AM003

Conceptual Design and Preliminary Testing of a Superheated Steam Spray Dryer Prototype

Maelada Fuengfoo[1]*, Chalida Niumnuy[2], Sakamon Devahastin[1], Somchart Soponronnarit[3]

[1]*Advanced Food Processing Research Laboratory, Department of Food Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha u-tid Road, Tungkru, Bangkok 10140, Thailand.*

[2]*Center of Advanced Studies in Industrial Technology, Department of Chemical Engineering, Faculty of Engineering, Kasetsart University, 50 Ngam Wong Wan Road, Chatuchak, Bangkok 10900, Thailand.*

[3]*Division of Energy Technology, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, 126 Pracha u-tid Road, Tungkru, Bangkok 10140, Thailand.*

Corresponding author: Maelada Fuengfoo. E-mail: fengmdf@ku.ac.th

Abstract

It is well recognized that using hot air as the drying medium leads to many adverse changes in terms of the dried product quality, including discoloration, losses of nutrients and other negative changes due to the oxidation reactions. To alleviate some of the above-mentioned limitations, superheated steam has been proposed and tested in this work as an alternative medium for spray drying. A superheated steam spray dryer prototype was designed and fabricated. The prototype, compared with a traditional hot air spray dryer, consists of an extra superheated steam generation unit and a powder separation unit, which was specially designed to avoid condensation of exhaust steam in the powder collector. This dryer prototype was then tested for its performance in terms of the percent powdery product recovery. The dryer was operated at the superheated steam pressure of 20 kPa (gage), inlet steam velocity of 15 m/s and temperatures of 150 and 170 ^{o}C. An aqueous solution of NaCl (20% w/v) was used as the test liquid feed at a flow rate of 3 mL/min. The percent powdery product recovery was noted to be in the range of 30.5 to 46.7%, which was still lower than that obtained in the case of hot air spray drying conducted in the same set-up.

Keywords: Powder collection; Product recovery; Steam condensation; Superheated steam drying.

1 Introduction

Although hot air is typically used as the drying medium in most spray dryers, it is well recognized that hot air drying leads to many adverse changes in terms of the dried product quality, including discoloration, losses of nutrients and other negative changes due to the oxidation reactions, among others (Devahastin and Mujumdar, 2014). To alleviate the above-mentioned problems, superheated steam has been proposed and tested as an alternative medium for spray drying since superheated steam drying results in negligible oxidation reactions which, in most cases, are undesirable. Besides, superheated steam exhibits superior thermal properties to hot air in both constant and falling rate periods under certain conditions and hence an improved thermal efficiency of the spray drying process (Ducept et al., 2002).

So far, the idea of superheated steam spray drying has been verified mainly only via theoretical analysis or numerical modeling. Crowe et al. (1985) numerically assessed the performance of a superheated steam spray dryer using a model for gas-particle flows in a conical cylindrical, concurrent spray chamber. The numerical predictions suggested that steam is a more effective drying medium because of its higher heat transfer coefficient and specific heat. Frydman et al. (1998) later employed commercial software to simulate the most important features of both superheated steam and hot air spray dryers, including fields of gas temperature and velocity. The simulations were validated by comparing the experimental and numerical values of temperature inside the chamber in the case of water drying (Frydman et al., 1999) and later in the case of a real product (Ducept et al., 2002).

The most recent study on superheated steam spray drying was that of Islam et al. (2016) who proposed the use of vacuum superheated steam spray drying to dry orange juice. Physicochemical properties of orange juice powder with different combinations of juice solids:

maltodextrin were determined. However, no attempt was made to investigate the effect of superheated steam as the drying medium in comparison with that of hot air.

In this work, a superheated steam spray dryer prototype was designed and fabricated. Preliminary experiments were performed to study some basic characteristics and limita-tions of this novel dryer; the results are reported here in terms of the percent powdery product recovery.

2 Experimental set-up and Methods

2.1 Superheated steam spray dryer set-up.

A schematic diagram of the superheated steam dryer prototype is shown in Figure 1. The drying chamber consists of a stainless steel cylindrical chamber, which is 24 cm in diameter and 50 cm in height, as well as a conical section of 30 cm in height. The chamber is insulated with 2-inch fiber glass to avoid possible condensation of steam in the chamber. A glass cyclone, which is 10 cm in diameter and 20 cm in height, as well as a conical section of 30 cm in height, and powder collector were insulated with 2-inch fiber glass to alleviate steam condensation, which would then lead to powder sticking to the cyclone and collector wall and hence low percent powdery product recovery.

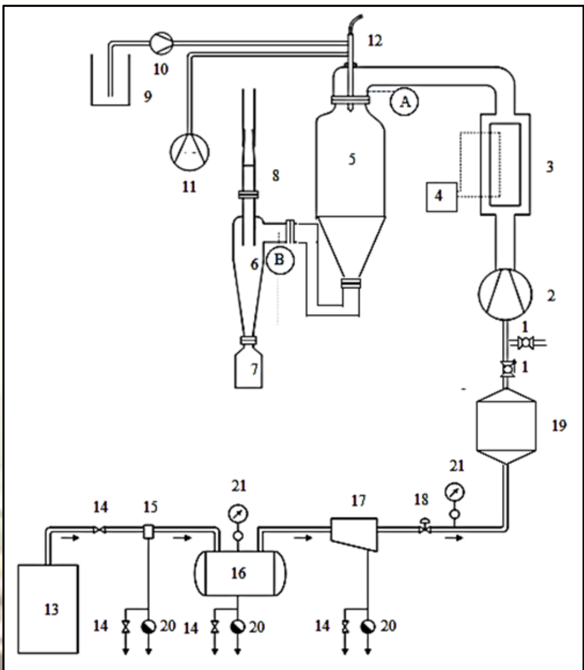

Figure 1 A schematic diagram of superheated steam spray dryer and associated units. (1) Ball valve; (2) Blower; (3) Supplementary electric heater; (4) PID controller; (5) Drying chamber; (6) Cyclone; (7) Powder collector; (8) Exhausted air pipe; (9) Feed tank; (10) Peristaltic pump; (11) Air compressor; (12) Two-fluid nozzle; (13) Boiler; (14) Globe valves; (15) Steam pocket; (16) Steam header; (17) Steam separator; (18) Pressure reducing valve; (19) Electric heater; (20) Steam trap; (21) Pressure gauges.

Saturated steam was first generated by a water-tube boiler. To remove excess moisture from the saturated steam, a steam pocket (1 inch in diameter), steam header (4 inches in diameter) and steam separator were used. Thermodynamic steam traps were used to drain excess water from the above three components. The steam pressure was adjusted via the use of a pressure reducing valve, which was used to control the steam pressure at near atmospheric pressure. An electric heater rated at 14 kW and a supplementary electric heater rated at 8 kW were installed as a steam superheater.

A peristaltic pump was used to feed the liquid to an atomizer; atomization was performed using a two-fluid nozzle, which recieved compressed air from an air compressor. A blower was used to supply the superheated steam to the system. The velocity of the superheated steam was adjusted by globe valves, while the superheated steam temperature was controlled by a PID controller. In the case of hot air drying, ball valves were used to adjust the velocity of the air; and the inlet temperature was controlled in the same way as that done in the case of the superheated steam drying. The inlet temperature and outlet temperature of both superheated steam and hot air were measured at points A and B, respectively.

2.2 Methods.

In this study, preliminary experiments were performed to test the performance of the superheated steam spray dryer prototype in terms of the percent powdery product recovery ($\eta_{product}$, %), which was determined as per the following eqution:

$$\eta_{\text{product}} = \frac{W_p}{W_F} \times 100\% \qquad (1)$$

Where W_p is the amount the solid mass of powder within the powder collector (g); W_F is the amount the solid mass of the liquid feed (g).

The experiments were divided into two cases, superheated steam drying and hot air drying. An aqueous solution of NaCl (20% w/v) was used as the test liquid feed at a flow rate of 3 mL/min. The dryer was operated at an inlet medium velocity of 15 m/s and inlet temperatures of 150 and 170°C.

In the case of superheated steam drying, prior to the start of each experiment, the system was preheated with hot air to the desired drying temperature to prevent steam condensation. First, the blower was switched on. When the inlet steam velocity reached the desired value, the heater was turned on. After that, superheated steam at a pressure of 20 kPa (gage) was fed into the system; steady-state condition was verified by checking if the steam temperature at both the inlet and outlet of the drying chamber was constant. Feeding of the liquid solution into the system then started. Finally, the powder within a powder collector was collected to evaluate the percent powdery product recovery.

In the case of hot air drying, when the inlet air velocity reached the desired value, the electric heater was turned on. After the temperature in the system reached the desired value, a steady-state condition was verified by checking whether the wet bulb and dry bulb temperatures at both the inlet and outlet of drying chamber were constant. Feeding of liquid solution into the system then started. Finally, the powder within a powder collector was collected to evaluate the percent powdery product recovery.

3 Results and Discussion

In the case of superheated steam, the time to reach the steady state after the system start-up was in the range of 20-25 min (as compared with 10-15 min in the case of hot air spray dryer). After feeding the aqueous NaCl solution, a new steady state was reached within about 3 min.

In the first set of the experiments, no powder was found in the powder collector (percent powdery product recovery approached zero) since condensation occurred, leading to the condensate accumulation in the powder collection unit. To reduce the steam condensation, a silicone oil bath was installed and used to control the temperature of the powder collector to a value higher than the saturation steam temperature at the dryer operating pressure. The percent powdery product recovery thus increased and noted to be 30.5 and 46.7% at the superheated steam temperatures of 150 and 170°C, respectively. These recovery values were nevertheless lower than those obtained in the case of hot air spray drying in the same set-up (61.7 and 63.5%, respectively). In any case, this condensation mitigation technique is not suitable for heat-sensitive food powder as the dried powder would have to stay in the heated collector for an extended period of time, at least until a particular drying run is over.

Further development to avoid condensation of exhaust steam in the powder collector is required. This may involve, for example, the use of a supplementary blower to increase the velocity of the exhaust steam at the cyclone outlet. Our expectation is to reduce as much as possible the existence of steam (and hence the possibility of steam condensation) in the powder collector.

4 Conclusions

A superheated steam spray dryer prototype was designed and fabricated. The prototype, compared with a traditional hot air spray dryer, consists of an extra superheated steam generation unit and a powder separation unit, which needs to be specially designed to avoid condensation of the exhaust steam. Although controlling the temperature of the powder collector could help reduce the condensation of exhaust steam in the powder collector and hence increase the powdery product collection efficiency.

5 Acknowledgements

The authors express their sincere appreciation to the Thailand Research Fund (TRF, Grant number RTA 5880009) and Agricultural Research Development Agency (ARDA, Grant number CRP5605010340) for supporting the study financially.

6 References

C Crowe, C.T., Chow, L.C., Chung, J.N. 1985. An assessment of steam operated spray dryers In: Toei, R., Mujumdar, A.S. (Eds.), Drying'85 (pp. 221-229). Heidelberg: Springer.

Ducept, F., Sionneau, M., Vasseur, J. 2002. Superheated steam dryer: simulations and experiments on product drying. Chemical Engineering Journal 86, 75–83.

Devahastin, S., Mujumdar, A.S. 2014. Superheated steam drying of foods and biomaterials. In: Tsotsas, E., Mujumdar, A.S. (Eds.), Modern Drying Technology, Vol. 5 (pp. 57-84). Weinheim: Wiley-VCH.

Frydman, A., Vasseur, J., Moureh, J., Sionneau, M., Tharrault, P. 1998. Comparison of superheated steam and air operated spray dryers using computational fluid dynamics. Drying Technology 16, 1305-1338.

Frydman, A., Vasseur, J., Ducept, F., Sionneau, M., Moureh, J. 1999. Simulation of spray drying in superheated steam using computational fluid dynamics. Drying Technology 17, 1313–1326.

Gauvin, W.H., Costin, M. 1980. Spray drying in superheated steam: a technoeconomic study. In: Mujumdar, A.S. (Ed.), Drying'80 (pp. 320-335). New York: Hemisphere.

Maa, Y., Nguyen, P., Sit, K., Hsu, C.C. 1998. Spray-drying performance of a bench-top spray dryer for protein aerosol powder preparation. Biotechnology and Bioengineering 60, 301–309.

Islam, M.Z., Kitamura, Y., Yamano, Y., Kitamura, M. 2016. Effect of vacuum spray drying on the physicochemical properties, water sorption and glass transition phenomenon of orange juice powder. Journal of Food Engineering 169, 131-140.