AFPM

Annual Meeting
March 19-21, 2017
Marriott Rivercenter
San Antonio, TX

AM-17-77

Improving FCC Economics through Computational Particle Fluid Dynamics Simulation

Presented By:

Peter Blaser
CPFD Software, LLC
Albuquerque, NM

Ray Fletcher
CPFD Software, LLC
Albuquerque, NM

Sam Clark
CPFD Software, LLC
Albuquerque, NM

American Fuel & Petrochemical Manufacturers
1667 K Street, NW
Suite 700
Washington, DC
20006.3896
202.457.0480 voice
202.457.0486 fax
www.afpm.org

Improving FCC Economics through Computational Particle Fluid Dynamics Simulation

Peter Blaser, ***Vice President of Engineering Services***
Ray Fletcher, ***FCC Senior Technologist***
Sam Clark, ***Senior Project Engineer, Chemical***

CPFD Software, LLC
10899 Montgomery Blvd. NE, Suite A, Albuquerque, NM 87111 USA
E-mail: peter.blaser@cpfd-software.com

Introduction

The FCC unit has a long history of upgrading low valued feed stocks into much higher valued LPG olefins and motor fuels. FCCUs are resilient to variations in feed availability, quality and cost as well as significant changes in the market value of the products produced. This resilience comes about via flexibility in the catalyst used and operational conditions employed, which are modified within an operational cycle between turnarounds.

Potential for increasing profitability through modification of the configuration or design of FCCU components is often limited due to challenges in diagnosing the root causes of under-performance and the risk of possible negative impacts of implementing changes on operational reliability. Gains obtained via modifications to a stable but sub-optimal process can be quickly erased if unforeseen, adverse effects are experienced, particularly if the changes result in an unplanned shutdown. The result is a strong preference for the status quo over uncertainty, due to the lack of means to test proposed improvements prior to implementation.

In recent years computational particle fluid dynamics engineering simulation technology has emerged as a powerful tool enabling refiners to "look inside" their FCCU and test the effect of proposed changes to equipment and process design. Simulation is being used to address issues such as erosion, catalyst losses, afterburn and emissions by identifying the root causes of operational problems and the effect of potential solutions.

Several papers have been published during the past 12 months in which the unique circumstances surrounding maldistribution in FCC regenerators has been discussed[1,2,3,4]. In recent years, numerous refiners have utilized Barracuda Virtual Reactor® to successfully identify the root causes surrounding long-term, persistent afterburn and emissions issues. Virtual Reactor™ has been used to substantially reduce or eliminate such afterburn.

This paper describes many additional structural issues which are endemic to the FCC operation resulting in limitations in operational flexibility with subsequent negative impact on economics. These issues include items such as incomplete combustion of spent catalyst within the regenerator commonly referred to as the "salt and pepper" appearance of regenerated catalyst, erosion of reactor or regenerator hardware leading to unscheduled shutdowns or reduced cycle length, and poor aeration at the inlets of regenerated catalyst hoppers and along the length of the standpipes leading to poor fluidization and reduced catalyst circulation rates.

Each of the above conditions results in limited operational flexibility with either direct or indirect negative impacts on profitability. An FCC unit capable of stable operation through the entire planned operating cycle will represent the greatest potential for maximum profitability for refiners today. In all cases, unplanned shutdowns remain one of the leading causes for reduced FCC profitability.

The remainder of this paper has been divided into three primary classifications: regenerator maldistribution, catalyst-impact erosion and catalyst circulation stability.

Regenerator Maldistribution

Regenerator maldistribution remains, for most refiners, the leading cause of reduced operating flexibility for the FCC unit. The two leading characteristics of maldistribution within the regenerator are observed as afterburn and/or increased emissions. In nearly every case of significant afterburn the leading cause is due to poor spent catalyst distribution over the cross-sectional area of the regenerator at the point of entry. There exists substantial mixing of catalyst in the vertical direction but very limited mixing in the horizontal plane[5].

Side entry spent catalyst injection frequently results in catalyst distribution over less than half of the regenerator cross-sectional area. This is accurate regardless of whether the injection point is equipped with a “ski jump”. Note: a ski jump typically refers to a flat plate at an angle of 20° to 30° above the plane of catalyst flow with the intention of imparting increased direction of flow of the spent catalyst towards the center of the regenerator cross-sectional area.

Regenerators in which the spent catalyst standpipe has been extended well into the regenerator vessel and equipped with inertial separation devices such as “snowplows” and multiple aeration points are also subject to maldistribution leading to afterburn. Note: snowplows refer to plates installed at the spent catalyst standpipe exit in order to distribute catalyst more evenly across the cross-sectional area of the regenerator.

In both cases, the region where the spent catalyst is deposited into the regenerator tends to be rich in carbon which quickly consumes all available oxygen leading to a partial burn condition within that quadrant of the regenerator. Substantial concentrations of carbon monoxide are observed within the dilute phase of this zone. The side opposite the point of catalyst entry tends to be lean in carbon with excess oxygen present in the dilute phase. The carbon monoxide-rich and oxygen-rich zones mix in the dilute phase or within the cyclones leading to afterburn[6] (see Figure 1).

Additionally, center entry regenerators having large diameters are also prone to maldistribution. The maldistribution observed in this case is one of a core/annular temperature distribution in which the core or center of the regenerator is rich in carbon and has quickly consumed available oxygen resulting in lower temperatures and higher concentrations of carbon monoxide in the dilute phase of the regenerator. The annular region of the regenerator tends to be lean in carbon having excess oxygen present in the dilute phase. These carbon monoxide- and oxygen-rich regions mix in the upper areas of the dilute phase or within the cyclones leading to afterburn (see Figure 2).

Occasionally, afterburn is observed towards the end of a long operating cycle as a result of damage to the combustion air grid. The root cause of such cases is generally straightforward to troubleshoot. Typically one sees simultaneous step changes observed in the horizontal and vertical temperature profiles of the regenerator while the pressure differential observed over the combustion air control valve experiences a step change decrease.

More frequently, however, the experience of the industry is that the afterburn being observed today is the result of less than optimal spent catalyst distribution and is structural in nature. CPFD Software has presented three papers in the last 12 months describing these scenarios in significant detail. The reader is directed to these papers[7] for detailed explanations of the symptoms, root causes and solutions for structural maldistribution leading to afterburn.

An additional aspect of maldistribution which has yet to be developed within the open literature is the observation of the so-called "salt-and-pepper" appearance of the regenerated catalyst in many units. The salt-and-pepper appearance of regenerated catalyst is the direct result of spent catalyst being short-circuited directly from the spent catalyst entry point into the regenerated catalyst hopper; any non-regenerated catalyst entering the standpipe results in reduced conversion and thereby directly impacts unit profitability.

Engineering judgment is often employed by observing the proximity of the spent catalyst entry to the regenerated catalyst hopper to extrapolate the root cause for short-circuiting. One successful solution to short-circuiting may be the installation of a baffle at the point of spent catalyst entry to direct spent catalyst away from the inlet of the regenerated catalyst hopper. However, the experience of many refiners suggests that such approaches are not always successful.

The use of simulation enables the refiner experiencing the salt-and-pepper appearance of their regenerated catalyst to identify the root cause behind the observed short-circuiting. Figure 3 shows the carbon on regenerated catalyst for all catalyst entering the regenerated catalyst standpipe. A bimodal distribution is detected in the plot. While most particles have less than 10% of the carbon relative to the spent catalyst, a peak is observed on the right of the figure, representing catalyst that short-circuited from the spent catalyst distributor directly to the standpipe, with little or no contact with combustion air. Analyzing only the spent catalyst with less than 100 seconds of residence time in the regenerator, a clear by-pass is observed as shown in Figure 4. Figure 5 shows a visualization of simulation results of the by-pass leading to the salt-and-pepper condition.

Frequently, it is observed that prevailing flow patterns within the regenerator are non-intuitive and difficult to predict. Simulation enables the refiner to identify both the presence and magnitude of such flow patterns. Such a refiner is then able to deliver the results of the simulation study to their chosen engineering company for solution. The refiner will then be able to verify the effect of the proposed modifications via simulation to ensure that the root cause has been adequately addressed, minimizing unexpected, adverse consequences of the change. In the authors' experience, adverse consequences are often present and surprising; for example, spent catalyst distributor changes or baffles can rectify salt-and-pepper catalyst but may, in turn, negatively impact afterburn and emissions.

Figure 6 shows the effect of a proposed change on the residence time distribution for the by-passing catalyst. In this case, the second geometry reduces the severity of the by-pass, but the root cause remains unchanged. By identifying the root cause in advance of turnaround planning, the probability of success is greatly increased for refiners seeking to optimize regenerator performance and, in turn, refinery profitability.

Erosion

Excessive erosion of regenerator internals frequently leads to unplanned shutdowns due to high catalyst loss rates. Such losses are generally the result of damage to cyclones, crossover tubes or the plenum itself. The end result of such damage is excessive catalyst losses to the point that continued operation is not possible. It is an unfortunate fact when circulating high volumes of abrasive catalysts that small increases in catalyst losses due to a cyclone hole eventually increase to the point that a shutdown is unavoidable. Erosion is not limited to regenerators, and also frequently affects riser termination devices and reactor internals.

A second observation in the industry is that once the FCCU is shut down for turnaround, inspection of internals often discloses substantial areas of erosion of metal surfaces and the abrasion lining of the unit walls. Such unanticipated areas of erosion lead to unplanned extensions to turnaround duration, and related lost revenue. Both the unplanned shutdown as well as the extended shutdown as a result of erosion have a direct and negative impact on the profitability of the FCC unit and the entire refinery.

Virtual Reactor simulation has the unique capability of identifying regions of high erosion which may lead to extensive damage to walls or internals. The simulation tracks both the direction of particle flows and the velocity of the catalyst upon impact with internal structures. Regions with excessive high velocity impacts are easily identified via simulation. The refiner is recommended to run an erosion simulation of their FCCU components if past inspections after shutdown have observed excessive wear. It is also recommended to evaluate the reactor and regenerator, in particular, for new potential regions of high erosion whenever changes are made to the design or configuration of internals.

Simulation is able to identify the root cause for high velocity catalyst impact, which was the first application of Virtual Reactor simulation of FCCUs[8]. Figure 7 shows the catalyst distribution inside a regenerator. While the spent catalyst distributor does a good job of evening out catalyst maldistribution exiting the transfer line, Figure 8 shows a surprisingly higher probability of erosion on the internals on the left side of the vessel. Use of simulation identified lift air jetting from the spent catalyst distributor as the root cause of the catalyst impact erosion on internals.

Similarly, simulation has been used to minimize reactor cyclone erosion[9]. Figure 9 shows that the Virtual Reactor-predicted erosion compared well with data from the refiner's past inspection reports. The calibrated baseline model enabled virtual testing of changes prior to hardware purchase and installation in anticipation of a scheduled turn-around. Simulation results revealed not only the presence of the excessive erosion, but the gas flows which accelerate the catalyst into the cross-over walls as shown in Figure 10. The results were used to select between various alternative designs during turnaround planning.

Knowledge of potential high-erosion zones enables the modification of internal structures such that the impact of the high velocity streams are minimized or eliminated. The solution may be as simple as modifying the direction of one or more air nozzles at the combustion air grid for regenerator erosion.

The use of Virtual Reactor simulation to identify and correct the root causes for high erosion enables refiners to achieve their cycle length goals and minimize or eliminate the need for extensive repairs during planned shutdowns. The use of simulation greatly reduces the risk of unplanned shutdowns, reduces or eliminates the need for extensive repairs to high erosion zones and reduces or eliminates the cost of such repairs, directly improving the long-term reliability and profitability of the FCC unit.

Catalyst Circulation Stability

The three most common causes for poor fluidization resulting in lower-than-designed catalyst mass flux rates within the regenerated catalyst standpipe are improper aeration at the regenerated catalyst hopper inlet, improper aeration at the aeration points along the length of the regenerated catalyst standpipe and the use of hybrid angled standpipes. Regenerated catalyst hopper inlets and standpipe aeration will be addressed in this paper. The subject of hybrid angled standpipes will be handled as a "standalone" issue in a subsequent paper[10].

Regenerated catalyst hopper inlet aeration. Proper aeration at the point of catalyst entry into the regenerated catalyst hopper has been a subject receiving much attention over the last 70+ years of FCC operations. This area may also represent one of the most difficult to effectively troubleshoot. In general, the design of regenerated catalyst hoppers has been non-symmetrical at both the horizontal plane of entry (i.e., oval rather than circular) and along the vertical axis of the hopper. The angle from the point of entry of the hopper to the standpipe itself is also nonsymmetrical on all sides (see Figure 11). Additionally, the hopper entry may be flush with the bottom of the regenerator head or elevated within the regenerator itself.

In many cases, large bubbles of combustion air may be drawn into the hopper inlet resulting in low density catalyst/air mixtures leading to unstable standpipe operations. The intention of the design of the regenerated catalyst hopper inlet is to create one capable of releasing excess combustion air back into the regenerator prior to the catalyst entering the regenerated standpipe itself.

An alternate possibility is that "slugs" of poorly aerated catalyst may enter the standpipe leading to a condition of under-aeration also resulting in poor standpipe fluidization. In such a case, the designer of the hopper will regularly include an air ring at the entrance of the hopper to avoid this condition of under-aeration. The risk experienced by the FCC operator is that the aeration ring airflow may be set too high or too low. Either case will result in suboptimal standpipe fluidization.

Experimentation via increases or decreases in hopper inlet aeration are generally avoided due to the uncertainty of whether such variations will either stabilize or destabilize the standpipe operation. The net result is that the operation may suffer from improper aeration for years leading to less than optimal standpipe mass flux rates with reduced catalyst circulation rates. Reduced catalyst circulation limits conversion with a direct negative impact on unit profitability. Similarly, variable circulation can be traced to variation in riser outlet temperature and directly impacts product selectivity.

Refiners may successfully utilize Virtual Reactor simulation to identify whether current hopper design or aeration rates are leading to a condition of over- or under-aeration. Figure 12 compares simulation results for two regenerators, with and without a regenerated catalyst hopper. In this example, the hopper acts to stabilize catalyst circulation out of the regenerator. A refiner utilizing simulation has the ability to manipulate the aeration rates within the computer model in either direction to determine whether the standpipe operation will be stabilized or destabilized. Virtual Reactor enables refiners to troubleshoot regenerated catalyst hopper inlet aeration rates with confidence.

<u>Regenerated catalyst standpipe aeration.</u> The catalyst/air mixture entering the regenerated catalyst hopper first undergoes de-aeration prior to entering the standpipe. The pressure exerted on the catalyst/air mixture within the standpipe increases as the mixture flows down the length of the standpipe leading to increased head. The increased head results in compression of the air with the result that the catalyst particles become closer packed.

For certain standpipes having long lengths the catalyst packing may continue until the point is reached that the catalyst begins to support its own weight on the standpipe walls leading to what is termed as a “slip/stick” flow. Slip/stick flow represents poor fluidization in every case and less than optimal catalyst mass flux rates. Aeration air is injected to counter the normal compression of the catalyst/air mixture as it proceeds down the length of the standpipe.

Much effort has been placed, over the last seven decades of FCC operations, to properly set aeration rates within standpipes. Many excellent correlations have been developed to calculate the required aeration rates at each elevation. The empirical experience of the industry indicates that most or all of these equations tend to over predict the amount of aeration rate required. The standard procedure is to calculate the “theoretical aeration rate” and multiply this rate by a factor of approximately 0.7 to achieve the “actual required aeration rates”[11]. It is further recommended that the process engineer troubleshooting poor fluidization on a catalyst standpipe avoid making aeration rate changes late on Friday afternoon! It has been frequently observed that changes in aeration rates may initially appear to be beneficial only to result in poor fluidization within a few hours or days.

Over-aeration of catalyst standpipes leads to the formation of a permanent bubble at the point of injection which forces the catalyst/air mixture to flow around the bubble or to free flow through the bubble leading to reduced head and catalyst circulation rates. Alternatively, under-aeration may result in slip/stick flow also leading to reduced catalyst circulation. The difficulty facing the process engineer is whether the new aeration rate will be optimal under all of the standpipe conditions normally experienced during operations. This uncertainty leads most refiners to set aeration rates at the beginning of a cycle and avoid making adjustments thereafter.

The use of Virtual Reactor simulation enables the process engineer to simulate the standpipe operation at various mass flux rates to determine whether current aeration rates may be further improved in terms of pressure build and circulation stability. Figure 13 shows the effect of aeration on standpipe pressure build[12]. In this example, increasing aeration improves pressure build. However, excessive aeration can negatively impact stability of catalyst circulation, as shown in Figure 14, manifesting as oscillation in the circulation rate. These oscillations can be traced to the formation and motion of large bubbles through the standpipe, as shown in Figure 15.

In actuality, the roles of regenerated catalyst inlet hopper design, hopper aeration and standpipe aeration are interrelated. Excessive standpipe aeration may form the bubble shown in Figure 15. However, a poorly designed or aerated hopper is more prone to bubbles entering the standpipe. Proper standpipe aeration will prove to be more forgiving than a poorly-chosen aeration rate.

Using Virtual Reactor simulation, process engineers are now able to understand the root cause of catalyst circulation instabilities and enact substantial improvements in reliability, increasing the circulation stability for a range of catalyst mass flux rates. Simulation enables the process engineer to perform his or her responsibility with a substantial increase in confidence.

Conclusion

Barracuda Virtual Reactor simulation continues to develop new techniques to successfully troubleshoot the most difficult issues surrounding the reliable operation of a Fluidized Catalytic Cracker. The FCC process engineer is increasingly able to successfully identify and seek solutions to the root causes resulting in regenerator maldistribution, FCCU erosion and catalyst circulation instability. Solutions to each of these conditions will result in a direct or indirect improvement in unit reliability and profitability.

Figures

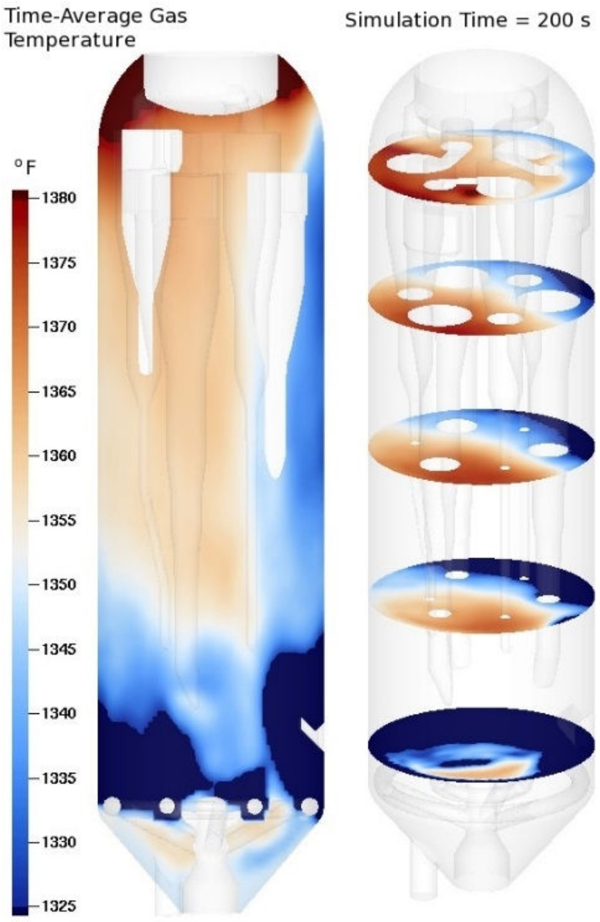

Figure 1. Side entry regenerator temperature profile

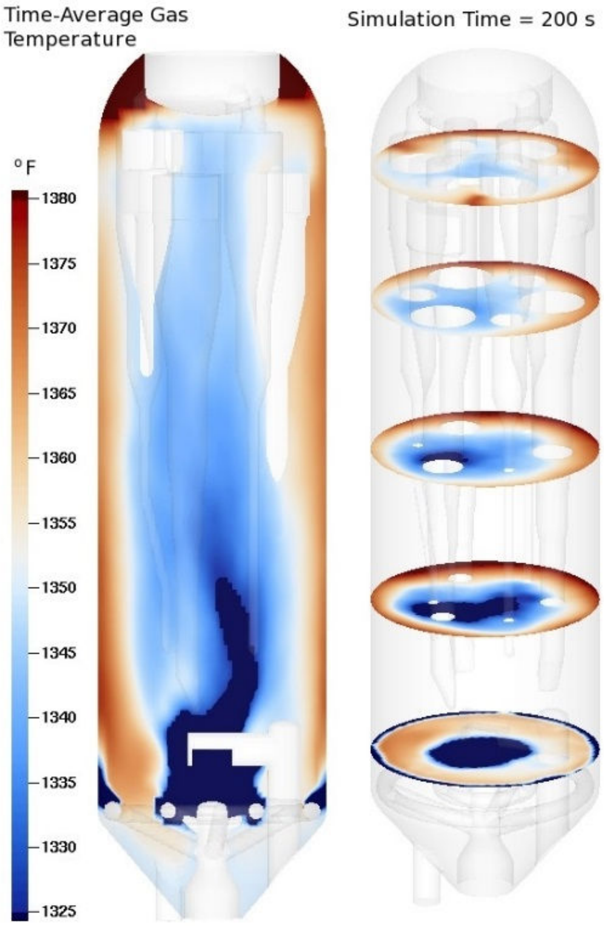

Figure 2. Center entry regenerator temperature profile

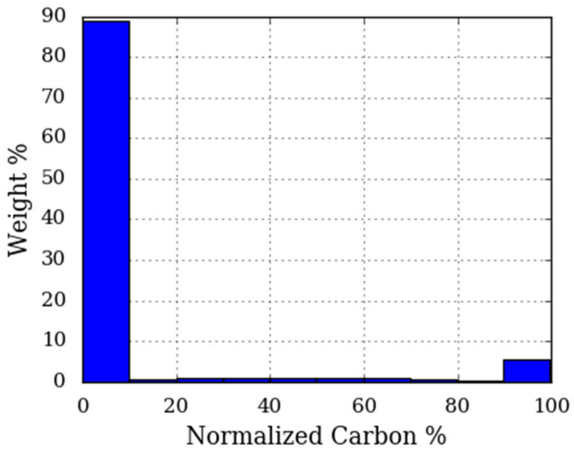

Figure 3. Salt and pepper catalyst (normalized by carbon on spent catalyst)

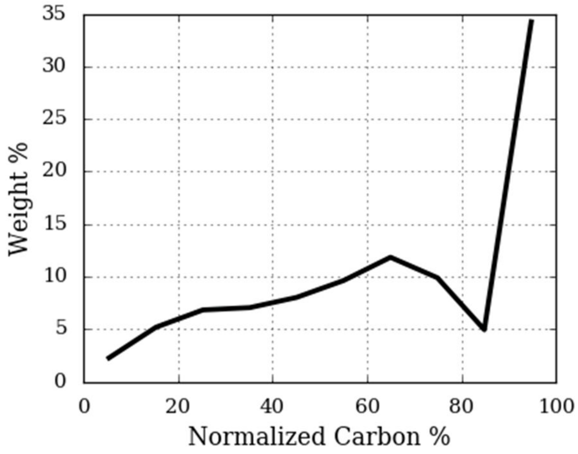

Figure 4. Carbon distribution for catalyst with short regenerator residence time

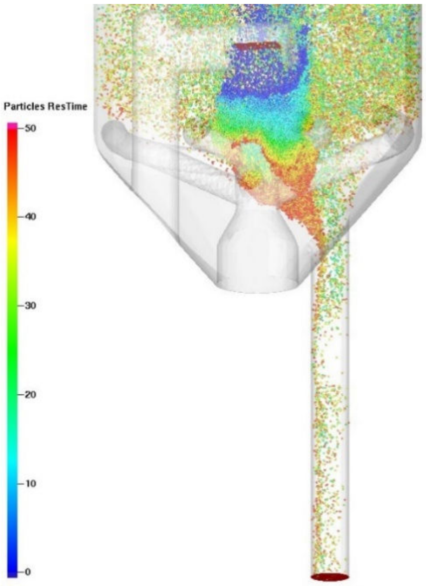

Figure 5. Spent catalyst bypassing (only catalyst with less than 50 seconds residence time shown)

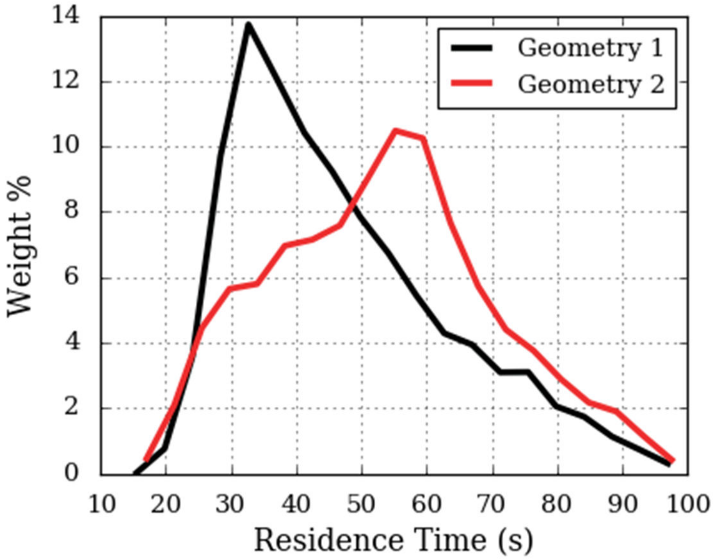

Figure 6. Effect of design change on spent catalyst bypassing (only catalyst with less than 100 seconds residence time shown)

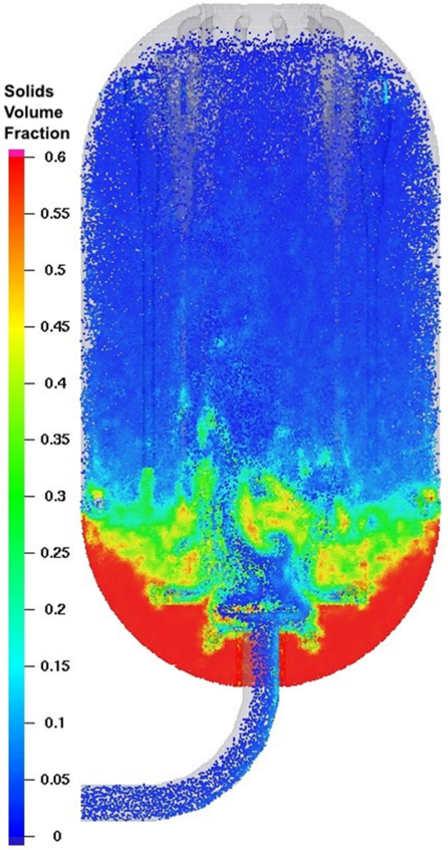

Figure 7. Simulated catalyst distribution in an FCC regenerator

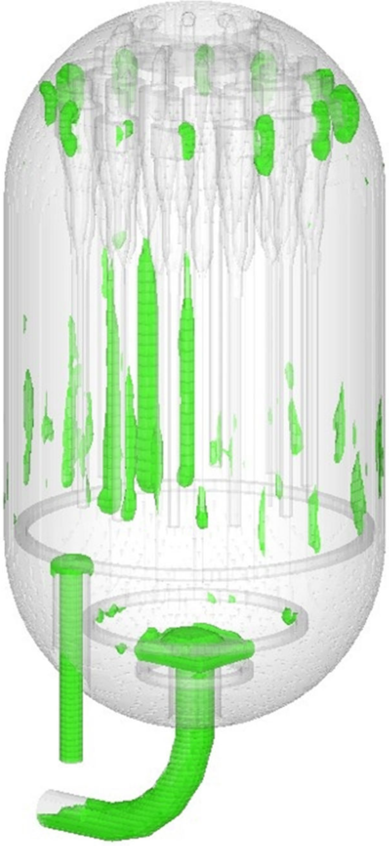

Figure 8. Simulated regions with high erosion

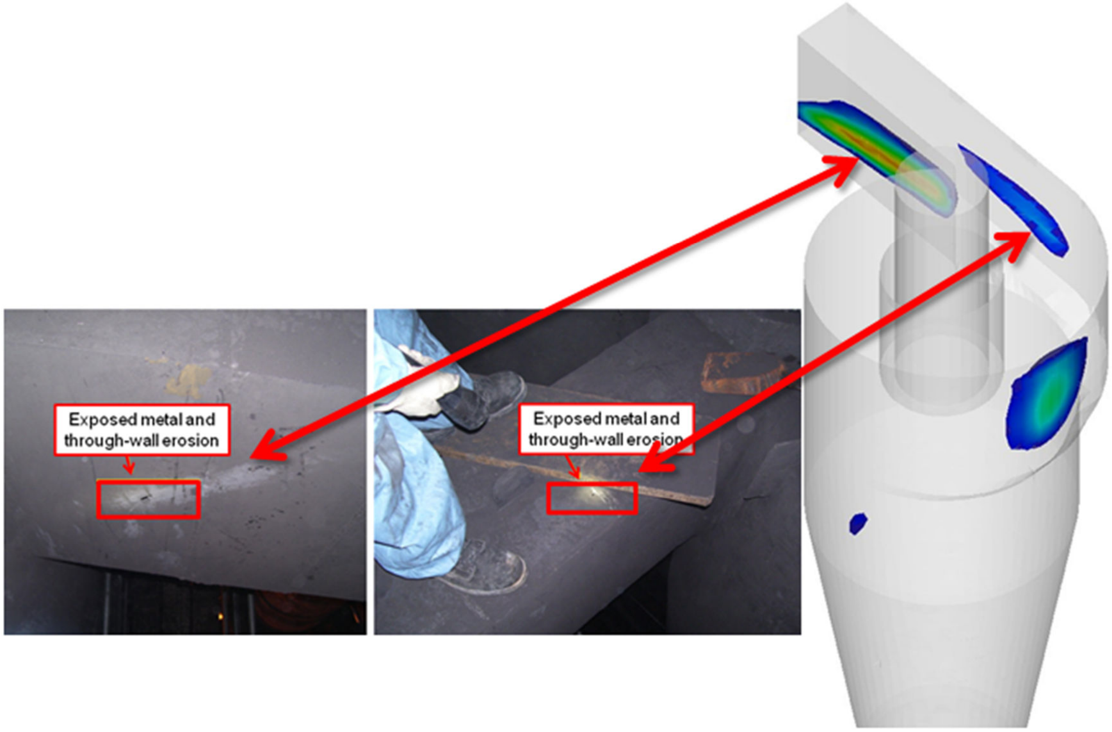

Figure 9. Simulated erosion compared with inspection report findings

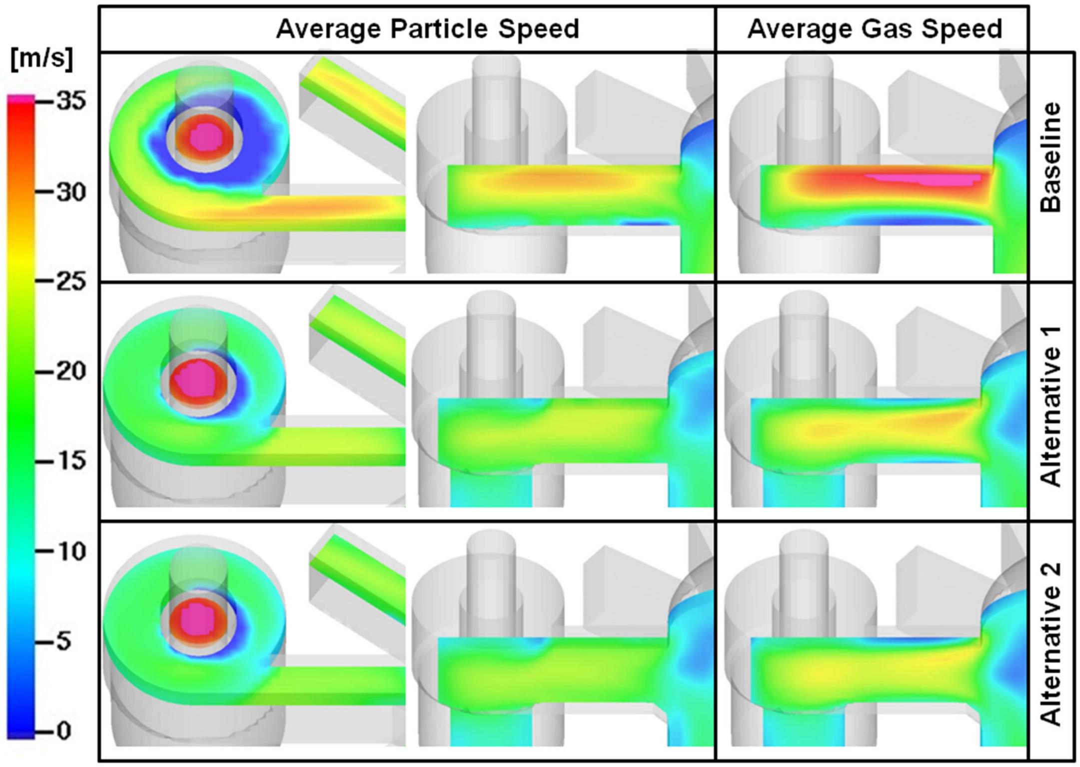

Figure 10. Root cause of high particle velocities in high erosion regions due to acceleration by high velocity gas streams. Alternate designs were verified via simulation during down selection in turnaround planning.

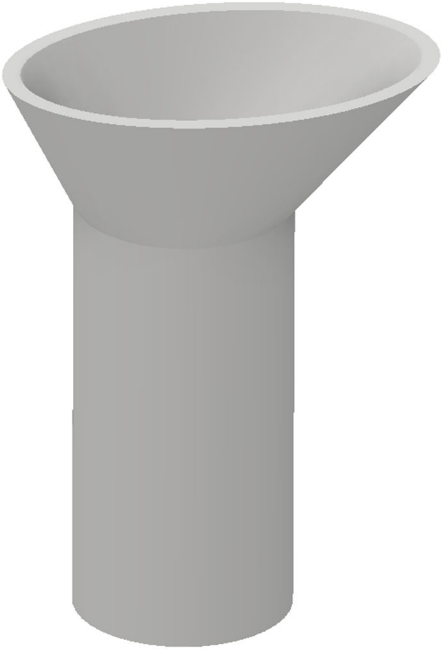

Figure 11. Sample regenerated catalyst hopper geometry

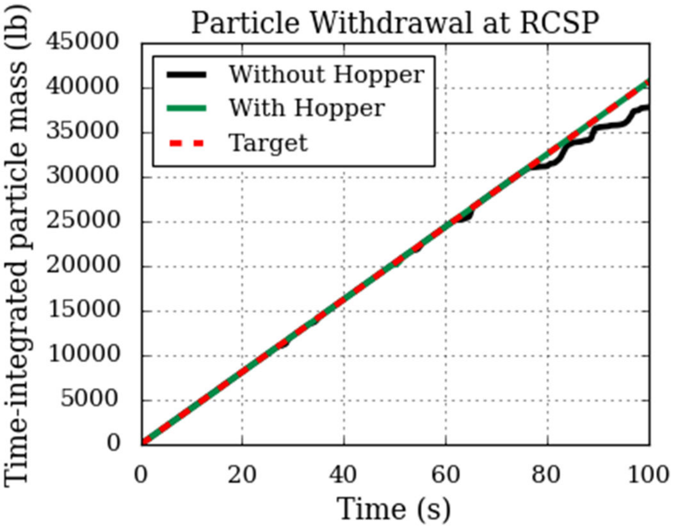

Figure 12. Effect of regenerated catalyst hopper geometry on stability of catalyst circulation

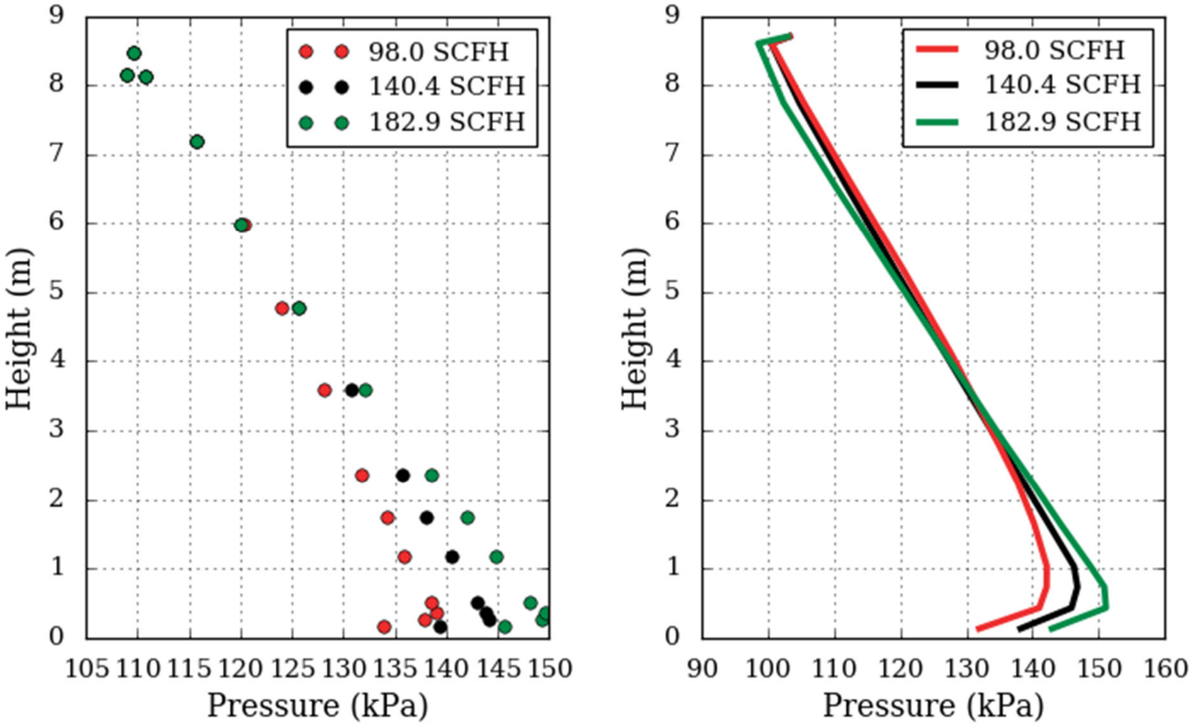

Figure 13. Pressure build in a standpipe as a function of aeration rate (left – experimental data, right – simulation)

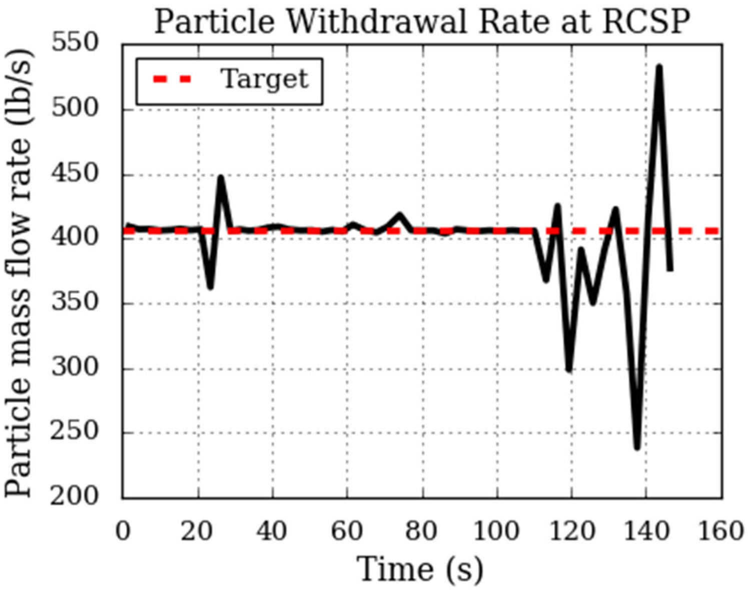

Figure 14. Effect of over aeration on catalyst circulation stability

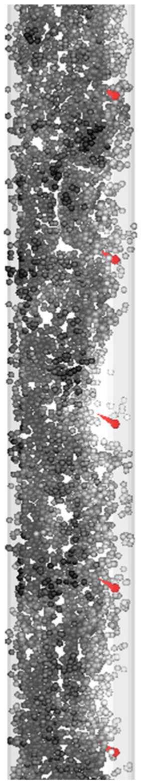

Figure 15. Role of bubbles in stability of catalyst circulation

---

[1] Fletcher, R., Clark, S., Parker, J., and Blaser, P. "Identifying the Root Cause of Afterburn in Fluidized Catalytic Crackers", AFPM 2016 Annual Meeting, AM-16-15 (2016).

[2] Fletcher, R., Blaser, P., Pendergrass, J., and Peccatiello, K. "The Experience of a Team of Experts to Resolve Severe FCC Regenerator Maldistribution", AFPM 2016 Cat Cracker Seminar, CAT-16-17 (2016).

[3] Singh, R., Gbordzoe, E. "Modeling FCC Spent Catalyst Regeneration with Computational Fluid Dynamics", Powder Technology (2016).

[4] Blaser, P. "Extension of Fluidized Catalytic Cracking Regenerator Modeling to Improve Emissions Performance", AIChE 2016 Annual Meeting (2016).

[5] The reader is directed to J.W. Wilson's analysis of afterburning as presented in the 2003 NPRA Annual Meeting ("FCC Regenerator Afterburn Causes and Cures", AM-03-44)

[6] See AM-16-15 for a detailed treatment of side-entry and center-entry regenerator afterburn

[7] In particular see AFPM papers AM-16-15 and CAT-16-17.

[8] Clark, S., "Particle-Fluid Flow Simulations of an FCC Regenerator" in "10th International Conference on Circulating Fluidized Beds and Fluidization Technology - CFB-10" (2011).

[9] Blaser, P., Thibault, S., and Sexton, J. "Use of Computational Modeling for FCC Reactor Cyclone Erosion Reduction at the Marathon Petroleum Catlettsburg Refinery", Proceedings of World Fluidization Conference XIV: From Fundamentals to Products, 347-354, (2013).

[10] Stripper catalyst circulation has also been explored using Virtual Reactor simulation, but is outside the scope of this paper. The reader is directed to Singh, R. and Gbordzoe, E. "Design and Troubleshooting FCC Operation Using CFD Techniques." AIChE 2016 Annual Meeting (2016) for stripper circulation stability considerations.

[11] For example, see Mott, R. "Troubleshooting FCC Standpipe Circulation Problems." Catalagram, 106, (2009).

[12] Experimental data taken from Srivastava, A., Agrawal, K., Sundaresan, S., Karri, R., and Knowlton, T. "Dynamics of Gas-Particle Flow in Circulating Fluidized Beds." Powder Technology, 100:173-182 (1998). Simulation results are original work.