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Research Article

Blasting Method for Improving the Secondary Combustion Efficiency in the Romelt Process Using CFD Analysis

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Abstract

The Romelt process is called liquid-phase smelting reduction process because in the metallurgical processes the reaction of coal and iron occurs in the liquid slag layer, which is boiling vigorously by oxygen-enriched air flow blown into the liquid slag. The bath of the furnace is charged with coal and iron ore, and an oxygen nozzle for secondary combustion is installed on both sides of the bath cavity to burn out the CO and H_2 gases generated in the bath. CO and H_2, rising from the boiling slag bath, are completely burned by oxygen blown into the secondary nozzle in the combustion chamber. The heat from this combustion reaction plays an important role in the Romelt process. 60-80% of the secondary combustion heat is transferred to the bath and becomes the heat source of the main process. At present, the Romelt process has a high CO content in the exhaust gas due to the low efficiency of combustion by oxygen blown into secondary nozzle and low oxidation of CO. This paper analyses the reason of the low efficiency of combustion by oxygen blown into conventional secondary nozzle using CFD, and based on it, suggests the blasting method to increase the secondary combustion efficiency by oxygen blown into the upper tuyere of the Romelt furnace. To improve the secondary combustion efficiency, a new type of catalyst for enhancing the oxidation of CO was investigated and more than 90% of efficiency of secondary combustion was achieved. At this time, oxygen concentration should be at least 95%.

Keywords

Romelt, Secondary Combustion Efficiency, Blasting Method, Oxidation Catalyst, Nozzle

1. Introduction

Recently the total production of pig iron in the world is more than 78 million tons a year. Rapid production of pig iron requires more coke, but the limited reserves have made it difficult to meet the demand.

Therefore, many countries tend to develop technologies and methods to reduce energy consumption and produce iron at low cost, while introducing technology which uses no coke in the iron-making field.

Those methods include Corex, Hismelt and Romelt processes.

The Corex process has already been used [1] to produce more than 6 million tons of pig iron.

The shortcomings of this process are the need to pelletize ores and concentrates composed of dust-sized particles (which in turn results in significant economic and environmental losses), the complex equipment which is used, and

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the impossibility of processing the dust-sized metallurgical wastes.

The processes which are based mainly on the liquid-phase reduction of iron (DIOS [2], Hlsmelt [3]) were the result of an attempt to better balance the chemical and energy aspects of the two reduction stages: solid-phase and liquid-phase.

With this as a goal, a large part of the heating and reduction was transferred to the liquid-phase stage.

The following techniques are used to ensure that the liquid bath is supplied with heat in reactors designed for liquid-phase reduction: the outgoing gases are reduced as much as possible, and the heat liberated by the reduction reaction is transferred to the slag bath; the raw material is heated and subjected to preliminary reduction; the blast is heated (with oxygen-air, nitrogen, etc.); coal, natural gas, and other gaseous and liquid fuels are burned in the slag.

Processes in which iron is subjected to solid-phase reduction and subsequent additional reduction in a slag bath have been developed on the basis of the assumption that heat from the secondary combustion of the gases cannot be efficiently returned to the slag bath if the entire reduction process is carried out in the liquid phase.

This explains the two-stage nature of the process and the complexity of the technology.

The AusIron process [4], involving the reduction of iron entirely in the liquid phase, has not gone past the stage of laboratory testing.

The Romelt process has now been sufficiently refined and is ready for commercial use.

The publications [4, 5] presented a detailed look at the Romelt technology for processing various types of iron-bearing raw materials (including metallurgical wastes) and analyzed features of the reducing and thermal performance of the unit.

Compared to other coke-less units for making pig iron, the Romelt process has progressed the farthest and is the simplest to execute.

Many of the technological and design innovations first introduced on this unit [6-8] were subsequently used to develop other modern processes for the liquid-phase reduction of iron (separate siphon-type removal of the iron and slag from the furnace; the feeding of an oxygen blast into the slag bath; conducting the process with slight negative pressure; the use of water-cooled barriers in the slag-bubbling and secondary-combustion zones, etc.).

CO and H_2, rising from the boiling slag bath, are completely burned by oxygen blown into the secondary nozzle in the combustion chamber. 60-80% of the secondary heat is transferred to the bath and becomes the heat source of the main process [9, 10].

Therefore, in the Romelt furnace it is necessary to increase the oxidation of CO and to provide the combustion space of oxygen injected into the secondary nozzle, so as to increase the secondary combustion efficiency and reduce the CO content in the exhaust gas [11-16].

2. Analysis of Secondary Combustion Efficiency in Romelt Process.

Currently, the secondary combustion efficiency in the Romelt process has been analyzed using ANSYS 2023R1.

The model of the Romelt furnace is shown in Figure 1.

Eight upper tuyeres, located at the furnace side walls, are installed horizontally on the furnace.

The part above the lower tuyere was modeled, assuming that the gas generated from the lower tuyere rises to the space of the furnace, since the secondary combustion efficiency is being analyzed.

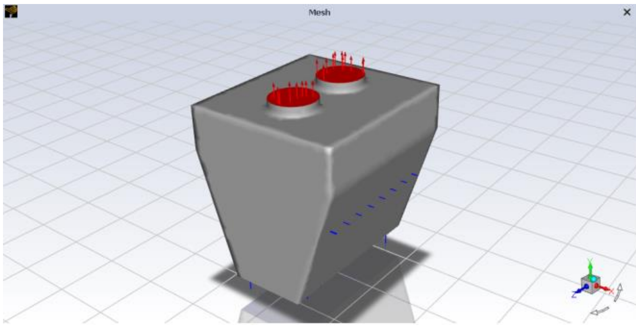


Figure 1. *Model of Romelt furnace.*

Boundary condition; composition of gas generated from lower tuyere: CO 50%, O_2 10%, N_2 40%,

Temperature of gas: 1400°C,

Concentration of oxygen from upper tuyere: 95%,

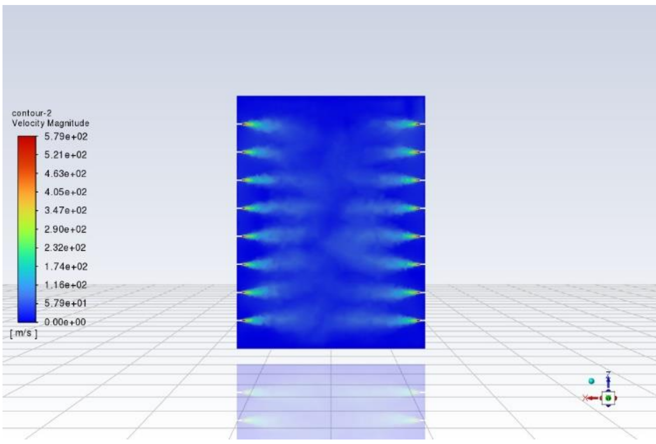
Temperature of blasting oxygen: 25°C,

Blowing pressure: 4

Inner diameter of nozzle: Φ32mm

The simulation of secondary combustion in combustion chamber was carried out when blowing pressures are 2 and 4 atm.

The velocity distribution and the distribution of CO gas at blowing pressure of 2 atm are shown in Figures 2 and 3.



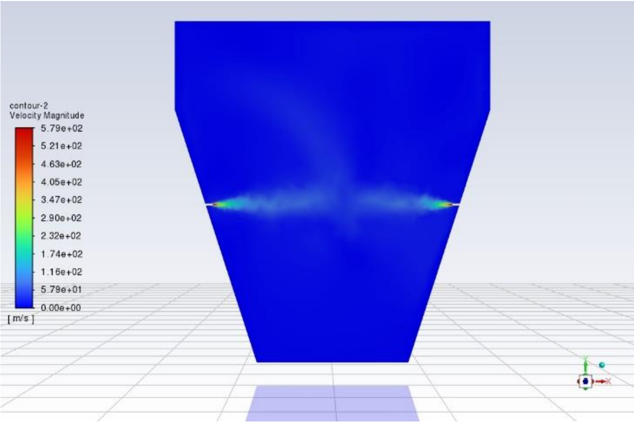


Figure 2. *Velocity distribution (2 atm).*

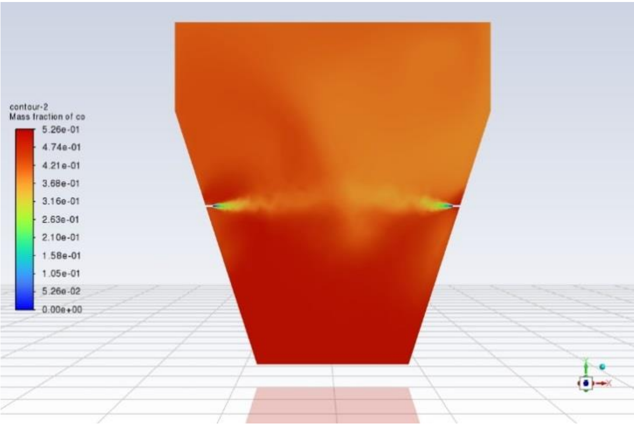
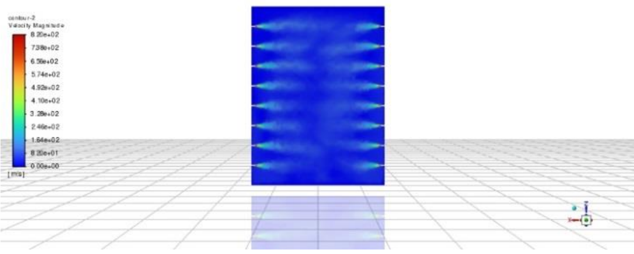


Figure 3. *CO gas distribution (2 atm).*

As can be seen in Figures 2 and 3, the upper tuyere is horizontally mounted to blow oxygen, as a result the mixing conditions of the reaction product gas with oxygen are poor and sufficient combustion space is not provided.

At this time, the CO gas in the exhaust gas of the Romelt furnace is 29%, and the secondary combustion efficiency is 42%. The temperature of the exhaust gas is 1530°C.

Then, the blowing pressure was raised to 4 atm to ensure sufficient oxygen. The velocity distribution and the distribution of CO gas at 4 atm are shown in Figures 4 and 5.



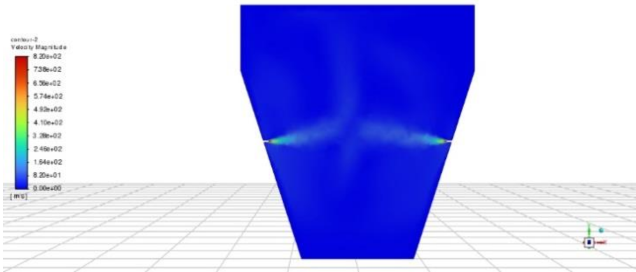


Figure 4. *Velocity distribution (4 atm).*

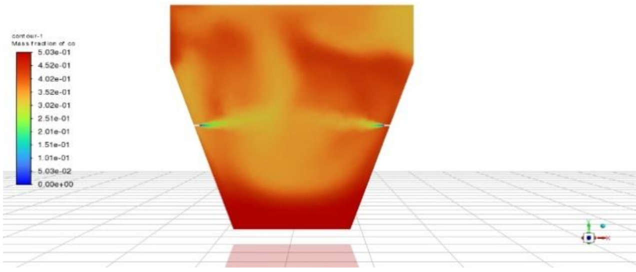


Figure 5. *CO gas distribution (4 atm).*

The CO gas in the exhaust gas of the Romelt furnace is 25% with a secondary combustion efficiency of 50%, while the temperature of the exhaust gas is 1620°C.

As can be seen, there is no significant difference in the mixing conditions of reactive gas and oxygen and in sufficient combustion space, compared with 2 atm.

However, increasing the oxygen pressure from 2 to 4 atm led to increase of combustion efficiency from 42% to 50%, due to sufficient oxygen.

3. Blasting Method to Enhance the Secondary Combustion Efficiency in the Romelt Process

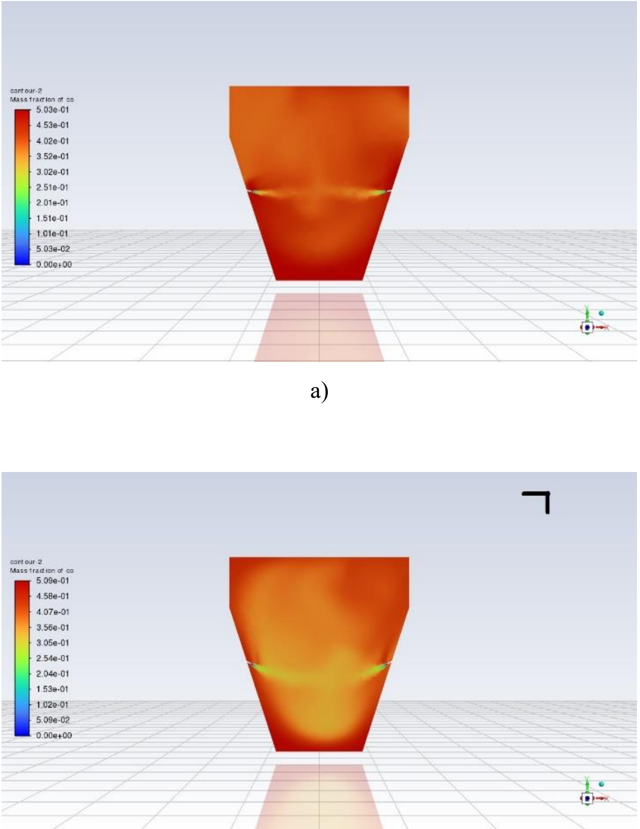
First, the conditions of mixing of the reactive gas with the oxygen should be improved, in the given operating conditions of the furnace and the volume of the combustion space.

One approach involves installing an upper tuyere that is tilted slightly from the horizontal to the surface of the bath.

The CO gas secondary combustion efficiency, when the upper tuyere is tilt at 10° and 30°tilt, was analyzed using ANSYS 2023R1.

The results are shown in Figure 6.

The oxygen blowing pressure is 2 atm.



a)

b)

Figure 6. CO gas distribution (a-10°, b-30°) when the upper tuyere is tilted.

It can be seen that the larger the tilt of upper tuyere, the more spacious the secondary combustion space.

When the downward tilt of the tuyere is greater, the contact time between the reactive gas and oxygen gets longer, so the combustion efficiency can be improved, but the bath surface can be over oxidized.

Therefore, the tilt angle should be chosen reasonably. The tilt angle of 10° is good.

As can be seen, the Romelt process needs to use oxygen as the oxidant, to create sufficient combustion space and to improve the mixing conditions of the reactive gas and oxygen so that it can increase the efficiency of secondary combustion of the CO gas.

However, thermodynamically, the efficiency of secondary combustion of the CO gas is not 100%.

It is because that the combustion products CO_2 and H_2O are thermally dissociated at high temperatures and change into CO gas, which is thermodynamically stable.

$$2CO+O_2=2CO_2 \quad (1)$$

At 1400°C, $\varphi(CO)/\varphi(CO_2)=10$

Therefore, the efficiency of secondary combustion of CO gas cannot be 100%, thermodynamically.

Thus, to achieve a secondary combustion efficiency of more than 90%:

First, the upper tuyere is blown with oxygen and oxidation catalyst to increase the efficiency of secondary combustion of CO. At this time, oxygen concentration should be at least 95%.

(1) The upper tuyere is blown with oxygen and oxidation catalyst to increase the efficiency of secondary combustion of CO. At this time, oxygen concentration should be at least 95%.

Let us now consider the action of the oxidation catalyst.

$$\left.\begin{array}{l} MnO_2+1/2O_2 \leftrightarrow MnO_2\cdot O \\ Fe_2O_3+1/2O_2 \leftrightarrow Fe_2O_3\cdot O \end{array}\right\} \text{adsorption reaction}$$

$$\left.\begin{array}{l} MnO_2\cdot O+CO \leftrightarrow MnO_2\cdot CO_2 \\ Fe_2O_3\cdot O+CO \leftrightarrow Fe_2O_3\cdot CO_2 \end{array}\right\} \text{surface reaction}$$

$$\left.\begin{array}{l} MnO_2\cdot CO_2 \leftrightarrow MnO_2+CO_2 \\ Fe_2O_3\cdot CO_2 \leftrightarrow Fe_2O_3+CO_2 \end{array}\right\} \text{desorption reaction}$$

The oxidation catalysts include Cu-Mn-Fe system low-temperature monoxide carbon oxidation catalyst and $CuMn_2O_4$ spinel-type oxide.

-CO oxidation catalysts manufacturing methods include mixing, coprecipitation and dipping.

The composition ratio of CuO and MnO is 3 to 7 for the catalyst manufactured by mixing and coprecipitation method, and the highest activity of CO oxidation is obtained when the content of Fe_2O_3 is 2.3%.

While the catalyst manufactured by dipping has the highest activity of CO oxidation is obtained when Fe_2O_3 content is 3% and CuO content is 4.5-7%.

The technical characteristics of such Cu-Mn-Fe system low-temperature CO oxidation catalyst are as follows.

Table 1. Technological characteristics of the low-temperature CO oxidation catalyst.

System	Packing density (g/cm^3)	True density (g/cm^3)	Specific surface area (m^2/g)	Similarity (%)	Air adsorption quantity (×10^{-5}mol/g)	
					CO	O_2
Cu-Mn-Co-Ag	0.61	4.32	108	43	3.85	0.98

System	Packing density (g/cm^3)	True density (g/cm^3)	Specific surface area (m^2/g)	Similarity (%)	Air adsorption quantity ($\times 10^{-5}$mol/g)	
					CO	O_2
Cu-Mn-Fe	0.53	3.78	118	52	3.80	0.79

As can be seen from Table 1, the amount of O_2 adsorption was slightly higher for the Cu-Mn-Co-Ag system catalyst, but the amount of CO adsorption was similar.

Besides, in the case of 70-80°C of reaction temperature, Cu-Mn-Fe system CO oxidation catalyst activity doesn't change a lot even after 200 hours of reaction.

-$CuMn_2O_4$ Spinel-type oxide

$CuMn_2O_4$ spinel-type oxides is manufactured in the way of mixing aqueous solution of metal nitrate and ammonia with stoichiometric ratio of spinel drop by drop to obtain metal hydroxide (precipitate) at pH = 8 and drying it at 100°C for 12 h, decomposing at 400°C for 1 h and then baking it at 900°C for 10 h.

The effect of baking temperature (500-1000°C) on the performance of the catalyst was investigated, and the higher the baking temperature, the smaller the surface area of the catalyst.

For samples with baking temperatures above 900°C, the crystal growth of the spinel phase is promoted.

The activity of the water-gas converting reaction is enhanced with higher baking temperature, and the maximum CO evolution is achieved at 900°C and 1100°C, and the reaction equilibrium at 250°C.

Next, the Cu/Mn ratio affects the performance of the catalyst. The catalyst baked at optimum temperature 900°C achieves a maximum revolution of CO at reaction temperature 225°C and Cu/Mn = 1/2.

Next it is more effective to reduce $CuMn_2O_4$ under warm temperature rather than to reduce it at higher temperature. The CO evolution is high when reduced at 250°C.

Second, to reduce the degree of dissociation of the combustion product, CO_2, the heat obtained by the secondary combustion must be transferred quickly to the slag pool to lower the temperature of the combustion chamber. This is because the lower combustion chamber temperature leads to less conversion of the burned CO_2 to stable CO at higher temperatures.

(2) To reduce the degree of dissociation of the combustion product, CO_2, the heat obtained by the secondary combustion must be transferred quickly to the slag pool to lower the temperature of the combustion chamber. This is because the lower combustion chamber temperature leads to less conversion of the burned CO_2 to stable CO at higher temperatures.

4. Results and Analysis

1) When the blowing pressure of oxygen is changed.

Table 2. *Secondary combustion efficiency according to oxygen blowing pressure.*

Oxygen blowing Pressure (atm)	CO content in exhaust gas (%)	Secondary combustion efficiency (%)	Temperature of the exhaust gas (°C)
2	29	42	1530
4	25	50	1620

As can be seen in Table 2, there is no significant difference in the mixing conditions of reactive gas and oxygen and sufficient combustion space, compared with the blowing pressure of 2 atm.

However, increasing the oxygen pressure from 2 to 4 atm leads to increase of combustion efficiency from 42% to 50% due to sufficient oxygen.

As a result increasing the blowing pressure of oxygen is not a good solution.

2) When the oxygen blowing angle is changed

Table 3 shows that the larger the tilt angle, the wider the secondary combustion space, and the higher the combustion efficiency.

Table 3. Secondary combustion efficiency according to tuyere tilt angle at a given oxygen blowing pressure (2 atm).

Tuyere tilt angle (°).	CO content in exhaust gas (%)	Secondary combustion efficiency (%)	Temperature of the exhaust gas (°C)
0	29	42	1530
10	25	50	1620
30	21	58	1680

However, as can be seen from Figure 6, when the tuyere is too downwards, the combustion space of oxygen gets wider, and the surface of the bath can be over oxidized.

Therefore, the tilt angle should be reasonably chosen, and 10° is the best.

5. Conclusion

To achieve a secondary combustion efficiency of more than 90%:

First, the upper tuyere is blown with oxygen and oxidation catalyst to increase the efficiency of secondary combustion of CO. At this time, oxygen concentration should be at least 95%.

1) The upper tuyere is blown with oxygen and oxidation catalyst to increase the efficiency of secondary combustion of CO. At this time, oxygen concentration should be at least 95%.

Second, the upper tuyere is set up with a slight tilt from the horizontal to the surface of the bath, with a tilt angle of about 10°.

2) The upper tuyere is set up with a slight tilt from the horizontal to the surface of the bath, with a tilt angle of about 10°.

Third, the heat gained in the secondary combustion space is transferred quickly to the slag pool, in order to lower the temperature of the combustion space.

3) The heat gained in the secondary combustion space is transferred quickly to the slag pool, in order to lower the temperature of the combustion space.

Conflicts of Interest

The authors declare no conflicts of interest.

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