INFLUENCE OF OXYGEN GAS ON THE IMPROVEMENT OF ENERGY EFFICIENCY IN INDUCTION FURNACE USING FOAMING SLAG

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Abstract

Since many years, the world has come together to face the challenge regarding the energy consumption and energy efficiency problems. In order to achieve and overcome these challenges, researchers have been focused on one of the most energy demanding sector worldwide which is the Industrial sectors and more specifically the Foundry. South Africa being one of the countries having the cheapest price of electricity and has brought a misusage of electricity and thus brought inefficiency in the industries and increase of prices in foundries. The purpose of this paper is to show the importance and impact of oxygen gas in the creation of a foaming slag during the melting process induction furnace (IF). Results have shown an optimum of oxygen gas injection of 100ml/sec and from 50 to 42 min which is a gain of almost 12 min in time (21% - 23.5%) and electrical energy consumption from 18.41kWh to 13.93kWh have been reduced to 2.56%. The thickness of slag foam increases from 0.2 - 0.9cm during the experimental process and decreases the temperature on the surface of the foaming slag from 912°C to 878°C. As such, a simple heat transfer modelling and calculation have been conducted to see the impact and the relation between the heat loss and the foaming slag and result as shown that the heat saving was made from 9.1 - 9.2%.

Keywords: Energy efficiency, foaming slag, induction furnace, foundry metal casting.

Introduction

The problem of energy consumption across the world has created a massive panic over the world and especially in South Africa. Many researchers have focused on the issue and conducted many experiments in the last decades. Since many years, conferences, debates and researches have been held worldwide and new regulations have came to light to solve the issues related on the energy. South Africa being one of the biggest users of energy also has the cheapest energy cost which turned the country in a big trouble of misusage of energy. Thus, the misusage has created a huge problem and price has increases for industry and especially foundries to over 49% in 2010 [1] . On the other hand, the foundry industry could search for opportunities to extensively diminish the costs without inevitably reducing the profits of the supplier. One of the first reasons of those regulations is to improve the energy efficiency, because such measures not only cut energy consumption and CO_2 emissions, but are often low-cost [2].

Therefore, the industrial sector is the biggest consumers of energy and the electricity demand assume a GDP growth rate of 2.8% as shown on Figure 1 below. Some countries use around 65-70% of the total foundry energy [3] in the melting, it also using 55% of energy usages [4] Figure 2. A wake-up call has been send to all the sectors and sub-sectors especially those which are created and spending more energy. Therefore, the industrial sector and precisely the South Africa foundry sector use very old technology material which is one of the reasons of spending too much energy.

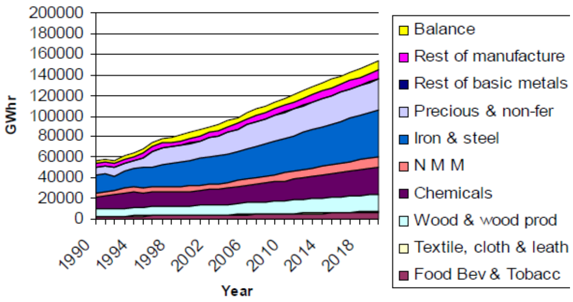

Figure 1: Electricity forecast for the industrial sector

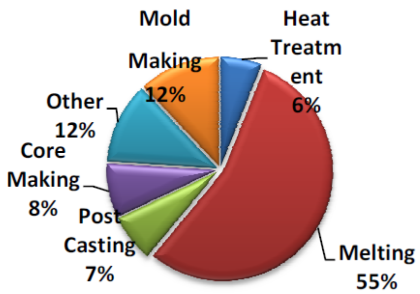

Figure 2: Energy consumption by foundry

In this paper, the author focused the attention to the melting process in the IF, which is one of the most demanding sector coming to the energy consumptions. The aim of this research is to optimize an IF by creating an insulation foaming slag to reduce the energy usage during the melting process. Foaming slag is a process created by gas and carbon particle injection. In our case, the oxygen gas (O_2) will be injected at different rates into the slag which will create bubbles and form a foaming slag. The insulation foaming slag layer on the molten surface will participate to the heat loss reduction in IF Figure 3. The energy study will carry on with the heat transfer calculation which will show the task of the foaming slag during the heat loss in the induction furnace process.

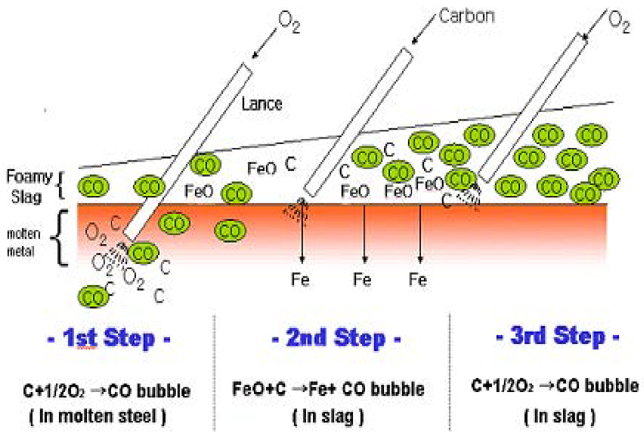

Figure 3: Mechanism of foaming slag creation

Experimental methods

Procedures and Materials

This study and experiment test has been conducted in a 5 kg laboratory induction furnace show in Figure 4. During this research, some other materials and apparatus have been used for measurements and melting processes, such as: Cast-Iron which was our material to melt, slag powder to increase the slag during our melting process, carbon particles, oxygen gas for the oxidation reaction and foaming process, a flow-meter to measure the flow-rate of the gas injected in the solution, a power station to read the electrical power (kWh) used during the melting process , Alumina lances to inject oxygen gas into the solution and a pyrometer for measuring the temperature on top of the foaming slag.

Figure 4: Apparatus used during the process

During the melting process, the induction furnace will be used either cold or pre-heated. Usage of cold or pre-heated furnace will shows the best way of melting and where the best results come. As shown on Figure 2, the first experiment has been conducted on a basic level to see how much energy has been consumed during the melting process and heat calculation has been conducted as well. First, a cold furnace has been used, after then a melting with a pre-heated furnace on a basic level has been made. Electrical power (kW) has been increased progressively until the optimum is reached. The starting point was 5kW.

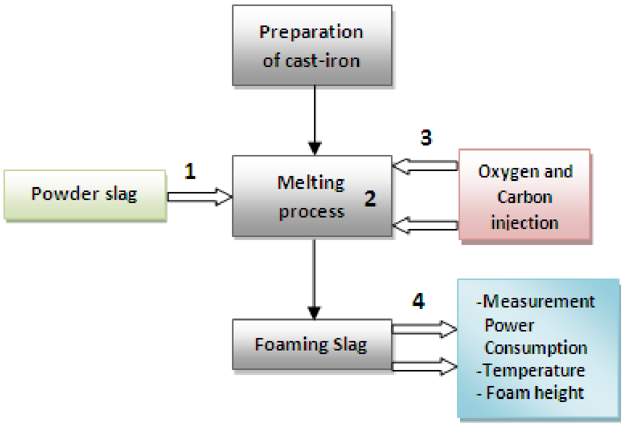

Figure 5: Schematic diagram of experiment procedure of foaming slag creation

Table 1: Basic experiment and melting of cast-iron in a 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

The second phase of the experiment was the oxygen gas variation. O_2 has been injected at the rate different rate: 30, 45, 55, 75, 90, 100, 110, 115ml/sec as shown on Table 2 below. During the process the amount of carbon particles have been kept constant at 21.27 gr. The schematic diagram shows that firstly, the slag powder was put into the crucible before the melting process. Around 900°C, the melt partially done, slag powder starts to float at the surface due to its property and due to differences of density (Figure 6.A). To enhance the heat and create the foam, carbon particles and oxygen gas were injected using an alumina lance inserted into the melt just a little bit next to the level of the slag (Figure 6.C.D) Figure 3. The oxygen gas combined with the carbon start creating bubbles which are the reason of foaming slag creation. So, combination oxygen and carbon create an exothermic reaction which produces heat and increases melting time.

A B C D E

Figure 6: Different steps of melting

The molten temperature has been taken during the processes and measurement has also been done on top of the foaming slag creation. Foaming slag height measurements have been done by injecting an alumina rod into the foaming slag, which helps to see the level of the foam on the alumina rod.

A very simple modelling has been conducted to measure the heat loss during the entire process and the calculation was manually done. Induction furnace has been used for various reasons to reach prescribed temperatures and design and optimization has been a very powerful tool for industrial applications [5]. Heat transfer modelling was generally governed by the heat dissipated by eddy currents in the work piece.

Results and discussion

Table 2: Parameters variation and results

	Carbon (gr)	Oxygen (ml/sec)	Foam Height (cm)	Melting time (min)	Electrical Power Consumption (kWh)	Temperature surface of foaming slag (°C)	Temperature of Molten	Heat Transfer Rate at Opening (kW)
1	21.27	30	0.2	50	18.41	912	1313	**32.62**
2	21.27	45	0.4	51	17	907	1258	**31.89**
3	21.27	55	0.6	56	19.05	895	1271	**30.23**
4	21.27	75	0.7	50	16.74	891	1233	**29.7**
5	21.27	90	0.85	45	15.75	888	1215	**29.3**
6H	21.27	100	0.9	42	13.93	878	1198	**28**
6C	21.27	100	0.88	47	16.84	880	1205	**28.26**
7	21.27	110	0.7	40	13.32	898	1245	**30.64**
8	21.27	115	0.6	35	11.08	901	1233	**31.43**

As shown on the table above, oxygen has influenced many other parameters during the melting process and as such contributed to the energy efficiency process.

Influence of foaming slag height

The flow-rate of oxygen optimum has been reached at 100ml/sec using a cold and pre-heated furnace. The optimum have been reached respectively for the cold and pre-heated furnace at the temperature 1205°C-1198°C for the molten and 880°-878°C on top of the foaming slag, 47and 42 minutes melting time were measured for the optimum. The electrical energy consumed 16.84-13.93 kWh was used for both cold and pre-heated furnace. With a cold and pre-heated furnace the optimum foaming slag are respectively 0.88- 0.9 cm.

Figure 8 and Figure 9 give and show the variation of the flow-rate of oxygen using a cold and pre-heated furnace and increase of the foaming slag height during the two process.

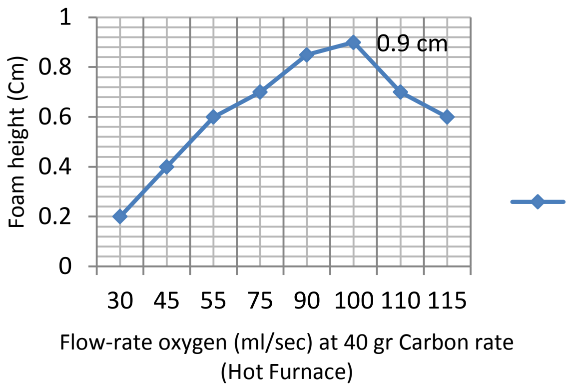

Figure 7: Variation of Flow-rate of oxygen at 40gr carbon in pre-heated furnace vs the foaming slag height

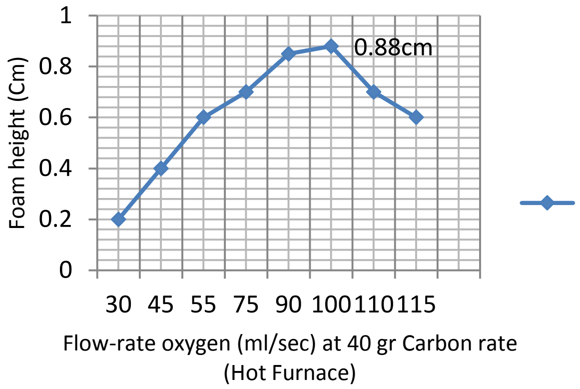

Figure 8: Variation of flow-rate of oxygen at 40gr carbon in cold furnace vs the foaming slag height

As shown above, the carbon content was kept constant during the injection and variation of the oxygen in the melt. From 35ml/sec the foaming slag height was 0.2cm. By increasing the flow, the reaction oxygen-carbon created more bubbles which increase and sustain the foam. After reaching the optimum of 100ml/sec, the foaming slag height started to decrease and the bubbles started to rupture due to too much oxygen-gas and lack of enough carbon particles for a sustainable reaction [6].

Using a cold and pre-heated furnace, helped save time during the melting process with 5min of difference comparing cold and pre-heated, 2°C difference at the surface of foaming slag.

Effect of melting time

The use of oxygen and carbon create due to their chemical reaction an increase of oxidation reaction. The oxygen injected varied from 30 to 115 ml/sec. Those reactions are exothermic because they raised the temperature into the furnace [7][8].

$$C + O_2 = CO_2 + 24.03\frac{Kcal}{g}mole \qquad [1]$$

$$C + \frac{1}{2}O_2 = CO + 26.42\frac{Kcal}{g}mole \qquad [2]$$

As shown in the Figure 9 the progressive increase of the flow increases the melting time as well sudden increase of the melting time at 56 minutes is due to the temperature of the cast-iron loaded to be melted. Due to the exposure of the material under a cold weather, the melting time has been influenced and took longer which plays a role in the overall time during the all process at 55gr carbon injected. From 75ml/sec to 115ml/sec of oxygen-gas injected, the cast-iron to be melt was under normal room temperature and the increase of oxygen enhance the heat and decreased the melting time till 35 minutes for 115 ml/sec.

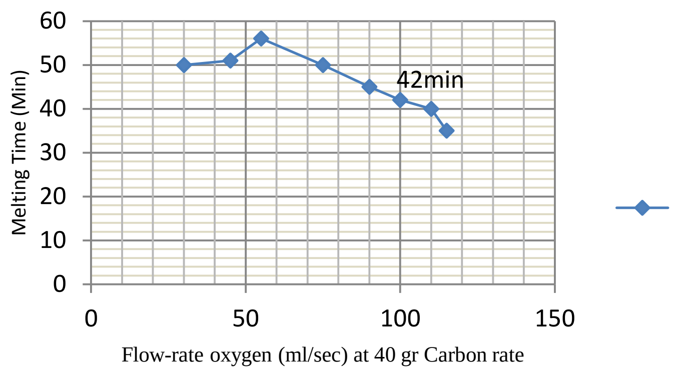

Figure 9: Variation of melting time due to Flow-rate oxygen (ml/sec) at 40 gr Carbon rate

In the pre-heated and cold furnace the optimum was reached respectively at 42min and 47min for the foaming slag height, the electrical energy consumption and the temperature on the surface of foaming slag.

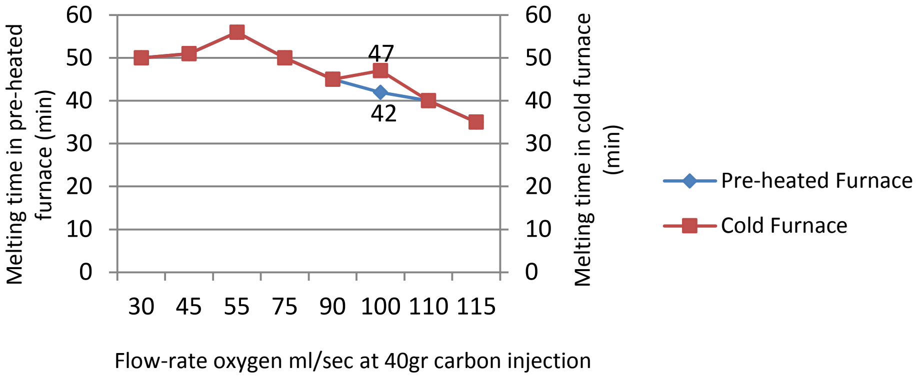

Figure 10: Variation of melting time in pre-heated and cold furnace at different flow-rate gas oxygen.

Influence of electrical energy consumption

The effect of the oxygen gas flow-rate on the electrical energy consumption has also to do with all the parameters study above. In fact, some other parameters not mentioned play also an important role in the reduction of electrical energy consumption such as the basicity of the slag [9].

At 30ml/sec the electrical energy consumption is 18.41kWh. The oxygen injection has a positive impact on the variation of the electrical energy consumption. At 55ml/sec the figure shows an increase in the power of 19.05kWh. The increase is due to the use of a cold furnace which influences the electrical energy consumption. From 55ml/sec until 115ml/sec, the furnace used was pre-heated that the reason of a decrease in the electrical energy consumption. The lowest point obtained was at 115ml/sec (Figure 6). The electrical energy consumption is decreased with increasing of foaming slag Figure 12 [9].

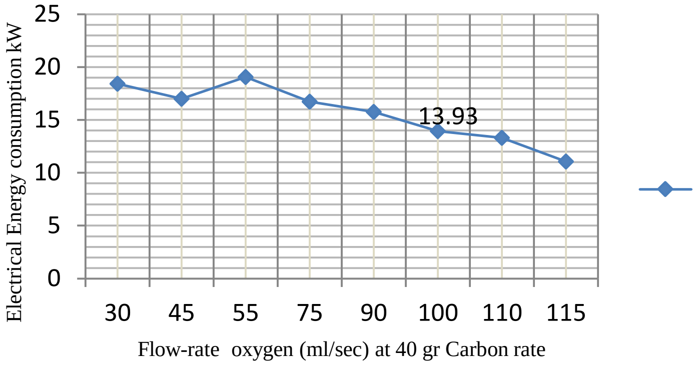

Figure 11: Variation of Electrical energy consumption due to flow-rate oxygen at 40gr carbon

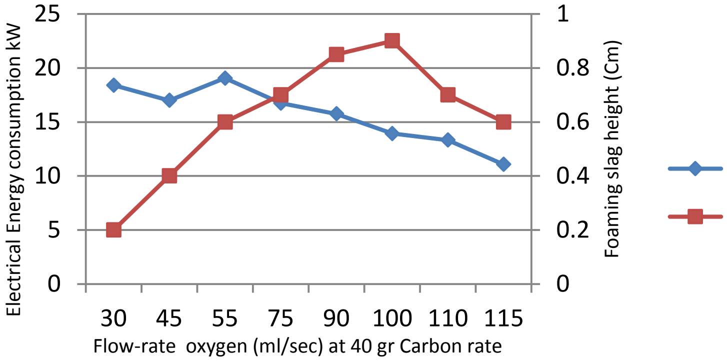

Figure 12: Relationship between electrical energy consumption (kW) and height foaming slag (cm) at flow-rate oxygen gas.

The foaming slag height optimum was obtained at an electrical energy consumption of 13.93kWh and the flow-rate of oxygen gas was 100ml/sec at 40gr of carbon rates.

Influences of temperature reduction on top of the foaming slag

To determine the minimum temperature reduction on top of the foaming slag due to the oxygen injection and everything has to do with the foam height. As shown in Figure 7, at 30 ml/sec of oxygen blow in the melt, the height of the foam is 0.2 Cm and the temperature at the surface of the molten is 912° C. Therefore, the more the oxygen gas is injected, the more the thickness of the foam increases and the temperature at the surface decreases. Thus, at 100 ml/sec the optimum height has been obtained and the temperature of 878° C, which is the lowest temperature obtained.

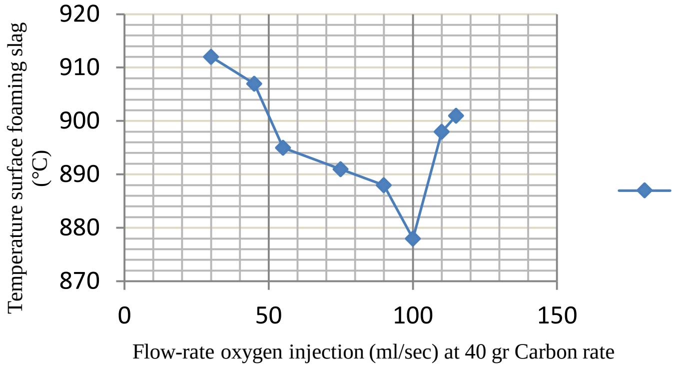

Figure 13: Variation of Temperature at the surface of foaming slag due to oxygen injection at 40gr carbon particles

The effect of temperature reduction on top of the foaming slag has a positive impact on the foam life. The foaming slag height increases with decreasing the temperature and the CaO/SiO_2 ratio [10] as studied by BAHRI OZTURK and R.J. FRUEHAN on the effect of temperature on slag foaming.

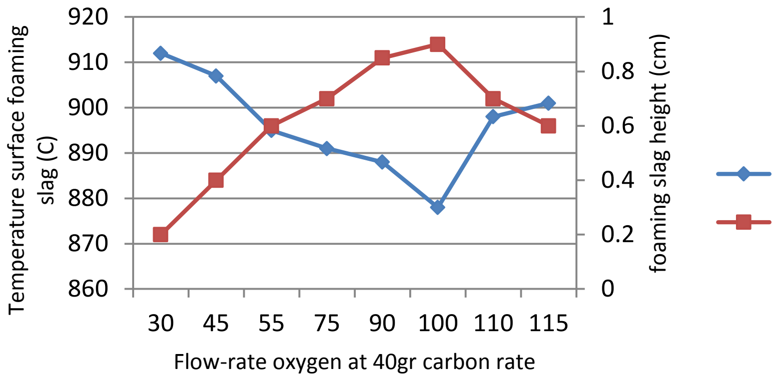

Figure 14: Relationship and influence of temperature on the surface of the foam with the foaming slag height at flow-rate of oxygen gas

Heat Transfer Calculation

The heat transfer in the IF is located and come from the metal to be heated. The thermal transfer is done to the wall and to the top or opening of the furnace. Induction furnace is a made of a crucible in graphite, some coils cooled by water circulation [11]. Those coils are protecting by an insulation material or refractory.

For a better understanding of the furnace a 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 types of kind of heat must must applied for. The aim is to find some domains which will influence and show which types are used: conduction, convection and radiation. Our focused will be on the thermal problems. The Figure 8 gives us a sketch of the furnace and the possible heat and domain which need to be measured.

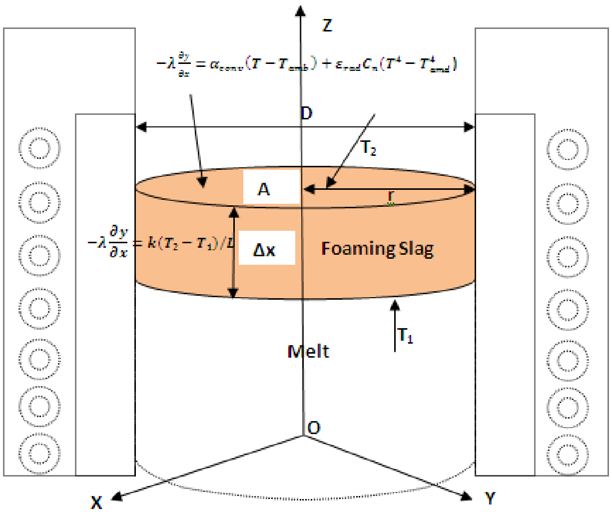

Figure 15: sketch of the induction furnace

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 the 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:

$$-\lambda \frac{\partial y}{\partial x} = \alpha_{conv}(T - T_{amb}) + \varepsilon_{rad} C_n (T^4 - T_{amd}^4) \quad [3]$$

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

In the inductor, the convection heat transfer will be considered because of the exchange between the inductor and the cooling water that circulate through the coils and it given by:

$$-\lambda \frac{\partial y}{\partial x} = \alpha_{conv\ ind-apa}(T - T_{med\ apa}) \quad [4]$$

Where $\alpha_{conv\ ind-apa}$ is the transmissivity between the inductor and cooling water whose medium temperature is $T_{med\ apa}$ [12] In this case the temperature of the molten, the surface temperature on top of the foaming slag has been considered in Figure 15. At the Interface melt and foaming slag the heat transfer is made by conduction:

$$-\lambda \frac{\partial y}{\partial x} = kA(T_2 - T_1)/L \quad [5]$$

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:

$$-\lambda \frac{\partial y}{\partial x} = \alpha_{conv}(T - T_{amb}) + \varepsilon_{rad} C_n \left(T^4 - T_{amd}^4\right) + kA(T_2 - T_1)/L \quad [6]$$

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*:

$$A = \pi \frac{D^2}{4} L = \pi r^2 L \quad [7]$$

$$A = \pi \frac{D^2}{4} L = 3.14 * 0.05^2 L \quad [8]$$

$$A = 0.00785 \text{ L} \quad [9]$$

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 6:

$$-\lambda \frac{\partial y}{\partial x} = 19.10 * (912 - 23) + 0.83 * 5.67.10^{-8}(912^4 - 23_{env}^4) + 0.15 * \pi * 0.0025(1313 - 912)$$

$$-\lambda \frac{\partial y}{\partial x} = 32.62k\text{W}$$

All the results are shown on Table 2 which is the table of variations of parameters. The heat transfer calculation for the basic experiments without any kind of foam or insulation has been considered as such and 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.

$$\lambda \frac{\partial y}{\partial x} = 19.10 * (1305 - 23) + 0.83 * 5.67.10^{-8}(878^4 - 23_{env}^4) + 0$$

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

$-\lambda \frac{\partial y}{\partial x} = 156.8kW$ for pre-heated furnace.

During the flow-rate oxygen gas injection into the molten an exothermic reactions took place and create more heat during the process and increases temperature into the furnace [7][8].

Figure 16 gives the variation of the heat loss compare to the height of the foaming; the figure shows at 0.9cm the optimum height was reached during the process for the pre-heated furnace and 0.88cm for the cold furnace as shown on Table 2. The height increases and the heat loss at the surface decreases due to the thickness of the foam.

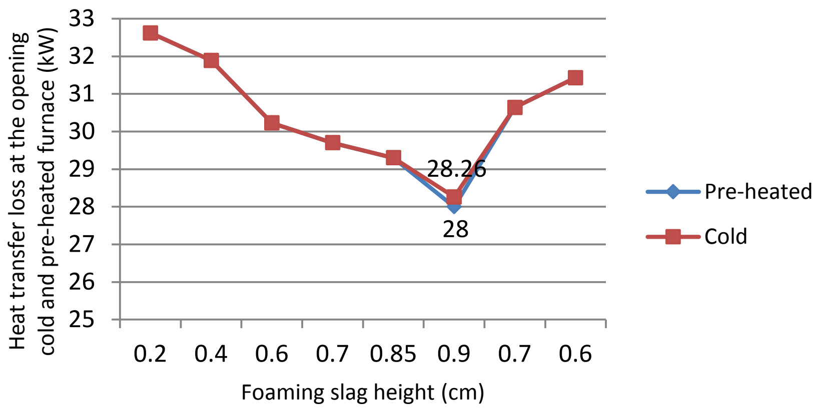

Figure 16: Variation of heat transfer loss with the foaming slag height in a cold and pre-heated furnace

Conclusions

The importance of energy conservation has been showed during the experimental process. This paper has allowed showing the use of foaming slag layer and its importance in the industry and especially the induction furnace. The furnace has been working either cold or pre-heated to melt the cast-iron. The experimental result shows that:

- Foaming slag reduces the electrical energy consumption from 18.41kWh to 13.93kWh – 16.84kWh respectively for pre-heated and cold furnace. The melting time decreases from 50min to 42min – 47min respectively for pre-heated and cold furnace. Foaming slag height increases from 0.2cm to 0.88 – 0.9cm respectively for cold and pre-heated furnace.
- Optimum injection rates of oxygen gas was reached during the all process at 100ml/sec, carbon rates injection was 40gr and a foaming height was obtained at 0.9cm.

- Heat Transfer loss on the surface of the foaming slag height was reduced from 32.92kW to 28 and 28.26 which is 9.2% and 9.3%. The flow-rate of oxygen influenced the heat transfer rate loss and temperature at opening and also been influenced by the foaming slag height.

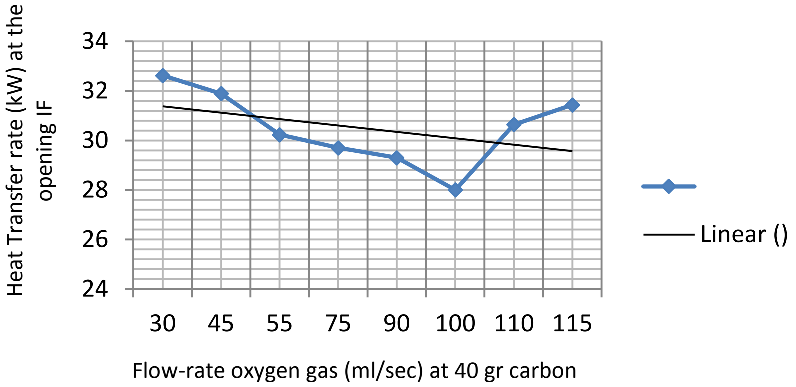

Figure 17: Comparison and variation of heat transfer at the opening due flow-rate of oxygen gas

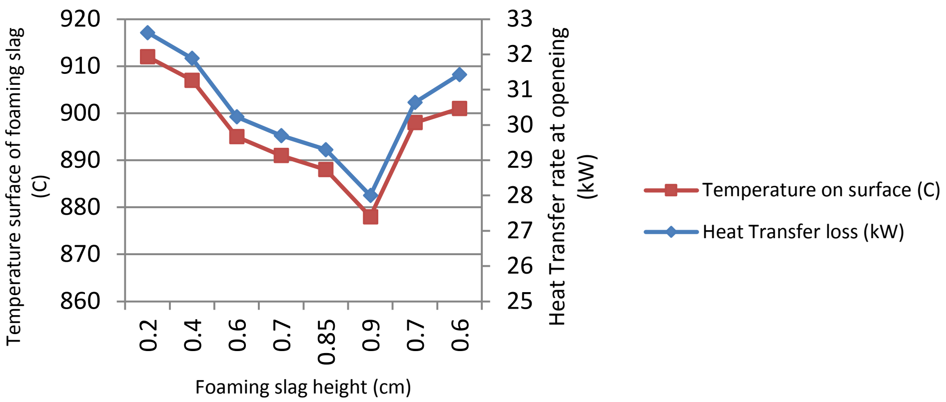

Figure 18: Relationship of temperature and heat transfer rate at the surface with the foaming slag height

- The flow-rate of the oxygen gas injected in the furnace during the process influences the heat transfer loss by bringing it down from 30ml/sec to 100ml/sec.

Acknowledgments

The author would like to gratefully thank the support of the University of Johannesburg (Foundry Laboratory) for this project. Our special thanks go to Dr. Xiaowei Pan from the University of Johannesburg for useful discussions and supervisions to Mr Gilbert Laboratory technician. Thanks go to colleagues MCTS and to my partner for her support and understanding.

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