

#### W H Т Ε Р Α Р E R Т

# A Virtual Engineering Methodology to Prevent Erosion-Related Accidents in the Petroleum Industry

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Erosion of oil and gas equipment has become a significant financial burden on both the upstream and the downstream components of the petroleum industry. Concerns over loss of life, injuries, lawsuits, downtime, and plant reconstruction are keeping plant and engineering managers awake at night. This paper outlines a cost-effective methodology for minimizing erosion and avoiding dangerous and expensive accidents.

"It is vital that companies who operate highhazard sites – such as oil refineries and chemical plants - put rigid and robust systems in place for inspecting pipework to detect corrosion or other defects." Kevin Allars Head of Chemical Industries Division, Health and Safety Executive, Great Britain

### THE CHALLENGE OF EROSION

Some indication of erosion's incurred cost can be ascertained from the event at a ConocoPhillips oil refinery in Humberside, UK in 2001. Erosion and corrosion caused a 15 cm diameter pipe to rupture. The released liquid petroleum gas (LPG) exploded and the resulting fire caused other pipes to fail, leading to yet another explosion. After burning for two and a half hours, there were, amazingly, no serious injuries. However, there was significant damage to process equipment and buildings reported both on- and off-site. ConocoPhillips was fined £895,000, which of course did not include the internal costs to replace the process equipment. If there had been injuries or loss of life, as often occurs during refinery accidents, the costs of fines, lawsuits, and the ensuing necessary public relations campaign would have been significantly higher.

The presence of solid particles is ubiquitous in the petroleum industry. On the upstream side of the industry, particles typically come from sand, crushed rock, or drilling mud, whereas they usually consist of catalyst in the downsteam end of the process. Erosion occurs when particles impact the solid walls of transport equipment, causing some of the wall material to break free. After millions or billions of impacts in equipment that is operated continuously, the wall can become dangerously thin, resulting in rupture, or equipment failure. Erosion corrosion is a variant of basic erosion, in which the rate of corrosion is accelerated due to the relative motion of a corrosive fluid and a metal surface. Increased turbulence caused by pitting on the internal surfaces of a tube can result in rapidly increasing erosion rates.

Erosion has been proven to affect a wide variety of upstream and downstream oil and gas equipment, including drill bits, other downhole machinery, heat exchangers, heat recovery boilers, fluidized beds (including all fluidized catalytic cracker, or FCC, hardware), process pumps, cyclones, and burner tips. Downstream refiners are motivated to minimize erosion costs because of pressure on profit margins as fuel and crude oil become more costly. Upstream drilling companies, on the other hand, are motivated by the need to extract oil from ever more challenging environments, and the difficulties in troubleshooting when failures occur in problematic places like the ocean floor. The pressure is on for engineers to "get it right the first time" rather than using a trial and error approach, which, as we've seen, can result in steep financial penalties, or worse yet, loss of life.

### VIRTUAL ENGINEERING TO THE RESCUE

Computer-aided engineering (CAE) enables plant and equipment engineers to test their designs for erosion characteristics to avoid failure in the field or costly and time-consuming physical testing of equipment. Engineers can use existing software technology which analyzes both fluid and particle motion, and predicts erosion rates on surfaces due to the particle impacts.

Erosion analysis may be done in troubleshooting mode, after equipment has failed and retrofit or redesign is necessary in order to avoid a future rupture. Ideally, however, the computational study should be performed upfront, before quipment is deployed in the field. This approach should be explored in any scenario involving suspensions of possibly eroding particles undergoing sharp changes in flow direction. Erosion corrosion can also be investigated for similar scenarios involving the flow of corrosive materials.

The first stage of virtual analysis is generating a three-dimensional flow solution within the component of interest. This involves three steps:

- 1) creating a three-dimensional computer model of the part geometry,
- 2) generating a computational mesh,
- 3) using a computational fluid dynamics (CFD) solver to render the 3D flow field.

Sometimes, the computer model is already available in computer-aided design (CAD) files originally used to draw the component. Alternatively, a model can be built using the virtual analysis software. Next, a mesh generation tool uses the



Figure 1. a) CAD geometry of part, b) computational mesh, c) flow field simulation showing flow pathlines - blue indicates the lowest value and red the highest

CAD model to split the flow volume into small cells, each of which will act as control volumes in the flow solver. Tools are currently available which provide a very high level of automation in this meshing process. The fluid material properties and boundary conditions are specified in the solver, which then uses an iterative method to solve for the flow field. Figure 1 illustrates a simple two-elbowed geometry in this process, with the final result showing flow pathlines through the pipe.

The next stage is simulation of particle tracks within the flow domain. These tracks will depend upon particle properties, including material and particle size. The flow solver will take these properties, the coefficient of restitution on the walls, and the effect of the surrounding fluid into account as it calculates the particle tracks. At locations where particles do impact the walls, an erosion model in the solver is used to translate the particle impact rate into an erosion rate. The selection of which model to use will depend on particle type and the wall material. Figure 2a shows particle tracks for the same pipe as shown above, which are subtly different than the fluid pathlines from Figure 1c, particularly in regions of high fluid acceleration. Figure 2b shows contours of erosion rate calculated from the impacts of these particles on the pipe wall. By visualizing these results, the engineer has a clear idea of where erosion is occurring and, from the particle tracks, can gain an understanding of what flow features are causing a high impact rate of particles. This knowledge, in turn, provides the engineer with insight as to what could be changed in the geometry in order to reduce the particle impingement rate. This may involve reducing the bend angle, inserting a guide vane, or some other geometrical change in the part.



Figure 2. In each example, red indicates the highest value and blue is the lowest a) Particle tracks in pipe colored by residence time, b) pipe wall erosion rates calculated from particle impacts

Figure 3. Shear stress distribution in a pipe, with red indicating the maximum value

In some cases, process equipment may be transporting very dense multiphase flows, such as a slurry. This type of material can be modeled using an Eulerian multiphase model in the solver analysis software, which tracks the local solid volume fraction and takes the effect of the solid phase into account for fluid properties and flow behavior. In this regime, erosion rate tends to be strongly correlated to shear stress. Similarly, erosion corrosion may depend upon either shear stress, or locally high levels of turbulence. The goal may be eliminating high shear stress or turbulence "hot spots," in which case the engineer can use the results of the flow model to indicate these regions, as shown in Figure 3. Once the regions are identified, methods to mitigate the shear stress levels can be devised and investigated with a new flow model. If quantitative rather than qualitative information about predicted erosion rates in slurry transport equipment is desired, then a new erosion rate function depending upon shear stress or other quantities can be programmed into the flow modeling software. Most packages allow custom postprocessing functions to be created interactively by the user.

## STUDYING GEOMETRIC CHANGES OVER TIME

It is often desirable to investigate how erosion will affect the equipment over time. Generally, the erosion rates for the initial geometry of the equipment cannot be extrapolated for the life of the part. As erosion takes its toll, the flow and

particle motion will change, modifying the local erosion rate in turn. There may be cases in which the erosion rates are reduced because of flow changes due to the wearing of surfaces, though the opposite could also be true.

In order to investigate the erosion characteristics over the life of a part, an unsteady flow model must be employed, along with the use of a moving deforming mesh capability in the flow solver. This capability allows a surface to deform as erosion occurs. The flow solution then adjusts over time as the geometry deforms, allowing the calculation of new erosion rates. An example of this type of calculation is shown in Figure 4. 4a shows the erosion rate at start-up, with a maximum value of 1.5 X 10<sup>-6</sup> kg/m<sup>2</sup>s. After 5-1/2 years of operation, the erosion rate contours change, as shown in 4b, with nearly the same maximum value but on a deformed surface.

#### AUTOMATED OPTIMIZATION

The highlighted examples illustrate how an engineer can use computational flow modeling to guide changes to design or operating parameters to reduce erosion rates in process equipment. The level of effort may be reduced even further, however, through the use of commercial computational optimization tools. By using these tools in conjunction with flow modeling, an engineer can specify what geometric and/or operational parameters are allowed to change, and what should be minimized. Variable parameters may include the size of a baffle, the angle of bend in a pipe, the flow rate, or any





Figure 4. For both figures, red is the maximum value and blue is the lowest a) contours of erosion rate for initial geometry, b) contours of erosion rate after 5-1/2 years of operation

combination of these. Mean erosion rate on a specific surface would be one example of a quantity to be minimized. The optimization software can be directed (usually through a graphical interface) how these parameters can be accessed in input files to the flow modeling software. The optimizer will then choose a range of flow modeling cases to be run automatically, create a multi-variable regression, and provide the user with the optimal parameters. This sophisticated automation saves a substantial amount of time for the engineer, who no longer needs to set up many similar problems by hand, and perform trial and error computations in order to arrive at the best design.

#### AN EXAMPLE FROM THE FIELD

The example above, while realistic, is also geometrically simple, and was chosen in order to illustrate the workflow process for erosion prediction. Following is a real-world industrial example of how flow modeling was used to troubleshoot erosion problems at a refinery.

Flow rates and catalyst loading inside TOTAL's Provence refinery in France had been steadily increasing over the last ten years. As a result, erosion in the cyclones became more and more significant. To better understand the phenomenon, a flow simulation was performed for one of the units. Catalyst particles with sizes ranging from 10 to 130 microns

were included in the calculation. The simulations accurately predicted several observed characteristics of the cyclone, such as the separation efficiency, catalyst trajectories, and gas velocity profiles. They were also used to identify troublesome zones, which matched observations as shown in Figure 5. The exercise led to a better understanding of the causes of erosion and pitting, and helped engineers to propose and evaluate a new cyclone design, which was implemented during a planned shutdown.





### CONCLUSIONS

The above example illustrates how erosion prediction tools are being deployed in the petroleum industry. Erosion has become a critical safety and cost concern in the upstream and downstream petroleum industry. This white paper has explained how virtual flow modeling can reduce risk, costs, and effort by predicting erosion in process equipment. The engineering effort required is minimal, particularly when safety hazards and the cost of troubleshooting in offshore and in deep wells are considered.

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