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Efficiency comparison of different techniques for drying coal

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Abstract— **The drying process is a necessary unit operation in many industrial processes such as food, construction, chemistry, energy, cosmetics, and so on., the properties of the material to be processed and the operating conditions are important factors for the selection of equipment and use of resources. This article presents a comparison in terms of energy efficiency of different drying technologies, operating time and temperature, and grain size.**

To take advantage of the energy contained in the biomass through processes of gasification and pyrolysis it is necessary to perform a pre-drying process as a pretreatment in order to increase the performance of the processes. The microwave assisted processes have been used in the industry because they allow to reduce the time of operation, to obtain greater yields to be selective and in some opportunities to provide economic savings.

This study presents a comparison of drying in a batch microwave oven and a convection oven with hot air. For testing the microwave oven, which operates at a frequency of 2.45GHz and 1kW of power, three pulses of microwave radiation and three height levels of the samples were evaluated. The energy consumption, sample temperature and weight were measured during the process. For tests carried out in the convection oven and conduction, three similar temperatures to those achieved in the microwave oven and the same height levels of the samples used were conditioned. From tests it was found that the drying process in the microwave oven remove greater proportion of the moisture contained by the samples; similarly, it was found that the energy efficiency of the energy supplied in the microwave oven is 0.1870kg/kWh, higher than achieved in the convection oven where energy efficiency 0.0007Kg/kWh was reached. To reduce experimental noise, relative humidity and temperature are monitored and strict for each defined protocol and runs were performed in duplicate.

Keywords— dry; oven; coal; conduction; convective.

I. Introduction

Microwave power applications have been extensively studied in the last decades in a broad spectrum, where the results inform a successful improvement in the results of the experiments with respect to the conventional methods. Most studies carried out with microwave power mainly focused on its heating capacity due to the direct transfer to the material allowing a rapid and volumetric heating of the sample, while avoid complications such as wide temperature gradients between the surface and interior as presented in conventional methods [1].

The volumetric heating of the samples is accompanied by the ability of the microwave power to penetrate the interior of the sample and induce deeper heating into the sample. The above is due the microwave energy through the electric and magnetic fields influences samples, polar and ionic molecules present try to align with the oscillating electric field, generating frictional heat because the ionic gradients, that constantly change and particles collide [2].

The ability of materials to respond to electromagnetic fields of the order of microwaves depends on their dielectric constant; Which makes effective the selective heating of heterogeneous samples with components that have different values of this physical property, causing an increase in the heating rate [3,4].

Some of the microwave industrial applications are: drying [5], pasteurization, cooking, processes that generate physical changes in materials, ceramic sintering, curing, catalysis of reactions, regeneration of materials, etc.

In the decade of the 80's it was already said that the thermal drying of coal generated energy loss and increased pollution [6], besides not being an economic process, due to the nature of heat transfer by conduction that would simultaneously heat coal and water [7]. Heating is done from the outer surface towards the inside, which creates a resistance to heat flow due to the low thermal conductivity which limits the drying rate and let a large amount of moisture inside the coal.

In other thermal drying applications, a hot air stream is added in order to accelerate drying by convective transfer, but in the particular case of coal it is not possible due to the risks it would generate from ignition and emission of dust. Filtration, vacuum drying, thermal drying and centrifugation are techniques used for the dehumidification of carbon. However, it is important to know that only the free water in the coal is easily to remove by these techniques.

Studies have shown that treatment at high microwave power (8kW) with short exposure times (0.1s) in a unimodal microwave cavity with 300gr of coal samples showed a significant increase in the breakage velocity of sulfur bonds contained in vitrinite. In generate cracks and fissures that help its later milling [8].

In a first study to determine the influential variables in the coal drying process, the particle size, the type of coal, the operating time and the microwave energy supplied in a conventional microwave oven and in a muffle were evaluated. This work showed that it was possible to remove 50% of the moisture contained in the 10% time required by the conventional technique studied [9].

In order to compare the performance of the drying of coal using different techniques, experiments were carried out in convective tunnel oven, in muffle, in batch microwave oven and in tunnel continuous microwave oven. The results obtained and analysis are presented in this article.

II. METHOD AND EXPERIMENTS

For the development of this work different equipment was used to carry out heating processes and as a consequence drying of wet materials. 0.15 kg of coal arranged in an aluminum tray were the samples selected for the experimental tests in each of the equipments. Each of them will be described below and the procedure carried out for the experimental runs.

A. *Muffle Furnace at 333K*

This equipment is an oven of $0.3{\times}0.3{\times}0.40m^3$ dimensions in (height×width×depth) with a front door that open by lateral movement. It has a system that measures temperature by a thermocouple and a control it in the desired, which was fixed in 333K for the essays.

B. *Hot air tunnel oven*

In order to perform the tests in the tunnel type convective oven, the conditions settled were: air velocity at 2m/s and the temperature at 60°C. In the development of the experiment records of the relative humidity inside the tunnel and the ambient temperature were taken; It was found that on average the relative humidity is maintained between 8 and 10%, and the ambient temperature between 22 and 25°C. This type of drying with air movement is not attractive at industrial level because it can generate drag of coal dust and some time is considered slow.

C. *Batch Microwave oven*

To perform these tests, a conventional microwave of 1kW of power was used. We chose for the radiation rate of 8 seconds of microwave radiation application for every 22 seconds of cycle, corresponding to the 30 power level.

D. *Tunnel Microwave oven*

Due to the equipment used is of a greater scale to the previous ones, for the development of these experiments the condition of the maximum power able to be delivered by the equipment (10kW) and the maximum height of the bed (50mm) was selected. As a basis of calculation, (1) was used to determine the radiation time ($t_{radiation}$) relating the belt speed ($V_{conveyor\ belt}$) and the distance of the drying chamber ($d_{drying\ Chamber}$) that is1.6m. 5 and 10 minutes were selected to evaluate the process residence time.

$$t_{radiation} = \frac{d_{drying\ Chamber}}{V_{conveyor\ belt}} \tag{1}$$

In each of the essays, the moisture content removed, the total moisture and the energy yield of the process were evaluated.

III. RESULTS

The proximate analysis was the characterization carried out on the processed coals, following the internationally accepted technical norms whose results are presented in Table I.

TABLE I. PROXIMATE ANALYSIS OF COAL.

Analysis	Result
Total Moisture (%) - ASTM D 3302	19.64
Fixed Carbon (%daf) - ASTM D 3172	43.81
Heat Value (Cal/g) - ASTM D 5865	5474
Volatile matter (%df) - ASTM D 3175	48.89
Ash Content (%df) - ASTM D 3174	6.47
Sulfur Content (%daf) - ASTM D 4239	1.12

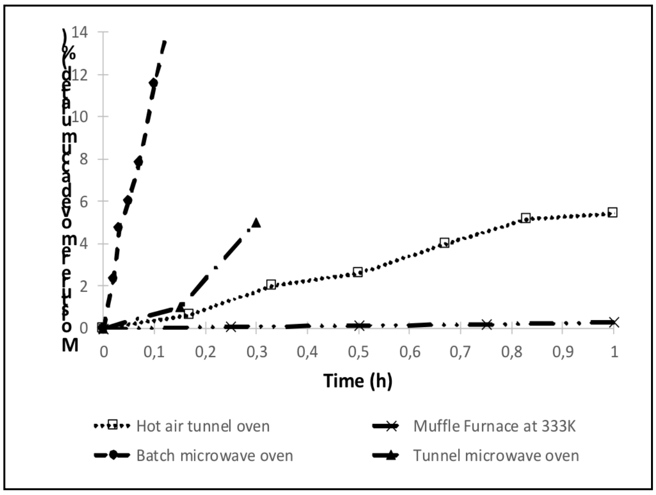
In the muffle drying at 333K, it was found that to remove 15% of the moisture present in the coal, 7 hours are required, evidencing this technique as the slowest of all evaluated, supplying 4.62kWh of energy.

In tunnel convective drying, six hours were required to remove 18% of the moisture present in the coal supplying 38kWh of energy.

In microwave batch drying it was found that operating times greater than 0.13 hours induce the ignition of the coal.

To compute the different drying techniques discussed above, a graph of the percentage of moisture removed accumulated through the drying time was constructed (Figure 1). It was found that the batch microwave oven was able to remove 15% of the moisture contained in the carbon in 8 minutes for the selected condition (radiation ratio of 8/22), in the tunnel continuous microwave oven a removal was achieved of 5% in 5 minutes for the highest operating condition (10kW) and the maximum bed height (50mm). The maximum removal achieved in the convective oven drying was 18% in 6 hours; In the muffle it was possible to remove 15% of humidity in 7 hours. This fact demonstrates that microwave drying is a technique that allows to accelerate the process of drying of coal and achieve greater removal of moisture in a shorter time with respect to conventional technologies.

Figure. 1. Comparison of coal drying time using different techniques.



From Figure 1, it can be deduced that, for the drying of coals with microwave technology, 10% of the moisture in the coal can be removed in about 0.1 hours. Meanwhile, conventional technologies are 30 times slower, requiring more than 3 hours of drying to achieve the same 10% moisture removal.

Because the processed mass can not be maintained for the tunnel microwave drying technique, the overall yield was calculated by (2), which relates the amount of moisture that can be removed by the system with respect to the energy delivered to the process. The other techniques where the processes are batch then the yield was calculated by (3).

$$R = \frac{\dot{m}_v t_{op}}{E} \qquad (2)$$

$$R = \frac{m_v}{E} \qquad (3)$$

Where,

R Is the yield of the process in each of the techniques used (kg/kWh)

$\dot{m}_v$ Is the mass of water withdrawn in the process (kg/h)

E Is the energy consumed in the process (kWh)

t_{op} Is the operating time (h)

Table II presents the results obtained from the yields for each of the drying techniques studied.

TABLE II. GLOBAL PERFORMANCE OF COAL DRYING TECHNIQUES.

Drying Technique	Yield (kg/kWh)
Batch microwave drying (radiation rate 8/22 s/s)	0.1870
Tunnel Microwave drying (Power 10kW), residence time = 10 minutes	0.0670
Tunnel Microwave drying (Power 10kW), residence time = 5 minutes	0.0410
Hot air tunnel oven drying at 333K	0.0007
Muffle Furnance at 333K.	0.0050

From Table II, it can be seen that the microwave drying gives a better use of the energy delivered to the system, allowing the drying process to be carried out in short times with a lower energy demand.

Even though the higher yields are obtained in microwave drying, it is remarkable that it is directly proportional to the residence time in both the continuous process and the batch process. To know the effect of the bed height on the belt in tunnel microwave oven, essays with 20, 35 and 50mm of coal bed height were carried out and analyzed.

Based on the experimental results in the continuous microwave tunnel type, where the largest removals of moisture in the coal are given at the lowest heights, energy yields were evaluated and compared as a function of height.

It was found that greater moisture removals are obtained with the lowest bed heights for the residence times studied (Figure 2). With the increase of the time of residence of the coal to the microwave radiation, a water removal near 12% is reached, operating the equipment with a bed height of 20mm.

Fig 2. Percentage of moisture removed as a function of operating conditions (residence time and bed height).

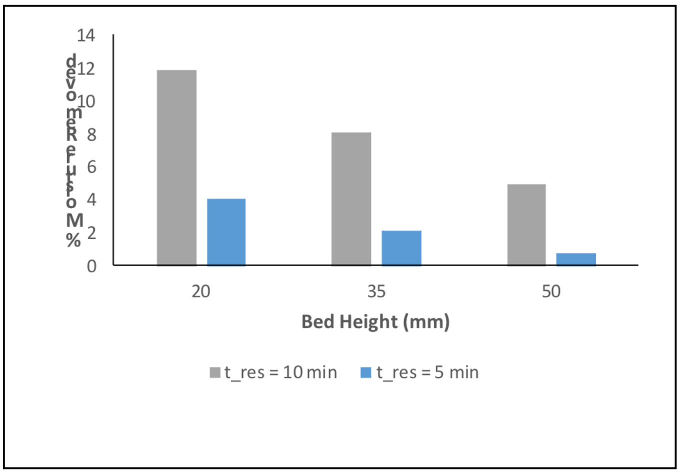
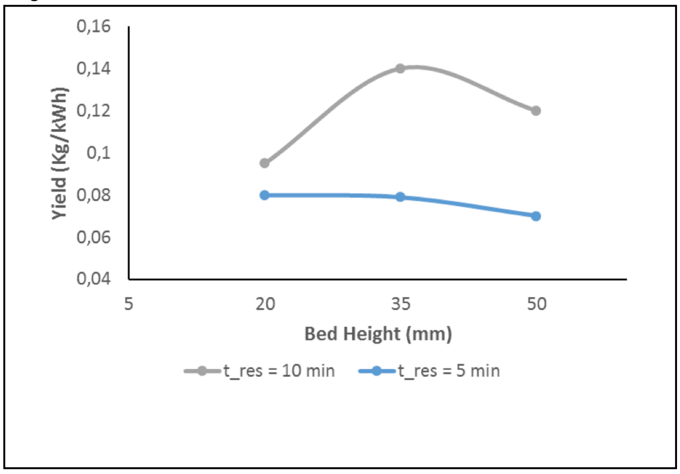


Figure 3 shows the yields expressed in terms of the kilograms of water removed per kWh of energy supplied to the tunnel microwave oven as a function of bed height and belt speed.

Fig 3. Microwave drying yield as a function of residence time and bed height.



In general, it is concluded that to operate with greater times of residence produces higher yields and these vary according to the height of bed. The increase in energy yield by modifying the velocity of the band from 0.3m / min to 0.16m / min for each of the bed heights studied, 20, 35 and 50mm, was 13%, 39% and 41%, respectively.

From Figure 3, it can be observed that for the bed height of 20mm the yield is very similar when compared in terms of the band speeds studied, and lower than the yield found for a bed of 35mm. However, when validated with the removal of moisture reached in the coal (Fig. 2), it is observed that it is possible to dry three times more with the speed of 0.16m / min represented in a loss of humidity of 12%, which shows results Microwave drying, taking into account that this was obtained in a residence time of 10 minutes. For the case of drying coal beds at a height of 35mm, the highest energy efficiency was observed and 8% of the coal moisture was removed at a rate of 0.16 m / min.

IV. CONCLUSION

The use of microwaves for drying offers an alternative to perform the process in a shorter time (less than an hour) to the conventional technologies and to a greater yield than the other methods. Therefore, it should be noted that the benefits found in microwave processes are greater, as it presents a better use of the energy delivered to the process, thus achieving greater moisture removal in less time and more material.

From the results at different heights of the coal bed, it is concluded that the drying rate increases to lower bed heights, but at the same time, the yield is reduced. In the same way, the yield increases when the residence time of the coal against the microwave radiation is increased.

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