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SCIENTIFIC PAPER

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THE REDUCTION OF FCCU AFTERBURNING THROUGH PROCESS OPTIMIZATION AND REGENERATOR REVAMPING

Article Highlights

- A methodology applied in FCC unit to investigate the afterburning causes
- Technical solutions to reduce the afterburning
- Symmetrical layout of the cyclones reduces the afterburning

Abstract

Operating the fluid catalytic cracking unit (FCCU) in afterburning conditions can increase the regenerator temperatures above the metallurgical design leading to mechanical failures of the cyclones and plenum chamber. This paper presents the methodology applied in a commercial FCCU to investigate the afterburning causes and the technical solutions that can be implemented to reduce the afterburning. Thus, by evaluating the regenerator temperature profile, regenerator as-build design, and the internals mechanical status, it was concluded that the main cause of afterburning was the non-uniform distribution and mixing of air and catalyst. The industrial results showed that optimizing the catalyst bed level, stripping steam, reaction temperature, and equilibrium catalyst (e-cat) activity reduced the afterburning by 39%. Other process parameters such as feed preheat temperature, slurry recycling, and excess oxygen did not significantly influence afterburning because of air and catalyst maldistribution. Revamping the regenerator to assure a symmetrical layout of cyclones reduced the afterburning by 86%, increased the fines retention in FCCU inventory, and provided a better regeneration of the spent e-cat. The reduction of operating temperatures at around 701°C removed the risk of catalyst thermal deactivation, and therefore the e-cat activity was increased by 10.2 wt.%.

Keywords: FCCU, regenerator, afterburning, e-cat, cyclones, revamping.

Fluid Catalytic Cracking Unit (FCCU) is one of the most important catalytic processes in the refinery that converts heavy hydrocarbon fractions into more valuable products. The FCCU design consists of a reactor and a regenerator interconnected to transfer the spent and regenerated catalyst between this equipment. In the reactor (riser), the feedstock (blends of gas oils and residue) is catalytically cracked at temperatures of 510-540 °C, to the following products: dry gas, propane, propylene, C4, gasoline, light cycle oil (LCO, hydrotreated downstream to produce diesel), heavy cycle oil (HCO, directed for processing to delayed coker unit) and coke. After stripping residual hydrocarbons with steam, the spent catalyst is directed to the regenerator, where the coke is burned off with hot air at 680-710 °C. The regenerated catalyst is then circulated to the riser and contacted with the pre-heated feedstock [1-3]. Taking into consideration the key role that FCCU has is mandatory for the refinery engineers to assure a successful operation of the reaction-regenerator section. One of the issues affecting the reliability and efficiency of the industrial unit is the regenerator afterburning.

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The FCCU afterburning is caused by incomplete burning of coke carbon in the regenerator dense phase. Consequently, the combustion of CO to CO_2 can occur in the dilute or gas phase, leading to increased temperatures in the corresponding regenerator area. This situation happens because the heat released from the CO combustion is about three times higher than the heat released from the carbon-to-CO combustion. This combustion must occur in the dense catalyst bed. Without the catalyst bed to absorb this heat of combustion, the temperature increases rapidly in the dilute phase and flue gas system [4,5].

Severe afterburning can damage the regenerator internals (as cyclones and plenum chamber) and contribute to catalyst thermal deactivation [3,5-7]. Many FCC units operate with a limited degree of afterburning, as long as the dilute and gas-phase temperatures do not exceed the metallurgical limit of the regenerator internals [5,7]. Of course, when the regenerator temperatures reach the maximum design limits of the equipment, it is mandatory to take the necessary measures for a safe operation. The level of the afterburning phenomenon depends on the unit's operating conditions and the regenerator design, which influences the effectiveness of the contact between the combustion air and the spent catalyst.

Operating solutions for afterburning control

The operating options recommended in the technical literature for reducing the afterburning are the following:

Usage of Pt-CO promoter. Pt-CO promoter is added to accelerate the CO combustion in the regenerator's dense phase and minimize the higher temperature excursions because of afterburning in the dilute phase and across cyclones [1-9].

Increasing the dense bed temperatures to speed up the rate of CO burning in the bed. This can be achieved by maximizing feed preheat temperature, increasing the catalyst activity, increasing the dense bed level and regenerator pressure [4,5,7,10].

Optimizing the catalyst stripping steam rate. If the stripper operation is not optimized, un-stripped hydrocarbon can enter the regenerator and burn in the dilute phase generating high temperatures/afterburning [4,5].

Optimizing the flue gas excess oxygen to assure enough oxygen for complete combustion of coke at CO2 [2,4,11].

Regenerator hardware that influences the afterburning

The regenerator design and mechanical integrity of the internals are critical in achieving low afterburning [4,5,7,10,12]:

The air distribution. It is essential to assure a uniform distribution of air through the regenerator. Any failure of the air grid can create a poor area air distribution and consequently can increase afterburning and CRC (carbon on the regenerated catalyst).

The spent catalyst distribution. The spent catalyst should be distributed as evenly as possible across the catalyst bed.

Regenerator design. The most well-known FCC unit is the bubbling bed regenerator, and in this design, the catalyst enters the top of the bed and leaves at the bottom in countercurrent flow to air. Usually, this type of FCCU is associated with different degrees of afterburning, but this issue was resolved with the introduction of Pt-CO promoters in the 1970s. Other designs, such as the Exxon Flexicracker, introduce the spent catalyst at the bottom of the bed with a catalyst overflow well in concurrent flow [5].

UOP introduces the high-efficiency combustor regenerator to minimize the afterburning, which is designed to burn the coke to CO_2 without CO promoter completely and with low excess oxygen [13]. Another advantage of this design is that the NO_x emissions are reduced. Improving spent catalyst distribution and adding horizontal baffles in the dense bed of the regenerator are effective measures that can be implemented to minimize the afterburning [14-16]. With the rapid development of computer technologies, computational fluid dynamics (CFD) simulation has gradually become an important tool available to the refineries to evaluate the regenerator's catalyst and air distribution [14,15,17].

This study was conducted over 1000 days to assure the time needed for monitoring and evaluating a commercial FCC Unit during regular operation. The FCCU has been experiencing the afterburning since changing the operation mode from partial burn to entire burn operation. To control the afterburning, Pt-CO promoter was dosed, but even in this situation, the afterburning remains at high rates up to 113 °C. The high-temperature operation led to regenerator cyclones and plenum chamber failure and consequently to an emergency shutdown of the unit. Also, it was considered that operating the regenerator at high temperatures affected the e-cat activity because of thermal deactivation. Therefore, the refinery needs to analyze and implement the necessary measures to reduce the afterburning and improve the FCCU operation.

MATERIALS AND METHODS

Materials

The FCCU process a heavy, non-hydrotreated feedstock (density = 914 - 945 kg/m^3, KUOP = 11.5 - 11.8) with high contaminant content (S = 1.0 - 2.2 wt.%, N = 1400 - 1900 wt. ppm). The FCCU feedstock is a mixture of around 90 wt.% vacuum gas oil (VGO) and 10 wt.% heavy coker gas oil (HCGO).

FCC Unit

The FCC Unit is a UOP side-by-side configuration with a bubbling bed regenerator and was first commissioned in 1980. The design capacity of the FCCU is 1,000,000 t/year. Initially, the FCCU was designed to operate in the partial burn, but later, the operation mode was converted to complete burn based on an engineering revamp project. The revamping involved implementing a new air grid and a new spent catalyst distributor.

FCCU catalyst and additives

During the study, the same type of commercial FCC fresh catalyst was dosed with Pt-CO promoter to assure 1.6 wt. ppm platinum on equilibrium catalyst (e-cat). The FCCU inventory is 200 tons e-cat.

FCCU afterburning

The afterburning was evaluated based on the temperature differences between the dense, dilute, and gas phases. The regenerator temperatures were measured using 12 Emerson thermocouples type K (four thermocouples were designated to register each regeneration phase's temperature: dense bed, dilute phase, and gas phase).

RESULTS AND DISCUSSION

Afterburning evaluation

During the FCCU operation, there were recorded high-temperature differences up to 97 °C between dense and dilute phases and 113 °C between dense phase and flue gas temperature (Figure 1a).

Different temperatures were seen between the regenerator's phases and on the same elevation level (the same phase) but other areas/quadrants. Therefore, by plotting the temperature profile on each phase, it was noticed that the temperatures registered by the four thermocouples were similar only in the dense phase (Figure 1b). In the dense and gas phases, the temperatures were higher in the regenerator area where the spent catalyst inlet and regenerated catalyst outlet lines are located (Figures 1b and c).

A better view of the temperature profile was achieved by correlating each temperature value with the location of the thermocouples on the regenerator (lateral and top view - as presented in Figure 2). The regenerator temperature profile was plotted based on the average values registered on the 143d operation day since, in this period, the FCCU was operated in severe afterburning conditions that eventually led to the unit emergency shut-down.

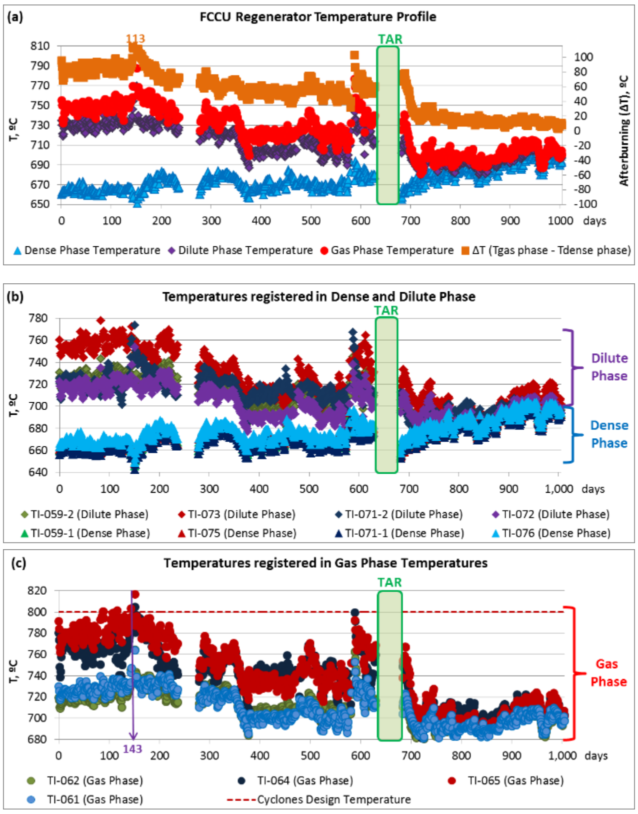


Figure 1. FCCU regenerator temperature profile: a. Average temperatures in dense, dilute, and gas phases; b. Temperatures registered by thermocouples in dense and dilute phases; c. Temperatures registered by thermocouples in the gas phase.

The data showed a 145 °C gap between the temperature registered in the dense phase by TI-075 (658 °C) and the flue gas at the 2nd stage cyclone outlet by TI-065 (803 °C). The 145 °C temperature difference demonstrated that the coke is not entirely burned. CO is formed in the dense bed that eventually is burned at CO_2 in the dilute and gas phases generating higher temperatures.

Afterburning effects

Regenerator internals metallurgy failure

Excessive afterburning is reported to cause significant mechanical damage to the regenerator internals [7,18]. The regenerator cyclones have a typical 15-30 years life depending on the erosion and mechanical fatigue. The base metal of cyclones will deteriorate with time leading to graphitization. Once this happens, the metal cannot be welded upon and repaired during a normal unit turnaround (TAR) [5]. High temperatures along with erosion and longtime

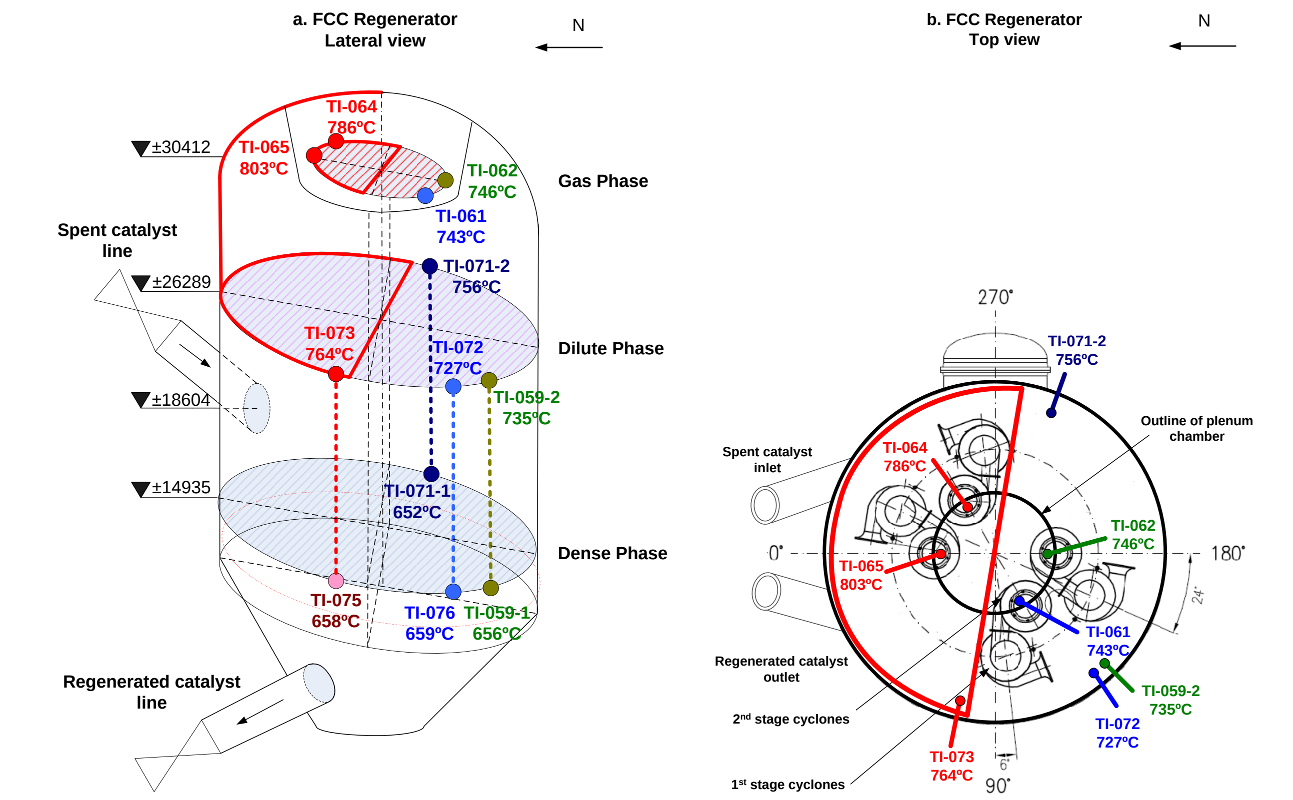


Figure 2. Temperatures registered by the regenerator's thermocouples on operation day no. 143: a. Regenerator lateral view - temperatures in dense, dilute, and gas phases; b. Regenerator top view - temperatures in dilute and gas phase.

operation for 21 years deteriorated the ASTM 304 type metallurgy of the internals and led to the following failures:

Cracks and holes in the 2nd stage cyclones: the unit experienced dipleg detachment from the cone of the cyclone at their welds which eventually led to unit emergency shut-down.

Cyclones and plenum chamber bodies' distortion and deformation due to stresses imposed by thermal gradients exacerbated by the afterburning.

The main reason for equipment failure is that the temperatures at the outlet of the 2nd stage cyclone (located near the spent catalyst inlet and regenerated catalyst outlet) exceeded the metallurgical design temperature, which is 800 °C for cyclones and plenum chamber. The data showed that during the 87-151 operation days, the gas phase temperatures (daily averages) were around 800 °C and increased to 817 °C on the 151st day (Figure 1 c). Also, it was seen that the highest operating temperatures were registered by the thermocouples TI-075, TI-073, and TI-065 that are located on the regenerator side near the spent catalyst inlet and regenerated catalyst outlet (Figure 2).

Due to the repeated mechanical failures of regenerator cyclones, the FCCU experienced six emergency shut-downs during 600 days of the operation (until the regenerator revamping).

E-cat thermal deactivation

The high catalyst deactivation rates in the units with a high afterburning were attributed to higher dilute phase temperatures [5,8,11]. Operating the regenerator up to 800 °C during the first 180 days of industrial evaluation led to the reduction of the e-cat activity at around 61.7 wt.% with a minimum registered activity of 56.6 wt.% (Figure 3). Once the afterburning was eliminated, and the regenerator was operated at a maximum of 725 °C (after TAR), the e-cat activity increased to 71.9 wt.% (+10.2 wt.%) even if the fresh catalyst dosage rate was maintained at a minimum of 0.52 kg/ton feed. The operating temperatures of the regenerator and the fresh catalyst addition rate influenced the e-cat deactivation rate. The fresh catalyst addition rate was adapted to balance the e-cat losses caused by the cyclone failure and maintain the catalyst level in the regenerator. Discontinuous fresh catalyst dosages between 0.52 and 14.33 kg fresh catalyst/ton feed are also the reason for achieving different e-cat activities in the range of 56.5-76 wt.%. However, high temperatures operation (up to ~800 °C) led to rapid deactivation of the e-cat (Figure 3 - before TAR).

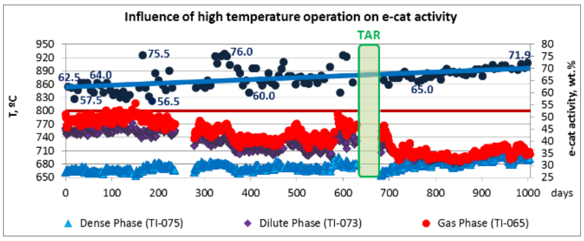


Figure 3. Influence of high-temperature operation on e-cat activity.

Carbon on regenerated catalyst

Carbon on the regenerated catalyst (CRC) registered during afterburning was between 0.1-0.38 wt.% (an average of 0.18 wt.%), higher than expected for a complete burn operation. After removing the afterburning, the CRC was reduced at 0.03 wt.%.

The inefficient coke burning due to non-uniform mixing of air and spent catalyst led to an increased CRC (Figure 4). The deposition of carbon on the catalyst temporarily blocks some of the catalytic sites, this being another factor that negatively influenced the catalyst activity.

Increasing of CRC in FCC units that are operating in afterburning conditions was also reported in other studies: one refinery reported an increase of afterburning and consequently of CRC from 0.05-0.10 wt.% to 0.15-0.2 wt.% because of the spent catalyst distributor failure and in another refinery case it was reported an increase in CRC up to 0.19 wt.% caused by air distributor failure [5].

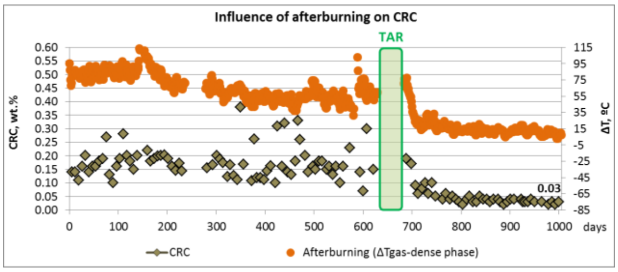


Figure 4. Increasing of CRC due to non-uniform mixing of air and catalyst.

Massive e-cat fines losses

Due to poor cyclone performances, all 0-40 µ e-cat fines from the regenerator were lost, as reported by others [6]. Loss of fines led to average particle size (APS) increase up to 110 µ. The coarse catalyst with no fines causes the formation of larger air bubbles and poor contact between air and catalyst. Low air and catalyst contact affected the complete burning of the coke in the catalyst bed and therefore increased the afterburning.

Replacing the old ineffective cyclones with new ones, it was seen better retention of e-cat in the FCCU regenerator that led to an increase of 0-40 µ fines up to around 11.7 wt.% and consequently to a decrease of the APS from 110 µ to 85 µ. Better e-cat quality improved the FCCU operation and reduced the afterburning.

Afterburning Root Cause Analysis

Cyclones condition

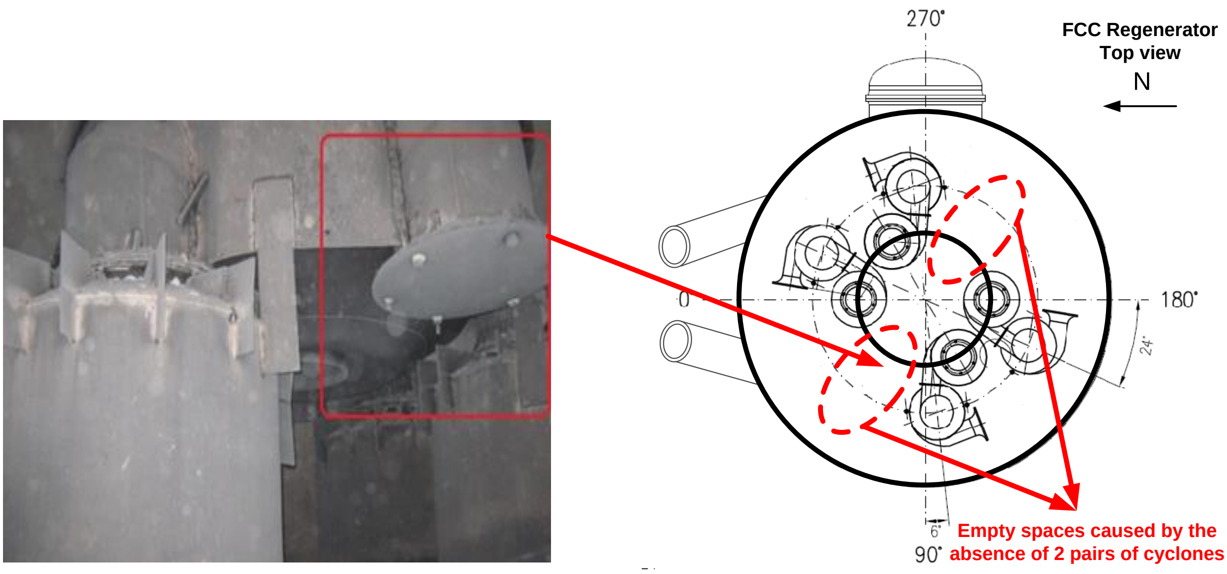
Long time operation and high temperatures affected the integrity and, therefore, the performances of the cyclones. As a result, the cyclones have lost their capacity to retain the 0-40 µ e-cat fines in the regenerator. Lack of fines, low fluidization characteristics, and low e-cat activity are factors that increased the afterburning and enhanced the thermal deactivation of the e-cat. Another factor that influenced the unit operation was the existing design of the regenerator: The original design was for six pairs of cyclones, but only four sets of cyclones were installed during the construction phase of the FCC Unit. Two of the six plenum cyclones support nozzles were blanked and seal welded (Figure 5). It was concluded by analyzing the cyclones layout that the space created by the absence of the two pairs of cyclones affected the distribution of gas flow in the dilute phase and led to higher temperatures in the cyclones located on the spent cat inlet/regenerated cat outlet side. Based on the observations on the status and positioning of cyclones, it was proposed to replace the old cyclones and assure a symmetrical layout with a 90º orientation. This solution required a new top head and a new plenum chamber to suspend new cyclones.

Air Grid Evaluation

High afterburning/temperatures recorded in the area with the inlet spent catalyst suggested insufficient air to burn the carbon completely in a dense bed. Since other FCC units experienced high afterburning because of the air distributor failure [4,5], evaluating the air grid status was considered. Upon inspection, it was concluded the following:

There was no erosion of the jets, and the refractory lining was in good condition and intact. The air grid jet pattern assured an even air distribution to all quadrants of the regenerator.

To address the non-uniform carbon distribution in the regenerator, it was proposed to revise the jets plugging pattern of the air grid to direct more air to the spent catalyst inlet area (Quadrant I) and less air to the other regions of the regenerator. The proposed air grid plugging uses the same total number of plugged jets as the current air grid layout



Blanked plenum cyclone support nozzle **Existing cylones layout**

Figure 5. Non-symmetrical regenerator cyclones layout.

to ensure no impact on the air blower performances. It uses all open jets in the incoming spent catalyst quadrant, 29% of the total volume of air discharged by the air blower. However, since operating the regenerator with a 4 vol.% excess oxygen in flue gas did not improve the afterburning, it was considered that the CO breakthrough in the spent cat inlet area is also caused by other factors besides the air grid design. Therefore, the refinery postpones the revision of the air grid jets plugging pattern until the results achieved by cyclones replacement are evaluated.

Spent Catalyst Distribution

As presented, the refinery implemented a new spent catalyst distributor “ski jump” type during the FCCU revamping for a complete burn operation. The purpose of the distributor is to divert the spent catalyst away from the regenerator wall toward the center of the regenerator. Since the most severe afterburning was recorded in the cyclone pairs located on spent cat inlet/regenerated cat outlet there were evaluated the following hypothesis:

The catalyst is short-circuiting from the spent catalyst inlet to the regenerated cat outlet. Coke burning is higher on this side, leading to increased CO breakthrough and higher temperatures.

The spent catalyst outlet distributes the spent catalyst above the bed and close to the wall. This leads to the un-stripped hydrocarbon burning in the dilute phase and the slight movement of the catalyst to the side opposite the inlet.

Considering these assumptions, the idea of removing the catalyst distributor and extending the spent cat pipe to submerge it into the catalyst bed was analyzed. This design will help discharge the catalyst further away from the wall and vessel entry point. Also, this modification would enable the un-stripped hydrocarbon to burn into the dense bed and not in the dilute phase.

Because the refinery did not have sufficient industrial evidence that replacing the spent catalyst distributor with a submerged pipe into the bed dense will reduce the afterburning, it was decided to postpone the implementation of this project until it was evaluated effect achieved by replacing the cyclones.

Influence of process parameters on afterburning reduction

Implementing a new refinery investment project requires time, depending on the size, cost, and importance. In our refinery case, the project for “Replacement of the regenerator cyclones and plenum chamber” took almost two years in which have been performed the following phases: preparation of the feasibility study, headquarter approval, organization of the tender for selecting the suppliers and contractor, equipment procurement, construction execution and so on. Since the cyclones replacement is a long process, the refinery needed to analyze the operating options recommended in the technical literature to reduce the afterburning. Unfortunately, it was seen that the results achieved are affected by numerous technological constraints. Therefore, the refinery target was to select those FCC process parameters that can be optimized to control the afterburning.

Usage of Pt-CO promoter. The FCC fresh catalyst was promoted with a commercial Pt-CO promoter (equivalent to 1.6 ppm Pt on e-cat). During the previous FCCU operation, it was noticed that higher Pt concentration did not improve the afterburning. Therefore, it was concluded that the afterburning was caused by the poor catalyst and air distribution as reported by others [6]. The FCCU optimization was performed at constant Pt-CO promoter dosage to not interfere with the results achieved by process parameters modification.

Maximize the feed preheat temperature (FPHT) to speed up the rate of CO burning in the catalyst bed. This can be achieved by modifying the following parameters:

Maximize the feed preheat temperature (FPHT). Analyzing the data collected, it seems that modifying the feed temperature between 170 °C to 280 °C had a different effect than the one presented in technical literature. Higher FPHT to riser increased the dilute/gas phase temperatures, and lower FPHT decreased the temperatures on top of the regenerator. This behavior is because an increase of the FPHT will reduce the cat/oil ratio, and consequently, the regenerator temperature will rise. Because of the air and catalyst non-uniform distribution, the temperatures will increase all over the regenerator (in all the 3 phases) and not only in the catalyst bed (Figure 6a).

Increasing slurry recycling to increase the coke production. The FCCU was designed for recycling the slurry to the riser. Increasing slurry recycling will increase coke production since slurry is a heavy feed with high aromatic content. Consequently, burning a higher quantity of coke in the regenerator will increase the dense bed temperature and reduce the afterburning [4,5].

During the study, slurry recycling did not have the results expected on the regenerator temperatures profile. On the contrary, in the first part of the evaluation (days no. 1 to 150), it was seen that the gas/dilute phase temperatures were increased when the slurry flow rate was increased. Therefore, in the period where the slurry recycle flow rate was also decreased (days no. 280–400), the gas/dilute temperatures decreased. For the rest of the evaluation (days no. 400-600), the slurry recycle flowrate fluctuation cannot be correlated with regenerator temperatures profile (Figure 6b). Since the slurry recycling did not affect afterburning, it was considered that the recycling flow rate insufficient to influence the process (+/-6 m^3/h), compared to the FCCU feed flowrate (90 – 130 m^3/h). That is why the refinery started to evaluate if the feed flow rate processed or the FCCU loading does affect the regenerator temperatures.

FCC Feed flowrate. The industrial data showed a direct proportionality between the feed flow rate and the dilute/gas phase temperature (Figure 6c). Moreover, the regenerator temperature pattern can be explained by the fluctuation of the FCC feed flow rates (days no. 360–380). This behavior explains that increasing the FCCU feed flow rate will generate more coke and, consequently, burn in the regenerator, leading to higher temperatures. Unfortunately, in our case, both dilute- and gas-phase temperatures increased, which suggested that the burning rate of CO to CO_2 was insufficient in the dense bed. It took place also in the dilute and gas phases. Since the air blower flow rate was monitored and controlled to maintain enough oxygen (1-5 vol.%) to assure the complete burning, it was concluded that the poor distribution of the catalyst and air was the main cause of the high temperatures in the dilute/gas phase.

The increase of the catalyst activity by increasing the catalyst dosage. A high activity e-cat increases the coke production, and more coke burned in the regenerator leading to an increase in the catalyst bed temperature [5]. Increasing the e-cat activity reduced the level of afterburning. Unfortunately, the e-cat activity could not be kept constant even in the condition of dosing higher fresh catalyst dosage rate because of the severe thermal deactivation caused by the operation at high temperatures above 730 °C (Figure 3).

Increase the regenerator pressure to increase the burning rate in the dense bed. Increasing the regenerator pressure from 1.85 to 2.13 barg reduced the temperature in the gas and dilute phases and consequently the afterburning in the 150–230 day period. The data registered in the 278–580 day period were not conclusive since these fluctuations were caused by the feed/air flowrate modification (Figure 6d).

The increase of the regenerator pressure is one of the measures recommended to reduce the afterburning [4, 5, 7]. Yet, the FCCU system pressure is affected by many other unit constraints:

The pressure drop on the main column overhead condensers increased in time (due to heat exchangers tubes plugging), and this phenomenon affects the regenerator pressure by increasing it. After cleaning the respective condensers during unit turnaround, the pressure drop on this equipment is lower, and therefore the regenerator pressure decreased.

The explanation for the high regenerator pressure differences registered before and after TAR (Figure 6.d) is that the main column overhead

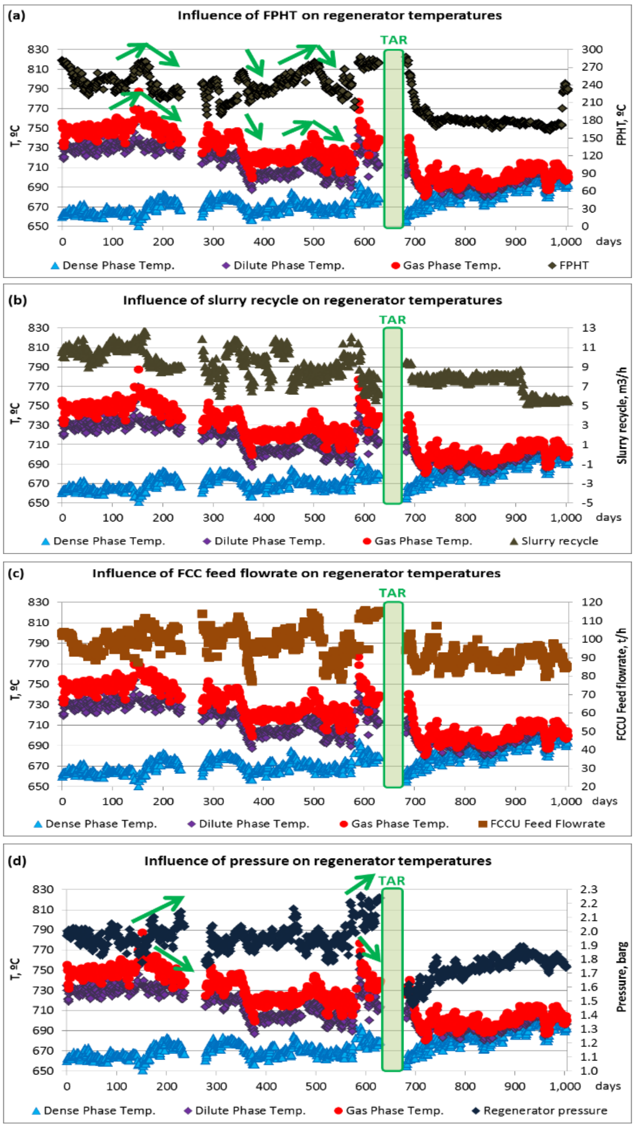


Figure 6. Influence of process parameters on regenerator temperature profile: a. Feed preheat temperature, b. Slurry recycle, c. FCC feed flow rate, d. Operating pressure.

shell & tube condensers were replaced with new, more efficient plate heat exchangers (which have reduced the pressure drops between reactor/regenerator and wet gas compressor suction).

Regenerator pressure is affected by the air flow rate operation, which depends on the FCCU feed flow rate. The FCC operator must adapt the air flow rate at the feed flow rate to ensure enough oxygen for burning the coke in the regenerator. Consequently, by increasing the air flow rate also, the regenerator pressure increased;

Higher pressure in the regenerator will increase the fines losses through cyclones.

The increase of the level of the catalyst bed provides enough gas residence time for CO burning. As presented in other studies, a deeper bed reduces the distance from the top of the bed to the cyclone inlet, increasing the catalyst load to cyclones and causing increased catalyst losses from the regenerator [5]. Therefore, finding the optimum bed level was recommended to minimize the catalyst losses and improve the afterburning. In this study, the FCC unit was confronted with massive catalyst losses caused by cyclones failure. In these conditions, it was difficult even to maintain the constant bed level in the regenerator, and for increasing it, high catalyst dosages were needed. Monitoring the unit operation, it was concluded that by maintaining the height of bed level at 78 - 83% (Figure 7a - operation days no: 380-560), it was achieved the lowest afterburning (~53 °C) and lowest catalyst dosage rate needed to compensate for the e-cat losses. After the regenerator revamping (TAR), because of the efficiency of the new cyclones, the bed level increased steadily even if the catalyst addition rate was maintained at 0.52 kg/t.

Optimizing the catalyst stripping steam rate. If the stripper operation is not optimized, un-stripped hydrocarbon can enter the regenerator and burn in the dilute phase. Increasing the stripping steam flow rate with 0.8 t/h reduced the dilute phase temperatures on average by 29 °C (Figure 7.b.). One of the main industrial unit constraints regarding the stripping steam availability/distribution can be the mechanical damage of the steam nozzles or trays. Non-uniform distribution leads to steam bubbles agglomerating to larger bubbles, reducing stripping effectiveness [7]. Based on equipment inspection during TAR, it was concluded that the stripper tray orifices were plugged with coke during the unit operation. This can lead to steam maldistribution and, consequently, decrease stripper efficiency. Because of tray orifices plugging, it is expected for the stripper efficiency to be higher immediately after unit turnaround (during TAR is performed the stripper tray orifices unplugging) and to decrease in time to the next turnaround. Therefore, the effect achieved by modifying the steam rate can be different depending on the mechanical status of stripper trays.

Some FCC licensors are proposing more efficient technologies like stripper packing nowadays to improve the catalyst stripping performance and reduce steam consumption. Therefore, the stripper-packing technology was planned to be evaluated later by the refinery, the main factors for its implementation being the investment cost, the economic effect achieved by steam consumption reduction, and the effect on regenerator temperatures.

Increasing the reactor temperature. Increasing the conversion and coke yield is expected to improve the stripper performance at a fixed catalyst circulation rate as the hydrogen in the coke will decrease. Consequently, this measure will minimize the burning of light hydrocarbon products from the spent catalyst in the dilute phase. Also, higher coke production will increase the regenerator catalyst bed temperature. Usually, the FCC reaction temperature is optimized depending on the production refinery objectives (higher conversion, gasoline or diesel maximization, octane number, increasing propylene/isobutylene yields, etc.) and unit constraints (wet gas compressor capacity limit, exceeding the dry gas production over the refinery fuel gas consumption, coke burning, mechanical design consideration, reactor metallurgy design temperature, etc.). Because of the refinery objectives, the ROT (Riser Outlet Temperature) increased to 526 °C (before TAR) to optimize the gasoline yield and minimize dry gas production. Evaluating the results achieved during different operation modes (Figure 7c – Operation Mode I and II), it was concluded that operating with +4 °C higher ROT reduces the temperatures in the dilute and gas phases afterburning with around 33 °C (Table 1).

Optimizing the flue gas excess oxygen to assure complete burning of the coke. The air blower capacity is the main FCCU constraint that affects the oxygen availability needed for coke burning (Figure 7d). If there is such a situation, increasing the feed flow rate over the air blower capacity can lead to partial burning of coke to CO, and therefore, afterburning will increase. During FCCU operation, the air flow rate was controlled and adapted at the FCCU feed flow rate to have enough oxygen for coke burning and assure 1 to 5 vol.% excess oxygen in the flue gas. High afterburning up to 113 °C was recorded at maximum capacity of the air blower (72,800 Nm^3/h), and an excess of O_2 in the flue gas was maintained between 2.3-3.4 vol.% (days no. 1-365). The reduction in air flow rate at 70,000 Nm^3/h decreased the afterburning at 50 °C (days no. 370-570). These results were explained by air channeling that appears when the air flow rate increases, causing oxygen breakthrough on one side of the dense bed and reacting in the dilute phase with the CO escaping from another part of the reactor. Therefore, lower afterburning is achieved at lower flue gas excess oxygen between 1.2-2.5 vol.% (operation days no. 365 - 470) and not at higher values above 3 vol.% O_2 that involved the higher air flow rates.

Results achieved by optimizing the process parameters. Optimizing the FCC process decreased the afterburning by 33 °C representing a reduction of 38% from the initial ΔTgas-dense phase. For an FCCU confronted with significant constraints (Cyclones failure and non-symmetrical cyclone layout – Figure 5), it was found that afterburning was reduced by optimizing the following process parameters (Table 1):

Increasing the height of the regenerator catalyst bed level by 4%.

Increasing the catalyst stripping steam by 0.8 t/h.

Increasing the reactor temperature by 4 °C.

Increasing the e-cat activity by 4.2 wt.%.

Other parameters such as FPHT, slurry recycling, and excess O_2 in the regenerator did not significantly influence the afterburning. Regarding the air flowrate/O_2 requirement, a minimum of 1 vol.% ensured an excess of O_2 in the flue gas to burn the coke completely. Suppose the regenerator is confronted with maldistribution/channeling of air/cat-

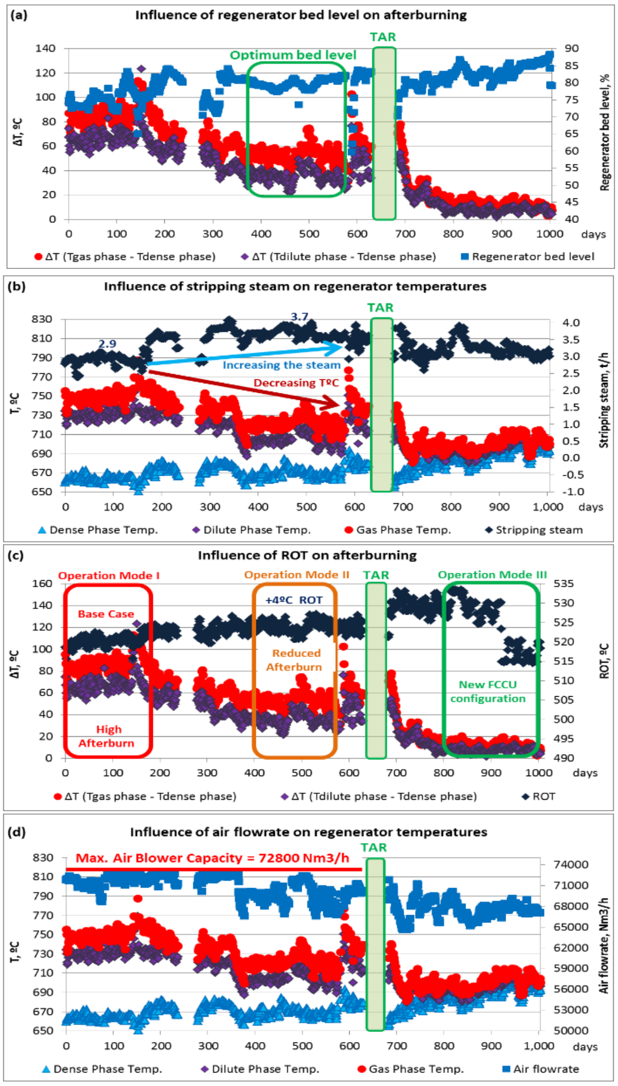


Figure 7. Influence of process parameters on regenerator temperatures: a. Regenerator bed level, b. Stripping steam, c. Riser temperature, d. Air flow rate.

alystat higher air flow rates between 3-5 vol.% because of channeling. In that case, the air will pass through the regenerator phases without being available for coke burning.

FCCU revamping for addressing the afterburning. Analyzing the afterburning causes and influence of process parameters on regenerator temperatures, it was considered that the best solution to address the afterburning is to replace the cyclones and plenum chamber and assure a symmetrical layout of the cyclones with a 90° orientation to cover the regenerator surface uniformly. This activity was performed during refinery turnaround and consisted of implementing a new set of cyclones according to the layout presented in Figure 8.

Table 1. Influence of FCCU process parameters on afterburning

No.	Process parameter Period - Days No.	Unit	1 Operation Mode I Base Case 1 - 180*	2 Operation Mode II FCCU Optimization 380 - 560**	3 Δ (2 - 1)
1.	Catalyst bed level	%	76	80	+4
2.	Stripping Steam	t/h	2.9	3.7	+0.8
3.	ROT	°C	520	524	+4
4.	e-cat activity	wt.%	61.7	65.9	+4.2
5.	Dense Phase	°C	665	669	+4.6
6.	Gas Phase	°C	751	722	-28
7.	Afterburning ($\Delta T_{gas\text{-}dense\ phase}$)	°C	86	53	-33
8.	Afterburn reduction ($\Delta T_{gas\text{-}dense\ phase}$) %			38	-38

* Daily average data recorded from the operation day no. 1 to 180 (Operation Mode I).; ** Daily average data recorded from the operation day no. 380 to 560 (Operation Mode II).

In the new regenerator configuration, a massive reduction of the afterburning was seen, demonstrating the efficiency of new symmetrical layout cyclones (Figure 1 – afterburning after TAR). Assuring a uniform distribution and mixture of the air and catalyst has maximized the burning of the coke at CO_2 in the catalyst bed and reduced at minimum the amount of generated CO that can burn in the upper area of the regenerator. Also, the removal of air/catalyst channeling decreased temperature differences registered at each regenerator level (in the same phase), as shown in Figure 1 (regenerator temperatures/afterburning before and after TAR).

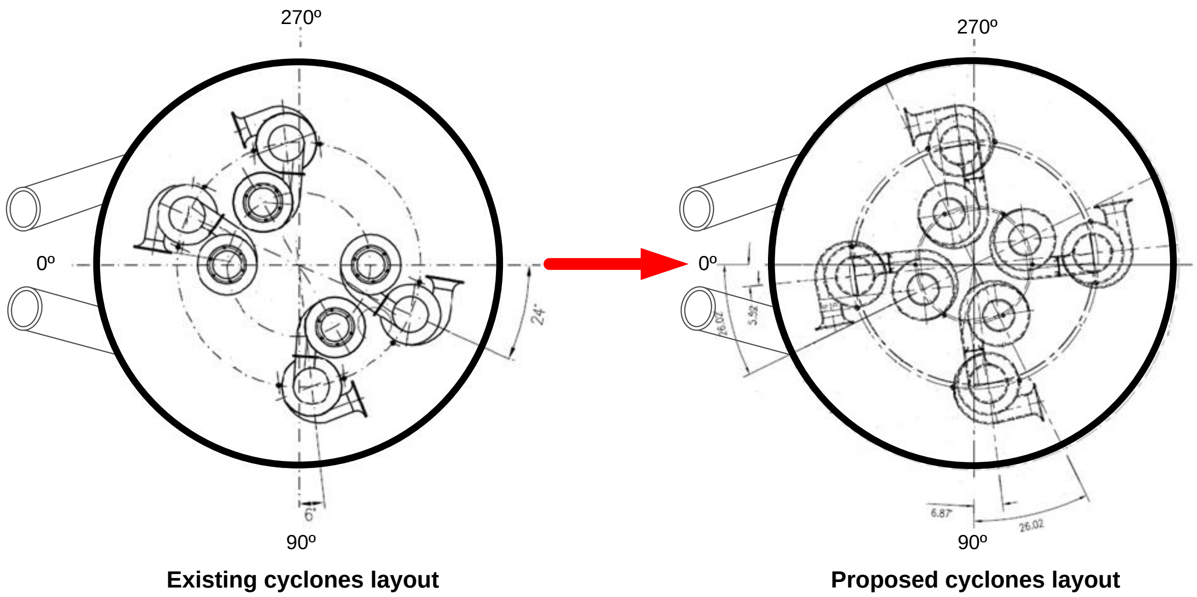


Figure 8. Replacing and assuring a symmetrical layout of the cyclones.

To evaluate the results, the average regenerator temperatures registered after TAR (Operation Mode III – operation days no. 800-1000) were compared with the temperature profile registered during Operation Mode I and II (before TAR). As a result, the temperatures in the dense bed increased by 24 °C, in the dilute phase decreased by 34 °C, and in the gas phase decreased by 50 °C. Therefore, the afterburning decreased by 74 °C, representing a reduction of 86% (Figure 9b.)

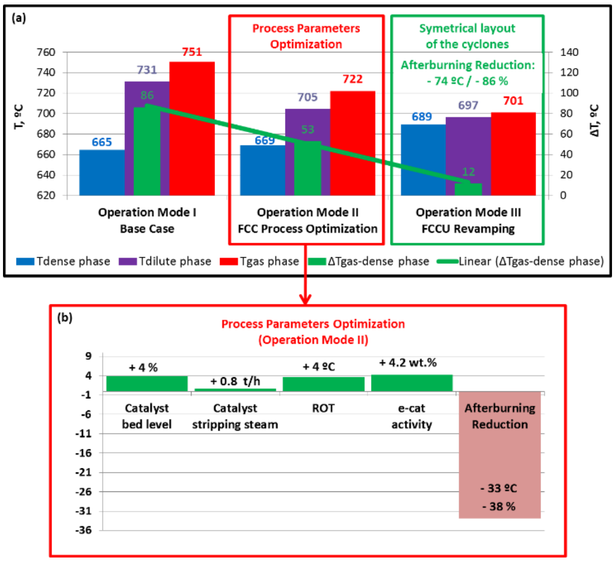


Figure 9. Afterburning reduction by FCC process optimization (a, b) and revamping (a).

In the new cyclone configuration, the FCCU operation is more stable since the afterburning is kept at a minimum and is not depending on the process parameters modification (Figures 1, 3, 4, 6, 7 - afterburning after TAR). Therefore, in these conditions, the technological process can be operated according to the economic targets of the refinery and not depending on unit constraints (Figure 7c - modification of ROT to maximize gasoline or diesel production did not influence the afterburning).

Afterburning reduction and the operation of the regenerator at lower temperatures below the internals design increased the reliability of the cyclones and plenum chamber and, therefore, their lifetime. As a result, there was no emergency FCCU shut-down reported after TAR.

From the catalytic perspective, implementing new and more performant cyclones and operating at lower regenerator temperatures/afterburning, it was positively influenced the equilibrium catalyst quality and FCCU conversion:

a. Eliminated the risk of e-cat deactivation increased the e-cat activity from around 65 to 71.9 wt.% even if fresh catalyst addition rate was maintained constant at 0.52 kg/t (Figures 3).

b. The new regenerator configuration assured a better burning of the coke on the catalyst, and consequently, CRC was reduced from an average of 0.18 wt.% to 0.03 wt.% (Figure 4). Therefore, it improved the catalyst regeneration and increased the regenerated e-cat activity.

c. Replacing the old and damaged cyclones with new ones reduced the e-cat fines losses and consequently increased the 0-40 μ fines into the FCCU e-cat inventory with APS reduction.

CONCLUSION

Operating the FCCU in afterburning conditions can increase the regenerator temperatures above the metallurgical design leading to mechanical failures of the cyclones and plenum chamber. Afterburning was decreased with 33 °C (38% reduction) by increasing the catalyst bed level height (+4%), catalyst stripping steam (+0.8 t/h), ROT (+4 °C), and e-cat activity (+4.2 wt.%). Other process parameters like FPHT, slurry recycling, and excess oxygen did not significantly influence afterburning because of maldistribution. The most efficient way to reduce the afterburning was to revamp the regenerator to assure a uniform layout of the cyclones. The new symmetrical cyclone arrangement decreased the afterburning by 74 °C representing an 86% reduction. Consequently, the regenerator temperatures decreased at around 701 °C, below the 800 °C internals design temperature, which is considered to increase the reliability and lifetime of the cyclones and plenum chamber. Eliminating the risk of catalyst thermal deactivation increased the e-cat activity from 61.7 wt.% to 71.9 wt.%. The uniform distribution/mixing of air and catalyst provided a better regeneration of spent e-cat, demonstrated by reducing CRC from 0.18 wt.% to 0.03 wt.%, and increasing the 0 - 40 μ fines retention in regenerator to 11.7 wt.%.

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NAUČNI RAD

SMANJENJE NAKNADNOG SAGOREVANJA U POSTROJENJU ZA FLUIDNI KATALITIČKI KREKING OPTIMIZACIJOM PROCESA I REKONSTRUKCIJOM REGENERATORA

Rad postrojenja za flidni katalitički kreking u uslovima naknadnog sagorevanja može povećati temperature regeneratora iznad projektovanih, što dovodi do mehaničkih kvarova ciklona i plenumske komore. Ovaj rad predstavlja metodologiju primenjenu za istraživanje naknadnog sagorevanja u komercijalnom postrojenja za flidni katalitički kreking i tehnička rešenja koja se mogu primeniti za smanjenje naknadnog sagorevanja. Dakle, procenom temperaturnog profila regeneratora, konstrukcije regeneratora, kao i mehaničkog statusa unutrašnjosti, zaključeno je da je glavni uzrok naknadnog sagorevanja neravnomerna distribucija i mešanje vazduha i katalizatora. Industrijski rezultati su pokazali da optimizacija nivoa sloja katalizatora, parni striping, reakcione temperature i aktivnosti ravnotežnog katalizatora smanjuju naknadno sagorevanje za 39%. Drugi parametri procesa, kao što su temperatura predgrevanja napojnog materijala, reciklaža suspenzije i višak kiseonika, nisu značajno uticali na naknadno sagorevanje zbog neispravne distribucije vazduha i katalizatora. Rekonstrukcijom regeneratora, kojom ss cikloni simetričnraspoređeni, smanjeno je naknadno sagorevanje za 86%, povećano zadržavanje finih čestica u postrojenju i poboljšana regeneracija istrošenog ravnotežnog katalizatora . Smanjenje radne temperature na oko 701°C otklonilo je rizik od termičke deaktivacije katalizatora, pa je stoga aktivnost ravnotežnog katalizatora povećana za 10,2 tež.%.

Ključne reči: postrojenje za fluidni katalitički kreking, regenerator, naknadno sagorevanje, ravnotežni katalizator, cikloni, rekonstrukcija.