Energy improvement in induction furnace using foaming slag with variation of carbon injection

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Abstract

Energy efficiency is nowadays one of the biggest concerns worldwide. It has become one of the critical matters to any country and industry particularly in South Africa. Because of the complexities and challenges found in industries and especially in foundry, many strategies have been established to measure and regulate more efficiently the energy. Many studies have been conducted in steelmaking process and electrical arc furnace using foaming slag to reduce energy consumption. As such, in this case study, the experiment will be conducted in a small foundry metal casting laboratory using an Induction Furnace (IF), which will reduce energy usage by using the foaming slag and as well pointing out the importance and the impact of carbon rate change on the foaming creation. After experiments all results show that the melting time can be reduced from 42min to 35 min, which is 20% time saving, the electrical energy consumption also has been reduced from 13.93kWh to 10kWh which is 39.3% saving. On the other hand, the foaming slag optimum height was reached at 1 cm. Therefore, a simple modelling has been designed and calculations have been made on heat transfer at the surface opening of the Induction Furnace and temperature loss has been reduced from 878°C to 870°C, with heat transfer loss reduced from 27.99kW to 26.38kW which was 6.10% of energy saving.

Keywords: energy efficiency, foaming slag, induction furnace, foundry metal casting

1. Introduction

For many years, trying to be energy efficient has become one of the first priorities all over the world. The energy efficiency goal is to reduce the amount of energy required to provide products and services (Wikipedia, 2014). The efficiency benefits can also be gained through environmental improvements.

More than ever, companies are facing increased competitive pressures to produce high quality products at equal or lower cost. With rising energy prices, companies are put under pressure to bring energy costs in line with standards of best practice. The efficiency is applied to all sectors so that they may be able to control and to use less energy by having a good result at the end of the process.

South Africa, for many years, is now facing very big challenges regarding energy consumption usage due to lower price of electricity which was a lack of motivation to save energy and has a negative effect of high energy usage (Rasmeni, 2014) (Figure 1). South African Industrial sectors (agriculture, mining, manufacturing and construction) are some of the biggest consumers of energy and use almost 45 to 49% of energy in South Africa (Davidson, 2006; Matlala, 2004). In the industrial sector, iron & steel use 29% of energy in the industrial sub-sector (Davidson, 2006). Therefore, in the iron & steel sector, foundries are the biggest consumers using different types of furnaces with the Induction Furnace known as the most efficient. Energy efficiency of any foundry largely rides on the efficiency of the melting process. Melting is the most energy-intensive operation in the metal casting industry with 55% of the total energy in the foundries (Incorporated, 2005) (Figure 2). The induction heating process has been considered as high productivity, repeatable quality, and green heating technology compared to other fuel-fired furnaces (Dang, 2012).

The aim of this paper is to increase the efficiency of the Induction Furnace (IF) by using a foaming slag layer as insulation material to reduce the heat
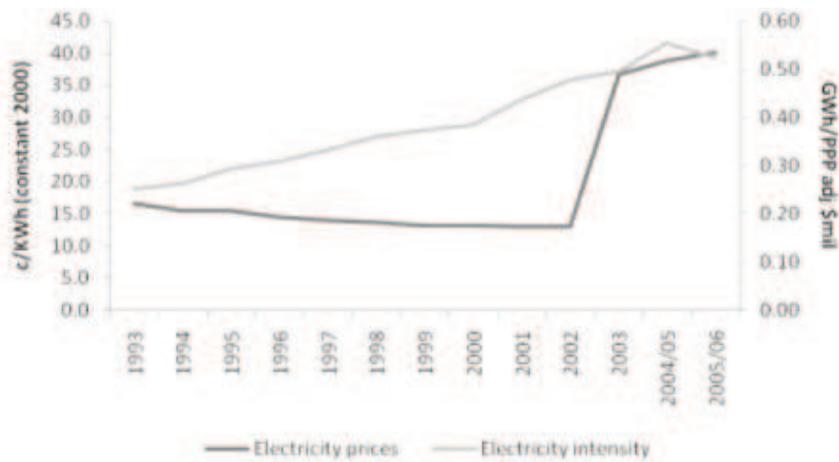
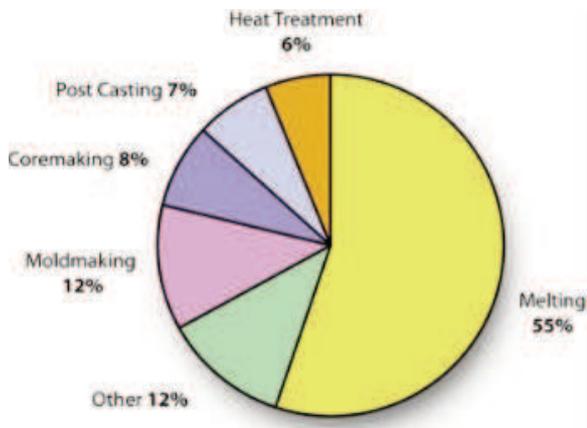**Figure 1: Electricity intensity and electricity prices in South Africa: 1993 to 2005**

Figure 2: Melting operation as the most energy-intensive operation in metal casting industry
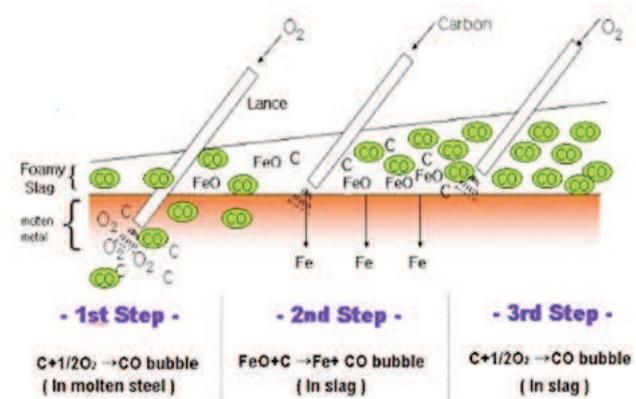

Figure 3: Mechanism of foaming slag creation

loss at the opening of the Induction Furnace (Figure 3). The importance of this paper is to show the value of the carbon rate change in the creation of the foaming slag and the impact that it plays during this process on the energy efficiency procedure. The use of the foaming slag will decrease the heat loss, which will increase the efficiency of the furnace. As such, a Heat Transfer calculation will be conducted at the opening of the Induction Furnace to measure the heat loss during the process and to show the

relation between the foaming slag and the heat transfer at the furnace opening.

2. Experimental methods
2.1 Materials, apparatus and procedure
For this investigation, the materials used were slag particles, oxygen gas, pure carbon particles and cast-iron scraps (Figure 4). In this paper, the experimental processes were done using a small laboratory Induction Furnace of 5 kg, an electrical power

Figure 4: Cast-Iron scraps and carbon particles

station (Figure 5), some alumina lances used to inject gas, a pyrometer to measure the temperature and a thermometer.

Figure 5: Laboratory induction furnace and electrical power station

Figure 5 shows the schematic diagram of the experimental procedure, which consists of 4 main steps.
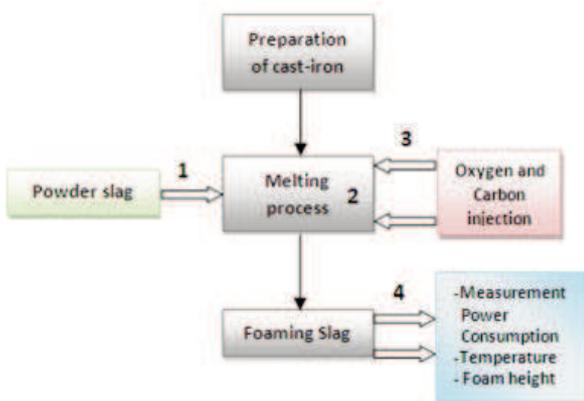

Figure 6: Schematic diagram of experiment procedure of foaming slag creation

Before any procedure, cast-iron scraps (5 kg) and the carbon particles in different weight of 21.27, 30, 35, 40, 45, and 55g were prepared. First step, the slag particles were poured into the crucible, followed by the cast-iron scrap reduced into small pieces and thereafter the laboratory's induction furnace was switched on.

At the temperature of 900°C when the cast-iron scraps are melting, the slag particles also melted and due to the difference of densities of the two melted elements, the slag has started floating and, at the same time, 100 ml of oxygen gas is injected
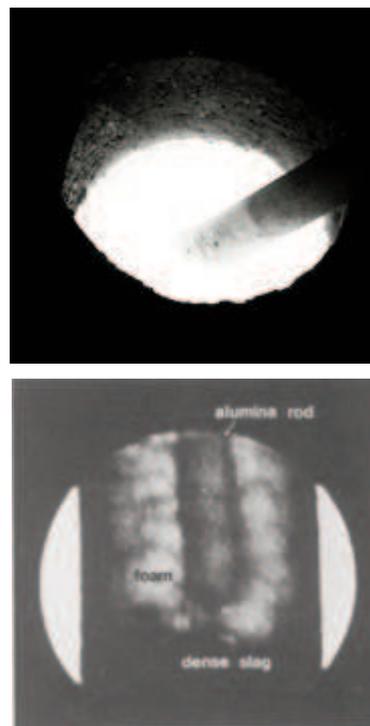

Figure 7: Overview of the measurement of height of the foaming slag using alumina rod

for 30 seconds into the molten. Thereafter, the carbon is now injected at 21.27g for the first experiment and the procedure went on and on until the last 55g of carbon was injected in the last experiment. The oxygen gas was injected for 30 seconds to ensure the reaction as shown in Figure 3 above. From the starting point until the measurement of the temperature on top of the foaming slag, the melting time and the power consumed were measured. The measurement of the height of the foaming slag was made by inserting an alumina rod into the molten and traces of the foaming slag left on the rod was allowing the reading of the height of the foam (Figure 7).

The melting process will be done using a preheated furnace for every experimental procedure due to the results obtained from the basic experimental procedure shown in Table 1.

3.   Results and discussion
The results and discussion will give the influences of the carbon rate changes and its effect on parameters mentioned in Table 2.

3.1   Influences of foaming slag height
The carbon particles used in the melting process for

Table 1: Basic melting experimental processes for cold and pre-heated furnace

	Melting time (min)	Electrical power) consumption (kWh	Temperature environment (°C)	Heat transfer rate (kW)
Cast-iron cold furnace	49	16.98	22	156.8
Cast-iron pre-heat furnace	43	14.66	22	136.53

Table 2: Variations of parameters during the experimental procedure

|	Oxygen (ml/sec)	Carbon (gr)	Foam height (cm)	Melting time (min)	Electrical power consumption (kWh)	Temperature surface of foaming slag (ºC)	Temperature of the molten (ºC)	Heat transfer rate (kW)	Percentages (%)
1	100	21.27	0.9	42	13.93	878	1275	32.62	38.21
2	100	30	0.9	39	13.85	878	1269	31.89	38.16
3	100	35	0.85	38	10.75	872	1263	30.23	37.20
4	100	40	1.0	35	10	865	1261	29.7	36.01
5	100	45	0.7	40	12.82	870	1271	29.3	36.86
6	100	55	0.6	41	14.34	877	1265	28	38.06
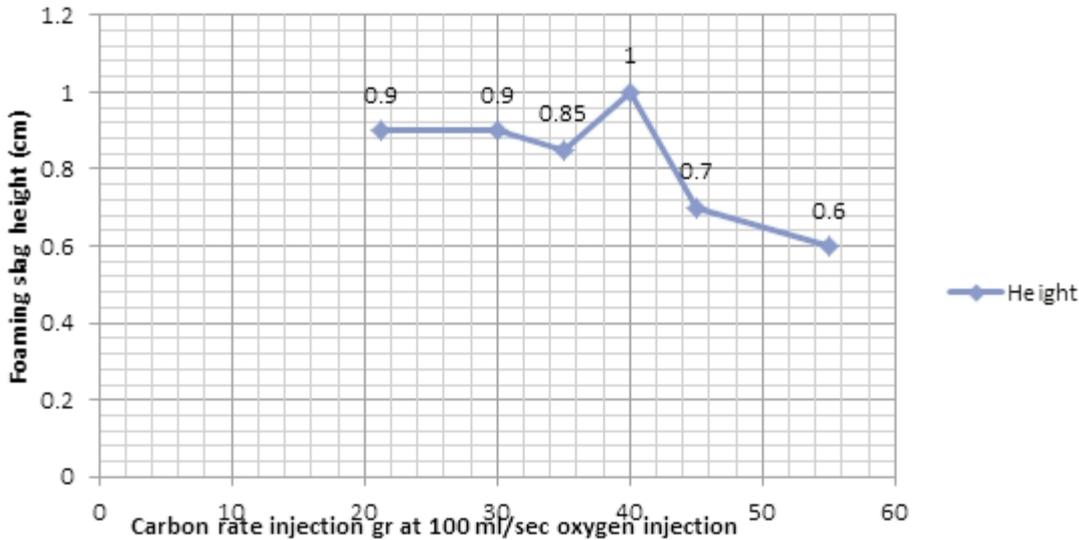
Figure 8: The effects of carbon rates variation on the foaming slag height

the foaming slag creation have been poured into the furnace at different rates from 21.27 to 55g. Figure 8 shows the variation of the height according to the carbon poured into the furnace; it also shows the height going up from 0.8 mm to 1cm for 40g of carbon poured. At 45g and 55g, the height started to decrease due to carbon particles which were now in excess and started destroying the foaming slag that was already made.

At the optimum, the temperature at the surface was 878°C, the melting time was 42 minutes and

Figure 9: Variation of carbon injection rate with slag height
Source: Aminorroaya and Edris (2002)

the optimum foaming slag height was 1cm, the electrical power consumption used was 13.93kWh.

At 40g of carbon poured in the molten, the reaction has reached the optimum and above this amount of carbon, the particles started destroying the bubbles because of the surface tension. A study conducted by Aminorroaya and Edris (2002) on the effect of foamy slag in electrical arc furnaces on electric energy consumption shows that the variation of carbon rate more than 9kg/min has no effect on slag foaming and increasing in electric energy consumption by increasing in melting time (Aminorroaya and Edris, 2002).

3.2 Effect of melting time and temperature of the molten

The melting time and the temperature of the molten during this operation were also influenced by the carbon that was poured into the molten during the procedure. Figures 10 and 11 show that increasing the carbon in the molten until a certain point was contributing to the oxidation which was exothermic and increasing the heat means decreasing the melting time of the cast-iron in the crucible.

Figure 10 shows that at 21.27g the melting was 42 min and slightly increases for 1min at 43 min. But at 35g and 40g, the melting time starts decreas-
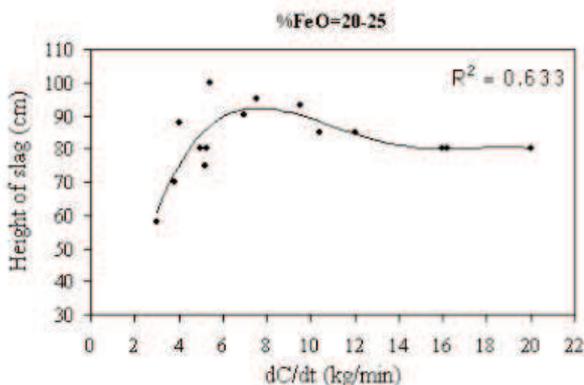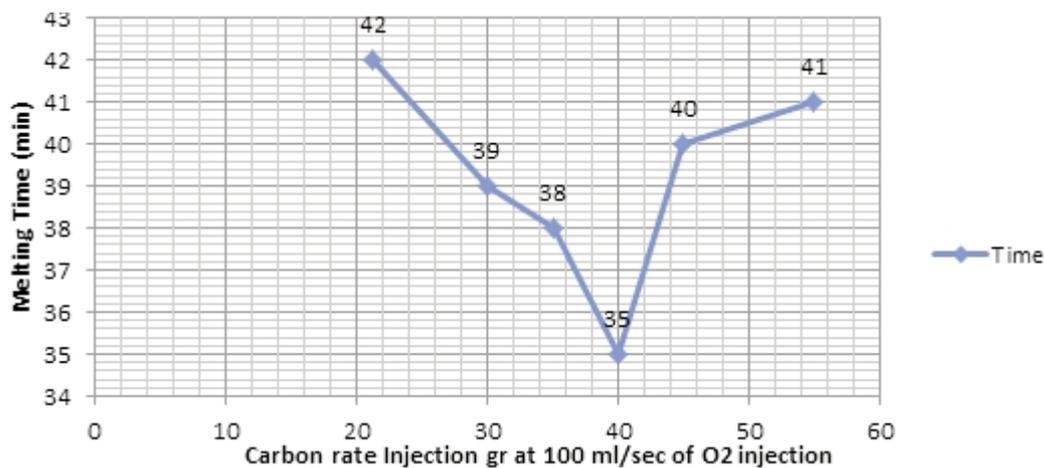
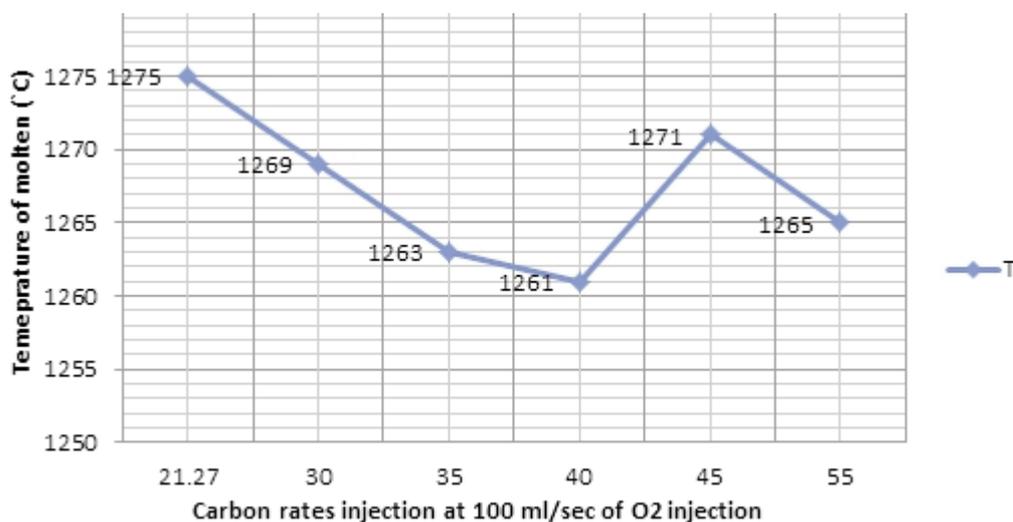**Figure 10: Influence of carbon rate on the melting time**

Figure 11: Influence of the carbon rate injection on the temperature of the melt

ing and the minima time was at 40g of carbon poured into the molten. From 45g until 55g, the melting time starts increasing again. During the melting process at 35g and 40g the oxygen gas injected at 100ml/sec has reacted until the major percentage of carbon injected was consumed due the reaction. But at 45 and 55g, the oxygen gas at 100ml/sec wasn't enough to oxidize all the carbon and that increases the time due the extra material added in the molten. But Figure 11 shows the relation between the temperature and the carbon rate injected in the molten from 21.27 to 40g, temperature was increasing due to the exothermic reaction which brought extra heat in the molten at 100ml/sec. But from 45 to 55g, heat was brought up and the rate of the oxygen could react with all the carbon particles poured in the molten. Ozturk and Fruehan have shown the impact of temperature on the foaming height. Foaming height on Figure 8 decreases with increasing the temperature (Fruehan, 1995). This shows the co-relation between the carbon and the temperature during the melting process.

3.3 Influence of electrical energy consumption

During the reading of electrical power, the carbon rate injection has shown some variation during the process. In fact, some other parameters have played an important role in the reduction of electrical energy consumption such as the basicity of the slag (Aminorroaya and Edris, 2002). Figure 12 shows the variation of the electrical power consumption. From 21.27g to 40g, the electrical energy went down and slightly started increasing from 40 to 55g.

Therefore, from 21.27g to 40g the room temperature was 23°C and from 40 to 55g room temperature was 9° less than normal. Room temperature also played a part on the heating process of the material, the time and eventually on the energy needed to heat the cast-iron. Figure 13 shows that the electrical energy consumption varies with the foaming slag height. If the foaming slag height increases, the electrical energy consumption decreases (Aminorroaya and Edris, 2002).

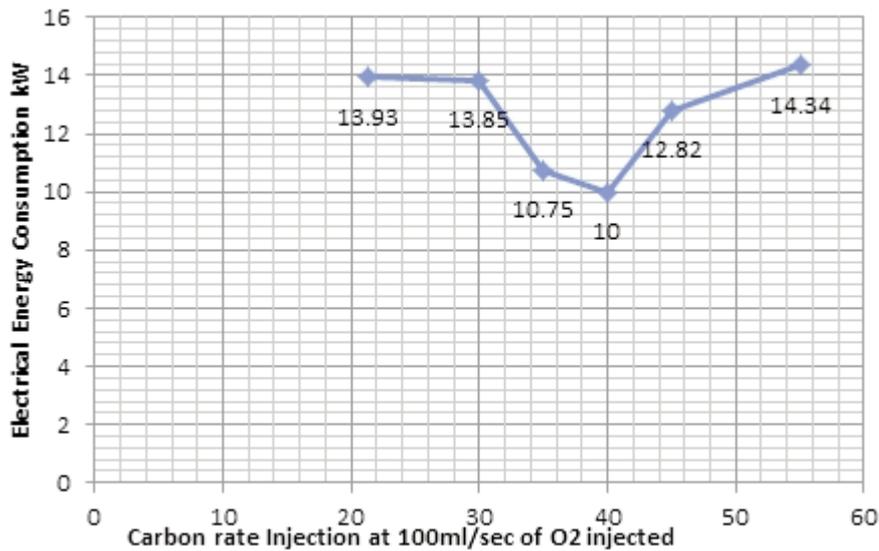Aminorroaya and Edris (2002) have also stud-

Figure 12: Influence of carbon rate injection on the electrical energy consumption kW
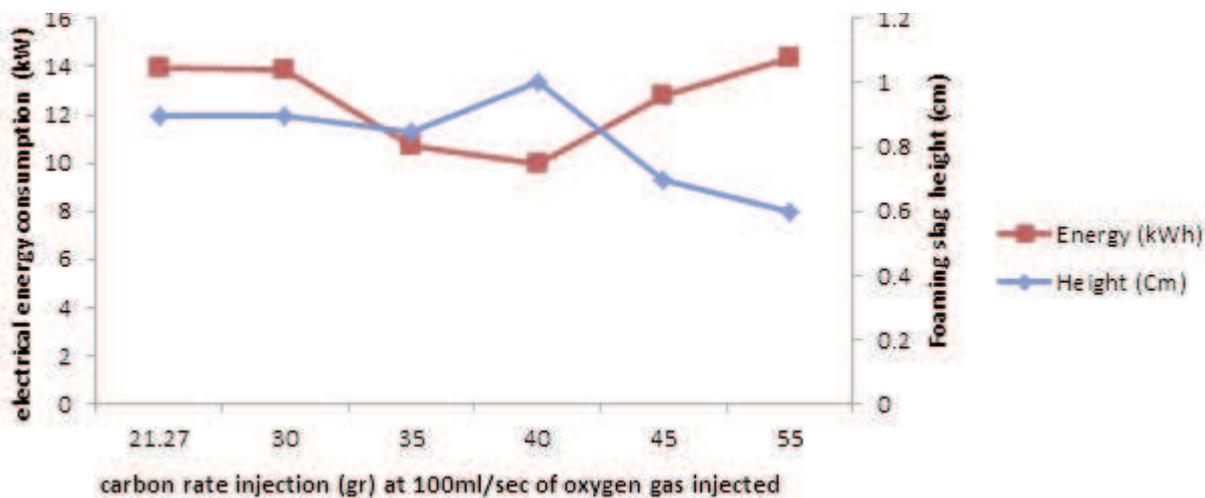

Figure 13: Relationship between the electrical energy consumption and the foaming slag height (cm)

ied and found the influence of the carbon rates on the electrical energy consumption and during their experience, electrical energy decreased with increasing carbon injection rate up to 9kg/min.

3.4 Influence of surface temperature of the foaming slag

The temperature determination on the surface of the foaming slag has all to do with the thickness of the foaming slag and the contribution of the carbon particles. The foam creation is one of the major elements during the process.

Figure 15 shows that from 21.27g to 40g the temperature decreases due to the carbon rate, which influences the foaming slag height, and increases the thickness of the foaming slag. Increasing the thickness means increasing the height which decreases the heat loss on top of the furnace (Figure 16). At 45g and 55g, the temperature starts increasing due to the fact that the foaming slag
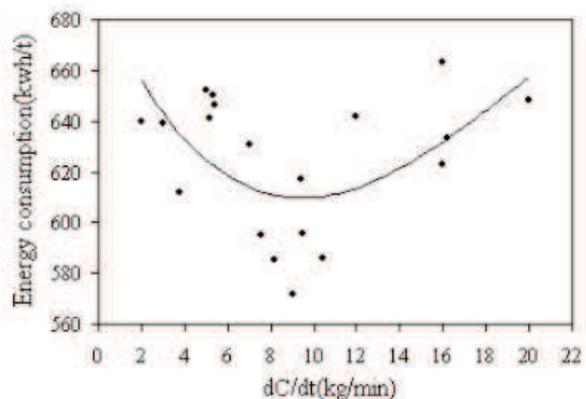

Figure 14: Variations of carbon injection rate with electrical energy consumption
Source: Aminorroaya and Edris (2002)

started to be destroyed due to the excess of carbon particles in the molten. The carbon particles reacted with the bubble and start destroying them and as
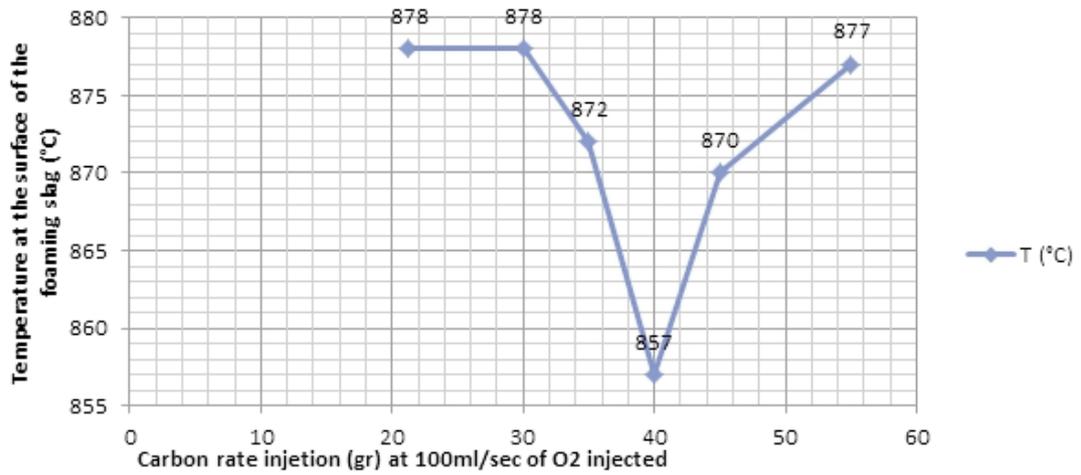
Figure 15: Influence of carbon rate injection (g) on the surface temperature of the foaming slag (°C)
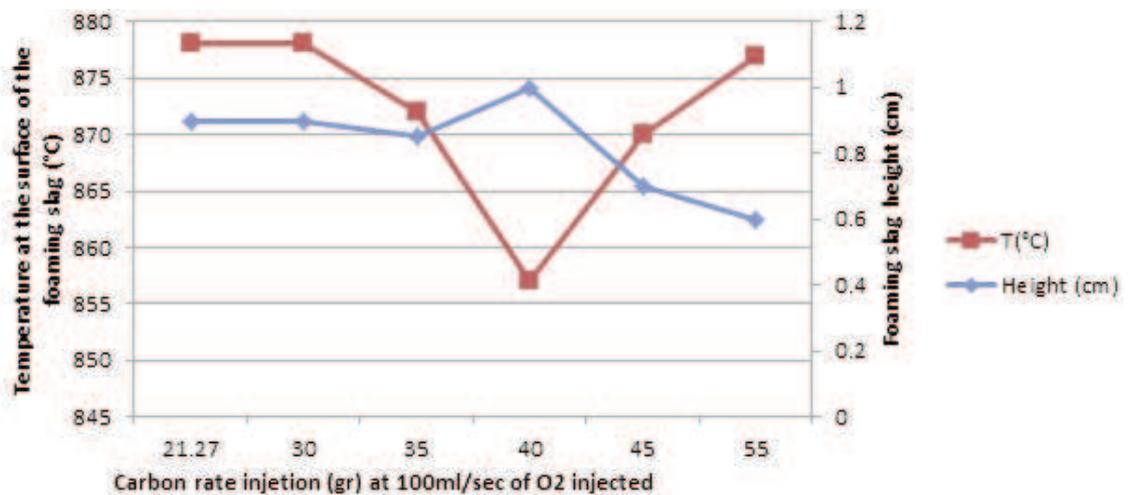

Figure 16: Relationship of temperature at the surface of the foaming slag with the foaming slag height at different carbon rate injection

such decreasing the foam height (Y. Zhang, 1995). The surface temperature of the foaming slag has also everything to do with the foaming height thickness.

3.5 Heat transfer calculation

The heat transfer in the induction furnace is located and comes from the metal to be heated. The thermal transfer is done to the wall and to the top or opening of the furnace. An Induction furnace is a made of a crucible in graphite, some coils cooled by water circulation (Mauricio V. Ferreira da Luz, 2010). Those coils are protected by an insulation material or refractory.

For a better understanding of the furnace, modelling should be done to see which part of the furnace might be influencing the calculation. The choice of the domain is very important because it shows and gives the kind of heat applied for. The aim is to find some domains which will influence and show which types are used: conduction, convection and radiation. Our focus will be on the thermal problems. Figure 17 gives us a sketch of the fur-
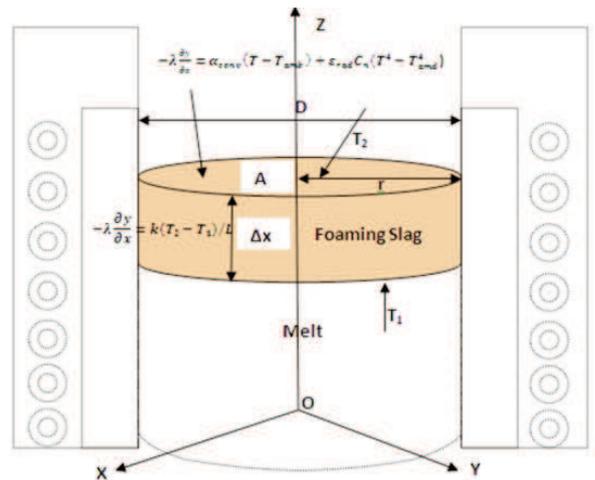

Figure 17: Sketch of the induction furnace

nace and the possible heat and domain which needs to be measured.

The calculus domain in our case will only be focused on the thermal problem, the inductor region will be considered as one single core and the

calculation will be done according to that.

The boundaries of the calculus domain are in fact the surface through that thermal transfer from the furnace parts to the surroundings.

At the surface of the furnace the domain will be given by and the heat transfer is a combination of convection and radiation:

$$-\lambda \, \partial y / \partial x = \alpha_{conv} (T-T_{amb}) + \varepsilon_{rad} \, C_n \, (T^4 - T^4_{amb}) \quad [1]$$

Where, α_{conv} is the convection coefficient. $\varepsilon_{rad} = 0.83$ is the total emissivity and $C_n = 5.67.10^{-8}$ W/m^{2}K^4 is Stephan constant, T is the surface temperature, T_{amb} is the temperature of surrounding environment. The coefficients α_{conv} and ε_{rad} could depend on temperature and ε_{rad} could depend in addition on surface quality.

If the heat transfer calculation in the inductor must be done, the convection heat transfer should be considered because of the exchange between the inductor and the cooling water that circulate through the coils and it given by:

$$-\lambda \, \partial y / \partial x = \alpha_{convind} (T-T_{medapa}) \quad [2]$$

Where $\alpha_{conv\,ind-apa}$ is the transmissivity between the inductor and cooling water whose medium temperature is $T_{med\,apa}$ (Pasca, 2004). In this case the temperature of the molten, the surface temperature on top of the foaming slag has been considered in Table 2: At the Interface melt and foaming slag the heat transfer is made by conduction:

$$-\lambda \, \partial y / \partial x = kA \, (T_2 - T_1)/L \quad [3]$$

Where k is the thermal conductivity, A is the surface of cylinder; L is the length of the layer.

During the calculation the ΔX changes according to the height of the foaming slag which influences the heat transfer operation.

The total heat transfer loss during the process on top of the furnace will be influence by the conduction, convection and radiation:

$$-\lambda \, \partial y / \partial x = \alpha_{conv} (T-T_{amb}) + \varepsilon_{rad} \, C_n \, (T^4 - T^4_{amb}) + kA \, (T_2 - T_1)/L \quad [4]$$

The influence of surface of the cylinder A in this case will be influenced by the height of the foaming slag and represented by L:

$$A = \pi \, (D^2/4) \, L = \pi r^2 L \quad [5]$$

$$A = \pi \, (D^2/4) \, L = 3.14 \times 0.05^2 L \quad [6]$$

$$A = 0.00785 \, L \quad [7]$$

The measurement of the heat transfer will depend on the variation of the thickness of the foam. As such, the results will show the variation of the heat according to the foaming height. The calculation has been made according to the equation 4:

$$-\lambda \, \partial y / \partial x = 19.10 \times (878-23) + 0.83 \times 5.67.10^{-8}$$
$$(878^4 - 23^4_{env}) + 0.15 \times \pi \times 0.0025 \, (1265-878)$$
$$-\lambda \, \partial y / \partial x = 27.99 \, kW$$

All the results are shown on Table 2 which is the table of variations. The heat transfer calculation for the basic experiments without any kind of foam or insulation has been considered as such the calculation was given by the formula in equation 10. The conduction was considered as zero because the temperature at the interface was the same solid (molten) and the gas.

$$-\lambda \, \partial y / \partial x = 19.10 \times (1905-23) + 0.83 \times$$
$$5.67.10^{-8} \, (878^4 - 23^4_{env}) + 0$$

$$-\lambda \, \partial y / \partial x = 136.5 \, kW \text{ for cold furnace and;}$$

$$-\lambda \, \partial y / \partial x = 156.8 \, kW \text{ for preheated furnace.}$$

During the carbon injection into the molten, the reactions below are exothermic because they increased the temperature into the furnace (N. Sahay, June 2014) (Pandey, 2003).

$$C + O_2 = CO_2 + 24.03 \, Kcal/g \text{ mole } (T<800°C) \quad [8]$$

$$C + ½ \, O_2 = CO + 26.42 \, Kcal/g \text{ mole } (T>800°C) \quad [9]$$
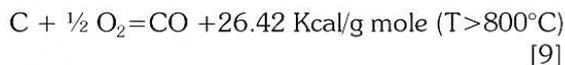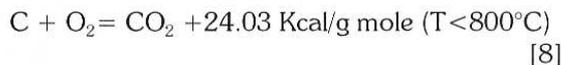
Figure 18 gives the variation of the heat loss compare to the height of the foaming; the figure shows that 1cm was the optimum height reached during the process. From 0.9cm the foaming height stays a little bit constant. When the height increases the heat loss decreases due to the thickness of the foam which reduces the heat loss.

4. Conclusion and summary
The importance of energy efficiency has been demonstrated during the experimental procedure. This paper illustrated the importance of the foaming slag during the melting process and the utility of the foaming slag during the heat loss. The results of the experiments and observations revealed that:
1. At 40g, the use of the foaming slag in the induction furnace has given a melting time saving of 5 minutes which is almost 17.15% of time.
2. The electric energy consumption has been saved from 13.93kW to 10kW at 39.3% of electricity energy. At 40g of carbon injected, the
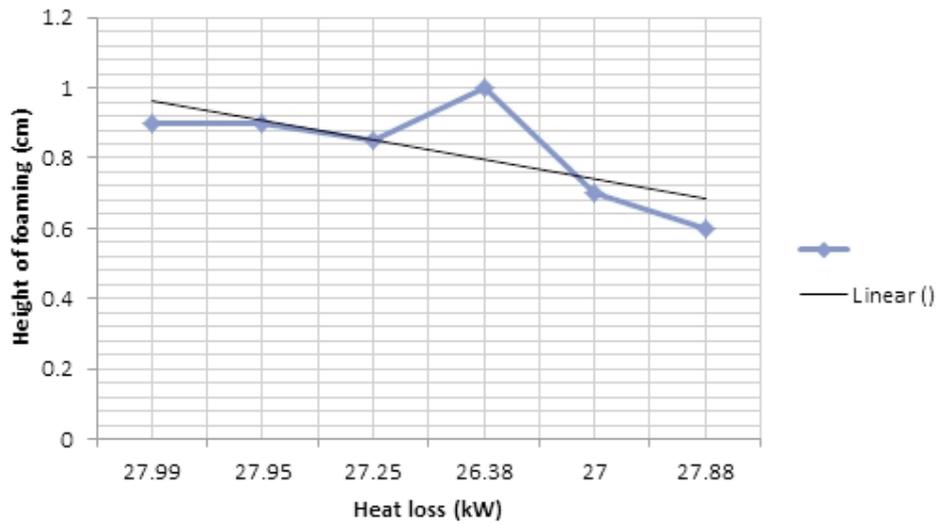
Figure 18: Relation of heat loss with height of foaming

foaming slag obtained its optimum at the height of 1 cm.

3. The foaming slag insulation has helped reduce the temperature radiation from 878°C to 870°C. The thickness of the foam creates a layer which could reduce the heat loss.

4. The heat transfer calculation during the parameters change shows a variation of the heat loss due to the height (Figure 18). The graph line goes down with the heat loss decreasing and that means if the height decreases the heat loss increases. The heat transfer loss during the calculation gives a variation of temperature from 27.99kW to 26.38kW, which give a saving of 6.10%.

5. Comparing the basic experimental heat loss (136.53kW) with the heat loss during the foaming slag (26.38kW) creation almost shows the importance of using foaming slag during the process because in this case, using foaming slag reduces the heat loss to 110,15kW which is almost 19.4% of the energy loss.

6. Usage of foaming slag in the induction furnace in this experiment shows that the foaming slag is theoretically and practically efficient but coming to the heat transfer a tremendous heat loss occurred due to the thickness of the foaming slag, which was very tiny and instead of reducing more heat radiation its reduces less.

7. The improvement of the induction furnace using carbon injection parameters in this research can be implemented to the actual furnaces and not only to the Lab situation.
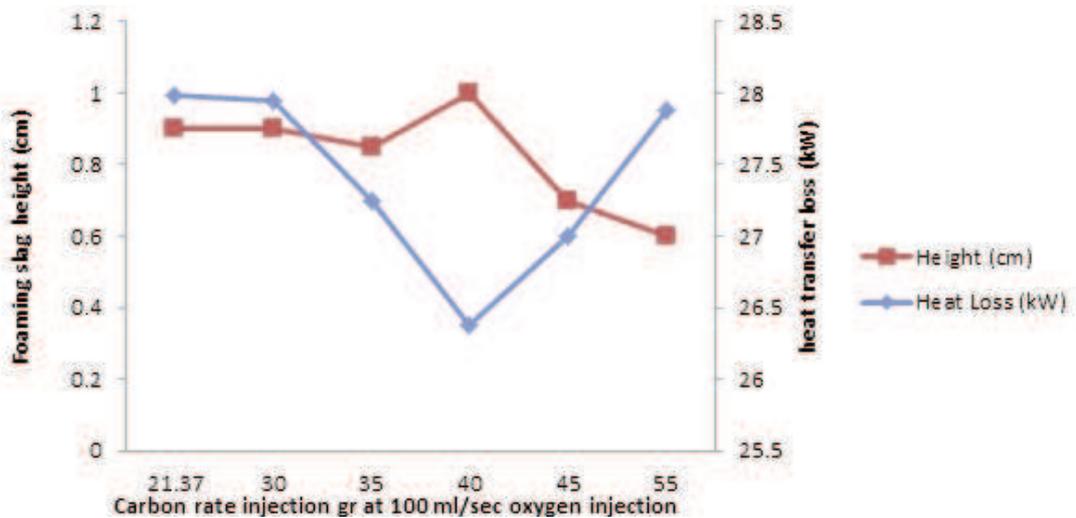

Figure 19: Comparison and variation of heat transfer (kW) and foaming slag height (cm) due to carbon rate injection at 100 ml/sec oxygen

Acknowledgments

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