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# Blast Furnace's Replacement Rate Calculation for Biomasses based on chemical and Thermal Properties

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***Abstract*— *The injection of pulverized materials in blast furnaces is a technique that has been used in iron making for reducing costs with reducing fuels and allows greater operational control. To be injected, the material needs some chemical, physical and thermal characteristics for the process. However, biomass presents as an economical and environmentally viable alternative to replace part of the coal used in this process. One variable analyzed in the reduction process is the replacement rate (RR), which is the amount of coke saved loading on the top of the reactor per quantity of material injected. There are some mathematical models for calculating the replacement rate based on properties, which are results of studies in determined blast furnaces. This work will show some calculations for replacement rate of biomasses using formulas from the literature. Some results show the technical feasibility for the use of biomass in blast furnaces.*

## I. INTRODUCTION

The earliest records of using iron ore for extraction metallic iron and produced weapons and other utensils date from years before Christ and even today it continues to be evolved to obtain iron and consequently steel. According to RICKETTS (2000), liquid iron was accidentally noticed when iron ore placed in a fire, with reducing fuels, and eventually melted. It was found that the ore together with a fuel, when heated, would melt and could be molded to produce weapons, tools and other utensils. The earliest historical documents showing human work with cast iron date from 1500 BC, written by the Egyptians. Only in the middle ages, there were a considerable production, due to the great demand for swords, shields and armor. From the second half of the nineteenth century investments made in steel and blast furnaces, which could produce 180 tons per day, began to appear. From 1940, steel industry starts to grew driven by increased demand for steel and new techniques and studies have being developing until today when some blast furnace can produce around 10,000 tons of hot metal per day.

The Blast Furnace is a counter-current metallurgical reactor where solid raw materials is charged in the top and reduced by rising gases came from the lower part. Blast furnaces with these concepts began to appear in the fourteenth century in France, Belgium and Germany. From then, reactors evolved to gain productivity and decrease the energy required for hot metal produces. Today, most of the hot metal produced in the world comes from blast furnaces. The large increase in productivity of these metallurgical reactors can be attributed to the fact that the continuous developments occurred mainly after 1970.

Blast furnace pulverized materials injection process is a consolidated technique that has been used in steel mills since the third part of the last century and is known worldwide, being applied in more than 500 blast furnaces around the world. In this process, the fuel is injected into the blast furnace by the tuyers, which is located in the lower part of the reactor, providing energy and reducing gases for the process of obtaining hot metal that is the basic raw material for the production of steel. The main advantage of this process is reducing the amount of solid fuel charged in the top of the furnace as coke and charcoal. The most commonly used fuel in the injection process is coal, which is a non-renewable fossil fuel. In addition, coal is responsible for almost all $CO_2$ emitted in the atmosphere by steel production and it is restricted to some countries that does not have quality reserves. Various materials such as plastics, tires and biomasses have already been tested, but, for some authors, it is necessary to have high injection rates (from 150 to 200 kg / t of hot metal) to have the maximum benefits that this technique can provide. Waste has been an alternative route, most often for the cost and environmental issues involved while industries are looking for more sustainable ways of producing and generating carbon credits.

Agribusiness waste can also become viable due to their low cost, and often do not have an adequate route leading to storage and disposal problems. In addition, carbon dioxide captured during photosynthesis during cultivation may compensate for its burning, what make these materials neutral in CO2 emissions. In general, biomasses have a high content of volatile materials; *in natura* have high moisture content and low fixed carbon content. These properties greatly influence the process of injecting pulverized materials in blast furnaces, which suggests a pretreatment of this material prior to use. In the literature, is possible to find several heat treatments for the use of biomass as fuel. These include gasification, pyrolysis, torrefaction and carbonization, these treatments heats biomass in predetermined temperatures, often without oxygen, and thus can have a fixed carbon increase by eliminating excess volatile materials.

An index widely used in the blast furnace operator is the replacement rate (RR) defined as the amount of coke saved (kg / t hot metal) for each kg of coal injected by ton of hot metal. Summarizing, the replacement rate represents the relationship between coke and coal consumption, which is economically important. Some researchers developed some methods to calculate the RR based in the chemicals and thermals properties of the materials, most of them for determinate blast furnace.

The rising cost of raw materials, such as coal, and the high charges of the steel industry make steel production have a high cost. Steel companies should look for alternatives to minimize spending, particularly in the area of energy, alternative raw materials and waste disposal. This requires a strong incentive in the area of research and development to find the best way to increase production and consumption in a sustainable way. In this sense, biomass, especially agribusiness tailings, becomes a viable alternative not only for the lower cost of these materials compared to coal, but also for the possibility of reducing the CO2 emission in the process and eventual carbon credit generation.

This paper aims to review the injection of pulverized materials in blast furnaces and the replacement rate (RR). Here, some methods, found in the literature, to calculate the replacement rate taking into account properties such as calorific value, ashes, carbon content and others will be shown. Thus, the use of these methods to calculate the replacement rate for some biomasses, studied at the Federal University of Ouro Preto and that they can be used in the PCI, will be presented. It will be notice that the replacement rates found are lower than that of commonly used coals, but biomass may be feasible depending on their cost for mills.

## II. REVIEW

### 2.1 Pulverized Coal Injection

Pulverized Coal Injection (PCI), has been very important for the steel sector survival because of the productivity and less cost with reduction raw materials, associated with the possibility of enriching the air with oxygen, producing more with low consumption of coke or charcoal (Oliveira, 2007). However,, the greatest benefit of this technique is the replacement of part of coke or charcoal loaded by the top of the blast furnace, which has a higher cost, with a fuel injected directly through the tuyers.

This technique had its origin documented in the 19$^{th}$ century, in France and later patented in Germany. There has been an evolution over the years, driven mainly by the economic aspect; Figure 1 shows the evolution of the number of blast furnaces that use injection. Over the years, several studies also pointed out that the method had a great influence on the reactor's behavior and productivity (Oliveira, 2007).

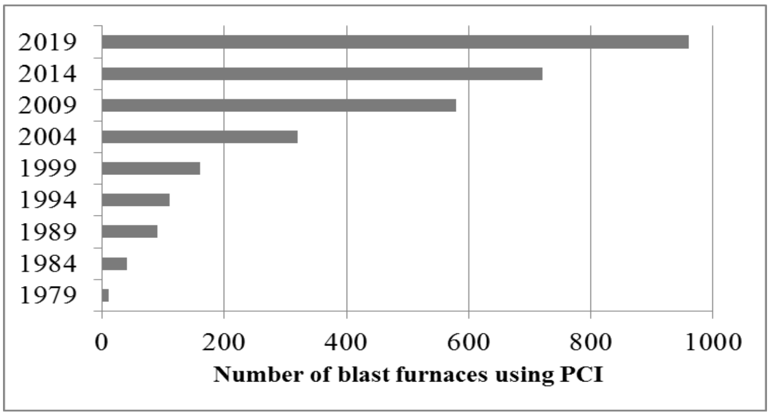


*Fig.1: Evolution of the number of blast furnaces that use injection in the world.*

Today the number of blast furnaces using the injection technique is around 900 and some reach injection rates above 200 kg / hot metal, which can generate significant savings in coke consumption.

The injection of auxiliary fuels is one of the main thermal control variables in blast furnaces and is used due to short response time. Its availability is limited in the lower range by the minimum injection rate and in the upper range by the minimum acceptable flame temperature, that is, there is a minimum quantity to be injected and a maximum quantity so there is no significant decrease in the flame temperature (Mourão, 2011).

For material being injected into the blast furnace it is necessary pass through some processes that will adapt it for injection in the combustion zone. First, grinding is carried out to achieve the ideal granulometry and drying to eliminate moisture. Then the material must be fluidized by mixing it with a gas, air or nitrogen, and transported pneumatically in pipes distributed by the tuyers (Assis, 2014). Figure 2 shows the preparation steps for the injection of pulverized materials in blast furnaces.

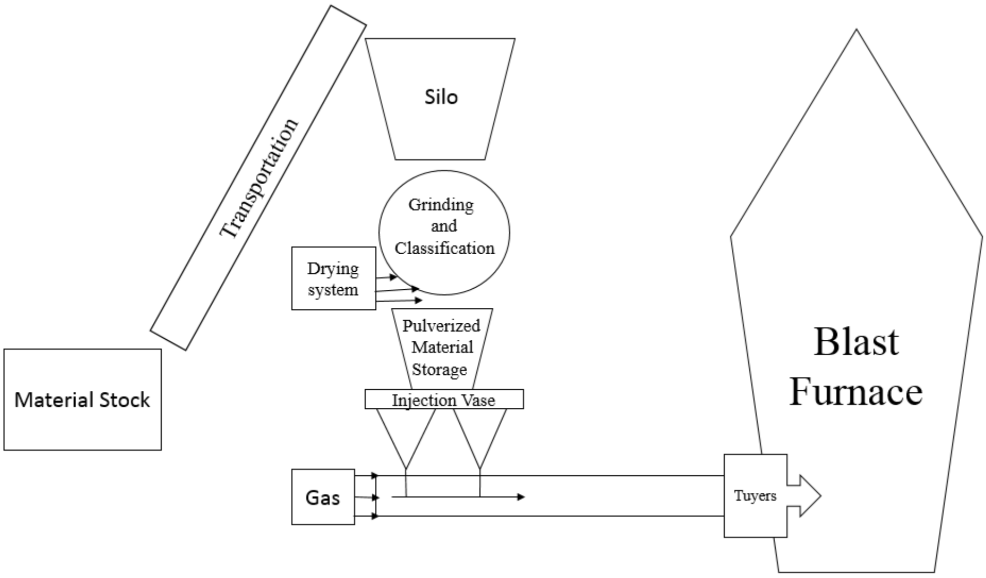


*Fig.2: Steps for preparing materials for injection in blast furnaces (Assis, 2008).*

The material is injected into the blast furnace inside the so-called raceway where it undergoes devolatization and burning, generating energy and gases necessary for the process. These phenomena start from the principle of the behavior of a particle of coal, which take place in three phases. First, the particle is heated, causing the degassing and ignition of the volatiles, which happens through the convective heat exchange with the blown air and radiant with the combustion zone. Second, there is the burning of volatiles, the pyrolysis that releases volatile material with high hydrogen content. Finally, the residue in the particle that is practically carbon, called char, is burned. These steps can occur in sequence or simultaneously depending on factors such as particle size, composition, heating and the amount of oxygen available.

The main benefits of this technique are listed below:

• Cost reduction by replacing reducer (coal and coke) with low-cost materials, in addition to reducing energy consumption;

• Increased productivity, due to the possibility of enriching the air blown with oxygen together with the injected materials;

• It can increase the useful life of the coking batteries due to the reduced demand for coke;

• Helps in the stability of the hot metal quality and in the control of the silicon content;

• Possibility of biomass injection, generating a reduction in the emission of greenhouse gases (GHG).

Aspects related to the quality of the injected material also influence the operating parameters of the blast furnace, not only in thermal control, but in other conditions such as permeability, load distribution and others.

### 2.2 Replacement Rate

The replacement rate is no more than the amount of coke replaced by the amount of material injected. In other words, it can be said that the replacement rate measures the efficiency of the injection process and can be calculated as follows (Fernandes, 2007):

$$\gamma = \frac{CECR - CECA}{TIP} \quad (1)$$

where CECR is the specific consumption of reducer charge in the top without injection (kg / t of hot metal), CECA is the specific consumption of reducer charge in the top with injection (kg / t of hot metal) and TIP is the injection rate (kg/t of hot metal).

In the early 1990s Hunty et al. (1990) proved in his studies that the replacement rate varies with the rank of coal. Brouwer et. al. (1992) proposed the calculation of the corrected replacement rate for the KNHS blast furnace in Hoogovens, a Dutch steel company, which is presented as:

$$RR = \frac{(2x\%Carbon + 2{,}5x\%Hydrogen + 0{,}9x\%ash - \%moisture - 86)}{100} \quad (2)$$

In addition to this study, Brouwer and Troxopeus (1991) also evaluated the operational results of injection into the Ijmuiden blast furnace, of the same company, reaching the following ratio of the replacement rate and the properties of the coal:

$$RR = \frac{(-118{,}9 + 2{,}3\%Carbon + 4{,}5\%Hydrogen + 0{,}97\%Ash)}{100} \quad (3)$$

Other authors, later, developed other formulas to predict the corrected replacement rate for the blast furnaces in which they studied, taking into account other factors such as calorific value, volatile content and others. Table 1 shows some data of different coals and mixtures of coals injected in the blast furnace of a company.

*Table 1. Characterization of coals usually used for blast furnace injection (Campos, 2017)*

| Coal | % ash | % Volatile | %C | %H | Injection Rate (Kg/t of hot metal) | Replacement rate |
|---|---|---|---|---|---|---|
| Monopol EB | 6.60 | 15.30 | 83.30 | 4.20 | 52.00 | 0.94 |
| Achenbach | 7.80 | 23.10 | 81.20 | 4.70 | 78.20 | 0.84 |
| Lohberg | 6.60 | 32.30 | 79.00 | 5.00 | 122.20 | 0.88 |
| Monopol GFI | 11.30 | 31.20 | 72.70 | 4.80 | 79.00 | 0.82 |
| Linhito | 6.40 | 51.30 | 58.30 | 5.30 | 97.30 | 0.47 |
| Carborat | 10.00 | 9.10 | 81.20 | 3.60 | 115.20 | 0.87 |
| 50% Antracito+50% Lohberg | 6.90 | 19.10 | 81.80 | 4.40 | 140.00 | 0.84 |
| Furst Leopold | 6.20 | 33.30 | 77.90 | 5.20 | 135.00 | 0.73 |
| Hew-Acken | 7.50 | 25.20 | 30.60 | 4.70 | 128.00 | 0.79 |
| 50%Hew-Acken +50%Monopol GFI | 9.40 | 27.10 | 77.50 | 4.70 | 141.70 | 0.75 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 70%Hew-Acken+30% Furst Leopold | 7.50 | 26.80 | 80.80 | 4.80 | 109.30 | 0.88 |
| 30% Hew-Acken+70% Monopol CK | 8.60 | 29.60 | 77.00 | 4.90 | 114.30 | 0.84 |

An important factor to be analyzed in the injection of pulverized materials is the combustion rate. This rate is given in percentage and represents the amount of material that burns completely in the combustion zone of the blast furnace. This measurement can be done experimentally in an injection simulator or in computer simulation systems.

Generally, coal injection rates range from 100 to 180kg / ton of hot metal and no changes are required in blast furnace operation. However, for higher rates, some changes in the operation are necessary, for example, the load distribution and the enrichment of the gas with oxygen, among other criteria that will ensure the quality of hot metal produced.

**2.3 Pulverized Biomass Injection**

A variety of research has been published in which the impact of using biomass in blast furnace injection is assessed using approximation models. These models range from models of simulation of nozzles - blast furnace combustion zone, static models in one dimension, models in three dimensions, in addition to numerical models. The laboratory results suggest that the use of biomass in blast furnace injection can increase the degree of reduction of iron ore, when compared to coal (Suopajärvi, 2017).

There are several biomasses that can be used for blast furnace injection, and many have already been studied, such as sawdust, sawmill residues, agribusiness residues, wood, charcoal, roots and others. The carbon content in these biomasses is lower when compared to that of fossil fuels. Oxygen revolves around 40%, which reduces the energy contained in these materials. The fixed carbon is low, while the content of volatile materials is high. The amount of sulfur is also low, which is an advantage for blast furnace production. The moisture content of biomass is considered high and can be a problem, but drying treatments, and even roasting and carbonization, can mitigate this fact (Suopajärvi, 2013).

According to Wei (2017), biomass can be injected into blast furnaces in three ways: pulverized solid, bio-oil or biogas. The most common studies are the use of pulverized solids, mainly fine charcoal, and the injection of 200-225kg / ton of hot metalin large blast furnaces may be viable.

Assis (2014) performed several combustion tests with pure pulverized biomass and mixed with mineral coal. In its results it was possible to notice that many biomasses have a higher combustion rate than mineral coal. This fact was related to the high reactivity of the biomass, as well as the larger specific surface compared to coal, which influences the combustion process. Figure 3 shows the results of the combustion rate of several biomasses compared to mineral coal.

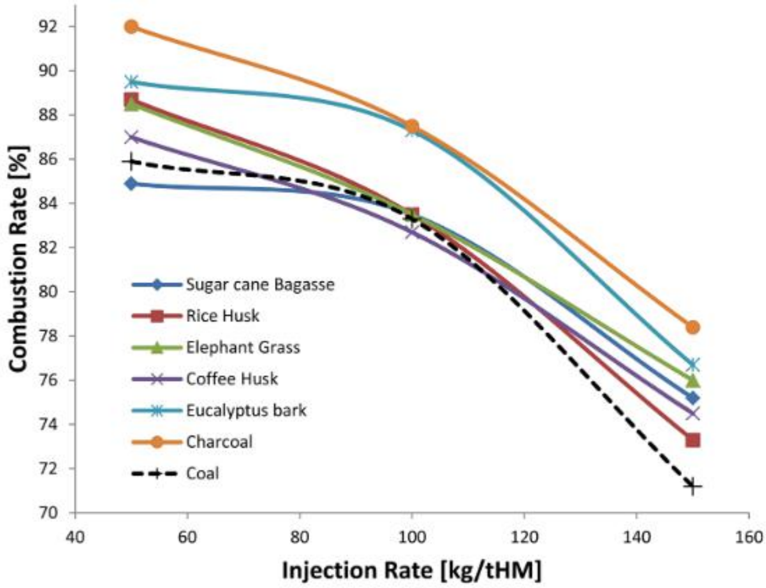


*Fig.3: Injection simulation of some biomass in Federal University of Ouro Preto (Campos, 2018)*

Some physical and chemical properties of biomass are essential to know for a good operation of blast furnaces, which influences the replacement rate and injection rate. Others characteristics that is possible to highlight is: humidity, granulometry, fixed carbon, volatile materials, ash content, sulfur, among others. In addition, some advantages and disadvantages of using biomass in conjunction with other primary fuels, is list below:

- Biomasses have a small amount of sulfur and nitrogen compared tocoal, they reduce the emissions of gases formed by these elements;

- $CO_2$ emissions are also reduced, as biomass can be considered $CO_2$ neutral;

- Ash content of biomass is generally lower;

- Because it has a density generally lower, transport can be facilitated from the silo to the tuyers;

- Biomass has lower calorific value;

- When compared to coal, biomass has a high amount of moisture;

- Biomasses have a lower activation energy than coal;

- The use of biomass makes carbon sequestration possible and can generate credits for the industry.

It is important to highlight that biomasses, even having similar characteristics, can vary according to the type of plant, form of planting, climate, soil, time of harvest, among other variables that interfere in their composition.

## III. METHODOLOGY

In the first part of this research was shown a brief review of the literature to understand the facts related to the injection of pulverized materials and a replacement rate, as well as the possible uses of biomass in the production of hot metal. After, several data were collected, mainly the defined properties of biomass tested in the injection simulator of the Metallurgical Engineering department of the Federal University of Ouro Preto, so that a replacement rate can be considered. For the mixtures contained biomass and coal, a weighted average was calculated.

Finally, some materials were selected and the replacement rates were calculated using equations (2) and (3) showed in the first part. A simple arithmetic mean was obtained by the two equations to obtain a measure of central tendency.

The data regarding the properties, as well as the calculation of the replacement rate and some discussions will be shown below.

## IV. RESULTS AND DISCUSSIONS

### 4.1 Estimate Replacement Rate

The replacement rate can be determined by the amount of coke or fuel that is no longer burdened at the top, as seen above. However, this calculation may not be so simple, so it is necessary to correct it for the operating conditions of each blast furnace.

Several authors have proposed calculations for the corrected replacement rate, each using the parameters of the blast furnace in which they studied. In this work, the replacement rate was calculated using the formulas of Brouwer et. al. (1992) (2) and Brouwer and Toxopeus (1991) (3), previously presented.

As the calculation presented was performed for KNHS blast furnaces, an average of the results obtained using the results of both equations.

The properties of coal, biomasses, as well as some mixture are shown in Table 1.

*Table1. Raw Materials Properties*

| Raw Material | %C | %H | %Ash | %Volatiles | %Moisture |
|---|---|---|---|---|---|
| Coal | 80,24 | 3,80 | 13,45 | 24,13 | 0,20 |
| Moringa Husk | 48,84 | 6,53 | 2,36 | 76,60 | 1,47 |
| 40%Moringa Husk+60%Coal | 67,68 | 4,89 | 9,01 | 45,12 | 0,71 |
| Charcoal | 69,7 | 3,2 | 7,73 | 25,8 | 0,63 |
| Eucalyptus Husk | 50,1 | 5,42 | 2,43 | 68,73 | 5,77 |
| Sugarcane Bagasse | 46,4 | 4,68 | 4,33 | 75,03 | 7,03 |
| Elephant Grass | 40 | 5,36 | 13,5 | 69,95 | 0,1 |
| Rice Rusk | 43,4 | 4,33 | 9,55 | 73,18 | 0,1 |
| Corn Cob | 45,5 | 6,7 | 1,16 | 81,31 | 0,79 |

| | | | | | |
|---|---|---|---|---|---|
| Corn Straw | 44,8 | 6,8 | 1,58 | 81,68 | 0,31 |
| Corn Stem and Leaf | 45,6 | 6,5 | 3,43 | 78,3 | 2,2 |

It is possible to see in the table that the mixtures have average properties, between coal and biomass. By increasing the content of biomass in coal, the carbon content and moisture content increase, while the hydrogen content, volatile materials and ash decrease. Table 2 shows the values obtained by calculating the replacement rate using the two formulas presented and the simple average of the rates obtained.

*Table 2. Replacement Rate Calculated.*

| **Raw Material** | **Replacement Rate (Equation 3)** | **Replacement Rate (Equation 2)** | **Replacement Rate Avarege** |
|---|---|---|---|
| Coal | 0,96 | 0,96 | 0,96 |
| Moringa Husk | 0,25 | 0,27 | 0,26 |
| 40%MoringaHusk+60%Coal | 0,68 | 0,68 | 0,68 |
| Charcoal | 0,63 | 0,67 | 0,65 |
| Eucalyptus Husk | 0,23 | 0,18 | 0,21 |
| Sugarcane Bagasse | 0,13 | 0,08 | 0,11 |
| Elephant Grass | 0,10 | 0,19 | 0,15 |
| Rice Rusk | 0,10 | 0,20 | 0,15 |
| Corn Cob | 0,17 | 0,21 | 0,19 |
| Corn Straw | 0,16 | 0,21 | 0,19 |
| Corn Stem and Leaf | 0,19 | 0,20 | 0,19 |

The replacement rate for biomasses is usually lower than coal, which, analyzing this point, makes its use unfeasible. When analyzing biomasses with lower moisture content an improvement is observed, however the great advantage is the use of these biomasses together with coal. The use of agriculture waste in the mixture with coal can generate an environmental gain, with the reduction of $CO_2$ emissions, and an economic gain, by exchanging the more expensive coal for biomass with lower added value. These factors can compensate for the decrease in the substitution rate when compared to pure coal.

It is possible to notice in the graph of Figure 4 that when the carbon content decrease, the replacement rate decreases. As in both formulas used the carbon content has greater value, a fall in the replacement rate is expected when adding biomass, as it has a lower carbon content, consequently the carbon content of the mixture will be lower. These raw materials, biomasses, can pass away from a pretreatment for take out the moisture and volatiles content, what can be increase the calorific value and consequently the replacement rate.

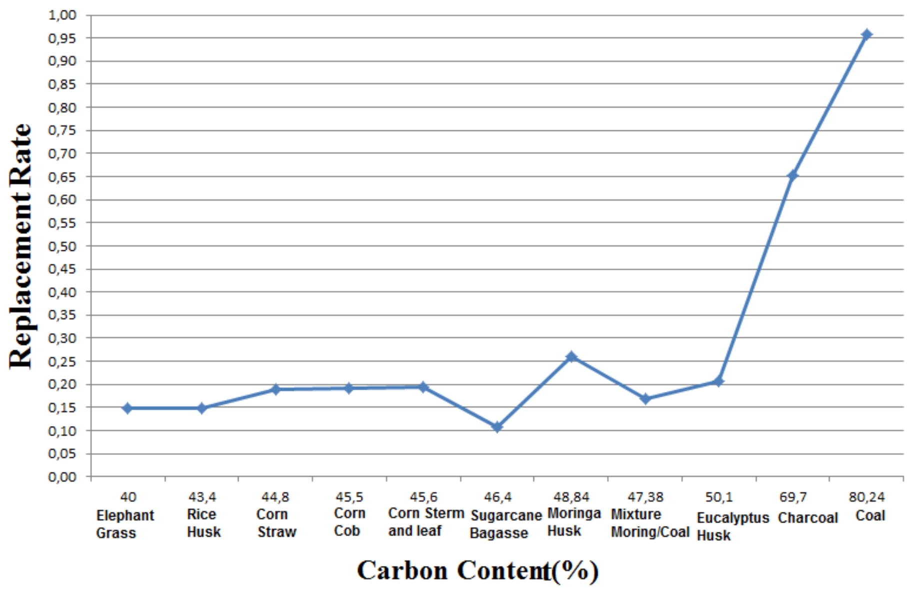


*Fig.4: Replacement rate x carbon content.*

According to Fernandes (2007), the replacement rate does not depend on the injection rate for the same operational condition, but changes always occur when the injection rate is increased. This is because when the injection rate is increased; the combustion efficiency is reduced, thus reducing the metal reduction efficiency in the preparation zone.

Emphasizing, these formulas were proposed for the blast furnaces studied by the authors and may not correspond to the replacement rate for other blast furnaces with different operating procedures. In addition, various material properties can influence the replacement rate, that is, a set of factors and / or properties can act simultaneously affecting the replacement rate. One very important point is related to CO content of the biomass volatiles. As it is known this CO can increase the replacement ratio. This factor was not considered in our calculations, due to the fact that the equations above do not consider this variable.

The calculation allowed us to have an idea of the influence of the using biomasses in the mixture with coal in the replacement rate, which is an important indicator for the productivity of the blast furnace.

## V. CONCLUSION

It is possible to conclude that the replacement rate is an important variable, not only in the operation of the blast furnace, but in the choice of raw materials to be used in the process. It is well known that the replacement rate of biomasses is much lower than that of commonly used coal, but if the mixtures are analyzed, the substitution rates will be a little higher, which would make their use feasible. Finally, it is necessary to comment that in order to use the biomasses in the injection process it is necessary a pre-treatment of grinding and heating so that they increase the content fixed carbon what is important to the process. The use of biomass can bring environmental and economic gains since there is a decrease in the burning of fossil fuels and the use of a material with low added value.

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