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Dedicated to Professor Liviu Literat, at his 80th anniversary

SOME ASPECTS REGARDING MICROWAVE DRYING OF MATERIALS

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ABSTRACT. The paper presents the experimental results of microwave drying for a granular material (siliceous sand). Drying kinetics and effective power absorbed by the material for two cases: compact volume (bulk) and extended volume (layer) were determined and analyzed.

Keywords: *microwaves, drying, thermal properties, heat transfer, power transport.*

INTRODUCTION

Traditionally, drying of solid materials is carried out by convective heating, transferring the thermal energy from the heater to the heated material. The penetration of this energy into material depends on the thermal conductivity of the material. While the material dries, the thermal and mass conductivity decrease. As a result, the penetration of the delivered heat is reduced progressively, and water is slower transferred to surface layers, where evaporation occurs. Consequently, the surface layers become overheated and it may even produce a crust, which will need to be mechanically broken up to transfer the dried material to shipping containers.

To increase the effectiveness of the drying process it is necessary to employ various tricks, such as stirring the substance, drying in fluidized bed etc. Normally this requires high power consumption.

Drying under microwave irradiation presents several advantages comparative to convective drying. The main advantages consist on high conversion of microwave energy into thermal energy, independence on thermal conductivity and selectivity [1]. In the same time, the influence of the resistance of the boundary layer between the material and drying air, as well as the thermal conductive transport through the material are eliminated, under microwave irradiation heating occurring simultaneously in whole volume of the heated material.

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Equipments used in microwave drying are relatively simple and can be easily adapted to the variable conditions; have no thermal inertia, therefore can quickly reach natural regime of operation; the volume of all installation is small and that for needs no large space.

The disadvantages of the method are: high exploitation costs and limited using field.

Depending on the type of radiation and material nature, when one irradiates solids with microwaves, the microwaves can be reflected, absorbed, or simply pass through the sample with no absorption occurring [2, 3]. Through vibration, elongation and successive contraction of bounds and atoms, the radiant energy is transformed into heat which propagates from the warmest zones towards the coldest zones through convection and conduction mechanisms.

During the microwave drying process in many cases the material being dried does not absorb or absorb a low level of microwave irradiation but the water molecules associated with it do. Thus the microwave drying process is caused by the property of water to absorb microwave irradiation. Consequently, removing of the water molecules from the drying materials eliminates the heating effect. In such a way the microwave drying appears to be self-regulative process.

Microwave irradiation consists in electromagnetic wave in the range 300 MHz to 300 GHz that corresponds to wavelengths of 1 cm to 1 m, and frequency between 2450 kHz - 434, 915 MHz, being defined by international regulations. The microwave region of the electromagnetic spectrum lies between infrared and radio frequencies [4].

In order to avoid local heating if the material is keeping static, shifting of material into irradiated space is necessary to be applied [5].

RESULTS AND DISCUSSION

Preliminary results obtained by the heating of water under microwave irradiation in two situations: compact volume (beakers) and extended volume (trays), at different power levels of the microwave oven are shown in Table 1 and Table 2.

Table1. Water temperature in beaker during microwave heating

Time [minutes]	L Level [^{0}C]	ML Level [^{0}C]	M Level [^{0}C]	MH Level [^{0}C]	H Level [^{0}C]
0	20	20	21	20	21
1	28	27	54	77	96
0	20	20	20	21	20
2	35	60	88	94	-
0	20	20	20	20	20
3	41	77	-	-	-
0	20	21	20	20	20
4	45	90			

Table1. Water temperature in beaker during microwave heating (continuation)

Time [minutes]	L Level [^{0}C]	ML Level [^{0}C]	M Level [^{0}C]	MH Level [^{0}C]	H Level [^{0}C]
0	20	20	20	20	20
5	50	-	-	-	-
0	20	20	20	20	20
6	60	-	-	-	-

L = low level; ML = medium - low level; M = medium level; MH = medium - high level; H = high level.

Table 2. Water temperature in tray during microwave heating

Time [minutes]	L Level [^{0}C]	ML Level [^{0}C]	M Level [^{0}C]	MH Level [^{0}C]
0	20	20	20	20
1	35	42	55	70
0	20	20	20	20
2	37	55	69	77
0	21	21	21	21
3	43	63	77	-
0	21	21	21	21
4	47	64	75	-
0	21	21	21	21
5	50	68	-	-
0	21	21	21	21
6	56	-	-	-

Each temperature is the average of at least three measurements carried out in the same conditions.

Considering the difference of temperature between initial moment and final moment of each heating experiment, the effective power absorbed by water can be determined by the relation [4]:

$$P_{ef} = (m_{water}\, c_{p\,water} \cdot \Delta T_{water} / \tau),$$

where: m_{water} is the mass of heated water, 100 [g] = 0.1 [kg]; $c_{p\,water}$ - specific heat of water 4,185 [J/kg ^{0}K]; ΔT_{water} - difference of temperature between the initial moment and the final moment of the heating process [^{0}K]; and τ - irradiation time [s].

The resulted values are presented in Table 3 and Table 4.

Table 3. The effective power absorbed by water during microwave heating in beaker

Heating time [min]	L Level [W]	ML Level [W]	M Level [W]	MH Level [W]	H Level [W]
1	55.8	128.825	230.175	397.575	523.125
2	48.825	129.5	237.16	372.025	-
3	48.825	123.212	-	-	-
4	43.594	120.319			
5	43.245	-	-	-	-
6	46.5	-	-	-	-
$P_{ef\,av}$	47.798	125.464	233.667	384.480	523.125

Table 4. The effective power absorbed by water during microwave heating in tray

Heating time [min]	L Level [W]	ML Level [W]	M Level [W]	H Level [W]
1	140.625	153.450	244.125	348.75
2	59.287	122.0625	170.8875	198.7875
3	51.15	97.650	-	-
4	45.3375	74.98125	-	-
5	40.455	-	-	-
6	40.6875	-	-	-
$P_{ef\ av}$	62.923	112.0575	207.5	273.76875

It is easy to see that calculated values of effective power increase with the increase of power level of the microwave oven and generally, the effective absorbed power is higher for compact volume (in backer) that for extended volume (in tray).

Temperature variation during microwave irradiation of siliceous sand (tested material) in both cases analyzed earlier (compact and extended volume) are shown in Figure 1 and Figure 2.

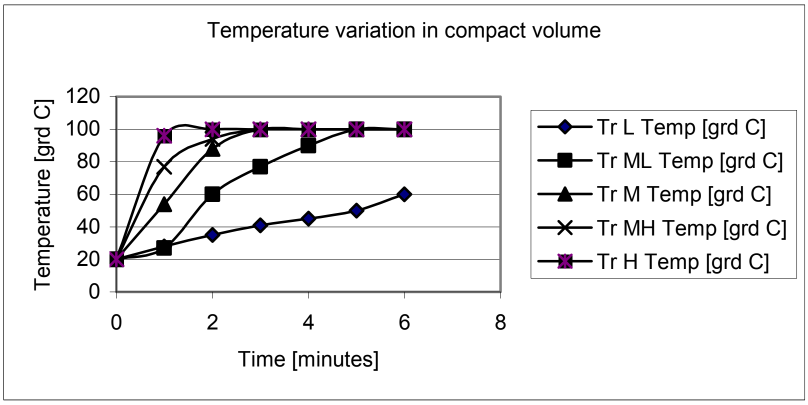

Figure 1. Temperature variation during microwave drying of sand in compact volume.

It can be seen that the temperature curves increase continuously, with a faster rhythm for higher power level of the microwave oven and with a slower rhythm for lower power level. In the same time the temperature increase slower in the case of extended volume comparative to compact volume. This phenomenon can be attributed to the higher heat lost into the chamber environment, which remains cold and does not increase its temperature, surface area exposed by tray was 181.366 cm^2, comparative to surface area exposed by backer, 28.6 cm^2.

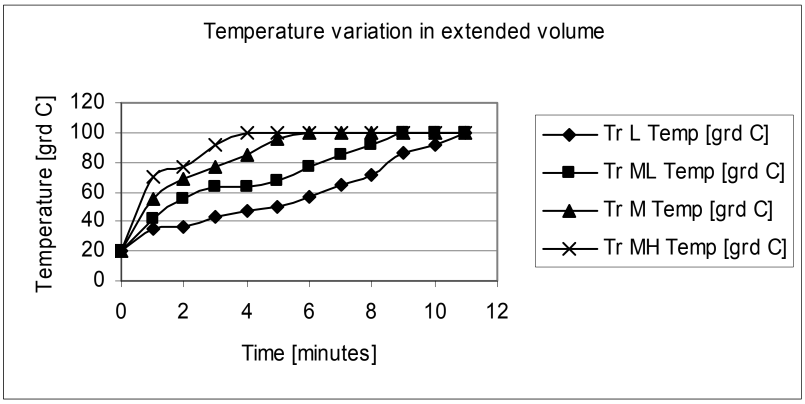

Figure 2. Temperature variation during microwave drying of sand in extended volume.

Regarding the effective power absorbed by siliceous sand, it was measured an almost constant power in the case of compact volume. The effective power absorbed by the sand decreases progressively with a tendency of stabilization in the case of extended volume (Figure 3). An explanation for such behavior of the system could not be found.

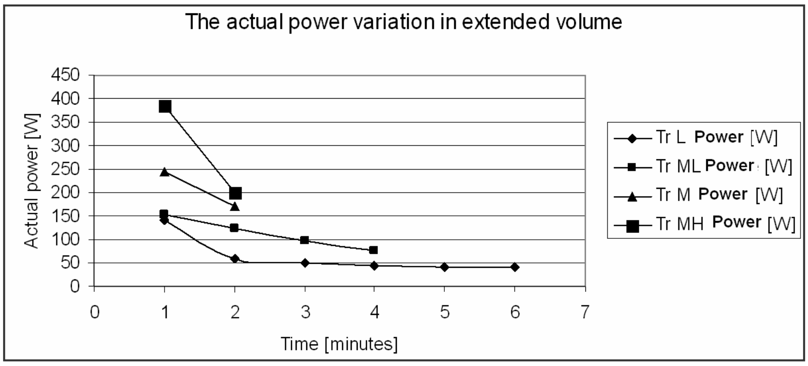

Figure 3. The effective power absorbed by the sand in extended volume.

Kinetic curves of drying for compact volume and for extended volume samples at lower power level of the microwave oven are shown in Figure 4 and 5. These curves present the variation in time of several characteristics of the system: weight, temperature and humidity.

During the microwave irradiation the sand temperature follows a tendency similar to the heating of water alone; the weight of the samples diminishes similarly in both situations.

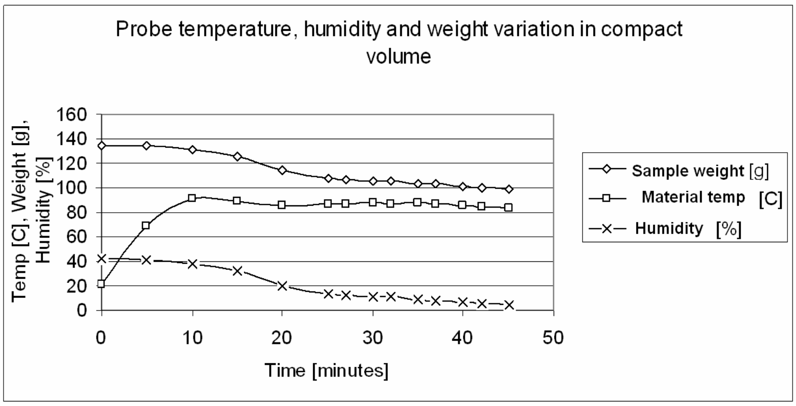

Figure 4. Drying curves for sand in compact volume.

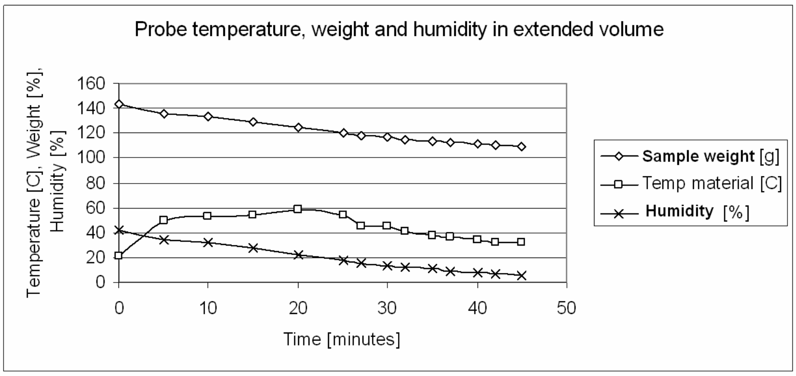

Figure 5. Drying curves for sand in extended volume.

To compare the results of microwave drying of sand in compact and extended volume, Figures 6, 7 and 8 are plotted.

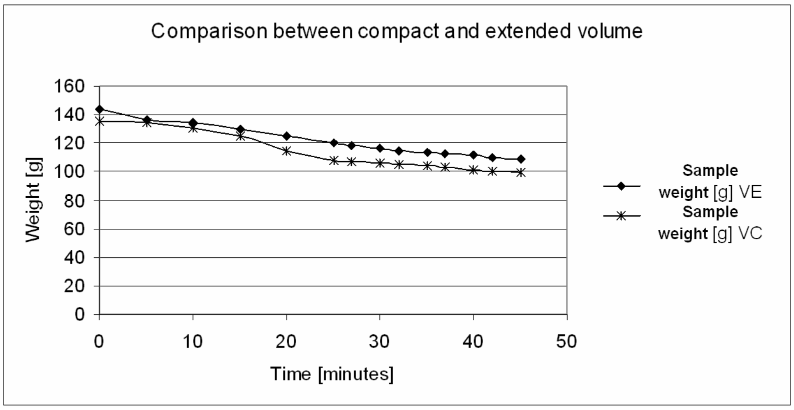

Figure 6. Weight variation for compact and extended volume.

Figure 6 shows a decrease of the weight almost linear in both cases. The detected difference between the curves can be attributed to the weight difference of the containers: 2, 4 g for beaker and 7, 7 g for tray, which means that the weight of containers can influence the drying process; containers heat up only by conduction.

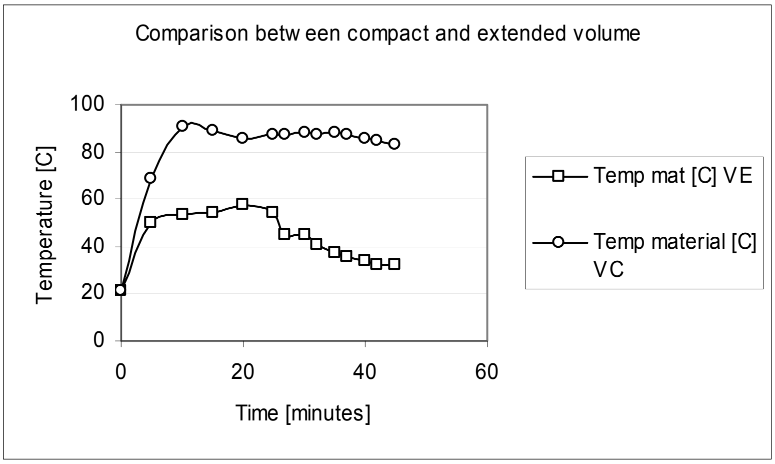

Figure 7. Temperature variation for compact and extended volume.

The evolution in time of temperature plotted in Figure 7 shows for extended volume a lower increase than in the case of compact volume. In both cases, at the end of the process, the temperature decrease more slowly, due to the decrease of the water quantity in the material.

The slope of the curves suggests the idea of using extended volumes in case of temperature-sensitive materials. In this way, these materials are less affected by the temperature and due to the higher heat lost, the material cooling occurs more rapidly.

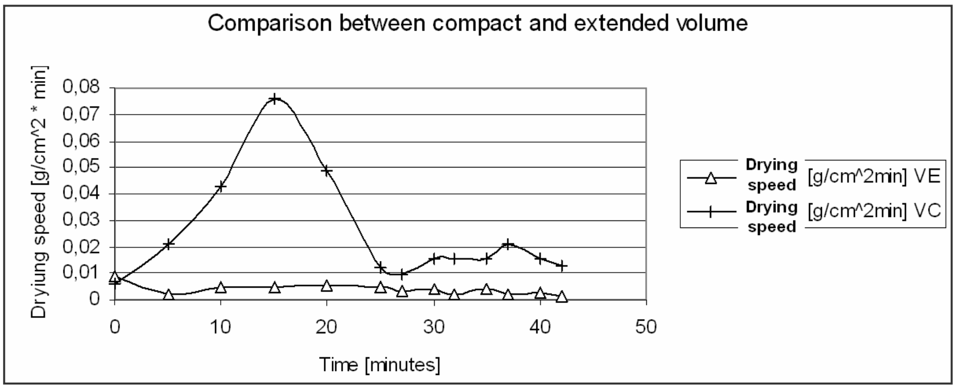

Figure 8. Drying kinetics for sand in compact and extended volume.

The drying rate, in terms of water amount eliminated per unit of time and surface, [g/cm^2·min] or in international system IS [kg/m^2·s], shows the rhythm of humidity elimination (Figure 8). It can be seen a relatively constant loss of humidity in the case of extended volume. In the case of compact volume, the drying rate presents higher variation. The following observations were made: in the first stage, the drying rate is reduced because of the heat lost by convection in the cold environment; at the end, the diminution of the rate is due to a decrease of the humidity amount.

This behavior was explained by the followings facts:

- during the first stage, the material is intensely heated and the losses to the external environment are diminished due to the smaller contact surface of the material to the cold environment;

- the heat of the material mass is near to the water boiling point value and this generates an intense evaporation and also water boiling. The generation of a larger amount of vapors indicates a higher drying rate, associated to material splash because of energetic formation and evacuation of steams (this phenomenon was experimentally observed);

- reaching of a minimum drying rate was explained by the formation of a "coating" of relatively dry material, which is difficult to be penetrated by the generated water vapors;

- the barrier penetration determines a growth of the released vapor amount, specifically an increase of the drying rate, but since the vapor amount is smaller, a maximum rate due to vaporization cannot be reached. In addition, the material temperature decrease contributes to this phenomenon;

- the decrease of the drying rate is attributed to the decrease of the material humidity amount in a relatively constant rhythm (Figure 9).

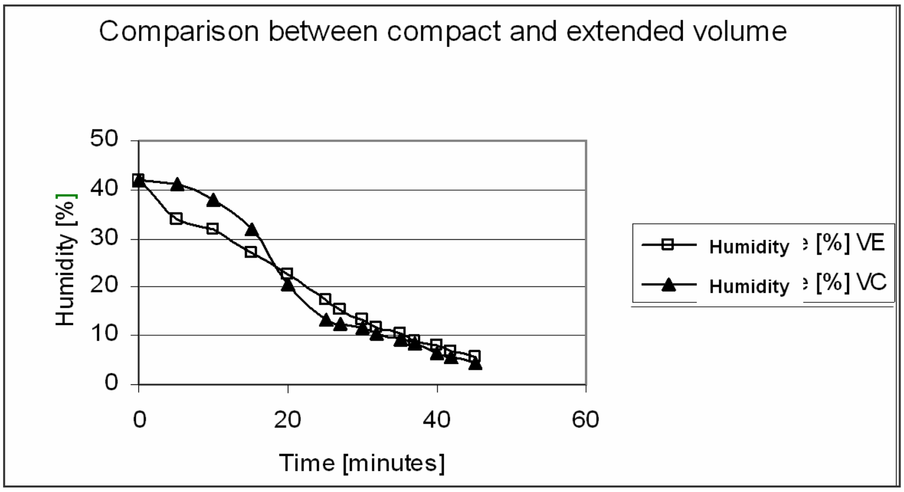

Figure 9. Comparison of humidity losses.

CONCLUSIONS

Microwave heating was experimentally studied using a household microwave oven, type CANDY-CMG-2180-M, in order to obtain useful experimental information, special for improving the process of the drying operation.

Effective emitted power of the generator and the power absorbed by the material were determined. Effective absorbed power was constant in the case of compact volume, while in the case of extended volume the effective absorbed power was progressively decreased, showing a stabilization tendency. An explanation for such system behavior was not found.

During microwave drying the temperature of the tested material has shown a continuous increase. The smaller increase of the temperature in the case of extended volume was attributed to the heat lost in the chamber environment. In the same time, the obtained results suggest the idea of using extended volumes in case of temperature-sensitive materials.

The humidity was reduced with relatively constant rate in the case of extended volume and with variable rate, in the case of compact volume.

EXPERIMENTAL SECTION

The drying process under microwave field was monitored in order to obtain valid experimental data that may be useful for the drying process improvement. The experimental measurements were focused on:

1. Determination of the technical characteristics of the equipment and

2. Determination of drying kinetics and effective absorbed energy.

In order to determine technical characteristics of the equipment, a household microwave oven, type CANDY CMG 2180 M was used. The technical features presented by the manufacturer in the technical book are:

Supply voltage	220 - 230 V;
Network Frequency	50 Hz;
Generator working frequency	2450 Hz;
Absorbed power from the network	1300 W;
Emission power	800 W;
Chamber sizes	300 x 295 x 205 mm;
Useful volume	21 dm^3;
Turntable diameter	270 mm;
5 power levels	

Preliminary measurements were made in order to determine the "active" power emitted by the generator of the microwave oven and absorbed by water.

The working method: 100 ml of water were introduced in the shock-absorbing polystyrene container. Two types of containers are used: backers for compact volume experiment and trays for extended volume. Parameters of containers at microwave heating tests were:

- beaker: truncated cone shape, small base (at the bottom), diameter ∅ 45 mm; large base (up) diameter ∅ 60 mm; and height 50 mm,
- tray: cylinder of negligible height, and diameter ∅ 152 mm.

Simple shock-absorbing polystyrene beakers and trays were chosen due to the following reasons: they are compatible with the microwave radiations and their effects; the shock-absorbing polystyrene does not warm up under the microwave action; they have a reduced weight and their mass is negligible in thermal subsequent calculations; the subsequent error entered is minor (the beaker mass is 2.4 g, and the tray mass is 7.7 g); it provides two significant forms for the drying process: compact volume and extended volume with a larger exposed surface to microwaves.

The initial water temperature was measured and then the container was introduced in the chamber of the oven. A power level was selected and then the material was irradiated for a determined period of time. The water temperature was measured at the end of the established time. Each experiment was repeated at least 3 times. This condition is necessary because of the special structure of the device, which has a power limiter mechanism that interrupts the microwave generation process when the generator is overheated. Therefore, the microwaves generation is not continuous; the limiter has the purpose of protecting the equipment against overheating.

In order to determine the drying kinetics, direct measurements were carried out using a synthetic blend consisting of siliceous sand and water. This blend was introduced in: beaker for compact volume experiment, and tray for extended volume experiment.

The working procedure was as follows: 95 g of siliceous sand were introduced in the container; the sand was considered as "perfectly dried" due to the drying in the oven at 105 ^{0}C for 8 hours. 35 ml of water were added to the sand. This amount is sufficient to cover all the sand in the container. Thus, it is possible to detect a phenomenon similar to that observed during the period I of the convective drying in constant conditions.

The material was irradiated with microwaves; e.g. "low level, L", and the temperature and weight of material were regularly measured.

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