Time and speed of fruit drying on batch fluid-beds

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Abstract. Drying of particles (pieces) in a fluidized bed affords better quality of end products, especially for better product structure and its shorter reconstitution time. Fluid-bed drying of different fruit particles has been investigated. Starting water content varies from grape berries 81.5% and peach 87.7% to apricot 86.9%. The temperature of fluidization varies from 70°C to 100°C at air velocities from 0.98 ms⁻¹ to 5.2 ms⁻¹. The product should be dried fruit with 10% to 14% of water content with good rehydration quality that varies from 8 to 20. Experimental data have been measured, relevant values have been calculated and a mathematical model introduced. The results have shown that drying of fruit in a fluidized bed produces dry fruit particles of improved quality in a much shorter time, with improved rehydration times and qualities, than in continuous belt-driers that are generally used.

Keywords. Dried fruit; fluidization; rehydration; exponential drying model.

1. Introduction

Dried fruits are often used in very wide variety of products such as muesli, candy bars, children's food etc. The heat treatment of fruit is a very important and crucial process, where the nutritional quality of fruit can change, and so also the process of rehydration which is connected with fruit quality. The appearance of the fruit can affect customers as well. It is important to produce dried fruit that is shelf-stable, microbiologically safe, with minimal degradation of nutrients and sensory properties. The heating rate of solids is generally slow. The advantage of high temperature – short-time process – decreases as the particle size increases. Drying of solids is usually divided into two stages, constant rate and falling rate periods (Perry & Green 1997). Most food materials have short constant rate periods and they dry entirely in the falling rate period (Saravacos & Maroulis 2001).

The prerequisite for technologically sound drying process is knowledge of biological, physical, chemical and nutritional characteristics of food materials and products and their

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A list of symbols is given at the end of the paper

behaviour under various conditions of drying (Ježek *et al* 2003). One of the promising fluid-bed drying processes is the drying of fruit, due to better heat and mass transfer, shorter drying time, better quality of products obtained and shorter reconstitution time. (Le Maguer 1986).

Depending on the pretreatment applied, rehydration times are up to 30% faster and the quality is very uniform. Lower drying temperatures can be used and substantial savings are possible. It is possible to shorten the drying time and produce a very open structure of dry particles that hastens drying and gives better rehydration times (Bobić *et al* 2001).

Drying experiments have been conducted to investigate the fluid bed drying time for various fruits and the hydrodynamics of the fluid bed. Composition, mass density and temperature are the main factors of process conditions affecting the thermal properties (Troller & Christian 1978) and therefore they were investigated in detail. Composition, initial moisture content of samples, density and temperature are the main parameters that affect the thermal conductivity and thermal diffusivity. Specific heat is affected by particle composition and process temperature (Kožišková 1983). Changes of the nutritional characteristics of dried materials have been investigated (Bobić *et al* 1988). In our work we are trying to determine if it is possible to shorten the drying time and produce very open structure in dried particles that could hasten drying time and give better rehydration times.

2. Experimental part

The apparatus for fluidized bed drying consists mainly of a column, which is a cylinder of 0.205 m diameter and 0.900 m height. It is constructed from four glass cylinders connected by flanges and rubber gaskets. The fluidization grid is placed 0.6 m from the top (figure 1). Temperature and pressure drop measurements are provided through specially designed connections. A teflon ring (of the same diameter as the cylinder's inside diameter) is placed 0.2 m from the bottom of the column. A stainless steel ring is placed inside this ring, carrying

Figure 1. Diagram of experimental apparatus.

the fluidization grid. Air is introduced through the conical bottom part by a centrifugal fan through a pipe 0.104 m in diameter. The fan is equipped with a monophasic electrical motor with continuous automatic speed regulation. Airflow is measured at the entrance to the column and in the middle of the column by an electrical anemometer (EDRA 4, Air Flow Corp.) in the ranges 0.12–1.0, 0.75–2.5, 2.0–20 and 7.5–25 ms⁻¹. The precision of this instrument is $\pm 2\%$. Air is introduced through a side entrance at the bottom of the column. The temperature measurement connections are inserted through side entrances in the glass cylinders. The specific placement of heaters provides good air mixing and good heat transfer in the shortest time possible. To get a flexible air temperature increasing range, a special electric heater with automatic temperature control has been constructed. It contains six electrical heaters (2.3 kW each) in a thermally isolated box. Two-point automatic regulators are built into the heater and connected to the outlet temperature-measuring device. During the drying process, the temperatures are measured by NiCr/Ni thermocouples and a digital temperature indicator, in the range 65° to 150°C. The pressure drop is measured through short diameter metallic pipes, which are placed in specific positions that allow measuring of the pressure drop over the grid, and in the fluidized bed. The pressure drop is measured statically with a micro manometer (Air Flow Corp.), with an operating range of 0–2500 Pa. The column can be turned over on a pivot for emptying and recharging.

3. Materials and methods

3.1 Materials

During the drying process many chemical changes occur inside the fruit. Therefore it is necessary to detect changes in water content, sugar, protein, acids, fats and vitamins, and in aroma and colour factors to obtain better rehydration results (Bobić *et al* 2001). Fruit samples were blanched, cooked (necessary additives were added) and treated with SO₂ (if colour retention was required) and starch solution. Three different fruits were investigated: grapes (as whole and half-berries), apricots and peaches. The main fruit characteristics and other important parameters for each type are shown in tables 1 and 2. Table 1 tells us about the physical properties of the fruit samples while table 2 shows the differences between fresh and dried fruit characteristics. Peaches and apricots were cut into small pieces. Equivalent diameter was calculated on average dimension, based on an average of 20 pieces (table 1). Layer porosity was determined by filling the beaker and by weighting particles. Samples were treated by blanching with SO₂ (if colour retention was required) and with starch solution. Grapes were blanched for 5 minutes at 50°C, with addition of 0.5% ascorbic acid.

Table 1. Initial physical characteristics of fruit particles.

Sample	Particle density ρ_p (kg m ⁻³)	Bulk density ρ_b (kg m ⁻³)	Porosity ε	Average particle diameter d_p (m)
Grape	1161	690	0.41	1.4×10^{-2}
Apricot	1688	640	0.62	5.2×10^{-3}
Peach	1720	671	0.61	5.2×10^{-3}

Table 2. Characteristics of fruit samples.

Fruit	Energy (kJ) (per 100 g)		Water (%)		Vitamin C (mg)	
	Raw	Dried	Raw	Dried	Raw	Dried
Red grape	301.2	1254.9	81	15	37	5
Apricot	203.3	991.8	86	14	31	4
Peach	179.2	997.7	88	12	6	2

3.2 Determination of the total solid/moisture content

Dry matter in the samples was determined according to the literature (AOAC 1995; AACC 1998). Time-dependent moisture content of the samples was calculated from the sample mass and dry basis mass. The sample mass was determined offline. This was done by weighting the samples outside the dryer periodically using an electronic balance (0.01 g). Mass loss data allowed the moisture content to be calculated as follows: Small quantities of each sample were dried in a vacuum oven (6 h at of 70°C and 30 mbar pressure). Mass loss data allowed the moisture content to be calculated as follows:

$$X(t) = m_{\text{H}_2\text{O}}/m_{\text{dm}}. \quad (1)$$

3.3 Rehydration

Rehydration characteristics were used as a quality index of the dried product (Vrac & Gruner 1994). Approximately 3 g (± 0.01 g) of dried samples were placed in a 250 ml laboratory glass (2 sets for each sample) and 150 ml distilled water was added, the glass was then covered and heated to boiling point within 3 minutes. The contents of the glass were then cooked for 10 minutes by simmering and thereafter cooled. The cooled content was filtered for 5 minutes under vacuum, and weighed.

The rehydration ratio (R) was used to express the ability of the dried material to absorb water (Troller & Christian 1978). It was determined by the following equation:

$$\text{rehydration ratio} = \frac{\text{weight of drip} - \text{dried rehydrated sample}}{\text{weight of dried sample}}. \quad (2)$$

3.4 Drying rate curve determination

Drying equipment has long been designed on the basis of rate-of-drying tests, but Van Meel was the first to make use of a drying curve characteristic (Keey 1977). Assuming that it is possible to obtain a normalized drying curve, specific for a given material, he was able to evaluate the variation of process conditions in batch drying.

The concept of drying curve characteristic has been applied to dryers through which solids progress without significant mixing. Mixing of solids, on the other hand (Bauman 2001) is important in fluid-bed dryers. Solid mixing inside progressive dryers where the particles are thrown into the drying medium, as in rotary dryers, is of lesser importance.

The exponential model successfully describes the drying kinetics of some porous materials, such as clay (Tomas *et al* 1994; Skansi & Tomas 1995), Al–Ni catalyst (Sander *et al* 1998) just as well as food materials (Tomas & Skansi 1996). The authors also used this model to describe

the changes of moisture content and drying rates. Time-dependent weights of samples were converted for the given time-dependence to moisture content.

For the approximation of experimental data and calculating drying curves, (3) below, and drying rate curves, (4) below, the simplified model was used as follows:

$$X(t) = X_0 e^{(-kt^n)}, \quad (3)$$

$$-\frac{dX}{dt} = k \cdot n \cdot t^{(n-1)} \cdot X_0 e^{(-kt^n)}, \quad (4)$$

where X_0 represents initial moisture contents. The parameters k and n were calculated by nonlinear regression method using a MATLAB 6.5 computer program with its curve-fitting tool. The correlation coefficient (R^2) was used as a measure of model equation.

4. Results and discussion

Drying experiments were conducted to investigate dynamic characteristics of fluidized beds and fluidized bed drying times for various fruits. Some changes in the nutritional characteristics of dried materials were investigated.

Fluidization (Geldart 1986) is used to achieve an intimate, uniform contact between hot air and solid pieces of fruit. Since the velocity of the hot air that is passing through the bed of fruit pieces is increasing, a point is reached at which the upward force is sufficient to lift the particles and expand the bed. The individual pieces of fruit are then no longer in continuous contact, but are more or less free to move throughout the bed. If the fluid velocity is further increased, the void fraction increases towards unity. The pieces are eventually sufficiently separated, so that they behave as single particles. If the upward force on a piece becomes distinctively greater than its weight, it is swept completely out of the bed. Fluidization resembles flow through a packed bed at the minimum fluidizing velocity and flows past a single particle at high velocity (an expanded bed). Chopped pieces of fruit are moist, therefore the expected pressure drop dependent on air velocity is essentially different from the one in a layer that has a similar mass to the mass of dried material. Pieces can be glued together so that greater force is needed to take the layer into the fluidized state.

In conventional drying processes, the drying time is between 3 and 6 hours. At these conditions, it is hard to keep the taste or the colour unchanged (because of the enzymatic browning). Samples are treated by blanching with SO_2 , so that they acquire the required colour retention.

In fluid bed dryers, drying time is greatly shortened and all the pieces are uniformly dried while they float in the fluidized bed (Kwauk *et al* 2000). During the fluidization process, the batch is fluffed with a stream of warm fluid until all the pieces float in the fluid and form a homogeneous bed. This homogenized bed of fruit pieces is mixed and stirred and at some point of time or the other, the surface of all the pieces is exposed to the same conditions of drying.

Figures 2 and 3 show the point of minimal fluidization for different fruit types. Data for grapes (whole berries and half berries) are shown in figure 2. We can see that the point of minimal fluidization for whole berries is almost double ($\Delta p = 0.95$ kPa) that for half berries ($\Delta p = 0.53$ kPa), as also the time $t = 22500$ (s) for whole berries and $t = 11600$ (s) for half berries, at velocities $v = 1.55$ m/s and $v = 1.4$ m/s. At the beginning the temperature is high for 5 minutes, so as to warm up the sample. After that the heating is continued at constant

Figure 2. Pressure drop across fixed and fluidized bed and critical velocities of air for fluidized bed of different grape berries.

temperature, which is lower than the initial one. Since the constant heating rate is relatively short, we can assume that heating of the product belongs to the range of falling speed of heating. Figure 3 shows us that data obtained for apricots and peaches are different from that obtained for grapes, which can be explained on the basis of the texture of each fruit. Apricots and peaches are very similar, and are different from grapes on the basis of water content, texture and density, as well as other parameters as shown in table 3. Therefore, the fluidization times for them vary from 2700 (s) for apricots to 1800 (s) for peaches, while both grape types have much longer drying times ranging from 6300 (s) for whole grapes to 4500 (s) for half grape berries.

If a batch of moist fruit pieces is dried in a fluidized bed, with periodic withdrawal of samples for determination of moisture content, the resulting curve of fruit moisture content versus time looks like the curves in figures 4 and 5. This type of curve is conventionally divided into two parts; the first part is called the constant rate period and the second one is called the falling rate period. The moisture content at the transition between these two periods is called the critical moisture content. If drying is continued for a long enough amount of time (X), the value approaches the equilibrium moisture content. For a given material this is a function of relative humidity and temperature.

Figure 3. Pressure drop across fixed and fluidized beds and critical velocities of air for fluidized beds, with peach and apricot samples.

Table 3. Fluidization parameters and drying time for fruit samples.

Fruit	Point of minimal fluidization		t (min)	m_o (kg)	T (°C)
	Δp (kPa)	v (m/s)			
Red grape berries (whole)	0.98	5.7	375	0.3	92 $\rightarrow$ 72
Red grape berries (halved)	0.55	4.2	193	0.3	92 $\rightarrow$ 72
Peach	0.13	1.4	30	0.5	100 $\rightarrow$ 78
Apricot	0.15	1.5	45	0.5	100 $\rightarrow$ 78

Figure 4. Experimental moisture contents versus drying time for whole red grape berries and half red grape berries. **Figure 5.** Experimental moisture contents versus drying time for peach and apricot small pieces.

During the constant rate period, fruit particle surface is wet enough for the air layer that is adjacent to the fruit surface to saturate. During this period the temperature of the particle surface remains constant at the wet bulb temperature of the air.

In the falling rate period, the rate of moisture migration to the surface of a fruit particle is insufficient to keep the layer of air adjacent to the particle surface saturated. Drying rate also depends on the pore structure of the material and on the mechanism of moisture migration. In fact, there may be several simultaneous mechanisms. They include capillary action, vapour diffusion along the internal surfaces and, in our case of cellular materials, diffusion across cell walls. On figure 2 one can see the effect of particle shape on pressure drop in fixed and fluidized layer (particles – pieces – had spherical and half spherical shapes). Observing data in figure 4 it can be seen that diffusion is lower in whole grapes from the inside out, as the whole grape has skin all over it. By destroying that skin (cutting the grape in half) moisture diffusing through the material towards the surface as well as from the skin less part towards warm air, becomes more intensive as well as faster. The same effect influences the curve shape in figure 6. when the drying rate is defined. Hence, the drying rate is not layer determined solely by conditions in the boundary layer. It also depends on the pore structure of the fruit material and on the mechanism of moisture migration. There may in fact be several simultaneous mechanisms. They include capillary action, vapour diffusion, diffusion along internal surfaces and, in some cases, diffusion of cellular materials across cell walls.

The rate of drying $-dX/dt$ can be determined at any point by differentiating the X versus t curve, as shown in figures 6 and 7. The difference in drying process for whole grapes and chafe grapes is noticeable on figure 6, while on figure 7 apricots and peaches imbibe typical drying curves.

Results of numerical adoptions of experimental data are summarized in table 4. The moisture contents (experimental and modelled data) vs. drying time are shown in figures 4 and 5. It can be seen that good compatibility between experimental data and the chosen mathematical

Figure 6. Drying rate versus drying time for grape berries.

Figure 7. Drying rate versus drying time for peach and apricot small pieces.

model exists, which is confirmed by the high values of correlation coefficients (0.9932–0.9974).

Stove or tunnel driers should have lengthy drying cycles and primary and secondary drying cycles as separate operations.

The first drying stage is for 2.5 to 3 hours with tray loadings of 10 kg per m². In this stage, the mass reduction is 50% of the feed mass, inlet temperature at 71°C cup-up position.

The second drying stage lasts between 5.5 and 7 hours at 71°C, reducing to 65°C half-way through the cycle at which stage the cups are inverted to cup-down position. Tank conditions should be at 49–50°C to achieve moisture equilibrium between 20 and 22%, and overall ratio 8 : 1; drying down ratio 7.46 : 1.

When drying in fluid bed driers, air temperature at the entrance is higher in the beginning when peaches and apricots are dried at 100°C for only 5 minutes, but somewhat lower (92°C) and for longer durations when grapes are dried (10 minutes). There is a very short drying time at constant velocity for all fruit products, which means that pieces are not heated up to drying temperatures. Therefore we can assume that drying is carried out almost in full at constant temperature in the last stage which is the main presumption for designing a model.

Necessary drying times for obtaining a product with about 6% moisture is much shortened when drying in a fluidized bed than when drying on continuous belt driers (not more than

Table 4. Results of numerical analysis.

Fruit	X_0	k	n	R^2
Red grape berries (whole)	4.7	8.76×10^4	0.70	0.99
Red grape berries (halved)	4.7	4.66×10^4	0.93	0.99
Peach	7.1	1.03×10^4	1.05	0.99
Apricot	6.6	1.26×10^4	1.33	0.99

Table 5. Organoleptic characteristics of samples.

Sample	Taste (1)	Odor (2)	Colour (3)	Look (4)	Overall appearance (5)
Grape	+	+	+	+	100
Peach	+	+	+	–	75
Apricot	+	+	+	+	100

Key

- (1) Excellent (+) 25 points, indefinite (0) 10 points, bad (–) 0 points
 (2) Excellent (+) 25 points, indefinite (0) 10 points, bad (–) 0 points
 (3) As in fresh samples (+) 25 points, bright (ϕ) 10 points, dark (0) 0 points
 (4) Good (+) 25 points, bad (–) 0 points

70 minutes as compared to 4 to 5 hours in belt driers) (figures 4 and 5). All fluidized-bed dried products retain after reconstitution their original colour, organoleptic properties (table 5) and good rehydration ratios (figure 8). Good rehydration ratios show how well the dried products are reabsorbing water and in how much time (Saravacos *et al* 2001). All samples dried on fluidized beds show much less colour degradation compared to fruit dried by other methods (Bobić *et al* 2001).

5. Conclusion

On the basis of experimental data, result interpretations, and calculations made, the following conclusions can be drawn.

The pressure drop that is dependent on airflow speed through the layer is also dependant on dimension, shape and density of particle, which can be best seen when looking at results obtained for whole and half grapes. It is influenced by moisture content of the material, mutual linking of moist particles, especially in places where there is a broken structure. The two-parameter model that was used gave sufficient results combining two phases in the drying

Figure 8. Rehydration ratios for different fruit dried on fluidized beds.

process – constant rate period and falling rate period, into one unique equation. Its plausibility is proved by the high correlation coefficients for all products ($R = 0.99$).

Drying time in a fluidized bed is shorter even when it is done at lower temperatures (they are important for fruit quality after rehydration), than when using conventional drying methods. Complicated mechanisms of moisture-diffusion through the skin of grape berries are clearer than in the case when grape berries are cut in half, when moisture content penetrates more easily through the soft part in kerfing place. Apricots and peaches when dried conventionally (two phases of drying) have their water content reduced by 50%. In our case, the reduction is up to 80% in the first drying stage. Final water content for our fruit is between 12 and 15% depending on the fruit (tables 2 and 3).

Final products are uniformly dried in relatively short time periods with very low rehydration time, which is important for the end user.

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List of symbols

d_p	particle (piece) diameter, m;
k, n	parameters in model (2);
m_o	mass of sample, kg;
m_{dm}	mass of dry matter, kg;
m_{H_2O}	mass of water, kg;
Δp	pressure drop, Pa;
R	rehydration ratio;
R^2	correlation coefficient;
T	inlet air temperature, °C;
t	drying time, s;
v	air velocity, m/s;
X	moisture content of sample, $\text{kg}_{H_2O}/\text{kg}_{dm}$;
X_0	initial moisture content of sample, $\text{kg}_{H_2O}/\text{kg}_{dm}$;
dX/dt	drying rate $\text{kg}_{H_2O}/(\text{kg}_{dm}\text{s})$;
ρ_p	particle density, kg/m^{-3} ;
ρ_b	bulk density, kg/m^{-3} .

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