УДК 66.047

PROCESS AND ENERGY OPTIMIZATION IN DRYING OF FOAMED MATERIALS

T. Kudra[1], C. Ratti[2]

Canmet Energy Technology Centre – Varennes, PQ, Canada J3X 1S6 (1); Department of Soils and Agri-Food Engineering, Laval University, Quebec, QC, Canada G1K 7P4 (2)

Key words and phrases: apple juice; drying efficiency; drying kinetics; drying time; energy consumption; foam; foam-mat drying.

Abstract: The paper deals with optimization of drying time and energy consumption in foam-mat drying of liquid bio-materials. A clarified apple juice mixed with methylcellulose in mass concentrations 0,5; 1,0; 2,0 and 3,0 % was whipped in a blender to generate foams of different density varying from 0,21 to 0,45 g/cm^3. The foam samples in layers of 6, 12 and 26 mm thick were then dried in a drying tunnel using air at 55 °C flowing past the sample surface at a superficial velocity of 0,7 m/s. Experimental data were interpreted in terms of drying kinetics and energy performance. It was found that the drying rate of foamed juice depends on foam density and its characteristics, as well as on the layer thickness. Shorter drying times were obtained for thinner layers of foams of the same density. A distinct minimum of a drying time was obtained for foam density of 0,21 g/cm^3 induced with 1 % methylcellulose. This foam exhibited the highest drying efficiency and the lowest energy consumption.

Nomenclature

b – thickness, m;
c_H – humid heat, kJ/(kg·K);
C – concentration, % w/w;
E_D – cumulative drying efficiency;
G – mass flow rate, kg/s;
ΔH – latent heat of evaporation, kJ/kg;
m – mass, kg;
Q – heat rate, W;
t – time, min;
T – temperature, °C;
u – superficial air velocity, m/s;
X – moisture content dry basis, kg/kg;
Y – absolute air humidity, kg/kg;
ε_D – instantaneous drying efficiency;
ρ – density, g/cm^3.

Subscripts

ev – evaporation;
g – gas;
m – material.

Acronyms

d. m. – dry matter;
MC – methylcellulose;
w/w – weight-by-weight.

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., favorable 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, 2006).

In general, drying of foamed materials is faster than that of non-foamed ones, although certain foams such the one from the 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 0.3 to 0.6 g/cm^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 (own unpublished data) and by 22 % when drying foamed banana puree (Rajkumar et al., 2007). A higher throughput can result in a smaller dryer, which would translate into cost savings. In case of foamed mango, the capital costs of the belt conveyer dryer and the drum dryer could be lower by about 11 % and 10 %, respectively (Kudra and Ratti, 2006). Our comparative study on drying of non-foamed apple juice and foamed apple juice of density equal to 0,21 g/cm^3 had indicated that foamed juice dries faster, and the energy consumption is only 0,2 of the one for drying of non-foamed juice which results from shorter drying time and higher drying efficiency (Kudra and Ratti, 2006).

This study presents the experimental results on drying kinetics and energy consumption during convective drying of apple juice foams of different density and layer thickness as these two parameters have the prevailing effect on drying characteristics over temperature and air velocity.

Materials and methods

Fig. 1 summarized the most important steps of the experimental methodology.

Foam preparation

Clarified apple juice (Rougemont, Québec, Canada) in 250 g 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., 2007), the methylcellulose (Methocel, 65HG, Fluka, Switzerland) at 0,5; 1,0; 2,0 and 3,0 % w/w, were used to generate foams having the respective density of 0,21; 0,21; 0,30 and 0,45 g/cm^3. Characteristically, the lowering of Methocel concentration from 1,0 to 0,5 % w/w did not result in lower foam density, and the similar trend was reported by Karim and Wai (1999) and Raharitsifa et al. (2006). Foam density was determined using the method described by LaBelle (1966). Thus, foam from the blender was transferred to a brand-crystallizing dish (80 mm in diameter and 40 mm height) and weighed with 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 0,5 g/cm^3. An exception is only the foam generated with 0,5 % w/w of Methocel, which appeared to be mechanically stable but thermally instable as noticeable drainage was observed during drying.

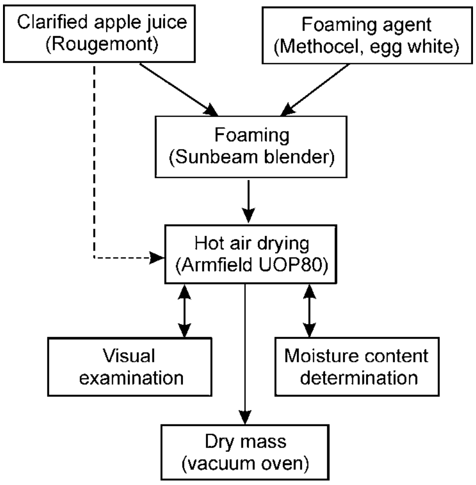

Fig. 1. Experimental protocol

Drying trials

Drying experiments were carried out with a commercial hot-air dryer (Armfield UOP80, UK), which resembles a single-pass wind tunnel having a 0,55 m long drying chamber with a 0,277 × 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 in 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 0,5 mm open junction thermocouple (Omega Engineering, Inc., Stamford, CT, USA) 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 flash to the rim of a Petri dish (14,7 cm 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 Toledo balance, accuracy ∓ 0,01 g). At the same time, the samples were visually inspected for cracks, shrinkage, color, 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, and the arithmetic averages were taken for data interpretation.

In the second type of experiments, twin samples each having embedded thermocouple for material temperature measurements, were not removed for weighing but dried continuously over the same time as in 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

Despite a number of studies on drying of foamed materials, only a few papers report on the effect of foam characteristics and operating parameters on drying kinetics. An analysis of the published data indicates that the drying characteristics, quantified by the drying time and final moisture content, are affected by foam density, layer thickness, air temperature, and air velocity. It is generally accepted that drying time shortens with increasing temperature. However, higher air temperatures and prolonged drying times result in such a significant deterioration of quality attributes that drying at lower temperatures of about 60 to 70 °C is recommended (Lewicki, 1975; Cooke et al., 1976; Karim and Wai, 1999; Sankat and Castaigne, 2004) unless higher foam temperature is compensated by shorter processing time as it is the case of microwave drying (Brygidyr et al., 1977).

The effect of air velocity was studied by Sankat and Castaigne (2004) and Lewicki (1975), who found the positive but not profound effect of air velocity on the drying rate. Thus, in this study, both air temperature and air velocity were not considered as process variables.

As expected for most of the food products, where the drying rate is controlled by internal mass transfer, the drying time extends with the layer thickness. Such an effect of the layer thickness on drying kinetics for foamed apple juice is shown in Fig. 2. A similar trend was observed for drying of foamed bananas (Sankat and Castaigne, 2004) and foamed tomato paste (Lewicki, 1975).

Aside from the foam microstructure, defined by the bubble size and size distribution (LaBelle, 1966; Brygidyr et al., 1977), the foam density regarded as a lumped parameter appears to have a crucial effect on drying characteristics. This effect is explicitly revealed only in papers by Lewicki (1975) and Brygidyr et al. (1977) who studied foam-mat drying of tomato paste. The paper by Karim and Wai (1999) presents this effect indirectly as drying characteristics of foamed starfruit were related to the Methocel concentration. As a result of extensive studies Lewicki (1975) found that drying time shortens with lowering foam density. Interestingly, he spotted the critical foam density of 0,32 g/cm^3 below which the drying either increases when 3-mm layer is dried at 60,2 °C, remains constant at 75,2 °C, or reduces progressively at 88,5 °C. These trends become more pronounced when drying progresses and the final moisture content

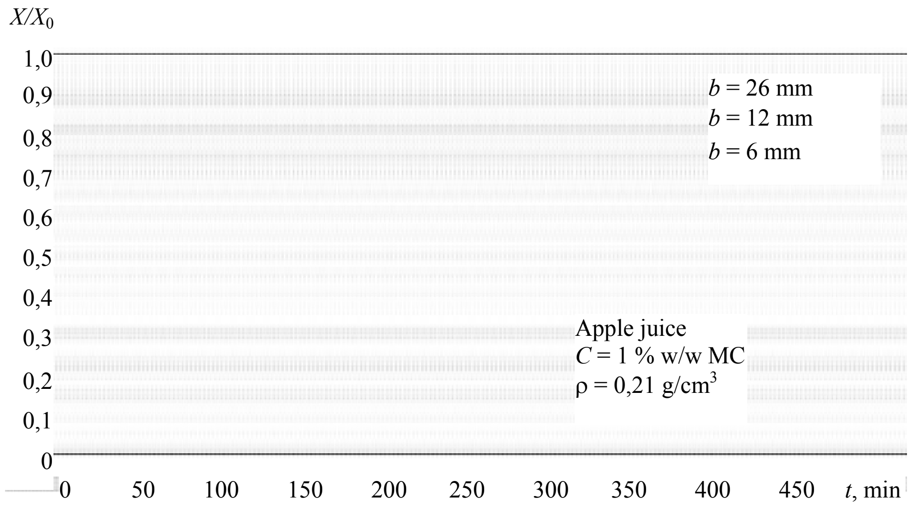

Fig. 2. Normalized drying curve for foamed apple juice – effect of layer thickness
(T_g = 55 °C; u = 0,7 m/s)

approaches 0,05 kg/kg. This critical density did not exist when the tomato paste was dried in a 1 mm layer. These findings are supported by the results of Brygidyr et al. (1977) who also found shorter drying time for lower density of tomato paste. No critical value for foam density in these experiments is credible as drying of 3,2 mm foam with density equal to 0,34 g/cm^3 was performed at 76,7 °C that is for values where no minimum was found by Lewicki (1975). Such a critical density noted for certain operating parameters indicates that foam-mat drying can be optimized with respect to drying time and thus to energy consumption.

A similar optimization problem was identified in the present study. As shown in Fig. 3, the fastest drying and thus the shortest drying time was obtained for apple juice foamed with 1 % Methocel (ρ = 0,21 g/cm^3) dried in a 12 mm layer at 55 °C. Further reduction of Methocel concentration did not affect foam density but resulted in longer drying time. This effect can be ascribed to the minimum concentration of the foaming agent that allows generation of the mechanically and thermally stable foam down to 1 % w/w. Although foam of the same density (0,21 g/cm^3) obtained with 0,5 % w/w Methocel was mechanically stable prior to drying, it became thermally-instable, as progressive drainage was observed in the course of drying. Such a phenomenon deteriorated the foam structure and altered the heat and mass transfer characteristics.

In our previous study we found that the drying efficiency varies with moisture content, and that the foamed materials exhibit higher values of drying efficiency and lower energy consumption than the not foamed ones (Kudra and Ratti, 2006). To identify the effect of foam properties, the cumulative drying efficiency was calculated from the following relationships (Kudra, 1998)

$$\varepsilon_D = \frac{\text{energy used for evaporation at time } t}{(\text{input energy} - \text{output energy}) \text{ at time } t} \tag{1}$$

and

$$E_D = \frac{1}{t}\int_0^t \varepsilon_D(t)\, dt\,. \tag{2}$$

The energy used for water evaporation during an incremental drying time was calculated as

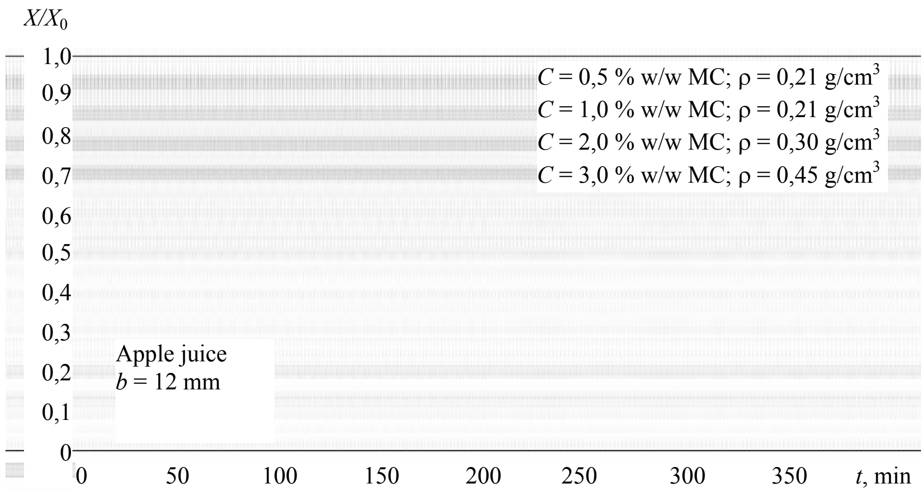

Fig. 3. Normalized drying curve for foamed apple juice – effect of foam density
(T_g = 55 °C; u = 0,7 m/s)

E_D

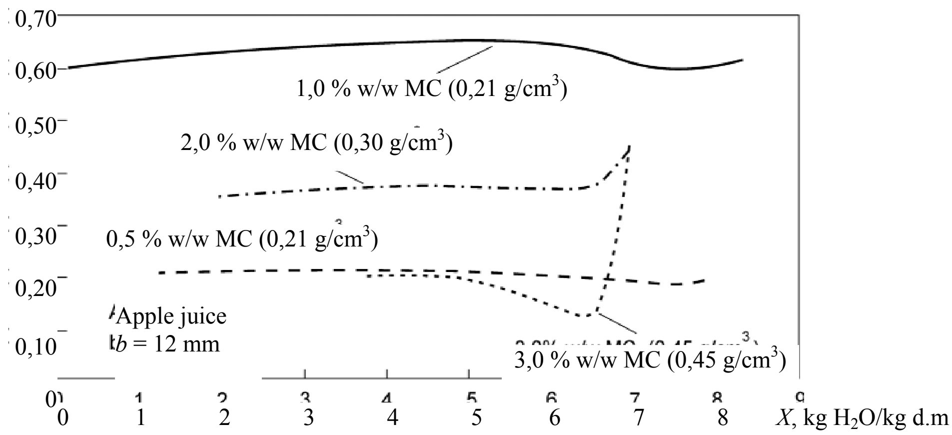

Fig. 4. Variation of cumulative drying efficiency with moisture content for foamed apple juice of different density

(T_g = 55 °C, u = 0,7 m/s)

$$Q_{ev} = \frac{\Delta m}{\Delta t}\Delta H = \frac{\Delta m}{\Delta t}(2502{,}3 - 2{,}376 T_m), \tag{3}$$

where T_m, °C is the average material temperature over the incremental time Δt.

The input and output energy with drying air was calculated from the following relationship with respective parameters determined for inlet and outlet conditions

$$Q = G_g c_H T_g = G_g (1{,}0059 + 1{,}861 Y) T_g. \tag{4}$$

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

Fig. 4 presents the variation of the cumulative drying efficiency with moisture content for different foam density. All curves exhibit very similar runs. Namely, after reaching a weak depression at the beginning of drying the cumulative drying efficiency increases to its maximum and the gradually decreases as water evaporates. Characteristically, the maximum drying (energy) efficiency was obtained for foam with density of 0,21 g/cm^3 induced with 1 % w/w of Methocel. Much lower efficiency was obtained for the same density foam but induced with 0,5 % w/w of Methocel. This maximum coincides with the maximum of drying rate and minimum drying time, and can be attributed to thermal instability of such foam. Characteristically, the maximum of energy efficiency and minimum of energy consumption were obtained also for foam prepared with 1 % w/w of Methocel. For example, taking the foam induced with 1 % of Methocel as the reference one, the specific energy consumption for foams induced with 0,5 % and 2 % w/w of Methocel were respectively higher by 3,2 % and 13, %, which documents the optimum conditions for both the process and energy use.

Conclusions

Drying kinetics of foamed apple juice depend on foam density and layer thickness. The highest drying rate thus the shortest drying time was obtained for the thinnest layers and the foams of the lowest density. However, a notable difference in drying rates is noted for the foams of the same density but generated with different concentrations of Methocel as the foaming agent. A distinct maximum of the drying rate with respect to Methocel concentration can be attributed to the combined effect of foam density and its structural stability which dramatically reduces at the lowest Methocel concentration. The maximum of drying efficiency thus minimum of energy consumption appear for the same foam density induced with the same Methocel concentration. This indicates that drying of foamed materials needs optimization of the process in order to minimize energy consumption.

The authors would like to acknowledge FQRNT (Fonds québécois de la recherche sur la nature et les technologies, Québec) for their financial support as well as the help of Monica Araya-Farias and Valérie-Anne Brouillard during the experiments.

References

1. Akintoye, O.A. and Oguntunde, A.O. 1991. Preliminary investigation on the effect of foam stabilizers on the physical characteristics and reconstitution properties of foam-mat dried soymilk. Drying Technology 9( ): 245–262.

2. Bates, R.P. 1964. Factors affecting foam production and stabilization of tropical fruit products. Food Technology 18: 93–96.

3. Brygidyr, A.M., Rzepecka, M.A. and McConnell, M.B. 1977. Characterization and drying of tomato paste foam by hot air and microwave energy. J. Inst. Can. Sci. Technol. Aliment. 9(4): 313–319.

4. Cooke, R.D., Breag, G.R., Ferber, C.E. M., Best, P.R. and J. Jones, J. 1976. Studies of mango processing; 1. The foam-mat drying of mango (Alphonso cultivar) puree. J. Food Technology 11: 463–473.

5. Karim, A.A. and Wai, C.C. 1999. Foam-mat drying of starfruit (Averrhoa carambola L.) puree. Stability and air drying characteristics. Food Chemistry 64: 337–343.

6. Kudra, T. 1998. Instantaneous dryer indices for energy performance analysis. Inzynieria Chemiczna i Procesowa 19: 163–172.

7. Kudra, T. and Ratti, C. 2006. Foam-mat drying: energy and cost analyses. Canadian Biosystems Engineering 48: 3.37-3.32.

8. LaBelle, R.L. 1966. Characterization of foams for foam-mat drying. Food Technology 19: 89–94.

9. Lewicki, P.P. 1975. Mechanisms concerned in foam-mat drying of tomato paste. Trans. Agricultural Academy in Warsaw 55: 1–67 (in Polish).

10. Raharitsifa, N., Genovese, D.B. and C. Ratti, C. 2006. Characterization of apple juice foams for foam-mat drying prepared with egg white protein and methylcellulose. J. Food Science 71(3): E142–E151.

11. Rajkumar, P., Kailappan, R., Viswanathan, R., Raghavan, G.S.V. and Ratti, C. 2007. Studies on foam-mat drying of alphonso mango pulp. Drying Technology 25(2): 357–365.

12. Ratti, C. and T. Kudra, T. 2006. Drying of foamed biological materials: opportunities and challenges. Drying Technology 24(9): 1101–1108.

13. Sankat, C.K. and Castaigne, F.F. 2004. Foaming and drying behaviour of ripe bananas, Lebensm.-Wiss. U.-Technol. 37: 517–525.

Оптимизация технологии и энергозатрат при сушке вспененных материалов

Т. Кудра[1], С. Ратти[2]

Энерготехнологический центр Канмет–Варенне, Монреаль, Канада (1); кафедра агропищевой инженерии, Университет Лаваль, Квебек, Канада (2)

Ключевые слова и фразы: время сушки; кинетика сушки; потребление энергии; сушка пенопластового мата; эффективность сушки; яблочный сок.

Аннотация: Рассматривается процесс оптимизации времени сушки и энергопотребления в ходе сушки пенопластового мата жидких биоматериалов. Очищенный яблочный сок, перемешанный с метилцеллюлозой в массовой концентрации 0,5; 1,0; 2,0; и 3,0 %, взбивается в блендере до получения пены различной плотности от 0, 21 до 0,45 г/см^3. Образцы пены слоями толщиной 6, 12 и 26 мм высушиваются в сушильном туннеле под воздействием воздуха при 55 °С, направленном на поверхность образца со скоростью 0,7 м/с. Данные эксперимента получили интерпретацию с позиций кинетики сушки и энергопотребления. Было установлено, что скорость сушки вспененного сока зависит от плотности пены и ее характеристик, а также от толщины слоя. Для сушки тонких слоев пены требуется меньшее время при одинаковой плотности слоя. Минимальное время сушки было получено при плотности пены 0,21 г/см^3, смешанной с 1 %-й метилцеллюлозой. Максимальная эффективность сушки и минимальное энергопотребление характерно для этого вида пены.

Optimisierung der Prozesse und der Energieaufwände bei dem Trocknen der Schaumelstoffe

Zusammenfassung: Im Artikel wird der Prozess der Optimisierung der Zeit des Trocknens und des Energieverbrauches bei dem Trocknen der Kunstschaumstoffmatte der flüssigen Biomaterialien betrachtet. Der mit der Metilzellulose vermischte gereinigte Apfelsaft in der Massenkonzentration 0,5; 1,0; 2,0 und 3,0 % wird im Blender bis zur Schumerhaltung der verschiedenen Dichte von 0,21 bis 0,45 g/cm^3 geschlagen. Die Schaummuster 6, 12 und 24 mm dick warden im Trocknentunnel unter der Einwirkung der auf die Oberfläche des Musters mit Geschwindigkeit 0,7 m/s gerichteten Luft bei 55 °C getrocknet. Die Experimentalangeben haben die Interpretation von den Stellungen der Kinetik des trocknens und des Energieverbrauches bekommen. Es wurde festgestellt, dass die Geschwindigkeit des Trocknens des Schaumelsaftes von der Schaumdichte, ihren Charakteristiken und auch von der Schichtdicke abhängt. Für das Trocknen der dünnen Schaumschichten braucht man weniger Zeit bei der enlichen Schichtendichte. Minimale Zeit des Trocknens wurde bei der Dichte des mit der 1 % Metilzellulose vermischten Schaumes von 0,21 g/cm^3 erhalten. Maximale Effektivität des Trocknens und minimaler Energieverbrauch sind für diese Schaumart kennzeichend.

Optimisation du procédé de séchage de matériaux moussés

Résumé: Ce travail vise à l'optimisation du temps de séchage et de la consommation d'énergie durant le séchage en tapis de mousse des biomatériaux liquides. Du jus de pomme clarifié mélangé avec de la methylcellulose à des concentrations massiques de 0,5; 1,0; 2,0; et 3,0 % a été fouetté avec un mixeur pour générer des mousses avec des masses volumiques entre 0,21 à 0,45 g/cm^3. Les échantillons de mousse en couches de 6, 12 et 26 mm d'épaisseur ont été séchés dans un séchoir à tunnel avec de l'air à 55 °C passant en flux parallèle à la surface avec une vitesse de 0,7 m/s. Les données expérimentales ont été interprétées en fonction de la cinétique de séchage et de la performance énergétique. Il a été observé que la vitesse de séchage du jus moussé dépend de la masse volumique de la mousse et de ses caractéristiques, ainsi que de l'épaisseur de l'échantillon. Des temps de séchages plus petits ont été trouvés à des épaisseurs d'échantillon plus minces pour des mousses avec des masses volumique identiques. Un temps de séchage minimal a été obtenu pour la mousse de masse volumique de 0,21 g/cm^3 fait avec 1 % de methylcellulose. Le séchage de cette mousse a montré également une efficacité de séchage maximale et une consommation d'énergie minimale.