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THERMAL AND ECONOMIC ANALYSIS OF LIME PRODUCTION

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ABSTRACT

The ore beneficiation process uses little technology, but mining companies have high economic performance. As an energy source, firewood plays a fundamental role due to its simple storage, low cost, great availability of forests, and lack of processing. Thus, the present work aims to analyze the consumption of firewood as fuel and possible improvements in the process for the production of lime in terms of harnessing raw materials and costs. Calcium oxide is obtained from the thermal decomposition of calcium and magnesium carbonates obtained from dolomitic deposits of limestone ($CaCO_3$: $CaMgCO_3$). After CaO extraction, it is subjected to a calcination process, removing carbon dioxide (CO_2) in ovens that work at temperatures between 900 and 1200 °C. The source of energy applied to the calcination furnaces in the analyzed area is wood. The wood has a calorific value between 2,250 and 2,700 Kcal/Kg, but the moisture content responsible for the thermal variation must be considered. The firewood burning process was carried out in a ravine type oven where the temperature at which operators are exposed to heat was evaluated. The results indicated that the cooking time dropped by 20% as the amount of wood is fed into the oven. This increase represents a significant gain in lime production, thus leading to a higher profit for the company.

Keywords: *Calcination, Limestone, Firewood, Dolomite, Biomass*.

1. INTRODUCTION

Among the most different products derived from mineral sources, lime, also called quicklime, virgin lime, or calcium oxide (CaO), is considered the most important in the market in terms of applicability and volume consumed (Dietzen *et al.,* 2018; De Souza and Bragança, 2017; Barbosa *et al.,* 2016; Nouri and Ebrahim, 2016; Van Straaten, 2006; Wallmann and Aloisi, 2012; West and McBride, 2005). Calcium oxide is obtained from the thermal decomposition of calcium and magnesium carbonates obtained from dolomitic limestone deposits ($CaCO_3$: $CaMgCO_3$) (Palma *et al.,* 2018; Khadra *et al.,* 2017; Chen *et al.,* 2016; Gomes *et al.,* 2016; Koenig and Liu, 2002). By definition, dolomitic limestone is a mineral that has limestone with the highest concentration of calcium and magnesium oxide (Erans *et al.,* 2019). After CaO extraction, it undergoes a calcination process, removing carbon dioxide (CO_2) in furnaces that work at temperatures between 900 and 1200 °C (Yuan *et al.,* 2018; Asano *et al.,* 2014; Stanmore and Gilot, 2005; Klunk *et al.,* 2020a; 2020b). In the current economic scenario, the rising price of energy resources has led many companies to seek efficient tools for their processes (Erans *et al.,* 2019). Plant biomass is widely used for energy production (Cataluña *et al.,* 2018; Caetano and Silva, 2017; Cataluña *et al.,* 2017; Nascimento *et al.,* 2017; Rodrigues *et al.,* 2016; Safari and Zeynizadeh, 2015; Ishmayana *et al.,* 2015).

The synthesis of nanopore materials such as molecular sieves (zeolites) has been gaining worldwide importance to increase the efficiency in obtaining high value-added products (Sadjadi and Reza Naimi-Jamal, 2019a, 2019b; Moreira *et al.,* 2018; Moradi *et al.,* 2014). In developed countries, advanced technologies allow a higher yield in CaO (Ferreiro *et al.,* 2019; Dai *et al.,* 2016). The energy source applied to calcination furnaces in the analyzed area is wood (Glasenapp *et al.,* 2019; Aguilar *et al.,* 2016; Arabatzis and Malesios, 2011). Wood has a calorific value between 2.250 to 2.700 Kcal/Kg, but the moisture content that is responsible for a thermal variation must be considered (Aguilar *et al.,* 2016; Song *et al.,* 2012; Couture *et al.,* 2012). As a result, the burning process can cause high raw material (wood) expenditures, excessive heat emitted by fire, and environmental pollution (Pereira *et al.,* 2018; Reguieg *et al.,* 2017). The use of wood for energy purposes has aroused the interest of the industrial sector because it is a renewable resource and low production cost (Caetano *et al.,* 2015a; 2015b; 2015c). The main species cultivated in Brazil to obtain energy belong to the genus Eucalyptus sp (Pimenta *et al.,* 2018; Flores *et al.,* 2016; Barbosa *et al.,* 2016). Knowing the importance of wood, it is necessary to know its characteristics, having as it fundamental principle its origin (Filomeno *et al.,* 2016; De Almeida *et al.,* 2017; Da Silva *et al.,* 2016; Mossi *et al.,* 2010).

Oven operators are exposed to high temperatures daily on their workday. Under prolonged conditions, this can lead to damage to health and loss of work performance, thus increasing the likelihood of accidents. For this reason, the monitoring of the temperature that the operators are exposed to is essential so that it is adequate for the execution of the activities. The company considers working conditions essential to increase production capacity and gain production. A field study verified the necessity of the company, located in the city of Caçapava do Sul, to improve the fuel efficiency (wood) used in the lime kiln. The amount of dolomitic limestone, firewood for energy generation, and lime produced seek to propose improvements in the process to obtain the final product (CaO), offering a higher yield. This paper aims to analyze the fuel consumption (wood), the raw material (limestone) for lime production in a calcining furnace in terms of raw material utilization and costs, as well as a temperature monitoring at which the operator was exposed. Quantitative analyzes of radiated heat were performed using a thermal stress meter (Tgd 400 Instrutherm). Thus, the results were compared with the tolerance limits established by Regulatory Standard NR 15.

The general parameters used by this study are: i) to analyze the consumption of raw material; ii) carry out an economic assessment of the costs involved in the process; iii) propose changes in the process to optimize production costs and yield and iv) analyze the occupational risks that employees are exposed to. Lime is a fundamental product of the economic activity of most countries and is used worldwide in the most varied sectors (construction, agriculture, food industry, among others) (Moradi *et al.,* 2014; Dai *et al.,* 2016). In this context, obtaining calcium oxide is expensive, and the main challenge for companies is to reduce the consumption of the fuel used (wood), thus optimizing production (Aguilar *et al.,* 2016; Arabatzis and Malesios, 2011).

The virgin lime manufacturing process takes into account the use of different types of fuels (Yuan *et al.,* 2018; Asano *et al.,* 2014). Fuel sources have an influence on product quality and manufacturing costs, so the choice of fuel must be carefully delineated. In quantitative terms, a calcining furnace uses on average 1,800 to 2,500 tonnes of firewood per month. The process of obtaining calcium oxide implies the emission of large amounts of carbon dioxide (1 ton of lime generates 1.2 tons of CO_2), mainly responsible for climate change (Sadjadi, 2019; Sadi-Nezhad, 2019; De Aguiar *et al.,* 2017; Soares *et al.,* 2016). These CO_2 emissions can be predicted by geochemical modeling (Bigarani *et al.,* 2016). Another important factor to take into account is changes in the landscape because of limestone mining and detachment of particulate matter (Lawer *et al.,* 2019; McPhail, 2009; Brunnschweiler and Bulte, 2008).

Lime companies increasingly need to ensure the quality of the end product, improve production processes, leading to sustainability and reduce operating costs to stay in such a competitive market (Pimenta *et al.,* 2018; Flores *et al.,* 2016). In this context, fuels represent today one of the largest costs in lime companies that have ravine ovens (Rodrigues, 2015). Concern about the health and safety of workers exposed to lime production and processing reflected positively on the industrial sector. In this regard, labor laws ensure that workers must be in a protected environment by adopting appropriate measures for their comfort and well-being.

2. MATERIALS AND METHODS

Provide sufficient details to permit repetition of the experimental work. The technical description of methods should be given when such methods are new.

2.1. Location and characterization of the study area

The studies of this work were performed in a company from Caçapava do Sul city, located in the Rio Grande do Sul/Brazil. Its territory is located in the so-called Campaign Zone, with large deposits of copper, lime and kaolin ores. In its topographic configuration, we can see grand fields and mountains, with dark lands and silica-rich soil (Horn *et al.,* 2017). Its economy is fundamentally supported by the agriculture, livestock, and mining sectors, where local limestone production represents more than 80% of what is produced in the Rio Grande do Sul. The extraction of minerals in the company, basically dolomitic limestone, is aimed at the production of mortar and lime, used in areas such as construction and agriculture to correct soil acidity, with the aid of a forno de barranco, named after being supported by a slope, with dimensions of four to five meters in height and conical trunk shape. The fuel (wood) can be added directly to the load or burned inside furnaces. In these configurations, the consumption of wood for energy purposes is high (Guimarães, 1998).

The ravine type analyzed in this work uses black wattle firewood (Acacia mearnsii) and eucalyptus (eucalyptus sp) as fuel. The calorific value in the dry state is 4,800.54 Kcal/kg, and in the wet state 2,500.61 Kcal/kg (Caetano *et al.,* 2018). It was verified the inexistence of moisture control in the wood leading to higher or lower levels of carbon dioxide emissions. This impairs the temperature control and, consequently, the calcination process. Without this control, the consequence is high costs, high raw material consumption, and loss of process efficiency.

The company has 258 employees, 14 of which directly involved in the lime calcination process. In this place, there are 4 ravine ovens with a capacity of 80 tons/day of dolomitic limestone with a production of 47 tons of lime. For each ton of lime produced, 1.3 m^3 of firewood is required. For the calcination process, temperatures in the range of 900 to 1,200 °C must be reached. The company operates 24 hours a day, seven days a week, based on foreign market demands. Refueling is done every 2.4 hours. As the dolomitic limestone goes down inside the furnace, the heat exchange by heating of the hot gases occurs until reaching a necessary temperature level for the combustion, initiating the calcination process. In the calcination process, the mineral (dolomitic limestone) is deposited in the oven where it remains for around 24 hours, cooking at initial temperatures of 300 to 500 °C until reaching higher temperature levels (900 °C). Product cooling is given in the lower chamber. The material is removed from the bottom of the cooling chamber, where it is waiting to be loaded for the next production step. The calcination process is completed by cooling and transported in wagons to a deposit, where it will proceed to the milling process. The current consumption of firewood is 1,936.06 m^3/month, being black wattle 922 m^3/month and eucalyptus 1,014.91 m^3/month. The cost of black wattle is R$52.00 per $m^{3,}$ and eucalyptus of R$53.00 per m^3. The energy was calculated by active power during the operating time.

Proper calcination will depend on dolomitic limestone, furnace operating conditions, and the quality of the raw material. However, the lack of knowledge of the relationship of these factors in the quality and productivity of virgin lime makes the operation of the ovens depend exclusively on the operator's experience. Some of these factors that may interfere with calcination, and whose careful handling of the furnaces allow its control, are the retraction of dolomitic limestone, recharge, and steam effect (Guimarães, 1998).

2.2. Firewood Consumption

The fuel consumption of the company's ovens was analyzed based on the wood used for each batch. The study performed a continuous follow-up of 10 batches (daily use). Whereas each batch has 2 tons of dolomitic limestone and is made around 10 daily. Characteristics of the calcination process, taking into account the company's theoretical data:
(i) kiln capacity: 1.7 m^3 firewood per tonne of virgin lime;
(ii) Consumption of firewood per batch: 10.4 m^3;
(iii) Firewood consumption/tonne of lime: 1.3 m^3 for 1 tonne of lime;
(iv) Time of the batch: 24 hours.

According to Silva (2009), ravine ovens have high fuel consumption (on average, 220 kg of fuel oil or 1.7 m^3 of firewood per ton of virgin lime). Firewood consumption in this process is 13.6 m^3 per batch, an increase of 30% when compared to the theoretical data of the companies. This discrepancy lies in the fact that there is no control of wood moisture parameters and stoichiometric weighing of the raw material.

The conversion rate in carbonate calcination is adjusted by providing heat for decomposition, taking into account particles larger than 40 mm. In this way, calcination is governed by diffusion law in controlled reactions: the decomposition time is proportional to the square of the particle diameter, so the conversion rate is inversely proportional to the particle diameter. According to Erans *et al.* (2019), the evaluation of calcination kinetics is relatively complex due to factors such as:

i) CO_2 concentration (slows the reaction);
ii) particle size (limiting factor in energy transfer);
iii) catalytic inhibition (presence of impurities).

The carbonate calcination rate becomes high when the temperature is reached, where the partial equilibrium pressure of CO_2 or water becomes equal to the total reactor pressure. This temperature is called the decomposition or calcination temperature. The reaction rates and reactivity of virgin lime are directly linked to the temperature at which lime was calcined. The higher the process temperature, the less the calcination time, resulting in lower production costs.

2.3. Cost analysis involved

It was verified in the analysis, and it was verified the fixed costs (firewood in the energy generation) to minimize the losses in the calcination process. This parameter is closely linked to the company's profit. Once we can reduce the quantities of this fuel, we will have a significant profit from the company.

3. RESULTS AND DISCUSSION

3.1. Firewood Consumption

According to the company's operational survey, there are 10 batches per day, with 2 tons of dolomitic limestone each, totaling 8 tons per batch of raw material. Considering that the process uses 1.3 m^3 of firewood for each ton of lime, at the end of the process, we have a total volume of 1,936.54 m^3 of burnt wood for power generation.

According to Lins (2007), 1.7 tons of limestone is required for each ton of virgin lime. Therefore, increasing the amount of firewood reduces cooking time by 20%. This way, it can increase the amount of matter per batch. The higher the heat flux transmitted to dolomitic limestone, the shorter the cooking time. In table 1, find the actual scenario of the company.

In an ideal operating condition, if the company used the full capacity of the oven (1.7 m^3 of firewood), the calcination time would decrease by 2 hours because the higher the furnace temperature, the higher the production of lime oxide. Table 2 shows these new values.

Using the ideal scenario, the production would gain 93 tons of lime produced per month, in a year would increase by 1,116 tons. If the company had greater control of the data, other types of process optimization could occur. According to Viana *et al.* (2012), the total loss basically consists of:

i) heat transfer losses - the heat absorbed by the oven walls, ceiling, and the threshold is released by radiation and convection.
ii) leakage losses in the furnace structure - which usually operate at higher than atmospheric pressure, and heat losses through the door when it is opened.
iii) chimney losses - are the losses associated with the dry gases formed in the combustion and the losses near the vapor present in the chimney.

3.2. Cost analysis

The company buys firewood from six suppliers in the region, with a black wattle price of R$ 52.00 and eucalyptus R$53.00/$m^{3,}$ respectively. The current consumption of firewood is 1,936 m^3/month, with acacia 922 m^3/month and eucalyptus 1,014 m^3/month, totaling a monthly expense of R$101,686.00. In table 3, find the fixed costs related to the oven.

Corrective maintenance is carried out, but usually due to the belts and trolleys involved in the furnace, but in the furnace itself, maintenance is performed every six years, with the replacement of some furnace components (refractory and revocations), having a hand cost of work and raw material of R$10,000.00.

Performing a profitable cost analysis, according to market research, we have according to table 4. Moisture control of firewood is recommended in order to reduce calcination time, reducing waste and waste, and optimizing the process as a whole.

3.3. Worker welfare analysis directly involved in the process

Temperature measurements were performed near the oven and where workers perform their duties. Climatic factors of the region contribute to the thermal overload of the operators, where they intensify in the summer periods. Another factor contributing to thermal overload is the opening of the furnace for cooling. In this process, heat conduction intensifies, leaving the workplace with temperatures higher than those determined by law. The results of temperature measurements are shown in Table

5. According to the results, temperature measurements in the various oven zones tell us that at the inlet of the oven, there is a warm environment ranging from 38 to 40 °C. This temperature directly affects the operator who is exposed to this location during his workday. This is due to the internal temperature of the oven (1000 °C on average), as thermal conduction to the outside occurs when measured at the top outside of the oven (300 °C on average).

According to NR 15, operator activity under these conditions is arduous and requires 15-minute breaks for every 45 minutes worked. Even if the operator is using individual safety equipment, exposure to high temperatures can affect their biological system, causing some health damage.

4. CONCLUSIONS

With the results obtained in this work, it was possible to characterize the fuel (wood) of the calcination furnace as well as the costs involved in the process. In this analysis, it is found that increasing the fuel capacity leads to gain in virgin lime production. The amount of wood used to burn dolomitic limestone has a significant impact on the company's final cost. Wood moisture measurements are a key parameter to increase the yield of calcination reactions. Regarding the exposure of workers to high temperatures, we can conclude that they are in an unhealthy work situation. These operators are above tolerance limits when compared to NR-15. The results indicate that the work environment in the company's furnace provides an exposure situation above the recommended by legislation. According to the company's board, these results were of fundamental importance, leading to corrective and preventive actions towards its operators. Thus we can conclude that the real and significant gain of the company is closely linked to the optimal working conditions of its workers and investments in new technologies, thus being competitive with the market and its competitors.

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Table 1. *Actual business operating condition*

Batch	Quantity of raw material	Time	Firewood used daily	Daily production
10 a day	80 tons a day	Every 2.5 hours the ovens are supplied, remaining for 24 hours	61.2 m^3	47 tons of lime

Table 2. *Ideal scenario.*

Batch	Quantity of raw material	Time	Firewood used daily	Daily production
11 a day	88 tons a day	Every 2 hours the ovens are supplied, remaining for 24 hours	58 m^3	47 tons of lime

Table 3. *Fixed Costs for the company's oven*

Firewood Acquisition	Maintenance	Employees	Total
R$ 1,220.232/year	R$ 10,000.00/year	R$ 543,365.05/year	R$ 1,773,597.05/year

Table 4. *Production versus gain*

Final product price of lime 0.02 tons	Values according to monthly production of 1.457 tons	Values according to monthly production of 1.550 tons	Earnings
R$ 12.00	R$ 874,200.00	R$ 930,000.00	R$ 55,800.00

Table 5. *Temperature measurements taken within 5 days*

Days	Initial temperature near oven inlet (ºC)	Oven top outside temperature (ºC)	Oven temperature (ºC)	Oven physical space temperature (ºC)
1	40	300	1030	9
2	39	240	1005	10
3	38	290	1000	9
4	40	285	1030	10
5	40	300	1000	12