Songklanakarin J. Sci. Technol.
32 (1), 55-62, Jan. - Feb. 2010

Songklanakarin Journal
of Science and Technology

http://www.sjst.psu.ac.th

Original Article

Air impingement drying of Spirulina *Platensis*

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Received 28 September 2007; Accepted 28 October 2009

Abstract

Spirulina is a cyanobacteria filled with therapeutic and nutritive properties that can be easily digested. It contains 71% protein by weight and a higher percentage of GLA (Gamma-Linolenic Acid) than any other plant. GLA has contributing properties of reducing blood pressure and blood cholesterol. After harvesting, the Spirulina is drained, sun-dried and dried in a convective oven. During the prolonged rainy season in Southern Thailand, convective drying alone can be very slow and energy consuming. Thus, this research investigated the effect of air-impingement technique on thin-layer drying of Spirulina. First, the effects of temperature (40, 50, and 60°C) and film thickness (2 and 4 mm) on the drying rate were obtained using a lab-scale dryer with a product capacity of 600 g. For an air velocity of 1 m/s, an increase in temperature up to 60°C resulted in an increase of the drying rate, while increasing the film thickness to 4 mm increased the drying time by 50%. In the second part of the study, a pilot-scale impingement dryer (1.2 m x 1.2 m x 1 m) was designed and constructed. The dryer consisted of 3 levels and can handle up 2.8 kg of fresh Spirulina per batch when arranged in a 2 mm layer film. The temperature distribution inside the dryer and the effect of air velocity (1.3 and 2.6 m/s) on the drying rate were investigated. From thermocouple measurements, the temperature deviation was less than 10% from top level to bottom level when compared to the average value. Moreover, using the specific moisture evaporation rate as the performance indicator, it was found that an air velocity of 2.6 m/s was more efficient than one of 1.3 m/s.

Keywords: drying, impingement, impingement drying, spirulina, forced convection

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1. Introduction

Spirulina is a cyanobacteria with therapeutic and nutritional properties (Samittivasana, 2000). It contains 71% protein by weight, which is the highest amount of protein ever known to man. The protein content in Spirulina is three times that of soybean which contains only 37%, five times that of meat and the protein quality is among the best with a good degree of aminogram (National Research Development Corporation, 2003). In addition, Spirulina also contains a higher percentage of Gamma-Linolenic Acid (GLA) than any other plant. GLA has contributing properties of reducing blood cholesterol, blood pressure, joint-aches, menstrual cramps, skin inflammation, acne, and pimples. Moreover, this unique seaweed also contains high amounts of vitamins and minerals, such as vitamin A (including Beta-Carotene), B6, B12, E, Niacin, Potassium, and Magnesium (Desmorieux and Decaen, 2005).

Spirulina is grown in ponds, harvested, and processed into capsules and jelly drinks (Figure 1). In a typical capsule production process, the Spirulina is drained of water, sun-dried, and dried in a convective oven. After most of the moisture content has been removed, the product is crushed and oven-dried again to remove the remaining moisture. The powdered Spirulina is then packed in capsule and sold as a diet supplement containing high protein, vitamins, and minerals. Yet, the traditional drying oven is slow and energy consuming. A typical oven can take 18-24 hrs to dry a 2 mm thick film of Spirulina at 40°C (Matinant 2006, personal communication). Therefore, this experiment investigated the

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Figure 1. Examples of Spirulina products: (a) capsules and (b) jelly drink.

effectiveness of drying Spirulina in thin layers (~2 mm) by direct forced convection (air-impingement).

Impingement drying has been successfully employed in drying or dehydration of food to extend its shelf-life. Dehydration involves a rather complex combination of application of heat and removal of moisture from a food medium (Fellows, 2000). In addition to air temperature, the rate of moisture removal is controlled by the air velocity. When hot air is locally blown over a moist food, water vapor diffuses through the boundary layer and is carried away as shown in Figure 2. Direct air-impingement not only provides a higher rate of heat transfer, but also minimizes the surface liquid film of evaporating water, causing a higher rate of mass diffusion and convection. Thus, air-impingement along with steam impingement drying have been studied using many food products, including apples, tortilla chips, and potato chips, as an alternative to parallel flow convective drying (Li *et al.*, 1999; Moreira, 2001).

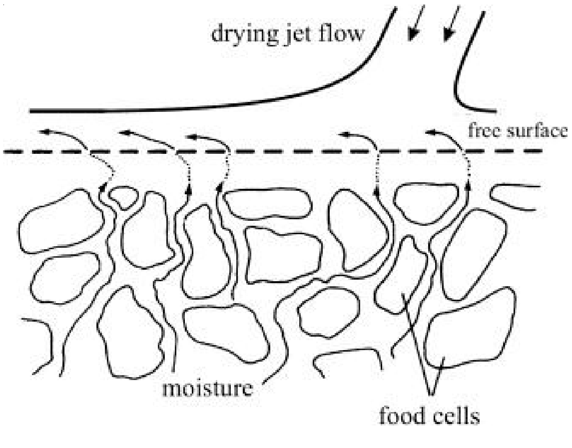

Figure 2. Diagram of air jet impinging onto a food slab (Desmorieux and Decaen, 2005).

Over the past few years, many researchers have investigated experimentally and numerically the idea of impingement drying. Dirita *et al.* (2007) studied the air impingement cooling of cylindrical foods. The result showed that the heat flux was strongly non-uniform along the cylindrical surface, and that the local Nusselt number is highly dependent on the conjugate effect. Simulation results indicated that the slowest cooling zone (SCZ) was strongly dependent on the given boundary conditions set. They found the SCZ to be across the cylinder center when placed in a cold environment, otherwise it was at the bottom when the food was initially in thermal equilibrium with the environment, and would lie on its upper half in the case of pure natural cooling.

De Bonis and Ruocco (2007) also studied the modeling of food slab dehydration by a heated impinging air jet. They integrated the time-dependent governing equations to predict the local moisture, temperature, and velocity distributions. The evaporation kinetics was tackled using a simple Arrhenius notation, while coupled moisture and temperature gradients were shown to develop distinct process non-uniformity. The model showed how the integration of transport and biochemical notations in foods could be employed to pursue process optimization of the impingement process.

In another study, O’Donovan and Murray (2007) found that impinging jets provided a means of achieving high heat transfer coefficients both locally and on an area averaged basis. They investigated the heat transfer distribution on a heated flat surface subjected to an impinging air jet at Reynolds numbers from 10,000 to 30,000 and for non-dimensional surface to jet exit spacing, H/D, from 0.5 to 8. In particular, they found that the velocity fluctuations normal to the impingement surface have a controlling influence on the enhancement of the wall jet.

Furthermore, Rajala *et al.* (2004) studied the influence of effective initial impingement drying on the quality of blade-coated paper and compared it to infrared (IR) drying. Three impingement temperatures (300, 450, and 550°C) and three impingement velocities (25, 40, and 60 m/s) were tested in an impingement dryer unit to determine the influence of drying on paper quality. Drying effects were compared with those obtained from two rows of an electrical IR at the same position. The results of the investigation indicated that back-trap (BT) mottle was reduced with increasing drying power of the impingement dryer. The paper quality parameters, gloss and smoothness, of the coated samples were better with air-drying than IR drying.

The objective of this study was to determine the effect of different parameters (temperature, velocity of drying air, and thickness of Spirulina layer) on the drying rate of

Figure 3. A sample of fresh Spirulina placed in the drying tray.

Spirulina. Information derived from this study along with future studies on product quality will be useful in designing a commercially effective dryer for Spirulina.

2. Materials and Methods

2.1 Material

Spirulina samples as shown in Figure 3 were provided by Herb Spirulina Co., Ltd. Songkhla, Thailand. Fresh Spirulina was filtered using a filtering cloth to drain the water entrained in the product. The initial moisture content varied from 84-90% wet basis (5.25-9.0 d.b.) after filtration.

2.2 Lab-scale impingement drying

The impingement dryer (laboratory scale) with tray size 37 cm x 79 cm x 2.5 cm and one perforated pipe is shown in Figure 4. About 500-600 g of Spirulina was dried in thin layers in an impingement dryer as shown in Figure 4. The air temperatures were 40, 50, and 60°C and the air velocity was fixed at 1 m/s. The thickness of the Spirulina film layer was 2 mm and 4 mm. The drying rate of the Spirulina was determined by weighing the sample every hour. A drying temperature above 60°C was not studied due to degradation of phycocyanin and the effect of Maillard Browning (Desmorieux and Decaen, 2005).

Figure 4. Air-impingement dryer used in the lab-scale experiment.

2.3 Design of the pilot-scale impingement dryer

The pilot-scale impingement dryer was designed according to the schematics in Figure 5 to test the effectiveness of impingement drying in larger batches. This particular design had dimensions of 1.2 m x 1.2 m x 1.0 m and was constructed from stainless steel (4 mm thick). The drying chamber was insulated with 25.4 mm of fiberglass. Inside, the dryer consisted of 6 stainless steel trays with 6 main impingement pipes aligned over each tray (see Figure 5). Each main pipe contained 4 sub-pipes and each sub-pipe contained 4 nozzles (see Figure 6). The size of each tray was 50 cm x 50 cm and each tray could handle up to 450-470 g of Spirulina. Thus, the total capacity for the dryer was about 2.7-2.8 kg. The inside of the pilot-scale impingement dryer can be seen

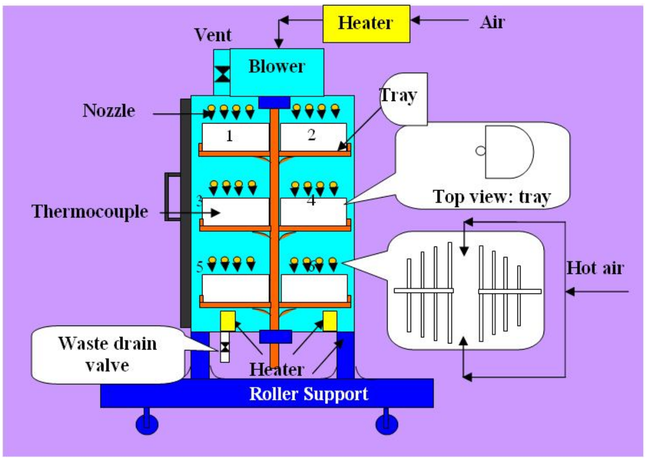

Figure 5. Schematic diagram of the pilot-scale impingement dryer.

Figure 6. Pilot-scale impingement dryer showing impinging nozzles and drying trays.

in Figure 6. Air was heated by a 20 kW electrical heater as it entered the drying chamber. The heated air was impinged into the dryer unit by an axial fan (Model HASCON electric motor.) with a nominal rotational speed of 2840 rpm. The fan speed was controlled by a variable electronic transistor inverter (Model NSI -2-003) with a frequency range of 0.1-400 Hz and 3 horsepower.

2.4 Temperature measurements

The temperatures inside the chamber and above each tray in the pilot-scale dryer were measured using type-K thermocouples.

2.5 Drying rate measurements

An electrical dryer was used to determine the initial moisture content of the Spirulina sample by drying at 103± 2°C 72 hrs (modified from AOAC, 1990). To obtain the moisture content at each time interval, the entire tray of sample was removed and measured using a digital kilometer (Model METTLER TOLEDO PG 5002-S). Tare weight of the trays had been measured prior to the drying process. Drying curves at various conditions were constructed using the transient moisture content data.

2.6 Experimental conditions

For the preliminary lab-scale study, the air temperatures were 40, 50, and 60°C while the Spirulina film thickness was 2 and 4 mm. The air velocity was 1 m/s. For the pilot scale study, the same temperatures were tested, while the film thickness was constant at 2 mm. The air velocities used were 1.3 and 2.6 m/s. The two air velocities were selected based on the capacity of the air blower at middle and top speed. The air velocities were measured at points directly above the product using a hand-held digital rotating vane anemometer (AirFlow Instrument, Model LCA501). Since the design of the equipment was to maximize the drying capacity, a total of 96 nozzles were needed. As a result, there was a substantial amount of pressure drop across the system and through the 2 mm diameter opening. The limited amount of air flow through each nozzle caused the maximum air velocity to be limited to about 2.6 m/s. The calculated Reynolds number was about 300 and the H/D ratio was 15.0. Despite the low air velocity, the implication of direct impingement on drying of a layer of thin film could be investigated.

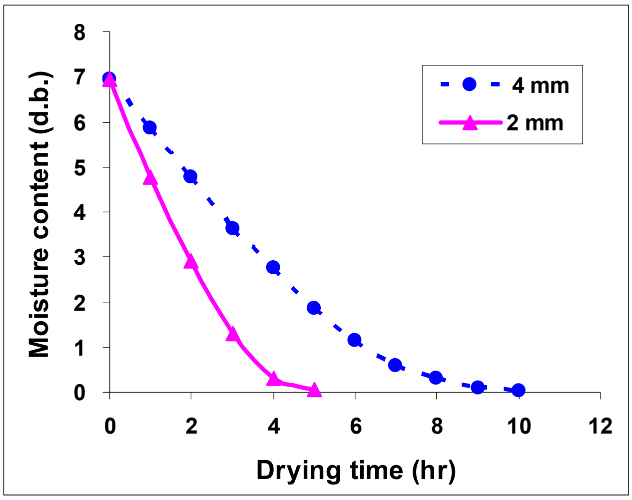

Figure 7. Drying curves at various Spirulina thicknesses (2 and 4 mm) using an impinging air velocity of 1 m/s and an air temperature of 60°C.

2.7 Data analysis

The experimental data were averaged and analyzed using Microsoft® Excel 2002. All experiments were performed at least in duplicate.

3. Results and Discussion

3.1 Effect of drying variables (lab-scale)

From industrial standards, dried Spirulina should not have a moisture content of more than 7% wet basis (w.b.) or 7.5% dry basis (d.b.) (Desmorieux and Decaen, 2005). Therefore, the drying process was continued until the moisture content reached the required value. In Figure 7, the effect of Spirulina thickness on the drying time is shown. As expected, it took longer to dry the 4 mm thick layer (10 hours compared to 5 hours). Thicker films have higher resistance to mass transfer as liquid water must travel a further distance (via diffusion and convection) to reach the surface of the product. In addition, the effect of air temperature on the drying time of Spirulina is shown in Figure 8. The drying curves are similar in their shape with the highest temperature resulting in the fastest drying time. The total drying time for a 2 mm layer of Spirulina at 40, 50, and 60°C was 12, 7, and 5 hrs, respectively. The results are shown in Table 1.

Table 1. Drying time for 2 mm film of Spirulina using an air velocity of 1 m/s.

Temperature	Initial Moisture Content	Final Moisture Content	Drying Time
(°C)	(% w.b.)	(% w.b.)	(hrs)
40	87.80	6.09	12
50	86.21	6.04	7
60	87.42	6.42	5

Furthermore, for all the drying conditions investigated, the final Spirulina product did not undergo significant color change, which is extremely important for customer appeal. Still, the nutritional values of the product will have to be examined in order to ensure the effectiveness of the drying process.

3.2 Drying rate analysis

As most drying processes, the drying of Spirulina can be divided into two periods: (1) the constant rate period (CRP) and (2) the falling rate period (FRP). From Figures 7 and 8, there is a steep, linear descent in moisture content from 7.0 d.b. to less than 1.0 d.b. This period represents the constant rate of drying period where a large amount of free water is readily removed. Since Spirulina contains up to 90% water (w.b.), the majority of the drying time will be contributed to this water removal. The removal of bound water contributes minimally to the overall drying time, but it is significant in order for the product to reach 7.5% d.b. While the slope of the drying curve at 60°C is extremely steep, the drying curves for temperatures of 40 and 50°C are not as drastic. Hence, a distinct falling rate period can be observed below 1.0 d.b.

In order to study the drying rate more effectively, a plot was made between the rate of water removal (g of water per kg of dry matter per minute) and the moisture content (d.b.). From Figure 9, the drying rate of the 2 mm thickness layer was much higher than that of the 4 mm layer. A constant rate of drying can also be observed from 7.0 d.b. to 2.0 d.b. During this period, the rate of water removal rate was about 13–17 g of water per kg of dry matter per minute. According to transport mechanisms, free water travels as liquid water and gaseous vapor via diffusion and convection from the product center to the product surface during the constant drying rate period (Yamsaengsung and Moreira, 2002). An increase in the film thickness subsequently decreased the rate mass transfer. As drying progressed, the drying rate decreased even more as the amount of free water was reduced. Finally, once all of the free water had been removed, the falling rate began, in this study probably between 0.2-0.5 d.b. A typical critical moisture content for the transition of the drying regime is usually 0.2-0.3 d.b. (Yamsaengsung and Moreira, 2002; Yamsaengsung and Buaphud, 2006).

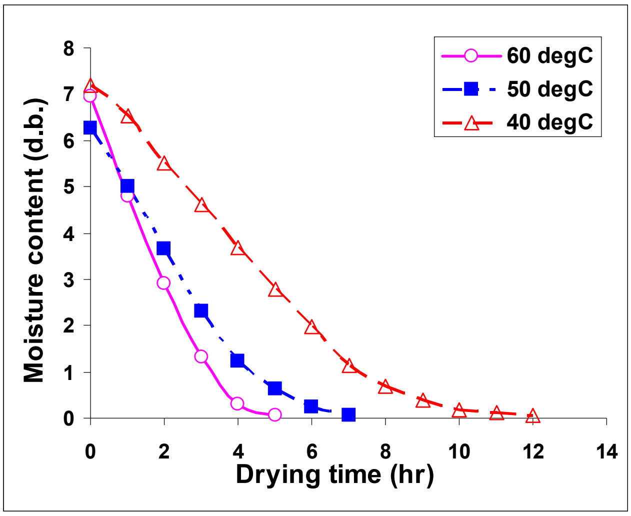

Figure 8. Drying curves at various temperatures (40, 50, and 60°C) for a 2 mm film thickness using an impinging air velocity of 1 m/s.

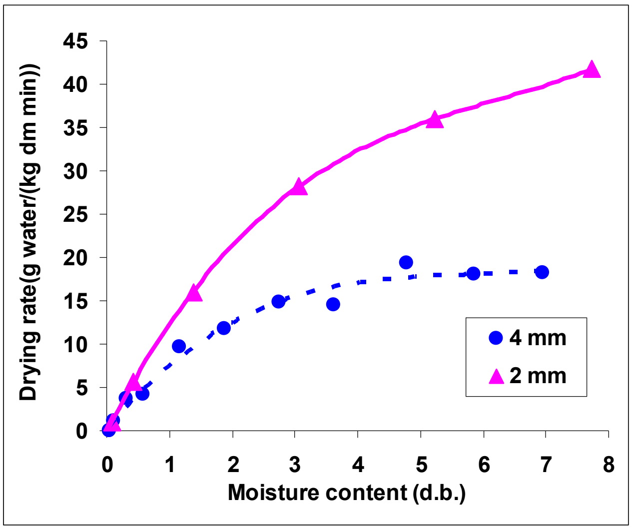

Figure 9. Drying rate at various film thicknesses (2 and 4 mm) using an impinging air velocity of 1 m/s and an air temperature of 60°C.

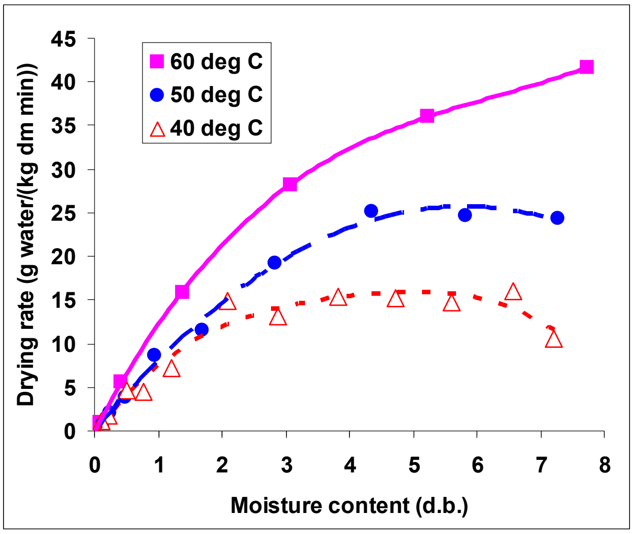

Figure 10. Drying rate at various temperatures (40, 50, and 60°C) and an impinging air velocity of 1 m/s.

From Figure 10, an increase in drying rate as a function of increasing temperature can be observed. For temperatures of 40 and 50°C, the rate of drying increases slightly during the initial period of heating, flattens out during the constant drying rate period, and begins to decrease during the falling rate period. For drying at 60°C, there was a high rate of water loss during at high moisture content. As the amount of water inside the product decreased, the rate also decreased, but was still much higher than at the lower temperatures. Thus, the higher temperature greatly increased the rate of heat transfer, which consequently increased the rate of mass transfer of water vapor from the product. In this case, the moisture content dropped almost in a linear fashion from 7.0 d.b. to less than 0.5 d.b. as stated above. Hence, the falling rate period which, is dominated by the removal of bound water, was very short compared to the overall drying time.

3.3 Pilot-scale drying

For the pilot-scale study, similar results were obtained despite drying a larger batch. To test the uniformity of the temperature within the dryer, the temperature of each of the tray sections was measured. The three sections were defined as top trays (trays 1 and 2 in Figure 5), middle trays (trays 3 and 4), and bottom trays (trays 5 and 6). From Figure 11, it can be seen that the temperature difference between each part was about 5-6°C. The temperatures of the bottom trays were higher than the top and middle trays (see Figure 11), respectively, due to the placement of the internal heater at the bottom of the dryer. On the other hand, the top trays were closer to the entrance heater, so their temperatures were higher than the middle trays. The overall average temperature in the dryer for an air temperature of 60ºC was 58.6ºC with a standard deviation of 5.7ºC. Still, after about 4 hrs of drying, the temperature in each section of the dryer converged to the set point. Even though the initial drying rate of each drying section varied significantly (see Figure 12), the final moisture contents of the product were not significantly different. From Figure 12, it an bee seen that the bottom trays dried faster during the first 2 hrs due to its proximity to the lower heater; however, after four hours of drying, the top two trays had significantly lower moisture contents. This result shows that the effect of the impinging air was more substantial than the heat from the electrical heater within the dryer. Nonetheless, after 5 hrs, the moisture content of all the sections was reduced from 9.0 d.b. to less than 0.07 d.b.

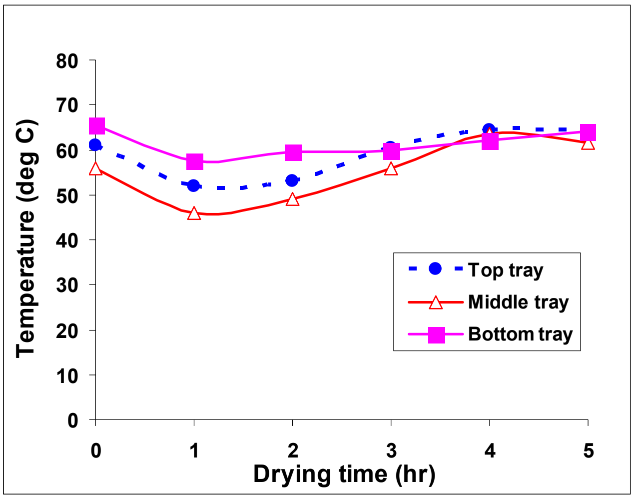

Figure 11. Temperature distribution in the pilot-scale dryer at 60°C and an air velocity of 2.6 m/s.

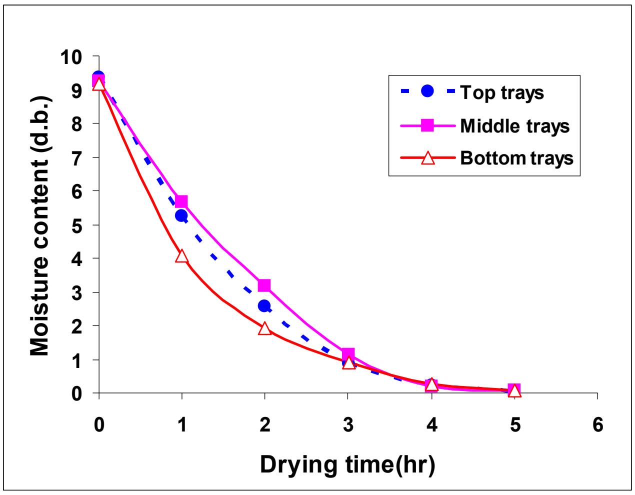

Figure 12: Drying curve for each tray section (top, middle, bottom) in the impingement dryer at 60°C and an air velocity of 2.6 m/s.

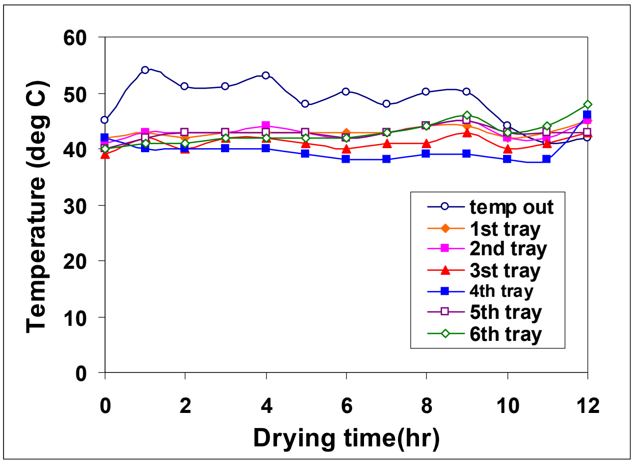

Figure 13. Temperature distribution in the pilot-scale impingement dryer at 40°C and an air velocity of 1.3 m/s.

Moreover, Figure 13 shows the temperature at each tray when the set point temperature was 40ºC and the air velocity was 1.3 m/s. The results indicate that all trays within the drying chamber have relatively the same temperature with the average temperature being 42.45±2.57ºC. For set point temperatures of 50 and 60ºC, similar results were obtained, 51.31±4.44ºC for a set point of 50ºC and 57.74±5.01ºC for a set point of 60ºC. In addition, Figure 14 illustrates the drying curve for each tray at a drying temperature of 40°C and an air velocity of 1.3 m/s. The results show that all the curves have the same trend. Furthermore, the air velocity for

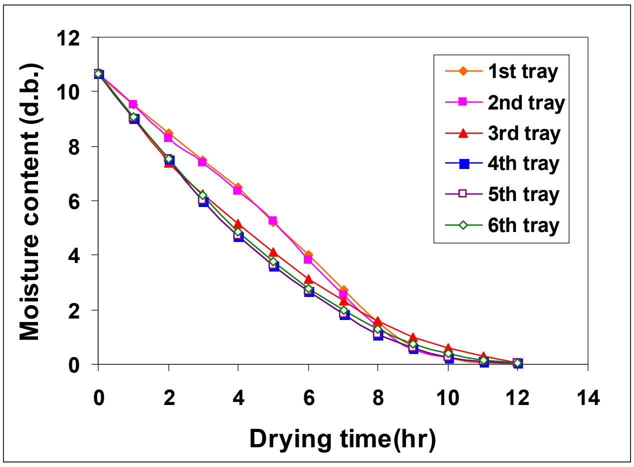

Figure 14. Moisture content distribution in the pilot-scale impingement dryer at 40°C and an air velocity of 1.3 m/s.

Table 2. Average air velocity distribution in each tray

Tray	Average Velocity (m/s)
1	1.22±0.16
2	1.31±0.16
3	1.29±0.15
4	1.46±0.24
5	1.23±0.45
6	1.41±0.25
Average	1.32±0.26

each tray is given in Table 2. Again, there was just a small difference in the drying air velocity.

Finally, Figure 15 and 16 show the influence of air velocity on the drying curve and the drying rate at 60°C. As expected, the higher air velocity resulted in a faster drying rate due to a higher heat transfer coefficient (Li *et al.*, 1999; Moreira, 2001; Yamsaengsung and Moreira 2002). At 60°C, the drying time using an air velocity of 2.6 m/s was twice as fast as that at 1.3 m/s for a 2 mm layer. According to Desmorieux and Decaen (2005), for air temperatures lower than 40°C and air velocities lower than 2.5 m/s, the drying curves should predict the existence of a long first drying period (constant drying rate) and for harsh conditions (air temperature above 40°C and air velocity greater than 2.5 m/s), the constant drying rate should not appear. However, for high moisture content product, the majority of the drying time can be contributed to the constant rate period. Even though Figure 16 indicates that there is a steady decrease in the drying rate, the removal of free water from 10.0 d.b. to about 0.5 d.b. should lie in the constant rate period. Figure 15 illustrates a nearly straight descent in the moisture content between these intervals. Hence, if the air velocity does not cause the drying to proceed too quickly, which could be detrimental to product quality, it plays an important role in improving the drying rate of the material.

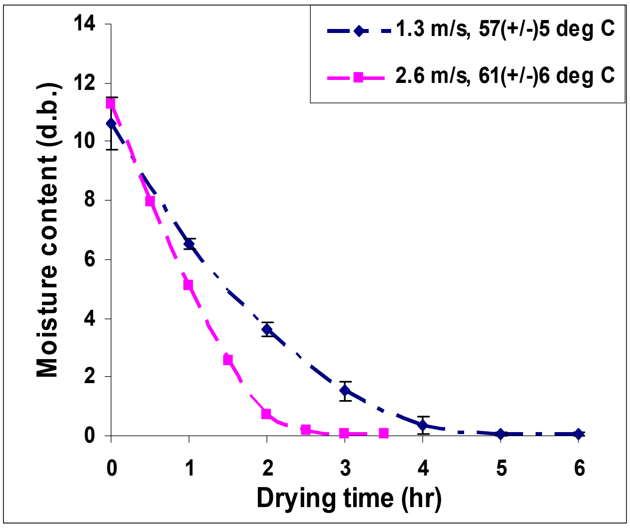

Figure 15. Drying curves at various air velocities (1.3 and 2.6 m/s) and a temperature of 60°C.

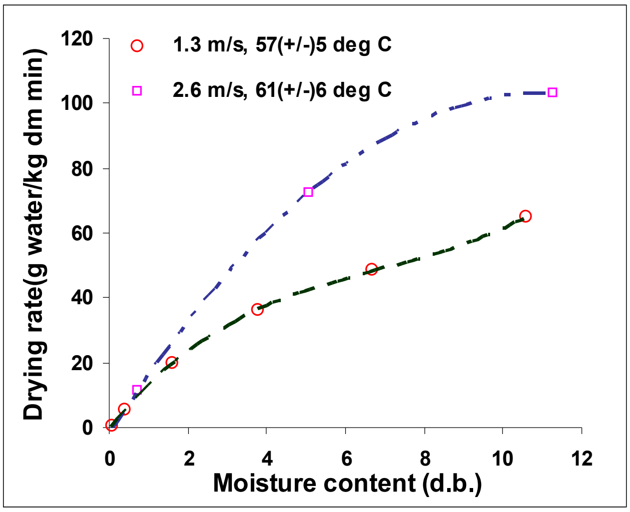

Figure 16: Drying rate at various air velocities (1.3 and 2.6 m/s) and a temperature of 60°C.

3.4 Specific moisture evaporation rate (SMER)

In order to truly evaluate the cost effectiveness of using a higher air velocity to reduce the drying time, the specific moisture evaporation rate (SMER), which is commonly used as a performance indicator, was calculated. Chua et al. (2002) defined the SMER as:

$$\text{SMER} = \frac{\text{Amount of water evaporated}}{\text{Energy input to the dryer}} \quad (\text{kg/kW h}) \qquad (1)$$

Analysis of the SMER revealed that there is a significant difference between the two air velocity treatments as related to the energy input of the process (Table 3). As far as the SMER is concerned, the air velocity of 2.6 m/s had a higher SMER than at 1.3 m/s, which makes the former air

Table 3. Effect of air velocity on the SMER index.

Air Velocity (m/s)	SMER (kg/kWh)
1.3	0.38
2.6	0.34

velocity the more suitable choice under these drying conditions.

4. Conclusions

From the lab-scale and pilot-scale experiments, the air temperature, air velocity, and thickness layer were all significant factors in the drying of Spirulina. Higher air temperature, higher air velocity, and lower thickness of the film layer resulted in shorter drying time. In addition, while the plot of the drying rate indicated a true constant rate at 40 and 50°C, the steady decrease in drying rate at 60°C does not correctly describe the characteristics of a falling rate period. Due to the high amount of free water present in the system, the removal of bound water from Spirulina did not begin until the moisture content reached 0.5 d.b. At this point, there is a major drop off in rate of water removal that can be contributed to the limited diffusion of bound water from within the product. Furthermore, a temperature higher than 60°C is not recommended because of the influence of Maillard Browning. From the SMER analysis, an air velocity of 2.6 m/s was more appropriate than one of 1.3 m/s when considering energy consumption. An improvement in equipment design could possible increase the air velocity of the process. Even though such a system could produce very fast drying rate, its effect on the product quality will have to be considered to ensure economic viability.

Acknowledgement

The authors would like to thank the Faculty of Engineering and the Graduate School at the Prince of Songkla University for financial support of this research. Equipment and facilities were also provided by the Department of Chemical Engineering at the Prince of Songkla University. Without their kindness, this research would not have been possible.

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