Foam-mat drying: Energy and cost analyses

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Kudra, T. and Ratti, C. 2006. **Foam-mat drying: Energy and cost analyses**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 3.27 - 3.32. Foam-mat drying allows processing of hard-to-dry materials such as tomato paste and a variety of fruit pulps and juices. Preferential product quality stems from accelerated drying at generally lower drying temperatures. Reduced density of foamed materials leads, however, to a decreased dryer load, which has to be compensated for by shorter drying time to maintain the dryer throughput. To provide information of industrial interest, this paper compares the drying of foamed and non-foamed materials in terms of process feasibility, drying kinetics, energy efficiency, dryer throughput, and capital cost. Convective drying of both foamed and non-foamed apple juice dried in a 19-mm layer at 55°C has indicated higher drying rates for foamed juice which resulted in reduced drying time from 500 to 200 min. Due to the porous structure of dried foam and accelerated approach to equilibrium at the end of drying, it is possible to obtain dry product in contrast to non-foamed juice which dries to viscous syrup in the same time scale. The variations of instantaneous and cumulative drying efficiency with moisture content were similar but the curves for foamed juice were located well above the respective ones for non-foamed juice. Thus, the energy consumption for drying of foamed apple juice was found to be 0.2 of that for drying of non-foamed juice. The dryer throughput was calculated as 0.83 and 0.68 kg $m^{-2}h^{-1}$, respectively. Because of higher throughput and shorter drying time, the foam-mat dryer can be smaller which would reduce capital costs by about 11% for a belt conveyor dryer and by 10% for a drum dryer. **Keywords**: apple juice**,** drying kinetics, drying efficiency, energy consumption, mango.

Le séchage en tapis de mousse permet de traiter des matériaux difficiles à sécher tels que la pâte de tomate et une grande variété de pulpes et de jus de fruits. Une meilleure qualité du produit final résulte de l'accélération du séchage à basse température. La masse volumique réduite des mousses diminue par contre la capacité de production du séchoir, laquelle doit être nécessairement compensée par une diminution du temps de séchage. Afin de donner de l'information d'intérêt industriel, cet article examine le séchage des matériaux moussés et non moussés en relation à la faisabilité du procédé, la cinétique de séchage, l'efficacité énergétique, la capacité de production du séchoir et les coûts fixes. Le séchage convectif à 55°C du jus de pomme moussé et non moussé en couche de 19 mm d'épaisseur a démontré l'atteinte de vitesses de séchage plus élevées pour le jus moussé réduisant le temps de séchage de 500 à 200 minutes. Dû à la structure poreuse de la mousse sèche, il est possible d'obtenir un produit final sec contrairement au jus non moussé qui forme un sirop visqueux en séchant durant la même période de temps. Les variations de l'efficacité du séchage instantanée et cumulatif en fonction de la teneur en eau ont montré des allures similaires pour les jus moussé et non moussé, mais les courbes pour le jus moussé montraient une efficacité nettement supérieure à celle du jus non moussé. Ainsi, le rapport de la consommation d'énergie pour sécher le jus de pomme moussé sur celle du jus non moussé a été de 0.2. Des calculs ont démontré une capacité de production du séchoir de 0.83 kg $m^{-2}h^{-1}$ et 0.68 kg $m^{-2}h^{-1}$ pour les jus moussé et non moussé respectivement. Parce que la capacité de production est plus grande dans un temps d'opération inférieur, le séchoir en tapis de mousse peut être plus petit ce qui pourrait ainsi réduire les coûts fixes d'un séchoir convoyeur de 11% et d'un séchoir à tambour, de 10%. **Mots clés:** jus de pomme, cinétique de séchage, efficacité de séchage, consommation énergétique, mangue**.**

INTRODUCTION

Foaming of liquid and semi-liquid materials has long been recognized as one of the methods to shorten drying time. Over the past decade, this relatively old technology, known as foam-mat drying, received renewed attention because of its added ability to process hard-to-dry materials, obtain products of desired properties (e.g., favourable rehydration, controlled density), and retain volatiles that otherwise would be lost during the drying of non-foamed materials. Thus, current research is directed not only to convective drying of purposely foamed materials in spray dryers, plate dryers, and band dryers but also to conventional freeze-drying, as well as microwave drying of frozen foams with and without dielectric inserts as complementary heat sources (Ratti and Kudra 2005).

In general, drying of foamed materials is faster than that of non-foamed ones, although certain foams such as the ones from soymilk (Akintoye and Oguntunde 1991) or starfruit (Karim and Wai 1999) exhibit higher drying rates in the beginning of foam-mat drying whereas for other materials such as tomato paste (Lewicki 1975), bananas (Sankat and Castaigne 2004), and mango (Cooke et al. 1976) drying rates are greatly accelerated at the end of drying.

Besides accelerated transport of liquid water to the evaporation front, drying experts have repeatedly pointed to the increased interfacial area of foamed materials as the factor responsible for reduced drying time. Because density of foamed materials is lower than that of non-foamed ones and extends from 300 to 600 kg/m^3, the mass load of the foam-mat dryer is also lower. However, shorter drying time can not only offset the reduced dryer load but also increase the dryer throughput. For example, the dryer throughput can be higher by 32% when drying foamed apple juice with pulp (unpublished data) and by 22% when drying foamed mango pulp as calculated in this study from the experimental data generated by Rajkumar et al. (2005). Because foam-mat drying is highly material and process dependent, these figures may vary with the drying material, dryer type, and drying conditions. Furthermore, shorter drying time per unit mass of foamed materials might not always bring about lower energy consumption and better process economics.

In view of scarce information on foam-mat drying, this paper aims at comparing the drying of foamed and non-foamed materials in terms of process feasibility, drying kinetics, energy

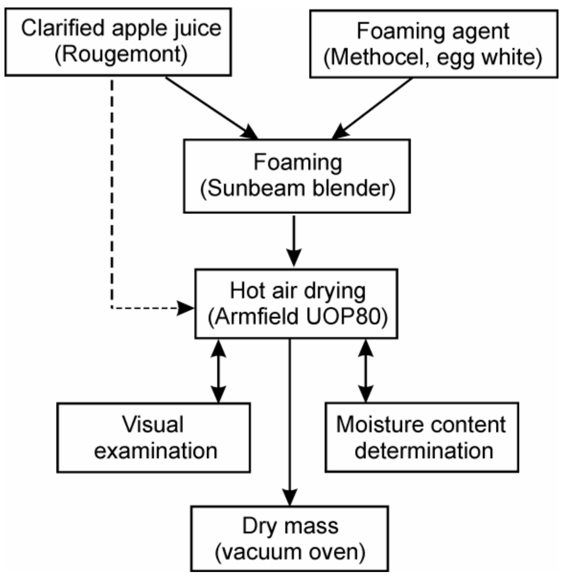

Fig. 1. Experimental protocol.

efficiency, dryer throughput, and capital costs. To evaluate energy consumption during drying of foamed materials and to identify possible differences when drying non-foamed materials, the instantaneous and cumulative drying indices have been calculated from experimental data for apple juice and related to the material moisture content. The dryer throughput and cost comparisons were made for foamed and non-foamed mango pulp as non-foamed apple juice dries in a reasonable time only to viscous syrup.

MATERIALS and METHODS

Figure 1 summarizes the most important steps of the experimental methodology.

Foam preparation

Clarified apple juice (Rougemont, Québec) in 0.25-kg batches was whipped with a pre-selected amount of the foaming agent in a domestic blender (Sunbeam, Mixmaster) operated at 800 rpm for 5 min. Following our own studies on foam characteristics (Raharitsifa et al. 2006), either dry egg albumin (provided by a local food ingredient company) at 3% w/w, or methylcellulose (Methocel, 65HG, Fluka, Buchs, Switzerland) at 0.5, 1.0, 2.0, and 3.0% w/w, were used to induce foams of required density. Foam density was determined using the method described by LaBelle (1966). Thus, foam from the blender was transferred to a 170-mL (80-mm diameter, 40-mm height) brand-crystallizing dish and weighed with an accuracy of 0.01g. Transferring of the foam was carried out gently to not destroy its structure or trap air voids while filling the dish up to the rim. Foams were deemed mechanically and thermally stable (Bates 1964) as no drainage and collapse was noted for foams at density below 500 kg/m^3.

Drying trials

Drying experiments were carried out in a commercial hot air dryer (Armfield UOP80, Hampshire, UK), which resembles a single-pass wind tunnel having a 0.55-long drying chamber with a 0.277 x 0.277 m cross-sectional area. In the centre of this chamber, a removable rack was placed to support two identical Petri dishes located one above the other at an adjustable distance allowing air flow past both samples at the same velocity. In these experiments, the superficial air velocity was kept constant at 0.69±0.03 m/s, and air temperature entering the drying chamber was set at 55°C and monitored throughout the experiment. To generate data for energy calculations, the air temperature at the dryer outlet was also measured, and the outlet air humidity was calculated from the mass of water evaporated and ambient air humidity (measured with the wet and dry bulb aspirated psychrometer). To trace the variation of material temperature with time, a K-type thermocouple was inserted into the geometrical centre of each sample.

Prior to each experiment, the dryer was thermally stabilized by passing hot air at pre-set temperature and velocity for 60 min. The temperature difference at the dryer inlet and outlet, resulting from heat losses was then used to adjust the measured temperature difference for energy calculations.

Two separate experiments were performed with identical samples. In drying kinetics experiments, the foamed apple juice was poured flush to the rim of a Petri dish (147 mm in diameter) and two dishes were placed on the rack in a drying chamber. After a given time interval (5 min at the beginning and then 10 and 15 min) the dishes were withdrawn from the chamber for mass determination (Mettler balance, accuracy ± 0.01 g). At the same time, the samples were visually inspected for cracks, shrinkage, colour, etc. The bone-dry mass of the samples was determined by drying at 60°C for 48 hours in a vacuum oven at 12 kPa, using P_2O_5 as desiccant. Measurements were done in duplicate.

In the second type of experiments, the twin samples, each with embedded thermocouple for material temperature measurements, were not removed for weighing but dried continuously over the same time as in the drying kinetics experiments. Separate experiments for drying kinetics and determination of energy consumption as well as the use of two identical samples in each experiment minimized errors due to the position of the sample, contact of the thermocouple with the drying material, and the variation of thermal conditions when withdrawing the sample for mass loss determination.

DATA INTERPRETATION

In this paper, only the results obtained for apple juice foam, having a density of 210 kg/m^3 and dried as a 19-mm layer at 55°C, are presented and compared with pure apple juice dried under the same conditions. Drying kinetics are presented to aid in interpretation of the energy data. The dryer throughput and capital cost are compared for mango pulp as both foamed and non-foamed pulp dry to a solid material in the same time scale.

Drying kinetics

Figure 2 compiles the experimental points showing the temporal variation of moisture content and material temperature. Figure 3 presents the smoothed drying rate curves for foamed and non-foamed apple juice calculated from mass of evaporated water over a respective time difference for the experimental points shown in Fig. 2.

As seen in Fig. 2, a drying curve for non-foamed apple juice is typical for drying of solutions or diluted suspensions where a

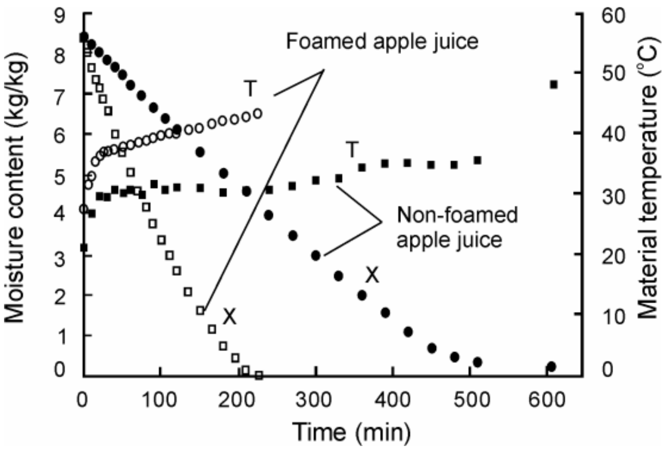

Fig. 2. Typical drying (X) and temperature (T) curves for foamed and non-foamed apple juice dried as 19-mm layer by air at 55°C.

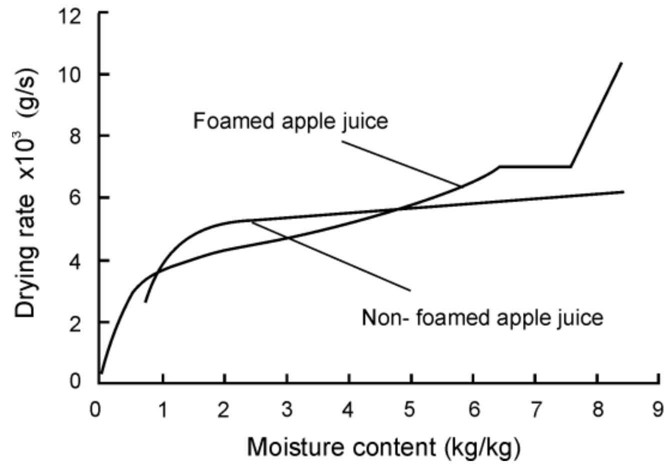

Fig. 3. Drying rate curves for foamed and non-foamed apple juice dried as 19-mm layer by air at 55°C (derived from experiments shown in Fig. 2).

large amount of free water is available for evaporation. Thus, the moisture content decreases almost linearly with time, down to about 2.5 kg/kg. The drying curve over this period can be approximated by a slightly inclined line. Except for its initial rise, the material temperature remains constant at about 32°C which, along with a constant rate period, indicates that the drying process is controlled by external conditions although with gradually increasing contribution from internal resistance to mass transfer. Such decay in the drying rate could be explained by the relative rise in concentration of sugars, organic acids, and other soluble components so evaporation from apple juice is not the same as from pure water. Below this moisture content, the falling rate period begins (Fig. 3), which is seen as a rise in material temperature and a decrease in drying rate. A dramatic drop in the drying rate starts at moisture content of about 1.0 kg/kg. Visual observations indicate that at this moisture content the juice turns into viscous syrup. At this drying stage, the normally convex drying rate curve transfers into the concave one. Such a concave curve is typical for food products which dry as colloidal or capillary-porous-colloidal materials.

The apparently similar drying curve for foamed apple juice (Fig. 2) generates, however, a different drying rate curve (Fig. 3). Here, at the inception of a drying process, the drying rate is extremely high (almost twice that of the one for non-foamed juice) but soon it drops and the constant value is maintained for a relatively short period of about 20 min. This constant rate period can be ascribed to unrestricted exposure of liquid lamellae to the drying air as well as sufficient amount of water transported to the evaporation surface. Starting from about 6.5 kg/kg, the falling rate periods develop as moisture flow to the evaporation front reduces with time. However, in contrast with non-foamed apple juice, the first falling rate period for foamed juice is represented by the concave curve whereas the second one is of convex type. No direct comparison of such a drying rate curve is possible for other juices as the published papers on drying kinetics report only on the final moisture content vs drying conditions (Berry et al. 1965; Bissett et al. 1963). Yet, this type of drying rate curve has been found for foamed pasty materials such as bananas (Sankat and Castaigne 2004), mango (Cooke et al. 1976), or tomato paste (Lewicki 1975). It appears that such rapid approach to equilibrium, promoted by the porous structure of dried foam, not only shortens the drying time but allows drying of certain materials which cannot be dried as a non-foamed layer in a technically acceptable time scale. The examples of such materials are tomato paste which forms an elastic gel and apple juice, peach juice, or maple syrup which dry to viscous syrup.

Energy consumption

It is commonly assumed that in conventional dryers heat supplied to the dryer is used for moisture evaporation, heating of the wet material and the dryer, as well as for compensation of heat losses. However, drying of a large number of materials, especially food products, involves energy not only for free water evaporation but also for capillary-bound water removal, heating of the wet material as its temperature changes in the course of drying, local superheating of the vapor, and overheating of the already dried layers of the material otherwise necessary to maintain the required temperature gradient and thus sufficient heat transfer rates. Therefore, the energy efficiency defined as the ratio of heat for moisture evaporation to total heat supplied to the dryer is a function of the material properties (e.g. porosity, hygroscopicity, size and shape, moisture bonding), dryer design (type, configuration, mode of heating, heat recovery, etc.), operating parameters (drying temperature, recycle ratio, fractional saturation, gas flow rate), and initial-final moisture content. Moreover, the energy efficiency reported in the technical literature is usually calculated from the initial-final or inlet-outlet data. For batch drying, the energy efficiency is therefore given as an average value over a drying time, while for continuous drying the energy efficiency is averaged over the range of moisture content or the dryer length.

The averaged energy efficiency is useful when comparing different dryers but has limited application when analyzing a drying process and dryer configuration in the design stage. This limitation can be overcome when using the concept of instantaneous drying indices which allow tracing of the energy use over drying time. Here, the instantaneous energy efficiency (ε_E) can be defined as:

$$\varepsilon_E = \frac{energy\ used\ for\ evaporation\ at\ time\ t}{input\ energy\ at\ time\ t} \times 100 \quad (1)$$

Integration of the instantaneous energy efficiency gives the cumulative energy efficiency (E_E) over a given time interval:

$$E_E = \frac{1}{t}\int_0^t \varepsilon_E(t)dt \quad (2)$$

The instantaneous energy efficiency indicates only the degree of energy utilization. To analyze the drying "Q-factor", the instantaneous drying efficiency (ε_D) (and by analogy - the cumulative drying efficiency (E_D)) which accounts for enthalpy of the exhaust air can be used:

$$\varepsilon_D = \frac{energy\ used\ for\ evaporation\ at\ time\ t}{(input\ energy - output\ energy)\ at\ time\ t} \times 100 \quad (3)$$

and

$$E_D = \frac{1}{t}\int_0^t \varepsilon_D(t)dt \quad (4)$$

The energy used for water evaporation (Q_{ev}) during an incremental drying time was calculated as:

$$Q_{ev} = \frac{\Delta m}{\Delta t}\Delta H = \frac{\Delta m}{\Delta t}\left(2502.3 - 2.376 T_m\right) \quad (5)$$

where:

T_m = average material temperature (°C) over the incremental time Δt,
Δm = mass of water (kg) evaporated over the incremental time Δt, and
ΔH = latent heat of evaporation (kJ/kg).

The input and output energy with drying air (Q) was calculated using Eq. 6 with respective parameters determined for inlet and outlet conditions:

$$Q = G_g c_H T_g = G_g\left(1.0059 + 1.861Y\right)T_g \quad (6)$$

where:

G_g = mass flow rate of air (kg/s),
c_H = humid heat of air (kJ kg^{-1}K^{-1}),
Y = absolute air humidity (kg/kg), and
T_g = air temperature (°C).

The outlet air humidity was calculated from the inlet humidity and mass of evaporated water.

A previous study (Kudra 1998) has indicated that the drying efficiency index is more suitable for energy performance analysis than the energy efficiency index, and the instantaneous indices are more useful than the cumulative ones. It is particularly valid for laboratory experiments such as these in a drying tunnel where the relatively small mass of the sample is dried using unnecessarily high input energy, yet needed to secure required conditions such as air velocity and temperature. Thus, the energy efficiency as defined by Eqs. 1 and 2 does not reflect the energy efficiency in industrial dryers. For this reason, the energy analysis in this comparative study has been constrained to the instantaneous drying indices.

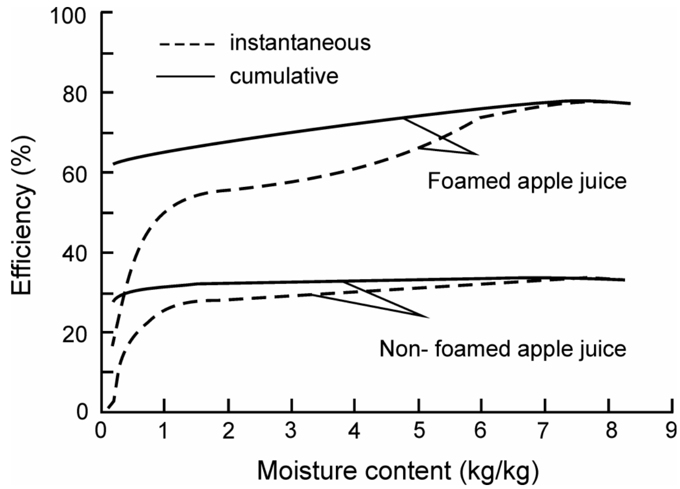

Fig. 4. Variation of the instantaneous (ε_D) and cumulative (E_D) drying efficiency with moisture content for foamed and non-foamed apple juice dried as 19-mm layer by air at 55°C.

As seen in Fig. 4, both indices for foamed and non-foamed juice exhibit very similar runs. Namely, after reaching a weak maximum at the beginning of drying the instantaneous drying efficiency gradually decreases as water evaporates. An abrupt drop occurs at the end of drying, and such a run conforms to the drying rate curve. The run of cumulative indices is more tempered than the respective run of instantaneous indices because the cumulative efficiency expresses the integral average value from the beginning of drying to a given instant.

As expected, drying of foamed juice is more energy efficient so the curves for both instantaneous and cumulative drying indices for foamed juice are located above the ones for non-foamed juice. Higher energy efficiency can be ascribed to: (1) the foam particularities facilitating the removal of moisture at the beginning of drying such as extended interfacial area and enhanced transport of liquid to the evaporation front, and (2) the porous structure of the foamed material developed at a certain instant and retained throughout drying. Thus, the foamed materials dry similarly to the capillary-porous solid, which opens several possibilities for energy savings. For example, once the rate of drying starts to be controlled by internal heat and mass transfer conditions there is no reason to maintain the same level of heat input because a greater fraction of it is used to raise the sensible heat of the solid rather than that needed for evaporation. It is logical to reduce the intensity of the heat input once the surface moisture is removed, especially for heat-sensitive materials. This will not only improve product quality but also increase the overall energy performance of the dryer. The energy consumption for drying of foamed apple juice was found to be 0.2 of the one for drying of non-foamed juice which results from shorter drying time (c.f., Fig. 2) and higher drying efficiency (c.f., Fig. 4).

Cost comparison

It appears that the only economic evaluation for foam-mat drying has been published for vacuum drying of whole milk foamed with nitrogen (Turkot et al. 1961a, 1961b). Even though

Table 1. Drying time and final moisture content for foamed and non-foamed mango pulp dried at 60°C in layers of different thickness, b.

Mango pulp	b = 1 mm	b = 2 mm	b = 3 mm
Foamed*	40 min 5.60% w.b.	60 min 5.60% w.b.	80 min 5.86% w.b.
Non-foamed	90 min 6.20% w.b.	120 min 6.20% w.b.	180 min 6.37% w.b.

*Pulp + 10% albumin + 0.5% Methocel

no cost comparison was made for drying of non-foamed milk, it is reasonable to expect financial benefits also for generally regarded foam-mat drying by analogy to foam-spray drying. In this case the drying rates for foamed drops were found higher compared to non-foamed ones in addition to lower final moisture content for foamed droplets due to longer residence time (Hanrahan and Webb 1961). This yields increased capacity for existing spray dryers and thus substantially reduces the plant investment required for a given output, since the cost of additional equipment is considerably less than that of adding spray drying capacity.

An examination of the process flow sheets for foam-mat drying indicates that the foam preparation unit complements the existing dryer such as the belt conveyor, the shelf, or the cylinder dryers. Depending on the particular technology, this unit combines either the gas disperser and the feed nozzle, or the blender and the foam dispenser. From a cost analysis for the foamed milk drying plant it follows that the three gas dispersing units constitute only 1.3% of the total processing equipment or of about 2% of the cost for two dryers. Thus, it is rational to compare only the cost of the dryer when switching from non-foamed to foamed materials.

As already indicated in the preceding section, non-foamed apple juice dries in a reasonable time only to a viscous syrup in contrast to foamed juice which dries to the brittle porous solid. Thus, to allow comparison we used our other data for foamed and non-foamed mango pulp where dry solids can be obtained in the same time scale (Rajkumar et al. 2005). Table 1 compares drying time and final moisture content for non-foamed mango pulp (X_0=79.6% w.b.; ρ=1020 kg/m^3) and mango pulp foamed with a mixture of 10% egg albumin and 0.5% methylcellulose (X_0=79.8% w.b.; ρ=540 kg/m^3). Both materials were dried in 1, 2, or 3-mm layers at 60, 65, 70, and 75°C in a batch cabinet dryer equipped with 24 trays of 0.9 m x 0.4 m each.

The following analysis was made using data for a 1-mm layer dried at 60°C because such conditions offered the best product in terms of retained biochemical and nutritional qualities. The baseline for the final moisture content of dry mango was set at 6.2% w.b., which gives a drying time for non-foamed and foamed pulp of 90 and 39 min, respectively. The mass load for a 1-mm layer equals 1.02 kg/m^2 for pulp and 0.54 kg/m^2 for foam, leading to the dryer throughput of 0.68 kg $m^{-2}h^{-1}$ for non-foamed pulp, and 0.83 kg $m^{-2}h^{-1}$ for foamed pulp. Similar throughput advantage exists for foamed apple juice with pulp (unpublished data) and foamed tomato paste (Lewicki 1975).

At the design stage, a higher throughput can result in a smaller dryer which would translate into cost savings. The capital cost of any dryer (P) can be estimated from the following correlation (Sztabert and Kudra 1995):

$$P = M\&SI \times A \times C^B \qquad (7)$$

where:
M&SI = Marshal and Swift equipment cost index,
C = characteristic dryer capacity defined either by its effective volume or its surface area, and
A, B = constants.

For the belt conveyor dryer the belt surface area is used with constants A=21 and B=0.59, whereas for a drum dryer the drum peripheral surface area applies with A=21 and B=0.5. Thus, the capital costs of the belt conveyer dryer and drum dryer could be lower by about 11 and 10%, respectively. Such a decrease in investment cost compensates for the additional cost of the foaming system.

CONCLUSIONS

1. In contrast to non-foamed materials such as apple juice which dries to a viscous layer, foam-mat drying makes it possible to obtain dry product of required quality in a technically acceptable time scale of about 3 hours.
2. Drying kinetics for non-foamed juice follow the ones for solutions and diluted suspensions whereas drying kinetics for foamed juice are typical for capillary-porous solids. Higher drying rates by about 1.2-1.6 at the beginning of foam-mat drying, along with an accelerated approach to thermodynamic equilibrium for foamed apple juice, result in reduced drying time from 500 to 200 min.
3. Drying efficiency for foamed apple juice is almost 2-fold that for non-foamed juice. Because of higher drying efficiency and shorter drying time, the energy consumption for drying of foamed apple juice is 0.2 of that for drying of non-foamed juice.
4. Lower density of foamed materials decreases mass load to the dryer. However, for certain materials such as mango pulp dried in a 1-mm layer, the lower mass load is so well compensated for by a shorter drying time that the dryer throughput is higher by 18%.
5. For a given production rate, the higher throughput translates into a smaller foam-mat dryer, allowing capital cost savings in the order of 10%.

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