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Bubble behavior of fructooligosaccharides syrup during the belt drying process

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Abstract

This paper is aiming to study experimentally the bubbling and drying characteristic of fructooligosaccharides syrup in the belt drying process. A series of bubble images were acquired by a high-speed image acquisition system during the drying process. By analyzing the characteristics of bubble and drying, the drying process of fructooligosaccharides was divided into three periods: boiling transfer, natural convection and conduction and diffusion period. The drying rate in different transfer stage was: boiling transfer > natural convection > heat conduction and diffusion. The results of the study are of reference value to belt drying.

Keywords: *fructooligosaccharides; belt drying; digital image processing; heat and mass transfer*

1. Introduction

Fructooligosaccharides (FOS), also known as fructo oligosaccharides or oligosaccharides, is a kind of functional food additive which is widely used in food, health care products, dairy products, daily chemicals and feed. FOS is not digested and absorbed into the human body, but goes directly into the large intestine. It achieves the purpose of health care by selectively stimulating the proliferation of Bifidobacterium. Japan, Europe, Australia, New Zealand, the United States, China and other countries have approved the FOS as a functional food additive to add in food, health care products, even infant, diabetic food [1,2].

FOS syrup is made from sucrose and inulin by enzymatic method. Dehydrated FOS powder is easier to store and further utilized. There are three main drying technologies in industry to drying FOS syrup: spray drying, freeze drying and belt drying. In spray drying process: the viscosity of FOS syrup is too high to be atomized; the product's powder collecting rate is only about 45%, most of the dried products stick in the pipeline because its lower melting point [3]. Although vacuum freeze-drying can guarantee product quality, higher equipment investment and operating costs and longer drying cycle make this drying method difficult to industrialize [4]. In belt drying, the heat efficiency and product’s powder collecting rate is far higher than spray drying. Many researchers thought that the heat transfer way in belt drying is only thermal conduction [5]. It was observed that the liquid material would boiling if the temperature of the conveyor belt was higher than the boiling point of the liquid material, so the heat transfer mode of the belt drying is not only thermal conduction but also boiling transfer and natural convection. The purpose of this study is to determine boiling heat transfer period, natural convection and thermal conduction period.

2. Materials and Methods

2.1. Materials and equipments

FOS powder: its purity was 95%; Distilled water; conveyor belt with a specification 80mm x 80mm; High speed image acquisition system; Digital display temperature controlled electric heating plate; Electronic balance.

2.2. Experimental method

Figure 1 showed the schematic diagram of the experimental system. The FOS syrup was dropped on the conveyor belt with a 1.5ml dropper, and then put it on the heating plate at a set temperature. The mass of the material was weighed in a certain time interval. Then the drying curve under different drying conditions was obtained. In this experiment, the temperatures were set at 120°C, 130°C, and 140°C, respectively.

During the drying process, the camera was placed above the material and the bubble image was taken and recorded at regular intervals. Placed the CCD high-speed camera horizontally, recorded the image of material's thickness at regular intervals.

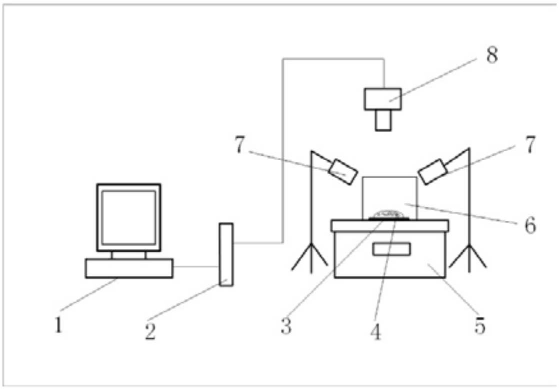


Fig. 1 Schematic diagram of an experimental device. 1. Computer, 2. acquisition card, 3. conveyor belt, 4. FOS syrup, 5. digital display temperature control heating plate, 6. transparent plexiglass cover, 7. LED lamps, 8. CCD high-speed camera.

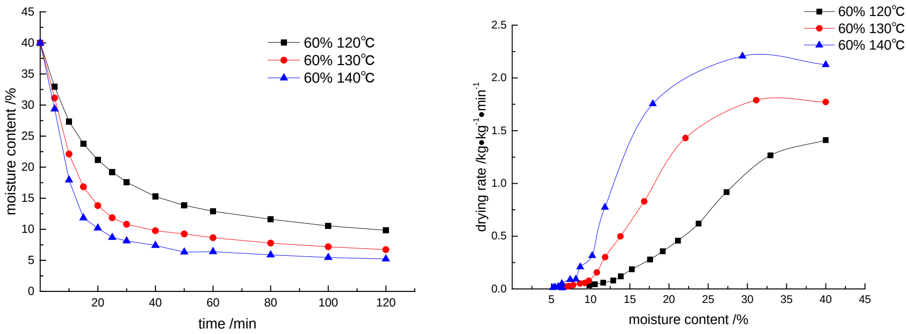
2.3. Image processing

The captured bubble images were imported to in the imageJ software to mark the bubble boundary, gray scale transformation, edge extraction, binaryzation, hole filling and watershed segmentation, and then the binary image of the bubble was obtained. By photographing the steel ruler and marking the pixel size of 1cm length, the conversion relation between the actual length and pixel could be obtained. In addition, The pixel area of bubbles was obtained by using the particle analysis tool in imageJ software, and then convert it to the actual area. In the same way, the total area of the material could be measured by marking the material boundary.

3. Results and discussion

3.1. Drying characteristic

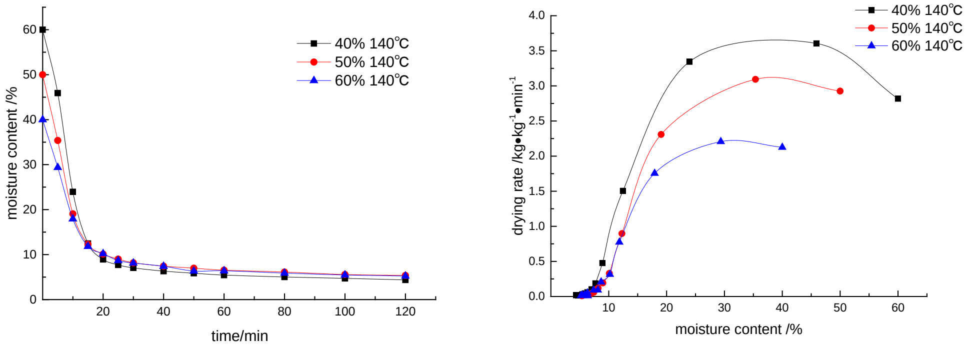
Figure.2 showed the drying curves and drying rate curves of FOS syrup with a concentration of 60% at different heating temperature conditions. Overall, the higher the heating temperature, the greater the drying rate, and the lower the final moisture content of the dried product. The drying rate had a distinct rising stage at 130°C, 140°C; while decreased from the beginning of drying at 120°C. The boiling point of the 60% FOS syrup was determined to be 105°C. When the heating temperature was 120°C, the degree of superheat, the difference between the heat plate temperature and the material saturation temperature, was too low to keep the material boiling. The boiling period lasted too short to show on the drying rate curve, and the transfer mode in liquid material turned from boiling transfer to natural convection mode along with the evaporating of the moisture. As the drying process proceeds further, the material concentration was greater and greater, the corresponding viscosity and boiling point increased, which made the material more and more difficult to flow, the transfer process was mainly heat conduction and diffusion, so the drying rate in the whole drying process was getting lower and lower.



(a) Drying curves (60%) ***(b) Drying rate curves (60%)***

Fig. 2 Drying characteristic curves at different drying temperature

At 130°C, 140°C heating temperature, the degree of superheat was great enough to keep the material boiling for a while. At the beginning of drying process (the preheating section was too short to be ignored), the transfer mode inside the FOS syrup was mainly boiling transfer mode, so there was a distinct raising stage in the drying rate curves at 130°C, 140°C. With the further development of the drying process, the transfer mode in the material changed into natural convection, heat conduction and diffusion in turn, this was the same like at 120°C.



(a) Drying curves (140 ℃) ***(b) Drying rate curves (140 ℃)***

Fig. 3 Drying characteristic curves (initial concentration comparison)

Figure 3 showed the drying curves and drying rate curves of FOS syrup with different concentrations at the same drying temperature 140℃. There was a distinct rising stage in drying rate curves under these three concentrations which indicated that there must be boiling transfer period during the drying processes. The lower the concentration, the greater the drying rate. As everyone knows: the boiling point of the solution decreased with the decreased of concentration. At the same heating temperature 140℃, the temperature difference between the heating plate and the lower concentration material was greater than that of the higher concentration material, so the boiling process was more intense which induced a greater drying rate.

3.2. Bubble behavior and transfer mode

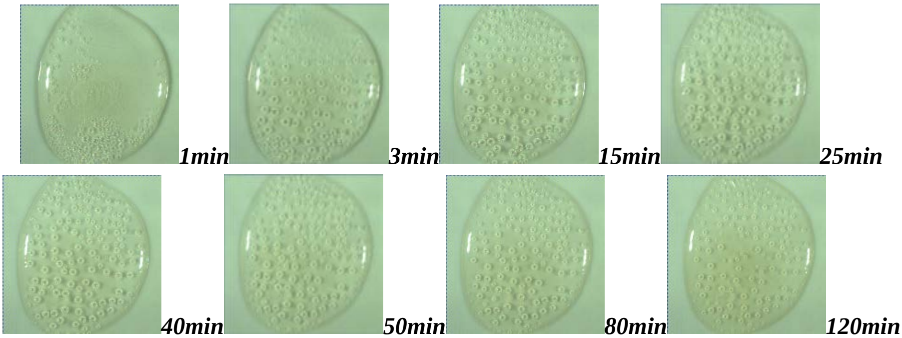


Fig. 4 Bubble images of different time (60% 120 ℃)

Figure4 showed the bubble behaviors inside FOS syrup with the concentration of 60% under 120℃ temperature. When the drying process was carried out for 1 minute, there were small bubbles formed on the heating plate. This indicated that the material had entered the boiling transfer period. The bubbles grew rapidly in 1-3 minutes because the material temperature was higher than that of the saturated vapor in bubbles. As the drying process proceeded, the degree of superheat decreased along with the increased of the liquid concentration, the bubbles grew up a little within 3-25 minutes. This indicated that the material temperature was a little higher than the saturated vapor temperature in the bubbles, the material concentration increased a little in this period, which meant that the drying rate was slower than the boiling transfer period. The transfer mode would be natural convection because the material fluidity was better in this period. After 25 minutes, the size of the bubble shrunk more and more slowly until the end of the drying. It was observed that the material had no fluidity in this period, so the transfer mode was heat conduction and diffusion.

Figure5 showed the bubble behaviors during drying process of 60% FOS syrup at 140℃. When the drying process was carried out for 5 minute, there were small bubbles formed on the heating plate. This indicated that the material had entered the boiling transfer period.

The bubbles grew rapidly in 5-7 minutes and joint together. In 7-10 minutes the bubbles interacted with each other, some formed larger bubbles, some ruptured. All of these bubble behaviors were because the material temperature was higher than that of the saturated vapor in bubbles. As the drying process proceeded, the degree of superheat decreased along with the increased of the liquid concentration, and the bubbles' behavior had a little change within 10-23 minutes. This indicated that the material temperature was a little higher than the saturated vapor temperature in the bubbles. The material concentration increased a little in this period, which meant that the drying rate was slower than the boiling transfer period. The transfer mode would be natural convection because the material fluidity was better in this period. After 23 minutes, the size of the bubble shrunk more and more slowly until the end of the drying. It was observed that the material had no fluidity in this period, so the transfer mode was heat conduction and diffusion. Table 1 showed the transfer modes during drying process under different drying conditions.

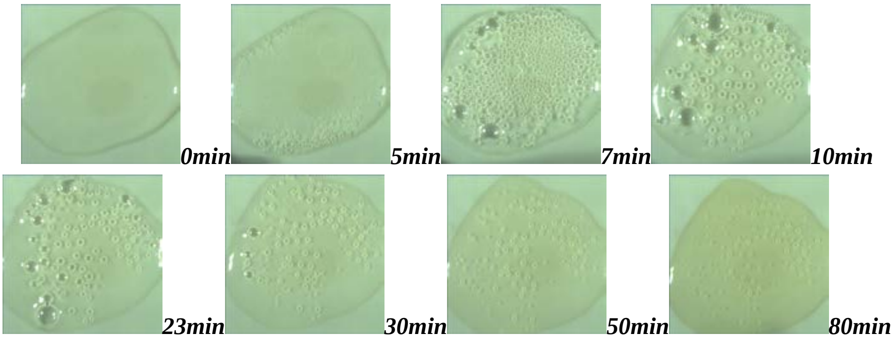


Fig. 5 Bubble images of different time (60% 140°C)

Table 1. The time of different stages (140°C)

FOS syrup concentration	**boiling transfer**	**natural convection**	**heat conduction and diffusion**
40%	0-13min	13-25min	>25 min
50%	0-12min	12-24min	>24 min
60%	0-10min	10-23min	>23 min

3.3. Drying rate

From the above analysis, it could be concluded: most of the moisture in the FOS syrup was removed in boiling and natural convection transfer period. Table 2 showed the average drying rate in different drying period at 140℃.

The calculation formula was as follows:

$$U = -\frac{mdX}{Adt} \qquad (1)$$

Where: U: the drying rate, kg/m^{2}h;

m: the weight of the dry material, kg;

X: moisture content (d.b.);

A: transfer area, m^2.

For boiling and natural convection transfer period, A was the area of the material projected on the heating plate, A_j.

For heat conduction and diffusion period, $A = A_j - A_b$

A_b :the bubbles projected area on the heating plate;

t: the drying time, min.

Table 2. The drying rate of different stages (140°C)

concentration	**The drying rate of different stages/kg*m^{-2}*h^{-1}**		
	boiling	**natural convection**	**conduction and diffusion**
40%	5.221	0.404	0.020
50%	4.408	0.381	0.030
60%	3.343	0.687	0.034

From Table 2 it could be concluded: the drying rate in boiling transfer period was 1 order of magnitude of that in natural convection period, and 2 orders of that in heat conduction and diffusion period.

4. Conclusion

(1) According to the bubble behaviors, the transfer mode in fructooligosaccharides syrup was divided into boiling transfer, natural convection and heat conduction and diffusion stage at higher heating temperature (130℃, 140℃, 150℃ for 60% syrup); at lower heating temperature (120℃), the boiling transfer was too short to be ignored and the transfer mode in material was mainly natural convection and heat conduction and diffusion.

(2)The drying rate in different transfer stage was: boiling transfer > natural convection > heat conduction and diffusion. At the same temperature, the lower the material concentration, the greater the drying rate; for the same material concentration, the higher the heating temperature, the greater the drying rate.

(3) In the boiling transfer period, there was distinct rising stage in drying rate curves, while decreased from the beginning without boiling transfer period.

5. Reference

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