

The Impact of Hot Metal Temperature on CO₂ Emissions from BOF Steelmaking [†]

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Abstract: Recycled steel is a key material for sustainable development. However, not all steel demand can be met by recycling, and therefore new metallic iron must be introduced in the global cycle. The transformation of iron oxides into steel requires carbon which is oxidized into CO₂. This paper focuses on the basic oxygen furnace (BOF) where molten iron is transformed into liquid steel. The process is modelled using mass and energy balances in order to assess the effect of molten iron temperature on CO₂ emissions. Model results show that, for a typical converter charge, a slight change of 10 °C in the hot metal temperature can lead to a direct variation of 0.01 t of CO₂ per ton of liquid steel. Finally, different actuation levers for carbon mitigation are suggested. It can be concluded that operation and modelling improvements should be jointly addressed to exploit their full potential for carbon footprint reduction.

Keywords: BOF charge model; carbon footprint; mass balance; energy balance

1. Introduction

Steel is on the road to be a major player for sustainable development and circular economy [1]. It can be produced at an integrated facility from iron ore or at a secondary facility, mainly from recycled steel scrap. As shown in Figure 1a, an integrated site typically includes coke ovens (CO), sinter plants (SP), blast furnaces (BF), and basic oxygen furnaces (BOF). Sinter plants prepare the iron ores for the blast furnaces while coke ovens transform coal into coke which is fuel and reducing agent for the blast furnace. By contrast, secondary steelmaking produces steel by melting scrap in the electric arc furnaces (EAF), as illustrated in Figure 1b.

From an economic global point of view, it is always more convenient to recycle steel than to mine iron ore. The same conclusion is met when considering energy, natural resources or emissions. However, several issues, as limited scrap availability or the lower quality of EAF steels has made BOF the prevailing route with more than 70% of world steel production [1]. Since not all steel demand can be met by recycling, new metallic iron must be introduced in the global cycle through integrated steelmaking.

The transformation of iron oxides into steel makes use of huge amounts of reducing agents, being carbon the most important [2]. This causes a substantial volume of carbon dioxide and, consequently, the environmental conscious steelmaker must be well aware about how his process is affecting CO₂ emissions [3]. There is a number of excellent publications on CO₂ emissions for the steelmaking industry [2–4]. These works are essential to understand the behaviour of the integrated mill and to ensure that improvements in a part of the process do not affect adversely the entire facility. However, these analyses tend to rely on fixed sub-processes models, not allowing BOF engineers to identify or assess local improvements.

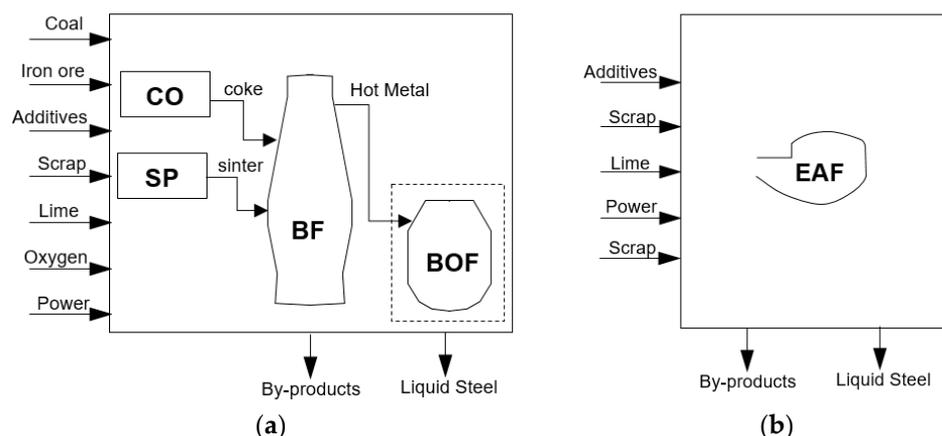


Figure 1. Systems for liquid steel production: (a) Integrated facility; (b) Secondary facility.

2. System Modelling

This research is focused on the BOF process, marked out by a dashed line in Figure 1a, where a carbon-rich molten iron (hot metal) coming from the blast furnace (BF) is transformed into liquid steel by blowing oxygen through the hot metal and making use of steel scrap and other additives [5].

A model based on mass and energy balances is proposed here. Materials properties and reaction enthalpies are estimated from data available in the literature and confirmed by real plant practice. This macroscopic and mechanistic approach provides a model that generalizes well for different plants and under diverse production scenarios [6].

Mass conservation applied to a liquid steel batch, implies that the total mass of loaded materials (hot metal, scrap, additions, oxygen, inert gasses) equals total mass of obtained products (liquid steel) and by-products (slag and off-gas):

$$\sum_{i \in input} m_i = \sum_{i \in output} m_i \quad (1)$$

where m_i represents the mass of material i . Furthermore, mass balance is satisfied separately for individual chemical elements:

$$\sum_{i \in input} m_i x_i^j = \sum_{i \in output} m_i x_i^j \quad (2)$$

where x_i^j represents the mass fraction of element j in material i . Quantities and chemistries are given in Table 1.

Similarly, energy balance of the system leads to

$$\sum_{i \in input} m_i h_i = \sum_{i \in output} m_i h_i + Q_{TL} \quad (3)$$

where h_i is the specific enthalpy of material i and Q_{TL} accounts for furnace thermal losses. Since reaction enthalpies at standard metallurgical conditions are available in literature, Equation (3) can be expressed in a more convenient way by

$$\sum_{i \in output} m_i \Delta h_{M-F_i} - \sum_{i \in input} m_i \Delta h_{M-I_i} + \Delta H_r^M + Q_{TL} = 0 \quad (4)$$

where $-\Delta h_{M-I_i}$ represents the enthalpy variation of the raw material i from initial to metallurgical conditions (including decomposition, heating and dissolution) while Δh_{M-F_i} is the enthalpy variation of product i from metallurgical to final conditions. The enthalpy difference between inputs and outputs at their respective conditions is due to reaction enthalpies, ΔH_r^M , and thermal losses. Transformation and reaction enthalpies were obtained from steelmaking literature and verified against plant data before being adopted.

Table 1. Mass, temperature and composition of BOF inputs and outputs.

Material	m (t)	T (°C)	Chemical Composition (%)										
			Fe	C	Si	Mn	P	O	N	Ar	CaO	MgO	
Hot metal	m ²	v ¹	94.39	4.80	0.46	0.27	0.08						
Scrap	m ²	25	99.42	0.05	0.01	0.50	0.02						
Lime	15	25									95	5	
Dol. lime	5	25									63	37	
Iron Ore	v ¹	25	70						30				
Anthracite	v ¹	25		100									
FeSi	v ¹	25	25		75								
N ₂	0.15	25								100			
Ar	0.25	25									100		
O ₂	m ¹	25							100				
Steel	300	1700	99.78	0.035	0.001	0.080	0.010	0.090					
Slag	m ²	1700	m ²		m ²	m ²	m ²	m ²				m ²	m ²
Off-Gas	m ²	m ²		m ²					m ²	m ²	m ²		

¹ v = variable of the study; ² m = model result.

3. Results and Discussion

CO₂ emissions were calculated for hot metal temperatures between 1200 and 1300 °C under four different hot metal strategies:

1. Neutral energy balance, just with hot metal and scrap, without cooling or heating additions.
2. Maximized hot metal, using iron ore pellets as coolant.
3. Minimized hot metal, using anthracite as heating addition and producing CO₂.
4. Minimized hot metal, using FeSi as heating addition and generating SiO₂.

Direct emissions from BOF were obtained directly from the model while indirect emissions were taken from Ryman [3], and are shown in Table 2. The maximum possible amount of each material, is also indicated.

Table 2. Coefficients for the model: indirect CO₂ emissions and constraints for input materials.

	Unit	H. M.	Scrap	I. O.	Ant.	FeSi	Lime	Dol.	Ar/N ₂	O ₂
Indirect emission [3]	(t CO ₂ /t)	1.1	0.02	0.18	0.05	3.9	1.35	1.35	0.3	0.3
Max. amount	(t)	280	80	4	4	2	-	-	-	-

Results are plotted in Figure 2 where the importance of the selected hot metal strategy can be recognized. When neutral balance is modified by adding anthracite or iron ore pellets, an increase on CO₂ total emissions of 0.03 and 0.05 t, respectively, is observed. By contrast, the use of FeSi not only saves hot metal but also avoids 0.09 t of CO₂, being the most environmental-friendly option.

The impact of hot metal temperature is very clear in the neutral strategy. As shown in Figure 2b, the higher the temperature, the lower the amount of hot metal required. Since direct and indirect emissions are lower for scrap than for hot metal, the total emission diminishes by 0.006 t of CO₂ every 10 °C. The use of anthracite results in a shifted curve. The curves for iron ore and FeSi strategies present a bending point at the temperature where the maximum hot metal or maximum scrap constraints are reached.

Usually, BOF charge calculation is based on an estimation of hot metal temperature since the real value is not normally known. An error of -10 °C in this estimation requires the addition of 800 kg of anthracite which will cause an increase on direct emission of 0.01 t of CO₂.

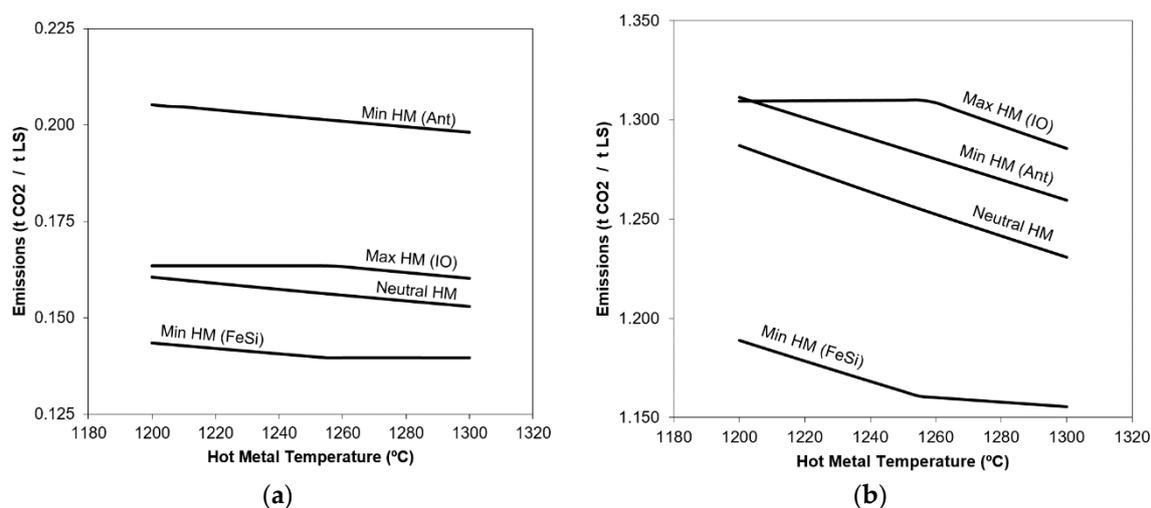


Figure 2. Calculated CO₂ emissions per ton of liquid steel: (a) Direct; (b) Total.

4. Conclusions

The developed model provides useful insights in how hot metal temperature is influencing CO₂ emissions. Based on this, three actuation levers can be envisaged: the reduction of thermal losses in metallurgical operations; the use of FeSi or other reducing agent with a lower carbon footprint [7]; and, finally, the improvement of control models and measurement systems [8,9].

It is finally concluded that operation and modelling improvements should be jointly addressed to exploit their full potential for carbon footprint reduction.

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References

1. Steel by Topic (Life Cycle; Sustainability; Circular Economy; and Statistics). Available online: www.worldsteel.org/steel-by-topic (accessed on 1 July 2018).
2. Yellishetty, M.; Mudd, G.M.; Ranjith, P.G.; Tharumarajah, A. Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects. *Environ. Sci. Policy* **2011**, *14*, 650–663, doi:10.1016/j.envsci.2011.04.008.
3. Ryman, C.; Larsson, M. Reduction of CO₂ emissions from integrated steelmaking by optimised scrap strategies: Application of process integration models on the BF–BOF system. *ISIJ Int.* **2006**, *12*, 1752–1758, doi:10.2355/isijinternational.46.1752.
4. Barati, M. Energy intensity and greenhouse gases footprint of metallurgical processes: A continuous steelmaking case study. *Energy* **2010**, *35*, 3731–3737, doi:10.1016/j.energy.2010.05.022.
5. Miller, T.W.; Jimenez, J.; Sharan, A.; Goldstein, D.A. Oxygen Steelmaking Processes. In *The Making, Shaping, and Treating of Steel*, 11th ed.; Fruehan, R.J., Ed.; Steelmaking and Refining Volume; The AISE Steel Foundation: Pittsburgh, PA, USA, 1998; pp. 475–524.
6. Mazumdar, D.; Evans, J.W. Elements of Mathematical Modeling. In *Modeling of Steelmaking Processes*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2010; pp. 131–174.
7. Norgate, T.; Haque, N.; Sommerville, M. Biomass as a Source of Renewable Carbon for Iron and Steelmaking. *ISIJ Int.* **2012**, *8*, 1472–1481, doi:10.2355/isijinternational.52.1472.
8. González, A.L.; Fernández, F.J.; Díaz, J.; Modelo de Predicción de la Temperatura de Arrabio en Acería. Master's Thesis, University of Oviedo, Oviedo, Spain, June 2016.
9. McLean, A. The Science and Technology of Steelmaking—Measurements, Models, and Manufacturing. *Metall. Mater. Trans. B* **2006**, *37*, 319–332, doi:10.1007/s11663-006-0017-8.

