Note

Modelling of the Off-gas Exit Temperature and Slag Foam Depth of an Electric Arc Furnace

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A derivation of a dynamic Electric Arc Furnace (EAF) model is shown in Bekker¹⁾ and Bekker, Craig and Pistorius.²⁾ This model describes the time-evolution of EAF furnace and off-gas system variables. A preliminary verification of this model with measurements taken from an industrial EAF, is discussed in Bekker, Craig and Pistorius.³⁾ In this note the Bekker model is improved and expanded to include some process variables not modelled previously. Improvements are made to the off-gas temperature model, and a slag foam depth model is added.

The off-gas model as derived by Bekker²⁾ is sufficient as far as the CO production rate is concerned. The mass flow through the cooling duct is also fairly accurately modelled. The off-gas temperature model, however, still had room for improvement.

There are two main processes in the cooling duct which affect the temperature of the off-gas mixture. Of these, combustion adds heat to the gas, and convective heat transfer to the duct sides extracts heat from the gas. The rates of both processes were initially modelled²⁾ as being proportional to the difference between the off-gas temperature at the entrance to the cooling duct, and the temperature of the cooling duct walls. These two processes were remodelled to better describe the mechanics of the heat transfer that occurs.

In the duct the off-gas from the furnace mixes with the air from the atmosphere that enters at the slip-gap. The CO then combusts with oxygen that enters with the air. The mass fraction of CO in the off-gas (QC_{CO}) reacting with the O_2 gas in the cooling duct is given by Eq. (1), where γ is given by Eq. (2)¹⁾:

$$QC_{CO} = 1 - e^{-\gamma} \dots\dots\dots(1)$$

$$\gamma = k_{\text{combust}} X_{CO} X_{O_2} T_{\text{mixed}} t_{\text{tcd}} \dots\dots\dots(2)$$

k_{combust} is a rate constant that is determined experimentally or calculated from steady state design values. X_{CO} and X_{O_2} represent the molar fractions of CO and O_2 respectively. T_{mixed} is the calculated average temperature of the mixed gas entrained from the furnace and from the atmosphere

through the slip gap before combustion, and t_{tcd} is the average residence time of off-gas in the cooling duct.

The rate at which heat is added to the off-gas mixture as it travels through the cooling duct is proportional to the rate of CO combustion by reaction with O_2 . This rate in turn depends on the off-gas composition as expressed by Eqs. (1) and (2), and mass flow rate, which determines the residence time in the duct and amount of CO available for combustion. The number of moles CO that reacts per second within the whole length of the off-gas duct is given by Eq. (3)¹⁾:

$$n_{CO} = \frac{x_9}{x_9 + x_{10} + x_{11}} \cdot \frac{(1 - e^{-\gamma}) \dot{m}}{M_{CO}} \dots\dots\dots(3)$$

where the gas composition inside the furnace is described by the CO mass x_9 , the CO_2 mass x_{10} , and the N_2 mass x_{11} . M_{CO} is the molar mass of CO and $\dot{m}$ is the mass flow of furnace off-gas into the cooling duct.

The rate at which heat added to the gas is then given by Eq. (4), where ΔH_{burn} represents the enthalpy of the reaction between CO and O_2 to form CO_2 .

$$\Delta H_2 = n_{CO} \Delta H_{\text{burn}} \dots\dots\dots(4)$$

The heat extracted from the furnace can best be described by the Petukhov equation for turbulent flow of gasses in tubes with a particular friction factor, f .⁴⁾ The Petukhov equation is given by Eq. (5), and the friction factor, f , by Eq. (6), with Re_d the Reynolds number, and Pr the Prandtl number for the particular gas, in this case equal to 0.7.

$$Nu_d = \frac{(f/8) Re_d Pr}{1.07 + 12.7 (f/8)^{1/2} (Pr^{2/3} - 1)} \dots\dots\dots(5)$$

$$f = \alpha (1.82 \log_{10} Re_d - 1.64)^{-2} \dots\dots\dots(6)$$

Nu_d is the Nusselt number, quantifying convection heat transfer, and α is a constant used to scale f to its correct value. The equation for f with $\alpha=1$, is empirically derived for smooth tubes. As the cooling duct is not perfectly smooth, an appropriate value for $\alpha>1$ should be chosen.

The Reynolds number is given in Eq. (7), with a duct of mean diameter d , a gas with a mean velocity v , a density ρ , and a viscosity, μ .

$$Re_d = \frac{\rho d v}{\mu} \dots\dots\dots(7)$$

The heat extracted is given by Eq. (8).

$$\Delta H_1 = \frac{k_f}{d} Nu_d A (\bar{T} - T_w) \dots\dots\dots(8)$$

$\bar{T}$ is the average gas temperature, T_w the temperature of the cooling duct wall and A the inner area of the off-gas duct. The values of k_f , the thermal conductivity of the gas, and μ were obtained from standard tables describing these parameters for nitrogen, since the off-gas consists mainly of nitrogen.¹⁾ Both k_f and μ are functions of the off-gas temperature.

The off-gas exit temperature is described by Eq. (9), with Cp_{gas} the molar specific heat of the gas, and M_{gas} the average molar mass of the gas mixture.

$$T_{\text{exit}} = T_{\text{mixed}} + \frac{(\Delta H_2 - \Delta H_1) M_{\text{gas}}}{\dot{m} Cp_{\text{gas}}} \dots\dots\dots(9)$$

Fig. 1. Comparison of original (solid line) and revised (broken line) off-gas temperature models at high flow velocities. Conditions are as given by Bekker *et al.*³⁾ except that the off-gas fan ran at a power of 3.6 MW until $t=50$ min, and was then turned to a lower power of 2.7 MW.

A simulation of the revised off-gas temperature model compared to the original model is shown in **Fig. 1**, for the off-gas flow close to its limiting value. In this simulation, the furnace conditions as used in Bekker *et al.*³⁾ were used. Briefly, these were that 53.5 t of scrap, 11.5 t of fluxes and 63 t of hot metal were charged before the simulation time started. Oxygen (totalling 4 220 Nm³) was blown during the tap, as was 0.1 t of carbon; 35 t of direct-reduced iron (DRI) was also added during the tap. The original model correlates well with the revised model when the off-gas variables are close to their limiting values. This is to be expected since the derivation was made using the limiting values. However, when the off-gas flow rate is decreased (at $t=50$ min), the original model becomes inaccurate, indicating excessive cooling and thus a too low off-gas exit temperature. The revised model remains accurate at low flow velocities and also takes additional heat generation due to the build-up of CO inside the EAF under low flow velocities into account.

In the derivation of the original EAF model,²⁾ Bekker *et al.* mentioned the use of a foamy slag practice to increase EAF efficiency by allowing higher arc power settings. No modelling effort of the slag foaming depth was undertaken. Slag foaming depth should typically be maintained at approximately 300 mm.⁵⁾ What follows is a derivation of a model describing the slag foam depth based on the EAF states described by Bekker *et al.*²⁾

The foam index of slag, Σ , is defined as in Eq. (10).⁶⁾

$$\Sigma = \frac{H_f}{V_g} \dots\dots\dots(10)$$

H_f is the increase in foam height due to gas flow (cm) and V_g is the superficial gas velocity (cm/s). In physical terms, the foam index represents the average travelling time of gas through the foam.

Industrial data for foaming of basic slags in an electric arc furnace⁵⁾ can be used to estimate the relationship be-

tween the foam index and slag FeO content. This relation can be approximated by Eq. (11), for slags containing 20–40% FeO.

$$\Sigma = 20\,172.58 (\%FeO) - 2.07 \dots\dots\dots(11)$$

Three mechanisms of gas production are described by Bekker.²⁾ Graphite injected into the slag reacts with FeO to form CO; the graphite is assumed to react as soon as it enters this slag. This reaction is described by Eq. (12), with w_2 the graphite injection rate [kg/s], M_{CO} the molar mass of CO and M_C the molar mass of carbon. G_1 is the CO generation rate (in kg/s).

$$G_1 = \frac{M_{CO}}{M_C} w_2 \dots\dots\dots(12)$$

Equation (13) describes the rate of CO production [kg/s] by decarburisation of the metal melt. k_{dc} is a decarburisation rate constant, and $(X_C - X_C^{eq})$ is the difference between the current carbon molar fraction in the metal and the equilibrium molar fraction carbon in the metal.

$$G_2 = \frac{M_{CO}}{M_C} k_{dc} (X_C - X_C^{eq}) \dots\dots\dots(13)$$

Since air is used as a carrier gas, nitrogen is injected together with the graphite. Approximately 1 kg nitrogen is injected with every 150 kg of graphite. The rate at which nitrogen enters the slag is therefore given by Eq. (14).

$$G_3 = \frac{1}{150} w_2 \dots\dots\dots(14)$$

The total molar flow rate of gas through the slag can be calculated using Eq. (15).

$$N = \frac{1}{M_{CO}} (G_1 + G_2) + \frac{1}{M_{N_2}} G_3 \dots\dots\dots(15)$$

The ideal gas law is then used to determine the gas volume produced, and dividing the volume by the EAF area yields the superficial gas velocity, V_g . In Eq. (16), R is the

Fig. 2. Calculated variations in slag foam depth with time. The foam depth is most sensitive to the FeO content of the slag, which reaches a maximum at $t=44$ min (at which point oxygen blowing ceases). Smaller changes (in slag FeO content and hence in foam depth) are due to changes in the DRI feed rate (since the DRI adds FeO to the slag); the DRI feed rate was lowered at $t=46$ min, increased at $t=58$ min, and turned off at $t=60$ min.

universal gas constant, T the gas temperature, assumed to be equal to the liquid steel temperature, and P and A the absolute pressure inside the EAF and its cross-sectional area respectively.

$$V_g = \frac{NRT}{PA} \dots\dots\dots(16)$$

The increase in slag foam height, H_p , can now be calculated by substituting Eqs. (16) and (11) into Eq. (10).

A calculation of the slag foam height, starting 20 min after charging the EAF, is shown in **Fig. 2**, for the same conditions as used in the calculation presented in Fig. 1. The calculation was not performed for times shorter than 22 min into the simulation, since only at this time was most of the solid flux additions molten (8.5 t out of the total of 11.5 t added). In the foam depth calculation, the foam index was constrained to its value for 20% FeO in the slag if the FeO content dropped below this value; this is the origin of the discontinuity in the calculated rate of change of the foam depth at $t=37$ min. The variations in the foam depth with time can mostly be attributed to the variation in the slag FeO content. At the start of the simulation the FeO

content is still very low, allowing good foaming. Hereafter the FeO content increases rapidly, reach a maximum at approximately 44 min, and then decrease again until tapping. The simulated depth of the foaming slag layer near the end of the simulation corresponds well with data from industry.⁵⁾

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