Development of a Laboratory Ink-Jet Spray Dryer

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Abstract

There has been continuing development in the area of spray drying technology to meet new challenges. Here, a concept of spray drying initially suggested by the second author is described to assess the possibilities of minimizing certain potential problems of spray drying. The principle of ink-jet technology is employed, where a single stream of uniform size droplets can be achieved. The ink-jet device was introduced to spray drying operations as an innovative atomizer due to its attractive ability to produce a monodisperse stream of uniform droplets with a better control over the droplet and possibly the particle characteristics. Several calculations on feasibility of this kind of drier are provided in this paper for the case of drying of a monodisperse stream of droplets. The advantages and possible drawbacks of the spray drying operation based on this relatively new concept of spray drying have been discussed. Finally, the recent laboratory results, using a single (ink-jet) atomizer spray drier developed at the University of Auckland (now located at Monash University), on the physical features of the lactose particles collected are reported.

1. INTRODUCTION

Spray drying has been a subject of extensive research due to its popularity and diversity for producing a wide range of products with very high production rates. Industries and researchers continue to consider this unit operation as a very complex and the least understood at the microscopic level (Kudra & Mujumdar, 2002). The key issues for the complexity are intricate air-droplets flow patterns, existence of a broad droplet size distribution and uncontrolled movement of innumerate droplets/particles in unsteady gas flows under changing temperature and humidity environment. This complexity does not allow researchers to establish the standard procedures for designing, optimizing and scaling up for industrial processes, equipments and product development. The control over the particle characteristics is also restricted. Current atomizers produce a spray of various patterns such as a thin sheet of liquid or a hollow cone, which consists of countless droplets of different size. High flow rates and different spray patterns lead to the intricate spray-air mixing and complex droplet trajectory, which further result in droplet-droplet and droplet-wall collisions, wall deposition, fouling, corrosion, unwanted agglomerates, broad particle-size distribution, and eventually nonuniform products. Each particle in the final product may have different shape, size, density, porosity, moisture content and also nutritional values. These potential problems ultimately lead to the inferior product quality and also the loss of products and money.

Nowadays all materials, which are produced partly or totally in the powder form, require continuously new and uniform particle characteristics. Some final products in biological and pharmaceutical industries require highly spherical particles for their final applications, for instance, some chemotherapeutic drugs and for DNA synthesis and cell sequencing. Also, a recent trend in the market is to meet the stringent product quality, i.e. all particles in the final product should have uniform characteristics, both physical and nutritional ones. Industries are continuously exploring ways to minimize potential problems, such as fouling, corrosion, large particle size distribution, nonuniform products and unwanted agglomeration at the same time reducing energy requirements and the overall cost. Very little efforts have been made by researchers to produce particles of uniform characteristics using spray drying. Therefore, this study aims to develop a new experimental technique to seek the possibility for minimizing product non-uniformity and to measure several droplet characteristics and drying parameters for studying the droplet drying process.

The present study has examined a spray drying technique, which is essentially drying of a monodisperse stream of uniform droplets. This concept is totally different from the conventional concept of drying a ‘spray’ of droplets with a broad droplet-size distribution. This innovative idea of producing a single vertical stream of droplets for the drying purpose was extracted from the ink-jet technology, where it is possible to produce a single or multiple streams of ink droplets with a predetermined trajectory using a device known as the ink-jet nozzle. An attractive feature of the ink-jet device is that it can produce uniform droplets with a better control over the droplet trajectory. The deviation in droplet volume was observed to be less than ± 1 % with most experimental studies in the literature (Cooley et al., 2001). The variation in droplet diameter is expected to be even smaller. Furthermore, it is possible to avoid droplet-droplet and droplet-wall collisions using a new technique. This feature has attracted great attention to seek a possibility of adapting the ink-jet device as an atomizer to the spray drying operation in order to minimize potential problems of the operation.

This paper has outlined the working mechanism of the ink-jet device, the construction of the laboratory ink-jet spray dryer, engineering requirements for the reliable operation, some energy and design aspects and also advantages and drawbacks of the novel spray drying technique. The ink-jet spray dryer was tested using lactose solutions and results are presented in this paper.

2. DEVELOPMENT OF THE INK-JET SPRAY DRYER

Authors have observed that some problems associated with spray drying can be minimized by controlling various spray characteristics such as droplet trajectory, droplet size distribution and droplet-droplet and droplet-wall collisions. A new atomising device has therefore been introduced to control the spray characteristics and to fulfil the requirement of precise control over the droplet trajectory and narrow and uniform spray in spray drying operations.

2.1. Ink-Jet Atomizer

Ink-jet printing technology is familiar to most people in the form of desktop office ink-jet printers, which consists of a number of ink-jet devices to produce small ink droplets of different colours. The ink-jet device used in this study was supplied by MicroFab Technologies Inc (USA). A schematic diagram of an ink-jet device is illustrated in Fig. 1. The device is 34 mm long, 12 mm in diameter with an orifice diameter of 80 µm. The ink-jet device consists of an annular piezoelectric transducer bonded to a glass capillary. The glass capillary is connected at one end to the feed reservoir and at the other end has an orifice. By applying a voltage to the piezoelectric transducer, the transducer produces a volumetric change in the fluid enclosed within the glass capillary. This volumetric change creates pressure waves, which propagate through the fluid to the orifice. A sudden change in cross-section of the liquid column at the orifice leads to the formation of a droplet. If the feed is pressurised and a continuous periodic pulse is applied to the piezo-transducer, the Rayleigh-type instability occurs that results in the break-off of the fluid column into a continuous single stream of uniform-size droplets. This mode of generating droplets is called a continuous jetting mode (Lee, 2003). A single ink-jet device can dispense a fluid from micro- to picolitre range and can produce 100 to 100,000 droplets (micron-size) per second using a continuous mode operation.

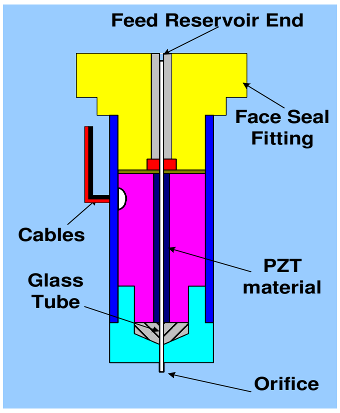

Figure 1: Schematic of a typical ink-jet device

Microfluidic devices have been used successfully in a commercial market for a number of applications to dispense various suspensions, slurries, polymers, solder materials, organo-metallic inks, adhesives and also biological fluids. In this study, we are testing such a device for the first time to dispense food materials, which are usually termed as complex biological materials.

2.2. Ink-Jet Spray Dryer

In this study, a lab-scale spray dryer that consists of an ink-jet technology is developed and tested based on an idea of drying of a monodisperse stream of uniform-size droplets. A schematic diagram of the experimental set-up is shown in Fig. 2. The ink-jet device was placed in the centre of the atomizing plate to generate a single, vertical stream of droplets. A continuous pulse is provided to the piezo-transducer using a pulse generator. Pulse characteristics were recorded using an oscilloscope. The cylindrical glass column is used in this study to act as a drying chamber, which allows for tracking of the droplet trajectory and monitoring a change in droplet size. Silica-gel beds are employed to dehumidify atmospheric air for dispersing ‘dry’ air into the glass column through the atomising plate. Temperature of the air stream was adjusted using an electric heater and a power variac. For efficient collection of dried particles, a vacuum pump is installed with a filter house at the exit of the glass column. Feed and hot air temperatures were monitored using thermocouples (K type) and recorded in a computer. Formation of droplets by an ink-jet device was observed using a video camera and a television set. Inlet and outlet air humidity were measured using digital sensors.

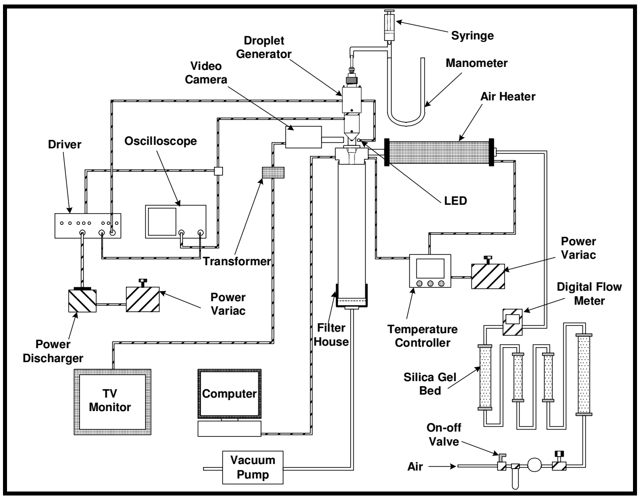

Figure 2: Schematic of an experimental set-up

2.3. Engineering Considerations

Success of a novel concept of spray drying completely relies on the consistent performance of the ink-jet device and the behaviour of a mono-disperse stream of droplets in the spray dryer. Generation of a monodisperse stream is not as simple as taking feed from the reservoir and pressurizing it through the nozzle. Unfavourable conditions may result in a misdirect or intermittent jet, more than two jets, satellite drops formation, blocking of nozzle, generation of random-size drops or leaking of fluid without drop formation. For a consistent and reliable operation, the following engineering requirements are important:

a. *Fluid properties*: Viscosity of the fluid should be between 0.5 and 40 cp and surface tension should be within 20 to 70 dyne/cm. Furthermore, the fluid should not have solid particles with a diameter greater than 5% of the orifice diameter of the atomizer. A common ink-jet device can work with fluid temperatures from 20 ºC to 150 ºC; however, some devices permit up to 240 ºC fluid temperatures.
b. *Pressure level*: Correct positive or back-pressure is required at the fluid inlet for ejection of a liquid jet at the orifice. Small positive pressure can be provided by positioning the feed reservoir a few feet above the ink-jet atomizer. When handling a large feed quantity, positive pressures up to 5 psig may be required and an air compressor needs to be employed.
c. *Pulse characteristics*: Stability of a monodisperse stream and uniformity of droplet size highly rely on the pulse amplitude, width and shape. A continuous unipolar pulse (a trapezoidal pulse) is effective for break up of a jet of low-viscous fluid. High-viscous fluids may require a bipolar pulse. A pulse generator and an amplifier have to be installed for generation of droplets.
d. *Drying and design parameters*: The control of air and droplet flows has a decisive influence on the end-product quality and trouble-free operation. The ink-jet device and the atomizing plate should be mounted symmetrically to the spray-chamber axis. The co-current laminar airflow is ideal for the ‘straightdown’ droplet trajectory and the reliable operation.

3. DESIGNING

Designing of an ink-jet spray dryer is far simpler than the designing of other kinds of spray dryers because one does not need to consider the droplet trajectories, droplet size distribution, entrainment effects and droplet collisions with other droplets and dryer walls during modelling and simulation of the drying process. The present study has proposed and designed a cylindrical spray dryer with no conical bottom for the case of drying of a monodisperse stream of uniform droplets. It was assumed here that the hot drying air was moving parallel around the droplet stream. Furthermore, the air velocity was adjusted in such a way that the droplet’s kinetic energy is higher than air friction forces until the desired moisture content is achieved and then droplets fall with a terminal settling velocity.

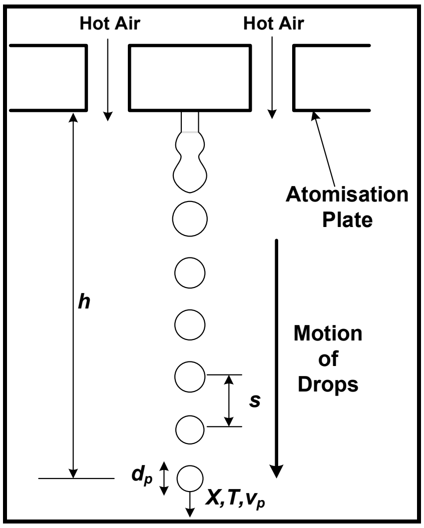

Figure 3: Drying of a monodisperse stream

Generation and behaviour of the droplets during drying of a monodisperse stream is shown in detail in Fig.3. The disintegration mechanism of a liquid jet into individual droplets can be explained by the Rayleigh theory of break-up of a cylindrical liquid jet (Bayvel & Orzechowski, 1993; Lee, 2003). If the liquid jet is disturbed with a constant wavelength at a regular time interval, then a monodisperse stream of uniform droplets can be produced with a desired droplet frequency (*F*). The spacing between two nearby droplets will be equal to a disturbance wavelength according to the Rayleigh's theory (Frohn and Roth, 2000). The distance h_0 is the axial distance at which the liquid jet disintegrates completely and droplet oscillations can be neglected. The initial velocity of the droplets was considered as the velocity of a liquid jet at the orifice. The initial velocity of a droplet was estimated using the volumetric flow rate of the feed and the cross-section area of the orifice as:

$$v_p = \frac{2}{3}\frac{d_p^{\ 3}}{d_o^{\ 2}}F \qquad (1)$$

The orifice diameter is known from the ink-jet atomizer manual and the droplet diameter can be measured during experiments. Generally, the initial droplet diameter is considered as twice the liquid jet diameter for the Rayleigh type disintegration with a continuous mode operation (Liu, 2000). For drying of a single vertical stream with plug flow conditions, all droplets ejecting from the orifice will have the same initial droplet characteristics and spacing between two neighbour droplets. Droplet properties will change during the flight of droplets in the drying-chamber due to the evaporation of moisture from the droplet surface and also due to the deceleration of droplets. However, at any time, all droplets traversing the cross-section of chamber at distance *h* will have the same history. In this ideal case, all dried particles at the exit will have same physical and nutritional properties because all drying and inactivation kinetics parameter profiles will be the same for each droplet.

In this study, models were formulated to estimate the theoretical size for an ink-jet spray dryer. The dryer diameter was calculated on the basis of the minimum dryer volume required to hold liquid droplets and drying gas flows per unit time. For ink-jet spray drying, the average air residence time is usually higher than the droplet residence time; therefore the dryer design calculation was based on the average air residence time data. Considering plug-flow conditions, the following model was developed to estimate the minimum dryer diameter:

$$d_d = \left[\left(\frac{4}{\pi}V_g + \frac{2}{3}d_p^{\ 3}F\right)\frac{t_g}{h}\right]^{1/2} \qquad (2)$$

The actual dryer cross section should be bigger than the one estimated using Eq.(2) by taking into account the deviation from the ideal flow. The dryer height can be estimated by multiplying the particle velocity with the average particle drying time considering the vertical trajectory for each particle. The average particle drying time data were obtained using drying kinetics and mathematical modelling. In this study, an additional length was provided to the drying column for ensuring cooling of dried particles. The energy requirements and the thermal and evaporative efficiencies were also calculated using appropriate models (Masters, 1991) to assess the performance of the ink-jet spray dryer.

4. EXPERIMENTS

Experiments were carried out to judge the characteristics of the particle produced using a new spray drying method. Gears were tested and calibrated using lab-grade isopropanol and then distilled water. In this study, reconstituted lactose solutions (made from distilled water and alpha-D-Lactose monohydrate powder) of different concentrations were used for drying experiments. The solution was filtered using a filter paper (Whatman™ 5) before feeding to the atomizer. The first experimental run was conducted for 12 hours using the 5 wt% lactose solution. A cylindrical glass column with 9.5 cm internal diameter and 50 cm height was employed as a drying chamber. The droplet frequency was set to 250 droplets per second. The inlet air temperature was kept at 70 °C and the outlet air temperature was recorded approximately 35 °C. The inlet air flow rate was adjusted to 11 litre/min. The humidity of inlet air was noted as 0.0001 kg water/kg dry air. Dried lactose particles were collected on conductive sticky tapes at regular time intervals for the SEM analysis.

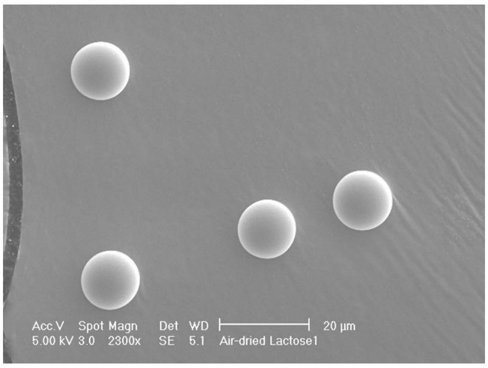

Figure 4: Air-dried lactose particles

Fig. 4 is a SEM photo of air-dried lactose particles produced in a lab-scale ink-jet spray dryer, built at the University of Auckland. It can be seen that particles have a spherical shape and they were not agglomerated. Furthermore, particles were highly uniform with respect to the particle size. The average particle size for this experimental run was 13 µm. When all samples were analysed, particles with size ranging from 5µm to 22µm were observed. With the current spray drying technology, the lactose particle size usually varies from 10µm to 300µm. The particle size distribution is very narrow using an ink-jet spray drying technique, which is an expected and encouraging achievement.

The ink-jet atomizer was successfully used to produce a single stream of droplets. The atomizer has performed very well up to 30 wt% lactose solutions. However, the nozzle was partly blocked after some period of operation when handling higher concentration solutions. The reason was the crystallization of lactose inside the glass capillary. This problem can be overcome by adjusting the feed temperature in the fluid reservoir.

5. DISCUSSION

The concept of drying of a monodisperse stream has successfully produced particles of very narrow size distribution. Droplets can be dried up to the desired moisture content before they collide with each other or the dryer wall; hence wall deposition, corrosion and unwanted agglomeration would be negligible. Also, the ink-jet spray dryer requires small space and the designing costs are low. An attractive feature of the ink-jet spray dryer is that this concept is highly suitable for drying of heat-sensitive materials as drying can be performed at relatively low temperatures. This spray drying technique could be very useful for testing highly valuable drug and biological products as very little fluid is required to run the operation. In addition, it is possible to measure drying and droplet parameters at all cross-sections of the dryer. The reproducibility of results is also very high. This experimental technique could be very helpful to study the droplet drying process and the particle formation mechanism in more depth.

Scaling up of this operation to the bulk production is restricted by the small feed handling capacity of an atomizer because a single atomizer can dispense up to 100 ml of fluid in an hour. Authors have proposed a multiple-nozzle array design to elevate the feed handling capacity. The grouping of several hundred ink-jet nozzles in a mechanical and hydraulic assembly is very common and used for many commercial ink-jet printing applications. Here, we have described such an array, illustrated in Fig.5, using three ink-jet atomizers. A circular perforated plate can be used for grouping a few hundred ink-jet atomizers, one atomizer in each hole. Several litres of feed could be handled using a dryer with a multiple nozzle array design. However, the fabrication and handling of such an array is complex and expensive.

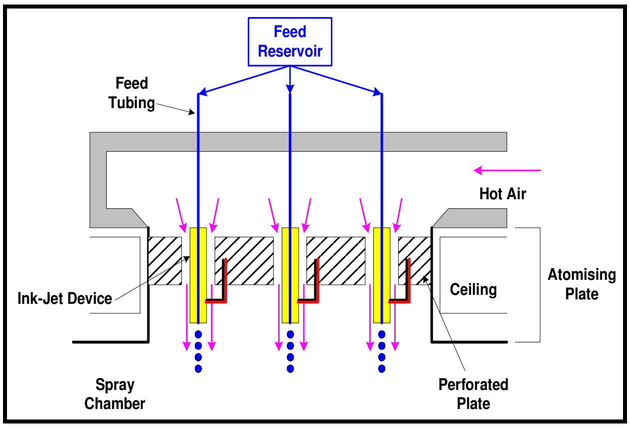

Figure 5: Schematic of multi-nozzle array

Here, some dryer design parameters are estimated for a case study of co-current air drying of 30 wt% (dry basis) skim milk with a feed handling capacity of 100 kg/hour. The idea is to disperse hot air around each ink-jet atomizer, using a dispersing hole, in such a way that a flow of droplets cannot be impeded by other streams and dryer walls. Mathematical modelling was conducted for uniform droplets with a frequency, initial diameter, velocity and temperature of 10,000, 200 μm, 1.35 m/s and 333 K, respectively. The air conditions include dry- and wet-bulb temperatures of 473 K and 316 K, respectively, and an initial velocity of 0.35 m/s. The diameter of a single air dispersing hole was estimated as 5 cm.

Table 1. Spray dryer design parameters

Parameter	Value & Unit
Dryer diameter	1.97 m
Dryer height	11.07 m
No. of nozzles required	548
Particle moisture content	0.04 kg/kg
Particle density	1511 kg/m^3
Particle size	150 μm
Thermal efficiency	77%
Evaporative efficiency	81%

The theoretical air flow rate requirement to achieve 10% particle moisture content was 38 times the liquid feed flow rate. In practice, the same task requires an air to feed ratio up to 100 with existing dryers (Keey, 1991). The spray drying concept proposed in this study would lead to the reduced energy costs due to the lower air flow rate requirements. Furthermore, the ink-jet spray dryer permitted higher inlet and lower outlet air temperatures. The greater difference between the inlet and outlet air temperatures resulted in higher efficiencies. High efficiencies would result in a lower energy requirement and also a lower production cost per unit weight of a product. However, a requirement of large number of atomizers makes the dryer design complex due to necessity of individual feed tubing and power cables for each atomizer. It may be possible that the overall manufacturing costs are larger with a multi-nozzle array compared to traditional atomizers when employing a few hundred nozzles into a single atomizing unit. Therefore, a limit needs to be set for the maximum number of ink-jet devices to be used in the atomising plate in order to provide simplicity and reduced atomisation costs to the operation.

6. CONCLUSION

A new concept of spray drying, which is drying of a monodisperse stream of uniform droplets, has been discussed and some configurations were designed in this study. This concept was found to be attractive compared with drying of a spray of droplets with a random trajectory and a huge drop size distribution. The ink-jet spray dryer offers simplicity to the operation and gentle treatment to the droplets, which may improve the product quality. Ultimately, the ink-jet spray dryer could effectively form a new approach for drug developments and testing and designing new products in the laboratory that would be faster, economical, use fewer resources and yield more predictive results than current techniques. The ink-jet spray dryer may be suited in small-scale spray drying operations in biological, pharmaceuticals and agrochemicals industries where valuable materials are handled and where micro- or nano-sized particles of uniform characteristics are required at a low production rate. Broad experimental studies and improvement in the design are under progress at Monash University.

7. SYMBOLS

d_d	diameter of dryer, m
d_p	droplet or particle diameter, m
d_o	orifice diameter, m
F	frequency of droplets
h	dryer height, m
t_R	gas residence time, s
v_p	velocity, m/s
V_g	volumetric flow rate of gas, m^3/s

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