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EFFECTS OF MW-HOT AIR PARAMETERS ON DRYING SOYBEANS IN THE ROTATING DRUM

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Abstract: The influence of microwave power, temperature and velocity of the hot air stream on drying rate, uniformity of drying and temperature of the material in microwave and microwave-convective drying of soybeans in the rotating drum was studied experimentally. Temperature of the material surface and drying uniformity were visualized and analyzed with the IR Thermal Imager. Compared with the sole microwave drying it was found that in the accelerating drying rate stage blowing hot air through the cascading bed of MW-heated soybeans is highly beneficial to reduce the material surface temperature, enhance drying rate and improve drying uniformity. However, in the falling drying rate stage the effect of hot air on drying rate was not so advantageous since the drying uniformity was worsened and the material temperature increased with hot air temperature. On the other hand, higher hot air velocity increases drying uniformity and reduces material temperature in the falling rate period which dominates the drying process but worsens the quality of soybeans quantified in terms of the cracking ratio.

Introduction

Microwave (**MW**) heating is characterized by rapid volumetric heating which results in an enhanced drying rate and much more uniform drying and improved product quality [1]. But MW drying alone has some major drawbacks that include uneven heating, possible textural damage, and limited penetration of the MW irradiation into the drying material [2] as well as economical constraints. To overcome these drawbacks the MW-based hybrid technologies were extensively studied, especially on MW-assisted air drying [3–12]. Two process configurations exist through which MW energy can be combined with hot air drying. In the first configuration, MW energy is applied simultaneously with hot or cold air throughout the entire drying whereas in the second one MW energy is added at different stages of convective drying, namely, at the beginning of drying to pre-heat the material to evaporation temperature, at the incipient of the falling drying rate period (booster drying), or at the end of drying to efficiently remove residual moisture (finish drying) [13].

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Overall, the findings point on shorter drying time, improved drying efficiency and product quality when compared to hot air drying. The improved product quality was mainly due to shorter drying time in microwave drying. But the effect of hot air on microwave drying uniformity has been occasionally reported in the literature through qualitative perception of better product quality as a result of improved drying uniformity [5].

Heating uniformity is a major contribution to product quality, which has been reviewed by Li et al. [14]. Focusing on the uniformity of microwave drying, this study has been performed in a microwave rotary dryer that offers more uniform microwave drying due to random movement of the particulate material in the rotating drum and therefore permits to overcome the drawback of limited MW penetration. The objectives of this study were to qualify the effects of temperature and velocity of hot air and microwave power on the drying rate, drying uniformity, and temperature of the material surface using soybeans as the model material.

Materials and Methods

Material and apparatus. Dry soybeans (variety Northeast yellow, produced in Northeast China) purchased in the local market were soaked for 30 minutes in distilled water at 20 °C. Then, the wet kernels were put in the airtight polyethylene bags and conditioned in the refrigerator at 4 °C for 72 hours with periodic mixing. Such a procedure secured initial moisture content of (40 ± 1) % d.b. and even distribution of water in the soybean kernels. The homogenized kernels were then screened for fissures and the only intact ones were selected for the experiments. Prior to drying, the batch of 400 g to be used in a single experiment was removed from the fridge and left for 2 hours to bring the kernels to room temperature. The initial moisture content (d.b.) of soybeans was determined by drying the wet kernels in the convective oven at 95 °C to a constant mass, which was attained after 6 to 7 hours of drying. The temporal moisture content was then calculated from the mass loss measurements and the final one was again determined with the oven drying method to confirm the correctness of drying curves.

A domestic microwave oven operated at 2450 MHz was used as the microwave power source offering 5 adjustable power levels, namely 126, 252, 406, 567 and 700 W. It should be noted that the power level does not reflect the absolute MW power as the domestic MW oven operates intermittently which is demonstrated by the scatter of experimental points in Figures 3 to 8. Temperature of the soybeans surface was determined with the IR Thermal Imager (Fluke, Ti50) with accuracy ± 2 °C.

A schematic drawing of the experimental MW-hot air drying apparatus is shown in Fig. 1. The rotary drum (150 mm in diameter and 200 mm long) made from Plexiglas

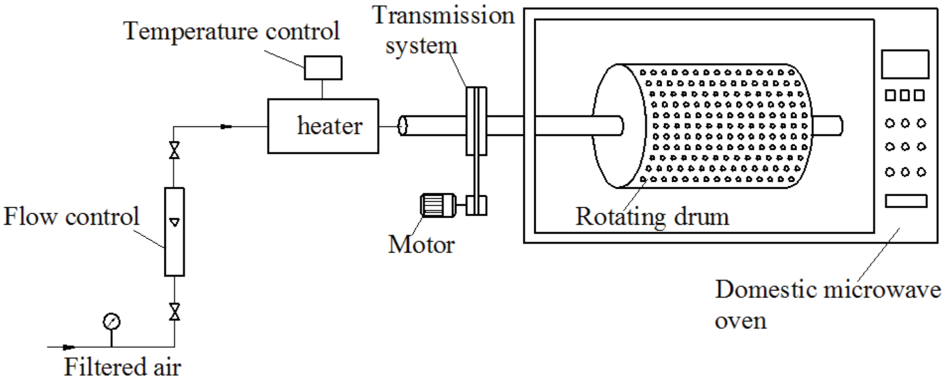


Fig. 1. Schematic of the MW-hot air rotary dryer

has 6 symmetrically positioned lifters (200 mm × 5 mm) parallel to the drum axis. The drum wall is perforated with 630 orifices 3 mm in diameter to evacuate water vapor. The drum is driven by a frequency-controlled AC motor. In these experiments, the rotational speed of the drum was set at 15 rpm. The air stream supplied to the rotating drum by a compressor was heated in an electric heater; the hot air temperature was maintained at the pre-set level of 30, 50 and (70 ± 1) °C by a temperature controller. Air velocity in the axially positioned supply tube (10 mm i.d.) was set at 0.5 and (1.0 ± 0.05) m/s.

Following earlier studies [15, 16] it was expected to get better drying uniformity in this microwave rotary dryer than in the static condition.

Experimental procedure. To secure the same experimental conditions, the microwave oven was operated before each experiment for 20 min with 500 g of water load in a glass beaker. To measure the soybeans mass loss and determine the temperature of soybean surface during experiments on both MW and MW-hot air drying, the microwave power was turn off every 5 minutes, the door of the oven was opened, and the photo of the drum was taken by the IR Thermal Imager. Then, the rotary drum with soybean kernels was quickly taken out of the oven to determine the current mass of dried soybeans. All these operations took about 30 s, which was assumed to have negligible effect on the drying process. When the dry basis moisture content attained 14 %, the experiment was terminated.

Analysis of the experimental data. Using the analysis software of the IR Thermal Imager, temperature distribution across the soybean batch can be seen intuitively through the image as presented in Fig. 2. However, the shortcoming of this technique is that it does not analyze the particular area of the interest. Therefore, in this paper the temperature data were extracted from the image and then re-analyzed.

At the drying time *t*, the recorded data over the material area comprised the local temperature T_i and pixel M_i. The proportionality factor κ_i at temperature T_i was calculated from the following formula:

$$\kappa_i = \frac{M_i}{\sum M_i} 100 \ \%. \tag{1}$$

In the experimental analysis, the following parameters were calculated:

The average surface temperature of soybeans $\overline{T}$:

$$\overline{T} = \sum \kappa_i T_i . \tag{2}$$

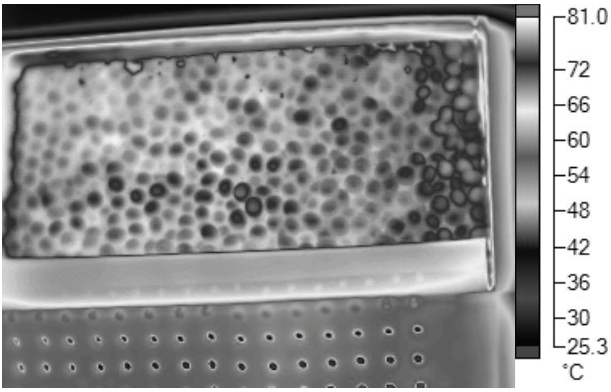


Fig. 2. Temperature distribution as visualized by the software of the IR Thermal Imager

The deviation of temperature δ:

$$\delta = \sum \kappa_i \left| T_i - \overline{T} \right|. \tag{3}$$

The temperature difference ΔT:

$$\Delta T = T_{t\,\max} - T_{t\,\min}. \tag{4}$$

Where $T_{t\,\max}$ and $T_{t\,\min}$ (°C) represent the highest and the lowest temperature at the drying time t.

In the drying process, the temperature of soybean surface T_s was expressed by the average temperature $\overline{T}$. Because the drying uniformity is related to the uniformity of temperature distribution, in these experiments the drying uniformity was quantified by the deviation of temperature δ and the temperature difference ΔT. It was accepted that the greater deviation of temperature and temperature difference the worse the drying uniformity.

It is widely accepted that high-intensity drying such as MW-assisted drying results in stress cracking extending from surface fissures to material fracture when the local tension exceeds the ultimate strength of the material [17–21]. The reason for cracking is the shrinkage phenomenon that induces internal stresses when distribution of moisture and temperature within the wet material becomes non-uniform. In the case of microwave drying this shrinkage phenomenon may be complemented with the internal pressure built-up which generates a pressure gradient imposing tension on the near-surface layers. With respect to grains, cracking is detrimental to product quality since affected kernels are more susceptible to mould attack, have reduced germination and inferior organoleptic features. The usual method of assessing grain quality is based on visual observation of surface fissures followed by germination tests. Detection and quantification of internal cracks which do not manifest through split kernels but affect the germ and thus reduces the seeding value needs sophisticated techniques such as magnetic resonance imaging [22] or soft X-ray photography [21, 23, 24]. Because in this study the source soybean was of food grade the grain quality was quantified by the cracking ratio defined by the mass fraction of split grains. The higher cracking ratio points on worse quality of dried soybeans.

Results and Discussion

The effect of hot air temperature on drying rate, material surface temperature and drying uniformity in MW-hot air drying of soybeans. To study the effect of hot air temperature, a series of experiments were performed for sole microwave drying (**MW**) and MW-hot air drying (**MWHA**) at air temperature T_a equal to 30, 50 and 70 °C.

As seen from the drying rate curves in Fig. 3, in the beginning of drying the water removal was greatly accelerated when microwave irradiation was combined with hot air. This effect can be ascribed to the following mechanism: in the beginning of drying, the material having high moisture content absorbs a large fraction of microwave power so both the temperature and internal pressure in the material core builds-up causing rapid increase in water evaporation. Thus, the fraction of not yet evaporated liquid water is forced by the water vapor to the material surface. At that time, the hot air stream enhances evaporation of liquid water from the material surface and thus augments the drying rate. In the falling drying rate stage, with increasing material temperature and decreasing water content in the near-surface layers, hot air does no longer contribute to the higher drying rate so the drying process is governed by internal conditions.

As concluded from temperature curves in Fig. 3, the average temperature of the material surface increased with the drying time irrespectively of the air temperature. Compared with sole microwave drying, the air stream could reduce the material surface temperature in the accelerating drying rate stage. This phenomenon can be attributed to the presence of liquid water on the material surface so the primary role of the air stream was to speed up evaporation of water. Because vaporization consumes thermal energy, the temperature of the material surface decreases due to evaporative cooling. But in the falling drying rate stage, lower temperature of hot air (T_a = 30 °C) reduced the temperature of the material surface in contrast to higher air temperature (T_a = 70 °C) which increased the material surface temperature. The rationale for this effect lies in lower temperature of the hot air stream flowing across the product than the material temperature during microwave drying that induced the cooling effect as opposed to air temperature higher than the temperature of the material surface. The excess heat over the fraction needed for water evaporation increases the material surface temperature. Thus, in the falling drying rate stage the temperature difference between hot air and the dried material will determine the rise or decay of the material surface temperature.

The curves in Fig. 4 show that the drying uniformity, whether with or without air flow, worsens gradually with time in the entire drying process. Compared with the sole microwave drying, in the accelerating drying rate stage, the drying uniformity was improved when hot air and microwave were combined. However, in the falling drying rate stage (below 30–35 % d.b.), the drying uniformity was reduced dramatically, and the degree of drying non-uniformity amplified with air temperature.

For the aforementioned reasons, the effect of hot air on the uniformity of microwave drying can not be generalized. When the moisture content in drying materials is high with a large fraction of free water the self-balancing of microwave drying is better. Thus, the drying uniformity is also better than at lower moisture content when the self-balancing of microwave drying is not as good as for highly wet materials.

Interestingly, the material surface temperature shown in Fig. 3 for T_a = 30 °C was lower than for sole microwave drying, but Fig. 4 points on less uniform drying at this temperature. As mentioned in the paper by Sharma and Prasad [7], lower temperature

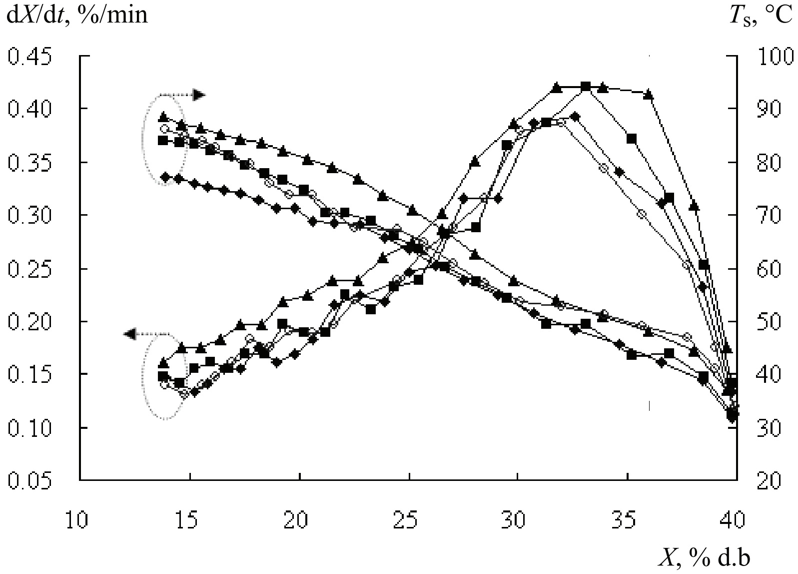
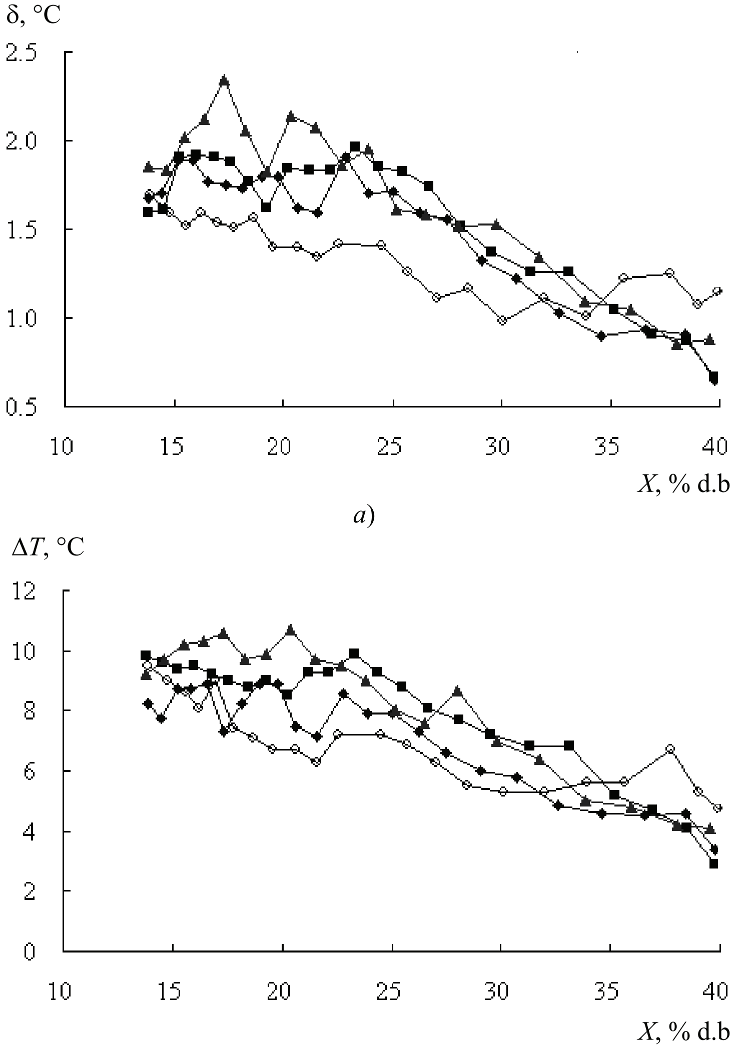


Fig. 3. Effect of hot air temperature on drying rate and temperature of soybean surface (P = 126 W, v = 0.5 m/s):
◆ – MWHA – 30 °C; ■ – MWHA – 50 °C; ▲ – MWHA – 70 °C; ○ – MW



a)

b)

Fig. 4. Effect of hot air temperature on drying uniformity (P = 126 W, v = 0.5 m/s):
◆ – MWHA – 30 °C; ■ – MWHA – 50 °C; ▲ – MWHA – 70 °C; ○ – MW

of hot air can reduce the temperature of the material surface and improve the product quality. As evidenced by these experiments, reducing the material surface temperature will not necessarily improve the uniformity of drying. So, we cannot simply conclude that better product quality means improved the uniformity of drying because the degree of drying uniformity is just only one of the factors affecting the product quality.

The effect of hot air velocity on drying rate, material surface temperature and drying uniformity in MW-hot air drying of soybeans. Fig. 5 shows the curves of the material surface temperature and drying rate when the temperature of hot air was 70 °C whereas Fig. 6 presents the drying uniformity.

In the accelerating drying rate stage down to 35 % d.b., the air stream velocity had no significant effect on temperature of the material surface. Over this stage the drying was more uniform at higher air velocity which contrasted the dominant falling drying rate stage. Namely, temperature of the material surface was reduced and the drying uniformity was improved with increasing hot air velocity as shown in Fig. 5 and Fig. 6.

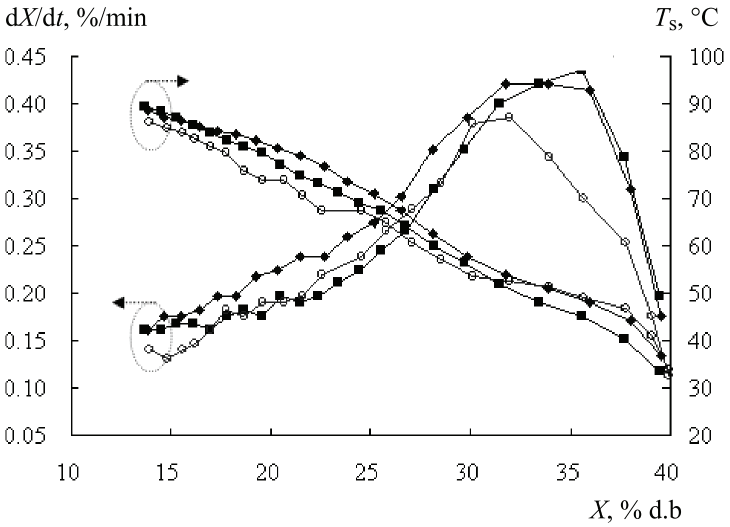


Fig. 5. Effect of hot air velocity on drying rate and temperature of soybean surface (P = 126 W, T_a = 70 °C):
◆ – MWHA – 0,5 m/s; ■ – MWHA – 1 m/s; ○ – MW

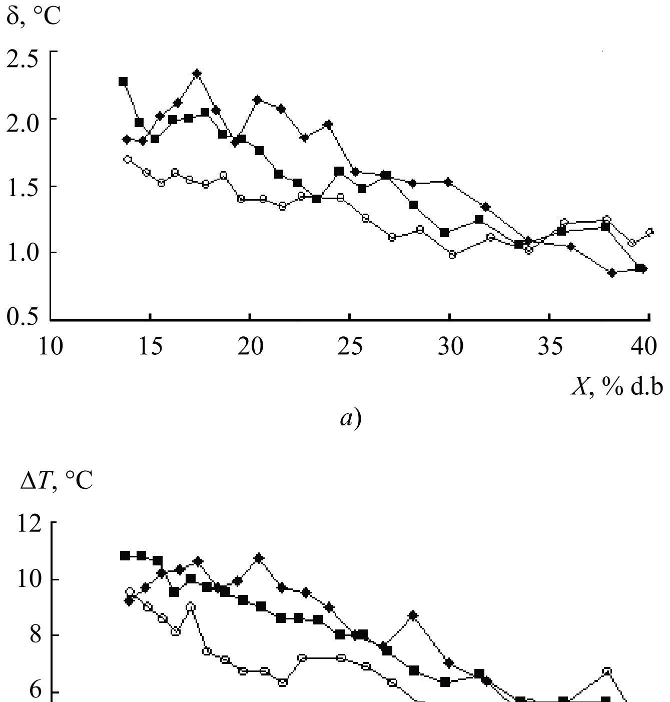


Fig. 6. Effect of hot air velocity on drying uniformity (P = 126 W, T_a = 70 °C):
◆ – MWHA – 0,5 m/s; ■ – MWHA – 1 m/s; ○ – MW

Hence, higher air velocity appears to be favorable for drying, but as shown in Fig. 9, the cracking ratio of soybeans increased with hot air velocity. The same conclusion was drawn by Wang and Li [15]. So, higher hot air velocity will deteriorate the quality of soybeans. In fact, the negative impact of hot air velocity on soybeans drying is mainly reflected in the falling drying rate stage. Therefore, it is necessary to reduce the hot air velocity in the falling drying rate stage of MW-hot air drying soybeans.

The effect of microwave power on drying rate, material surface temperature and drying uniformity in MW-hot air drying of soybeans. As seen from the curves for drying rate in Fig. 7, when the microwave power level was changed from 126 W to 252 W the drying rate increased rapidly over the similar range of moisture content, and therefore the drying time was greatly reduced. The temperature curves in Fig. 7 show that the material surface temperature was significantly raised with the increasing microwave power, which points on the excessive microwave energy absorbed by the drying materials. At the microwave power of 252 W, the material temperature was above the boiling point of water, and the material quality worsened sharply.

From Fig. 8 it is clear that the drying uniformity reduced sharply with increasing microwave power. This is mainly due to stronger absorption of microwave energy and therefore enhanced differentiation of heat generation at higher microwave power.

The cracking ratio. Cracking is the ultimate destruction of kernels during drying caused by mechanical stress owing to moisture and temperature gradients.

To quantify the extent of damage to the kernels, the cracking ratio was calculated in this study as the ratio of m_b/m_a, where m_b is the mass of cracked soybeans and m_a is the total mass of dried soybeans. It has been found that at microwave power set at 252 W and over, all kernels were deeply or completely split because internal vapour pressure has lead to internal cracks development and finally to splitting of the soybean kernel. Figure 9 which presents the influences of the hot air temperature and velocity on the cracking ratio at the favourable microwave power level of 126 W indicates that the effect of hot air velocity was stronger than temperature to induce cracking. Higher hot air velocity in conjunction with air temperature hardens the soybean coat (pericarp) to a greater extent thereby hampers evaporation of water in the endosperm (cotyledons)

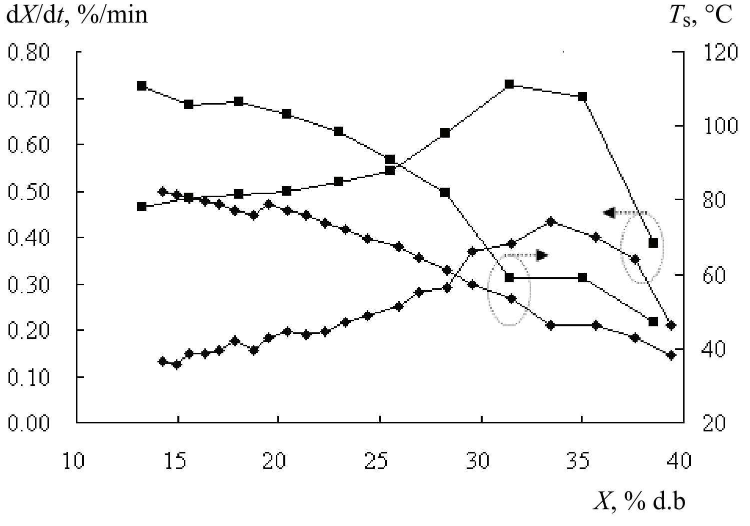
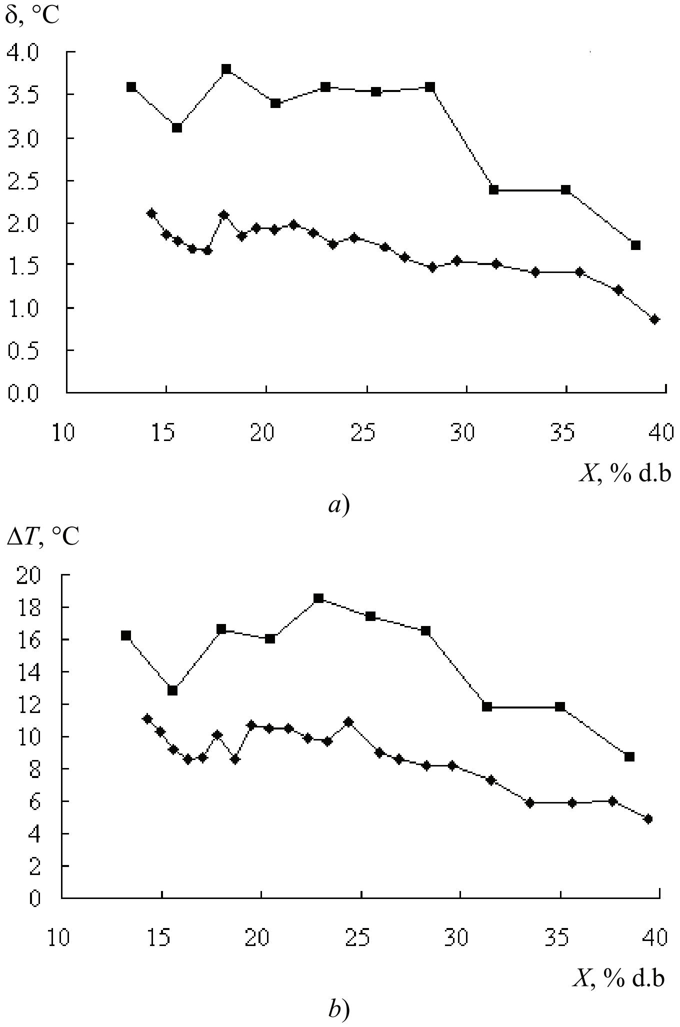


Fig. 7. Effect of microwave power on drying rate and temperature of soybean surface (v = 1 m/s, T_a = 70 °C):
—◆— – MWHA – 126 W;—■— – MWHA – 252 W



a)

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Fig. 8. Effect of microwave power on drying uniformity (v = 1 m/s, T_a = 50 °C):
—◆— – MWHA – 126 W;—■— – MWHA – 252 W

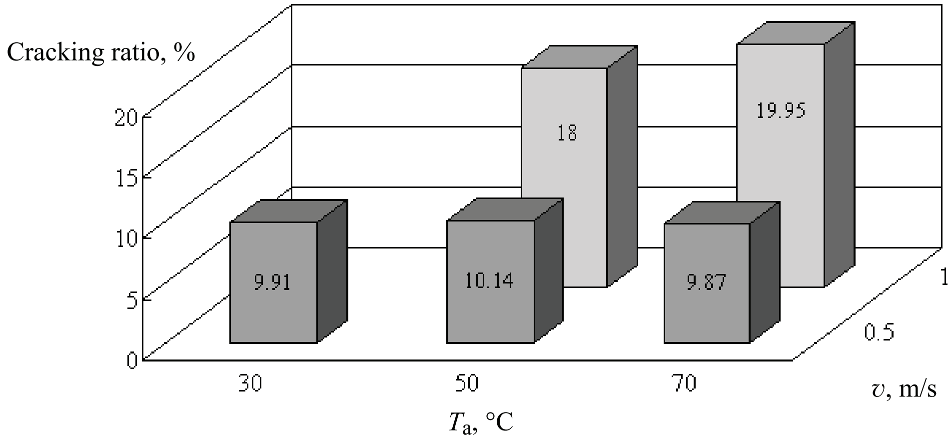

Fig. 9. Effect of air temperature and velocity on the cracking ratio

which has lower resistance to moisture transport than the pericarp does. Thus, the increasing pressure difference between the pericarp and endosperm induces the pericarp tension which leads to fissures and then to eventual split of the kernels.

Summary

In the MW-hot air rotary drying of soybeans, the appropriate microwave power is highly important to control the drying uniformity and further the soybeans quality. When the hot air stream was blown during microwave drying it impacted, although at different degree, the drying rate, temperature of the soybean surface, and drying uniformity. It was found that the effects of hot air on drying were different in the accelerating drying rate stage and the falling drying rate stage. In the accelerating drying rate stage it was beneficial to blow hot air to the microwave rotary dryer as this increased the drying rate, decreased the soybeans temperature and improved the uniformity of drying. But in the falling drying stage, the function of increasing drying rate by the hot air stream was marginal. At this stage, the drying uniformity worsened when blowing hot air through the microwave-dried soybeans. When temperature of hot air was lower than the soybean temperature the hot air stream reduced this temperature as opposed to the case when the temperature of hot air was higher than the soybean temperature.

Although the temperature of the soybean surface and the drying non-uniformity decayed with increasing hot air velocity, the quality of soybeans got worse. Therefore, for rational use of hot air in MW-convective drying it is crucial not only to select the appropriate microwave power level but also to determine the incipient of the falling drying rate stage in order to adjust the operating parameters to minimize energy consumption for air heating as well as secure product quality evaluated in terms of cracked kernels.

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Влияние параметров горячего воздуха при микроволновой сушке сои во вращающемся барабане

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Ключевые слова и фразы: коэффициент расщепления; барабан; гомогенная сушка; микроволна; распределение температуры при вращении.

Аннотация: Экспериментальным путем было проведено изучение влияния мощности СВЧ, температуры и скорости потока горячего воздуха на скорость, равномерность сушки и температуру материала при микроволновой и конвективной сушке сои во вращающемся барабане. При помощи инфракрасного тепловизора были визуализированы и проанализированы температура и однородность поверхности высушиваемого материала. При сравнении с обычной микроволновой сушкой было установлено, что увеличение периода с повышающейся скоростью сушки при подаче горячего воздуха через слои сои, разогреваемой микроволнами, оказывает благотворный эффект и позволяет снизить температуру поверхности материала, увеличить скорость сушки и повысить ее однородность. Однако в период с понижающейся скоростью процесса влияние горячего воздуха на скорость сушки не настолько значительно, так как ухудшаются гомогенные характеристики, а также увеличивается температура поверхности материала при подаче горячего воздуха. С другой стороны, увеличивающаяся скорость горячего воздуха улучшает однородность сушки и снижает температуру материала в период с понижающейся скоростью процесса, который преобладает в процессе сушки и ухудшает качество сои с точки зрения коэффициента расщепления.

Einwirkung der Parameter der Heißluft bei dem Mikrowellentrocknen der Sojabohne im drehenden Trommel

Zusammenfassung: Es wurde das Erlernen der Einwirkung der SHF-Kapazität, der Temperatur und der Geschwindigkeit des Stromes der Heißluft auf die Geschwindigkeit, die Gleichförmigkeit des Trocknens und die Temperatur des Stoffes bei dem Mikrowellen- und Konvektivtrocknen der Sojabohne im drehenden Trommel experimentell durchgeführt. Es wurden die Temperatur und die Gleichartigkeit der Oberfläche des trocknenden Stoffes mit Hilfe des Infrarotsichtgerätes sichtbargemacht und analysiert. Bei dem Vergleich mit dem gewöhnlichen Mikrowellentrocknen wurde festgestellt, dass die Vergrößerung des Periodes mit der steigernden Geschwindigkeit des Trocknens bei der Zubringung der Heißluft durch die von den Mikrowellen erwärmenden Sojabohneschichte einen guten Effekt leistet und die Temperatur der Oberfläche des Stoffes zu senken, die Geschwindigkeit des Trocknens zu vergrößern und seine Gleichartigkeit zu erhöhen erlaubt. Aber in der Periode mit der senkenden Geschwindigkeit des Prozesses ist die Einwirkung der Heißluft auf die Geschwindigkeit des Trocknens nicht bedeutend, weil sich die homogenen Charakteristiken verschlechtern und auch die Temperatur der Oberfläche des Stoffes bei der Zubringung der Heißluft vergrößert. Von anderer Seite verbessert die vergrößernde Geschwindigkeit der Heißluft die Gleichartigkeit des Trocknens und senkt die Temperatur des Stoffes in

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der periode mit der senkenden Geschwindigkeit des Prozesses, das im Prozess des Trocknens dominiert und die Qualität der Sojabohne vom Standpunkt des Koeffizientes der Spaltung verschlechtert.

Influence des paramètres de l'air chaud lors du séchage à microondes du soya dans un tambour de rotation

Résumé: Par une voie expérimentale a été vérifée l'influence de la puissance des microondes, de la température et du courant de l'air chaud sur la vitesse, la régularité du séchage et la température du matériel lors du séchage à microondes du soya dans un tambour de rotation. A l'aide de l'imageur thermal ont été visualisées et analysées la température et l'homogénéité de la surface du matériel séché. Lors de la comparaison avec le séchage ordinaire a été établi que l'augmentation de la période avec la vitesse accrue du séchage pendant le débit de l'air chaud à travers les couches du soya chauffé par les microondes donne un effet favorisant et permet de diminuer la température de la surface du matériel, d'augmenter la vitesse du séchage et d'élever son homogénéité. Tout de même, lors de la période avec une vitesse diminuée du processus l'influence de l'air chaud sur la vitesse du séchage n'est pas si important, puisque les caractéristiques de l'homogénéité deviennent pires et la température de la surface pendant le débit de l'air chaud augmente. De l'autre côté, la vitesse augmentée de l'air chaud améliore l'homogénéité du séchage et diminue la température du matériel lors de la période avec une vitesse diminuée du processus qui prédomine dans le processus du séchage et empire la qualité du soya du point de vue du coefficient de la désagrégation.

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