Erosion caused by solid particles in process flows impacting on the surfaces of downhole equipment or pipe walls is a common cause of damage and wear in oil and gas production as well as many other process industries. In the oil and gas industry, erosion can pose a significant integrity risk in flowlines, valves and connectors in production systems if not managed appropriately. Computational fluid dynamics (CFD) is a cost-effective means of predicting the location and magnitude of erosion damage. In practice, different flow regimes and particle loadings can lead to a range of erosion mechanisms that require different simulation approaches, all of which can be analyzed in STAR-CCM+® software, and are covered in this white paper.
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Executive summary

Erosion can be caused by particles impacting or abrading a surface, as shown in figure 1. This is of particular concern for solids transported through subsea systems and process piping networks in the oil and gas industry. A variety of approaches are available to model erosion within STAR-CCM+, which require no set up of user-defined functions. Using the multiphase models available, the Lagrangian method allows a reasonably efficient calculation of impact erosion, depending on the number of particles modelled. By using Discrete Element Modeling (DEM) both impact and abrasive erosion can be calculated, along with particle to particle collisions. For very high particle loadings, an Eulerian approach models the particles as a continuum, so simulations can be carried out that approach maximum packing.

As erosion occurs, it can change the internal geometry and subsequent flow profile, this can either increase or decrease the rate of erosion. The computed erosion rate within STAR-CCM+ can drive the simulation of material loss, thereby fully automating through-life asset predictions by automatically deforming the mesh and altering the geometry. This allows a complete understanding of erosion during system design in order to help minimize its effects from the outset as well as reducing design conservatism by performing simulation earlier in the product development cycle.

![Mechanisms for impact and abrasive erosion](image)

*Figure 1: Mechanisms for impact and abrasive erosion*
In general, the erosion rate is calculated by summing up contributions of material damage from each particle (or parcel depending on the multiphase models used) as it collides with the surface being eroded. The erosion caused by each collision is calculated using a semi-empirical erosion ratio, which are a function of calculated flow variables and experimentally obtained constants. The expression used to calculate the erosion rate is:

$$E_f = \frac{1}{A_f} \sum_{\pi(f)} \dot{m}_\pi e_r$$

Where:
- $A_f$ is the area of the face
- $\dot{m}_\pi$ is the mass flow rate of particles in parcel $\pi$ impacting on the face
- $e_r$ is the erosion ratio

The variables used in the calculation of the Erosion Ratio depend on the type of erosion being considered, as shown in figure 1.

Impact erosion models aim to predict erosion for high angles of incidence. Following from figure 1, the erosion ratio is a function of the angle of incidence and particle velocity at impact. The user can define their own or choose from four well known correlations for erosion ratio built into STAR-CCM+:
- Ahlert (Tulsa)
- DNV
- Nelson-Gilchrist
- Oka

Abrasive erosion occurs where a particle slides along the wall or impacts at a very low angle. In this case the erosion ratio is calculated from the length of contact and the normal contact force (figure 1). STAR-CCM+ includes the Archard Correlation for abrasive wear as a built-in function. As with impact erosion, the user can alternatively specify their own formulation.
Multiphase modeling

In order to use the erosion model previously described in a CFD model, it is necessary to include a solid ‘phase’ (grains of sand, for example) in the simulation. In this way, the motion of particles moving under the influence of the transporting fluid can be predicted. STAR-CCM+ contains a comprehensive suite of multiphase models to allow this to be done over a large range of flow regimes. Broadly speaking, multiphase models fall into two categories – Lagrangian and Eulerian. Lagrangian methods are used more commonly for erosion prediction, and so will be examined first.
Lagrangian multiphase modeling

Modeling particle flows in a Lagrangian frame of reference tells us about the evolution of the properties (e.g. velocity, temperature, position) of each particle over time.

The Basic Lagrangian Multiphase (LMP) model in STAR-CCM+:
- Tracks multiple particles grouped together to form ‘parcels’ – a group of individual particles given the same properties. This approximation reduces computational effort.
- Particle-wall collisions are resolved however particle-particle collisions are not. The basic LMP approach is suitable for cases with particle volume loading below 20%.
- Can be run in either steady state or transient modes, depending on which is needed to resolve the background fluid flow and particle interactions.

- Sliding contact between particles and walls is not captured by this method and so only Impact Erosion models are available with this method.

Figure 2 shows a simulation run in steady-state using the LMP model. Sand particles of 100µm are transported by air flowing around a 90 degree elbow. Erosion rate measurements are made along the centerline of the outside of the bend and compared to experimental results. It is evident that the agreement in erosion rate compares favorably to the experimental data.

**Figure 2:** Impact Erosion Validation Case Using the Lagrangian Multiphase Model
Experimental data from: Eyler RL. Design and analysis of a pneumatic flow loop, M.S. Thesis, West Virginia University, 1987
The discrete element method

The Discrete Element Method (DEM) is a higher fidelity Lagrangian method where the mechanics of each individual particle are fully resolved. Its features are:

- DEM can resolve particle to particle collisions.
- A Coarse Grain approximation can be applied to reduce computational effort (similar to Parcel approach in LMP).
- Because particle-particle collisions are fully resolved, this model is capable of modelling the full range of particle volume loading (up to the maximum packing ratio).
- Particles can be of any shape.
- All contact forces are calculated and so both impact and abrasive erosion models are available with this method.

Figure 3 shows an example of a high solids loading in a gas flow through an elbow modeled using DEM. Due to the dense packing of the particles, abrasive wear is the most significant erosion mechanism as the particle-bed passes through the bend. The particle-particle contact results in fewer direct impacts between particles and the pipe walls.

![Figure 3: Abrasive wear with high solids loading modeled using DEM](image-url)
Eulerian multiphase modeling

Modeling particle flows in an Eulerian frame of reference treats the particle phase as a continuum (rather than individual particles), tracking the evolution of the properties of the whole field with time. Particle-particle contact is modeled as a Granular Pressure Force, which tells us about the frequency of particle-wall contact. The velocity field represents the averaged particle trajectories and this information leads to an averaged erosion rate, in contrast to the Lagrangian methods discussed earlier which track individual collisions.

The Granular Flow Model in STAR-CCM+:
- Continuum-based approach for modeling a particle phase
- Suitable for high values of particle volume fraction (approaching maximum packing)
- Lower computational effort than DEM, however only homogenous spherical particles can be modeled. Collisions between particles and wall boundaries are not individually simulated, rather the particle phase velocity field provides an averaged collision rate.
- Since the forces arising from particle-wall interaction are modeled, both impact and abrasive erosion models are available with this method

Figure 4 shows an example simulation of flow in a horizontal pipe bend. Sand particles (15% by volume) are carried by a flow of water from right to left resulting in both abrasive and impact wear on the outside and inside surfaces of the pipe bend, respectively.

Figure 4: Erosion rate (combined impact and abrasive wear) on an elbow due to sand particles present in a water flow (volume fraction of sand = 15%), using the Eulerian Multiphase Model
Using erosion calculations to predict the life of an asset

A ‘standard’ erosion calculation using CFD will provide the erosion rate for the as-built component at the start of its design life. Is it then acceptable to assume that the same erosion rate is maintained over the life of the asset? The answer is that as a component suffers erosion, the resulting change in shape of the eroded surfaces may then alter the flow field to such an extent that it can exacerbate or reduce the erosion occurring.

In STAR-CCM+ the computed erosion rate (expressed for example in millimeters per year) can be used to drive the motion of wall boundaries to simulate the effect of material loss resulting from erosion. The time interval and magnitude of the mesh deformation can be adjusted by the to speed up the erosion calculation, increasing computational efficiency. By performing this coupled analysis, the effect of material erosion on the flow field and thus the ongoing erosion rate.

This approach can add fidelity to a through-life prediction and can help to reduce conservatism in design decisions based on CFD predictions. Agrawal and Khanna (Presented at ERCOFTAC Oil, Gas and Petroleum: Best Practices and Technology Trends, March 2015 as well as at NAFEMS Engineering Analysis & Simulation in the Oil & Gas Industry in Houston, April 2016) studied erosion on a mitred bend, observing that including erosion driven moving boundaries in the CFD simulation had a significant effect on erosion rate for geometries involving sharp corners and recirculation regions. In a study of a mitred bend, erosion rate measurements in the contraction region, at the sharp corner on the bend, and on the pipe downstream of the bend were taken. Initially, the highest rate of erosion was seen at the sharp corner. Over 45 hours of subsequent operation, erosion rate was seen to reduce in the contraction and bend regions, while increasing downstream of the bend where the flow was recirculating. By the end of the test, erosion rate measured downstream of the bend was around 50% higher than the initial measurement at the sharp corner in the bend.

Figure 5 shows how erosion by sand particles carried in a gas flow have removed pipe wall material at the change of inner pipe diameter as sand that is carried towards the bottom of the pipe impacts the inclined pipe wall.

Figure 5: Erosion of the Worn Component
Conclusions

Thanks to a comprehensive range of multiphase modeling capabilities combined with built-in erosion models, STAR-CCM+ is uniquely positioned to tackle all erosion challenges faced in design or operation, under any flow conditions and at any level of solids loading.

Depending on the time available and the level of fidelity required from the simulation, the user can choose either to simulate a steady state erosion condition, or to establish how this rate may vary over time due to fluctuating flow conditions. Furthermore, the change in component shape over time due to erosion may be assessed by allowing the effect of material loss to be accounted for. In this way, a more accurate assessment of product lifetime can be made.