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Microwave Drying of Biomass

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Abstract: *Pilot studies were performed on the identification of drying conditions in the microwave field leading to the obtaining of dry biomass with humidity in the range of 5… 8%, starting from initial humidity of 14… 20%.*
Sets of tests were performed with biomass sample masses of 5 and 10 kg for which the applied microwave power was varied, recording: variation of drying time with microwave power, average value of the final moisture in the sawdust (7.075, 60.6%) and variation of power density with drying time.
The existence of the direct relationship between the applied power density and the drying time allows the optimization of energy consumption. Thus, one can choose the amount of biomass to be dried at a target humidity, while setting the equipment at the appropriate power of the process.

Keywords: *Dying, dry biomass, microwave drying, microwave power*

1. Introduction

Drying is not only an energy-intensive operation, but also a complex phenomenon of the process of heat transfer and mass transfer, including that related to the drying of hygroscopic and porous materials such as wood and agri-food [1]. Consequently, improving knowledge about the interconnected physical, chemical and thermodynamic processes involved in drying, as well as the energy efficiency of drying equipment are the most relevant objectives of future research and development worldwide.

The main objective of the development of drying technology is to further improve the biomass drying process by applying new technologies and advanced measurement, modeling and simulation techniques.

Biomass refers to a non-fossilized biological material derived from living / recently living organisms and from biodegradable organic or carbon-based materials from plants, animals, plant matter and microorganisms. The most common industrial biomass can be grown from many types of plants, including miscanthus, hemp, corn, poplar, willow, sorghum, bamboo, sugar cane and a variety of tree species.

Regardless of the source, biomass materials can be divided into two broad categories: woody and non-woody. Forests provide only wood materials; agricultural sources provide both woody biomass and non-woody biomass for bioenergy production. The main source of wood biomass comes from forest and agricultural residues. Agriculture is a source of non-wood materials used to obtain bioenergy. Biomass-based materials from agriculture are represented by annual crops such as maize and soybeans, residues collected after harvesting annual crops for food or feed and perennial crops such as grass and fruit trees.

The use of biomass as a source of renewable energy is attracting even more attention nowadays due to concerns about heating and care for fossil fuel depletion. However, not all biomass is suitable for direct combustion, except for dry biomass.

In the past, biomass, such as wood or rice straw, was naturally dried before being burned. Recently, due to high energy costs and environmental concerns, some high-moisture organic wastes, such as microalgae, are used as fuel. They have a high moisture content so they must be mechanically and / or thermally dried before burning. Practice has shown that drying biofuels before burning can increase combustion efficiency. [2].

The high moisture content reduces the combustion temperature generating an incomplete combustion as well as a series of unwanted reaction products. In addition, a biofuel with a high moisture content requires a large amount of auxiliary fuel to burn [3]. Some data on how moisture content affects combustion efficiency as well as other combustion parameters, such as flame temperature, were reported by Voima et al. [4].

Basic knowledge of microwave heating refers to heat dissipation and the typical propagation of microwaves in which dipoles begin to vibrate and rotate angrily through the electric field. When the microwave energy emitted from a microwave oscillator (Pin) is irradiated in the microwave applicator, dielectric materials that have a dielectric loss factor absorb energy and are heated with a dielectric loss factor. Then the internal heat generation takes place. The basic equation for calculating the density of the microwave power absorbed by the dielectric material (P1) is given by the relation:

$$P_1 = \omega \varepsilon_0 \varepsilon_r'' E^2 = 2\pi f \varepsilon_0 \varepsilon_r (\tan \delta) E^2 \quad (1)$$

where E is the intensity of the electromagnetic field; f is the microwave frequency; ω is the angular velocity of the microwave; ε_r is a relative dielectric constant; ε_0 is the dielectric constant of the air and tan δ is the tangent coefficient of the dielectric loss.

As it results from the equation, the power P1 is directly proportional to the frequency applied to the electric field and the tangent coefficient of the dielectric loss and the average root - the square value of the electric field. This means that an increase in the tan, of the object, energy absorption and heat generation are also increased. While the tan δ is small, the microwaves will penetrate the object without generating heat. However, the increase in temperature probably depends on other factors, such as the specific heat, size and characteristics of the object.

When the material is heated unilaterally, it is found that as the dielectric constant and the loss coefficient vary, the penetration depth will change and the electric field in the dielectric material will change. The penetration depth is used to indicate the depth at which the power density has decreased to 37% of its initial surface value.

$$D_p = \frac{1}{(2\pi f/\upsilon)\sqrt{\left[\varepsilon_r'\left(\sqrt{1+\left(\varepsilon_r''/\varepsilon_r'\right)^2}-1\right)\right]/2}} = \frac{1}{(2\pi f/\upsilon)\sqrt{\left[\varepsilon_r'\left(\sqrt{1+(\tan\delta)^2}-1\right)\right]/2}} \quad (2)$$

$$P_2(W) = \frac{4.18 W C_p \Delta T}{t} \quad (3)$$

where W is the weight of the dielectric material (g), CP is the specific heat of the dielectric material (Cal / gr ◦C), ΔT is the temperature rise (T2 −T1) (◦C), t is the heating time [s].

Assuming an ideal condition, all the oscillating energy of the microwave (P_in) is absorbed in the dielectric material; internal heat generation as Equation (1). In this case, the relationship between P_in and ηP2 is presented below:

P = in (W) = P2

However, from a practical point of view, the transformation energy (η) in the applicator exists due to the rate of absorption of microwave energy by the dielectric factor.

Green biomass is an organic, hygroscopic, capillary, porous, anisotropic, non-uniform and heterogeneous mixture of solids, liquids and gases. It contains considerable amounts of moisture (water and liquid vapor) depending on the relative humidity of the surrounding air. For many industrial applications, many national laws require the removal of moisture from biomass / wood for minimal damage, quality preservation and reduction of transport costs [5].

Drying techniques generally refer to the use of energy depending on how the drying medium is heated (for example by fuel or electricity), how the residual energy is recovered from the exhaust air and how the control system is used to maximize energy use etc. Specialized drying techniques such as direct heat, radio frequency and microwave, infrared, vacuum, solar (more attractive in remote locations for small ovens) and assisted heat pumps (dehumidification) are usually more expensive and oriented towards special final products. In addition, some of these technologies use higher energy (electricity), which is generally expensive [6, 7]. Heat pumps can also include auxiliary heating sources, such as electromagnetic radiation, radio frequency, microwave, infrared and solar energy.

One of the important properties of biomass in terms of combustion process and thermo-chemical conversion processes is the moisture content, which influences the energy content (calorific value) of the fuel. The moisture content of biomass is given by the amount of water in the product, expressed as a percentage by mass. Currently, two methods (dry and wet) are used to express total humidity.

For most fuels it is used dry. This is due to the fact that different types of biomass have different moisture contents, because the humidity of the wood depends on the place, type and duration of storage and preparation of the fuel. Dry moisture reports moisture to the mass of dry material. Moisture is related to the total mass of the material. It varies from less than 10% (by-products of the wood processing industry) to 50% (forest residues). The moisture content is relevant not only for the calorific value but also for the storage conditions, the combustion temperature and the amount of flue gases.

In the case of waste in heterogeneous mixtures - urban and similar - in addition to its influence on the specific mass, moisture has a direct influence on the calorific value and fermentation processes, when they are intended for the formation of compost. Humidity is directly influenced by the climate of the region, being different from one season to another.

Microwave heating is an efficient method for transferring energy to water molecules inside biomass pieces.

Water molecules are dipolar in nature (i.e. have an asymmetric center of charge) and are normally randomly oriented. The rapidly changing polarity of the radio frequency and microwave field tries to bring these dipoles into alignment with the field. As the field changes polarity, the dipoles return to a random orientation before being pulled in another direction. This accumulation and degradation of the field and the resulting stress on the molecules determine a conversion of the energy of the electric field to the stored potential energy, then to the random kinetic or thermal energy. Therefore, dipole molecules, such as water, absorb energy in these frequency ranges. The field strength and frequency are fixed by the equipment, while the dielectric constant, dissipation factor and loss factor are material dependent. The actual power of the electric field also depends on the location of the material inside the microwave / radio frequency cavity.

The dielectric constant of water is more than an order of magnitude larger than most basic materials (such as wood pulp), moisture is preferentially heated, a process that leads to a more uniformly moist product over time, while the overall dielectric density of most materials usually almost proportional to the moisture content up to a critical value, often around 0.2 0.3. Therefore, microwave and radio frequency methods prefer to heat and dry wetlands in most materials, processes that tend to lead to a more uniform final moisture content. For water and other small molecules, the effect of increasing the temperature is a slight decrease in the heating rate, which leads to a self-limiting effect [6, 8]. The force and frequency of the field are fixed by the equipment, while other parameters are dependent on the material. If the energy requirement is higher than 50 kW, the use of tubes with higher power in the radio frequency range seems to be economically favourable. The least expensive guides are the microwave oven guides, which have an output power of 750 W.

Microwave heating works on the same principles as radio frequency heating, but with higher frequencies in the range of 300 MHz-300 GHz; thus, the thermal power ratios of the heating can be significantly increased. The unit cost of drying wood for microwave drying is influenced by the initial moisture content and density of the wood, while for conventional drying, the unit cost of volume depends mainly on the length of the drying cycle required to reach the levels. acceptable degradation. The cost of the whole system, including the generator, The waveguide from generator to dryer, applicator, control system and conveyor is much higher, but lower unit costs are associated with higher power equipment [6]. Microwave drying seems to be suitable where hardwood species have a low initial moisture content, causing problems with degradation in conventional drying and / or is relatively valuable, so the capital load is significant. For example, microwave drying is economical for Douglas fir with an initial low moisture content of 40%, but not for wood with an initial moisture content of more than 86%. On this basis, microwave drying would find the most applications for hardwood species [9].

Electromagnetic radiation with varying wavelengths (0.2 m - 0.2 μm) can be combined with forced conventional air convection and / or vacuum wood drying [10]. The low frequency of electromagnetic radiation (generated by magnetroons and clystrons) covers the range 1-100 MHz, while the high frequencies range from 300 MHz to 300 GHz [6]. At radio frequency, the impedance of the wettest materials decreases dramatically, although they are poor conductors of 50-60 Hz current, thus reducing the internal resistance to heat transfer. Energy is selectively absorbed by water molecules and, as the product becomes drier, less energy is used.

The advantages of such methods of electric heating include (i) the direct supply of heat to the product, so that a drying environment is not required; (ii) the possibility of precise temperature control by drying; (iii) uniform control of the moisture content within a period of minutes without the development of defects, thus avoiding dangerous humidity gradients; (iv) the small size of the dryer is not required; (v) clean, easy to maintain and without handling flammable fuel; (vi) better quality, no contamination and no risk of combustion; (vii) short start and stop time; and (viii) may be used to complete the drying of conventionally dried timber that has not met the target moisture content.

2. Experimental activities

The biomass drying tests were performed in a microwave field with a frequency of 2.45 GHz. Fresh sawdust obtained after cutting softwood (pine) with an initial moisture content of 72% by mass was used as biomass.

Drying tests were performed in average quantities of 10 kg. After drying tests in which the biomass was placed in a layer with a thickness of 3 ... 5 cm, it was found that there are areas with microwave concentrations that generate thermal degradation. These areas can become biomass ignition points, taking into account that the sawdust has a dimensional distribution from dust to fragments with an average size of 2 mm.

Under these conditions, the concept of drying finely divided biomass was rethought, the identified solution consisting in the use of a cylindrical foil made of transparent material in the microwave, resistant to working temperatures up to 150ºC.

The working method consists in introducing in the microwave field a quantity of biomass (sawdust) limited by the length of the cavity and the diameter of the cylindrical foil. The cylindrical foil filled with sawdust is insulated at the ends with elastic systems that have the role of preventing the exit of biomass as well as the function of valves as the pressure of water vapor increases with increasing temperature in the sawdust mass. At a microwave power of 3 kW (3 magnetrons x 1000W), 13000g was heated from room temperature to 103ºC, within 25 minutes. The heated biomass was transferred to the conveyor belt for drying in hot air at 35 ° C. Following the drying step in a stream of hot air, a humidity of 12% in the sawdust mass was determined. Completion of drying is performed on the conveyor belt by entraining vapours from a stream of warm air with a temperature between 25 ... 40ºC, depending on the type of material subjected to drying.

Among the advantages of this new mode of operation can be mentioned:

- minimizing deposits of fine biomass powders inside the furnace, minimizing the risk of ignition,

- removal of the effect of local warming accompanied by carbonisation of the biomass and even its ignition, due to the existence of a controlled atmosphere of water vapour

- ensuring a controlled geometric shape (cylinder) of the material subjected to drying - biomass - with the possibility of optimizing the process following a series of tests

- optimizing the distribution of the electromagnetic field accompanied by the need to supplement the microwave power to reduce the duration of the drying process.

A type of dryer was developed which was based on several requirements identified in the application area:

- type of raw material: sawdust, biomass chop, corn cobs,
- raw material size: micronic range up to 50 mm
- dry biomass humidity: 5 - 8% by mass
- use of dry biomass: briquetting.

3. Microwave field heating oven

3.1 Geometry identification

A technological process of controlled drying of biomass in the microwave field was developed and studied.

The drying of biomass in a controlled dimensioned form is performed in a first stage inside a drying oven, under the action of microwaves. The processes in which microwave energy is used are characterized by a direct relationship between the nature and geometry of the body exposed to radiation and the efficiency of the process.

3.1.1 Planar geometry

In the case of biomass, the arrangement of the biomass in a layer with a thickness in the range 10… 50 mm was tested in a first stage, for which the surface exposed to irradiation was given by the surface generated by the width of the conveyor belt and the length of the furnace (800 x 1500 mm).

Under these conditions, drying tests were conducted in the following conditions:

- microwave power: 5 - 9 kW
- microwave frequency: 2.45 GHz
- thermal gradient: 1… 5 ºC / min.
- working temperature: 60… 110ºC
- layer thickness: 10… 50 mm
- type of biomass: softwood waste
- initial humidity of the biomass: 64.3%.

It was found that, although the distribution of the electric field in the plane of the biomass layer is homogeneous (see Fig.1), burned areas were observed in the drying layer. The study was conducted using a specialized software QuickWave Professional 2017. With this software you can draw 3D structures and simultaneously simulate the effects of the electromagnetic field in relation to the thermal field. The appearance of these burned areas was observed regardless of the thickness of the layers, noting in general, an accentuation of the phenomenon in case of reduction of thickness.

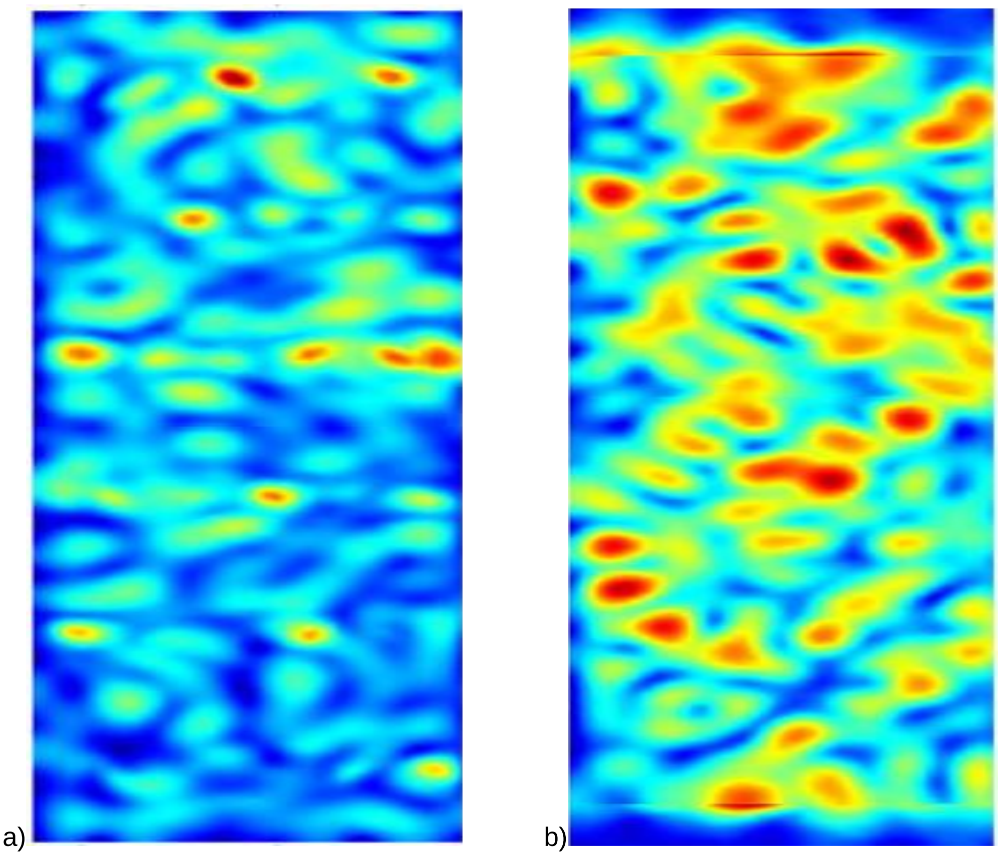

Fig. 1. Electric field distribution in the microwave - biomass arrangement plan: a) at 10 cm above b) at 1 cm above

From the analysis of the observations resulting from the development of 15 tests performed in planar geometry, the following were found:

- the use of high microwave powers is accompanied by rapid increases in temperature, reduction of drying time at the level of 5 precum 10 minutes as well as an increase in the incidence of burned areas in the biomass bed,

- the use of small microwave powers is characterized by longer drying times of 15… 50 minutes, lower temperature rises in irradiated biomass and a reduction in the incidence of burned areas in the biomass bed.

3.1.2 Cylindrical geometry

Bound moisture is associated with the hygroscopic nature of wood components. There are some uncertainties about the limits of hygroscopic behavior, especially in forests with high extractive content. For practical reasons, a maximum moisture content has been defined, called the fiber saturation point (PSF). If the effects of capillary condensation in pores larger than 0.1 mm in equivalent cylindrical diameter are ignored, the PSF of the wood can be defined as the equilibrium moisture content (CUE) in an environment of 99% relative humidity. This produces a value of 30 to 32% for most commercial species (Keey et al., 2000) [11] at room temperature. PSF decreases with increasing temperature. For a softwood such as Sitka spruce (Picea sitchensis), PSF decreases from about 31% at 25 ° C to 23% at 100 ° C (Stamm, 1964) [12].

The water absorbed from the cell wall has a lower enthalpy than liquid water. However, unlike other forms of water, such as the solid form, the enthalpy of bound water increases with increasing moisture content to PSF. Above this value, the enthalpy of wood water is essentially the same as that of liquid water.

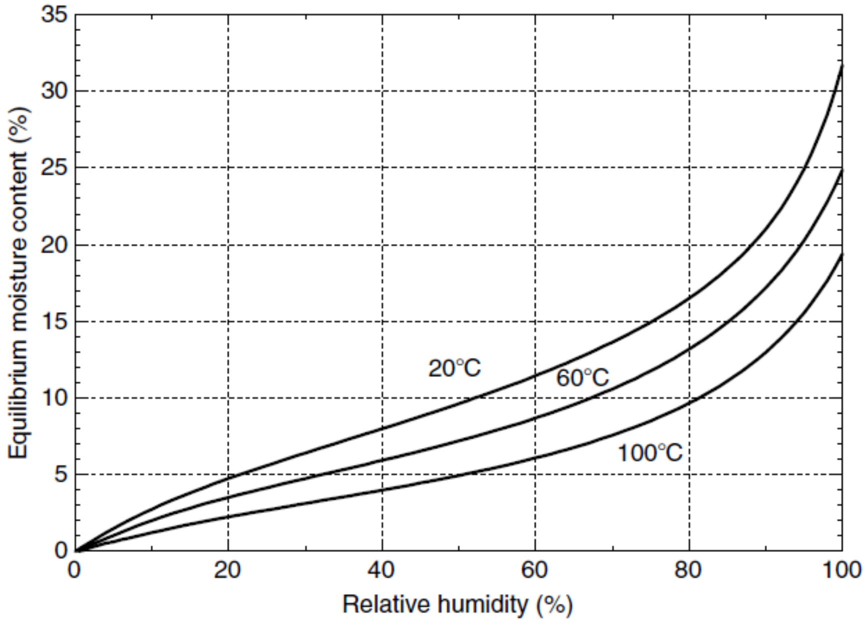

Fig. 2. Absorption isotherms calculated by a mathematical expression obtained from published data.

The drying process of the wood biomass can be differentiated by the operating temperature (low and high respectively) and by the operating pressure (vacuum and atmospheric).

3.1.3 Selecting the geometric pattern

As a result of the deepening of some theoretical and practical aspects specific to the drying of the wood material corroborated with the specific aspects of the drying in the microwave field, a specific drying process was developed. The specificity of this process consists in placing the biomass (wood waste) in powder or granular form in a controlled geometry that simultaneously fulfills the conditions:

- transparent in the microwave
- thermal resistance up to 165ºC
- resistance to lowered pressures (max. 3 bar)
- vapor resistance.

Several geometries were studied from the perspective of ergonomics and efficiency, finally choosing the cylindrical shape. As a material used to make the geometry, a partially cross-linked, heat-resistant polyethylene foil was used. Under filling conditions, the cylindrical geometry has the following dimensions: outer diameter approx. 300 mm, length of approx. 1500 mm, with a capacity of approx. 106 liters. For drying reasons, one end of the test geometry is sealed while at the other end the controlled evacuation of pressure is ensured by means of a valve. In Fig.3 the cylindrical geometry with the test material is presented, positioned inside the microwave assisted drying equipment.

Fig. 3. Microwave-assisted drying equipment before testing, with biomass sample in cylindrical geometry

Subsequent tests to optimize the microwave drying process were performed using cylindrical geometry.

3.2 Determination of drying time

As a result of the preliminary data accumulated, microwave heating was performed in the batch dryer variant (Fig. 1). The microwave cavity had a rectangular shape with a cross section of 80cm × 42 cm. The dryer operates at a frequency of 2.45 GHz and a maximum operating temperature of 200 ºC. Microwave power is generated by 10 air-cooled magnetrons by means of fans. The maximum microwave capacity is 11.2kW at 2.45 GHz. The power setting can be individually adjusted in 1000W steps. The measurement of the temperature inside the enclosure as well as in the biomass introduced in the cylindrical geometry is made with the help of some thermocouples. The equipment is equipped with a timer for setting the irradiation time after establishing the operating program for a certain type of material.

The tests performed after establishing the cylindrical geometry consisted in a first stage in determining the humidity profile for pine sawdust samples, freshly produced, with the humidity in the range of 75 ... 85%. The determination of the humidity was made by means of a thermobalance with the dedicated operating program for wood, the measuring temperature being 105ºC. Determinations were made between the duration of irradiation at a given power and the humidity in the irradiated biomass.

In this sense, for each power level a sample with a mass of 15 kg was used. Each sample was placed in a cylinder with a radius of 30 cm. At regular intervals (5 min.) 50 g of sawdust exposed to the microwave were taken. Each sample was exposed for 60 seconds to a 45C hot air stream to remove water from the sawdust particles. Subsequently, a small sample of the prepared sample (approximately 3-4 g) was used to determine the humidity with thermobalance. The results of these first tests are represented in graphical form in Fig.4.

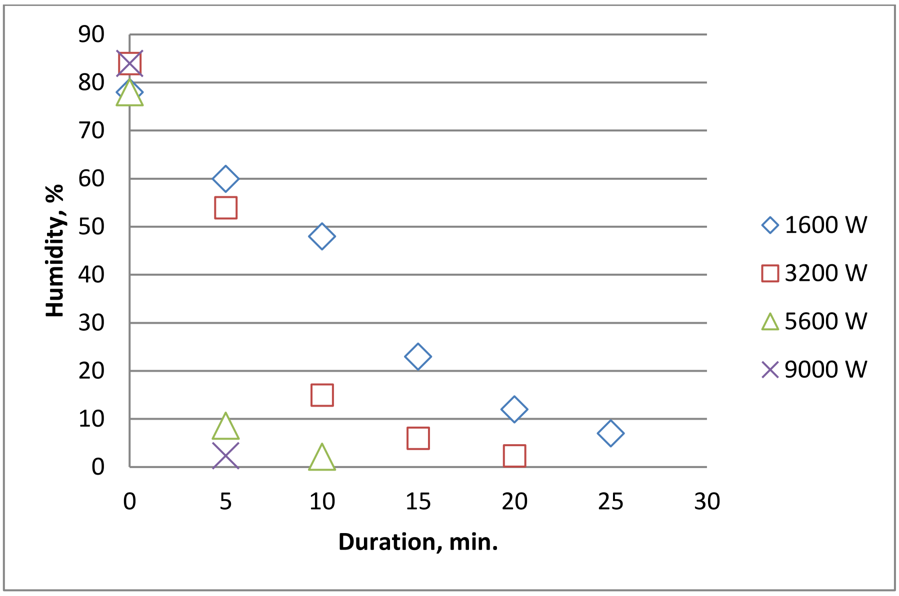

Fig. 4. Humidity profile depending on the duration for different microwave power levels

In the next step, the amount of pine sawdust was left to dry naturally in a bed with a thickness of 50.80 mm to dry naturally. The obtained humidity was between 15… 20%.

Using samples from this natural dry pine sawdust, determinations were made to reduce the humidity to values in the range of 5… 8%. This humidity range is necessary for processes such as briquetting, pyrolysis, being a strong energy-consuming and expensive to achieve through conventional heating.

Two drying sets were performed for which the operating parameters were:

- biomass material type: softwood sawdust
- quantity of biomass sample: 5 kg, 10 kg
- initial humidity of biomass samples: 14.55□0.6%
- proposed final humidity: 5… 8%
- applied microwave power: 3000, 5000, 7000, 9000 W.

Each sample was introduced in a cylindrical shape, according to the established geometry. The test results are represented in graphical form in Fig.5.

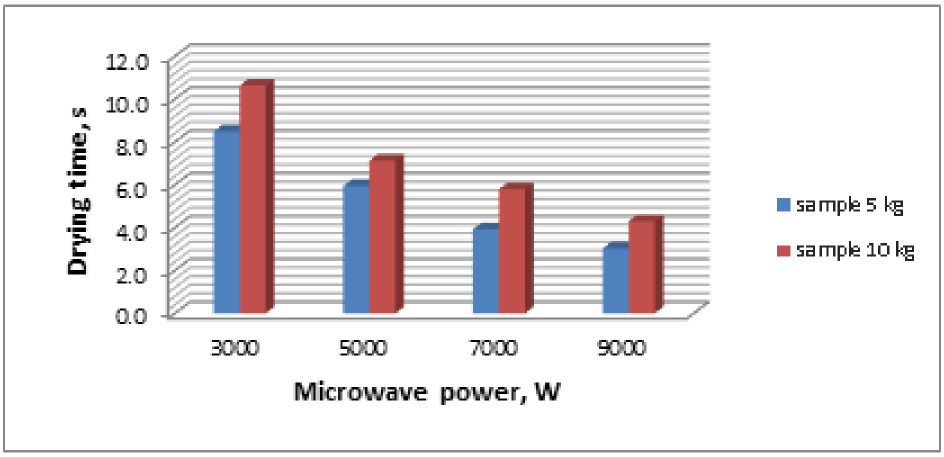

Fig. 5. Variation of drying time with microwave power

Following these tests, the average value of the final moisture in the sawdust was 7.075±0.6%.

3.3 Determining the optimal power

An important parameter in the drying process is the power density (DP) which is defined as the ratio between the microwave power and the sample mass exposed to microwave irradiation. The unit of measurement can be W / g, W / kg. The values of the power densities related to the samples and the applied microwave powers were calculated. Fig.6 shows graphically the variations of the power densities with the drying time for two sets of samples.

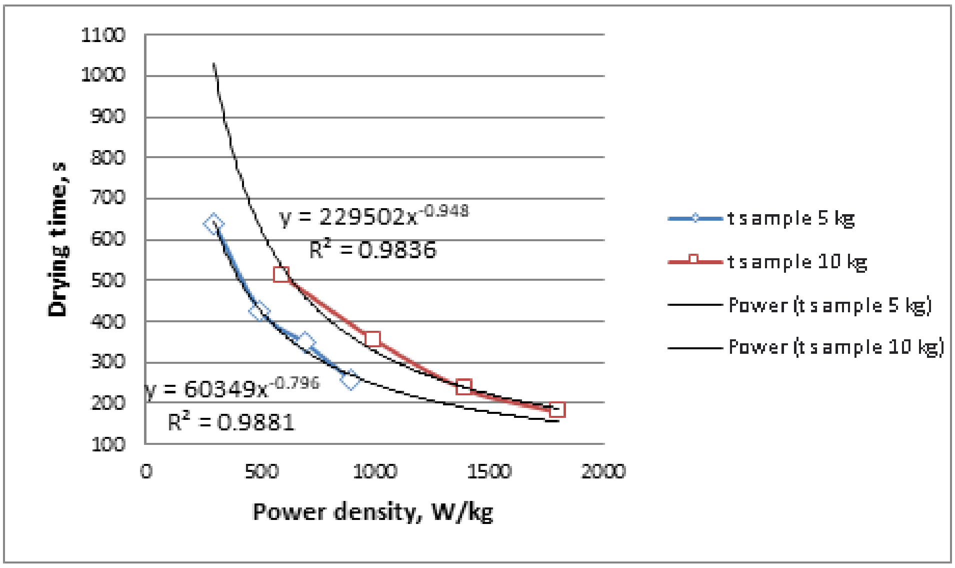

Fig. 6. Power density variation with drying time

Based on the test data, exponential equations were generated to mathematically describe the variation of power density with drying time.

It can be seen from the graphical representations that there are points on the theoretical curve that are not aligned. In this case, the set of measurements may be resumed in order to identify the nature of the causes which led to this aligned result, simultaneously with the use of statistical instruments.

The existence of the direct relationship between the applied power density and the drying time allows the optimization of energy consumption. Thus, you can choose the amount of biomass to be dried at a target humidity, while setting the equipment at the appropriate power of the process.

3.4 Possibilities for process optimization

Microwave drying of lignocellulosic biomass waste can be achieved under energy and process conditions by identifying the relationships between the various parameters encountered: nature of lignocellulosic biomass waste, initial and final humidity, sizing, microwave power density, geometry.

4. Conclusions

Pilot studies were performed on the identification of drying conditions in the microwave field leading to the obtaining of dry biomass with humidity in the range of 5… 8%, starting from initial humidity of 14… 20%.

The field of humidities with low values is the largest energy consumer. Under these conditions, the use of microwave drying equipment is preferable for this type of process by the specific heating mechanism, it being known that microwaves act inside the irradiated material.

For the microwave oven designed and made for drying biomass waste, the test conditions for establishing the biomass geometry in the cavity of the microwave oven were established. Two geometric models of planar and cylindrical type were analysed, choosing as performance criteria: homogeneity of heating, absence of burns, process safety, and quality of the finished product.

Based on the experimental data and the observations during the tests performed, the cylindrical geometry was selected.

The conditions for the material from which to make the cylindrical geometry were listed:
- transparent in the microwave
- thermal resistance up to 165ºC
- resistance to lowered pressures (max. 3 bar)
- vapor resistance.

Tests were performed to determine the drying time, performing tests to obtain humidity between 14 ... 20% followed by tests to obtain humidity of 5 ... 8% in biomass.

Sets of tests were performed with biomass sample masses of 5 and 10 kg for which the applied microwave power was varied, recording:
- variation of drying time with microwave power
- average value of the final moisture in the sawdust (7.075, 60.6%)
- variation of power density with drying time.

The existence of the direct relationship between the applied power density and the drying time allows the optimization of energy consumption. Thus, one can choose the amount of biomass to be dried at a target humidity, while setting the equipment at the appropriate power of the process.

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