	2666	2.60	1.46
C4 Olefins	3.154	1929	1.74	1.06
C5-350F	21.80	1.587e+004	12.03	8.71
350-650F	52.05	4.527e+004	28.73	24.85
650+F	56.42	5.470e+004	31.14	30.03
Coke		4.578e+004		25.13

Figure 3: Design condition product yields results by HYSYS.

4. Results and discussion:

4.1. The results from changing in process variables:

4.1.1. Recycle ratio:

The recycle ratio is the total natural recycle and distillate recycle ratio and it is the percentage of the difference between the total feed to the heater and the fresh feed to the fractionator to the fresh feed. It's one of the most important variables on the delayed coker unit that effect on the product yields. Natural recycle is called natural sounds like it's out of being controlled but actual the flash zone temperature in the fractionation section playing the main role in this factor as it's the quenched vapor temperature from the drum after it fed to the fractionator usually this quench is done by the fresh feed or the heavy heavy gas oil pump around this quench is done mainly for the coke fines from the coke drum that carried with the drum vapors to settle down and taken out with the modern system flash zone large filters that cleaned periodically the flash zone filters allow coker unit to run more continuously years instead of shutdown for clean the fractionator bottom section from the accumulated coke. So the main role of the spray heavy heavy gas oil quench should be controlled to target only the coke fines and not allow the flash zone temperature to more drop as this will allow more condensation to take

place in the bottom section of the fractionator. The high level of liquid in the flash zone tray will have only one way either pumped or carried down to the bottom of the fractionator which later take up the capacity of the unit by occupying the bottom of the fractionator level instead of the fresh feed that should be decreased to control the level of the bottom of the fractionator that act as a surge drum to heater.

The distillate recycle is a medium distillate heavy gas oil or naphtha stream that preheated and fed with the feed to the heater before heater passes. Also, this stream has main roles as it forming a protection layer inside the heater passes due to its vaporized rapidly and act as a stripping media through the coke bed inside the coke drum during the cycle time.

Controlling the recycle ratio is available and by studying it's effect it will found that when the recycle ratio increased the lower the gas oil yield produced as the total fresh feed is decreased and the cracking of flash zone gas oil or recycle oils is going more easier than the vacuum residue at the same cracking temperature these oils will converted mainly to light vapors and more coke products.

Now, we will start studying the recycle ratio changing effect on the delayed coker product yields by Aspen HYSYS simulation while keeping all the other variables as constant see figures [4-5].

Conclusion of the results:

By studying the effect of the recycle ratio variable see table 2 and figures [4-5] it's indicated that by lowering the recycle ratio the higher the gas oil yield Wt% produced from the delayed coker unit. It's also indicated that the gas oil yield wt% increasing more rapidly when the recycle ratio wt% is become lower.

By lowering the recycle ratio wt% it's found that there will be a low drop in coke yield wt% but further more lower in the recycle ratio wt% the more drop rate in the coke yield wt%.

It's recommended to keep the recycle ratio around 3 to 5 % as possible for further benefits from the delayed coker cracking unit, Also there are fears from running delayed coker heaters without distillate recycle stream as the velocity of flows inside the heater passes will start to drop but this could be solved by increasing the velocity steam flow rate to keep the velocity inside the heater passes as required or decreasing the heater passes diameter.

Table 2: Recycle ratio WT% change versus delayed coker product yields WT%.

Recycle Ratio %	20%	15%	10%	5%	3%
Gases + Naph Yield wt%	19.99	19.75	19.47	19.23	19.14
Gas Oil Yield wt%	54.88	55.12	55.58	56.10	56.34
Coke wt%	25.13	25.13	24.95	24.67	24.52

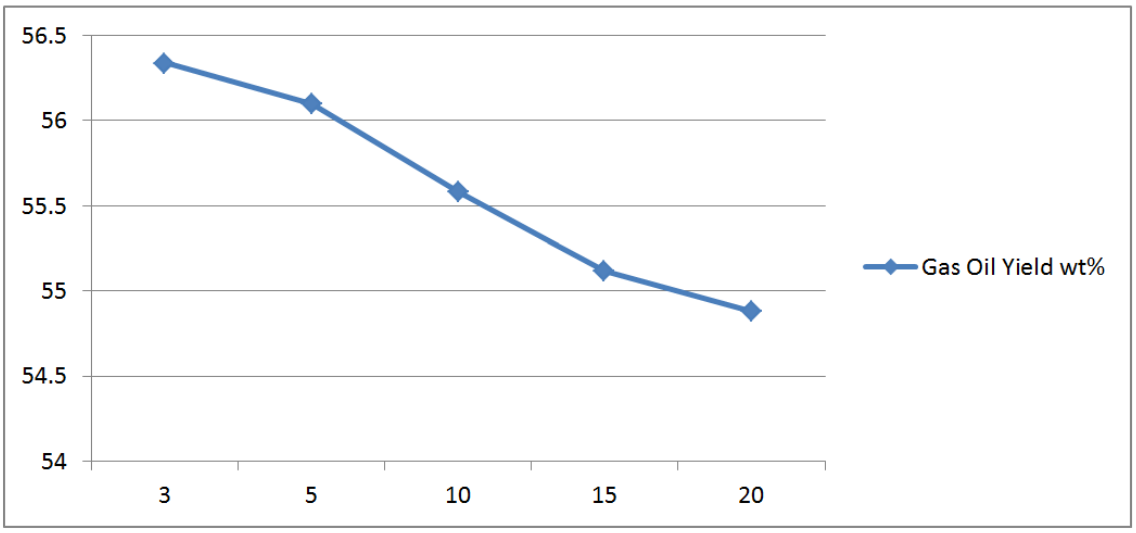


Figure 4: The effect of change in recycle ratio wt% to delayed coker gas oil yield produced wt%.

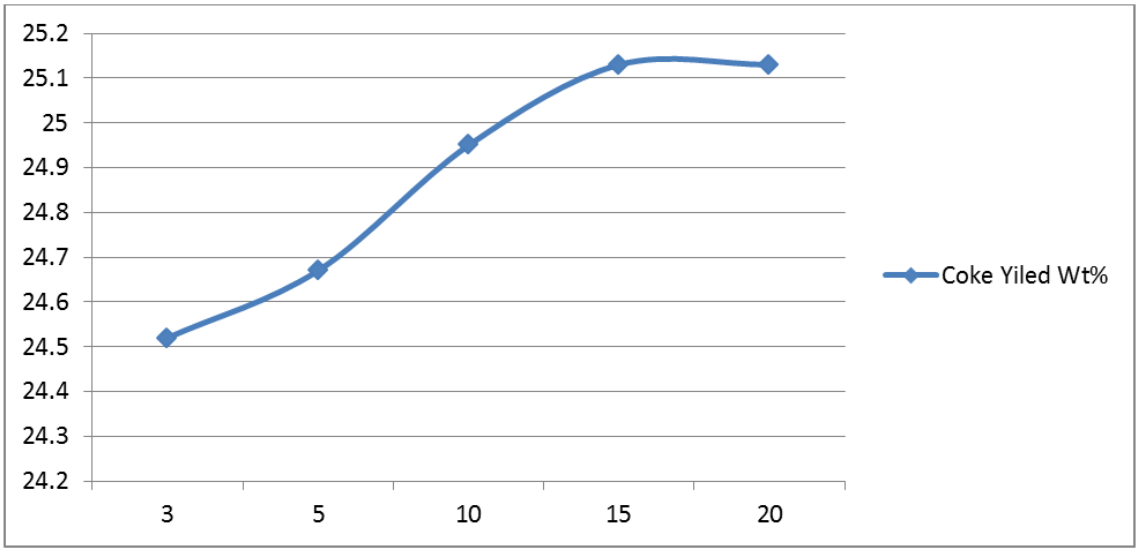


Figure 5: The effect of change in recycle ratio wt% to delayed coker coke yield produced wt%.

4.1.2. Temperature effect on thermal cracking:

One of the critical variables on the delayed coker process is the cracking temperature to be more specific it's the furnace outlet temperature is the most effective. Some process depend on the coke drum inlet temperature but to be more accurate the cracking reaction is endothermic, So there will be a loss in temperature between the coil outlet or furnace outlet temperature and the coke drum inlet temperature.

As discussed before that the coker transfer line temperature is maintained between 480°C to 500°C and the furnace outlet temperature between 490°C to 510°C. Changing in furnace outlet temperature may not have a limit and while increasing it the delayed coker yields start to change. There will be a significant increase in the gas oil yield and lower in the gasses and coke yields.

Following up this increase in the furnace outlet temperature out of the discussed limits will start to form more coke layer inside the heater coils as the cracking will be more faster and may start to happen inside the heater coils, So if we will need to increase the temperature out of the boundary little more like 510°C to 520°C we should increase the velocity of the flow inside the heater passes by the velocity steam facilities to prevent going through the decoker system like steam / air decoker or online spalling in short periods.

The relation between the heater outlet temperature and the flash zone temperature is very important on our study that concerns about increasing the gas oil yield. It was found that the increase in the heater outlet

temperature will increase the drum inlet temperature and later will increase the vapor effluent temperature from the drum to the flash zone this will also allow the gas oil cut range to increase and its yield due to raising in the flash zone temperature and further more lower in the recycle ratio. This will be happen while keep the any other process variables as constant.

Now, we will start studying the furnace outlet temperature changing effect on the delayed coker product yields by Aspen HYSYS simulation while keeping all the other variables as constant see figures [6-7].

Conclusion of the results:

While studying the change in cracking temperature by changing in the heater outlet temperature of the delayed coker heaters through 480°C to 520°C and its effects on the delayed coker product yields WT% see table 3 and figures [6-7] it's indicated that by raising the heater outlet temperature by 5°C will increase the gas oil yield by an average of 0.64 WT% with a highest increase rate in the initial of the raising in heater outlet temperature and further more increase in heater outlet temperature will also increase the gas oil yield but with lower rate. It's also indicated that while increasing in the heater outlet temperature by 5°C, the gases plus naphtha yield increased by an average of 0.26 WT% and coke yield decreased by an average of 0.9 WT%. The rate of decreasing in coke yield produced from delayed coker unit while increasing the cracking temperature will be higher in the first raising in the temperature than in further increasing. It's recommended to keep the heater outlet temperature as high as possible within the discussed range to allow higher degree of cracking reactions to take place for vacuum residue while taking care from the coke formation rate inside the heater passes. It should be noticed and lowered by increasing the velocity a little more by the means of velocity steam or distilled recycle streams.

Table 3: Heater outlet temperature °C change versus delayed coker product yields WT%.

Heater Outlet Temperature °C	480	485	490	495	500	505	510	515	520
Gases + Naph Yield WT%	19.42	19.71	19.99	20.27	20.53	20.78	21.04	21.28	21.52
Gas Oil Yield WT%	53.53	54.21	54.88	55.53	56.18	56.83	57.46	58.09	58.71
Rate of increase in gas oil yield WT%	0.68	0.67	0.65	0.65	0.65	0.63	0.63	0.62	0.62
Coke WT%	27.05	26.08	25.13	24.20	23.29	22.39	21.50	20.63	19.77
Rate of decrease in coke yield WT%	0.97	0.95	0.93	0.91	0.90	0.89	0.87	0.86	0.85

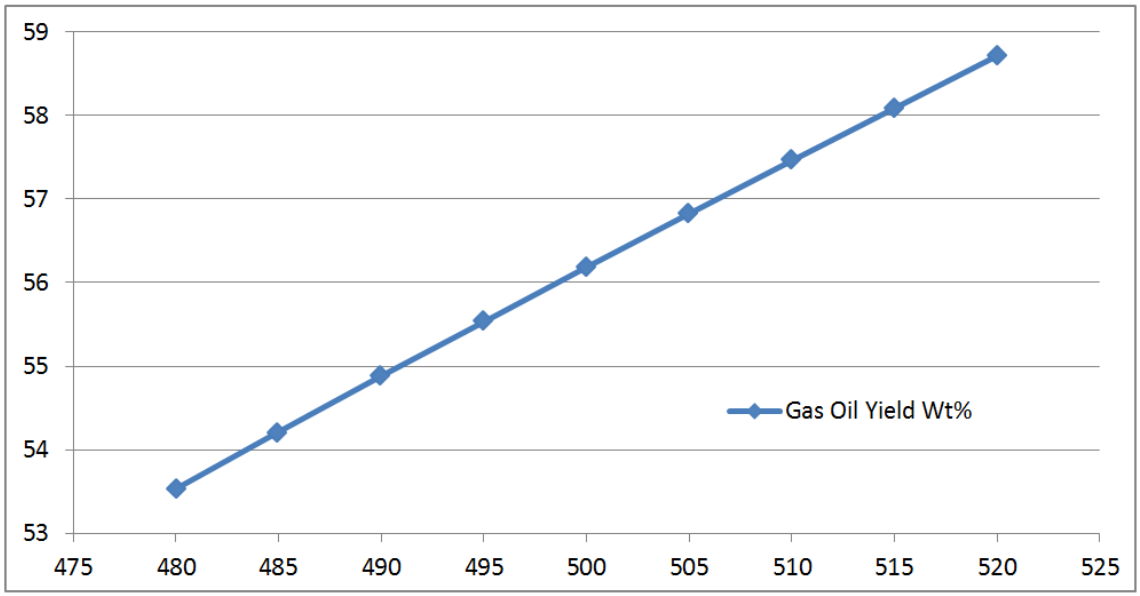


Figure 6: The effect of change in Heater outlet temperature °C to delayed coker gas oil yield produced WT%.

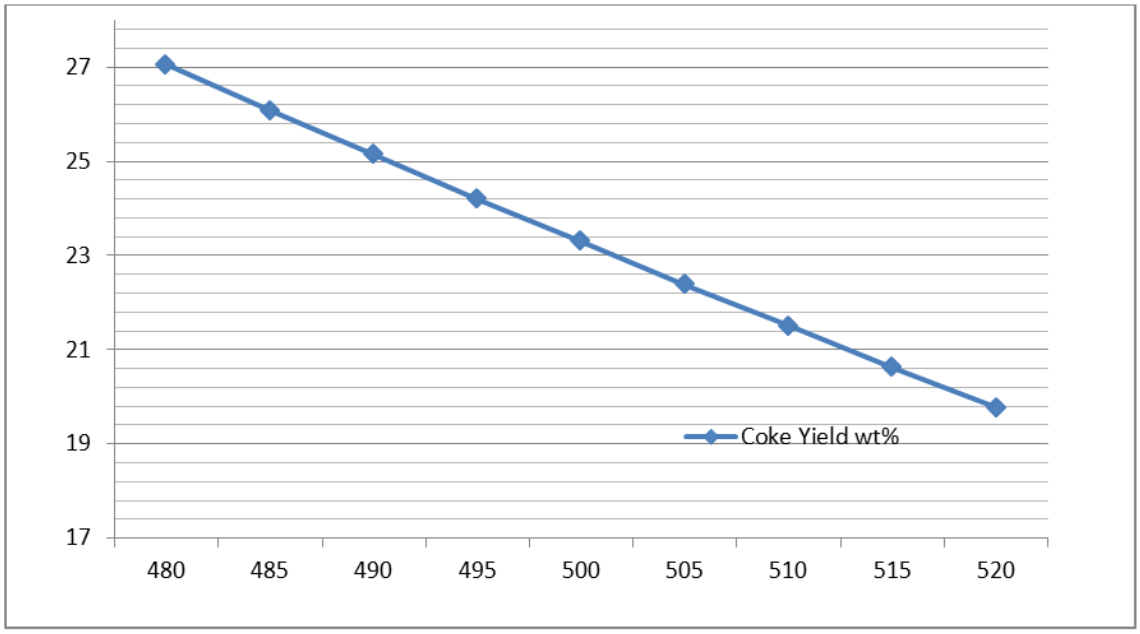


Figure 7: The effect of change in Heater outlet temperature °C to delayed coker coke yield produced wt%.

4.1.3. Pressure effect on thermal cracking:

Delayed coker unit is a low pressure thermal cracking unit, however the change in thermal cracking pressure will also effect in the product yields. The drum overhead pressure could be controlled by the fractionator overhead pressure control valve. By increasing in the drum pressure the cracking reactions gain more residence time inside the coke drum. Condensation and polymerization reactions are increased this will allow more coke formation and lower in the gas oil yield due to more condensation taking place inside the coke drum. Lowering the coke drum overhead pressure will allow vapors of product liquid yields to accumulate more inside the main fractionator this means more gas oil and also lower the volatile component matter (VCM) in coke yield preventing loss in hydrocarbon liquids. Change in drum pressure should be closely monitored as more lowering in drum pressure might cause the initiation of foam level appearance especially during the end of coke drum cycle as the foam formed based on the amount of VCM inside the coke drum and these amounts of VCM and liquid layer inside the coke drum are much more at the end of each cycle. Starting injection of antifoam and its consumption should be increased if the pressure is going more lowered during the end of drum cycle, so it's preferred to keep the drum in stable pressure during the cycle time as possible.

Studying the effect of change in coke drum pressure and its effect on the delayed coker product yields by Aspen HYSYS simulation while keeping all the other variables as constant see figures [8-9].

Conclusion of the results:

It's observed that while changing in the coke drum pressure will have a little effect on product yields compared to the change in other process variables see Table 4 and figures [8-9]. When the coke drum pressure increased by 50 KPa the coke yield WT% increased by an average 0.07%, the gas oil yield WT% decreased by an average 0.025 % and the gases WT% increased by an average 0.015%. It's recommended to keep the pressure as low as possible to maximize the gas oil yield and lower the coke yield produced from the delayed coker unit. Due to the minor effect of change in coke drum pressure on the delayed coker unit product yields its preferred to keep the pressure as constant to prevent any disturbance in coke drum pressure that causing foam over especially at the end of coke drum cycle.

Table 4: Coke drum pressure in KPa change versus delayed coker product yields WT%.

Coke Drum Pressure KPa	100	150	204.7	250	300	350	400	450
Gases + Naph Yield WT%	19.95	19.98	19.99	20	20.02	20.03	20.05	20.05
Gas Oil Yield WT%	54.93	54.9	54.88	54.86	54.83	54.82	54.79	54.78
Coke WT%	25.12	25.12	25.13	25.14	25.15	25.15	25.16	25.17

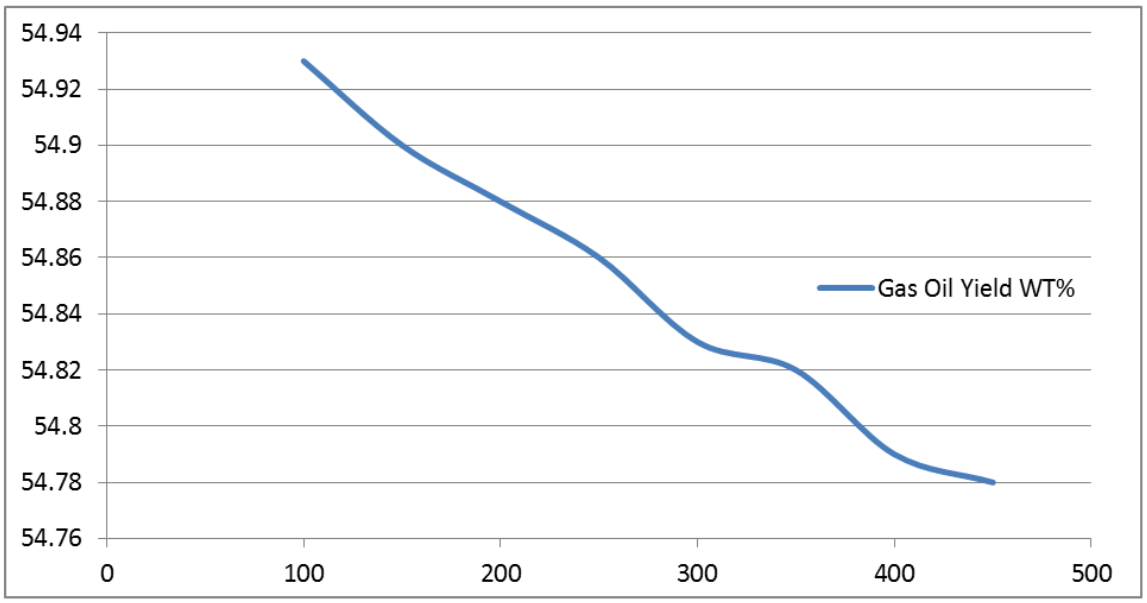


Figure 8: The effect of change in coke drum pressure KPa to delayed coker unit gas oil yield produced WT%.

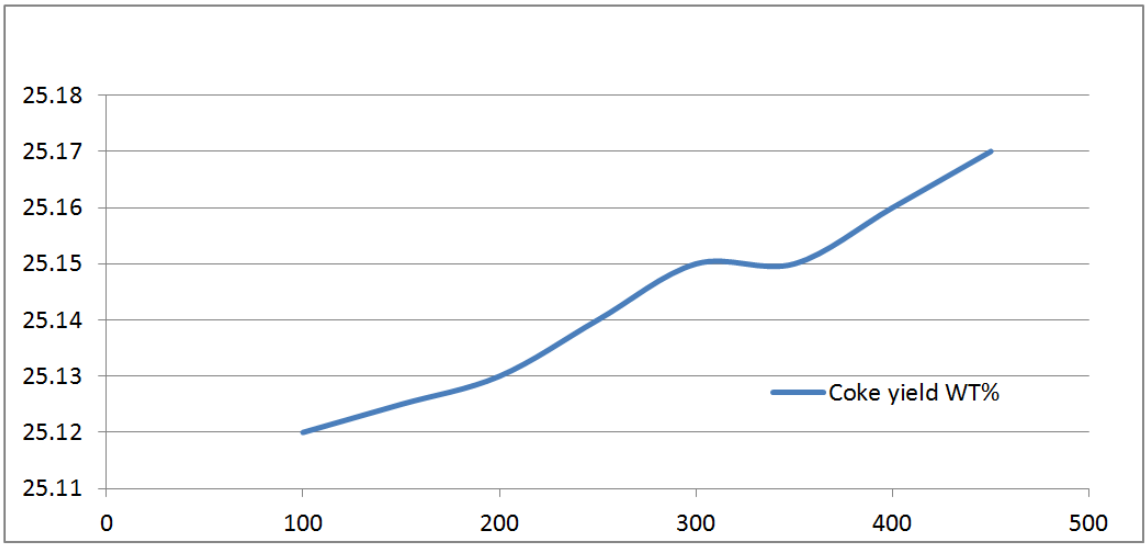
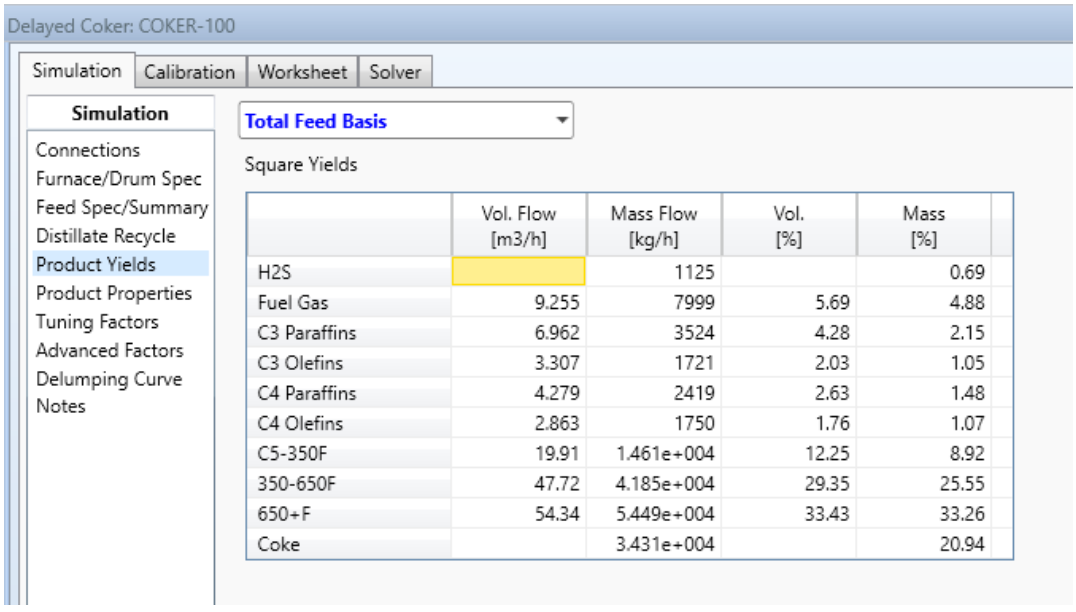


Figure 9: The effect of change in coke drum pressure KPa to delayed coker unit coke yield produced WT%.

5. Conclusion:

5.1. Optimization between process variables:

Now we will start to optimize the change in process variables that achieving the maximum gas oil yield WT% and minimum coke yield WT% from the delayed coker unit. About the recycle ratio effect as illustrated in Figure [4-5] we can find that the optimum recycle ratio is around 5% that is achieve high liquid yields while further more lower in recycle ratio will have lower effect in product yields. From Figures [6-7] it's indicated that the optimum heater outlet temperature is the maximum temperature 510°C that could be achieved while keeping safe operation for delayed coker heater, also further more increase will have a lower effect in gas oil yield WT%. As discussed before the change in coke drum pressure should be as low as possible to prevent any disturbance that may lead to foam over of coke drum to main fractionator, So we can find that the optimum coke drum pressure is 150 KPa that achieve more liquid yields and lower the coke yield WT% while keep safe coke drum operation. See Figure [10] the figure shows the most expected results from changing in process variables that achieve maximum gas oil yield WT% and lower the coke WT%.



	Vol. Flow [m3/h]	Mass Flow [kg/h]	Vol. [%]	Mass [%]
H2S		1125		0.69
Fuel Gas	9.255	7999	5.69	4.88
C3 Paraffins	6.962	3524	4.28	2.15
C3 Olefins	3.307	1721	2.03	1.05
C4 Paraffins	4.279	2419	2.63	1.48
C4 Olefins	2.863	1750	1.76	1.07
C5-350F	19.91	1.461e+004	12.25	8.92
350-650F	47.72	4.185e+004	29.35	25.55
650+F	54.34	5.449e+004	33.43	33.26
Coke		3.431e+004		20.94

Figure 10: The effect of change in delayed coker unit process variables that achieving maximum liquid yields.

5.2. Comparison between changing in process variables:

Notice the changing in product yields WT% while changing in delayed coker unit process variables see table 5 and figure [11].

Table 5: Comparison between process variables change.

Operating parameters	Design condition	Modified condition
Furnace Outlet Temp C°	490	510
Drum Press KPa	204.7	150
Recycle WT%	20%	5%
Feed m3/hr	156	156
Gases + Naph Yield WT %	19.99	20.25
Gas Oil Yield WT %	54.88	58.81
Coke WT%	25.13	20.94

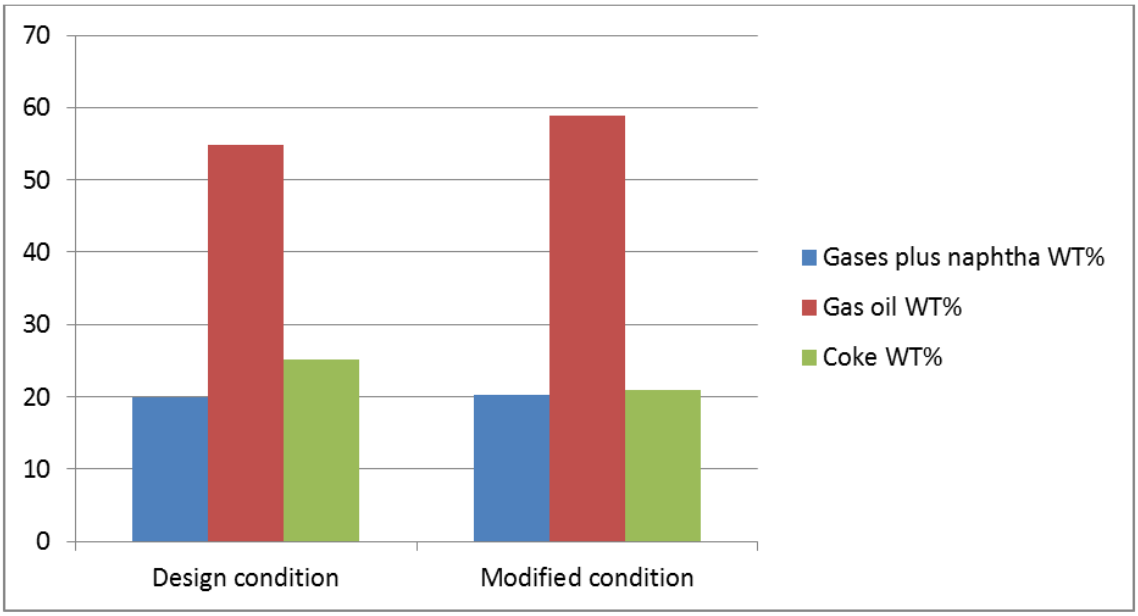


Figure 11: Comparison between design condition and modified condition.

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