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Abstract

In electric arc furnace steelmaking units, the essential parameters that considered important are reducing price, increasing production and decreasing environmental pollution. Electric arc furnaces are the largest users of electric energy in industry. The most important techniques that can be used to reduce the electric energy consumption in electric arc furnaces are scrap preheating, stirring, use of burners and hot charge and foamy slag.

Between these methods, use of foamy slag is the most useful and economic factor. Foamy slag can reduce the amount of energy, electrods, refractory consumption, tap to tap time and increases productivity. In this research, method of production and optimum conditions for foamy slag in 200 tons electric arc furnace were investigated. The use of foamy slag in this research shows that it can reduce the electric energy consumption from 670 to 580 kwh/ton and also the melting time from 130 to 115 min. and the electric power input can be increase with foamy slag. It also shows that with foamy slag the optimum amount of FeO in slag is 20-24 percent and the optimum basicity is 2-2.2.

Keywords

electric, arc, furnaces, energy, foamy, consumption, effect, slag

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THE EFFECT OF FOAMY SLAG IN THE ELECTRIC ARC FURNACES ON ELECTRIC ENERGY CONSUMPTION

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ABSTRACT:

In electric arc furnace steelmaking units, the essential parameters that considered important are reducing price, increasing production and decreasing environmental pollution. Electric arc furnaces are the largest users of electric energy in industry. The most important techniques that can be used to reduce the electric energy consumption in electric arc furnaces are scrap preheating, stirring, use of burners and hot charge and foamy slag.

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In this research, method of production and optimum conditions for foamy slag in 200 tons electric arc furnace were investigated. The use of foamy slag in this research shows that it can reduce the electric energy consumption from 670 to 580 kwh/ton and also the melting time from 130 to 115 min. and the electric power input can be increase with foamy slag. It also shows that with foamy slag the optimum amount of FeO in slag is 20-24 percent and the optimum basicity is 2-2.2.

KEYWORDS: electric arc furnace , energy , DRI , foamy slag

INTRODUCTION:

Electric arc furnaces (EAFs) are the largest electric energy consumers in industry. In order to reduce the electrical energy in EAFs, researchers found that using two stage and continuous charge electric arc furnaces are useful. There are several significant techniques that can be used to decrease electric energy consumption in EAFs such as: Using air-tight system, scrap preheating, stirring, using burners, using hot charge (e.g. hot DRI, hot metal), aluminum arms for electrods, post combustion, decrease of DRI percent in charge by scrap, higher percent of metallization and carbon content in DRI, foamy slag.

Foamy slag production is the most useful and economic technique among the others. Foamy slag can reduce energy consumption and also reduce electrod, refractory consumption by covering the arc and as a result of radiation reduction. It can also increase heat recovery, protect cooling panels, reduce tap to tap time and soluble gases in steel and also the amount of slag. On the other hand by using foamy slag, it is possible to increase arc length without losing energy.

The main factor which influences on the production of foamy slag is CO gas which is evolved in melting and refining period by reaction of carbon content of steel with FeO in slag, carbon content in steel with injected oxygen and injected carbon with FeO of the slag as shown below:

$$\underline{C} + (FeO) = CO + Fe \qquad (1)$$

$$\underline{C} + \tfrac{1}{2} O_2 = CO \qquad (2)$$

$$(FeO) + C = Fe + CO \qquad (3)$$

The above reactions occur in the interface of slag-melt, gas-melt and solid-slag, respectively[1]. It was shown[2,3] that diffusion of FeO in slag layer controls kinetic of CO formation in EAFs. Foamy slag formation includes nucleation and growth of CO bubbles, separation from nucleation sites, flow of bubbles to top of the slag and then joining of bubbles to each other. This process causes tearing off the slag film[4].

In order to measure the bubbles residence time in slag and to suggest criteria for exhibition of slag foaming, foamy index was defined. Bickerman[5] presented this criterion for the first time. Foamy index is:

$$\Sigma = H / V \qquad (4)$$

Σ : Foamy index (s)
H : Foam height (height of foamy slag – height of slag) (m)
V : Superficial gas velocity (m/s)
Ito and Fruehan[6] studied on foamying of $CaO–SiO_2–FeO$ slags (which are related to EAFs and convertors slags). They observed that the "Σ" for the ideal slags is constant and correlate to physical and chemical properties of slag. So, they suggested the following relation:

$$\Sigma = 5700\ \mu / (\rho\sigma)^{0.5} \qquad (5)$$

σ : Surface tension (mNm^{-1})
ρ: Density (kg/m^3)
μ: Viscosity (pa.s)
The above relation was modified by Jiang and Fruehan[7] with measuring the slag viscosity as below :

$$\Sigma = 359\ \mu / (g\rho\sigma)^{0.5} \qquad (6)$$

As in real furnace slag, the bubbles can grow in different size by chemical reactions, Zhang and Fruehan[8] considered the size of bubbles in foamy index :

$$\Sigma = 115\ \mu^{1.2}/\rho\sigma^{0.2}d^{0.9} \qquad (7)$$

Wu and coworkers[9] who are studied on slags in laboratory scale showed that these kind of slags in higher temperature and lower additives can be consider as Newtonian fluid and then Σ is constant, where Σ is not constant for the slags in lower temperature and higher additives.
Foamy slag behavior also improves with increasing in viscosity, reduction in surface tension and density. It was shown that the second phase particles presence in slag increases the viscosity. So, the appearance viscosity is introduced as (μ_e):

$\mu_e = \mu\ (1-0.35\ \varepsilon)^{-2.5}$ (Roscoe's formula[10])(8)
$\mu_e = \mu\ (1+ 5.5\ \varepsilon)$ (modified Einstein equation given by Brinkman[7])(9)
$\mu_e = \mu\ (1- \varepsilon\ )^{-2.5}$ (modified Einstein equation given by Happel[11])(10)

ε : Second phase content
In equations 9 and 10, the upper limit of the particle size of second phase is considered 100 µm.
It should be mentioned that the basicity, FeO and MgO contents in slag influence on viscosity, density and surface tension of slags. On the other hand the kind of charge materials, injection angle, injection depth, type of carbon powder materials for injection in slag and the furnace transformer power have effects on the slag properties. Therefore, optimum conditions for a suitable foamy slag production are necessary to be defined. These optimum conditions should be determined for each furnace by experimental methods.

EXPERIMENTAL:

In this study, experimental tests has been done in AC electric arc furnaces of Mobarake Steel Company which is in Mobarake about 50 km to Isfahan, a centrally located city in Iran. The inside diameter of furnaces hearth was 5.5 m and liquid steel capacity of each furnace was 200 metric ton per heat by 90 MVA transformer power. The electrod diameter was 60 cm. At the end of a heat, a hot heel of around 5-10 tone is left in the furnace to start the next one and avoiding, at the same time, excess slag carryover to the ladle. The charging materials were included 40 tone scrap and 1 tone lump coke. The reminder of the charging materials was DRI with the ratio to scrap of 81.6/18.4. Table1 shows some chemical characteristics of DRI charges employed in this plant. The Figure 1 shows charging method The furnaces werwe equiped with eccentric bottom tapping (EBT). A triple supersonic lance were used to inject oxygen, methane and carbon. The injection steps were as below:

At 18 minutes from the beginning, the lance was inserted in the furnace and oxygen and methane injections were began with the rate of 1150 m^3/hr and 400 m^3/hr, respectively. After 30 minutes, the injection rates were increased to 2300 m^3/hr O_2 and 800 m^3/hr CH_4. At this time, petroleum coke at 0-3 mm size was injected into EAF at different mass flowrates. It is reported[10,11] that the carbon in the form of petroleum coke is the most suitable form of carbon for injecting into slag. In this study, injection was performed 10-60 cm beneath slag surface and the lance angle was 43° to horizontal line.

Table1: Mean of DRI composition

Component	C	Fe_m	Fe_t	Mt	FeO	SiO_2	CaO	Al_2O_3	MgO
Percent	1.93	81.58	88.97	91.6	9.54	2.26	2.1	0.38	0.76

In this process, the temperature was measured using Pt–Pt,13%RH thermocouples. The chemical analysis was performed at the end of process by taking melt and slag samples and using spectrometer and X-Ray fluorescence, respectively.

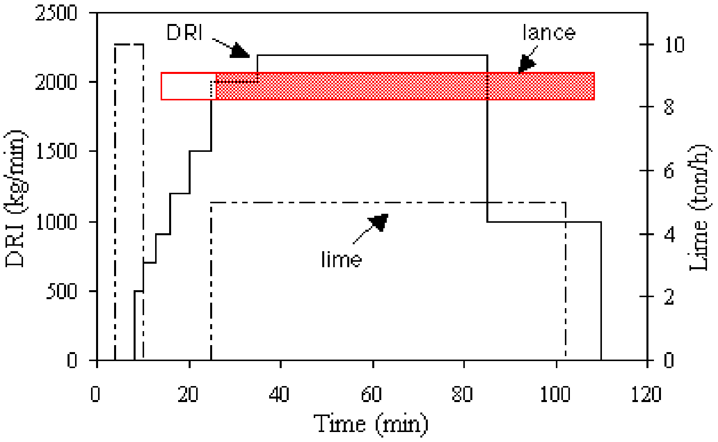

Fig.1: Charge regime of the electric arc furnace

In this research the optimum conditions of foamy slag production and stabilization such as injection rates of carbon, oxygen, methane and the rate of DRI and lime charges were determined. To have a quantitative identification for foamy behavior of slag, a foamy index was calculated using equation 6. To calculate foamy index, it is necessary to have density, surface tension and viscosity of the slag (equation 6). These physical properties of the slag achieved using following equations:

$$\rho = 2460 + 18\ (\%FeO + \%MnO)[13] \qquad (11)$$
$$\sigma = 754.24 - 569.4\ (\%SiO_2/100) - 137.13\ (\%FeO/100)[13] \qquad (12)$$
$$\mu = AT \exp (B/T)[14] \qquad (13)$$

A, B : Constants related to slag properties
T : slag temperature (K)

The viscosity of the slag was calculated using models suggested by Urbain and Riboud[14]. In these calculations the temperature of slags was assumed 1550ºC. The slag composition is considered as a ternary system of FeO, CaO+MgO+MnO, Al_2O_3+SiO_2+P_2O_5 groups and the content of second phase particles were estimated using the ternary diagrams of FeO-CaO-SiO_2. at 1550 °C Three correlations, suggested by Roscoe, Brinkman, Happel in equations 8 to 10, were substituted in equation 6. These calculations were done using a software computer program.

RESULS AND DISCUSSION:

As a general rule, it can be said that when the oxygen consumption in EAF increases, the electrical energy consumption decreases but in this research, the limitation of fume system limited the flowrates of both oxygen and methane. As a result, the injection rates of oxygen and methane was chosen according to fume system limitation. To determination of the carbon flowrate in slag was the second goal to be achieved. In this study, slag hieght and electric energy consumption were measured directly as indicators for studying the various aspects of slag foaming.To identify the optimum injection rate of carbon in slag, the variation of electric energy consumption with carbon injection rates are shown in Figure 2. The electric energy consumption is decreased with increasing of carbon injection rate up to 9 kg/min(Figure 2).

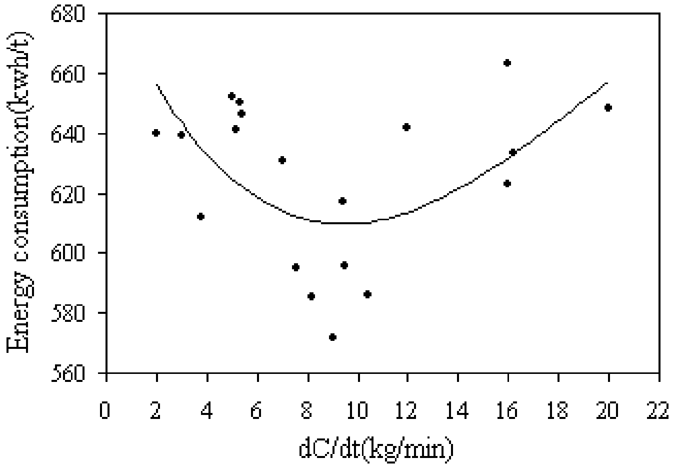

Fig.2: Variations of carbon injection rate with electrical energy consumption

As the carbon injection rate increases, higher carbon particles are placed beside FeO molecules and produce higher volume of CO. Therefore, foamy slag improves and the electric energy consumption reduces. As it can be seen in Figure 2, if flowrate of carbon increases more than 9 kg/min, electric energy consumption increases. when carbon injection rate increases more than this point, it causes a low content of FeO in slag and as a result a low content of oxygen in melt. Low oxygen content in melt can cause lower elimination velocity of carbon content and as a result longer melting time which can increase energy consumption. On the other hand as can be seen in figure 3, where slag height is considered against carbon injection rate, the flowrate of carbon more than 9 kg/min has no effect on height of slag. Therefore, it can be concluded that the carbon injection rates more than 9 kg/min has no effect on slag foaming and increasing in electric energy consumption can cause by increasing in melting time.

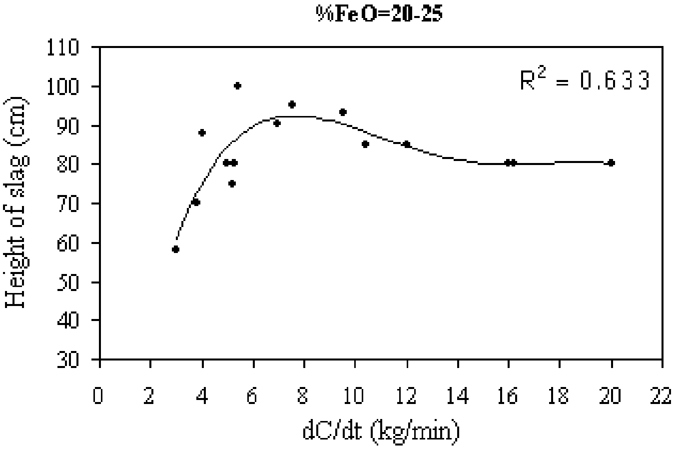

Fig.3: Variations of carbon injection rate with slag height

Figure 4 shows the relation between slag height and electric energy consumption. This relation is shown in two different range of iron oxide content in slag. As can be seen in these diagrams, the electric energy consumption has a linear correlation with slag height. Figure 4 shows that when FeO content is in the range of 20-25%, the electric energy consumption is lower and slag height is higher. It maybe further noted that higher FeO content of slag is associated with lower viscosity of slag and higher surface tension and density[6]. These physical properties variation reduce slag foamying.

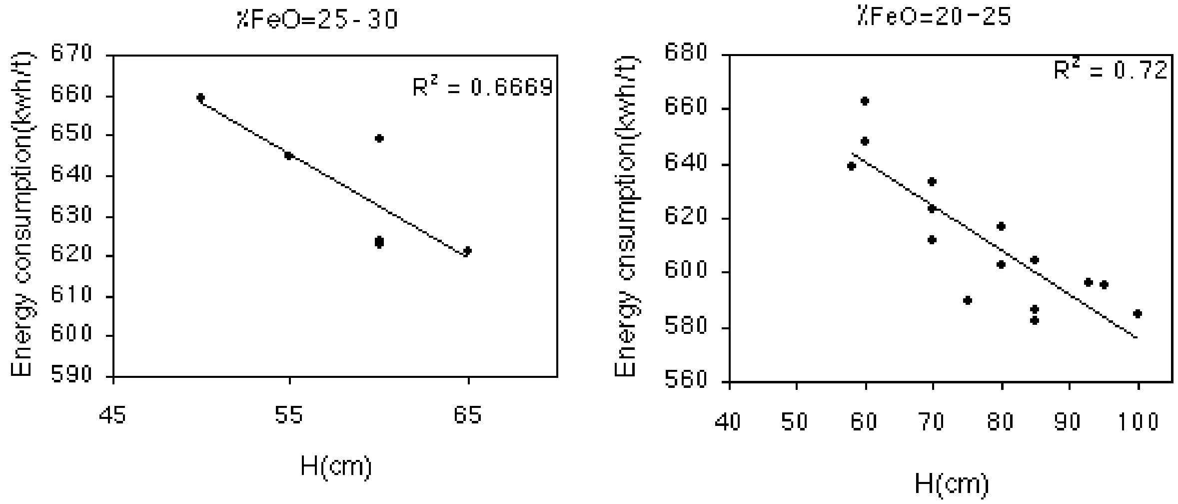

Fig.4: Relationship between height of slag and electrical energy consumption at different iron oxide percentage

Slag basicity is another parameter which influence on the electric energy consumption. Figure 5 shows relation of slag basicity and electric energy consumption in the range of 20-25% iron oxide content of slag. Figure 6 illustrate the relationship between basicity and the slag height at 20-25% FeO content. This figure also shows that the maximum height of slag is achieved at about CaO/SiO_2=2.1. It is clear from Figure 5 that basicity reduction up to 2.1 can decrease electric energy consumption. The reducing basicity might increase viscosity and decrease surface tension[11] and as a result, it improves slag foamying. But figures 5, 6 show that in basicity below 2.1, the electric energy consumption increases and slag height decreases by reduction of basicity. It maybe assumed that the presence of second phase particles causes these phenomena. In the presence of second phase particles, the viscosity increases and overcomes the process of viscosity reduction and increased surface tension due to lower basicity.

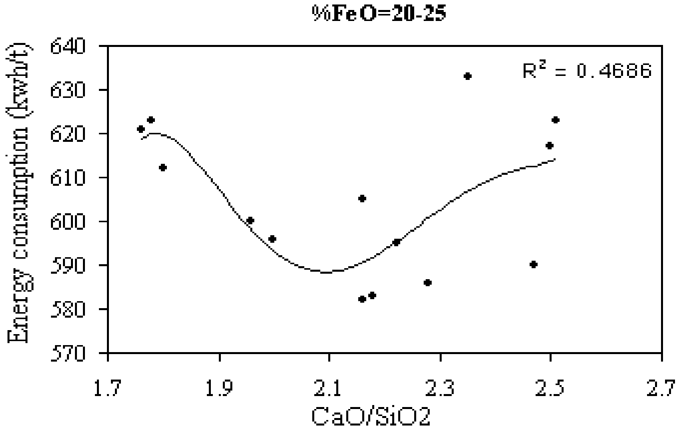

Fig.5: Relationship between slag basicity and electrical energy consumption at 20=25% of iron oxide

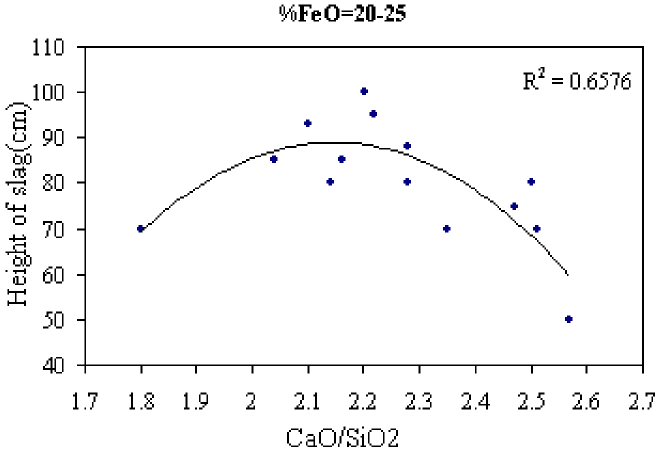

Fig.6: Relationship between slag basicity and slag height at 20=25% of iron oxide

Figure 7 exhibits the relationship between basicity and foamy index which is calculated by Roscoe correction on viscosity at 20-25% FeO content of slag. There is a maximum foamy index in figure 8 around CaO/SiO$_2$=1.95-2.15. The relationship between basicity and foamy index which is calculated by Brinkman correction on viscosity is shown in Figure 8. There is maximum foamy index around CaO/SiO$_2$ =1.9-2.2 . Happel correction was applied on viscosity in Figure 9. The maximum amount of basicity is around 2-2.2. With comparison of the Figures 5 to 9, the optimum basicity for slag foaming at 20-25% FeO percentage is about 2-2.2.

It can be concluded that basicity equal to 2-2.2 is the optimum amount in our study. Now, it is necessary to obtain the optimum FeO content in slag. Figure 10 shows the relation between FeO content of slag and electric energy consumption at basicity in the range of 2-2.2. As shown in this figure, as FeO content increases up to 22-23%, the electric energy consumption decreases. The cause for this is pronounced affect of CO generation as a result of oxygen reaction by carbon in slag. Morales and coworkers[1] explained the strong resistance to iron oxide reduction by carbon not only because of low iron oxide activities but mainly owing to the surface active nature of silica in slags.

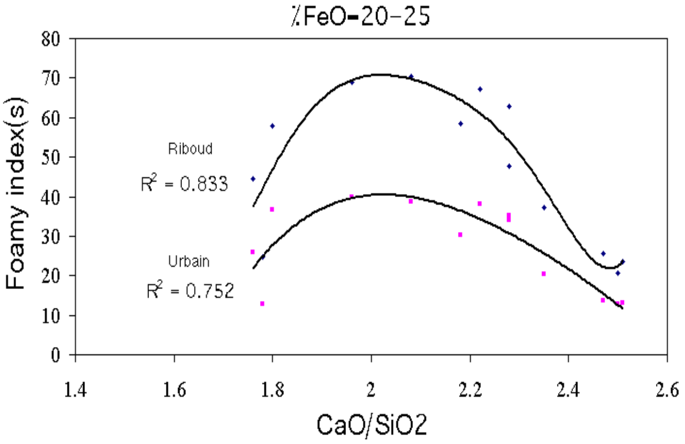

Fig.7: Relationship between slag basicity and foamy index (100Σ) with Roscoe correction on viscosity at 20-25% iron oxide

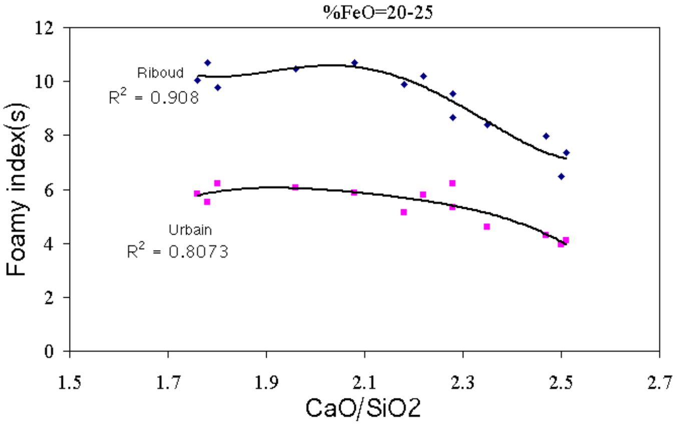

Fig.8: Relationship between slag basicity and foamy index (100Σ) with Brinkman correction on viscosity at 20-25% iron oxide

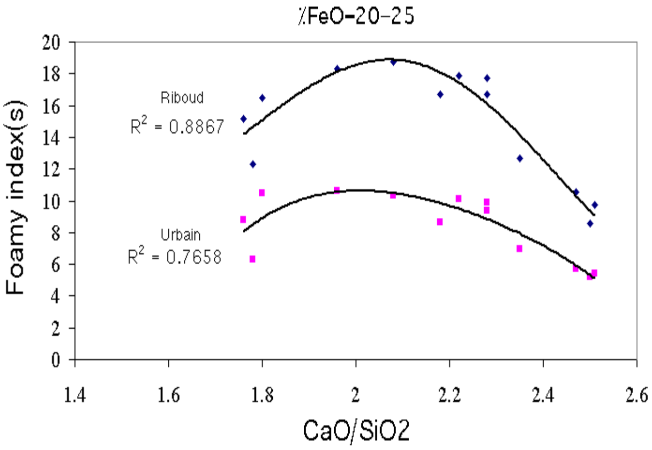

Fig.9: Relationship between slag basicity and foamy index (100Σ) with Happel correction on viscosity at 20-25% iron oxide

The higher activity of silica in the slag causes the lower surface area available for the reduction reaction[13]. This condition accelerates at low FeO percentage in slag. Above 22-23% of FeO content of slag, the electric energy consumption increases again. High viscosity and low surface tension and density of slag as the result of decreased FeO content of slag are specific conditions for a stable foam[11].

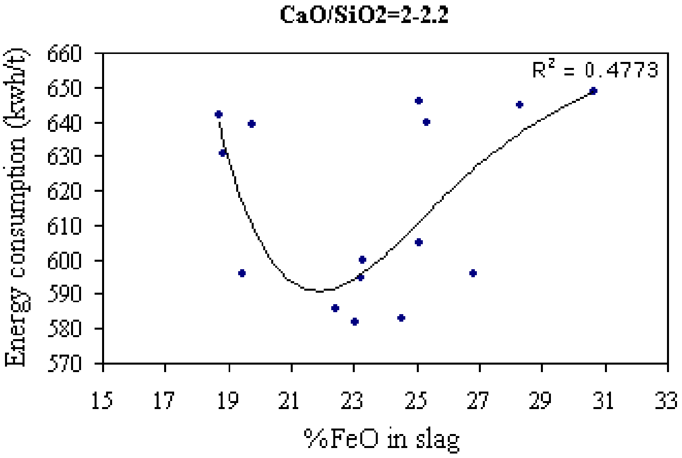

Fig.10: Relationship between FeO percentage of slag and electrical energy consumption at basicity of 2-2.2

Figure 11 shows variations of slag height and FeO content in slag at CaO/SiO$_2$=2-2.2. As can be seen in this figure, the maximum height of slag is correspond to 22-24% FeO. Therefore, it can be considered that the optimum FeO content at basicity equal to 2-2.2 is 20-24%.

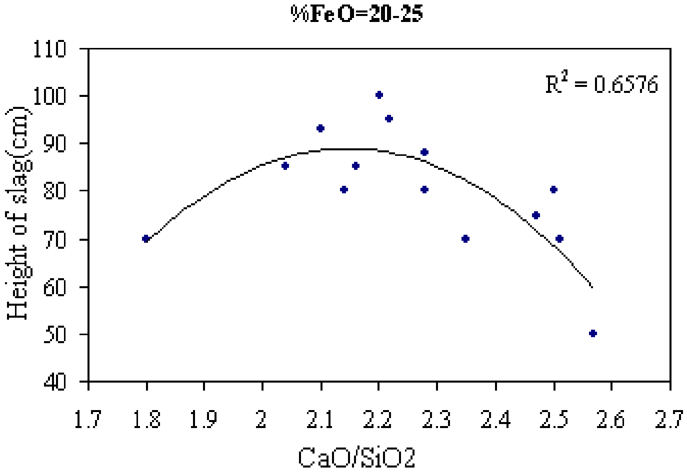

Fig.11: Relationship between FeO percentage of slag and its height at basicity of 2-2.2

To compare the calculated foamy index with experimental results of foamy slag, figures 12, 13 and 14 exhibit the relation between FeO content in slag and foamy index which are calculated by Roscoe, Brinkman and Happel corrections, respectively. These figures show that higher FeO content in slag decrease foamy indices. The foamy index formulas has been calculated with this assumption that the gas velocity in slag is constant but in fact in real condition (non laboratory), the velocity of CO is dependable on FeO content of slag.

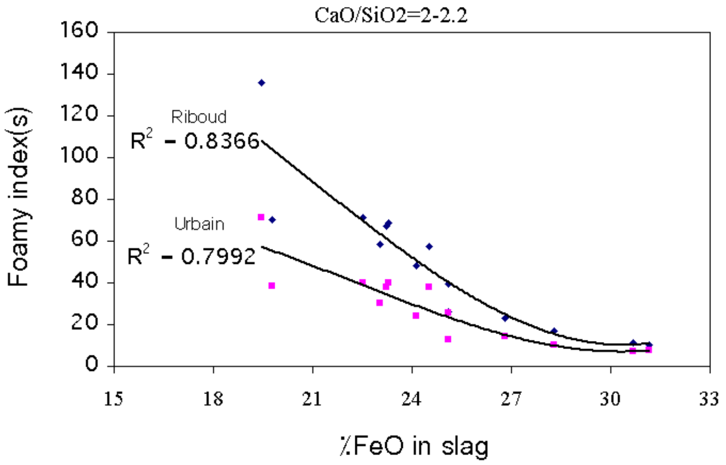

Fig.12: Relationship between FeO percentage of slag and foamy index (100Σ) with Roscoe correction on viscosity at basicity of 2-2.2

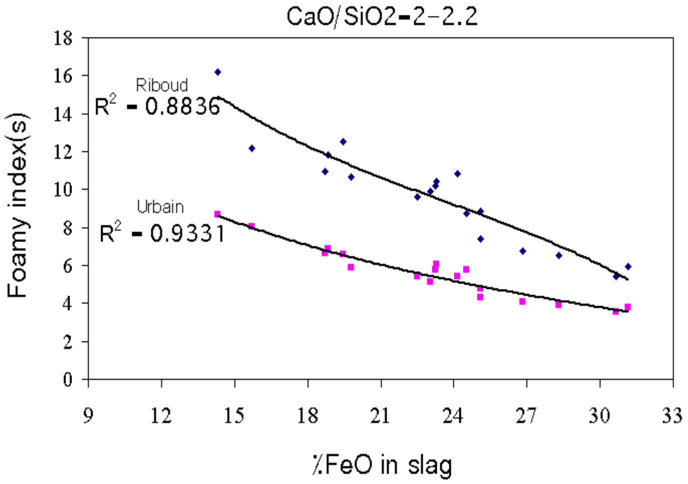

Fig.13: Relationship between FeO percentage of slag and foamy index (100Σ) with Brinkman correction on viscosity at basicity of 2-2.2

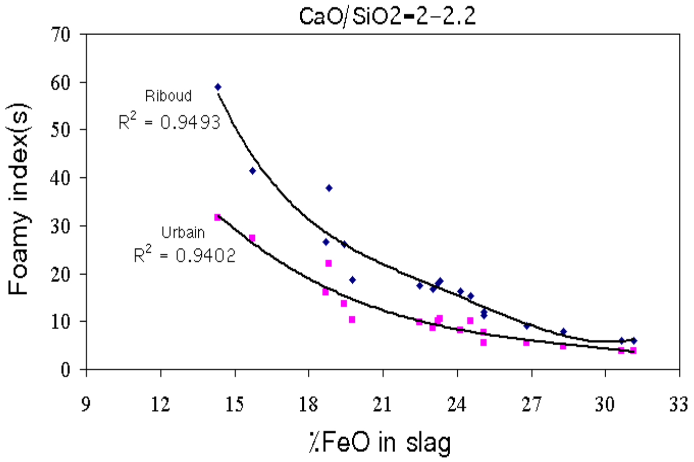

Fig.14: Relationship between FeO percentage of slag and foamy index (100Σ) with Happel correction on viscosity at basicity of 2-2.2

CONCLUSION:

- Foamy slag managed to reduce the electric energy consumption from 670 kwh/t to 580 kwh/t and also decrease the melting time from 130 min to 115 min.
- The percentage of FeO in slag reduced from 25-35% to 20-24%.
- Optimum injection rates for carbon, oxygen and methane were 9 kg/min, 2300 m^3/h and 800 m^3/h respectively.
- The optimum percentage of FeO in slag for a suitable foamy slag in these furnaces was 20-24% and of the basicity was 2-2.2.
- Foamy index is not able to predict the optimum percentage of FeO in the slag.

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