Microwave Finish Drying of Diced Apples in a Spouted Bed

H. FENG and J. TANG

ABSTRACT

The combination of a spouted bed with microwave heating to improve heating uniformity was evaluated. Experiments were performed on a laboratory system in which evaporated diced apples of about 24% moisture were dried to about 5% at 70°C air temperature using four levels of microwave power density (0 to 6.1 W/g). With the combination method, temperature uniformity in diced apples was greatly improved as compared to that with a stationary bed during microwave drying. Products had less discoloration and higher rehydration rates as compared to conventional hot air drying or spouted bed (SB) drying. Drying time could be reduced by >80% compared with SB drying without microwave heating.

Key Words: microwave, fluidized bed, drying, apple, heating uniformity

INTRODUCTION

A MAJOR DISADVANTAGE OF HOT AIR DRYING OF FOODS IS LOW energy efficiency and lengthy drying time during the falling rate period. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced moisture transfer and, sometimes, reduced heat transfer. Prolonged exposure to elevated drying temperatures may result in substantial degradation in quality attributes, such as color, nutrients, and flavor. Severe shrinkage also reduces bulk density and rehydration capacity.

Combining hot air with microwave energy has shown advantages over traditional hot air drying. Microwave heating is characterized by rapid volumetric heating. When applied to drying, it results in a high thermal efficiency, a shorter drying time and, sometimes, an improvement in product quality (Garcia et al., 1988; Prabhanjan et al., 1995; Torringa et al., 1996). An inherent problem associated with microwave drying is the non-uniformity in heating caused by an uneven spatial distribution of the electromagnetic field inside the drying cavity. During drying processes, non-uniform heating may cause partial scorching in high sugar products. Various field-averaging methods have been developed to achieve heating uniformity. With such methods, a product is in constant movement within the microwave cavity so that different parts of the product will receive a microwave radiation of about the average of the spatial electromagnetic field intensity over a period of time. The microwave energy averaging can be accomplished by either mechanical means (Allan, 1967; Huxsoll and Morgan, 1968; Torringa et al. 1996) or through pneumatic agitation (Salek-Mery, 1986; Kudra, 1989).

Fluidization provides pneumatic agitation for particles in the drying bed. It also facilitates heat and mass transfer due to a constantly renewed boundary layer at the particle surface. Salek-Mery (1986) combined fluidization and microwave heating as an intermediate stage of a fluidization system for grain. The drying rate was increased by 50% compared to conventional hot air drying. The enhancement of drying was also reported by Kudra (1989) for microwave drying of wheat in a fluidized bed where a uniform temperature distribution was found within the samples. Coarse food particles such as diced apples are difficult to fluidize, especially when their moisture content is relatively high and surface is relatively sticky. Spouted bed is a specially designed bed for fluidizing coarse particles that are not suitable for a conventional fluidized bed. A spouted bed consists of a downward moving bed in the peripherical section with an upward moving “spurt” like dilute phase (Fig. 1) in the central section (Mathur and Epstein, 1974). A spouted bed has not been reported in combination with microwave heating in food drying applications.

Our objectives were to improve microwave heating uniformity by incorporating a spouted bed in a laboratory system and to evaluate the quality and drying characteristics for diced apples. The feasibility of the microwave and spouted bed (MWSB) combined technique for uniform drying was tested on apples because high sugar content makes dehydrated apples extremely sensitive to scorching and nonuniform heating would cause obvious discoloration.

MATERIALS & METHODS

Evaporated diced apples

Evaporated diced Red Delicious, Golden Delicious and Granny Smith apples (*Malus domestica Borkh*) with a moisture content 22.8% to 25.2% on a wet basis (wb) were supplied by Tree Top, Inc. (Selah, WA). Diced apples had been pretreated with sulfite to prevent browning. The size of the fresh diced apples for all three varieties was 12.7 × 9.5 × 6.4 mm. Moisture content, color and bulk density of the diced apples were measured before drying tests. The samples were placed in sealed plastic bags and stored at 4°C before the finish drying tests.

Laboratory drying system

An experimental dryer was developed for the drying tests (Fig. 1). The system consisted of microwave power source, cavity, hot-air source, spouted bed, and water load. The microwave generator operated at 2,450 MHz. The generator output power was regulated between 0 and 1.4 kW by an Alter SM445 power controller (Casselberry, FL). The multimode microwave drying cavity had a dimension of 393 × 279 × 167 mm. The spouted bed was constructed with microwave-transparent perspex. It consisted of a cylindrical section

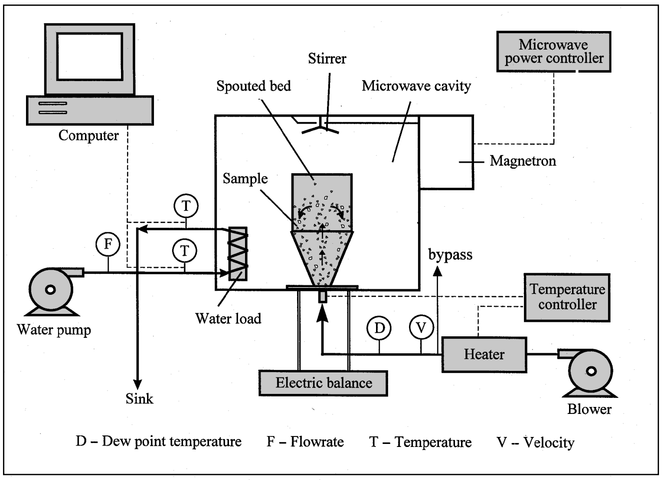

Fig. 1—Schematic of microwave and spouted bed (MWSB) drying system.

Authors Feng and Tang are with the Dept. of Biological Systems Engineering, Washington State Univ., Pullman, WA 99164-6120. Direct inquiries to Dr. Juming Tang

and a 31 degree conical base. The bottom of the cone was made of a plastic screen to hold the particulate samples and provide a pass for hot air. The spouted bed was supported by a metal plate and a metal screen with holes small enough to stop the microwave leaking. The metal plate was supported by three plastic legs on top of an electrical balance. This arrangement provided the flexibility to weigh samples either on-line or off-line. A blower (Fuji Electric Co., Ltd, Tokey, Japan) provided an air velocity of up to 8 m/s in the spouted bed. Before entering the spouted bed, air was pre-heated by a 1.7 kW electric heater. The air temperature was controlled by a Set-Temp(r) digital controller (Laboratory Devices, Inc., Holliston, MA).

A water load was placed to protect the magnetron from overheating. It consisted of an AC-2CP-MB water pump (MFG., Inc., Glenview, IL), a Flo-Sensor flowmeter (MaMillan, Copperas Coup, TX), and two temperature sensors. The inlet and outlet temperature difference of the water was monitored by a Labview data logging system (National Instruments, Austin, TX). The power absorbed by the water load was calculated accordingly.

The microwave power output from the generator was calibrated following the 2L method recommended by the International Microwave Power Institute (Anonymous, 1989). The power absorbed by the samples during drying was calculated as the difference between the power absorption by the water load and the total magnetron power output.

Drying tests

Drying tests for Red Delicious were conducted at microwave power levels equivalent to 3.7, 4.9 and 6.1 W/g of evaporated apple dice. Evaporated Golden Delicious and Granny Smith apples were dried with a microwave power intensity of 4.9 W/g (wb). The hot air was controlled at 70°C with a superficial velocity of 1.9 m/s in the spouted bed. This velocity was determined by dividing air flowrate by the cross-sectional area of the large end of the spouted bed. It was the minimum requirement for the particles of 24% moisture content (wb) to be spouted and agitated. Samples of 40g were used for all tests and sample weight changes during drying were monitored by removing the spouted bed and weighing on a Sartorius electric balance (3000±0.01g). For quality evaluation, control tests using the spouted bed hot-air drying without microwave heating were conducted under the same air conditions. After the drying tests, samples were kept in air tight containers until measurement of color, bulk density and rehydration capacity within 2 wk after the drying. All drying tests, except the spouted bed hot-air drying of Red Delicious and Granny Smith apples, were repeated 3 times and average values were reported and plotted.

Heating uniformity

Heating uniformity within a sample during drying with the MWSB method was examined by measuring core temperature of individual apple piece. Red Delicious apples were dried at a microwave power density of 4.9 W/g (wb) and with air at 70°C and 1.9m/s. The core temperature of 10 randomly chosen apple pieces was measured at different drying times using a TMQSS-020U thermocouple (Omega Engineering, Inc., Stamford, CT) with a response time of 0.8s. The temperature readings were taken by inserting the thermocouple into the core part of each randomly chosen piece. For each preset drying time, temperature measurements were completed within 1.5 min and the temperature drop during this period was <3°C. For comparison, similar measurements were made in a stationary bed during microwave drying with hot air flowing horizontally through the surface of a deep bed of diced apple. The color of the dehydrated diced apple was also observed as an indicator of heating uniformity, because uneven heating would cause partial scorching and hence obvious non-uniform color.

Moisture content

The initial and final moisture contents were determined using the vacuum oven method at 70°C and 37.3 kPa (AOAC, 1990). The means of 3 measurements were reported. The moisture contents in between were extrapolated from weight readings and initial and final moisture contents.

Rehydration capacity

Rehydration capacity (RC) is defined as the ratio of the moisture regained when submerged in water to the moisture removed during the drying (Loch-Bonazzi et al., 1992). A dehydrated sample (5g) was weighed and submerged in boiling water for 2 min. The sample was immediately drained on a metal sieve for 5 min and weighed. The rehydration capacity was determined by:

$$RC = \frac{[\text{Regained moisture (g)}]}{[\text{Initial moisture (g)} - \text{Residual moisture (g)}]} \qquad (1)$$

The amount of initial and residual moisture of the samples was determined from the moisture content of fresh apples and the moisture content of dried products, respectively. The regained moisture was calculated from the sample weight difference before and after the rehydration. The dehydration measurements were conducted 3 times for all tests and means were reported.

Bulk density

Samples (5g, containing 67±5 pieces) were used to measure bulk density. The weight of the samples was taken with an analytical balance (±0.01g). The volume of the samples was determined by the water displacement method. Measurements were made three times.

Color

Sample color was measured using a Minolta Chroma CR-200 color meter (Minolta Camera Co. LTD, Japan). For fresh apples, three measurements were made at random locations of sliced apples, and the mean was reported. For evaporated or dehydrated diced apple, 40g sample was wrapped with transparent Saran Wrap (Dow Brands L.P., Indianapolis, IN) into a square shape. Measurements were made at five different locations at the surface of the pack. For each location, 5 measurements were made and the average was used.

The color readings were expressed by the ICI chromaticity coordinates (L*a*b*) system. Color difference from the fresh apples ΔE, as defined the following, was used to describe the color change during drying:

$$\Delta E = \sqrt{(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2} \qquad (2)$$

where subscript "o" refers to the color reading of fresh apple flesh. L*, a* and b* indicate brightness, redness and yellowness, respectively. Fresh apple tissue was used as the reference. The larger the ΔE, the greater the color change from the reference color of the fresh apple flesh.

RESULTS & DISCUSSIONS

MOISTURE AND TEMPERATURE HISTORY OF A TYPICAL MWSB drying test is shown (Fig. 2). For this test, the sample temperature passed the air temperature of 70°C in 2 min after the start of the drying. After that point, the temperature gradually reached a plateau about 14°C higher than ambient air, and then slightly decreased.

To explain the temperature change, a thermal energy balance equation could be written for the sample:

$$\begin{aligned}&\text{Energy accumulation } \Delta E = \\ &\text{Energy generation } E_G + \text{Energy in } E_I - \text{Energy out } E_o \qquad (3)\end{aligned}$$

where, $E_G(>0)$ is the energy input due to microwave heating, E_I is the thermal energy input due to air-particle heat transfer, and E_o is energy loss due to moisture evaporation. A positive energy accumulation would lead to an increase in sample temperature. E_I could be positive or negative, depending upon direction of heat transfer. Moisture level decreased throughout the drying processes, thus, E_o was always greater than zero.

E_G in Eq. (3) is related to the local electromagnetic field intensity and effective loss factor (Goldblith, 1967):

$$E_G = 5.56 \times 10^{-4} \times f\epsilon''E^2 \qquad (4)$$

where, E_G = the conversion of microwave energy into thermal energy (W/cm^3); f = frequency (GHz); ϵ'' = relative dielectric loss factor; E = electric field (V/cm).

The heating curve (Fig. 2) could be partitioned into three stages. In stage I, sample temperature was less than air temperature. Sample was, therefore, heated by heat transfer from the hot air ($E_I>0$) and microwave heating ($E_G>0$). The microwave heating in this stage should be relatively intense due to the high loss factor of the moist sample. As a result, sample temperature increased rapidly and surpassed air temperature in 2 min, although there was heat loss due to moisture evaporation. In stage II, the sample temperature was higher than ambient air, therefore, the air helped to remove heat from the sample ($E_I<0$). But the sample center temperature continued to increase ($\Delta E>0$), due to intense microwave heating, and then reached a plateau. In stage III, the sample temperature remained stable ($\Delta E=0$). The energy due to microwave heating was balanced by evaporative cooling and heat transfer from the sample to the ambient air. In this stage, the positive temperature gradient from the sample center toward the surface was in sharp contrast with that when dried with hot air. This positive temperature gradient in a MWSB system maintained a positive vapor pressure and helped to speed up the drying process.

A slight temperature reduction occurred toward the end of the MWSB drying. It is likely that the material loss factor (ϵ'') was sharply reduced as the diced apples lost most of moisture. A moisture leveling effect resulted in a reduction in absorption of MW energy (Metaxas and Meredith, 1988). Thus, sample temperatures were slightly reduced due to the more predominant combined effects of evaporative cooling and heat transfer from sample to air. Similar temperature reduction was reported by Adu and Otten (1993) in soybean microwave drying tests.

Temperature distribution among sample particles during drying, indicated by error bars (Fig. 2), was very uniform. A comparison was made (Fig. 3) of center temperature variation in 10 apple pieces after 2.5 min of drying with the MWSB method and the stationary bed microwave drying method. With MWSB method the measured maximum temperature variation was ±1.4°C about the average temperature. However, this variation was reduced to ±4°C towards the end of a 22.5 min drying period. With a stationary bed and horizontal flow of hot air at 70°C, however, MW drying caused severe localized heating. For example, the center temperature of one piece was 193°C, while another was at 65.5°C. Some apple pieces were charred, while others were still very moist.

We, therefore, concluded that the spouted bed in microwave heating served two purposes: (1) it provided pneumatic agitation to help avoid uneven microwave heating; (2) it reduced possible overheating because high air velocity and effective mixing increased particle-air heat and mass transfer.

The drying curves of the three apple cultivars were compared (Fig. 4). These curves exhibited typical exponential decay, indicating an internally controlled mass transfer (Tulasidas et al., 1993). To produce crunchy texture in dehydrated apples, it is desirable to have a final moisture of about 5% (wb). The time to dry evaporated Golden Delicious apple dice from 25.2% (wb) to 5% (wb) was 147 min when using the spouted bed alone with a stream of air at 70°C and

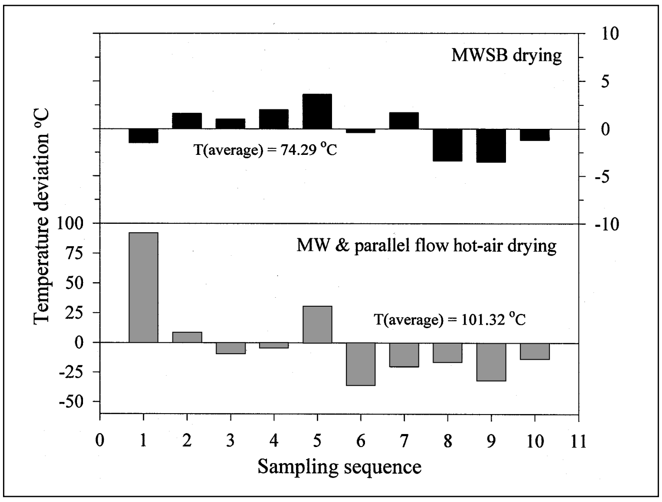

Fig. 3—Core temperature variation about the mean temperature of 10 Red Delicious apple pieces randomly taken from the spouted bed after 2.5 min of drying with MWSB (4.9 W/g and air 70°C) and from a stationary bed with MW and flow hot-air drying (70°C).

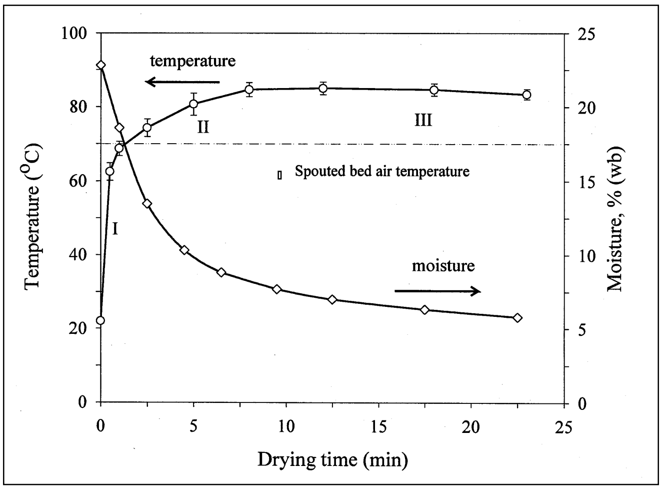

Fig. 2—Temperature changes and average moisture content of diced Red Delicious apple during microwave drying at 4.9 W/g and 70°C hot air temperature.

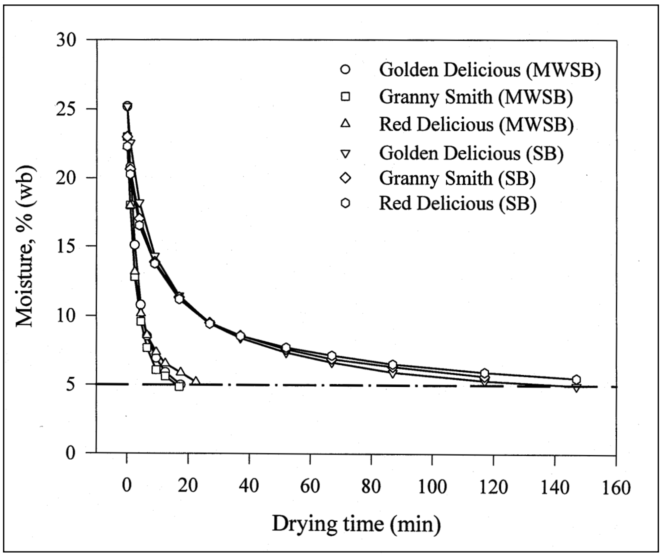

Fig. 4—Drying curves of three apple cultivars dried with the MWSB (4.9 W/g and hot air of 70°C) and SB (70°C hot air).

1.9 m/s. The drying time was reduced to 17.5 min when microwave energy of 4.9 W/g (wb) was included or an 88% reduction in drying time. Similar reductions in drying time were recorded for diced Red Delicious and Granny Smith apples by the MWSB method.

The influence of microwave power density (Fig. 5) for diced Red Delicious apple showed enhanced moisture transport as power density increased. The drying time required for an evaporated sample from 22.8% (wb) to 5.5% (wb) was reduced from 22.5 min at power density 3.7 W/g (wb) to 9.5 min at power density 6.1 W/g (wb).

The reproducibility of the drying data was evaluated by standard deviations of final moisture contents from replicated tests (Table 1). The low standard deviations indicate good reproducibility of drying curves. Drying characteristics were slightly different among the 3 cultivars (Fig. 4). Since the evaporated apples had been obtained from a commercial supplier, we had insufficient data and sample history to explain any differences.

The lightness of 3 cultivars processed with different methods was compared (Table 2). Preferred colors are those closest to the original color of fresh apple flesh. In this study, the evaporated diced apples were the starting point. Some discoloration had been experienced for the evaporated apples as indicated by a reduction in the L* value. MWSB drying caused further slight darkening. Color degradation of the product caused by SB drying was slightly more than that by MWSB drying. Commercial hot-air dried products exhibited the greatest reduction in lightness.

Table 1—Standard deviations of final moisture contents from different drying processes

	Evaporated MC(%)	MWSB drying MC(%)			SB drying MC(%)
		3.7 W/g	4.9 W/g	6.1 W/g	
Red Delicious	22.8±0.8	5.5±0.9 (22.5)[b]	5.2±0.2 (22.5)	5.3±1.0 (9.5)	6.1[c] (147)
Golden Delicious	25.2±1.9		4.8±0.8 (17.5)		5.0±0.3 (147)
Granny Smith	23.0±0.1		4.9±0.2 (17.5)		5.7[c] (117)

[a] Mean of three replicates ± standard deviation.
[b] Drying time (min).
[c] One test was conducted.

Table 2—Lightness (L) for diced apple dried with different methods as compared with fresh apple flesh

	Red Delicious	Golden Delicious	Granny Smith
Flesh	82.1±1.2[a]	82.4±0.8	79.1±1.0
Evaporated	80.3±3.7 (2.2%)[b]	80.4±3.2 (2.4%)	78.8±5.1 (0.3%)
MWSB dried	76.2±2.3 (7.3%)	76.9±4.6 (6.6%)	77.6±3.3 (1.8%)
SB dried	73.4±1.9 (9.4%)	76.6±3.3 (7.0%)	72.0±4.5 (8.9%)
Commercially hot-air dried	70.4±6.2 (14.3%)	73.4±2.5 (10.9%)	69.5±2.6 (12.1%)

[a] Mean ± standard deviation.
[b] Relative changes in lightness compared to apple flesh.

The total color change ΔEs, which takes into account changes in redness and yellowness, was also compared (Fig. 6). MWSB drying caused little color change from that of the evaporated apples. SB dried products also experienced less discoloration than commercial hot-air dried samples. The development of discoloration of the evaporated diced apples during finish drying may be related to nonenzymatic browning (Salunkhe et al. 1991). The heat sensitive polyphenoloxidase activity had probably been blocked during preliminary drying (Kostaropoulos and Saravacos, 1995) which reduced the moisture content of fresh apple to that of the evaporated apples (20~25%). The presence of glucose, fructose, and malic acid in apples would promote browning reactions when heat was applied. Drying temperature and time are important parameters for the development of browning during apple drying (Tulasidas et al., 1995). The lower color degradation of MWSB dried dice may, therefore, be due to the substantial reduction in drying time. This may also be true for the SB drying because of higher heat and mass transfer (Mathur and Epstein, 1974) that facilitate a higher drying rate. Less discoloration in grapes after microwave drying was reported by Tulasidas et al. (1995).

The rehydration characteristics of a dried product are widely used as a quality index (McMinn and Magee, 1997). They indicate the physical and chemical changes during drying as influenced by processing conditions, sample pretreatment and composition. The rehydration capacities for 3 cultivars dried with different methods were compared (Fig. 7). The MWSB dried products generally had higher rehydration rates than the other two methods. The rehydration capacity of Red Delicious apple dried with the MWSB method had the highest value (0.71±0.02). This was a 20% increase compared with commercial hot-air dried apples. None of the dried products regained the initial moisture. Irreversible physico-chemical changes might have occurred during drying. Pendlington and Ward (1962) studied structure changes of hot-air and freeze dried carrots, parsnips and turnips

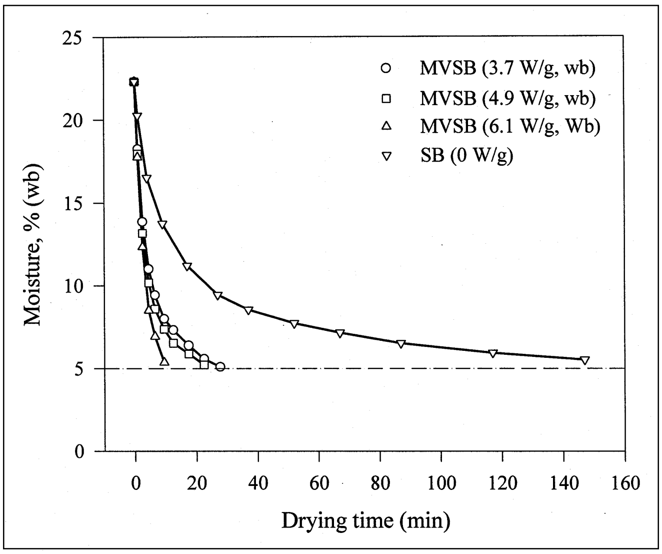

Fig. 5—Drying curves of Red Delicious apples dried with MWSB method with different microwave power levels.

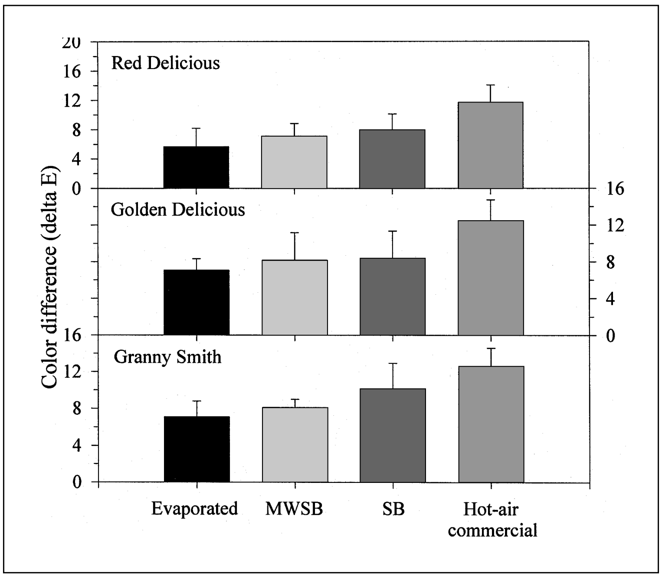

Fig. 6—Color comparison of apples dried with different methods.

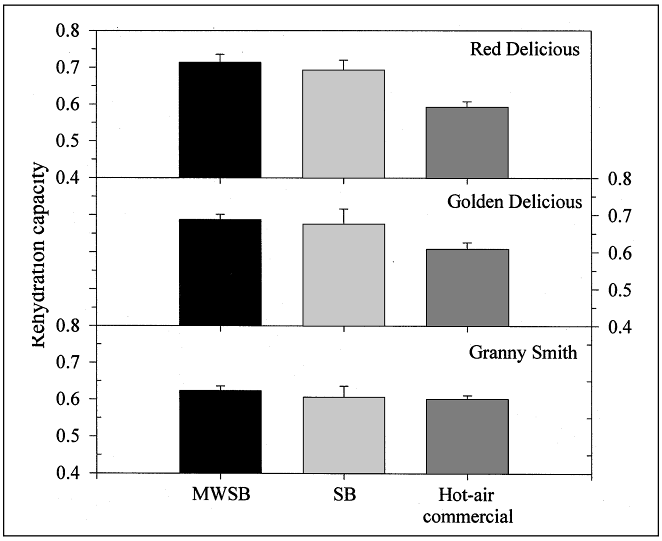

Fig. 7—Rehydration capacity of apples dried with different methods.

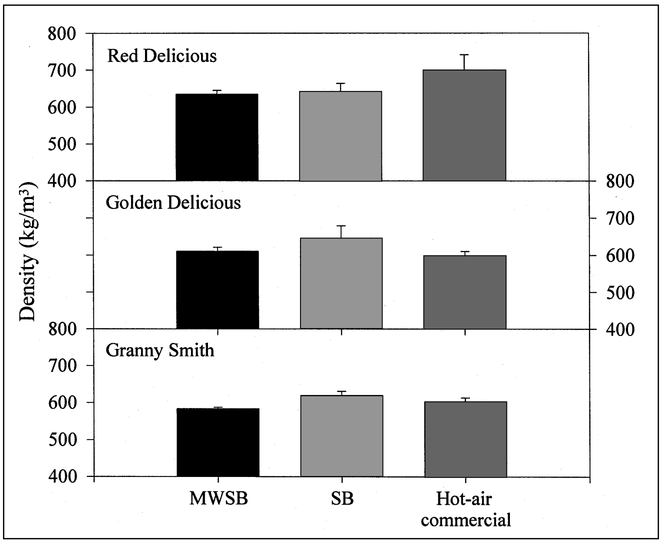

Fig. 8—Density of apples dried with different methods.

by a histological examination. They postulated that the migration of soluble solids during hot-air drying was also important in physical changes. The solutes leaking from damaged cells migrated to the surface to form a crust and resulted in a relatively close surface structure. Probably the internal microwave heating facilitated a predominant vapor migration from the interior of the material as compared to a more predominant transfer of sugar solution during conventional drying. This difference in vapor and sugar transfer, combined with high internal pressure, would likely result in a more porous structure compared with conventional hot-air dried products. The higher rehydration capacity of microwave dried products might be the result of such enhanced porous structure.

Results from density measurements (Fig. 8) confirmed that densities of MWSB dried products were lower than hot-air dried products because of the internal heating and vapor generation as expected. However, the difference was not substantial for Red Delicious and Granny Smith. For Golden Delicious a slightly higher density than commercial product was measured. Microwave dried products have been reported to show a higher porosity because of the puffing effect caused by internal vapor generation (Torringa et al., 1996). During the course of MWSB drying in our study, noticeable puffing was visually observed, but the products shrank toward the end of drying. Further research is needed to investigate drying conditions that would minimize such shrinkage after microwave puffing.

CONCLUSIONS

THE MICROWAVE AND SPOUTED BED METHOD PROVIDED MUCH more uniform heating within the microwave cavity as indicated by more uniform temperature distribution among sample particles during drying and even color in final products. The drying time needed to reduce moisture from evaporated apples to low moisture dehydrated apples (≈5%) was greatly shortened. The MWSB dried products exhibited least discoloration compared with hot air spouted bed or commercially dried products. The MWSB dried products had better reconstitution characteristics. An improvement in density was also achieved for Red Delicious and Granny Smith cultivars by MWSB drying.

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