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EVALUATION OF FCC UNIT PROCESS VARIABLES IMPACT ON YIELD DISTRIBUTION AND PRODUCT QUALITY

PART I. EVALUATION OF FCC UNIT VARIABLES IMPACT ON YIELD DISTRIBUTION

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Abstract

Catalytic cracking in fluidized bed is one of the most complicated and difficult processes in the sense of understanding. The reason for this is due to the fact, that change of one single parameter is related with changes of one or several parameters, which is consequence of utilities system balance. Statistic data processing from manufacturing FCC Unit can accede to more complete information regarding regularities, which relate yields and product quality to process parameters at acceptable parameters variations.

By means of regressive analysis of 49 operating days of FCC Unit type “side by side” G-43-107 (Grozni design) equations were obtained, which take in consideration the impact of process variables on conversion and yields. It is clear that conversion depends on catalyst activity, on the ratio catalyst/feed and on presence of naphtha precursor in feed. It is clear, also that naphtha production ca be increased by reduction of reactor temperature and increase of catalyst-feed ratio. It was found out, that for the investigated range of process parameters the octane number (by Research Method RON) of cracking gasoline is in linear relation with reactor temperature (1,0 RON/10°C). Equation validity is confirmed by trials in plant operation. It was established good conformity between foreseen and actual conversions and yields.

Obtained equations can be used for improvement of data basis, for evaluation of impact of unit design changes, catalyst replacement and use of different feed on plant operation at standard conditions.

Key words: FCC, heat balance, dependent variables, independent variables, correlations

1. Introduction

Flexibility of FCC process is very important instrument for improvement of refinery performance from economic point of view. This is due to the rising processing of heavier feeds, to the limited demand for boiler fuel and to the continuous increase of requirements for improvement fuels quality improvement. Nevertheless, continuous monitoring of the operating data is required to get a good understanding whether the unit is operating at most efficient way [1].

The FCC Unit is actually very sophisticated unit with many factors and sometimes it is difficult to handle the great variety of information that is generated. In many processes the investigation of factors impact on plant operation, yields and product quality can be done by change of one factor at constant other factors and relevant reflection of such change. In the case of FCC it is not possible to achieve such clear indication, because the change in one single factor leads to changes in one or more other factors. This is natural consequence of the “heat balance” of FCC Unit. “Heat balance” is related to stationary FCC process state, where heat requirements are satisfied by coke burning. This energy or “heat” is transferred from regenerator to the reactor by means of hot circulating catalyst.

For example, in case of temperature rise in FCC reactor the rate frequency of catalyst circulation and regenerator temperature also shall be increased. The yields and product quality are depending not only on reactor temperature, but also on increased catalyst circulation and regenerator temperature. Due to this reason, it is not possible clearly to identify isolated impact of reactor temperature only.

Because of this, the investigation of different parameters dependence in FCC unit in relation with their management, including optimization can be done by statistical methods of data processing. Results from the use of statistical methods for data processing can lead to better understanding of the impact, exercised by process parameters on yields and product quality. Even more, these methods can be used to improve data basis, to evaluate design modifications and possibilities for use of different feeds.

Examples of this are based on average daily data from FCC Unit “shoulder to shoulder type” G- 43-107 with capacity 180 t/hr and 160 tons of catalyst in the reactor- regenerator system.

The investigation was made on relatively long period of time – 31 months. The main purpose was to improve the reliability of statistic method for data processing and to compare plant operation at different operating conditions, with different feed distribution systems. For this period of time processing was made only of data, for which the condition of material balance is fulfilled 100 +/- 2 and situation of plant operation for 72 hours at equal operating conditions. This was made in purpose to guarantee process stationary.

The purpose of present investigation is to establish the impact of different process variables, feed and catalyst properties and design modifications on conversion and cracking product yields.

2. Results and discussions

2.1 Heat balance

The heat balance of FCC Unit is of great importance for evaluation of operation [2,3]. The most significant variables of heat balance of reactor and regenerator are as follows:

1. Quantity of processed feed
2. Properties of processed feed
3. Circulating catalyst properties (activity and selectivity by coke)
4. Temperature of combined feed
5. Temperature at discharge of lift reactor
6. Relation of combined feed
7. Regenerator temperature
8. Catalyst/ feed ratio
9. Coke production

Usually, the first six variables are called independent. This means, that their values are set and controlled by process operator. Remaining variables are dependent and this means that their change is result of change of independent variables.

Each change in independent variables leads to alteration in frequency rate of catalyst. This is due to the reason that hot catalyst circulation is the means, which automatically redistribute the energy between reactor and regenerator for reaching of new stationary state.

The conversion depends considerably on the catalyst-feed ratio and catalyst activity. The increases of catalyst-feed ratio or circulating catalyst activity lead to increase of catalytic active contact centers, which cause conversion increase. This can be expressed as follows:

$$\mathrm{CTO} = \mathrm{CCR}/\mathrm{FR} \tag{1}$$

where: CTO is catalyst-to-oil ratio, t/t, CCR catalyst circulation rate, t/h, FR – feed rate, t/h.

The catalyst circulation rate is determined by heat balance requirements and is calculated as follows:

$$\mathrm{CCR} = \text{Coke make}*100/\text{Delta Coke} \tag{2}$$

where: Coke make is quantity of produced coke, t/h, Delta Coke – difference between coke on spent catalyst and coke on regenerated catalyst.

As it can be seen from equations (1) and (2), the ratio catalyst-feed depends on the quantity of processed feed, quantity of produced coke and on the delta coke. The establishing of quantitative dependence between independent variables and produced coke and delta coke could provide possibility to foresee catalyst-feed ratio at different operating conditions.

In purpose to develop correlations, expressing coke production and delta coke as a function of independent variables were used average data from 49 twenty-four hours period of FCC unit. The fluctuations of these data are given in Table I.

Table I Variation range of independent and dependent variables in FCC unit

Variable parameters	Variation range
Hydrocarbon content and feedstock properties in fresh feedstock, %wt	
Alkanes + cyclo alkanes	53-58
Light arenes	17-24
Medium arenes	5-10
Heavy arenes	12-18
Resins	0.9-1.2
Gasoline precursors	77-81
Sulphur content	0.3-o.5
Total nitrogen content	0.01-0.015
Distillation, ASTM D-1160, °C	
T_{10}	379-399
T_{50}	429-452
T_{90}	487-508
Properties of equilibrium catalyst	
MAT activity by Davison	65-73
Surface area- BET m^2/g	74-110
Ni + V content, ppm	628-1118
Rare earth content, wt%	1.28-1.78
Apparent bulk density, g/cm^3	0.98-1.00
Coke on regenerated catalyst, wt%	0.05-0.20
Process parameters	
Quantity of processed fresh feed stock, t/h	100-170
Quantity of processed combined feed stock, t/h	129-184
Discharge temperature of lift reactor, °C	505-535
Feedstock temperature, °C	332-373
Relation of combined feed, t/t	1.0-1.30
Steam purging for carried hydrocarbons in stripping section of reactor, kg/h	1650-2050
Regenerator temperature, °C	616-654
Catalyst - feed stock ratio, t/t	6.2-10.3
Combined feed ratio between	1- 1.30

Table I shows that the quantity of fresh feedstock is varying in very close range and can be accepted as constant. Nevertheless, quality of combined feed stock (fresh feed + slurry recycle) is not constant, since ratio of combined feed (fresh feed + recycle/fresh feed) varies depending on heat balance requirements. It is known that slurry recycle consist mainly of poly-aromatic structures, which lead to production of coke and aggravate combined feed stock quality [4]. As criterion for combined feed quality it is possible to use its content of gasoline precursors. In purpose to make quantitative determination of precursor it was used multiple linear regressions and equation was established for 28 feed stocks with different recycle content. These feed stocks contain between 64 % and 81 % gasoline precursors (content of gasoline precursors in combined feed is determined according test method, described in [5].

The correlation is shown below:

$$GPCF = 1.068*GPFF - 45.82*CFR + 40.44 \qquad (3)$$

correlation coefficient = 0.998, standard error = 0.3,
where,
GPCF is gasoline precursor content in combined feedstock, wt%
GPFF is gasoline precursor content in fresh feed, wt%
CFR is ratio of combined feed stock, t/t

Equation (3) can be used for establishing of feed stock quality on coke production, delta coke and later on the conversion.

During the period of investigation there was circulation of equilibrium catalyst of octane-barrel type. The catalyst activity is within the range of 65 – 73 % (MAT conversion by Davison) and this activity has been changed due to change in fresh catalyst activity.

Coke production depends mainly on the processed feedstock quantity, discharge temperature of lift reactor and combined feed temperature. By means of processing of average data of twenty-four hour period of plant operation and regression analysis equation (10) for coke production was established. Consistency between calculated data by equation (4) against experimental results is shown in Figure 1.

$$\text{Coke} = 0.0207*\text{CFR} + 0.0117*(\text{TRX}-\text{CFT})-0.02 \qquad (4)$$

coefficient of multiple correlation = 0.985, Fisher criterion = 798, standard error = 0.08,
where: CFR is combined feed rate, t/h , TRX is reactor temperature, ^{o}C, CFT is combined feedstock temperature, ^{o}C

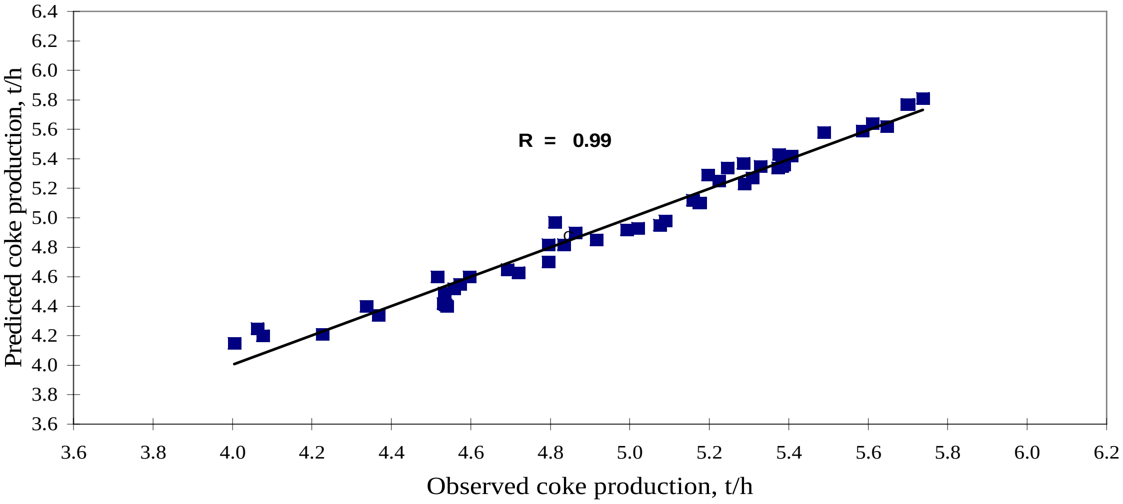

Figure 1 Prediction of coke production

The most significant factor in the heat balance is not coke production itself, but the coke, deposited on the catalyst. In other words this is delta coke. Delta coke depends on feed stock quality, unit design, stripping conditions and catalyst properties.

On the basis of these data it was found out that delta coke correlates with difference of regenerator temperature and discharge temperature of lift reactor. This dependence is shown on Figure 2. Anyway, regenerator temperature is dependent variable and the data were processed in purpose to get correlation between delta coke and independent variable parameters. As a result, the following equation was established:

$$\text{Delta coke} = -0.004*\text{delta T}-0.00006*\text{SSR}+0.0018*\text{CFR}+0.003*\text{CSA}-0.006*\text{GPCF}+0.6 \qquad (5)$$

coefficient of multiple correlation = 0.93, Fisher criterion = 51, standard error = 0.02
where: Delta T is difference in temperature between diluted and dense phase in regenerator,^{o}C,
SSR is stripping steam rate, kg/h, CSA is catalyst surface area, m^{2}/g.

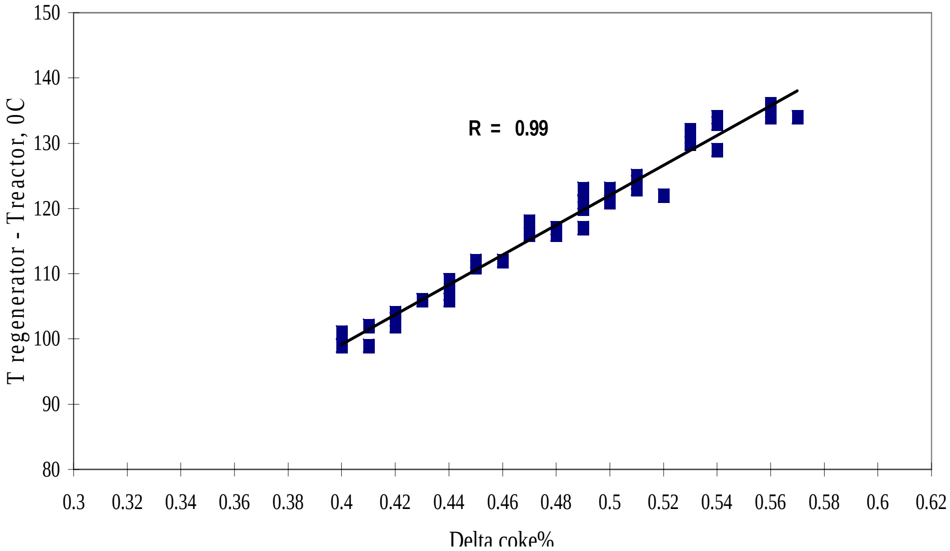

Figure 2 Difference between dense bed regenerator temperature and riser outlet temperature vs. delta coke

From equation (5) it can be seen clearly that delta coke goes down with increase of temperature difference between diluted and dense phase in regenerator (reduction of oxidation degree of CO), with increase of catalyst stripping steam and increase of gasoline precursors in the feed. The increase of processed feed stock quantity and specific area (activity) of equilibrium catalyst lead to increase of delta coke.

From equations for coke production and delta coke it is possible to reach conclusion that catalyst-feed stock ratio can be increased by increase of discharge temperature of lift reactor, reduction of combined feed temperature and increase of steam for purging of carried hydrocarbons in reactors stripping section. This can be reduced by increase of processed feed quantity, by reduction of gasoline precursors in feed and by increase of specific area of equilibrium catalyst.

2.2 Impact of feedstock properties, catalyst properties and operating conditions on conversion and yields in FCC Unit

In purpose to establish quantitative dependence between conversion and product yields from feedstock quality, catalyst-feed ratio, equilibrium catalyst activity and discharge temperature of lift reactor we have processed average data for twenty-four hours period by regression analysis. As a result the following correlations were established:

Equation for conversion and product yields	Coefficient of multiple correlation	Fisher criteria	Standard error
Conversion = 1.2.CTO+1.4*GPCF+0.4* MAT+0.04*TRX-89	R=0.989	F=440	0.87 (6)
Gasoline yield= - 0.28*CTO-0.262*TRX=0.853*conversion+126.6	R=0.963	F=171	0.84 (7)
Yield of butane-butylene cut = 0.345*CTO-0.0868*TRX + 0.0467*conversion – 41,51	R=0.944	F=86	0.45 (8)
Yield of propane/propylene cut=0.0392*TRX=0.0969*Conversion–21.89	R=0.899	F= 86	0.40 (9)
Yield of LCO+HCO = 0.0535*TRX – 1.157*Conversion + 79.97	R=0.926	F=123	1.07 (10)

MAT is MAT activity of equilibrium catalyst.

Dry gas yield is expressed as follows:

Dry gas yield = conversion- gasoline yield - butane/butylene yield - Propane/propylene Yield – Coke yield

Slurry yield is defined as follows:

Slurry yield= 100 – Σ products yield

The equations show that conversion depends on catalyst-feed ratio, MAT activity of equilibrium catalyst and on the content of gasoline precursors in the feed. Therefore, to increase conversion at constant feedstock quality it is necessary to search for ways to increase catalyst/feed ratio and equilibrium catalyst activity in the scope of unit capabilities.

Reduction of gasoline precursors in feed leads to conversion drop. As it was emphasized before increase of temperature at lift reactor discharge is one of the ways for increase of catalyst-feed ratio. Nevertheless, from equation (7) it can be seen that increase of reactor temperature has negative effect on gasoline yield. This is due to the fact that higher reactor temperature leads to lower selectivity toward gasoline production and higher selectivity for propane-propylene fractions, butane/butylenes fractions and dry gas [6]. Therefore, if the main objective is maximum gasoline production it is recommended to operate at low discharge temperatures of lift reactor and high catalyst/feed ratios.

Reliability of established correlations for conversion and products yields was subject of confirmation at actual operating conditions. Table II shows operating conditions, feed and catalyst quality, actually observed in the plant as well as those, foreseen by correlations. These data show that it is possible to achieve acceptable foreseeing of yields and cracking products quality on the basis of information for feed properties, catalyst properties and actual operating conditions.

Correlations, established by present investigations can be used as internal standard for comparison of operating data. One significant deviation from these data could mean that: 1) the data are wrong and 2) new phenomena was found. In this way it is possible to evaluate effect of eventual changes in plant design, catalyst replacement by another type and etc.

Table II Prediction of FCC yields from feedstock quality and FCC unit operating conditions

Parameters	Values	
Variable parameters	Variation range	
Hydrocarbon content and feedstock properties in fresh feedstock, %wt		
Alkanes + cyclo alkanes	56,2	
Light arenes	23,4	
Medium arenes	8,7	
Heavy arenes	11,1	
Resins	1,1	
Gasoline precursors, wt %	80,5	
Sulphur content, wt%	0,5	
Total nitrogen content, wt%	0,012	
Distillation, ASTM D-1160, ^{o}C		
T_{10}	390	
T_{50}	442	
T_{90}	499	
Properties of equilibrium catalyst		
MAT activity by Davison	70	
Surface area- BET m^2/g	90	
Ni + V content, ppm	800	
Rare earth content, wt%	1,5	
Apparent bulk density, g/cm^3	0,91	
Pore volume, cm^3/g	0,32	
Coke on regenerated catalyst, wt%	0,17	
FCC unit operation conditions		
Fresh feed rate, t/h	132	
Combined feed rate, t/h	132	
Riser outlet temperature, ^{0}C	534	
Feed temperature, ^{0}C	339	
Combined feed ratio, t/t	1,0	
Stripping steam rate, kg/h	2362	
Regenerator dense bed temperature, ^{0}C	646	
Catalyst-to-oil ratio, wt./wt.	Observed	Predicted
Yields,wt.%		
Dry gas	4,6	5,5
C_3	7,1	6,9
C_4	12,9	11,4
Gasoline	53,4	54,2
LCO+HCO	13,5	13,2
Slurry	4,6	4,4
Coke	4,0	3,8
Conversion	82,0	81,8

3. Conclusions

Correlations were established by statistic data processing for FCC unit. These correlations express the impact on process variables on the conversion and cracking products yields. It was found out that conversion depends on catalyst-feed ratio, MAT activity of equilibrium catalyst and gasoline precursors content in feed. Increase of lift reactor discharge temperature leads to increase of catalyst-feed ratio, but at the same time to decrease of selectivity toward production of gasoline and increase of selectivity toward production of butane/butylenes fractions, propane/propylene fractions and dry gas. If the main objective of plant operator is achievement of maximum gasoline production it is recommended to operate at low temperatures at lift reactor discharge and high catalyst-feed ratio. The correlation reliability has been verified in actual operating conditions and the conclusion is that there is good consistency between predicted and observed conversions and products yields. The correlations can be very helpful on improvement of data basis, as well as for evaluation of changes in design of the unit, catalyst change with different type, use of new feed stocks and etc.

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