A NEW SPRAY DRYER SUPPORTED WITH FREELY ROTATABLE PROPELLERS ENABLES MORE EFFICIENT DRYING OF MILK SAMPLES

by

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A new type of spray dryer was developed for drying milk and the like efficiently. To this end, freely rotatable propellers powered with air-flow were placed in the drying chamber to increase thermal efficiency and the product yield in the newly developed spray dryer. Milk samples were dried in both the developed system and a standard spray dryer to compare thermal efficiencies and product yields of each. It was observed that the propellers placed in the drying chamber of the developed spray dryer had caused a change in the flow direction of the drying air, decreased the temperature of the drying walls, and increased the thermal efficiency and product yield in drying. Consequently, in the developed dryer, the adhesion of the powder particles to the drying wall and to each other is significantly reduced, resulting in a more efficient drying.

Key words: *spray drying, milk powder, thermal efficiency, wall deposition, product yield, particle size*

Introduction

Spray drying process is a widely used method for producing powder products such as pharmaceuticals, powdered foods, dairy products, detergents, and chemicals [1, 2]. It minimizes the thermal damage to liquid samples as it provides a shorter exposure (5-100 second) to heat during the drying process, and thus protects qualities of the end-products, such as the color and taste [3-5]. Moreover, spray drying process, because of low operating costs, is regarded as the most economic drying technique [6, 7]. For example, Hammami and Rene [7] reports that spray drying is 4 to 5 times more economical than freeze-drying due to less electricity consumption and short drying times.

In order to produce a dry powder product from a fluid, atomization of the liquid and a particular drying method are required [8]. An atomizer at the top point in the dryer forms small droplets with a certain size distribution. Simultaneously, a heated air stream is sent to the drying chamber to evaporate the water content of the droplets to form powder particles. Last, the powders obtained in different sizes and shapes are taken from the hopper under the drying chamber [9]. In this way, regular and spherically shaped powder particles are being produced [10].

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Along with the mentioned advantages of spray drying, various problems such as: deposition of the powder particles to the drying wall and/or adhesion of powders to each other [11, 12], loss of heat and dried product by means of exhaust air [13-16], and low product quality (color, taste, aroma, moisture content, particle size, *etc.*) [17-21], are often encountered. To lessen the deposition of the powder particles to the drying walls of the chamber and the particles to each other, additive agents like maltodextrin and gum arabics are generally added to the liquid samples. However, sometimes necessary, excessive use of these additives are reported to constantly lower the quality of the powdered end-products (color, taste, aroma, *etc.*). Therefore, without making use of any additive agents, we herein wish to report the design of a new laboratory-scale spray dryer, the performance of which is enhanced by a simple mechanical/aerodynamic manipulation. The design involves the placement of two units of 3-vane propellers in the drying chamber of the spray dryer to ensure a more homogenous air flow throughout the chamber and concomitantly lowering the temperature of the glass wall of the drying chamber. In brief, we propose this newly designed spray dryer for drying daily milk samples-the model liquid-to reduce the deposition of the powders to the glass walls and their self-agglomerations with enhanced product quality characteristics. Besides, if our hypothesis works as expected, this new drying system would also help facilitate the discharge of the chambers and help clean the glassware apparatus more readily for the next runs.

Figure 1. The experimental set-up: *1 – spray dryer, 2 – milk sample, 3 – feed pipe, 4 – pump, 5 – digital screen, 6 – nozzle, 7 – hot air inlet, 8 – drying chamber, 9 – product chamber, 10 – propellers, 11 – junction point, 12 – exhaust air, 13 – thermocouples, 14 – digital thermometer*

Materials and methods

A 1000 mL portion of daily cow milk samples were used for the experiments, fig. 1. Milk samples were collected from the farmers in Elazig, Turkey, and were tested on the day of supply. The experiments were run in both the standard dryer and in the newly developed dryer for comparison. The average density of milk samples was determined to be ρ = 0.9825 g/ml. The maximum drying capacity of the dryers was 1500 mL per hour. The technical specifications of the spray dryer are given in tab. 1.

The propellers which can rotate freely with the airflow of the sprayer are placed in the drying chamber of the developed spray dryer (DSD). They are made of heat-resistant plastic material and have 3-vane with a diameter of 6 cm. Two propellers with a 5 cm spacing were placed in the drying chamber, fig. 2. The propellers are used to increase product yields by preventing the dry product from sticking to the glass surface and each other by means of reducing the glass temperatures.

Spray-drying experiments were run in both the standard dryer and in the newly developed dryer for comparison. The nozzle diameters of 0.5 mm, 1.5 mm, and 2.5 mm and inlet air temperatures of 140 °C, 170 °C, and 200 °C were tested throughout this work. The spraying process was carried out in a cylindrical glass chamber with a downwards co-current,

Table 1. Technical specifications of the spray dryer used [22]

Maximum capacity	1500-2000 mL per hour
Inlet air temperature interval	40-300 °C
Outlet air temperature interval	40-140 °C
Temperature sensitivity	±1 °C
Drying time	1.0-1.5 seconds
Rate of spray pump	50-2000 mL per hour
Nozzle diameter	0.5:1.5:2.5 mm
Spray direction	Downwards Co-current
Heater power	3 kW/h, 220 V
Net weight	110 kg

two-fluid pressure nozzle atomizer. Operation parameters were kept constant throughout the study and set as air pressure in the dryer, 413685 kPa, air-flow rate, 60 m^3/h, feed fluid-flow rate, 5 mL per minute, feeding interval, 5 seconds, and nozzle airflow, 700 Lph.

The drying chamber has a cylindrical shape with a diameter of 16 cm and a length of 60 cm. The air temperatures in the drying chamber and the product chamber were measured with digital thermometers, for which thermocouples were placed in a manner that would not disturb the airflow into the chambers, fig. 3. The temperature measurement points are given in fig. 4. The measured air temperatures are denoted as T_n (n = 1-5) and that of glass-wall temperatures are denoted as L_n (n = 1-11).

The technical specifications, tab. 2, of the devices used to measure temperature, humidity, and air-flow rate are given in fig. 5.

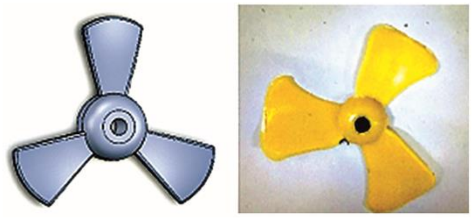

Figure 2. Front view of the propeller placed in drying chamber

Figure 3. Temperature measuring set-up; (a) of the drying chamber and (b) of the product chamber

Results and discussion

The thermal efficiency, product yield, moisture content, particle size, particle microstructure, and temperature variations throughout the chambers in the DSD and standard spray dryer (SSD) were determined during spray drying of the milk samples. The obtained results are summarized.

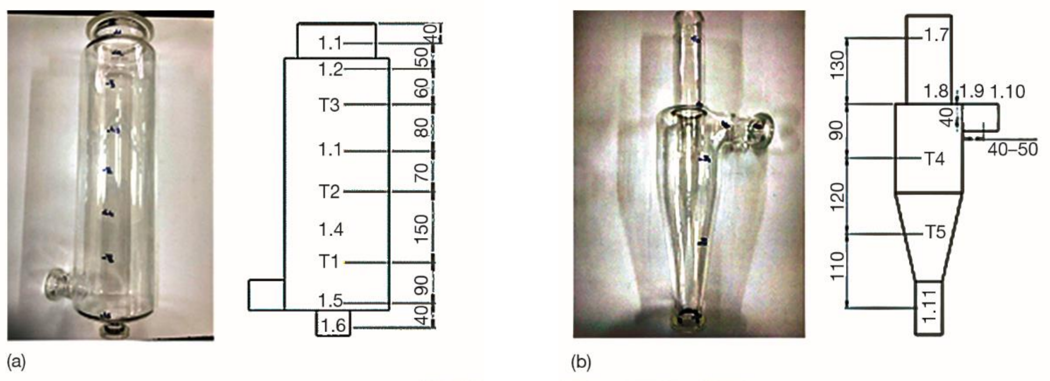

Figure 4. Measurement points of air and glass temperatures; (a) drying chamber and (b) product chamber

Table 2. Technical specifications of the measurement devices

Device name	Measuring range	Accuracy	Purpose of usage
Elimko E-680 series	–200-1120 °C	±1 °C	To measure the air temperatures in the dryer chambers
E-SUN non-contact infrared thermometer	–20-520 °C	±2 °C	To measure the temperature of the glass walls
LYK BGM 1361 Probe temperature and humidity measurement	The sensitive probe: –10-50 °C K-type probe: –50-400 °C Humidity measurement: 5% RH-98% RH	Temperature measurement accuracy: ±1℃ Humidity measurement accuracy: ±3% (30-95%) ±5% (10-30%)	To measure the outlet-air-humidity and -temperature of the dryer
CEM DT-8880 Air velocity and temperature measurement with telescopic probe	Air velocity: 0.1-25.0 m/s Temperature: 0-50 °C	±(5%+1d) reading or ±(1%+1d) full scale	To measure the dryer output air velocity
JSM-6510 series SEM	Image mode: Electron image, REF image, Composition, Topography Shadowed	±50 μm	To measure the morphological structure and particle sizes of the milk powders
Denver instrument IR-60 moisture analyzer	% 0.1-99.9	%0.01 moisture content	To determine moisture content of the milk powders

Thermal efficiency of the dryer

The thermal efficiency of spray dryers is stated as the ratio of the heat dissipated to drying to the total heat [23]. In the experiments, the ambient temperature was kept constant. Since the operating conditions (T_{amb}, *etc.*) were kept constant throughout all the runs, the system is considered adiabatic since the amount of heat loss from the surface of the dryer to the outside is equal for all. Accordingly, the thermal efficiency of the spray dryer is written as eq. (1) [22]:

$$\eta = \frac{T_{\mathrm{air,in}} - T_{\mathrm{air,out}}}{T_{\mathrm{air,in}} - T_{\mathrm{amb}}} 100 \tag{1}$$

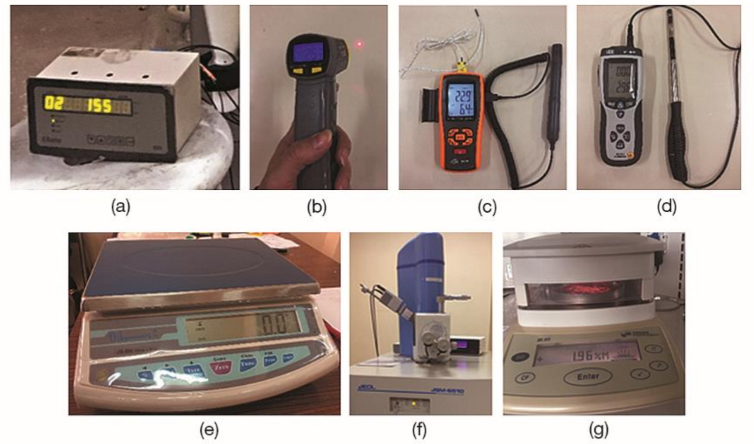

Figure 5. The devices used in the experiments: (a) thermometer, (b) laser thermometer, (c) air humidity meter, (d) air velocity meter, (e) assay balance, (f) SEM device, and (g) moisture analyzer

The thermal efficiency of the spray drying process was calculated for the standard and DSD. In all experiments, the ambient temperature was around 23 °C, and that of the products was 18 °C. While drying the milk, none of a carrier material was used. Only, inlet air temperatures ($T_{\mathrm{air,in}}$: 140 °C, 170 °C, and 200 °C) and nozzle diameters (0.5 mm, 1.5 mm, and 2.5 mm) were altered throughout the experiments; and the other parameters were kept constant. The thermal efficiencies of the SSD and DSD are compared in fig. 6. As shown in fig. 6, the thermal efficiency of the DSD was higher than that of SSD. Considering the varied parameters, maximum thermal efficiencies have been achieved with the use of a nozzle diameter of 2.5 mm and an inlet air temperature of 200 °C. This maximum thermal efficiency was 66.72% in SSD and 68.97% in DSD. In both dryers, it was observed that the thermal efficiencies were increased with increasing nozzle diameter and inlet air temperature. However, it was observed that the thermal efficiencies of the DSD was constantly higher than that of SSD for about 2-3%.

Product quantity

One-litter milk sample was used for each run and the amount of milk powder obtained so is given in fig. 7. The maximum product yield was 109 g on the SSD and 119 g on the DSD at a nozzle diameter of 2.5 mm and an inlet air temperature of 140 °C, fig. 7. It was observed that the amount of milk powder obtained decreased with increasing temperature and increased with increasing nozzle diameter. In comparison, it has been determined that the DSD is more advantageous in terms of the amount of powder obtained, *i.e.* approximatly 10% more efficient.

In the experiments with DSD, we observed less adherence of the powder particles to the drying- and product-chamber glasses; and obtained smoother particles, fig. 8. Thanks to the propellers installed in the designers DSD, the sprayed liquid feed was converted to powders by rotating in airflow direction. At the end of the drying process, the cleaning of the system/glassware was much easier in the DSD where the adhesion to the glass was less. Figure 8 illustrates milk adhesion to the glass walls during drying of milk in SSD and DSD.

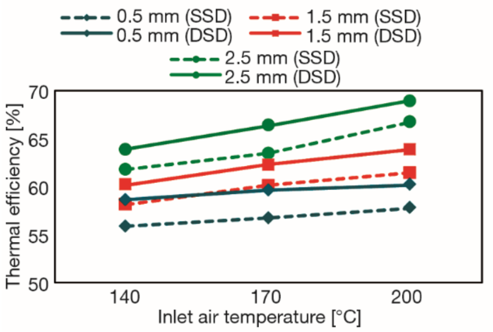

Figure 6. Thermal efficiencies of the SSD and DSD

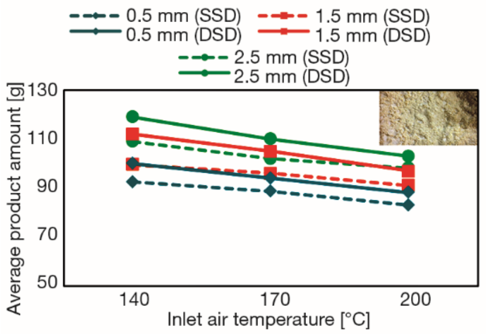

Figure 7. Amount of milk powder obtained according to varied parameters in SSD and DSD; Inset: digital photographs of the milk powders obtained at best conditions

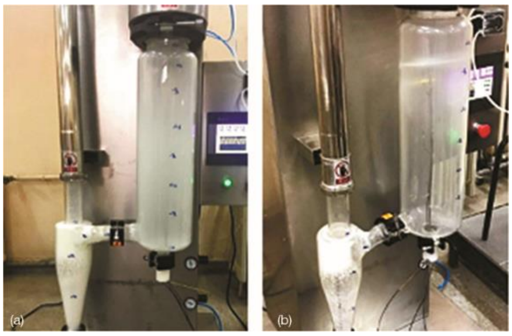

Figure 8. Drying- and product-chamber-walls; (a) SSD and (b) DSD

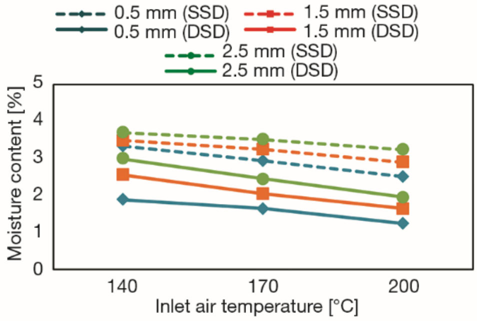

Figure 9. Milk powder moisture contents obtained according to varied parameters in SSD and DSD

Analysis of moisture content

Milk powder samples put into moisture analyzer were heated up to 105 °C with infrared rays to determine their moisture content (%M), fig. 9. For both types of dryers, the minimum moisture content was attained when the nozzle diameter was 0.5 mm and $T_{\mathrm{air,in}}$: 200 °C, and the maximum moisture content was obtained when nozzle diameter of 2.5 mm and $T_{\mathrm{air,in}}$: 140 °C were used. The moisture content of the milk powders obtained in the SSD was minimum 2.51 %M, maximum 3.71 %M. The moisture content of the powders obtained in the DSD**,** however, was minimum 1.25 %M, maximum is 2.99 %M. Couto *et al.* [24] reported that the powders produced by spray drying methods had a minimum moisture content of 2.90-4.66% (w/w). As can be seen from fig. 9, milk powders having lower moisture contents were obtained using the DSD and this value is lower than the commonly observed typical moisture contents of spray-dried products.

Analysis of particle size distribution and microstructure

The variation of the particle sizes of the milk powders obtained from the two compared dryers according to the tested parameters is given in fig. 10. The parameters tested have significant effects on particle size. This was investigated by SEM analysis. Increased inlet air temperature would reduce the moisture present in the droplet faster. Thus, this would result in a reduction in the size of the powder particles by reducing the chances for self-agglomeration. The particle sizes generally decrease as the temperature of the inlet air increases in spray drying processes [25]. The smallest milk powder particles were obtained at $T_{air,in}$: 200 °C for both of the dryers, but the products were obtained in yellow to beige colors, which would be a result of possible air-oxidation and/or Maillard reaction that typically occur at relatively high temperatures. Therefore, the particle size of the powders was determined to be between 5.5 μm and 8.5 μm on average in the SSD, and between 4 μm and 7.5 μm on the DSD. Typically, diameters of powder particles obtained with DSD are one-micrometer smaller on average than those obtained with the SSD. Considering the other test parameter, the nozzle diameter, particle sizes of the powders were found to decrease with decreasing nozzle diameters. The resulting particle sizes were found to be in accordance with the literature values and less than 10 μm on average. In parallel with our results, Thybo *et al.* [25] also reported that they obtained particle diameters smaller than 15 μm when the two-fluid nozzle was used in a laboratory-scale spray dryer.

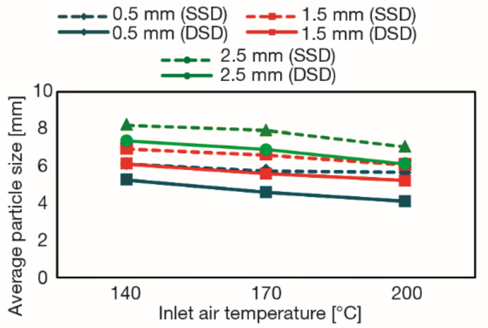

Figure 10. Particle size variation in the SSD and the DSD

The SEM micrographs of milk powders obtained with the nozzle diameter of 1.5 mm and at 140 °C ($T_{air,in}$) are shown in fig. 11. The powders obtained with the two compared systems are morphologically equally well with comparable particle diameters. The DSD gave a 1 micrometer smaller particles. Non-aglomerated fine powders having particle diameters of 6-7 μm are obtained at the end of the drying processes (both in SSD and DSD). This produces products with higher bulk density. Thanks to their better stability and enhanced solubility, small-sized spray-dried products are in high demand [26].

Nozzle diameter and inlet air temperature had significant effects on the morphology of spray dried milk powder particles. Roughness and wrinkles were observed on the powder particles with increasing inlet air temperatures and nozzle diameters. During the drying process, crusty layers were seen to be formed on the wall of the particles due to instant moisture loss.

Analyses done during drying processes

During the drying process, keeping the temperature of the drying chamber low is required as sticking of the powder material to the glass walls of the chamber is observed otherwise. In the system we developed (DSD), it was observed that the air- and glass-temperatures in the drying chamber were 3 °C lower than those of the SSD, figs. 12-15. Air- and glass-temperatures of the product chamber were observed as low as 6 °C on average compared to SSD.

The outlet air temperature, humidity, and velocity of SSD and DSD were measured for the optimized drying process (140 °C inlet air temperature and 1.5 mm nozzle diameter) and compared in fig. 16. Phisut [27] discussed that the outlet air temperature should be between 50-80 °C for a drying process in order not to damage the food product. In our study, the average outlet air temperature of 72 °C in SSD and 69.5 °C in DSD were obtained in accord-

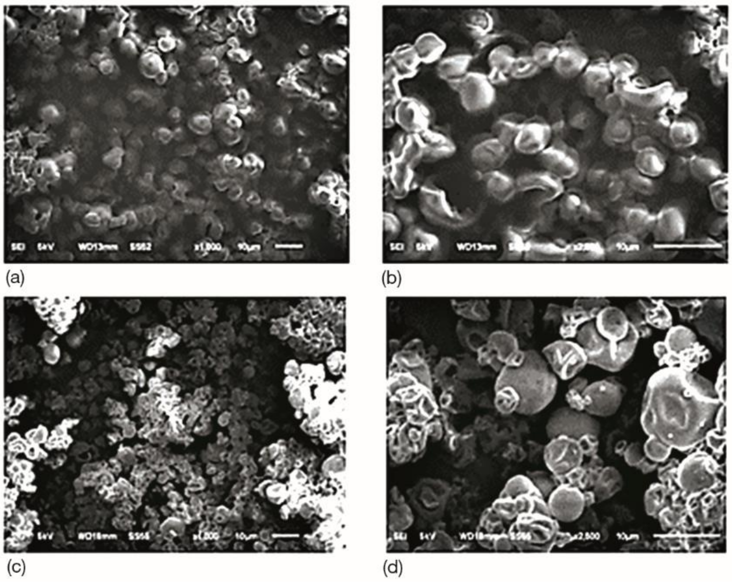

Figure 11. The SEM images of milk powder particles obtained with the nozzle diameter of 1.5 mm; (a) 140 °C, ×1000, (b) 140 °C, ×2500 (SSD), (c) 140 °C, ×1000, and (d) 140 °C, ×2500 (DSD)

ance with the literature. A more drastic result was observed in outlet humidity levels: the average humidity of the air leaving the dryer was 11.5% RH in the SSD and 24.3% RH in the DSD. In other words, this meant we afforded a much better-dried product with DSD, which can also be confirmed with the product moisture content analysis results. The average velocity of the outlet air was 7.7 m/s in the SSD and 10.3 m/s in the DSD. Collectively, the results were in agreement with relevant precedent studies [28, 29]. In the DSD we designed, the lower temperatures of the outlet air observed means higher temperatures inside the drying chamber are achieved; and this is why liquid droplets dry better. It has also been observed that the propellers remarkably increase the velocity of outlet air in the DSD.

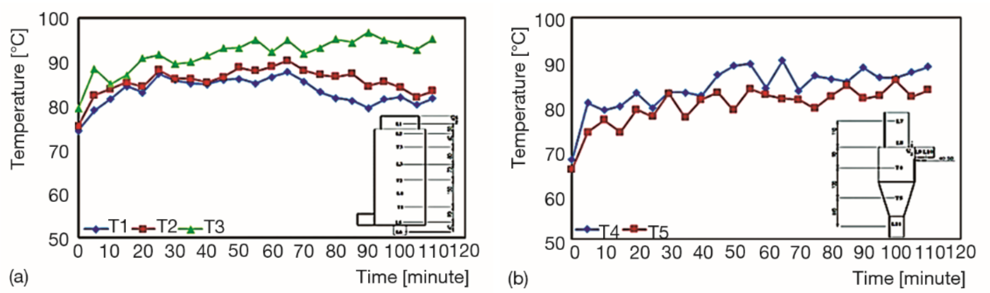

Figure 12. Variation of air temperatures in the drying (a) and product (b) chamber over time in the SSD

Comparing the SSD and DSD dryer in the milk drying process, it was observed that the propellers used in the DSD spray dryer affect both drying air temperatures and glass temperatures. It has been found that the drying and product chamber glass temperatures in the

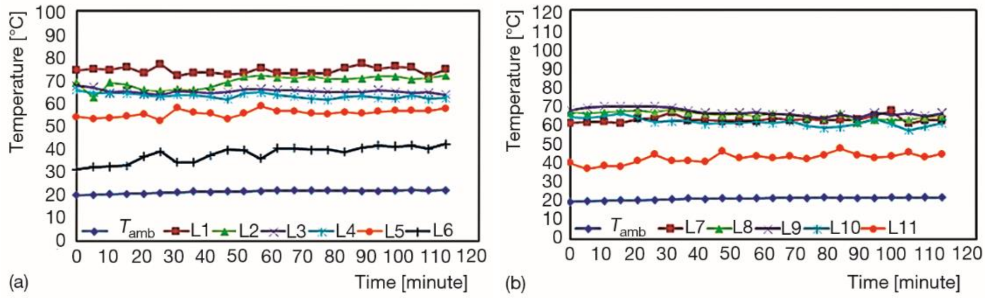

Figure 13. Variation of glass temperatures in the drying (a) and right (b) chamber over time in the SSD

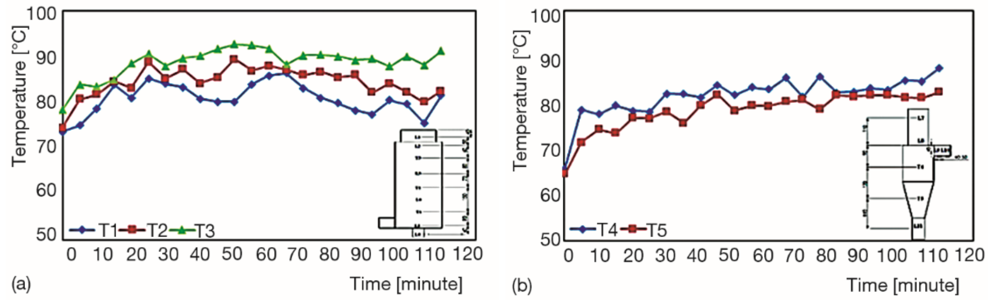

Figure 14. Variation of air temperatures in the drying (a) and product (b) chamber over time in the DSD

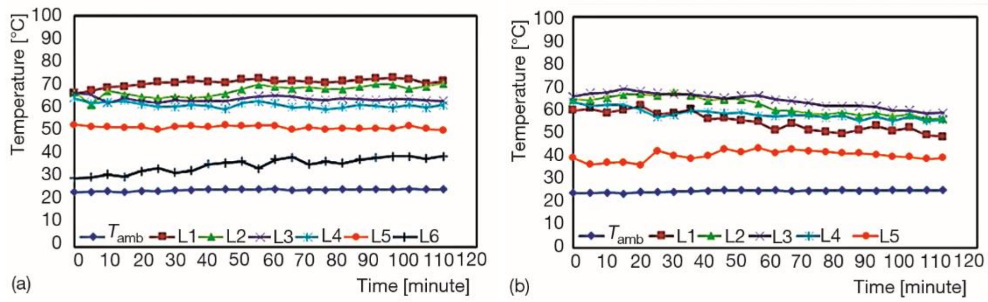

Figure 15. Variation of glass temperatures in the drying (a) and product (b) chamber over time in the DSD

DSD were lower than those in the SSD. The propellers used in the drying chamber helped lower the air and glass temperatures in the dryer. This significantly reduced the adhesion of milk powder particles to the glass walls and to each other in the DSD. In this way, more efficient, high-quality, and low-diameter sized milk powders were obtained in the DSD.

Conclusions

In conclusion, a new type of drying chamber design has been developed herein to dry liquid food samples more efficiently, *i.e.* to reduce product deposition on the glass walls and thus increase product yield without damaging the quality. To this end, propellers that can

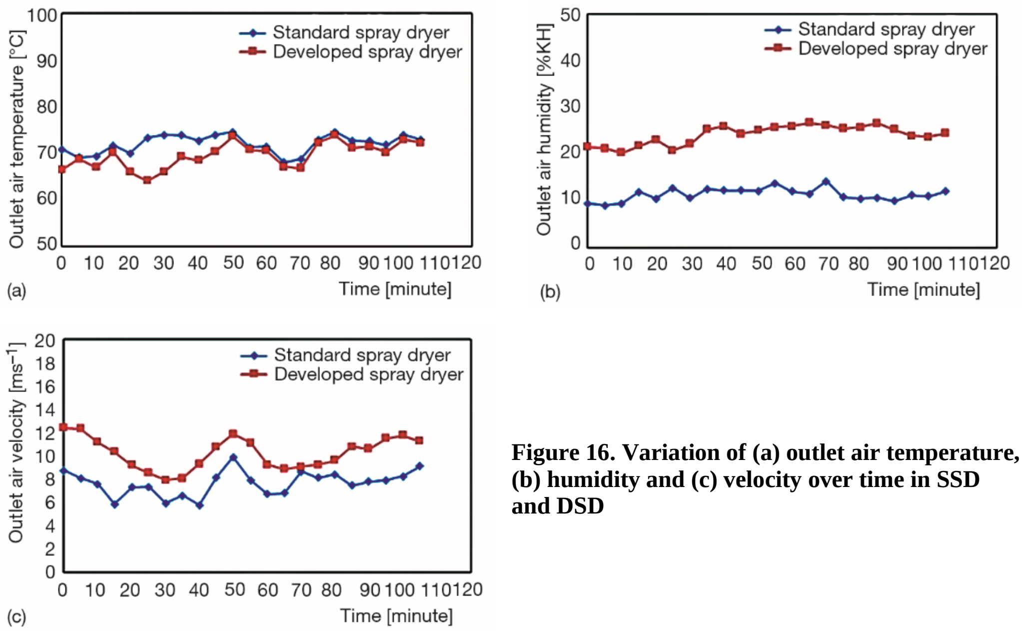

Figure 16. Variation of (a) outlet air temperature, (b) humidity and (c) velocity over time in SSD and DSD

easily rotate with the air blown from the atomizer are placed in the drying chamber. The performances of the newly developed dryer (DSD) and the standard dyer (SSD) were compared.

When the thermal efficiencies of the two dryers were compared, DSD was seen to be the most efficient for all the runs. Although the highest thermal efficiency was achieved at an inlet air temperature of 200 °C, this temperature adversely affected both the content of the milk powders and the drying chamber. In other words, at 200 °C, milk powders adhered more to the drying chamber glass and to each other. The drying process at this high inlet temperature damaged the milk powder as well, and the milk powders were obtained in yellow to beige colors. For this reason, the inlet air temperature was set to 140 °C. The most suitable nozzle diameter was determined to be 1.5 mm.

The use of propellers in the DSD has lowered air- and glass-temperatures compared to those of SSD. This significantly reduced the adhesion of milk powder particles to the glass walls and to each other in the DSD. Thus, more efficient, high-quality, and small-diameter sized milk powders with low moisture content were obtained in the DSD.

The most important factor affecting the efficiency of spray-drying-the most preferred method for obtaining powder product-is powder adhesion. Therefore, as we show herein with this study, it is quite possible to enhance the efficiency of a drying process by a small, but effective manipulation (propeller) that excludes the use/need of additives. Our works along these directions are in progress.

Studies to prevent dust adhesion are of great importance. In order to prevent adhesion of the product to the glass walls of chambers, the glass may be coated with non-stick coating material. Therefore, as drying and product chambers, chambers coated with non-stick materials can be used instead of bare glass materials. In addition, anti-sticking carriers/additives can also be added to the liquid samples to prevent adhesion.

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Nomenclature

DSD – developed spray dryer
SSD – standard spray dryer
$T_{\mathrm{air,in}}$ – inlet air temperature, [°C]
$T_{\mathrm{air,out}}$ – out inlet air temperature, [°C]
T_{amb} – ambient temperature, [°C]
η – thermal efficiency, [%]

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