

CHAPTER 2: PROCESS OVERVIEW.

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2.1. INTRODUCTION.

An overview of EAF steelmaking is presented as well as an overview of the model used for the simulation study. The control objectives are also motivated based on theoretical motives and practical considerations. Additional modelling required in describing the slag foam depth inside the EAF is described.

2.2. PROCESS DESCRIPTION.

One of the big advantages of EAF steelmaking is that practically all grades of steel can be produced in an EAF with a basic lining. These grades include the plain carbon steels, high manganese steels, high silicon steels, high aluminium steels, the entire range of stainless steels and high-speed steels and other alloy tool steels [12]. The process used for simulation purposes in this work produces plain carbon steels using an EAF.

A functional layout of an EAF with its off-gas system is shown in Figure 2.1.

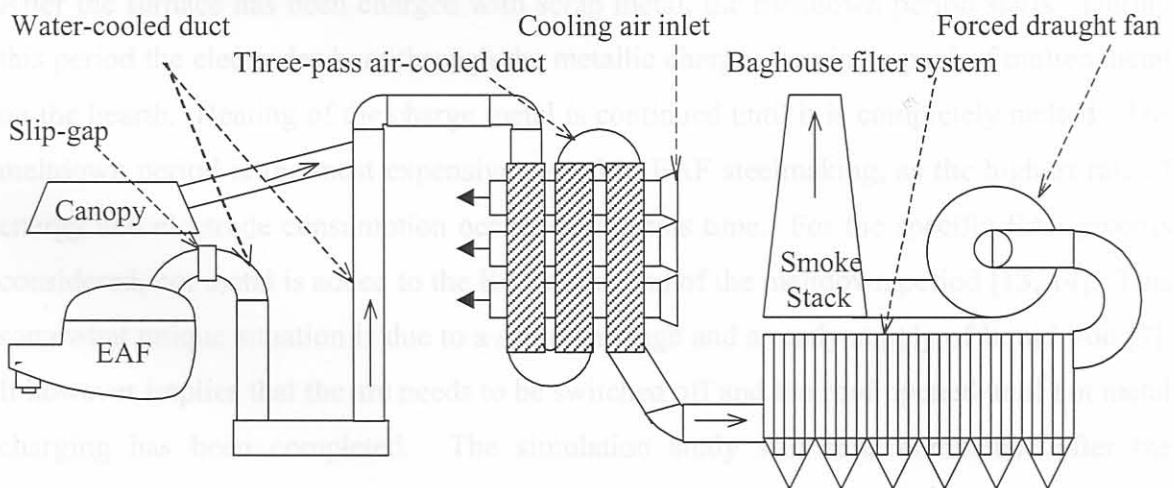


Figure 2.1. Functional layout of an EAF with an off-gas system.

The EAF off-gas system consists of an off-gas fan, a slip-gap and a bag-house. The off-gas fan provides a draught force to extract gases from the furnace. The slip gap serves the purpose of entraining air from the atmosphere for combustion of CO extracted from the furnace, and of cooling the off-gas. The combination of the slip-gap and off-gas fan provides a negative relative pressure inside the furnace. Before being emitted into the atmosphere, the off-gas needs to be filtered by the bag-house filter in order to satisfy environmental regulations.

EAFs produce steel by melting scrap and other sources of iron, using a three-phase electrical supply as the main energy-source. Graphite electrodes are used in a triangular arrangement to create the three-phase arc. The aim of the steelmaking process is to raise the steel temperature to a level suitable for further processing (secondary steelmaking) and to remove unwanted elements from the steel melt, especially silicon, carbon, sulphur, manganese and phosphorus [7].

The EAF steelmaking process can be divided into 4 phases: The meltdown period, the oxidising period, the composition and temperature adjustment period and the tapping period [12]. The 4 phases will now be discussed in more detail.

After the furnace has been charged with scrap metal, the meltdown period starts. During this period the electrodes bore through the metallic charge, forming a pool of molten metal on the hearth. Heating of the charge metal is continued until it is completely melted. The meltdown period is the most expensive period in EAF steelmaking, as the highest rate of energy and electrode consumption occurs during this time. For the specific EAF process considered, hot metal is added to the EAF at the end of the meltdown period [13, 14]. This somewhat unique situation is due to a scrap shortage and a ready supply of liquid iron [7]. It however implies that the arc needs to be switched off and the roof opened until hot metal charging has been completed. The simulation study will thus commence after the meltdown phase has been completed, as continuous off-gas control is impossible if the roof still needs to be opened.

During the oxidising period, phosphorus, silicon, manganese, carbon and iron are oxidised in the temperature range of 1300 - 1480°C. The reactions of silicon, phosphorus and manganese are exothermic and occur at a lower temperature, whereas the carbon reaction is less strongly exothermic and only occurs later in the tap. Practically all silicon in the metal is oxidised to SiO₂ early in the melt period, and enters the slag. It is thus essential to charge lime early in this stage to prevent damage to the refractories [5]. For the EAF under consideration, the main source of oxygen is oxygen gas injected through side lances. The direct injection of oxygen gas is extremely important in modern steelmaking practice, from the view of rapidly removing carbon from the bath. Excess carbon reacts with the oxygen to form carbon monoxide gas that bubbles out of the steel. This "carbon boil" stirs the bath, makes it more uniform in temperature and composition, whilst also removing some hydrogen and nitrogen from the steel [12]. The oxygen also provides an additional energy source.

To increase productivity, the oxidising period often overlaps with the composition and temperature adjustment period. During this period the temperature is adjusted to meet the tapping specification and the composition is adjusted if required. If a double slag process was used, the oxidising slag would be removed and a new slag formed during this period. Most carbon and low alloy steel grades made in EAFs are produced using a single slag process. If further refining of the steel is required to lower sulphur and oxygen contents, this is accomplished by means of ladle metallurgy treatment after the steel has been tapped from the EAF [12].

During the tapping period, the electrodes are raised, the tap hole opened and the furnace is tilted so that the steel is drained into a ladle. Steel is often refined further in the ladle after tapping to lower oxygen and sulphur content. Since the slag in the furnace contains iron oxide that inhibits the removal of sulphur and oxygen, various methods are employed to prevent the slag from mixing with the tapped steel. One method is to leave some steel in the furnace after tapping, to be used during the following tap. This is commonly referred to as the "wet heel" practice and prevents steel-slag mixing without wasting the excess steel.

In the basic EAF process, the function of the oxidising slag is to provide a reservoir for oxides of silicon, manganese, phosphorus, iron, etc. The slag also protects the bath from excessive oxidation, acts as a medium for the transfer of oxygen to the slag-metal interface, shields the arc from the atmosphere, protects the furnace refractories from the arc and provides an insulating blanket to minimise heat losses from the melt. Fluxes (burnt lime (CaO) and dolomitic lime (CaO, MgO)) are continuously added to the slag using conveyor belts, to adjust the basicity of the slag [5]. The slag basicity has a direct influence on the removal of silicon, phosphorus and manganese from the steel melt.

In some operations Direct Reduced Iron (DRI) is preferred to scrap, because it has a known and uniform composition and contains no residual elements such as chromium, copper, nickel and tin. Where scrap supplies are limited, DRI would form a significant part of the total iron charge. When DRI is melted, it furthermore forms a foamy slag, because it contains both carbon and iron oxide [12].

The "foamy slag" practice is used to protect the furnace refractories from the arc and thus allows more power to be applied to the arc, yielding higher efficiency. This practice involves a controlled carbon boil in the slag that results in the formation of a foamy slag layer of 300 mm or deeper. Carbon is often added to the slag at a controlled rate to react with the iron oxide in the slag, creating the carbon boil [12].

The off-gas system of an EAF serves the purpose of regulating the relative furnace pressure, limiting carbon monoxide (CO) emission and removing solid particles from the off-gas before being emitted into the atmosphere. A dangerous working environment results if CO present inside the furnace is emitted into the melt shop. This can be avoided by always maintaining a negative relative pressure between the furnace and its surroundings. It is typically attempted to keep the relative furnace pressure at approximately -5 Pa, as this value provides a good trade-off between energy-wastage and safety [13,14]. Environmental legislation also exists regarding CO emission and the dust composition of the emitted gases.

2.3. SIMULATION MODEL.

An EAF model presented by Bekker [13] and Bekker *et al.* [14] is used as a basis for all simulations. The off-gas temperature model was improved by Viljoen [10], and the revised off-gas temperature model used in the simulation study.

The EAF model consists of 17 mostly non-linear equations representing 17 state variables in the EAF. The first 14 states are tabulated in Table 2.1 and the other 3 states are used to model the second order mass flow with dead time in the off-gas duct.

Bekker [13] also derived additional output equations describing the off-gas mass-flow, the CO fraction in the off-gas and the percentage carbon in the steel melt. Additional to the revised off-gas temperature model by Viljoen [10], the modelling of the slag foam depth is discussed in Section 2.5.

Table 2.1. States of the EAF model.

State variable.	Description.
x1	Solid scrap mass.
x2	Liquid metal mass.
x3	Mass of carbon dissolved in the steel melt.
x4	Mass of silicon dissolved in the steel melt.
x5	Solid slag mass.
x6	Liquid slag mass.
x7	Mass of iron oxide in the slag.
x8	Mass of silicon oxide in the slag.
x9	Carbon monoxide gas in the furnace.
x10	Carbon dioxide gas in the furnace.
x11	Nitrogen gas in the furnace.
x12	Liquid metal temperature.
x13	Scrap and solid slag temperature.
x14	Relative furnace pressure.

Bekker [13] defined the relative furnace pressure, the off-gas temperature and the off-gas CO mass fraction as controlled variables. The manipulated variables used were the off-gas fan power and the slip-gap width. The other inputs were defined to be disturbances. Viljoen [10] added the liquid metal temperature, the carbon content and the liquid metal mass to Bekker’s controlled variables and DRI addition rate and oxygen addition rate as manipulated variables.

The MPC controller designed in this dissertation will build on the work of Bekker and Viljoen by adding the graphite injection rate to the manipulated variables. The list of controlled variables will also be extended to include the depth of the foamy slag layer (see Figure 2.2). Emphasis will also be placed on unmodelled variations in feed compositions that occur under typical EAF operation. The choices of the manipulated and controlled variables will be discussed in more detail in Section 2.4.

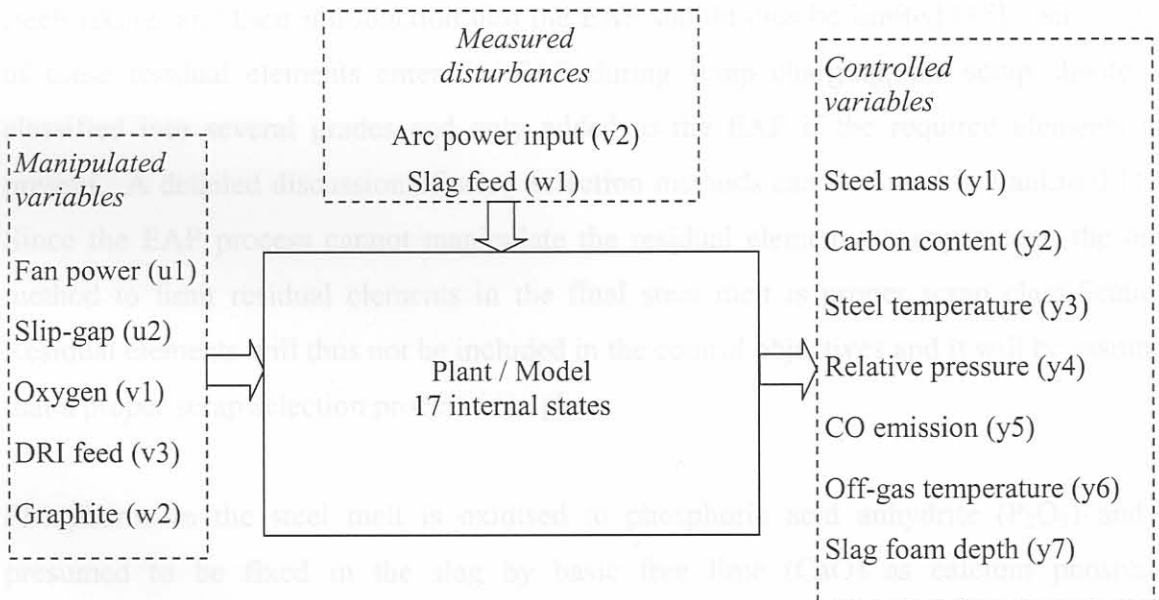


Figure 2.2. Schematic diagram of the EAF model.

2.4. CONTROL OBJECTIVES.

High iron oxide (FeO) content in the slag

In order to define proper control objectives, steel specifications and commonly used control strategies were investigated. The choices of controlled variables indicated in Figure 2.2 will be discussed, based on the above-mentioned considerations.

The conditions favouring manganese removal are very similar to those favouring

For carbon steels, chemical composition limits are defined for carbon, manganese, phosphorus and sulphur. Limits also exist on residual elements including copper, nickel and tin. Residual elements cause the greatest problems during reheating and subsequent rolling operations, particularly tin and copper. These elements are enriched at the surface during reheating and form low melting point phases with iron. In many plain carbon steels, elements such as molybdenum, chromium and nickel have a deleterious effect on e.g. weldability [15]. The important feature about residuals such as copper, tin, nickel, molybdenum and to some extent chromium, is that they are not removed during EAF steelmaking, and their introduction into the EAF should thus be limited [15]. Since most of these residual elements enter the EAF during scrap charging, the scrap should be classified into several grades and only added to the EAF if the required elements are present. A detailed discussion of scrap selection methods can be found in Lankford [12]. Since the EAF process cannot manipulate the residual elements to any extent, the only method to limit residual elements in the final steel melt is proper scrap classification. Residual elements will thus not be included in the control objectives and it will be assumed that a proper scrap selection process is in place.

of the steel melt. Sulphur removal from a steel melt is dependent on the

Phosphorus in the steel melt is oxidised to phosphoric acid anhydrite (P_2O_5) and is presumed to be fixed in the slag by basic free lime (CaO) as calcium phosphate ($4CaO \cdot P_2O_5$) [5]. Not only the basicity of the slag, but also the iron oxide content of the slag play a role in the removal of phosphate. The following conditions favour the removal of phosphorus from the steel melt:

- High slag basicity ($\text{CaO}/\text{SiO}_2 > 2.2$).
- High iron oxide (FeO) content in the slag.
- Relatively low temperature.
- A high slag volume of good fluidity.

The conditions favouring manganese removal are very similar to those favouring phosphorus removal. The following factors favour low residual manganese in metal:

- High slag volume.
- High iron oxide content in the slag.
- Relatively low temperatures.
- Semi-basic slag with a lime/silica ratio (CaO/SiO_2) < 2.2 [5].

Keeping the slag basicity as close as possible to 2.2 would thus favour both manganese and phosphorus removal. Since a high iron oxide content in the slag translates into a production loss, the iron oxide content cannot be raised excessively. The iron oxide content of the slag varies with the carbon in the steel at the end of the boil and typically ranges from 13% to 20% [12]. A slag FeO content of 15% thus favours manganese and phosphorus removal without resulting in excessive production losses.

The presence of the element sulphur in steel products has been a challenge both to operators and metallurgists ever since the early age of steel. The detrimental effect of sulphides in the steel results in inferior surface quality at the higher ($>0.03\%$) sulphur end of the usual steel range. Sulphur removal from a steel bath under an oxidising slag is relatively limited, such that at best only half of the sulphur load introduced into the heat can be removed from the steel bath. Some sulphur is removed during the oxidation period (probably between 20% and 30%), but its removal is uncertain and not easily controlled [5]. The following conditions favour sulphur removal:

- High slag basicity.
- High temperature.
- Good slag fluidity.
- Intimate mixing of slag and metal.
- Low FeO content in the slag.
- Low dissolved oxygen content in the bath [5].

The first three conditions can easily be satisfied in a single oxidising slag furnace process. The last two conditions together with the first three can be obtained only in the final finishing period (reducing slag) of the double slag practice. If scrap with a low enough sulphur content cannot be obtained, the most efficient sulphur removing would occur during secondary ladle metallurgy.

Slag control is a very important factor in EAF steel production. The EAF permits the slag to be controlled to meet almost any desired characteristic, a fact that is the real basis of the flexibility of the EAF [12]. Sulphur, phosphorus and manganese in the melt are not modelled explicitly by Bekker [13]. Manipulation of the slag properties can however be used effectively to favour removal of the above-mentioned elements from the steel melt. The ratio between MgO and CaO is also of importance. Lankford [12] suggests that the CaO content of the slag should be at least 40%, although 50% is preferable for good sulphur removal. Taylor [5] suggests an MgO content of at least 12% in the slag to limit erosion of the refractories. To simplify the charging process a constant MgO/CaO ratio of between 0.3 and 0.4 should be used to obtain the required slag properties [5]. The following slag properties are suggested, based on the reasoning above:

- A slag basicity of 2.2.
- High FeO content in the slag (15%).
- Maintaining the MgO/CaO ratio constant at 0.35.

Although the above-mentioned slag properties can easily be derived from the existing model, an extensive modelling effort would be required to model the influence of improved slag control on the removal of inclusions in the melt (e.g. sulphur, phosphorus and manganese). Such an extensive modelling effort is outside the scope of this work.

Instead of manipulating variables related to the slag properties without confirmation that the strategy is efficient, it will be assumed that the existing slag additions satisfies the requirements defined above. De Vos [7] performed a thorough analysis on optimal slag additions to an EAF, and it is thus considered a reasonable assumption that slag additions are close to optimal. The slag addition rates as described in Bekker [13] will therefore be modelled as a measured disturbance, and no further effort would be made on manipulating slag properties more efficiently.

The most common method to reduce the carbon content of the steel bath is the injection of gaseous oxygen into the bath [12]. DRI has the further advantage that it contains both oxygen (FeO) and carbon. The residual oxygen inside the DRI is thus capable of oxidising the carbon without any oxygen additions. DRI however seldom contains the required balance between carbon content and residual oxygen, but by additional oxygen blowing carbon control is achieved fairly easily.

The two main disadvantages of EAF steelmaking are the inability of an EAF to produce low residual steels from high residual scrap (as discussed earlier) and the fact that the nitrogen content of EAF steel is about twice as high as steel made in Basic Oxygen Furnaces (BOFs) [12]. For certain grades of steel, particularly those produced for deep drawing applications, low nitrogen contents are desirable. The high nitrogen content of EAF steels occurs because of the breakdown of the N_2 molecule producing some atomic N in the vicinity of the arc. The local high temperatures close to the arc further increase the solubility of nitrogen in the steel bath. It was found experimentally that the nitrogen content in an EAF during the oxygen blow is very similar to that of other furnaces. After the oxygen blow, the nitrogen level tends to increase with time [5]. If low nitrogen levels are required, the following steps are suggested:

- The heat should be tapped as close to the completion of the oxygen blow as possible.
- The temperature profile should be at the required level for tapping at the end of the blow.
- Power should not be applied after completion of the blow.
- Avoid raising the temperature higher than required to limit nitrogen solubility.
- Add ferroalloys including manganese, chromium and vanadium as late in the heat as possible, as they increase nitrogen solubility.

Hydrogen is introduced in the EAF by rusted and damp charging materials and by additions of lime and fluorspar. The arc itself also dissociates water vapour in the atmosphere to molecular and atomic hydrogen. High quality low alloy steels are especially susceptible to "hair-line" crack formation caused by hydrogen. Hydrogen is removed in the ladle during secondary metallurgy and very little can be done during EAF operation to limit hydrogen absorption.

Temperature control can be obtained by matching the DRI-addition rate to the electrical power input. Operators typically adjust the DRI feed rate based on the bath temperature that is checked at 10 – 15 minute intervals. DRI feed rates typically vary between 28 and 33 kg/min/MW once the scrap is melted [5], but Dressel [16] reported feed rates varying between 5 and 35 kg/min/MW. Bath temperature should be maintained in the range between 1570 and 1630°C for good melting performance and good slag fluidity [5]. The tapping temperature may vary only within a very narrow range, and should equal approximately 1630°C [14].

The final steel mass will be determined by the EAF capacity and the requirements of the secondary metallurgical processes. A higher than required steel mass will necessitate additional heating to prevent the excess steel from solidifying, if the capacity of processes further downstream are exceeded. A too low mass will prevent continuous secondary processes, e.g. continuous casting to be operated efficiently. The continuous addition of DRI allows the control of the final steel mass, independent of the initial scrap charge.

The off-gas system limits the emission of dust by baghouse filtering, and regulates the emission of CO by adjusting the ratio between fan speed and slip gap width. It is assumed that the baghouse is functional and that visible emission and opacity regulations will thus be met. The exposure of workers to dust and other contaminants is governed by regulatory requirements. The threshold limit value for CO exposure as prescribed by the Occupational Safety and Health standards is 55mg/m³ [5]. This translates into a CO emission fraction [mass/mass] of 9.14×10^{-5} at atmospheric pressure and an average temperature of 600K. CO emission should thus be limited to the greatest extent, since a 0.009% CO mass emission fraction is already considered a health hazard.

The off-gas exit temperature should also be controlled to prevent baghouse explosion. A non-functional baghouse necessitates a plant shutdown for repairs, which causes great production losses. The off-gas temperature is not measured directly before the bag-house, but at a point before the three-pass air-cooled duct (see Figure 2.1). The limiting temperature at this point is 773K (500°C), but Bekker [13] suggests controlling the temperature at approximately 100K lower to provide an adequate safety margin.

The negative relative pressure cause a loss of energy as a large amount of heat is extracted with the off-gas [13, 14]. A negative relative pressure is however essential in preventing hazardous gases inside the EAF from being emitted into the workshop. Process efficiency can be improved by reducing the magnitude of the relative pressure, thereby reducing energy wastage. A proper control system is however required to maintain safety standards when the relative pressure is operated closer to its limits. Although the theoretical optimal relative furnace pressure is 0 Pa, it is frequently suggested to control the relative furnace pressure at -5 Pa, as this is a good trade off between safety and efficiency [13, 14].

The foamy slag practice protects the furnace refractories from heat radiated from the arcs. Normal practice requires that the power to the arcs be decreased as soon as most of the slag has been melted and the furnace walls become exposed to the arc. However, this decrease in power slows down the heat. By using a foamy slag practice, a decrease in power is unnecessary and furnace productivity can be increased by the use of high power inputs [12]. Excessive foaming should also be avoided as the slag could foam out of the vessel [17]. A foamy slag layer of 300 mm or more is suggested to provide the required protection to the furnace walls [12].

The control objectives (excluding slag properties) are summarised in Table 2.2, based on the practices and motivation given before.

$$E = 20172,38(\%FeO)^{2,3} \quad (2.2)$$

Table 2.2. Control objectives.

Control objective	Motivation
Regulate carbon content.	Meet steel specification.
Bath temperature 1570 - 1630°C.	Good melting performance and slag fluidity. Meet tapping requirements.
Steel tapping mass.	Secondary metallurgical demands.
CO emission < 0.009%.	Health and environmental standards.
Relative pressure slightly below 0 Pa.	Safety and energy efficiency.
Off-gas exit temperature < 773K.	Prevent bag-house explosion and accompanying economic implications.
Foamy slag-layer 300 mm or more thick.	Protect refractories and increase furnace productivity.

2.5. MODELLING OF SLAG FOAMING.

In order to control the slag foaming depth accurately, additional modelling of the slag foam characteristics was required. Jiang and Fruehan [17] defined the foam index of the slag (Σ) as

$$\Sigma = \frac{H_f}{V_g}, \quad (2.1)$$

where H_f represents the foam height (cm) and V_g is the superficial gas velocity (cm/s). In physical terms, the foam index is the average travelling time of the gas in the foam [s].

Conditions favouring slag foaming are slag basicities larger than 2.5 and an FeO content between 15% and 20% [17]. Jiang and Fruehan [17] presented experimental results showing the dependence of the foam index for a typical oxidising slag on the FeO content of the slag. Experiments were conducted for FeO contents up to 40% and a slag basicity of approximately 3. Linear regression yielded the relation given in Equation 2.2, with unit [s], which is valid for FeO contents between 20% and 40%.

$$\Sigma = 20172.58(\%FeO)^{-2.07} \quad (2.2)$$

Since the FeO mass in the slag and the liquid slag mass have already been modelled by Bekker [13], the foam index can easily be calculated for various slag compositions.

The superficial gas velocity (V_g) is determined by the amount of gas being produced by the steelmaking process and the physical dimensions of the EAF. Bekker [13] describes the various masses of CO, CO₂ and N₂ being formed by the steelmaking process in the calculation of the gas composition inside the EAF. Two sources of CO are modelled and one source of N₂. CO₂ is not formed by reactions in the steel or slag, but rather by combustion of CO in the gas phase. This occurs above the slag layer and can thus not be included in the calculation of the superficial gas velocity. The sources of CO and N₂ will be discussed in turn.

The rate of CO produced by injection of graphite into the slag is proportional to the rate of graphite injection. An assumption was made that all carbon introduced by the graphite injection reacts instantly with FeO to form CO and iron [13]. The rate of CO production is thus described by

$$G_1 = \frac{M_{CO}}{M_C} w_2, \quad (2.3)$$

for M_{CO} the molar mass of CO, M_C the molar mass of C and w_2 the graphite injection rate. The unit of G_1 is thus [kg/s].

The rate of CO produced by decarburisation due to reaction with FeO is given by

$$G_2 = \frac{M_{CO}}{M_C} k_{dC} (X_C - X_C^{eq}), \quad (2.4)$$

for k_{dC} the decarburisation rate constant, X_C the molar fraction of carbon in the steel and X_C^{eq} the equilibrium molar fraction of carbon in the steel [13].

Graphite is injected into the furnace using air as a carrier gas. For every 150 kg of graphite injected, 1 kg of N₂ is injected together with the carrier gas. The rate of N₂ production due to graphite injection is thus given by Equation 2.5.

$$G_3 = \frac{1}{150} w_2 \quad (2.5)$$

The molar quantity of gas produced can be calculated as

$$M = \frac{1}{M_{CO}} (G_1 + G_2) + \frac{1}{M_{N_2}} G_3, \quad (2.6)$$

for M the number of moles gas produced.

The ideal gas law is now used to determine the volume of gas generated. Dividing the gas volume by the area of the slag layer yields the superficial gas velocity (V_g).

$$V_g = \frac{MRT}{PA} \quad (2.7)$$

R represents the universal gas constant, T the gas temperature that is assumed to be equal to the liquid steel temperature, P is atmospheric pressure and A the area of the slag inside the furnace.

The slag height (H_f) can now be calculated using Equation 2.1. Conversion of measurement units is required since the units of V_g is [m/s] whilst H_f has the units of [cm].

2.6. CONCLUSION.

An overview of EAF steelmaking was presented and the simulation model used was described briefly. A more detailed discussion of some aspects of steelmaking was presented, and some control objectives typically used in industry discussed, to justify the objectives chosen for the EAF under consideration. Modelling of the foamy slag layer was described to expand the available EAF model. Although the slag foam depth model was derived under steady state conditions, the exact slag depth is not critical and an approximation should suffice.