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PHOENICS Case Study: Process - Steel Ladle Desulphurisation
CFD Simulation of Slag-Metal Mixing, communicated by Harry Claydon, CHAM London, May 2020

A major steel manufacturer requested CHAM's support in applying a PHOENICS-based CFD model, developed for simulating a gas-stirred steel ladle, to investigating the slag-metal mixing which controls desulphurisation in the production of ultra-low sulphur (ULS) grade steels. Enhanced slag-metal mixing is required at the top interface of the ladle to induce faster refining reactions for reducing sulphur in the melt. This is achieved by injecting Argon gas through plug locations in the bottom of the ladle. For the production of ULS grade steels, typically, a gas flow rate of 50 SCFM is required per plug to melt the flux powder, and cause sufficiently intense metal-slag mixing at the interface. An unsteady, three-dimensional, two-phase PHOENICS CFD model was used to evaluate the difference in mixing efficacy between using a single plug and two plugs.

The following plug designs were considered in the CFD study:

1. Case A – This is the base case of a single 5" (0.127m) diameter plug injecting 50 SCFM of Argon, and located roughly 60% radius at the ladle bottom.
2. Case B – The same as Case A, but with a 7" (0.178m) diameter plug.
3. Case C – Two plugs at the same radial location as Case A, but displaced some 60 degrees from each other; and each with a 5" diameter plug and a gas injection rate of 50 SCFM.
4. Case D – The same as Case C, but with 7" diameter plugs.

In this study, mixing time is determined by solving for a passive concentration C2 (tracer) which is injected through the plugs at time zero. The actual mixing time is defined as the time required to attain 90% homogenisation throughout the molten steel.

The CFD model geometry was created by using PHOENICS' principal objects without the need for proprietary CAD software. The model consists of a ladle with a height of ~3m and a diameter of ~3m; only half of the ladle was modelled to exploit symmetry. Within the ladle there is an inlet of Argon (the plug), modelled as air in this simulation, with an inlet velocity of ~1m/s. Using air is a valid modelling assumption as the reaction is unimportant for the purpose of this particular simulation. The domain fluid was set to the density of molten steel; temperature effects were not considered because the primary aim was to investigate the degree of mixing produced by the various gas-injection configurations. The standard k-ε turbulence model was used for the study.

In reality, the top surface of the ladle is covered with a layer of slag which can deform as the Argon bubble plume strikes and breaks through the free surface. However, for the purpose of the investigation described, it is sufficient to ignore the slag layer and model the free surface as a rigid lid through which gas is allowed to escape into the atmosphere.

The model was run as a transient simulation without scalar injection until the hydrodynamics reached a quasi-steady state. After this, the tracer was injected and the transient run was continued using a time step of 25ms for a total duration of 120s. Below, Fig.1 and Fig.2 show predicted contour plots of the tracer concentration results 0.5s into the simulation.

As the run progresses, the entire domain gradually turns red indicating the higher tracer concentration and an homogenised mixture.

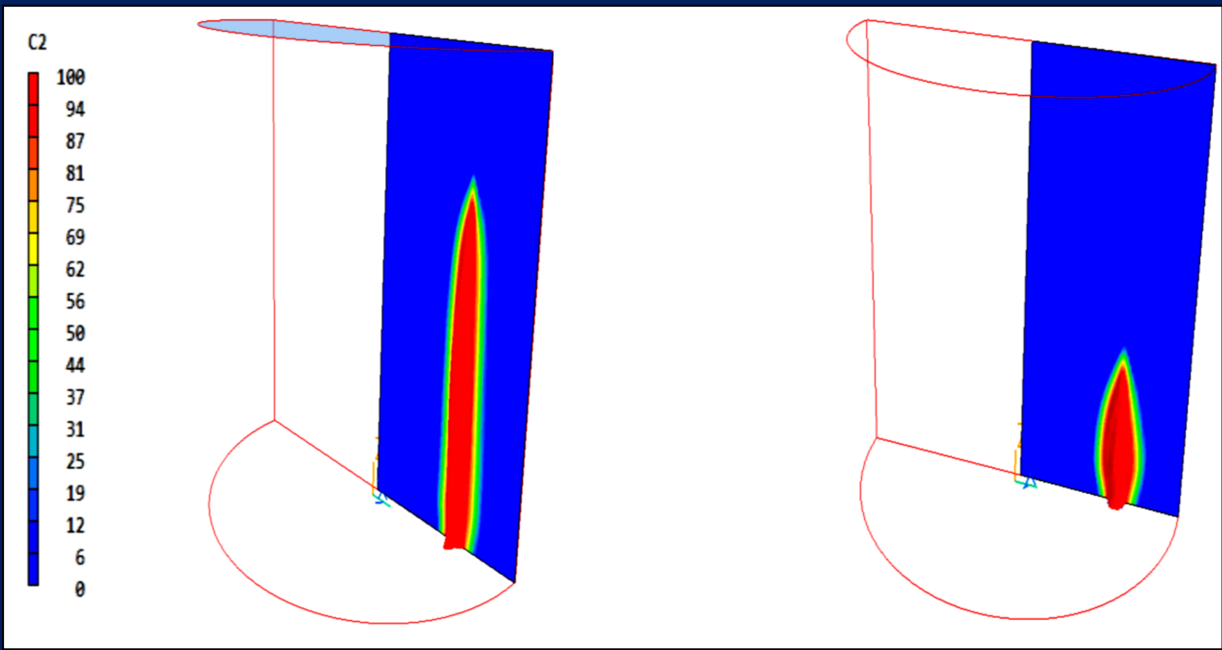


Figure 1: Single-plug Design: Contour plots of C2 scalar (tracer) concentration along plane of injection at 0.5 s. This also shows the 90% tracer iso-surface. Case A, left and case B, right.

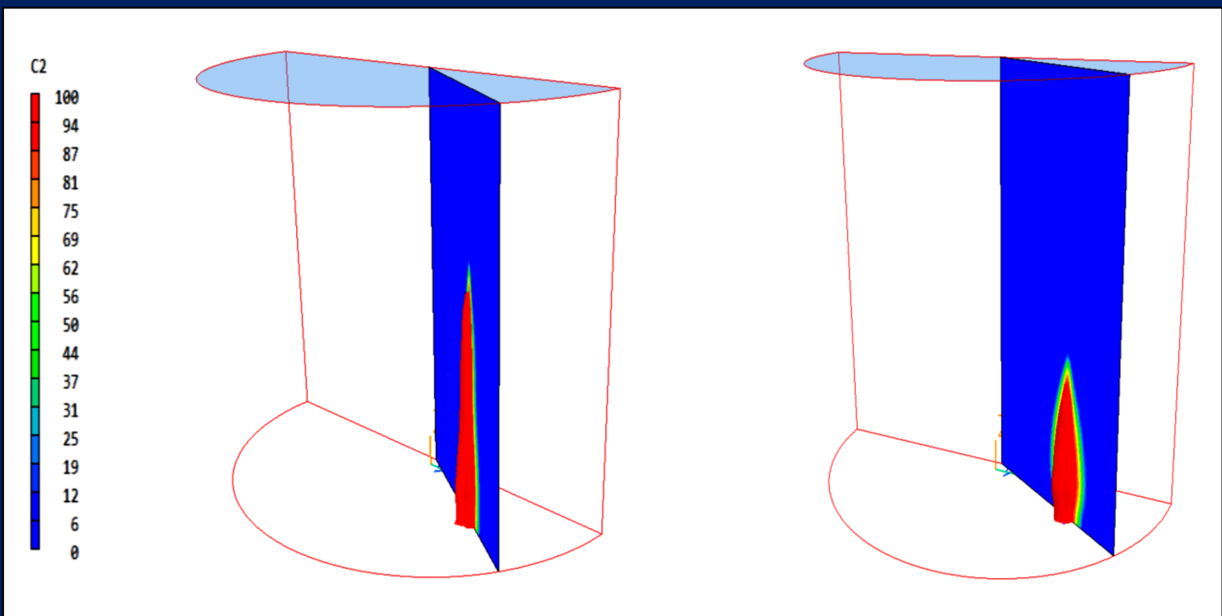
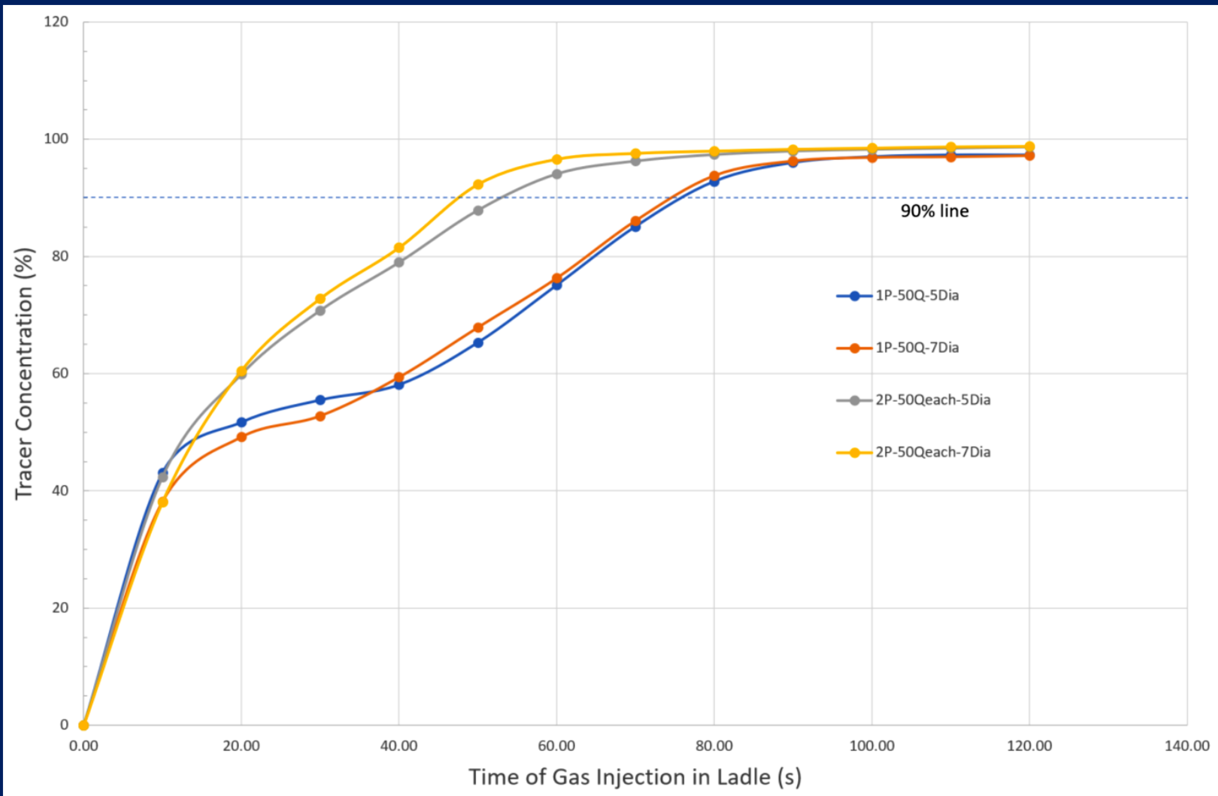


Figure 2: Two-plug Design: Contour plots of C2 scalar (tracer) concentration along plane of injection at 0.5 s. This also shows the 90% tracer iso-surface. Case C, left and case D, right.



Fiigure 3: Graph showing the volume-averaged tracer concentration over time for each case, including the 90% concentration threshold line. Case A, blue; Case B, red; Case C, grey; Case D, yellow.

The mixing time curves in Fig.3 show that:

a. The 2 plug cases achieve 90% homogenization much sooner (~50 sec) than the 1 plug cases (~75 sec).
b. There is not much difference in mixing behaviour between 5” and 7” diameter plugs.

The researchers’ results showed that:

a. The use of 2 plugs with 50 SCFM flow causes intense stirring and mixing of the steel in the ladle required for achieving low sulphur level in steel.
b. The mixing time is not very sensitive to the plug design, as long as the desired 50 SCFM flowrate can be achieved.
c. For the 2 plug cases, the tracer homogenisation is effectively complete in less than 1 minute, indicating a higher degree of turbulent mixing in the ladle.

The researchers’ conclusion was that, for faster sulphur removal and shorter processing times, the 2-plug design is desirable for use on this steel ladle.

The simulations also identified further modelling studies to investigate the possibility of steel splashing and spillage from the top tip of the ladle (freeboard). Such studies will extend the CFD model to allow for a deformable free surface in order to predict the dome height where the gas plume breaks through the steel surface, and also the accompanying surface waves produced during bottom gas stirring.

These simulations helped the manufacturer to investigate and visualise the melt mixing of the various design cases, and to create a proposal for improving the equipment. In addition, they also led to ideas for further simulations and investigations leading to further design improvements.