

Application Example:

Using the Process Metallurgy Module to Calculate the Desulphurization in a Ladle Furnace (LF)

| Database(s): | TCOX11 or newer, OXDEMO | Module(s): | Process Metallurgy Module |
|-----------------------|-------------------------------|--------------------|---------------------------|
| Version required: | Thermo-Calc 2021b or newer | Calculator(s): | Equilibrium |
| Material/Application: | Ladle furnace / Desul | phurization | |
| Calculation name: | PMET_02_Desulphur | ization_in_Ladle_F | urnace |

INTRODUCTION: LADLE FURNACE, STEEL-SLAG REACTIONS, DESULPHURIZATION

The ladle furnace fulfils many purposes in the steelmaking process. Desulphurization, which we will focus on in this example, is merely one of them.

Desulphurization is usually performed by transferring S that is dissolved in the liquid metal to a CaOrich slag phase. For this process to be successful, two conditions need to be fulfilled:

- The slag must be fully liquid (liquid fraction > 0.9). This is required for kinetic reasons. The slag phase must be fluid so that it can emulsify with the liquid steel and form a large surface area where the reaction between steel and slag can take place.
- 2. The slag must take up a large amount of S from the liquid steel (have a "high sulphur capacity") so that a significant amount of sulphur will move from the liquid steel to the slag phase.

It is difficult to decrease the S content in the liquid steel during steelmaking in a basic oxygen converter (BOF) or an electric arc furnace (EAF) because conditions are predominantly very oxidizing. Desulphurization is therefore usually performed in a subsequent step, during steel refining in a ladle furnace or a vacuum degasser after the steel is fully killed by a suitable deoxidizing agent and the oxygen activity is low (Figure 1).

The following example explores these two conditions for an equilibrium between liquid steel and slag in a ladle furnace, trying to find good slag compositions. We also investigate why excessive slag carry-over from the BOF or EAF is detrimental for desulphurization in the LF and show how slag conditioning with CaC2 or adding CaF2 as fluxing agent can recover the desuphurizing ability of the slag.





Figure 1. The principle of desulphurization is to transfer the sulphur dissolved in the liquid steel to a CaO-rich slag phase. This process is typically carried out in a ladle furnace (LF). Image of the ladle furnace at Swiss Steel (www.swiss-steel.com).

How to Run the Calculation

If you have a license for Thermo-Calc 2021b or newer, as well as the databases and products listed below, you can follow along with this example in your software. Otherwise, you can read the PDF, which discusses the materials challenges and how Thermo-Calc can be used to solve them.

To run this example, open Thermo-Calc and navigate to the Help Menu \rightarrow Example Files... \rightarrow Process Metallurgy. This example includes two calculation files:

- **PMET_02a_Ladle_Furnace:** a simplified version that can be run with the OXDEMO database but requires a full license for Thermo-Calc.
- **PMET_02b_Desulphurization_in_Ladle_Furnace:** requires a full license for Thermo-Calc 2021b or newer, the Metal Oxide Solutions Database TCOX11 or newer, and a license for the Process Metallurgy Module.



There is also a <u>video demonstrating the setup</u> of the PMET_02a_Ladle_Furnace example.



Read additional in-depth <u>Application Examples available for the Process Metallurgy Module</u>, which discuss topics such as Steel Deoxidation on Tapping and the Basic Oxygen Furnace process.



EXAMPLE: DESULPHURIZATION IN A LADLE FURNACE

Figure 2 is a screenshot of the Process Metallurgy Module which shows how to set up the calculation. We perform an isothermal calculation at 1620 °C (1), which is a typical temperature in a ladle furnace. The amount of steel in the ladle furnace is 100 t (2) and it contains a rather high S content of 0.1 wt% (3). We then add 1000 kg of a slag phase (4) containing CaO, Al₂O₃ and SiO₂ (5). We are interested in finding out how the composition of the slag phase influences the sulphur content in the steel. For this we perform a grid calculation, changing the SiO₂ and the Al₂O₃ content of the slag (6).

| Conditions Options | |
|--|--|
| Database | 2020 |
| The second secon | |
| Thermal control: Iso | |
| Temperature: Ce | elsius v 1620.0 |
| Pressure: Pa | iscal v 100000.0 |
| 00 | |
| Material: | Steel V Steel LF |
| Amount: | Tonne v 100.0 2 A Hide composition |
| Input type: | Mass percent v Element V Save material |
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| Material: | Slag v Slag_LF |
| Amount: | Kilogram V 1000.0 4 Hide composition |
| Input type: | Mass percent V Component V Save material |
| Major component: | ○ ○ CaO ∨ 60.0 |
| | |
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| | 10tai: 100.0 |
| Calculation Type | |
| ○ Single | ○ One axis |
| Grid Definitions | 6 |
| Quantity | Min Max Number of steps |
| Composition Al2C | 03 in Slag_LF (SLAG) [Mass percent] 🗸 0.0 50.0 20 🜩 |
| | |
| | |
| Composition SiO2 | 2 in Slag_LF (SLAG) [Mass percent] V 0.0 50.0 20 🜩 |

Figure 2. Screenshot of the Process Metallurgy Module showing how to set up the example on steel desulphurization as a function of the slag composition.

Eq. 2



Quantifying Furnace Slag Tapped into the Ladle

A common problem during steelmaking is that some of the furnace slag, which is oxidized and rich in FeO, is tapped into the ladle. It is known that this reduces the desulphurizing ability of the slag in the ladle furnace. To quantify this effect, we perform the same calculation as above, except that we add 10 wt% FeO to the slag phase (1) (Figure 3).

| Material: | Slag | | \sim | Slag_LF 🗸 🗸 | | | |
|------------------|----------|-------|--------|-------------|--------------------|---|--------------|
| Amount: | Kilogram | | ~ | 1000.0 | A Hide composition | | |
| Input type: | Mass per | cent | \sim | Component 🗸 | Major component | ~ | Save materia |
| Major component: | 0 🔾 | CaO | ~ | 50.0 | | | |
| | 0 0 | Al2O3 | ~ | 20.0 | | | |
| | 0 😑 | SiO2 | ~ | 20.0 | | | |
| | 0 0 | FeO | ~ | 10.0 | | | |
| | Total: | | | 100.0 | | | |

Figure 3. Same calculation as outlined in Figure 2 except that the slag composition now contains 10 wt% FeO (1).

Recovering the Desulphurizing Ability with Deoxidation Agents

There are various methods of recovering the desulphurizing ability of the ladle slag phase after accidentally contaminating it with furnace slag. For example, the slag can be conditioned with deoxidation agents such as CaC₂ or Al pellets. These react with the FeO in the slag according to the following reactions:

$$(3FeO) + 2AI \rightarrow (Al_2O_3) + [3Fe]$$
 Eq. 1

 $(FeO) + CaC_2 \rightarrow (CaO) + [Fe] + [2C]$

Round brackets () indicate compounds that dissolve in the slag phase and square brackets [] indicate elements that dissolve in the liquid steel. These slag conditioners essentially deoxidize the slag and return the iron that is bound up as FeO in the slag phase back to the steel. One way of calculating the conditioning of the slag with CaC₂ is shown in Figure 4.

| Material: | Slag | ~ | User-defined 🗸 | | |
|------------------|--------------|---|----------------|-------------------|---------------|
| Amount: | Kilogram | ~ | 100.0 | Hide composition | |
| Input type: | Mass percent | ~ | Component | Major component v | Save material |
| Major component: | 🕑 🌑 CaC2 | ~ | 100.0 | | |

Figure 4. Same calculation as shown in Figure 3 except that 100 kg of CaC_2 is added as slag conditioner (1).



Adding a Fluxing Agent to Improve Desulphurizing Ability

Alternatively, the melting point of the slag can be reduced by adding the fluxing agent CaF₂. This allows the CaO content of the slag to be increased without the slag turning hard (solidifying). The higher CaO content improves the desulphurizing ability of the slag, even if it is contaminated (oxidized) by FeO. One way of calculation this is shown in Figure 5.

| Material: | Slag | User-defined | | |
|------------------|--------------|--------------|--------------------|--------------|
| Amount: | Kilogram | 40.0 (1) | ⇒ Hide composition | |
| Input type: | Mass percent | Component ~ | Major component v | Save materia |
| Major component: | 🔘 🔵 CaF2 | ✓ 100.0 | | |

Figure 5. Same calculation as shown in Figure 3 except that 40 kg of CaF_2 is added as slag fluxing agent (1).



EXAMPLE RESULTS

Figure 6, top left plot, shows that a slag composition of CaO - 10wt% SiO₂ - 15 wt% Al₂O₃ (area shaded blue) is ideal for this particular process, as the slag is over 90 % liquid and is able to reduce the S content in the liquid steel to below 0.01 wt%. If the slag is contaminated by 10 wt% FeO (for example from slag carry-over from the furnace, plot top right) its desulphurizing ability is markedly reduced (blue lines showing the S content in the liquid steel move towards CaO corner) and it is not possible to find a slag composition that is both liquid and reduces the S content of the steel to below 0.01 wt%.

This situation can be somewhat recovered by de-oxidizing the slag by a slag conditioner, such as Al or in this case CaC_2 . The bottom left plot is calculated for a slag contaminated by 10 wt% FeO, but 100 kg of CaC_2 is added to condition the slag. It can be seen that this de-oxidation of the slag recovers its desulphurizing ability.

The plot in the bottom right finally shows the situation when 40 kg of CaF_2 are added to the slag phase, again assuming it is contaminated by 10 wt% FeO. While the addition of CaF_2 does not deoxidize the slag and the slag's desulphurizing ability is not improved for a given composition, it does allow the use of a slag that is richer in CaO without risking the formation of a hard, partially solidified slag. When adding CaF_2 as a fluxing agent, an ideal operation window for the slag composition opens up at about 7 wt% SiO₂ and 10 wt% Al₂O₃.

The example file has a reduced number of steps in the grid calculation compared to the calculation shown in Figure 6 and the results might therefore deviate slightly. This is to reduce the simulation time when running the example.





Figure 6. Plots showing the fraction of liquid slag as a function of SiO_2 and Al_2O_3 content (red contour lines) and amount of S in the liquid steel phase in equilibrium with the slag (blue contour lines). The optimum slag composition is where the slag is at the same time liquid and the S content in the steel is low. No optimum is found when the slag is contaminated with FeO (top right), but the slag desulphurizing ability can be recovered by either conditioning it with CaC₂ (bottom left) or fluxing it with CaF₂ (bottom right).



KINETICS OF THE DESULPHURIZATION PROCESS

Steel desulphurization is strongly limited by reaction kinetics and never reaches equilibrium. While the calculations shown are useful and interesting as they show where the reactions are heading and if -in principle- sound process parameters are chosen, they will not predict the final composition of the liquid steel. A better understanding of the process can be obtained by introducing kinetic models.