Prosimy cytować jako: Inż. Ap. Chem. 2014, 53, 5, 334-336

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Determination of the relationship between drying rate and internal temperature development during microwave drying of porous materials

Introduction

Using microwaves gave positive feedback in drying various materials especially biological origin like ginseng [*Ren and Chen, 1998*], kiwi fruits [*Maskan, 2001*], banana [*Maskan, 2000*], okra [*Dadali and Apar, 2007*] and many more. The most significant advantage of microwave drying is reduction of process time [*Garcia and Bueno, 2010*], lesser risk of overheating the material surface and its shrinkage [*Kowalski and Mielniczuk, 2008*], and overall much better control of a drying process. The problem with temperature non uniformity during microwave drying is discussed by *Li et al.* [*2011*]. Also the same problem was discussed in Authors' previous work [*Araszkiewicz et al., 2006*].

The overall product quality can be increased during microwave assisted process. One can use microwaves as a mean of pre-treatment of the biological material before traditional drying [*Dev et al., 2008*]. The size of a material can have influence on the internal resistance which may lead to increment of vapour pressure and increase the dynamics of water removal from the material [*Jia and Afzal, 2008*]. That phenomenon can also lead to the material destruction and internal damage of its solid matrix. That problem was profoundly discussed by *Kowalski and Rybicki*, [*2007*].

Microwave drying of heat-sensitive biological materials has different drawbacks that should be considered prior to the process. Due to the material shrinkage its volume reduces and power dissipated within the material can lead to overheating even if moisture content is not so significant [*Roques and Zagrouba, 1997*].

The most important difference is connected with the general microwave drying mechanism, which depends on the intensity of internal heat generation and moisture flow outside the dried material. The heat generation appears to take place inside the material and widen towards the surface. The temperature increment is a direct reason of moisture evaporation. That process is not regular as it can be observed during traditional drying with hot air. The following two general stages of drying can be determined: a constant one when the moisture is constantly transferred towards the material surface, and a falling rate stage when the moisture removal rate gradually diminishes. During microwave drying process the moisture removal takes place according to the different mechanisms. The main driving force of moisture removal is connected with increment of vapour pressure inside the material placed within an electromagnetic field.

The material porosity and its ability to let the vapour out of the solid matrix is an important factor that decides about dehydration kinetics. In the case of a mechanically sensitive (fragile) material it could lead to the material destruction. The rate of microwave drying strongly depends on the temperature distribution inside the material. There is a serious problem with conducting experiments with the material placed inside an electromagnetic field. Therefore, using advanced technology like fibre optic temperature sensors or IR camera seems to be necessary to reveal processes that take place inside the material [*Araszkiewicz et al., 2007*]. Therefore, an analysis of mutual relationship between these two parameters can result in better understanding of the mechanism of water removal during that process and help in proper designing of microwave drying processes. That is the main subject of this study.

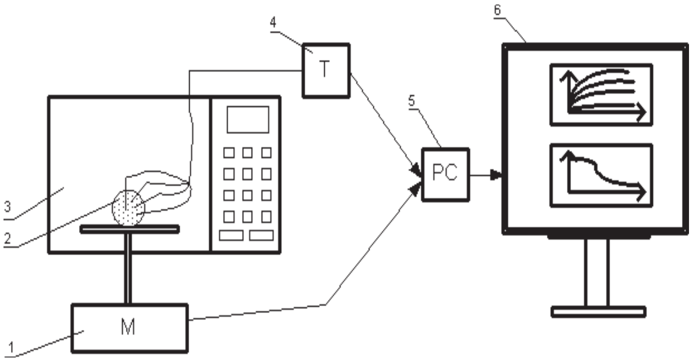

Fig. 1. Experimental setup: *1* – scale, *2* – sample, *3* – microwave chamber, *4* – system of fibre optic sensors, *5* – PC unit, *6* – monitor

Experimental setup

The experiments were conducted in a laboratory setup shown in Fig. 1. There were done experiments of microwave drying with 200, 300, 400 and 500 W of nominal microwave power. The microwave reactor was fed with microwave power with stable microwave power level.

The main idea of experiments was to monitor continuously both the sample mass and its temperature during microwave heating. Series of experiments were also done on drying with hot air (air temperature 150°C and velocity approx. 1 m/s) for comparison.

The temperature was read with fibre optic sensors (*Lumasense*, USA, STF probes with 0.25 seconds of response time, temperature range 0÷296°C).

Mass reduction was measured with the scale (Radwag, Poland, model WLC A2 with accuracy ±0.03 g). Both mass and temperature reading devices were connected with PC unit where the data were collected in a real time.

Two software were used for collecting data from fibre optic sensors – *True Temp* and from scale – *PomiarWin*. The only exception was made for experiments on drying with hot air where standard thermocouples were chosen for temperature reading – that was done specially for fibre optic sensors protection, which turned out to be extremely mechanically fragile and thermally sensitive.

The gypsum spheres were chosen as a model material. That is a quite popular and comfortable material for a testing various microwave parameters. The authors used such a material in previous experiments [*Araszkiewicz et al., 2006*]. It is isotropic, hygroscopic capillary-porous material which can be formed into any desired shape. Also, it does not shrink during drying experiments [*Holtz et al., 2009*].

The spheres prepared for experiments had 4 cm in diameter. Four holes with different depth (2 cm, 1.6 cm, 1.1 cm and 0.6 cm) have been drilled radially in every sample where the fibre-optic temperature sensors were placed. The sample was placed inside the microwave cavity on a scale pan. The gypsum spheres were submerged for 5 min into distilled water to fill completely the pores within the sample. The initial moisture content was equal to 0.40±0.02 kg/kg. After that they were blotted with paper towel to remove the surface moisture before placing in the microwave cavity. Each drying experiment was scheduled for 10 minutes.

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Experimental results

As seen in Fig. 2, material temperature increases gradually during microwave drying with 200 W of nominal microwave power. There are distinct differences in temperatures between surface and centre of the tested material. The highest temperature differences (approx. 40 K) can be noted after 200 seconds of drying. A rapid temperature rise can be noted during first 80 seconds of the drying process.

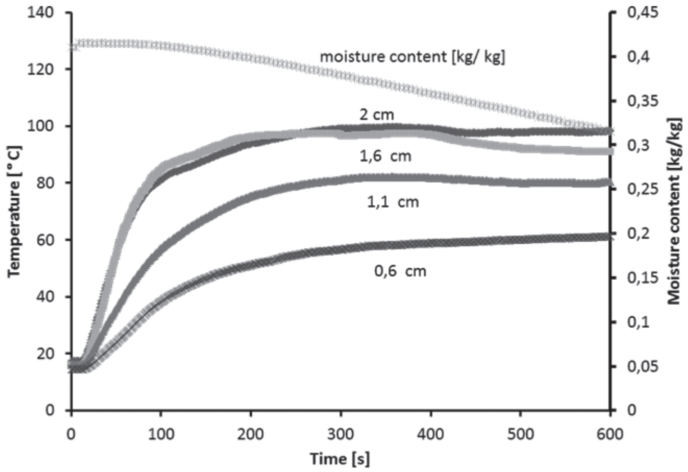

Fig. 2. Internal temperature distribution and moisture removal during microwave drying at 200 W of power setting

After that, temperatures in all tested depths rose moderately. Temperatures remained almost at the same level after approximately 300 seconds of process. The moisture removal started after first 100 seconds of microwave irradiation which is connected with temperature development inside the tested material. After that point moisture is removed constantly till the end of experiment.

Generally, the whole drying process can be divided into two stages: gradual temperature rising and stable temperature during the rest of the process.

Microwave drying with higher power level (300 W) brings considerable changes in drying process course. Temperature distribution inside the material is quite leveled. The significantly lower temperature was noted near the material surface. During first seconds of drying the material temperature rose gradually. Next, after 250 seconds temperature remains almost stable. After that there is seen an instantaneous temperature peak (approximately between 10 to 20 K, Fig. 3). That phenomenon lasted almost 40 seconds. Moisture content fell gradually during drying. However, there is significant rise of the drying rate during noticed temperature growth. The final moisture content reached 0.17 kg/kg, which is almost two times lower than in the previous case in the same time. There is clearly seen an irregularity in moisture removal during microwave drying. Similar effect was observed by *Roques and Zagrouba* [*1997*].

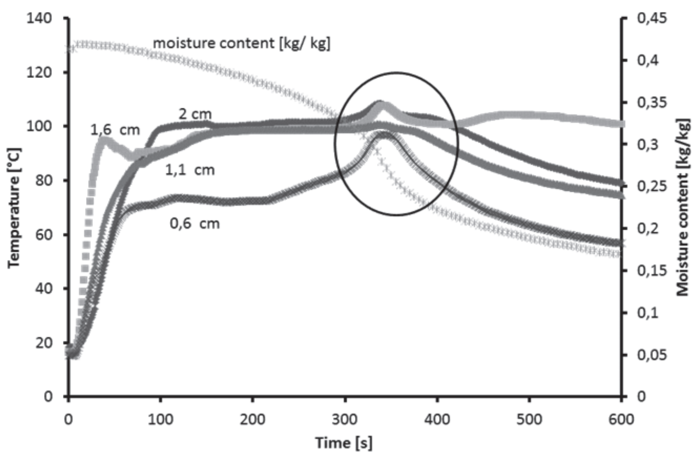

Fig. 3. Internal temperature distribution and moisture removal during microwave drying at 300 W of power setting

Temperature development during microwave drying at 400 W of microwave power is similar to the previous case (Fig. 4). The noticed temperature peak takes place earlier (approximately at 250 seconds of drying). The material temperature remains still constant after that moment and even decreases at 300 seconds which can be attributed to high water removal and lack of heat source. There is a difference between surface and core temperature, almost 40°C in the first minutes of drying. Near the visible temperature peak the temperature distribution within material is almost leveled. After that moment, the temperature difference inside the material rises. Final moisture content is also smaller than in the previous cases – 0.09 kg /kg.

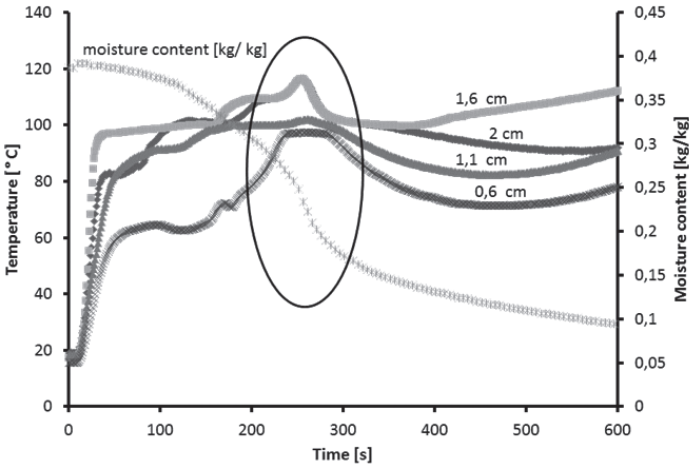

Fig. 4. Internal temperature distribution and moisture removal during microwave drying at 400 W of power setting

Fig. 5 presents the characteristics of drying at the highest power level used in that series of experiments, namely at 500 W of nominal power setting. Interestingly, two distinct temperature peaks appear at approximately 280 and 440 seconds of drying. Temperature development has, without two mentioned earlier peaks, general upward trend. At the end of experiment (10 minutes) temperature reached almost 140°C. The temperature behavior has its influence on the moisture removal intensity. The instants with temperature peaks are strictly connected with the increasing rate of drying. The final moisture content attains also the lowest value from the other cases. On the other hand, using hot air (150°C) did not bring any spectacular results (Fig. 6). The moisture content decreases steadily during the entire drying process.

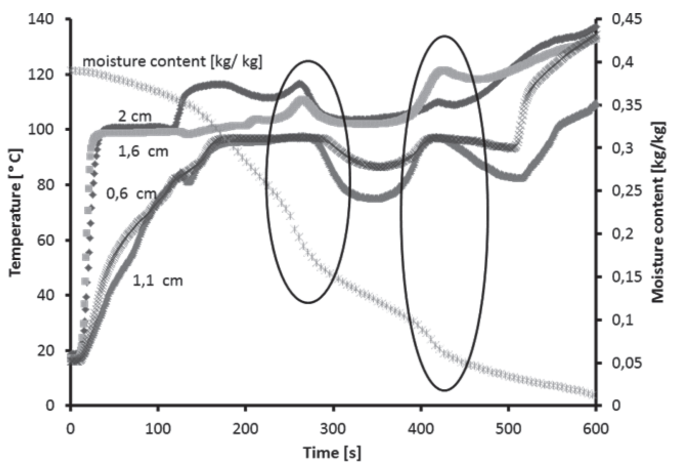

Fig. 5. Internal temperature distribution and moisture removal during microwave drying at 500 W of power setting

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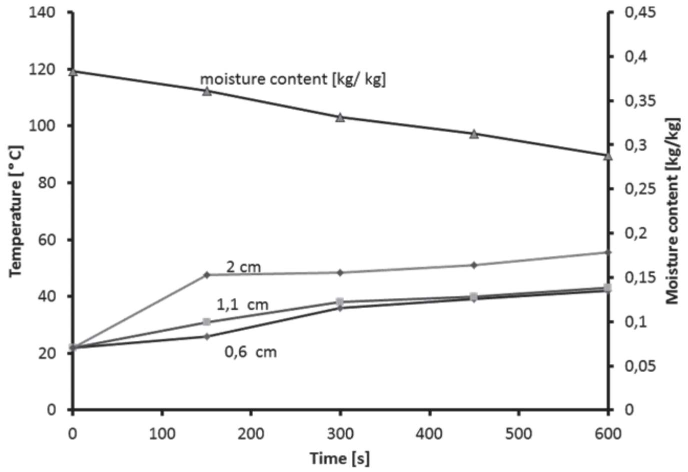

Fig. 6. Internal temperature distribution and moisture removal during hot air drying with 150°C

Temperatures inside the material rise gradually with obviously higher temperature at the material surface. Internal thermal gradients were not higher than 20°C at 150 seconds of drying. Drying process in that case took place quite gently and free from unexpected phenomena.

An analysis of the drying rate shown in Fig. 7 reveals how rapid can be microwave drying. The values of drying rates for microwave drying cases are significantly higher than the hot air ones. An analysis of experiments at 300, 400 and 500 W brings to the conclusion about some regularity of temperature development during microwave drying. Firstly, the highest temperature is not reached in the beginning of the drying process. The material temperature rises gradually and after the specific time period (shorter for higher microwave power level) reaches its maximum.

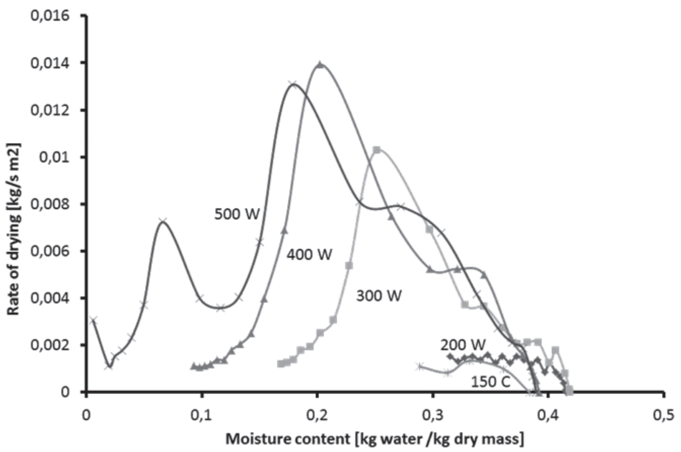

Fig. 7. Rate of drying in all analysed cases

Quite interesting appears to be the mutual relationship of that phenomenon with instantaneously increasing rate of drying. It seems that water is pushed out from the dried solid after reaching specific temperature and possibly the vapour pressure level. That phenomenon has already been observed during experiments in semi-technical scale with microwave drying of rapeseeds [*Lupinska et al., 2009*]. That local forming of temperature maximum was observed once during drying at medium microwave power levels: 300 and 400 W. However, using slightly higher power (500 W) brought quite interesting result. The mentioned earlier temperature maximum appears twice in that case. It seems that due to the rapid temperature generation water is not able to escape from the drying material. That residual water generates heat and the second peak can be observed.

Conclusions

- There are some irregularities in temperature rising during microwave drying in second (falling) period of drying. That phenomenon was connected with fleeting changing rate of drying.
- Magnitude of used microwave power has its influence on the process dynamics. Higher microwave power level leads to the higher rate of drying and temperature reached (almost 140°C for process with 500 W of microwave power level).
- Intensity of water removal during microwave drying is not constant. The course of rate of drying has distinct peaks especially visible in 500 W series. These peaks are somehow mutually connected with temperature increment in the same moment.

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