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Operational Costs of Hot Metal Desulphurization Processes

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Abstract

The main components of the operational costs structure of the Kanbara Reactor, Magnesium Mono-Injection and Co-Injection desulphurization processes for hot metal are discussed here. The pros and cons of lime, magnesium and calcium carbide as desulphurization agents are discussed, too. The aim of this work is to compare the updated operational costs reported in the literature in the last decade among the above processes using the accumulated annual inflation rates of US dollar, euro and Indian rupees. Besides, the operational costs of the process are discussed in terms of the initial and final sulphur content and the degree of desulphurization. The KR process presents the lowest reagents costs, whereas the co-injection process presents the highest reagents costs. The KR process presents the highest iron and temperature losses given the great amount of slag generated and the intense agitation of the rotary impeller. The co-injection process presents an exponential growth of the desulphurization costs as higher desulphurization degree is required.

Keywords

Co-Injection, Desulphurization Reagents, Hot Metal Desulphurization, KR Process, MMI Process, Operational Costs

1. Introduction

In addition to sponge iron and scrap, hot metal is one of the main raw materials to produce crude steel. Hot metal is obtained in the Blast Furnace by chemical reduction of the iron ores with carbon monoxide and coke, and is transformed into steel in the Basic Oxygen Furnace (BOF) by oxidation of some of its impurities (carbon, manganese, phosphorus and silicon) with a top blown supersonic jet of gaseous oxygen. Sulphur is commonly considered an impurity in steels and it is undesirable in most applications due to that it affects the internal and surface quality of the steel products, causes hot steel brittleness, and behaves as a stress raiser. Besides, sulphur worsens the mechanical properties of steel. By technical and economical reasons sulphur must be removed in the transfer ladle before being processed in the BOF. In the desulphurization of hot metal powdered reagents are injected into the hot metal. The reagents chemically react with the dissolved sulfur forming sulphides that ascend and are captured in the upper slag layer that covers the hot metal.

Nowadays three processes are the most employed at industry to carry out the desulphurization of hot metal, and they are summarized in **Figure 1** (Ji et al., 2017, Da Silva et al., 2009, Schrama et al., 2015). **Figure 1(a)** depicts the Kanbara Reactor (KR) rotary impeller process, where powdered lime is added to the containing ladle. The rotary impeller with a rotation speed around 100 rpm produces a strong stirring action in the hot metal and an intimate contact between the hot metal and the desulphurizing powder is obtained. The lime particles chemically react with the sulphur dissolved in the hot metal and the resulting calcium sulphide is collected in the upper slag layer. The mixing power of the impeller depends on its design, its rotation speed, and its immersion depth (Da Silva et al., 2009). **Figure 1(b)** depicts the Magnesium Mono-Injection (MMI) process (also named Ukraina-Desmag process) which employs only granulated magnesium as desulphurizer reagent and nitrogen as carrier gas. A ceramic lance with an evaporation chamber at the end is usually employed, however, straight lances can be used, too. Evaporation of the magnesium granules creates turbulence, and at high injection rates, turbulence becomes a problem due to iron loss by splashing (Schrama et al., 2017). In the co-injection method shown in **Figure 1(c)**, a mixture of powdered desulphurization reagents (lime, calcium carbide or magnesium) is injected into the hot metal using an inert carrier gas, usually nitrogen, through a ceramic lance. The gas bubbles, the desulphurizer particles and the formed sulphides ascend towards the upper slag layer due to buoyancy forces. To prevent re-sulphurization of the hot metal, the top slag is skimmed after the injection.

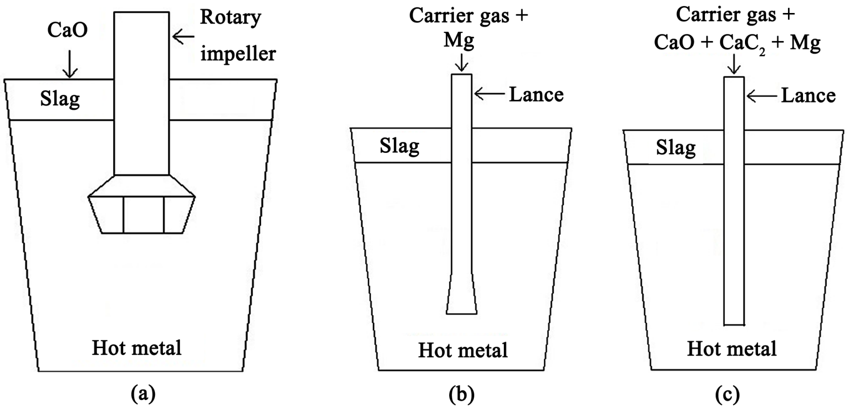

Figure 1. The considered desulphurization processes [10]. (a) KR; (b) MMI; (c) Co-injection.

A lot of works have been published in recent years about the desulphurization mechanisms and their physical and mathematical modeling (Visuri et al., 2020). However, few works have been reported on the operational costs of the most employed desulphurization processes at industry. In (Gadsdon & Han, 2010) a comparison between some operating costs of the co-injection and the KR processes is presented. Desulphurization reagents cost, iron loss during slag skimming and temperature loss are employed for comparison purposes. The authors conclude that the KR process is more expensive than the co-injection one due to the elevated iron loss of KR in spite of the lower costs of its reagent consumption. Operational costs of the MMI and the co-injection (using lime and magnesium) processes are analyzed in (Shevchenko & Rudenko, 2012) for heavy (200 - 300 tonnes) hot metal ladles. The costs of reagent consumption, hot metal loss, temperatures loss and tuyeres wear are compared for each of the aforementioned process. In accordance to the authors the operational costs of the MMI process are less than a half of the costs of the co-injection process. A breakdown of the operational costs of the co-injection process is reported in (Sener et al., 2012). The costs structure is composed of reagent consumption, temperature loss, nitrogen consumption, slag processing, lances wear, slag loss, maintenance cost and iron loss. The desulphurization costs of the whole process are reported as function of the initial and final sulphur contents. If the final sulphur content is kept constant, the desulphurization costs are increased as the initial sulphur content is increased. A comparison of the operating costs among the KR, the MMI and the co-injection processes is presented in (Schrama et al., 2015). An analysis of the operational costs is made using factors such as the iron loss, the reagent costs, the equipment wear and the temperature loss. In accordance to (Schrama et al., 2015) the main drawbacks of the KR process are the elevated costs of the iron and temperature losses, being this process the most expensive among the three considered. The costs of the reagent consumption for the KR and the co-injection processes are reported in (Mahendra et al., 2017). The authors affirm that the reagent costs of the KR process are around one third of the reagent costs of the co-injection process.

A breakdown of the main components of the operational costs structure of the KR, MMI and co-injection processes for hot metal desulphurization is the objective problem in this paper. The pros and cons of lime, magnesium and calcium carbide as desulphurization agents are discussed. The specific objective of this work is to compare the updated operational costs reported in the literature in the last decade among the above processes using the accumulated annual inflation rates of US dollar, euro and Indian rupees. Besides, the operational costs of the processes are discussed in terms of the initial and final sulphur contents and the degree of desulphurization.

2. Desulphurization Reagents

Currently, powdered lime (CaO), powdered calcium carbide (CaC_2) and granulated magnesium (Mg) are the most employed desulphurization reagents in the steel industry. In the MMI and the co-injection processes a carrier gas, usually nitrogen, transports the desulphurizer particles into the hot metal. In the KR process lime is directly added to the melt in a batch or a continuous way, however sometimes a carrier gas is employed. The sulphur dissolved in hot metal is removed by chemical reaction, as follows:

$$\mathrm{CaO}+[\mathrm{S}]\rightarrow(\mathrm{CaS})+[\mathrm{O}] \tag{1}$$

$$\mathrm{CaC_2}+[\mathrm{S}]\rightarrow(\mathrm{CaS})+2[\mathrm{C}] \tag{2}$$

$$[\mathrm{Mg}]+[\mathrm{S}]\rightarrow(\mathrm{MgS}) \tag{3}$$

where [ ] and ( ) represent the melt and the slag phases, respectively.

Reactions 1 and 2 are first order diffusion controlled reactions. This means that a sulphide layer covers the unreacted desulphurizer particles and sulphur must diffuse through the sulphide layer in order to react (Levenspiel, 1999). This inconvenience can be overcome using grain size of desulphurizer agents less than 45 μm (Gitterle, 2007). In accordance to (Schrama et al., 2015) reaction 3 is three times as fast as reaction 2 and twenty time as fast as reaction 1. As a consequence, among the above desulphurization agents, magnesium is the fastest one. The sulphides formed during the chemical reactions ascend through the molten metal and are collected in the upper slag layer. The sulphide and the desulphurizer particles ascend by themselves or attached to the carrier gas bubbles due to the buoyancy forces. As the bubble size and the diameter of the desulphurizer particles decrease their residence time is increased. The residence time of the desulphurizer particles in the hot metal is an important factor that determines the efficiency of the desuphurization process given that the residence time determines the reaction time.

The low cost of lime and its everywhere availability in nature as limestone has encouraged its widespread application as desulphurization reagent since long time ago. Around 90% of the lime grains must have a size between 45 and 100 μm (Gadsdon & Han, 2010, Gitterle, 2007). However, lime has important drawbacks as desulphurizer: it has low efficiency, and in this way large quantities of lime must be employed during the process and a great amount of slag is generated which increases the iron loss; lime has poor conveying properties and therefore lime grains must be surface treated with certain oils. Besides lime forms lumps with moisture which sometimes cause nozzle blockages (Gitterle, 2007).

During the seventies and the eighties of the last century calcium carbide was the most used desulphurization reagent in hot metal ladles and electric arc furnaces. For calcium carbide manufacturing lime and coke are employed as raw materials. Particle sizes of calcium carbide less than 75 μm are required to get an effective desulphurization (Brodrick, 2009). Handling of calcium carbide is risky and dangerous given that it reacts with water to form acetylene gas which is extremely explosive. Therefore calcium carbide must be stored in moisture free and well ventilated argon purged spaces. Due to this, in the last three decades calcium carbide has experienced a significant reduction in its usage as desulphurization reagent. Nowadays calcium carbide is employed mixed with magnesium or calcium carbide in the co-injection process.

Magnesium is the fastest desulphurization reagent among the three considered here. It is industrially obtained from chemical reduction of magnesium oxide with ferrosilicon and coke. Magnesium is injected into the hot metal as solid granules using a carrier gas (nitrogen or argon), and immediately it becomes vaporized at the hot metal temperatures. The bubbles of the magnesium vapor dissolve in the melt and then react with dissolved sulphur to form magnesium sulphide. In the MMI process only magnesium is employed as desulphurizer. It is reported that injection of pure magnesium yields the highest absorption and the lowest consumption (Shevchenko & Rudenko, 2012). Size of magnesium granules must be between 200 and 1000 μm (Gitterle, 2007). The MMI process has not been widely adopted in USA or Europe given to the security problems that arise by the violent nature of the desulphurization reaction.

3. Factors That Determine the Operational Costs of a Hot Metal Desulphurization Process

Capital costs are defined as money spent on long-term investments (buildings, machines, equipment, office furniture, and so on). On the other hand, operational costs are defined as expenses incurred in running a business (raw materials, maintenance, repairs, material and energy losses, and operational costs in general) (Warner & Hussain, 2017). High operational expenditures reduce the current year profits. Therefore it is crucial to identify the factors which determine the operational costs of a desulphurization process. In this section the most important factors that influence the amount of operational costs are described.

3.1. Reagents Consumption Costs

Consumption of desulphurization reagents depends on several factors such as the initial and final sulphur contents, injection time, hot metal temperature, hot metal weight, and so on. The reagent consumption costs depend, among others, on the local and international market prices, and the quality and the particle size of the reagents (Gadsdon & Han, 2010). Reaction kinetics of magnesium indicates that this material is the fastest desulphurizer reagent among those considered here, however, the sulphur thermodynamic equilibrium of lime and calcium carbide is lower than that of magnesium. In other words, when a fast desulphurization is required magnesium is the option, and lime and calcium carbide are the options when low final sulphur concentrations are required (Schrama et al., 2015).

3.2. Slag Generation and Iron Loss

Slag is generated during the injection of the desulphurization reagents, and the amount of slag is proportional to the reagents consumption. Iron in hot metal is trapped in the slag, and the slag sometimes contains around 50% of iron (Gadsdon & Han, 2010). When the slag is skimmed at the end of the injection process iron loss occurs. In accordance to (Schrama et al., 2015) iron loss is the most important contributor to the operating costs of a desulphurization process. Iron loss is around 1% of the hot metal charge for the co-injection process, while for the KR process is around 2.5% (Gadsdon & Han, 2010).

3.3. Temperature Loss

In the Basic Oxygen Furnace (BOF) the hot metal is converted into steel using a supersonic jet of gaseous oxygen. The sensible heat of the hot metal represents around 50% of the energy input to the furnace. A temperature loss of 10˚C of hot metal causes a 0.88% decrease in the scrap charge to the BOF, and this decrease in scrap means that more hot metal must be charged into the furnace to meet the required tonnage (Gadsdon & Han, 2010). As the hot metal is more expensive than scrap, a significant temperature loss during desulphurization means an increase in the operational costs of a desulphurization process.

3.4. Equipment Wear and Maintenance

High temperature and chemical attack of the hot metal and the slag during the desulphurization process cause severe wear and cracking of the ladle refractory, the injection lance and the rotary impeller. The wear issue is more pronounced in the KR process given the high turbulence generated by the rotating ceramic impeller. Replacement of worn or damaged parts, preventive and corrective maintenance and associated labor costs contribute to increase the operational costs.

Selection of a determined desulphurization process for a given plant must consider, besides the capital costs, the availability and costs of the reagents employed in that process given that each reagent has its own advantages and disadvantages discussed in Section 2, and the corresponding operational costs described in Section 3.

4. Operational Costs of the Most Employed Desulphurization Processes

Several reports from different dates, countries and currencies have been consulted in order to obtain information about the operational costs of the KR, the MMI and the co-injection desulphurization processes. Local currencies such as US dollar, euro, and Indian rupees were updated to the current year (2020) using the corresponding accumulated annual inflation rates, and then converted into current US dollars using a currency converter. In this way the operational costs of the above desulphurization processes, expressed in US dollars per tonne of hot metal ($US/tHM), could be compared.

In (Gadsdon & Han, 2010) the operational costs for the co-injection and the KR processes are reported originally in $US for plants located in Canada, and are shown updated in **Table 1**. Data were updated considering an accumulated annual inflation rate of 16.69 % for $US from 2011 to 2020 and a co-injection ratio (Mg/CaO) of 1:4. **Table 1** shows that the KR process exhibits the highest iron loss cost, whereas its reagent cost (just cheap lime) is the lowest one. Use of magnesium as desulphurization agent in the co-injection process causes that the reagent cost for this process be greater than that of the KR process. Temperature loss of the KR process is high due to the intense turbulence and heat transfer caused by the rotary impeller. In the end, in accordance to (Gadsdon & Han, 2010), the co-injection process presents the lowest operational costs than the KR process.

A comparison between the operational costs of the MMI and the co-injection processes, originally reported in $US in (Shevchenko & Rudenko, 2012) for plants located in Ukraine, is presented in **Table 2**. Costs were updated considering an accumulated annual inflation rate of 11.48% for $US from 2013 to 2020. In accordance to the above report the operational costs of the MMI process are less than a half of those of the co-injection process whenever the magnesium is injected in pure form. Magnesium granules are used without passivation, diluents or any additives, which in accordance to (Shevchenko & Rudenko, 2012) give the highest absorption and the lowest consumption of magnesium. In this way less slag is produced and less iron loss is obtained. However, to prevent hot metal re-sulphurization slag conditioning with low cost wastes is required.

Table 3 presents operational cost for the MMI, the KR and the co-injection processes for plants in the Netherlands (Schrama et al., 2015). Originally reported in euros, data were updated considering an accumulated inflation rate of 4.97% for euro from 2016 to 2020 and then converted into $US using a currency conversion of 1 euro = 1.10740 $US. The co-injection process presents the lowest operational costs, and the costs of the MMI process are very similar than

Table 1. Operational costs in $US/tHM for the co-injection and the KR processes in Canada (Gadsdon & Han, 2010).

PROCESS	Reagent costs	Iron loss	Temperature loss	Total
Co-injection	2.64	2.66	0.71	6.01
KR	0.62	8.41	1.07	10.11

Table 2. Operational costs in $US/tHM for the MMI and the co-injection processes in Ukraine (Shevchenko & Rudenko, 2012).

PROCESS	Reagent costs	Iron loss	Temperature loss	Tuyeres wear	Total
MMI	1.00	0.11	0.11	0.05	1.28
Co-injection	1.97	0.82	0.15	0.09	3.03

Table 3. Operational costs in \$US/tHM for the MMI, the KR and the co-injection processes in the Netherlands (Schrama et al., 2015).

PROCESS	Reagent costs	Iron loss	Temperature loss	Equipment wear	Total
MMI	1.68	3.49	0.29	0.81	6.28
Co-injection	1.86	3.49	0.29	0.48	6.11
KR	0.81	8.72	0.87	1.16	11.56

those of co-injection process. The KR process, in spite of its lower reagent costs, presents the highest operational costs because of its elevated iron and temperature losses. These losses are explained due to the great amount of slag generated by lime and the strong agitation and turbulence produced by the rotary impeller, respectively.

A detailed analysis of the operational costs for the co-injection process for plants located in Germany is reported in (Sener et al., 2012). In accordance with this report the operational costs are increased as the hot metal initial sulphur content is increased. This is caused by the higher reagents consumption, lance wear, nitrogen consumption, and maintenance. Final sulphur content affects adversely the operational costs given that as lower is the required final sulphur content the reagent consumption and the reagent costs become bigger. Besides low final sulphur content increases the injection time and therefore the lance wear and the nitrogen consumed. In (Sener et al., 2012) a desulphurization degree D_S is defined as follows:

$$D_S = 100\eta_S \left[\frac{S_0 - S_f}{S_0} \right] \tag{4}$$

where η_S is the efficiency of desulphurization, S_0 is the hot metal initial sulphur content, and S_f is the hot metal final sulphur content. Costs data, originally reported in \$US, were updated from (Sener et al., 2012) using an annual accumulated inflation rate of 11.48% for \$US from 2013 to 2020 and recalculated with Equation (4) considering that $S_f = 140$ ppm and $\eta_S = 0.825$. Results are presented in **Figure 2**, where an exponential growth of the desulphurization costs as function of the degree of desulphurization is appreciated. An average desulphurization costs of 6 \$US/tHM for S_0 = 600 ppm and S_f = 140 ppm, are reported. Besides, 2.5 \$US/tHM in concept of labor, services, administrative costs, selling and capital costs must be added (Sener et al., 2012).

A report on the reagent costs for the KR and the co-injection processes in plants in India is presented in (Mahendra et al., 2017). Original costs were published in rupees and were updated to current rupees using an accumulated annual inflation rate of 11.31% from 2018 to 2020 and converted into \$US using a currency conversion of 1 \$US = 75.38 rupees. Desulphurization reagents for the KR process were lime and calcium fluoride while for the co-injection process the reagents were calcium carbide and magnesium. Results are summarized in **Table 4**. The reagent costs for the KR process are lower than those of the co-injection

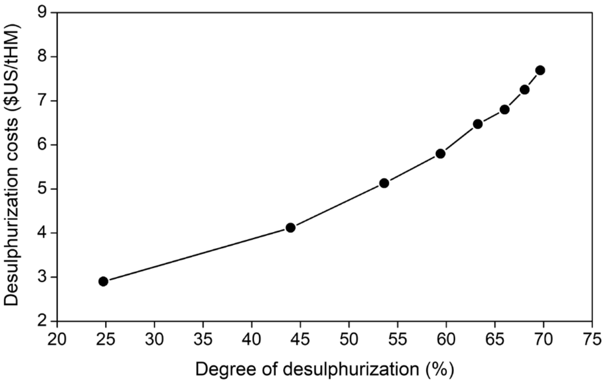

Figure 2. Desulphurization costs for the co-injection process as function of the degree of desulphurization. Data adapted and updated from (Sener et al., 2012) considering a final sulphur of 140 ppm and an efficiency of desulphurization of 0.825.

Table 4. Reagent costs in $US/tHM for the KR and the co-injection processes in India (Mahendra et al., 2017).

PROCESS	Reagent costs
KR	0.12
Co-injection (CaC_2 + Mg)	0.34

process given that KR employs cheap lime. No data on iron and temperature losses are presented.

To facilitate interpretation of the results shown in **Tables 1-4** in geographical terms, information in these tables was organized by countries as is shown in **Tables 5-8**.

5. Findings and Analysis

Irrespective of the considered country the KR process presents the lowest reagent costs, as is shown in **Table 5**. The inverse can be said for the co-injection process: irrespective of the country in question the co-injection process presents the highest reagent costs. Regardless of the country the KR process exhibits the highest equipment wear and iron and temperature losses, as is seen in **Tables 6-8**. The MMI process presents the lowest reagent costs, and iron and temperature losses. However, the equipment wear of the MMI process is almost twice than that of the co-injection process. This is due to the violence of the magnesium vaporization.

6. Conclusion

Current operational costs for the most employed hot metal desulphurization processes are presented. Reports from different countries, currencies and dates have been consulted in order to collect information about the operational costs of the KR, MMI and co-injection desulphurization processes. Local currencies were updated to the current year (2020) using the corresponding accumulated

Table 5. Reagent costs by country, $US/tHM.

PROCESS	Canada (Gadsdon & Han, 2010)	India (Mahendra et al., 2017)	The Netherlands (Schrama el al., 2015)	Ukraine (Shevchenko & Rudenko, 2012)
KR	0.62	0.12	0.81	-
MMI	-	-	1.68	1.00
Co-injection	2.64	0.34	1.86	1.97

Table 6. Iron loss by country, $US/tHM.

PROCESS	Canada (Gadsdon & Han, 2010)	India (Mahendra et al., 2017)	The Netherlands (Schrama el al., 2015)	Ukraine (Shevchenko & Rudenko, 2012)
KR	8.41	-	8.72	-
MMI	-	-	3.49	0.11
Co-injection	2.66	-	3.49	0.82

Table 7. Temperature loss by country, $US/tHM.

PROCESS	Canada (Gadsdon & Han, 2010)	India (Mahendra et al., 2017)	The Netherlands (Schrama el al., 2015)	Ukraine (Shevchenko & Rudenko, 2012)
KR	1.07	-	0.87	-
MMI	-	-	0.29	0.11
Co-injection	0.71	-	0.29	0.15

Table 8. Equipment wear by country, $US/tHM.

PROCESS	Canada (Gadsdon & Han, 2010)	India (Mahendra et al., 2017)	The Netherlands (Schrama el al., 2015)	Ukraine (Shevchenko & Rudenko, 2012)
KR	-	-	1.16	-
MMI	-	-	0.81	0.05
Co-injection	-	-	0.48	0.09

annual inflation rates and then were converted into current $US dollars. In this way, operational costs of the above desulphurization processes could be compared. From an analysis and comparison of the obtained data, the following conclusions arise: The KR process presents the lowest reagents costs given that it employs cheap lime. The co-injection process presents the highest reagents costs due to the usage of expensive reagents such as calcium carbide and magnesium. The KR process presents the highest iron and temperature losses given that a great amount of slag is generated and the intense agitation of the rotary impeller. The MMI and the co-injection process have similar iron and temperature losses due to the low amounts of slag generated and the employment of carrier gas for reagents injection. For the co-injection process, the desulphurization costs have an exponential growth as higher desulphurization degrees are required.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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