Title: Recent Advances in FCC Technology

Author: Ye-Mon Chen, Shell Global Solutions (US) Inc.

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Abstract

Although the fluid catalytic cracking (FCC) process has been commercially established for over 60 years, the technology continues to evolve to meet new challenges. This paper presents examples of recent FCC technology advances through integrated R&D programs that bridge understanding in process science and engineering practice in which Shell Global Solutions* has contributed significantly.

On the reactor side, advances in feed injection, riser internals and riser termination have been proven to work synergistically to improve reactor performance. Earlier generation of modern feed injection technology was introduced in the 1980's, using direct impact mechanisms for atomization. This paper discusses the newest generation of the technology utilizing two-phase choking for atomization, which has been demonstrated to be much more energy efficient, as validated by consistently achieving more uniform temperature profiles across the riser.

The FCC riser is known for its shortcomings of density and velocity variations. The newest riser internal technology minimizes these shortcomings and promotes ideal plug flow. The FCC is a sequential reaction process in which many desirable products are the intermediates. Thus, cracking reactions must be terminated after a desirable reaction time; otherwise, desirable products will continue to crack, leading to excess productions of light gases and coke. Improved riser termination technology sharpens the termination of reactions by the combination of the unique design of primary stripper cyclones and close coupled secondary cyclones.

On the regenerator side, conventional flue gas cleaning requires two stages of cyclone separation followed by electro-static precipitators (ESP) or scrubbers. New developments in the Third Stage Separator (TSS) technology provide enhanced capability for achieving low particulate emissions in flue gas to comply with the requirements more stringent, particulate control environmental regulations.

The majority of FCC units in the US have gone through various stages of de-bottlenecking, and many are limited by catalyst circulation. Catalyst circulation enhancing technology (CCET) has been demonstrated to improve standpipe stability, resulting in significant improvements in catalyst circulation rates.

* Shell Global Solutions is a network of independent technology companies in the Royal Dutch/Shell Group. In this material the expression 'Shell Global Solutions' is sometimes used for convenience where reference is made to these companies in general, or where no useful purpose is served by identifying a particular company.
Introduction

The fluid catalytic cracker (FCC) is the primary conversion unit in most US refineries. It converts, or cracks, low value heavy ends of the crude oil into a variety of higher-value, light products. In US, the primary function of FCC units is to produce gasoline. About 45% of worldwide gasoline production comes either directly from FCC units or indirectly from combination with downstream units, such as alkylation. Although FCC is a mature process commercially deployed for over 60 years, the technology continues to evolve to meet new challenges [1, 2, 3]. Modern FCC units can take a wide variety of feedstocks and can adjust operating conditions to maximize production of gasoline, middle distillate (LCO) or light olefins to meet different market demands.

The success of developing new FCC technology requires the integration of in-depth understanding of the underlying process science and innovation in engineering practices. This paper presents selected examples of recent FCC technology advances in which Shell Global Solutions has played a significant role.

1. Feed Injection System

Process Considerations

The feed injection system is by far the most critical component of the modern FCC reactor design. Several recent developments in the FCC process have made the feed injection system increasingly important.

First, due to the development of highly active zeolite FCC catalyst, the reaction time has been shortened significantly to a few seconds in the modern riser reactor. Since catalytic cracking reactions can only occur after the vaporization of the liquid hydrocarbon feedstock, mixing and feed vaporization must take place in the riser as quickly as possible. Otherwise, thermal cracking reactions will dominate.

Second, the regenerator temperature is getting higher to achieve more complete catalyst regeneration. Because of the higher regenerator temperature, control of thermal cracking in the riser has become more critical. The typical modern riser top temperature is controlled in the range of 950 to 1050 °F, but typical regenerated catalyst temperature is much higher, in the range of 1250 to 1350 °F. The feed injection system plays the key role in reducing thermal cracking reactions by cooling off the lower riser quickly with fast mixing and vaporization of the feed.

Third, the FCC feedstock is getting heavier. As the feed gets heavier, the boiling point increases, which makes feed vaporization more difficult. At the same time, the viscosity of the feed also increases, which makes feed atomization more difficult.
The success of a feed injection design depends on bridging the underlying science to the engineering design aspects in order to achieve the process objectives. The three key aspects of a feed injection nozzle design are: Feed atomization, feed distribution and mixing with catalyst.

- **Feed atomization** – This aspect of the feed nozzle design is the most obvious. The objective of feed atomization is to generate fine droplets for fast vaporization. The challenge of a successful feed nozzle design is to produce the finest feed atomization using the least amount of energy. Many different FCC feed nozzle designs have been patented [4, 5, 6, 7 and 8].

  The first generation of modern FCC feed nozzles [4] was introduced in the 1980’s. The atomization mechanism of this design was based on generating a high velocity liquid jet to impinge on a target, shattering the liquid jet into droplets upon hitting the target, and conveying the droplets with steam to the nozzle exit. Although this design belongs to Lefebvre’s [9] definition of twin-fluid atomizers, which utilize steam to assist atomization of liquid feed, the primary atomization mechanism is still a single fluid atomizer utilizing the energy of liquid alone for atomization. As a result, this nozzle requires high feed pressure and high steam usage to achieve desirable feed atomization.

  The second generation of modern FCC feed nozzles [5] were introduced in the early 1990’s which all belong to Lefebvre’s [9] definition of internal mixing, twin-fluid atomizers. The atomization mechanism of these designs was based on internally mixing the steam and liquid feed upstream of the nozzle exit, using some forms of proprietary mixing devices, and conveying the two-phase mixture to the nozzle exit. These designs were an improvement over the first generation of feed nozzles, particularly in reducing the requirement of high feed pressure. However, all internally mixed twin-fluid atomizers have a common drawback: the two-phase mixture will stratify during conveying to the nozzle exit, regardless how well the two phases are mixed initially, leading to less efficient atomization.

  The newest generation of FCC feed nozzles [7, 8] were introduced in the late 1990’s which are twin-fluid atomizers using two-phase chocking as the atomization mechanism. These nozzles have the atomization steam mixed with the feed just before the final outlet of the nozzle, preventing the stratification of two-phase flow. As the homogeneous two-phase flow passes through the final outlet, the sudden expansion of the two-phase flow shatters the liquid into fine atomization.

- **Feed distribution** – Feed distribution in the FCC riser, sometimes called riser coverage, is as critical as feed atomization in achieving FCC processing objectives. Due to space limitation in the riser area, only limited number of nozzles can be used. The industry trend [2] is to use multiple nozzles at a single riser elevation with
each nozzle generating a wide angle spray. The more uniform the individual nozzle generates in a wider angle, the less number of nozzles is required to achieve desirable feed distribution in the riser.

It is important to recognize that a feed nozzle generates a spray with some form of liquid flux and droplet size distributions across the entire spray pattern. These distributions vary both in time and space. The challenge of a successful feed nozzle design is not only to produce the finest feed atomization, but also to produce the most stable and uniform spray. The newest generation of FCC feed nozzles [7, 8] tends to have more uniform feed distribution as a result of better control of homogeneity of two-phase flow at the nozzle exit.

**Mixing with catalyst** – The objective is to achieve a uniform radial riser temperature profile as quickly as possible. In doing so, the regenerated catalyst is uniformly cooled down by vaporization of the hydrocarbon feedstock, thus minimizing thermal cracking reactions in the lower riser section. The newest generation of FCC feed nozzles [7, 8] tends to have faster mixing with catalyst because of sudden expansion of two-phase choke flow at the nozzle exit, creating a strong suction to draw in catalyst. Commercial experience has shown that, in addition to feed atomization and feed distribution, the feed injection angle also plays a significant role in mixing with catalyst and hence the temperature profile in the riser. Although most of modern FCC units have the feed nozzles installed through riser shrouds at a fixed angle, a new feed nozzle design [8], shown in Figure 1, enables an FCC unit to adjust the feed injection angle while using the existing riser shrouds. This enables an FCC unit to optimize mixing of feed and catalyst by adjusting the injection angle to achieve the best performance of the unit.

*Figure 1  Feed injection system with adjustable injection angle (US Patent 5, 979, 799, 1999)*
Figure 2 shows radial temperature profiles of a commercial FCC riser right above feed injection before and after the feed nozzle change, including adjusting the injection angle. As shown prior to the change, the riser temperature profile was rather non-uniform, with lower temperature at the center and higher temperature near the wall. The temperature differential was close to 100 °C. After replacing the feed injection nozzles of the latest design and adjusting the injection angle for optimum mixing, the temperature profile became much more uniform, with temperature difference reduced to about 20 °C. The remaining non-uniformity of the temperature profile was due mainly to the asymmetrically catalyst inlet from the regenerator standpipe, which can only be addressed by changing the lower riser design.

Figure 2 Comparison of temperature profile across a FCC reactor riser

In addition to the temperature profile change, commercial experience has confirmed that using the newest generation feed nozzles, such as the one shown in Figure 1, can substantially reduce dry gas and increase gasoline yield. These results are in line with the expectation that better feed injection design reduces thermal cracking reactions, which are the primary source for dry gas. As a result, catalytic cracking reactions are maximized and more desirable products are produced.
2. Riser Internals

Process Considerations

Chemical reactions taking place in the FCC riser are numerous and complex. Thermal and catalytic cracking reactions as well as many side reactions, such as hydrogen transfer, are progressing simultaneously. In addition, FCC feedstock is a cocktail of hydrocarbon mixture with different chemical species vaporizing and reacting at different rates.

Although it is difficult to cover all aspects of FCC reaction kinetics in the riser, several process considerations are critical:

- First, catalytic reactions require the presence of catalyst. More even catalyst distribution across the riser is important because it leads to more uniform local catalyst-to-oil ratio and more even reaction rates.
- Second, catalytic reactions result in coke deposition on the catalyst, which reduces catalyst activity and selectivity. Spent catalyst back-mixing down the riser is highly undesirable.
- Third, thermal cracking reactions are more sensitive to reaction temperature. More even temperature distribution across the riser is desirable because it leads to overall reduction in thermal cracking reactions and more even catalytic reaction rates.
- Fourth, gas radial mixing in the riser is relatively slow. More even gas velocity distribution across the riser is desirable because it leads to more even reaction residence time distribution.

Engineering Practice

Modern FCC units use vertical risers for cracking reactions with very few design variables downstream of feed injection. Still, the critical process considerations can be partially achieved by applying engineering innovations.

Successful design of a FCC riser must consider the following hydrodynamic trends of a co-current gas-solids two-phase upflow:

- Solids concentration is higher near the wall than the center
- Solids always move upward in the center zone, but can be either upward or downward near the wall.
- Gas velocity is higher near the center and lower near the wall.
Furthermore, due to the progress of the cracking reactions, the molar flow rate, and hence the volumetric flow rate of the hydrocarbon vapor, increases as it moves up the riser. In a typical FCC unit, the volume expansion is in the range of 3 to 4 times of the vapor of the original feedstock. Thus, the riser diameter may be increased once or twice after feed injection to keep the vapor velocity within the desirable range. These step changes in riser diameter promote catalyst reflux near the wall. Modern riser design also includes a sharp 90 degree turn at the top, which further promotes catalyst reflux down the riser wall.

An effective engineering solution to improve the riser hydrodynamics is the use of wall baffles [10, 11]. Figure 3 shows the comparison of velocity and concentration profiles in the same riser before and after installation of wall baffles. As shown in Figure 3, both gas and solid velocity profiles are more uniform in the riser with wall baffles, improving the riser hydrodynamics closer to desirable plug flow reactor. Furthermore, the overall pressure drop through the riser is reduced with the wall baffles, due to the reduction of catalyst back-mixing. Commercial experience confirms the benefits for the use of the wall baffles in the FCC riser.

The concept of a downer FCC reactor has been an active research subject of circulating fluidized bed. The concept of the downer is based on the premise that solids back-mixing would no longer be an issue in co-current gas-solids two-phase downflow. However, the downer has its own challenges and drawbacks. A few cases of commercial experience with downer FCC reactors by others have not been clear success at all [12].
3. Riser termination and close-coupled cyclones

Process Considerations

It is important to recognize that FCC is a sequential reaction process in which many desirable products, such as gasoline, are intermediates. Modern FCC risers are designed with the residence time required for maximizing desirable products. However, once the reactor mixture leaves the riser, cracking reactions must be terminated as sharply as possible; otherwise, desirable products will continue to crack, leading to excess productions of light gases and coke.

Engineering Practice

A successfully designed riser termination device (RTD) terminates the cracking reactions as soon as possible. There are a number of variations of riser termination devices to achieve such objective by combination of some or all of following three process tactics:

- Separating catalyst from the product gas, which will terminate catalytic reactions
- Reducing product gas residence time, which will reduce both catalytic and thermal cracking, and
- Reducing temperature [13], which will reduce catalytic cracking, but more importantly, will reduce thermal cracking reactions

A couple of related process considerations should also be kept in the background in the design of riser termination:

- At riser outlet, product gas consists of both interstitial gas phase and the intra-particle gas trapped inside catalyst pores.
- Reducing temperature generally reduces stripping efficiency downstream.

Older FCC units have the reactor mixture discharged from the riser into an open reactor vessel, leading to substantial post riser residence time and over cracking. Modern FCC riser design includes an improved riser termination device, which allows quick separation of catalyst and product gas to minimize post-riser cracking. One such device is called the pre-stripping cyclone [14], which incorporates all three process tactics above. Figure 5 shows a schematic drawing of this cyclone design in which the upper part is a typical cyclone for fast separation of catalyst and interstitial product gas. The lower part of the stripper cyclone serves as the stripper bed where steam is injected to further remove entrained interstitial product gas as well as part of the intra-particle product gas trapped inside catalyst pores. The upper and lower part of the stripper cyclone is separated by a stabilizer, which separates the vigorous spinning motion above from the more quiescent stripper region below. The stripping steam also serves to reduce the temperature by a few degrees. The advantage of this design is
to achieve earliest possible disengagement of product gas and catalyst, thus minimizing post-riser cracking.

Modern FCC units’ riser termination further includes the arrangement called close-coupled cyclones. The objective of the close-coupled cyclones is to reduce post-riser cracking by not allowing product vapor to enter the reactor vessel. There are several variations of close-coupled designs deployed in the industry. Figure 5 shows one example [14] in which the vapor outlet from the primary cyclone is “closely coupled” to the inlet of the secondary cyclone, by aligned the two hydrodynamically. There is a gap between the primary cyclone outlet duct and the secondary inlet duct to allow stripper vapor to enter the secondary cyclones. In this arrangement, since the secondary cyclones are operating below reactor pressure, the product vapor passes from the riser, to the primary cyclones, secondary cyclones and straight to the fractionation without entering the reactor vessel.

3. Standpipe Flow

Process Considerations

The FCC process requires continuous catalyst circulation between the reactor and the regenerator in order to achieve two main process objectives. One is to restore catalyst activity by burning off coke deposition on spent catalyst. The other is to keep the FCC unit in heat balance by continuously removing heat from the regenerator and providing heat to the reactor for vaporizing and cracking the liquid hydrocarbon feedstock.

Catalyst circulation between the reactor and the regenerator is driven by unit pressure balance. Although the pressure balance of the FCC unit consists of numerous parameters, most of these parameters are set by overall unit layout and process conditions and, therefore, seldom vary. In contrast, pressure gains in the standpipes can vary significantly, which ultimately determine the pressure differentials available for slide valve control for achieving several critical functions in the FCC process:

- controlling reactor riser temperature and cracking severity,
- regulating reactor catalyst level, and
• serving as safeguard against flow reversal.

Engineering Practice

The standpipe is a simple catalyst transfer conduit with very few critical design requirements. Pressure gain in a standpipe is known to depend mainly on two design elements. The first element is aeration along the standpipe, which is relatively straightforward. As catalyst flows downward in the standpipe, the static pressure increases, and the gas phase moving along with the catalyst is compressed. In order to maintain proper fluidization of the catalyst flow and to continue the pressure gain, aeration gas is added to compensate for the volumetric loss due to the increase in static pressure.

The second key design element of a standpipe is the standpipe inlet, which is the focus of this discussion. The conventional standpipe design adds an inlet hopper at the top of the standpipe [15]. The basic design concept is that bubbles are known to enter the standpipe together with the catalyst flow. The inlet hopper provides residence time for bubbles to coalesce and grow into large bubbles; since large bubbles have a higher riser velocity, they have a better chance of escaping back into the fluidized bed, thereby reducing gas entrainment in the standpipe.

The fundamental flaw of the conventional design concept is that, while the objective of the standpipe inlet design is supposed to reduce gas entrainment into the standpipe, the design requires that many bubbles be drawn into the hopper in the first place. The consequences are that

• If the inlet hopper is too small, many bubbles drawn into the inlet hopper do not have enough residence time to coalesce and grow; instead, the bubbles flow directly into the standpipe, leading to high gas entrainment.
• If the inlet hopper is large enough to allow small bubbles to grow, large bubbles could hang stationary inside the hopper for an extended period of time, which can temporarily restrict catalyst flow into the standpipe. When the bubbles finally grow large enough to escape, the release of the large bubbles creates a sudden surge of catalyst flow, causing a sudden pressure swing in the standpipe. Thus, even if the inlet hopper functions as intended, the sequence of growing and releasing of large bubbles leads to an unstable standpipe operation, which it is supposed to prevent.

It is also important to recognize that a FCC unit is designed to operate in a wide range of conditions. Therefore, a standpipe inlet hopper could be too small at the high end of catalyst circulation and too large at the low end.

The new standpipe inlet design, called catalyst circulation enhancement technology (CCET) [16], takes a different approach. The basic concept of this design is to remove excess bubbles from the fluidized bed before catalyst entering the standpipe. As shown in Figure 6, this standpipe inlet design uses the disk outside the standpipe to trigger a local, partial de-
fluidization and to form a dense bed region outside the standpipe, as shown conceptually by the circle in Figure 6. By re-introducing a small amount of fluidization gas above the disk, the fluidization condition of the standpipe inlet region is optimized and controlled independently from the process conditions of the process. This enables standpipe to operate a wide range of conditions with high pressure build-up and stable operation. Commercial experience confirms that this new technology can improve catalyst circulation rate by as much as 50%.

4. Third Stage Separator (TSS)

Process Considerations

The FCC process requires continuous regeneration of spent catalyst by burning off coke with air in the regenerator operating at relatively high fluidization of ~ 3 ft/sec superficial velocity. The regenerator is typically designed with multiple pairs of two-stage cyclones to capture and return entrained catalyst back to the fluidized bed. However, in order to handle large volume of flue gas, these regenerator cyclones are relatively large in diameter and are not very effective in capturing small catalyst particles.

New environmental regulation mandates reduction in flue gas particulate emission. In addition, the new regulation also requires major reduction in flue gas NOx emission, which is typically achieved by Selective Catalytic Reduction (SCR) process with a catalyst bed prone to plugging. Conventional technology for flue gas particulate removal includes electro-static precipitators (ESP) and wet scrubbers. New cyclonic technology provides an alternative as a viable solution.

Engineering Practice

The cyclonic design of the catalyst fine removal downstream of the regenerator cyclones must achieve two objectives:

- a high separation efficiency for catalyst fines, which requires a small diameter cyclonic separator
- a capability of handling a large flue gas volume.

The solution is a device called a Third Stage Separator (TSS), shown in Figure 7 [17]. In order to achieve high separation efficiency of catalyst fines, the TSS system uses a
A specially designed separation element, called a swirl tube, with a relatively small diameter. A key difference from conventional cyclone design is that the swirl tube is an axial flow cyclonic separator using a swirl vane at the inlet to induce fast rotating motion. By using the axial flow separator, a large number of swirl tubes can be installed in a common TSS vessel to handle the large volume of flue gas.

![Diagram of Shell Global Solutions' Third Stage Separator (TSS)](image)

**Figure 6 Shell Global Solutions’ Third Stage Separator (TSS)**

Recent advances in the swirl tube design enable the technology to reach a cut point of 2 microns. This has been proven commercially to meet the most stringent particulate emission requirements in the world, including MACT II requirement in the US. Furthermore, by reducing the catalyst fine loading to below 50 mg/m³, downstream flue gas treatment equipment, such as SCR, is protected.

**Concluding Remarks**

The FCC process has been the most important refining conversion process in the past 60 years. Through a few examples, this paper highlights some recent advances of the technology to meet new demands and challenges. Although the FCC process continues to evolve, there is no doubt that it will continue to serve a central role in the future of the refining business.
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