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USE OF COMPUTATIONAL MODELING FOR FCC REACTOR CYCLONE EROSION REDUCTION AT THE MARATHON PETROLEUM CATLETTSBURG REFINERY

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ABSTRACT

Modifications to the Fluid Catalytic Cracking (FCC) reactor internals at Marathon Petroleum Company's (MPC's) Catlettsburg Refining facility were planned to mitigate severe erosion in the reactor cyclones. A computational model, specific for gas-particle flows, was created to calculate erosion patterns in the reactor cyclones. The erosion characteristics of candidate redesigns were compared and contrasted with the validated model of the existing unit.

BACKGROUND & OVERVIEW

A Fluid Catalytic Cracking Unit (FCCU) is critical to the performance of many refineries, particularly those focused on gasoline production. The FCCU converts a heavier, lower-value feedstock into a wide variety of higher-value products such as gasoline, diesel and other lighter gases. The process is flexible, allowing for a wide range of feedstocks, and can be utilized to produce a variety of product mixtures by varying operating conditions and catalysts.

A schematic of a generic FCCU is shown on the left of Figure 1 and consists primarily of reactor and regenerator vessels. The heavy hydrocarbon feedstock is injected onto hot catalyst particles and rapidly vaporizes. The gas-particle mixture quickly reacts as it moves swiftly up a riser section, forming lighter-molecule gases and depositing coke on the catalyst particles. Upon exiting the top of the riser, the catalyst is separated from the product gas stream. Remaining hydrocarbons are removed from the catalyst in the stripper section, which may be internal or external to the reactor vessel. The coke is then burned off the spent catalyst particles in the regenerator vessel, cleaning the catalyst while providing the heat that drives the process. Once regenerated, the catalyst is re-introduced to the bottom of the reactor riser, completing the circulation loop.

The primary drivers of refinery economics are performance and reliability, with on-stream reliability being the more important of the two; even a short unplanned outage represents a more significant loss to the operator from lost production than does a small deterioration in conversion or selectivity. Performance relates to how efficiently the feedstock can be converted to the desirable products while minimizing undesirable products and emissions. Reliability relates to how long a unit can be consistently and safely operated without deterioration of performance. For most FCCU's, reliability is often limited by erosion due to impingement by the circulating catalyst. Meanwhile, the reactor and regenerator cyclones are very often the main areas where this erosion occurs.

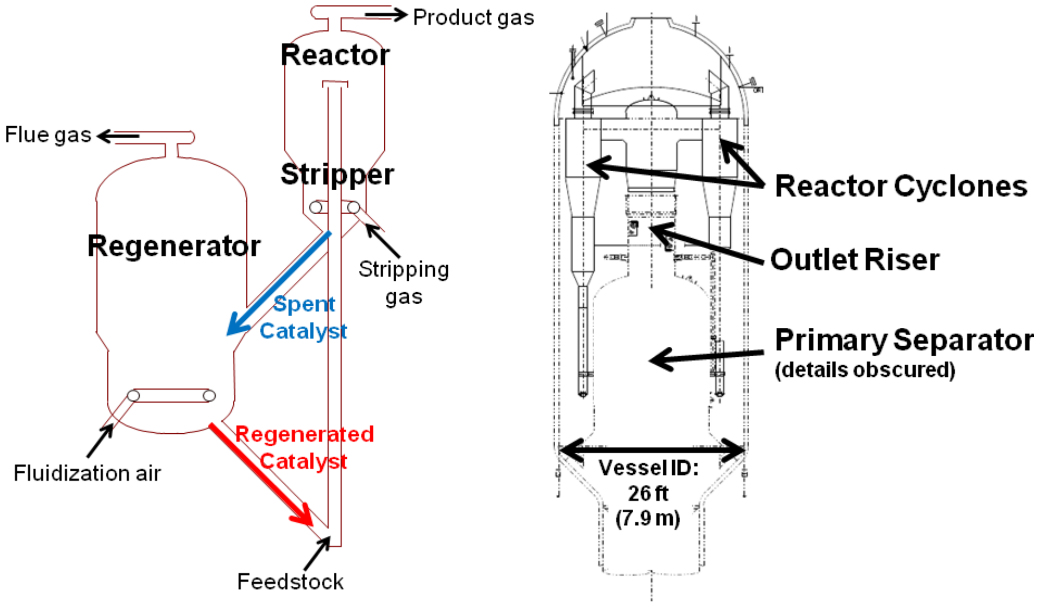

Figure 1. Schematic of FCCU (left), Catlettsburg upper reactor vessel (right)

CATLETTSBURG FCC UNIT

The Catlettsburg FCC unit was originally commissioned in 1983 as the world's first Reduced Crude Conversion (RCC) process unit. The process was jointly developed by UOP and Ashland with a nominal capacity of 43 kbpd. The reactor/riser system was operated at low pressure in order to minimize hydrocarbon partial pressures and promote full and rapid vaporization of the resid feedstock. The RCC unit was converted to an FCC unit in 2003 as part of an overall refinery re-positioning project. The result was a nominal 95 kbpd FCC design with hydrotreated feed. The unit pressure was increased and the 2-stage regenerator was converted to full-burn operation (1).

An elevation drawing of the upper reactor vessel is shown on the right of Figure 1. The vessel internal diameter is 26 feet (7.9m). The current FCC reactor cyclones are 30 years old and are at their mechanical end of life. During a unit turnaround, erosion was found on the cyclone crossover duct. New cyclones will be installed during the next unit turnaround. Changes were planned in an effort to mitigate the erosion, including: enlarging the upper section of the outlet riser, the design and installation of new cyclones, enlarging the crossover connecting the outlet riser to the cyclones, and the installation of anti-vortex baffles in the outlet riser. An additional option was considered whereby the transition between the outlet riser and the crossover was sloped. For the purposes of this work, the primary changes are referenced as the "Alternative 1" design, and the inclusion of the sloped transition with these changes defines the "Alternative 2" design.

MPC desired to better understand the root cause(s) of the excessive erosion in the Catlettsburg FCCU, plus to evaluate the likelihood that the candidate redesign alternatives would minimize the extent and severity of the erosion. To accomplish these dual purposes, a unique multiphase computational fluid dynamics (CFD) method was used to create a detailed 3D computational model of the relevant portions of the FCC reactor cyclone system. The validity of this model was first established by comparing the predicted erosion characteristics for the as-built case with the erosion observed at the refinery. Additional cases were then run to evaluate the erosion performance of the two alternative designs.

COMPUTATIONAL MODEL

The CPFD®, or Computational Particle Fluid Dynamics, method was used to simulate the gas-particle flow inside the upper portion of the reactor. The CPFD method solves the transient fluid and particle mass, momentum and energy equations in three dimensions. The fluid is described by the Navier-Stokes equation with strong coupling with the discrete particles. The particle momentum has been adapted from the Multi-Phase, Particle-In-Cell (MP-PIC) numerical approach (2, 3, 4) which is a Lagrangian description of particle motion coupled with the continuum fluid. The CPFD method is utilized by the commercially-available Barracuda Virtual Reactor™ software package, which has been validated for a wide range of fluid-particle flow problems (5, 6, 7, 8) including refractory erosion studies (9). Barracuda VR™ was used for this erosion study.

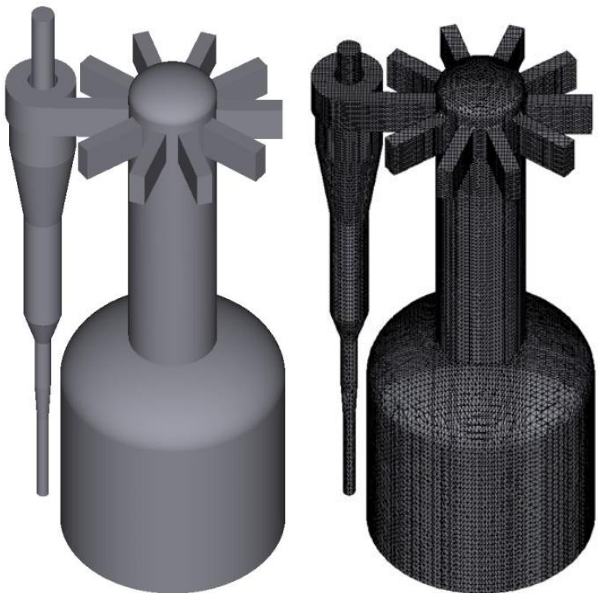

Figure 2. Upper reactor section: 3D solid model (left) and CFD grid (right)

A 3D solid model was created, as shown in the left of Figure 2, consisting of the primary separation chamber, outlet riser, and ten crossover ducts with one of ten cyclones modeled in detail. A computational grid was cut from a 587,000 cell Cartesian mesh, as shown in the right of Figure 2. The resulting numerical model included 190,000 computational cells for scalar calculations; 619,000 cell faces for vector calculations; and 1.6 million computational particles to resolve the catalyst flow field. Note that cell counts in Barracuda VR models are often lower than those used in many CFD models due to the added sub-grid resolution of the discrete, particulate phase. Internal details, including the reactor disengager geometry, anti-vortex baffles, and cyclone vortex tubes, were present in the model but are not visible in Figure 2.

Gas was introduced to the primary separation chamber at the end of multiple disengager arms located at the exit of the reactor riser. A pressure Boundary Condition (BC) was applied at the cyclone exit. Pressure BCs were also used at the end of the other nine crossover ducts. These pressure values were taken from a transient monitoring point in the inlet to the cyclone, and were adjusted slightly to maintain a similar time-averaged gas distribution between the ten crossovers. A pressure boundary condition was also utilized at the bottom of the primary separation chamber, to allow for a mixture of gas outflow with the swirling particle stream while permitting an overall gas inflow from the stripper section below. A minimal amount of gas was permitted to exit at the bottom of the cyclone dipleg. The system pressure was maintained at approximately 2 atm. absolute.

FCC catalyst, with a particle density of 90 pcf (1,450 kg/m^3), was introduced at the disengager arms at a rate exceeding one million lb/h (454 tonnes/hour). The particles were permitted to exit at any of the other BC locations. Some particles were initialized in the cyclone dipleg at the start of the calculation to ensure a proper pressure balance seal.

Since the primary focus of the computational model is related to the extent and severity of surface erosion, simplifying assumptions were made to reduce computational complexity. The chemical reactions were neglected and the gas was modeled as a single species. The entire system was modeled as isothermal at 990°F (805K).

An erosion index was defined to tabulate particle impacts on the refractory-lined surfaces of interest. The erosion index is calculated as follows:

$$I = \frac{\sum_p C_{\propto p} m_p^{1.5} v_p^{3.5}}{A\,T} \tag{1}$$

where C_α is a coefficient that is a function of impact angle, m is the particle mass and v is the particle velocity. The angular coefficient, C_α, was set with a maximum value for impacts normal to the surface in order to simulate the erosion characteristics of a brittle material. Sample angular dependence curves have been reported by Tilly (10) or Karri and Davuluri (11). A velocity exponent in the range of 2.5 to 5.0 can be justified based on the literature (see Mills and Mason (12), or Karri and Davuluri, for examples). In particular, Mills and Mason suggest that erosion in pipe bends is proportional to velocity to the 3.5th or 4.5th power. The lower value was taken as conservative. Less has been published on a reasonable mass exponent. Some data suggests larger particles may have a greater impact on erosion than an equivalent mass of smaller particles (see Karri and Davuluri), but the data are inconclusive. A mass exponent of 1.5 skews the erosion toward regions where the larger particles impact but subsequent analysis showed that a mass exponent of 1.0 would result in similar conclusions.

The functional form is summed for all particles, p, impacting a given wall surface and is normalized by time, T, and the area of the surface patch, A. Note that this model is dependent upon particle-specific parameters (the mass, velocity, and impact angle are all properties that are determined on a per-particle basis). As such, this erosion index requires an Eulerian-Lagrangian formulation: discrete particles must be modeled in order to use this impact-based erosion calculation.

MODEL VALIDATION

The computational model was first used to simulate the existing configuration with known erosion characteristics. The catalyst Residence Time Distribution (RTD) at ten seconds of simulation time is shown on the left of Figure 3. Some of the catalyst travels up the outlet riser with the swirling gas flow and distributes between the ten crossovers. All the particles entering the cyclone have a residence time of four seconds or less. Thus, it was deemed that ten seconds were sufficient to establish a quasi-steady particle flow pattern. The erosion model and time-averaging of data were activated at ten seconds and the calculation was run for a total time of 30 seconds. The sufficiency of a 30 second simulation was further established by monitoring the split of catalyst flux through the bottom of the primary separation chamber and up through the outlet riser. These fluxes reached a quasi-steady-state value within four seconds as well. Thus, the total calculation time is more than seven times greater than a timescale that is characteristic of the particle flows in the region of interest, providing for meaningful averages.

The regions with the highest likelihood of erosion are shown on the right of Figure 3. Only regions where the erosion index exceeds a given tolerance are shown, colored by severity, with red representing the highest erosion index. The three most significant regions are found: (1) on the short side of the crossover; (2) the top side of the crossover; and (3) on the inlet sweep area of the cyclone main body.

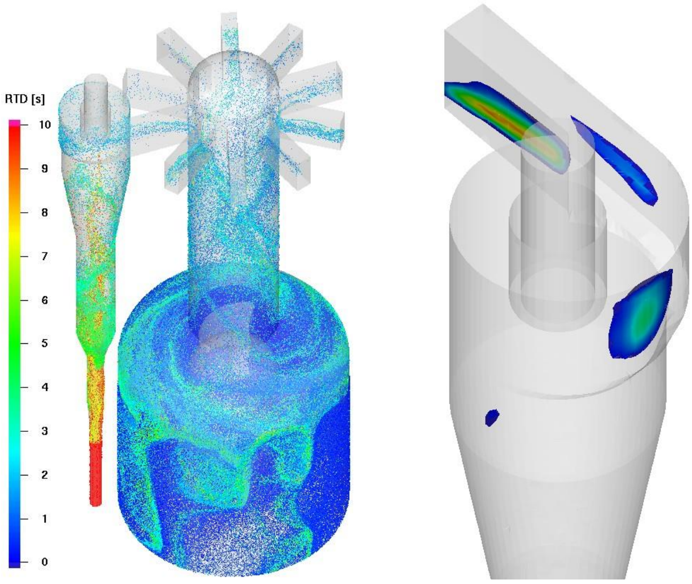

Figure 3. Calculation start-up (left), computed erosion patterns (right)

Figure 4. Erosion and wall holing: short side of crossover (left), top side of crossover (right)

The inspection report from the prior turnaround revealed extensive damage in all of these areas. The locations and extent of the damage varied from cyclone to cyclone, but the general patterns were identical. In some cases, the refractory was eroded to the extent that bare metal was exposed to the circulating catalyst which, in rare cases, resulted in holing through the metal walls. Two such examples are shown in Figure 4.

It should be noted that although the results of the erosion model are quantitative, additional data are required to determine meaningful erosion index values. The model is entirely based upon the mass, velocity and impact angles of the particles striking the wall. In actuality, erosion could depend upon a wide range of additional factors, such as surface material, refractory installation procedures, particle material, particle shape, etc. Thus, by comparing the model results with prior inspection report data, it was possible to discern what threshold levels of the erosion index were cause for concern. Erosion index values below the identified threshold were considered acceptable. Based on this comparison between the baseline case and the field observations, the model was deemed validated and ready for use for comparison of the alternative designs to one another and to the baseline case.

MODEL RESULTS AND FINDINGS

Figure 5 shows the extent and severity of erosion index for the two alternative designs compared with the baseline model. Both alternatives greatly reduce both the extent and severity of overall erosion. The models predict that no regions of the crossover show any erosion index values greater than the tolerance level that had proved problematic in the past. Alternative 2, compared to Alternative 1, seems to help further reduce the erosion on the inlet sweep area of the cyclone body.

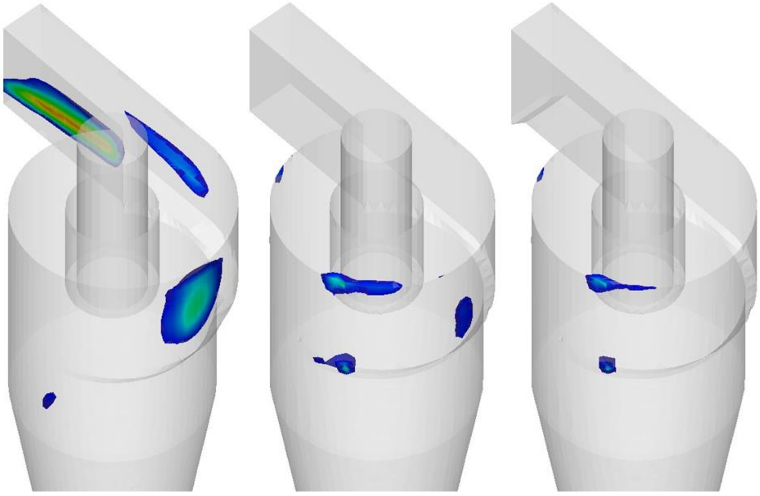

Figure 5. Cyclone erosion patterns: Baseline (left), Alternative 1 (center), Alternative 2 (right)

The cause of the erosion reduction from the alternative designs is evident in Figure 6. The time-averaged particle speed is shown on the left and center columns of the figure. Two views are shown representing horizontal and vertical slices, respectively. All three designs are compared with the baseline shown on the top row, Alternative 1 in the middle and Alternative 2 on the bottom.

The regions with highest average particle velocities are clearly evident on the short side and top of the crossover, in the same regions as the peak erosion occurs. In both alternative designs these peak velocities are reduced. This is somewhat expected due to the larger cross-sectional flow areas. However, what would not necessarily be expected is how the flow distributes through the duct. Both alternatives are more efficient at utilizing more of the cross-sectional area for particle transport, both horizontally and vertically, further reducing the average particle speed.

Note that gas speeds can vary substantially from particle speeds. The reason for the reduced and more uniform particle velocities is evident from the time-averaged gas speed, shown on the right of Figure 6. Since the gas speed locally exceeds the particle speed, it is evident that the highest particle velocities are a result of the aerodynamic drag from the gas. This locally high gas speed is a result of a flow separation that occurs as the gas abruptly changes direction upon entering the crossover. This separation zone is reduced in both alternative designs. The angled inlet, unique to Alternative 2, seems to further promote attached flow on the bottom of the duct. This better attached flow promotes greater utilization of the available cross-sectional area, which reduces catalyst velocities and thus, erosion, as erosion is very dependent on the impact velocity.

A study of cyclone efficiency was not undertaken as part of this work. In this case, the primary catalyst separation device is used to separate the vast majority of the particles, with the cyclones used for secondary separation only. At these high speeds, the decrease in average particle velocity is not expected to significantly impact separation efficiency. However, a CPFD model could be used to explore the effect of changes on other aspects of the system, such as cyclone efficiency.

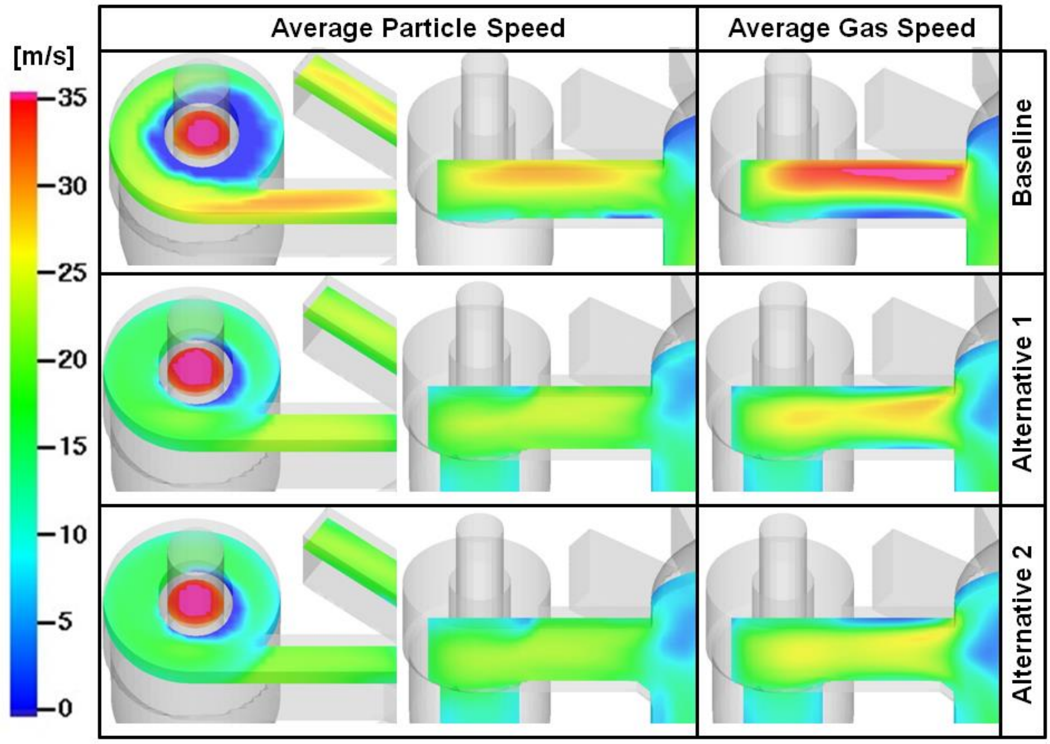

Figure 6. Time-averaged particle and fluid speed comparison

CONCLUSIONS

The case shown illustrates effective use of a computational model, based on the CPFD numerical approach, for understanding the root cause(s) of particle impact erosion in FCCUs. The model was validated against operational experience in the Catlettsburg refinery, accurately predicting the locations of maximum erosion. The validated model was then used to evaluate two candidate redesign alternatives that aimed to minimize the extent and severity of erosion and showed that either design would be effective, though Alternative 2 perhaps slightly more so.

Reducing erosion in FCC units has clear advantages for extending operating cycles and overall FCC unit life, plus reducing the risk of unplanned outages. Computational models, such as that shown here for MPC's Catlettsburg reactor, simplify designing or redesigning to mitigate erosion by providing powerful new insights into gas-particle flow patterns and thereby a sound engineering basis for making design changes with confidence. It has been shown in other work (13), that the same modeling technology can be extended to include reaction kinetics and, thereby, be used to calculate the impact of changes to an FCCU on performance, as well as on erosion. Modeling the reactions in this way has been done for other units but was beyond the scope of the Catlettsburg work described here.

NOTATION

I – Erosion index [$kg^{1.5}m^{1.5}s^{-4.5}$]
p – Particle index [-]
C_α – Coefficient on erosion index, a function of impact angle [-]
m – Mass of particle [kg]
v – Velocity of particle [m/s]
A – Area of surface patch [m^2]
T – Time [s]

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