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The Role of Fluid Catalytic Cracking in Process Optimisation for Petroleum Refineries

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Abstract**—**Petroleum refining is a chemical process in which the raw material (crude oil) is converted to finished commercial products for end users. The fluid catalytic cracking (FCC) unit is a key asset in refineries, requiring optimised processes in the context of engineering design. Following the first stage of separation of crude oil in a distillation tower, an additional 40 per cent quantity is attainable in the gasoline pool with further conversion of the downgraded product of crude oil (residue from the distillation tower) using a catalyst in the FCC process. Effective removal of sulphur oxides, nitrogen oxides, carbon and heavy metals from FCC gasoline requires greater separation efficiency and involves an enormous environmental significance. The FCC unit is primarily a reactor and regeneration system which employs cyclone systems for separation. Catalyst losses in FCC cyclones lead to high particulate matter emission on the regenerator side and fines carryover into the product on the reactor side. This paper aims at demonstrating the importance of FCC unit design criteria in terms of technical performance and compliance with environmental legislation. A systematic review of state-of-the-art FCC technology was carried out, identifying its key technical challenges and sources of emissions. Case studies of petroleum refineries in Nigeria were assessed against selected global case studies. The review highlights the need for further modelling investigations to help improve FCC design to more effectively meet product specification requirements while complying with stricter environmental legislation.

Keywords**—**Design, emissions, fluid catalytic cracking, petroleum refineries.

I. Introduction

THE main processes in FCC designs are reaction, separation and regeneration. Operating conditions of FCC cyclones involve varying temperature and pressure of gas flow (reactor 525 ^{o}C, regenerator 700 ^{o}C) and the loading of the catalyst with highly abrasive properties. Failure mechanisms arising from the FCC process include coke depositions on reactor gas outlets, plugging of cyclone dipleg, catalyst carryovers in the cyclones, erosion or attritions in the cyclones due to higher throughputs, and reduced cyclone efficiency subsequent to an increased capacity [1]. Refiners highly seek FCC capacity increase for the better economic performance of the operation. However, this often introduces a loophole for significant catalyst losses by either the mechanisms of poor catalyst flowability or dipleg plugging. The cyclone dipleg is relative to its backup height for sustaining catalyst loads. Increase in capacity and, subsequently, an increase in pressure drop leads to dipleg plugging with catalysts, and on reaching the cyclone's bottom, catalysts losses may occur due to it being carried over. The inadequate performance of the unit would lead to significant catalyst losses, operation at reduced capacity intake, and reduced process performance in achieving specified product yields and emission limits. FCC separation systems are installed in a variety of ways such as single, two-stage, third-stage separation (TSS) and fourth-stage separation (FSS) [2]-[4]. According to the Climate and Clean Air Coalition (CCAC) [5], a majority of countries in 2020 would adopt the use of low sulphur diesel fuels with less than 50 parts per million (ppm) sulphur content by 2020, and ultra-low sulphur fuels with less than 10 ppm sulphur content by 2030. A 90% reduction in black carbon and atmospheric particulate matter emissions from vehicles is also expected by 2030.

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II. FCC Unit Evolution

The Houdry process developed the first cracking reactions which occurred on a fixed bed up until the fluidisation regime [6]. Refiners now prefer the fluidised bed processes which have advanced in technology as detailed in the various FCC types discussed below.

A. Upflow Unit

The Upflow unit also known as Model I (1942) was the first commercial FCC unit in the fluidisation regime developed by Standard Oil Development Co. (SOD) with cyclones located externally. The regenerator and reactor system circulates the catalyst using an up-flow configuration in multiple vessels as shown in Fig. 1. The non-heat balanced process employed preheating, catalyst cooling and a low pressure operated regenerator. Although the up-flow reactor pipe featured a section with a wider diameter, it allowed an insufficient contact time and a less dense bed required for the natural clay catalyst used; this led to catalyst losses until the invention of zeolite containing catalysts which require less contact time. The catalyst losses experienced with the up-flow unit led to the development of a modified unit known as Model II, with catalyst down-flow configuration and elongation of the section of the reactor with a wider diameter thus, allowing a dense bed and sufficient contact time [7].

B. Stacked Unit

A stacked unit features a regenerator below the reactor vessel as shown in Fig. 2; the UOP stacked design (1947) was the first of its kind developed with the feature of spent catalyst stripping. The spent catalyst flows to the regenerator section by gravity while the regenerated catalyst is carried on by feed vapour to the cracking reactor bed [8].

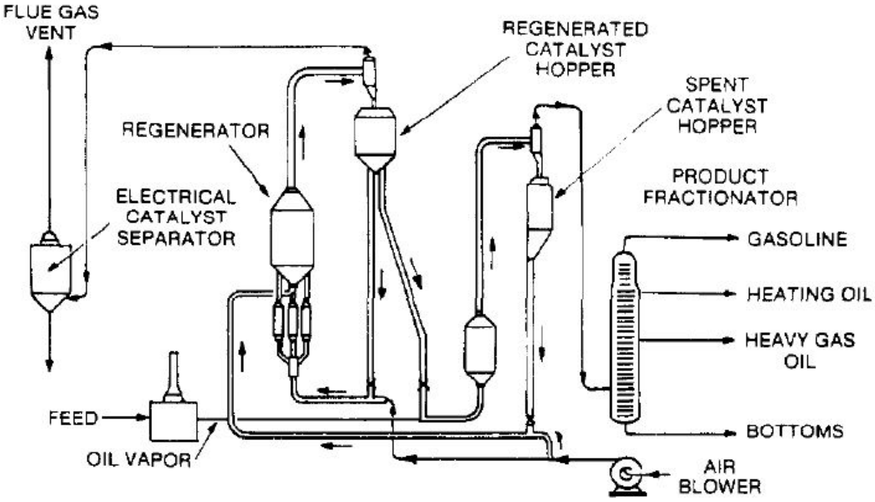

Fig. 1 Upflow Unit -Model I FCC unit by SOD [7]

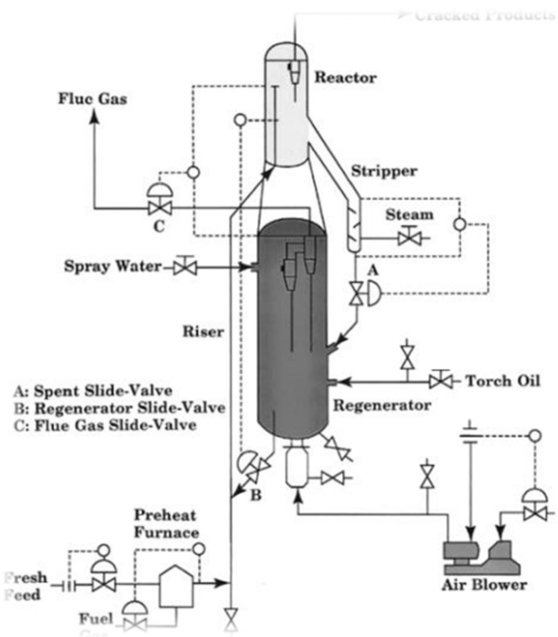

Fig. 2 Stacked unit by UOP [8]

C. Orthoflow Unit

M.W. Kellogg Cooperation (now Kellogg Brown and Root Inc.) developed the Orthflow unit (1951) [8] with a riser reactor fed to two-stage reactor cyclones overhead in the internals of regenerator vessel as shown in Fig. 3. A light crude processing refinery in Warri, Nigeria, owned by Nigerian National Petroleum Cooperation (NNPC) which uses the M.W. Kellogg unit is in use with a carbon monoxide (CO) boiler for complete combustion of CO to carbon dioxide (CO_2). There are fewer chances of coke deposition given that coking is more significant with heavier feedstocks [9]. Advanced models of the Orthoflow design developed by Kellogg Brown and Root Inc. (KBR) features four regenerator cyclones in two stages are shown in Fig. 4.

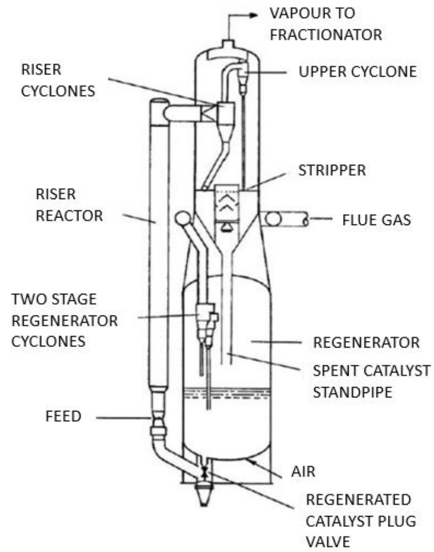

Fig. 3 M.W. Kellog Orthoflow Unit [10]

D. Side by Side – Two Vessel Unit

SOD (now ExxonMobil) developed a side by side unit in 1952 known as Model IV with a U bend feature as shown in Fig. 5. Standard two vessel units are widely employed, and the most common are the Exxon Flexicracking unit (see Table I) [11], the Shaw and Axen design, and the UOP model shown in Fig. 6 [12]. An example is the UOP FCC unit in Port Harcourt refinery where the reactor is an all riser cracking system. The regenerator system is designed for complete CO combustion and feeds hot flue gas to a flue gas cooler for heat recovery via steam generation. There are other FCC models with a side by side configuration designed for two stage regeneration. The UOP design performance has improved with piped spent catalyst distributor [13].

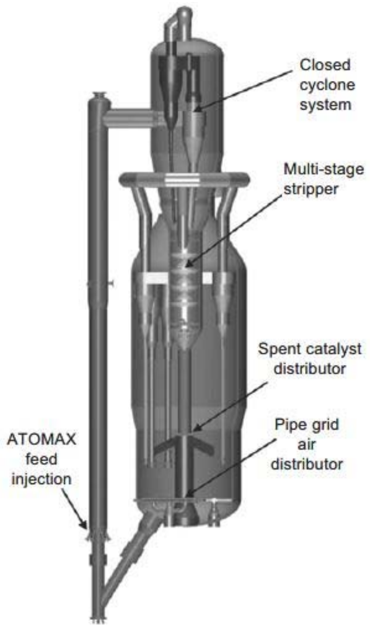

Fig. 4 KBR orthoflow Unit [12]

E. Standard Two Vessel Unit with TSS and FSS

Shell first proposed riser cracking unit in 1957, a feature maintained by new FCC designs following the innovation of zeolite catalysts [8]. According to Shell Global Solutions, Shell FCC cyclones has attained greater separation efficiency (99.9%) by improvement of cyclone geometry, mechanical design and construction materials; this is now a customised Shell FCC design, unlike standard unit designs equipped with separation systems made by cyclone manufacturers. The solutions feature the application of a set of axial cyclones in parallel in a TSS at the regenerator for meeting particulate emission legislation (50 milligrams of dry NOx per normalised meter cube of exhaust [mg/Nm^3]), other than power recovery expander (rotor blade) protection. A FSS with a single cyclone processes the TTS under-flow gas. Furthermore, the afterburn conditions that lead to catalyst losses in the regenerator are reduced by an improved construction of the cyclone crossover and plenums (single point anchoring, shot-creting the lining method) and a new type of refractory material. The design improvements include cyclone geometry modifications to reduce wall thickness erosion and coke depositions, cyclone compartment redefinition as per catalyst flow analysis from its interior into the dipleg, adjustments to the tolerance of cyclone suspensions and plenums to bear after-burn conditions with low risks of crack formation, allowing quick repair to parts other than the cyclone. Shells standard two vessel design features close-coupled reactor cyclones and direct-coupled regenerator cyclones. Notably, other features that make up Shell's innovations reported having no significant erosion effects are the direct coupling of rough-cut steam-stripping reactor cyclone to 2^{nd} stage cyclones, the inclusion of vortex stabiliser device at the 2^{nd} stage reactor cyclones for improving the pressure balance in the cyclone [14].

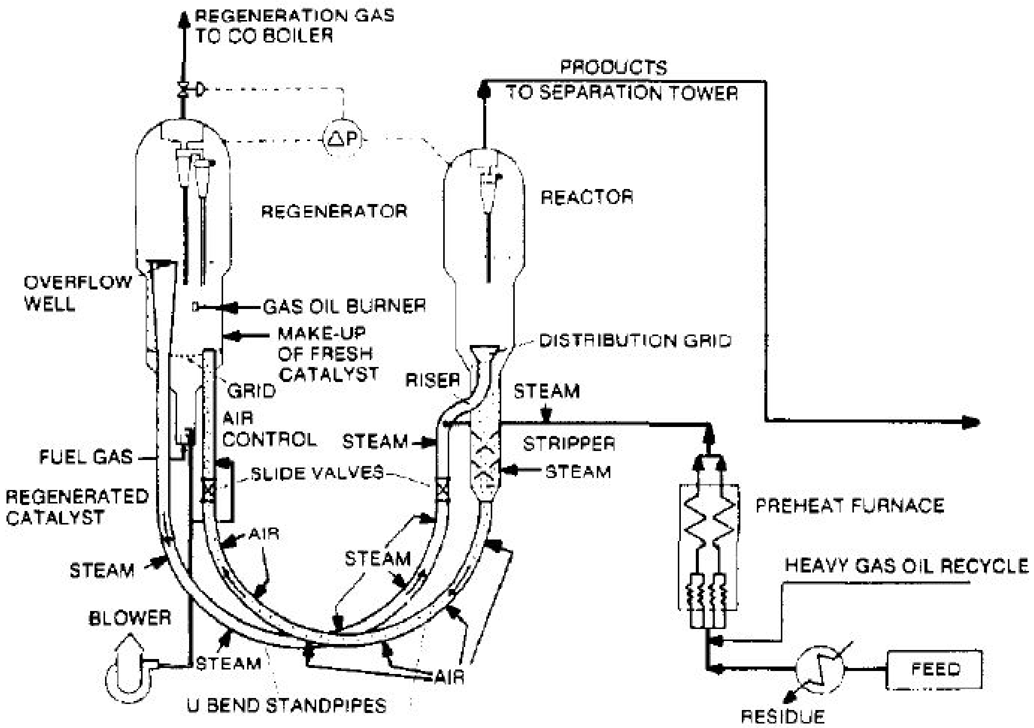

Fig. 5 Model IV SOD (1952) [7]

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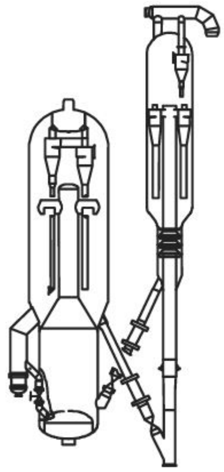

Fig. 6 UOP High-Efficiency Regenerator [12]

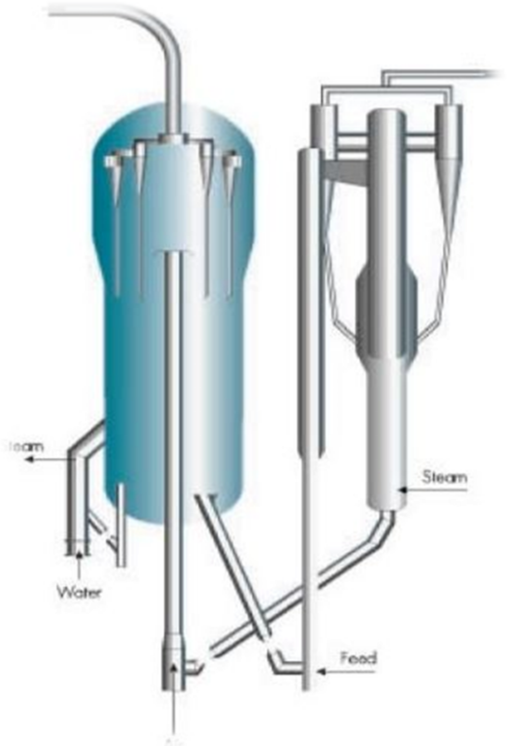

Fig. 7 Shell external reactor design [14]

F. Side by Side – External Reactor with TSS and FSS

Shell's heavy feedstock processing unit in Stanlow refinery, UK is an external reactor design. Fig. 7 shows shell external reactor design with a rough-cut cyclone for pre-stripping directly coupled to 2nd stage cyclones. Its main feature for technology improvement is an external reactor riser with the advantage of less stagnant areas hence, reduced chances of coke deposition and accessibility for blasting of reactor dipleg to re-establish flow in the case of blockages. Gas carry-under due to dipleg catalyst overloading is suppressible by adequate sealing of primary and riser end cyclones by lowering its bottom end in the stripper bed; as applied in a third-party Shell unit in the USA (a one vessel internal reactor and regenerator system). As reported, TSS and FSS have been applied to the unit to meet particulate legislation, with the added advantage of the recovered catalyst (typically about 200mg/Nm^3) reused in the reactor and regenerator system. Other safeguards against catalyst losses are temperature indicators, DP measurement, gate valves and fluidisation gas injection provisions at the dipleg externals of the 2nd stage reactor cyclones [14]. Summarily, Table I highlights the features of various FCC unit types.

TABLE I
VARIOUS FCC UNIT DESIGN FEATURES

FCC Unit Designs	Features
Upflow unit - Model I	• External multi-cyclone systems. • Smaller reactor diameter and less contact time, less dense bed • Catalyst up-flow configuration. • No centrifugal fans, low-pressure regenerator, non-pressure balanced. • Quick separation. • Catalyst coolers, feed preheat as non-heat balanced
Downflow unit	• Internal multi cyclone system. • Larger reactor for increased catalyst circulation rate.
Stacked unit - UOP	• Spent catalyst stripping. • Catalyst up-flow to the reactor by feed vapours due to the configuration.
M. W. Kellogg Orthoflow	• Riser reactor, reactor cyclones stacked above regenerator, • Stripper below reactor cyclones.
KBR Orthoflow	• Closed reactor cyclone system • Multistage stripper. • Two-stage regeneration hence coke reduction in regenerated catalyst
Side by side -Model IV by SOD	• Pressure balanced. • Catalyst flow rate not adjustable over a wide range as controlled by changes in differential pressure between reactor and regenerator
Side by side Exxon Flexicracking	• Catalyst downflow configuration. • Transfer line reactor with steam stripper elevated above regenerator level. • Maintained at heat balance, nearly adiabatic.
Side by side - UOP high Efficiency	• All riser cracking. • Complete combustion of CO to CO_2.
Side by side - Shaw and Axen	• Two-stage regeneration for reducing the rate of catalyst deactivation and improving regeneration.
Side by side - Shell two vessel unit	• TTS and FFS included.
Side by side - Shell External Reactor Design	• TTS and FFS included. • External reactor, hence less stagnant area. • Used mainly for processing heavier feedstock.

III. FCC SEPARATION SYSTEMS

Cyclones are gas-solid separators used in two main points in the FCC process; separation of the product gases from the used catalyst (in the reactor) and separation of regenerated catalyst from flue gas (in the regenerator). On the reaction of a catalyst with the long chain hydrocarbon (feedstock) in the reactor, the molecules are broken down into olefins, separated from the catalyst and fed to a fractionator. The catalysts used (spent-catalyst) becomes inactive due to coke deposition on the surfaces, hence are fed to the regenerator for reactivation. Recycling of the spent-catalyst occurs in the regenerator where coke is removed by combustion to reactivate the acid sites on the catalyst for reuse in the reactor. A cyclone in the regenerator separates the reactivated catalyst (regenerated catalyst) from flue gases which are products of the combustion reaction. The heat produced from combustion vaporises the regenerator flue gases while the regenerated catalyst is fed to meet a new stream of feedstock in the reactor repeating the reaction, separation and regeneration processes. The regenerated catalyst is high in metal concentrations and becomes less active while recirculated continuously. Hence fresh catalyst additions are required. Hydro cyclones are often used downstream of the reactor to meet the product quality requirements. The fluid medium in the hydro cyclone is liquid whereas cyclones separate particles in a gas or liquid stream using centrifugal force[15].

Given the flow field pattern within a cyclone system cyclone, the various types are standard reverse flow and uniflow. Table II gives a summary of their differences.

TABLE II
DIFFERENCES BETWEEN CYCLONE TYPES

Cyclone Types	Features
Uniflow or axial	• No conical section for particle collection hence compact construction easily integrated into pipes • particle leaves the cyclone body with a small portion of the inlet gas stream • Lower energy consumption due to lower pressure loss • Clean gas leaves the cyclone body in the same inlet direction. • Commonly installed in series
Reverse flow	• The conical section included for collecting particles, often bulky when designed for processing high gas flow rates. • Particles hit the sides and slide down to the conical section. • Prone to higher corrosion, an effect of higher tangential velocity due to flow field pattern. • Vortex reversal; gas stream enters the cyclone, the clean gas flow reverses and leaves at the top • Usually installed standalone.

Uniflow cyclones are built with no conical section and are commonly installed in series. The inlet and outlet are in the same direction such that the clean gas product flows out of the cyclone body from the same inlet direction. Uniflow cyclones are otherwise known as axial or swirl tube. Unlike uniflow cyclones flow, in reverse flow cyclones, the inlet is at a tangent to the top of the cyclone. The dust particles collide with the side and fall to the bottom of a conical section included in the design. The vortex reversal within the cyclone system causes the clean gas product to flow to the centre and leave the cyclone body from the top[15], [16].

A. Close-Coupled and Direct-Coupled Cyclone Systems

Close coupled cyclone systems are installed with the primary cyclone in an orientation such that separation of catalyst from products occurs immediately after the cracking reaction; hence the product gas feeds are prevented from further cracking at the fractionator[14]. Avidan et al. [17] discussed the use of closed cyclone systems as a riser termination device; separation of the catalyst from the product occurs in a short contact time to discriminate non-selective post-riser cracking hence, obtaining the desired product yields. However, a direct-coupled cyclone (DCC) system gives a minimum vapour residence time between the riser exit and reactor outlet compared to rough-cut and close-coupled cyclones. A DCC systems with negative pressure (operation at reduced pressure relative to the dilute phase of the reactor vessel) have minimal hydrocarbon blowdown at the primary reactor cyclone dipleg in comparison to close coupled or rough cut cyclones with positive pressure (irrespective of if the dipleg of the positive pressure device is submerged in a stripper bed or otherwise)[18].

IV. ADVANCES IN FCC CYCLONE OPTIMISATION

The FCC process optimisation is in the context of mechanical design and model-based control [8]. Additives are often introduced in the processes to promote combustion, modify the product yields and, for removal of SOx, NOx, and metals. A good choice of composite materials can be used to achieve enhanced structural performance. The choice of catalyst is also an essential factor to consider as a safeguard against attrition [14]. Ultimately, an improved cyclone separation system is essential for maximising output, yielding specified product quality and meeting emission requirements. By design performance, there are standard and high-efficiency cyclone systems.

A Shell third-party unit in the USA adopts primary reactor cyclones close coupled (to avoid post-riser coke formations), further improved to perform a pre-stripping function as well as separation by the exclusion of the cyclone dipleg area and injection of steam for catalyst stripping. A vortex stabiliser added in the cyclone bottom improves pressure balance and dampens the effect of high particle velocities [14].

Computational fluid dynamics (CFD) modelling has played a vital role in FCC cyclone optimisation. Other than improvements in construction materials and methods, under a given pressure loss, the separation efficiency of the cyclone may be optimised. Lower pressure drops in the process correspond to a reduced energy cost. The separation (or collection) efficiency is an evaluation of the performance of the process in collecting the particles. Pressure drops in cyclones increase with increasing gas flows. In making a dimensional analysis, pressure drop, and the separation efficiency are two critical parameters for optimisation of the FCC separation process [19].

Various CFD investigations have analysed the geometric parameter and shape adjustments as well as the inclusion of additional structure to the cyclone body. Direct coupling of cyclones in two stages has often improved their overall performance.

A CFD study on reverse flow cyclones highlights a method of achieving the optimum values of a cyclone system's dimensions by supplying permissible values of pressure drop, inlet gas velocity, height and cyclone diameter. Some geometric parameters have an impact on efficiency, but no effect on the systems pressure drop. These parameters include the dust discharge pot diameter, the ratio of the height of the separation space to the diameter of the cyclone, the outlet tube insert depth, the width to height ratio of the inlet cross-section and the inlet configuration. The dust hopper dimension may benefit from operation margin considerations but is known not to affect efficiency and the systems pressure loss. On the other hand, cyclone geometric parameters with a significant effect on efficiency and pressure drop include the cyclone diameter, the ratio of the inlet cross-section to the cyclone cross-section (at a given inlet velocity) and the ratio of the exit tube entrance diameter to the cyclone diameter [20].

According to Gimbun et al. [21], higher collection efficiency is achieved with a smaller cone tip diameter but leads to higher pressure drops.

The dipleg length has been found to impact significantly on collection efficiency [22].

A cyclone with a variable cross-sectional area and its vortex length stretched produced a secondary swirling flow which is favourable for the particle collection efficiency with a particle diameter less than 5 µm [23].

Elsayed [24] reported an optimised vortex finder shape by the adjoint method for improved performance. Given studies comparing various cyclone designs, the vortex finder shape affects the collection efficiency and pressure drop. [25] Also, the eccentricity of the vortex finder is detrimental to the collection efficiency and pressure drop. [26]

Huang et al. [27] investigated the impact of adding a laminarizer with 15 tubes at the entrance of the cyclone and found it to improve the collection efficiency but leading to higher pressure drops.

Considering that fine particle may be trapped by tangential velocity on the cyclone sidewalls, Zhang et al. [28] investigated two new cyclone designs with the redistribution of several collection areas (dustbins) at the sides of the cyclone body in addition to the collection at the bottom. The first case employs a cross-sectional separation area of six variable diameters connected in series while the second case replicates the interior of the Stairmand high-efficiency cyclone [29] with an outer shell-like dustbin included. The two novel designs were found to be more efficient than the Stairmand high-efficiency cyclone by 3% and 33.9% respectively. As reported, the collection efficiency of the first case was improved 6% with a particle diameter of less than 1µm. On the other hand, the second case showed lower collection efficiency due to reduced tangential velocity in the interior with the range of 1.6µ – 3.1 µm particles diameters.

V. Conclusion

The FCC unit processes the heavier portion of the oil barrel; hence this shows the critical role it plays in the era of stricter environmental legislation and cyclone separators are essential for improving the overall FCC processes. In optimising FCC cyclones, it is vital to have a precise understanding of the flow regimes in the process. The centrifugal forces within the cyclone displace the particles contained in the catalyst and product mixture. In most cases, the products from primary cyclone flow through the vortex finder to secondary cyclones connected in series to provide greater collection efficiency before feeding it to the fractionation section. Various studies show improvement of collection efficiency with an increase in flow rate, but also the impact on the pressure within the system. Vortex stabilisers can be included at the bottom of the cyclone to improve the pressure balance; however, this does not result in overall system performance, due to a reduction in separation efficiency. The shell custom FCC unit discussed highlights two features to take into consideration: submergence in a stream stripper bed and blasting of the externals of the reactor and regenerator system to re-establish flow. An erosion modelling of the separation system needs to take account of the loading conditions considering the thermal stresses and strains absorbed. Lessons learned from other refiners are often valuable in improving existing equipment; however, it is essential to assess the undesirable impact of alternative solutions in plant operations. In order to meet specified product quality and stringent legislation on particulate emission, FCC revamping requires optimised separation systems and their virtual testing to eliminate unexpected afterburn conditions. Research efforts to date have yielded the optimisation of FCC cyclones, usually with improvement in a given parameter, but shortfalls in another. The stricter emission and fuel quality regulations imposed by CACC call for a collaborative effort within the petroleum industry. There is a need for further engineering design and CFD modelling of FCC separation systems towards improved overall system performance.

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