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INTRODUCTION

Microwave appears to be especially attractive for food and pharmaceutical industries. Although there has been growing interest in industrial applications of microwave heating for last 20 years, the actual usage of this technology is still relatively small. [1] In spite of the costs of microwave-assisted technologies being higher than traditional drying with hot air, microwave heating offers some unique features including less hazardous processing and better product quality quantified by such attributes as color, flavor, texture, nutrient content, shrinkage, and bulk density. There are many works on microwave drying of thermally sensitive materials like kiwi fruits,[2] ginseng,[3] apple, and mushroom,[4] garlic,[5] banana,[6] strawberries,[7] rapeseeds,[8] cranberries,[9,10] grapes,[11,12] and peppercorns. [13]

Aside from numerous studies on microwave-assisted drying there are only few papers which report on nonuniform temperature profiles inside the single particle of a porous material saturated with water and heated with microwaves. [14–17] It appears that the sphere, cube, and ellipsoid are the shapes for which the highest temperature is noted in the centre of such a particle. Thus, the heat flow is directed from the centre to the surface of the material. The evaporation of water in the particle core should proceed faster than in the layers close to the surface. This phenomenon generates a pressure gradient inside the particle, which is the main force for the moisture transport both as liquid and vapor. This brings considerable changes into the mechanism and drying kinetics in comparison to conventional drying with hot air. It is noticeable that if particle dimensions are smaller than the microwave length (approximately 12 cm at 2450 MHz) the microwaves penetrate the whole volume of the material, thus affect the temperature and moisture profiles.

MATERIALS AND PROCEDURE

The tests comprised of the measurements of temporal moisture content and material temperature at various depths inside the spherical particle. This sphere was randomly moved and rotated by the air stream with respect to the electromagnetic field generated by a microwave generator. The parameters of the air stream (temperature, humidity, air velocity) were also collected. The tested spheres were 9, 18, 28, and 38mm in diameter.

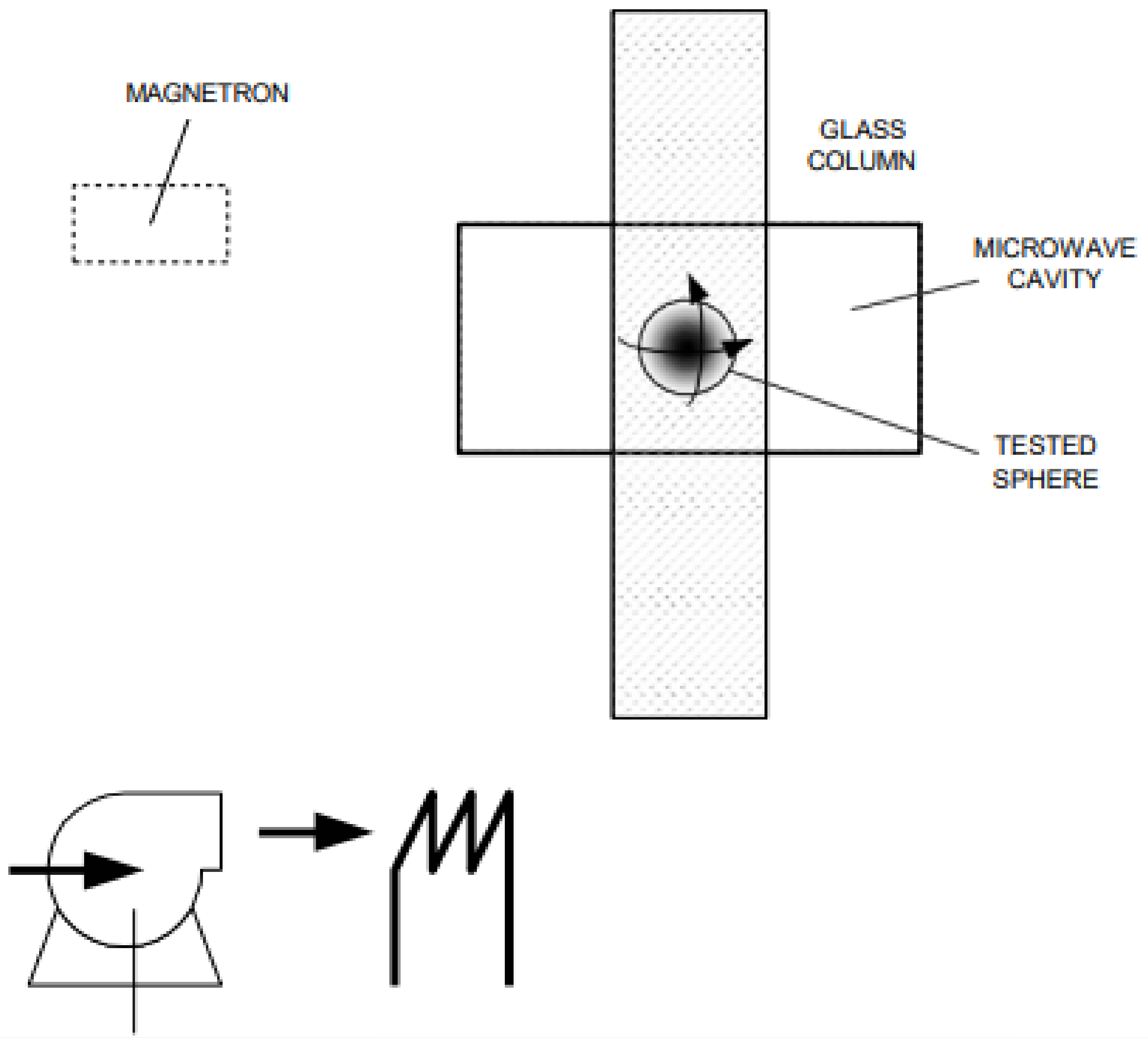

Figure 1. Scheme of the experimental set-up.

To achieve the same shape and size of the tested particles they were made from gypsum, because this material does not shrink during drying. It was also easy to make small (0.5 mm in diameter) holes at different depths, where thermocouples were inserted. Before each experiment the tested spheres were saturated with distilled water in order to achieve specific predetermined saturation of 0.6–0.7 kg/kg.

The tests have been conducted in a laboratory dryer (Fig. 1) comprising a microwave cavity, a fan, a pipe system, a rotameter, and a PC collecting data from thermocouples. The microwave generator at 2450 MHz and 800 W of nominal power has been equipped with a special device, allowing continuous supply of microwave power at controllable level from 100 to 800 W with 100 W increment. Inside the microwave cavity a quartz tube 100 mm in diameter was placed and connected with the air fan. The tested sphere was freely suspended in the air stream inside this column. A plastic pipe with water flowing at a controlled rate was wrapped around the lower part of the tube. The inlet and outlet water temperatures were measured to determine microwave power absorbed in this water load.

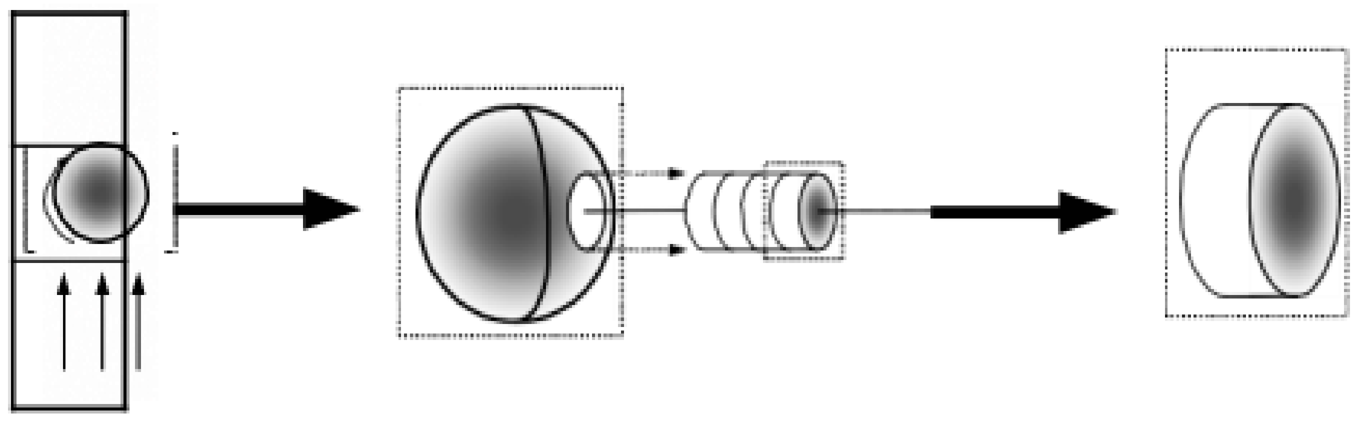

Figure 2. Taking the samples for determination the moisture profile inside the tested particle.

The experiments were conducted in a batch mode. After a specific time of drying the microwave heating was stopped, the material was taken out of the drying cavity to take measurements. The temperature was measured with a K-type thermocouple 0.5 mm in diameter inserted to a specific depth inside the tested sphere. Additional tests revealed that the measuring time (10–15 s) have no influence on the whole drying process. The accuracy of temperature measurements was 2ºC.

The determination of moisture profiles required several identical gypsum spheres with the same initial moisture content. They have been dried for a specific time and under the same conditions. Then, the sphere dried over a predetermined time was taken out and 10 mm cylinder has been cut at off at its center. That cylinder has been cut into 5 equal slices and moisture content was determined (drying to the constant mass) for every slice (Fig. 2).

RESULTS

Figure 3 presents the representative evolution of temperature profile during microwave-assisted drying. The temperature has increased inside the particle immediately after turning on the microwave heating.

After 30 s of heating the temperature at the centre of a particle was about 40ºC. The surface temperature rose by about 10ºC. The maximum temperature was attained after next 190 s of heating (t ¼ 210s), the core temperature was 76ºC and the surface one 46ºC. Further heating, however, did not increase the temperature; on the contrary, the temperature started to decrease. After next 360 s of heating the temperature inside the particle reached 40 and 29ºC on the surface. Such a characteristic run of temperature can be attributed to particularities of microwave heating,

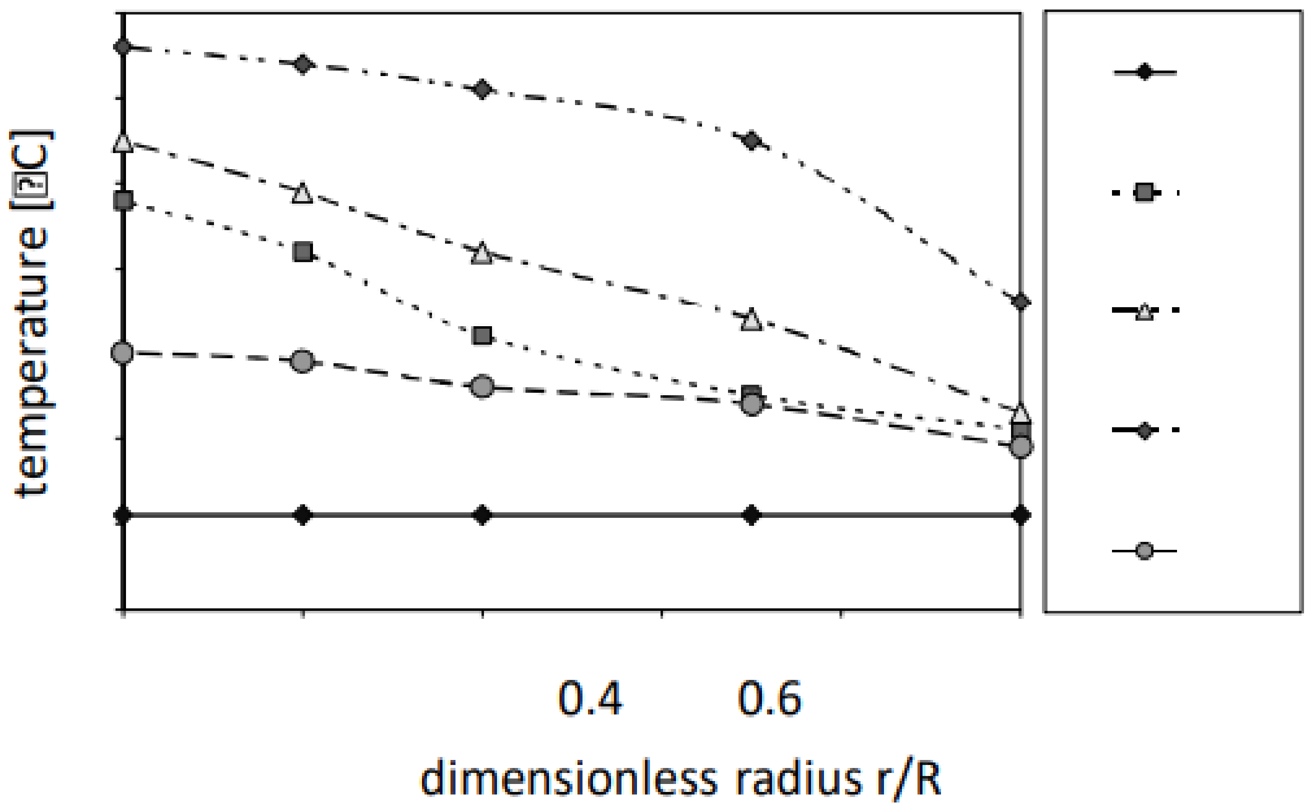

Figure 3. The temperature profiles inside the 28 mm particle heated with microwaves (600 W) and floated in air (40ºC).

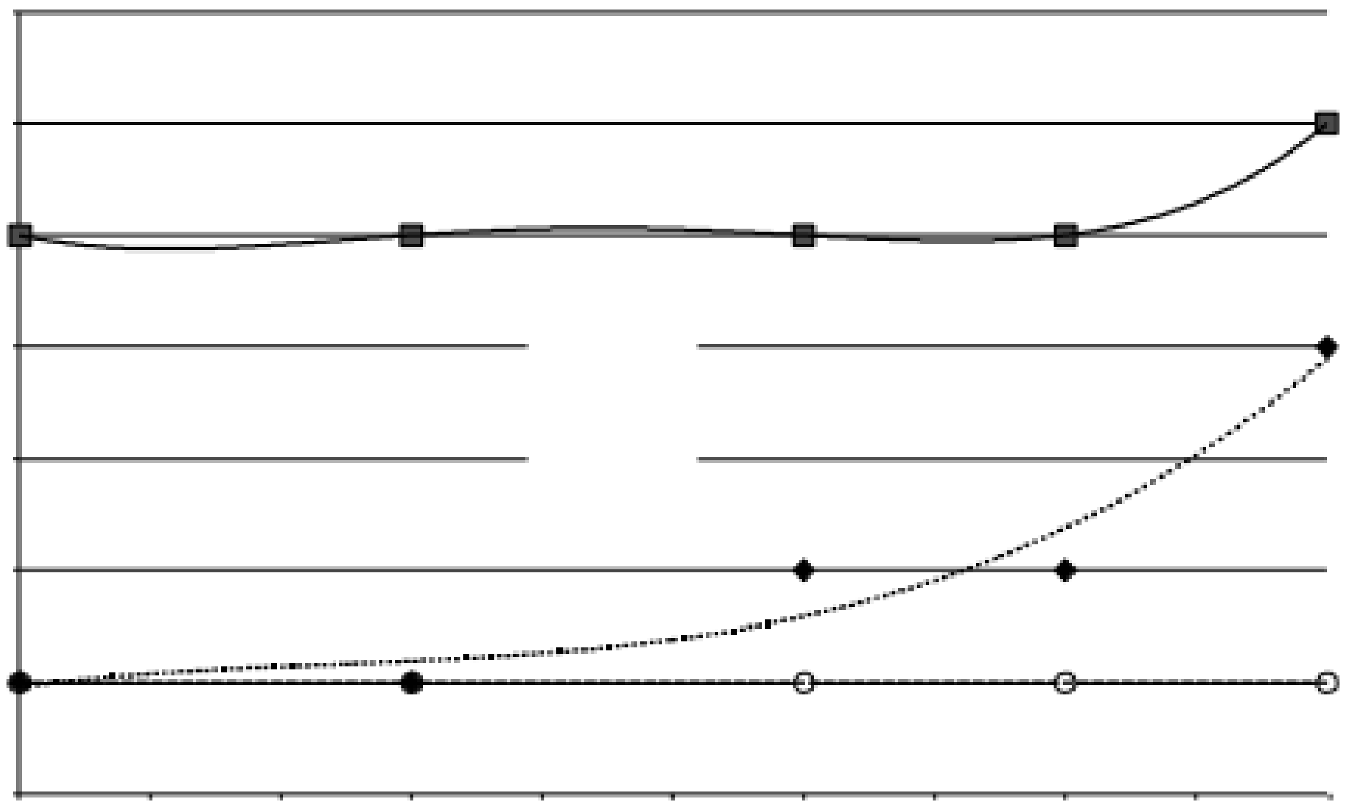

Figure 4. The temperature profiles inside the 28 mm sphere heated with only air (40ºC).

where the amount of heat generated by water interaction with microwaves decreases with moisture reduction in the material. Figure 4 presents the temperature profiles obtained during convective drying of a 28 mm spherical particle. As expected, the maximum temperature was noted at the surface of the particle. . The temperature increase was slower than during microwave-assisted heating, because of lower energy input. However, the temperature of the material was growing during the whole process of drying regardless of the material saturation. This is one of the most important differences between the dielectric and convective heating.

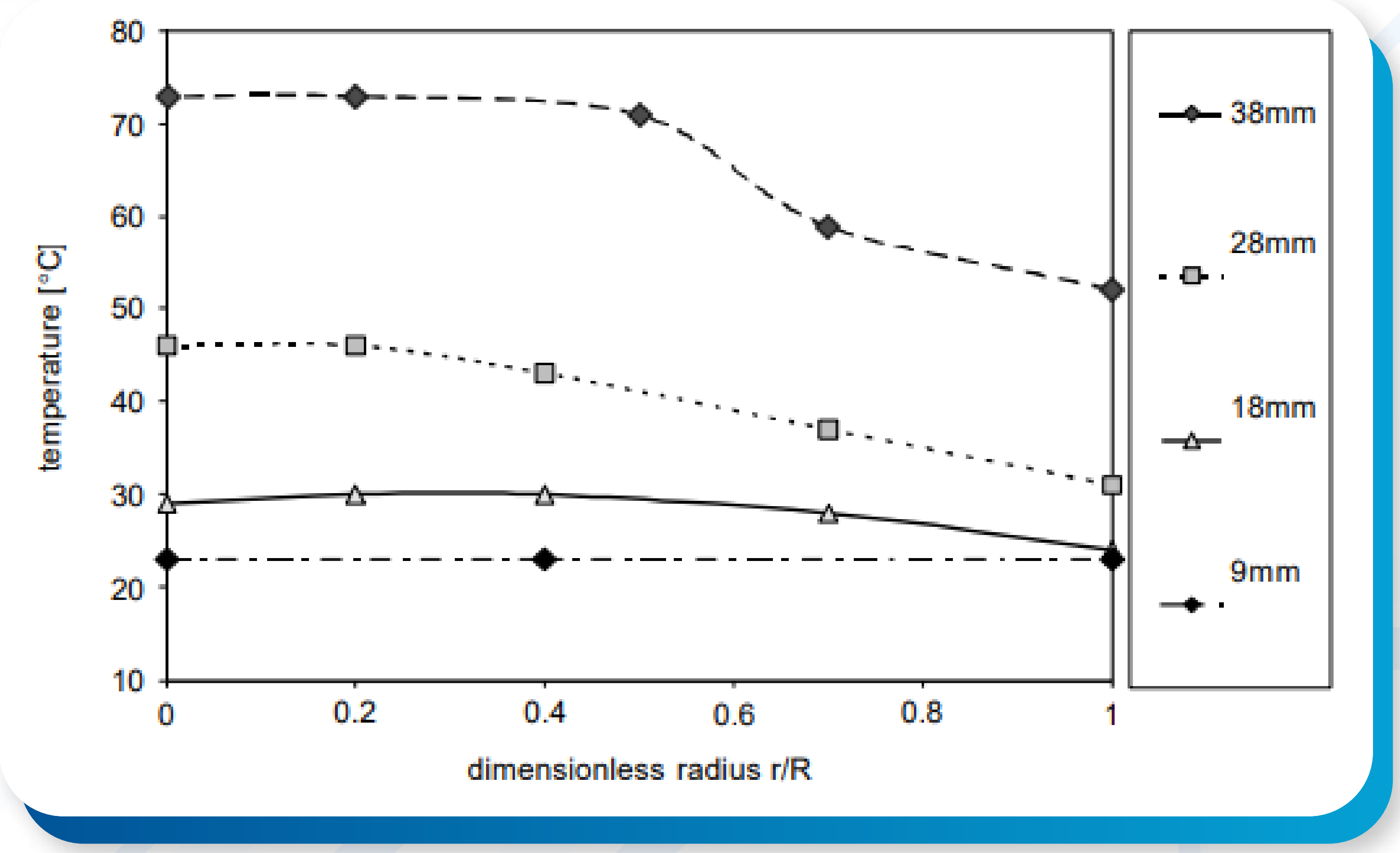

Figure 5. Changes in the temperature distribution profiles inside spheres of various diameters.

Temperature profiles in heated spheres of different diameter are compared in Fig. 5. The average drying time was 300 s at 800 W. Temperature of the biggest sphere (38 mm) reached 73 and 52ºC in its core and surface, respectively. For the smaller sphere (28 mm) the temperature readings were lower than for the larger one, namely 46ºC in the centre and 31ºC on the surface. The difference in temperature between the 18 mm sphere's centre and surface is approximately 6ºC. The smallest sphere (9 mm) has no noticeable temperature maximum inside.

The increase of temperature inside the geometrical centre of the sphere during microwave heating is shown in Fig. 6. The rise of temperature is clearly connected with moisture content. During the beginning of the process the material is heated greatly by internal heat generated due to interaction of liquid water with microwaves. When most of the water trapped inside the material vaporised, the temperature of material decreased significantly to the level of air temperature.

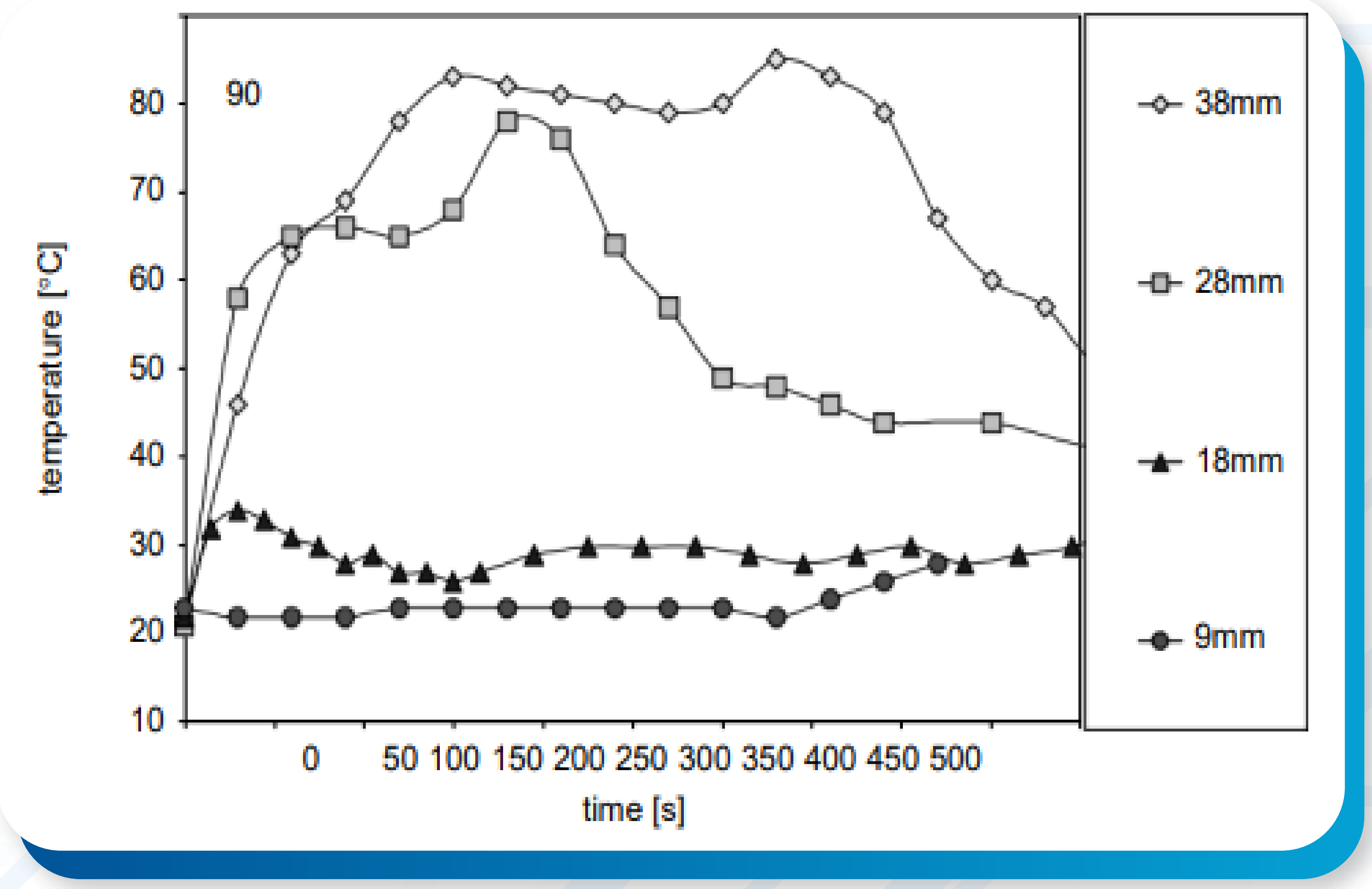

Figure 6. Evolution of temperature in the centre of spheres dried with microwaves (600W) and hot air (40ºC).

The moisture content tests were conducted to reveal the relationship between moisture content and heat generation inside the material. Due to the chosen measurement technique the moisture profiles were not very precise. Nevertheless, in view of no reported data these experiments gave some general information about moisture migration and profiles during microwave heating. The fastest removal of water appears to be in the centre of sphere (Fig. 7) in contrast to drying with hot air, where the highest dehydration is at the material surface. During microwave heating the mass flow of vapor in radial direction is strong enough to remove the liquid water from the pores located near the surface. Also, the high internal rate of evaporation increases the vapor pressure inside the material. This is the risk of destroying the heated material having closed pores.

However no changes was noted in radial moisture profiles for the smallest spheres (9 mm). Likely in this case the mass of moisture was too small to produce a strong vapor–liquid flow from the centre to the particle surface. The analysis of drying rate gives more information about the course of the whole drying process. The removal of water trapped inside the material is not so gentle like in the traditional drying with hot air (Fig. 8). The biggest differences appear to be in the case of drying 38 and 28 mm spheres.

That is clearly seen, that these particles were saturated with the largest amount of water in the four analysed spheres, and all processes connected with dielectric heating proceeded in this two cases with highest.

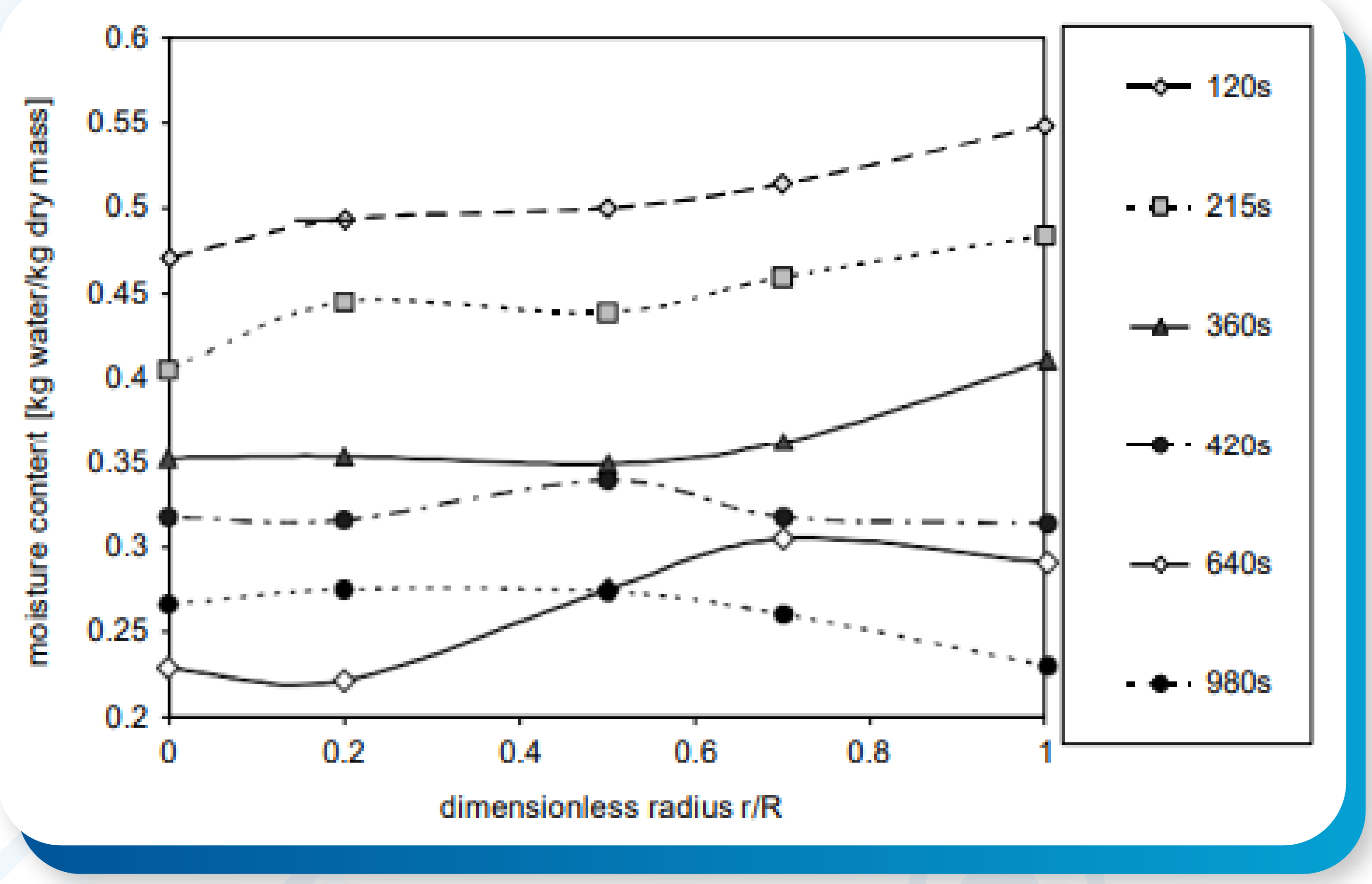

Figure 7. The profiles of moisture distribution inside the 38 mm sphere dried in 400 W microwaves.

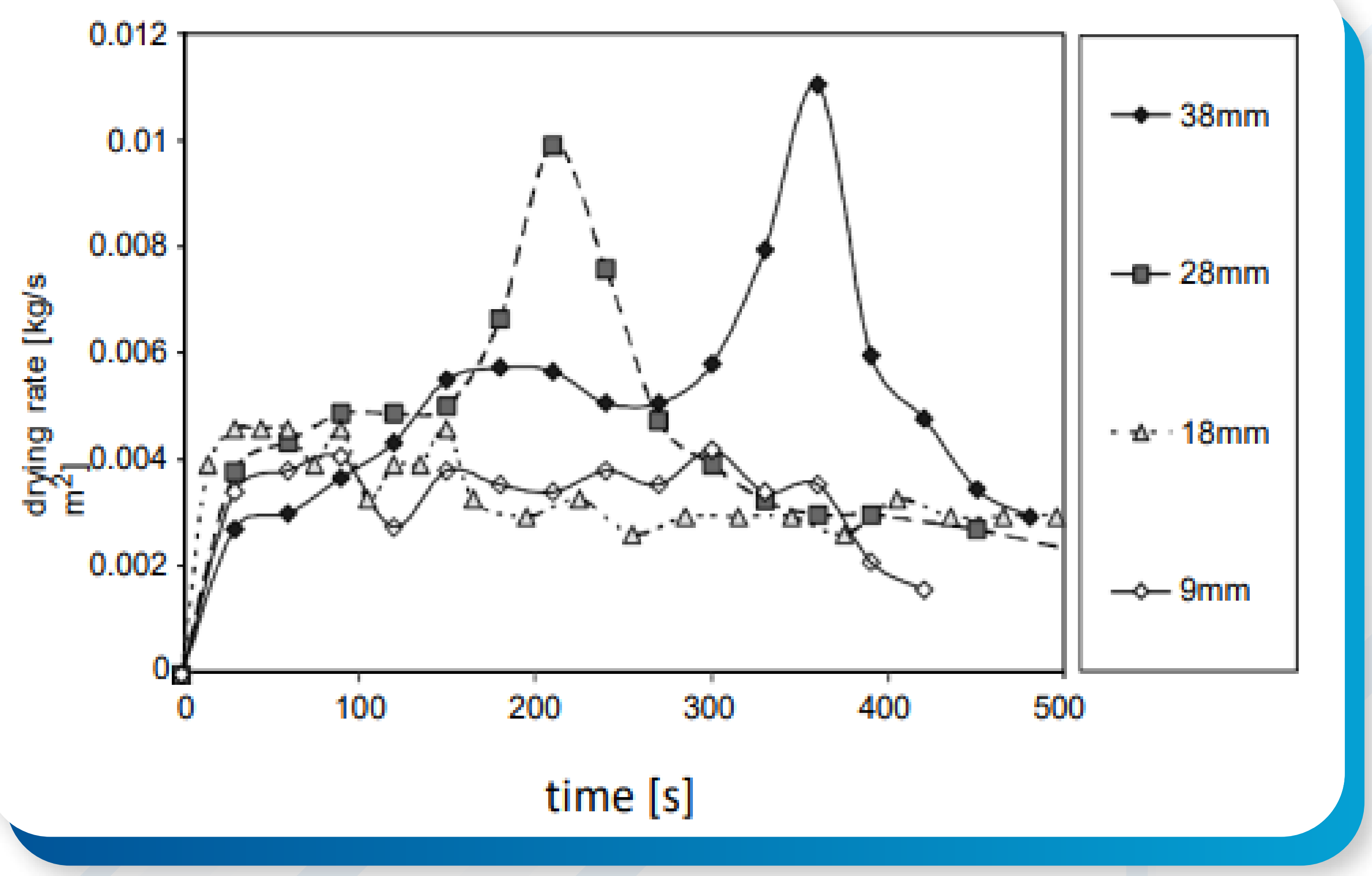

Figure 8. The changes in drying rate of different sized spheres dried with microwaves at 600 W. intensity. Here, the rate of drying rose rapidly in the beginning of the process and after that there was a short period of time, when the rate of drying stabilized. After that the rate of drying increased to the highest value in the whole process. Thereafter, the intensity of water removal decreased rapidly until the end of the experiment.

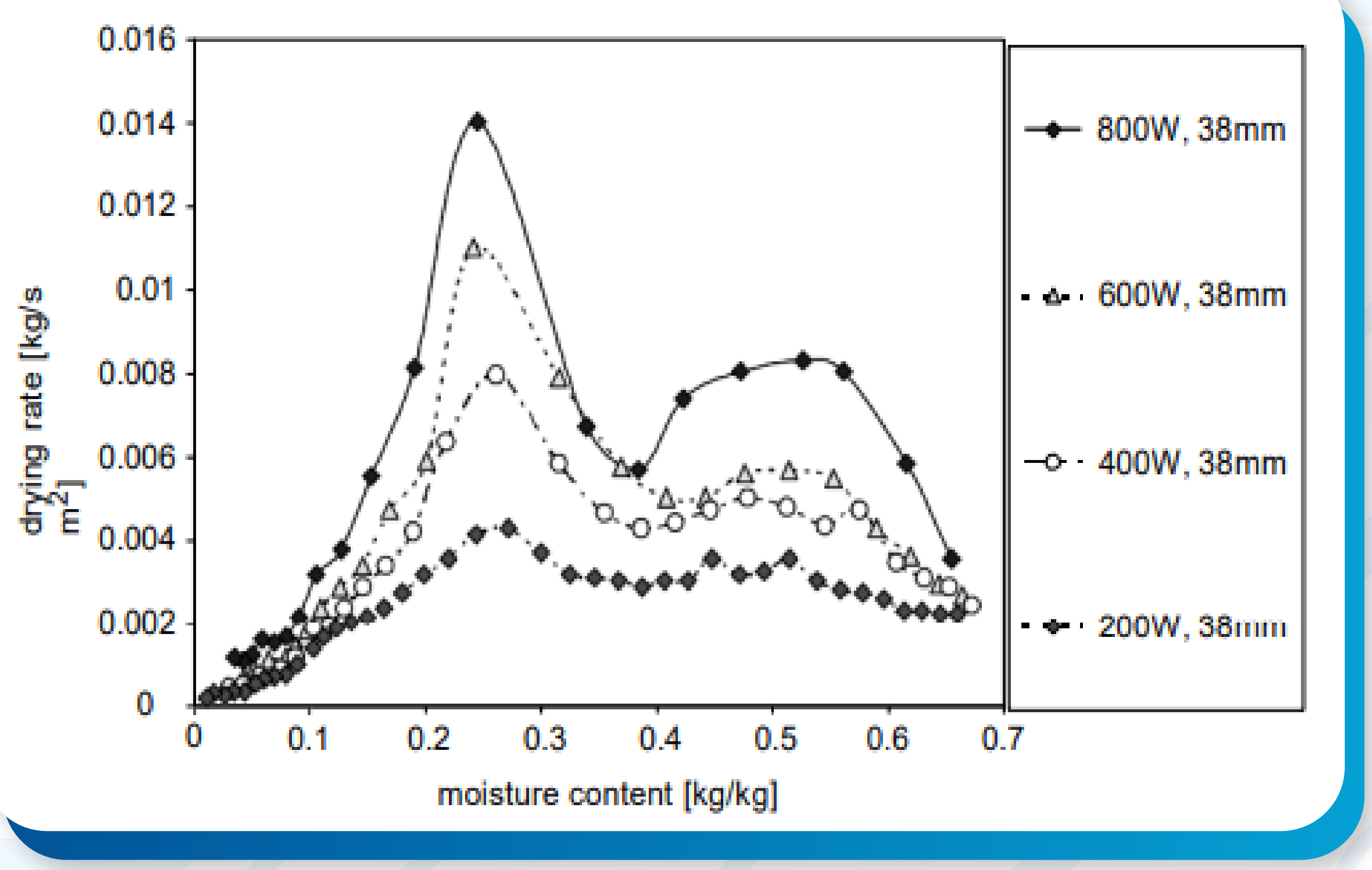

Figure 9. The changes in drying rate of 38 mm sphere heated at various levels of microwave power.

The magnitude of visible maximum of the drying rate is strongly connected with microwave power used in the processes. Figure 9 presents the comparison of changes in the drying rate of particles with the same size (38 mm) exposed to different levels of microwave power. The shapes of the curves are similar and level of drying intensity is proportional to the microwave power. The interesting fact is that the highest rate of water removal appears not in the beginning of the drying process. The maximum of the drying rate seems to appear near the same saturation value for each considered sphere with the same diameter (0.23 kg/kg in Fig. 9). The smaller particles (28 mm) had their maximum of drying rate slightly shifted to the higher saturation level, so the most intense removal of water in that case took place earlier during the drying process (cf. Fig. 8). The studies on mutual relationships between the rate of drying and particle temperature are in progress and future results will be published.

CONCLUSIONS

The temperature inside the porous sphere during drying is much higher than the temperature of its surface during microwave and microwave–convective heating. The intensity of heat generation is proportional to the content of moisture in a dielectrically dried material. The heat generation decreases due to the reduction of moisture during the drying process. Therefore the risk of excessive overheating of the dried material is considerably lower than during the traditional drying process with hot air. The changes in drying rate depend on the microwave power level. The drying conducted at lower microwave power gives more stable and gentle process of water removal. The size of the tested spheres has considerable effect on the intensity of the whole drying process. The bigger amount of water trapped inside the material provides higher intensity of heat generation. In that case, the level of all phenomena that appears inside the material are much more spectacular and intense.

ACKNOWLEDGMENT

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