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Abstract

A new technique for spray drying of egg white was developed and termed as pulse combustion spray drying (PCSD) which uses high temperature pulsating jets generated by the pulse combustor to atomize and dry the liquid feed simultaneously. The pilot-scale PCSD testing of egg white was conducted and the drying energy efficiency was evaluated. Selected product properties of the PCSD egg white powders were measured. It was found that compared with traditional spray drying, the PCSD process achieved a higher energy efficiency of 2604 kJ/kg water evaporated and the PCSD powders had a superior surface characteristics, smaller mean particle diameter and more homogeneous size distribution. Additionally, the egg white proteins and their foaming and gelling properties were protected well in the PCSD process. Experimental results showed the PCSD technique is promising for drying of egg white and even other heat-sensitive food feeds.

Key words: Egg white powder; Foaming; Gelling; Pulse combustion drying; Protein denaturation

1 INTRODUCTION

Egg white is qualified as a multi-purpose ingredient due to its high nutritional qualities and excellent foaming and gelling properties (Mine, 1995; Lechevalier et al, 2007). It can be commercialized under the liquid solution forms but the more frequently encountered form is in particulate state obtained by traditional spray drying (SD). By spraying the feed into a hot drying medium using rotary atomizers or nozzles, the liquid egg white is transformed into a dried particulate form, which has longer shelf life, easier transport and storage, and specific functional properties (Rao and Labuza, 2012).

In drying of egg white, energy efficiency and product quality are two main concerns but there is a contradiction between them. First, the liquid egg white comprises of about 86% water and a lot of energy is consumed to evaporate the water. Second, more than 80% of dry matter of egg white are proteins and these proteins are heat-sensitive materials. Proteins denaturation will occur in the high temperature drying process which reduces the foaming and gelling properties of the egg white (Lechevalier et al, 2007; Landfeld et al, 2008). To protect the nature of the egg white proteins, it is necessary to use the low drying temperature in the traditional spray drying of the egg white. However, low drying temperature will reduce the drying rate of egg white and lowers the production capability and energy efficiency of the spray dryer. Thus, like the egg white, the contradiction between energy-saving and product quality was often encountered in traditional spray drying of some heat-sensitive materials.

The above contradiction may be solved by a novel spray drying technique- pulse combustion spray drying (PCSD). Unlike traditional spray drying where the liquid atomization and drying are separated, PCSD technique uses the pulse combustion technology to produce high temperature and high velocity pulsating jets, which are used to atomize and dry the liquid simultaneously (Kudra and Mujumdar, 2001; Zbicinski, 2002; Wu and Liu, 2002; Wu and Mujumdar, 2006a). Since PCSD dryers use "gas dynamic" atomization and no mechanical atomizers/nozzles are needed, they can handle liquids with high viscosity and/or high solid content which are difficult materials for traditional spray drying (Kudra, et al, 2003; Wu and Mujumdar, 2006a).

More importantly, PCSD dryers can provide an advantageous superposition of unsteady gas flow and high-intensity sonic waves. Such a combination increases the momentum and heat/mass transfer rates in industrial drying processes and thus improves the dryers' energy efficiency. PCSD dryers have other merits such as very low pressure in the liquid feed system, lower maintenance costs, etc. Due to these merits, PCSD techniques have been tested to dry lignite (Ellman et al, 1966; Chowdhury, 1984), sewage sludge (Wu et al, 2012), chemicals (Zbicinski, 2002; Joni et al, 2009), and pharmaceuticals (Xu et al, 2007). However, there are few papers to discuss PCSD drying of food materials (Swientek, 1989) since the PCSD drying is still a developing technique.

The aim of this paper was to evaluate the application potential of PCSD technique in drying of a typical heat-sensitive food material-liquid egg white, by comparing the energy efficiency and product quality of the egg white powders obtained by PCSD or traditional SD techniques. The PCSD drying experiments of the liquid egg white were conducted and the process parameters were monitored. Their values were used to calculate the energy efficiency of the PCSD drying process. Selected product properties of the egg white powders obtained by PCSD were measured and then compared with the properties of a commercial product obtained by traditional spray drying (SD).

2 MATERIAL AND METHODS

The research work was conducted jointly by research members from Tianjin University of Science and Technology (TUST), Tianjin, China and members from Pulse Combustion Systems (PCS), Payson, Arizona, USA (www.pulsedry.com). The drying of egg white was completed in the PCS company using its pilot PCSD dryer and the product properties of PCSD dried egg white powders were measured in TUST.

2.1 PCSD Dryer

Pulse combustion originates from the intermittent (pulse) combustion of the solid, liquid or gaseous fuel in contrast to the continuous combustion in conventional burners (Putnam et al, 1986). The controlling mechanism behind the operation of a pulse combustor is a complex interaction between an oscillatory combustion process and acoustic waves that are propagated from the combustor. Take the Helmholtz type pulse combustor shown in Figure 1 as an example, pulse combustion starts when fuel and combustion air are drawn into the combustion chamber and mixed to form a mixture. The mixture is ignited by a spark plug and combust explosively, resulting in a rapid pressure rise. At this moment, this rising pressure closes the air and fuel inlet ports and forces the combustion products to flow out through the tailpipe. As the hot flue gases flow out, the resulting outward momentum causes the pressure in the combustion chamber to drop to the minimum so the inlet ports open, which admits fresh fuel and air into the combustion chamber. This new charge ignites itself due to contact with remnants of hot flue gases left in the tailpipe from the preceding cycle which reenter the combustion chamber during the minimum pressure period. These combustion cycles repeat at a natural frequency depending on the geometry of the combustion chamber and characteristics of the tailpipe-applicator system.

Figure 1

Pulse combustion generates intensive pressure, velocity, and to certain extent, temperature waves propagated from the combustion chamber via a tailpipe to the process volume (applicator) such as a drying chamber. Because of oscillatory nature of the momentum transfer, pulse combustion intensifies the rates of heat and mass transfer thus accelerates drying rates. Typically, a pulse combustor may operate at frequencies that vary from 20 to 200 Hz. Pressure oscillations in the combustion chamber of the order of ±10 kPa produce velocity oscillations of about ±100 m/s and the velocity of the gas jet exiting the tailpipe varies from 0~100 m/s. The input power ranges from 20 to 1000 kW for commercially available pulse combustors. More details of this instrument and its industrial applications are provided in references (Putnam et al, 1986; Zinn, 1992; Wu and Mujumdar, 2008).

Figure 2

The major function of the pulse combustor in a drying system is to supply heat for moisture evaporation, and to generate large-amplitude high frequency pressure pulsations within a drying chamber, which enhances the drying rate. The strong oscillating hot flue gas jet generated by the pulse combustor has also been used to promote dispersion of the feed. Figure 2 presents a pulse combustion spray drying pilot testing installation developed by Pulse Combustion System, USA, which consists of a pulse combustor, a tall-form drying chamber, a cyclone and a bag house. Figure 3 shows how the pulse combustor was used to atomize/dry liquid: air (1) is pumped into the pulse combustor outer shell at a low pressure, where it flows through the unidirectional air valve (2); The air enters a tuned combustion chamber (3) where fuel (4) is added; The air valve closes; The fuel-air mixture is ignited by a pilot (5) and explodes, creating hot air, pressurized to about 2 kPa above combustion fan pressure; The hot gases rush down the tailpipe (6) toward the atomizer (7); The air valve reopens and allows the next air charge to enter; The fuel valve admits fuel, and the mixture explodes in the hot chamber; This cycle is controllable from about 80 to 110 Hz;

Figure 3

Just above the atomizer, quench air is blended in to achieve desired product contact temperature; The exclusive PCS atomizer releases the liquid (9) into a carefully balanced gas flow, which dynamically controls atomization, drying, and particle trajectory; The atomized liquid enters a conventional tall-form drying chamber (10); Downstream, the suspended powder is retrieved using a cyclone and bag house. Figure 4 shows the snapshot of the egg white liquid atomization process observed in the PC spray dryer during the pilot testing experiments.

Figure 4

This installation was designed to have a heat release of 29.3 kW and evaporative capacity of 40 kg water/hour. The pulse combustor operated on the gaseous fuel-propane and the tall-form drying chamber has a diameter of 1.3m, height of 3m and volume of 4 m^3. A-low pressure, open pipe feed system is used supply the liquid which provides the ability to process higher-solids feeds without dilution, yielding higher powder production rates and much lower processing costs per finished pound.

The installation also has a state-of-the-art control system that allows for adjusting of operation parameters and three remote monitoring cameras to view all stages of powder production.

2.2 PCSD Drying Experiments

Production of the egg white powder was conducted on the above PCSD pilot test installation. The raw material- Great Value TM 100% liquid egg white was purchased from local Wal-Mart store in Payson, AZ, USA. According to its nutrition label, the liquid egg white comprises of 10.87% protein, almost 0.0% total fat, 2.17% total carbohydrate, 86.96% water. That is, the solid content in the feed is 13.04%. 25 kg liquid egg white was purchased and mixed in the feed tank for the experimental use.

At the beginning of the experiment, the PC dryer was ignited and then warmed up in the first 30 minutes without liquid feed. During warming up, the PC dryer setup was being adjusted to an optimum drying condition for the liquid egg whites: the heat release was set to be 24.32 kW and taking the heat value of propane as 2321 kJ/m^3, the fuel flow rate was calculated to be 0.63 m^3/min. The combustion gas temperature at the atomizer was adjusted to be 326.6 ^{O}C. After the warming up of the PC dryer, liquid egg white was feed into the dryer at a speed of 0.6 kg/min. Then, the egg white was atomized and dried simultaneously by the oscillating combustion gas in the drying chamber. The gas temperature in the chamber bottom was measured to be 76.6 ^{O}C and ambient air temperature was 25 ^{O}C. The whole egg white drying process lasted about 28 minutes. At the end of the experiment, the dried egg white powders were collected from the cyclone, baghouse, and the blow-down of the wall deposit in the drying chamber. All the powders were mixed together and stored in a tightly closed bag for sequent testing of its product properties.

2.3 Product Properties

The product properties of the egg white powders obtained by the PCSD technique were measured and compared with the ones of a commercial egg white powder product obtained using traditional SD technique from Kangde Company, Nantong City, China who was one of biggest egg white powder producers in China.

2.3.1 Product color

The color of the PCSD and SD egg white powders was measured using the DC-P3 colorimeter (Beijing Xingguang Color Measurement Instrument Co., Ltd, Beijing, China). The color was measured using an absolute measuring mode following the manufacturer's instruction and calculated automatically using the CIE 1976 L⁄a⁄b⁄ colour space system (International Commission on Illumination, 2008). The L values (lightness) extend between 0 for black and 100 for white.

2.3.2 Particle size

The size distribution of PCD egg white powders were measured using the laser diffraction method on a LS-C(III) Laser Particle Size Analyzer (OMEC, Zhouhai, China) with a size range of 0.1-1000μm. Each sample was measured three times and the size distribution curves were plotted in Figure 5. The differential distribution in Figure 5 is the percentage of particles from the total are within a specified size range. the cumulative distribution is the sum of the differential distributions.The distribution width expressed as the relative span factor (RSF) was calculated according to the equation RSF= (D90−D10)/D50, where D10, 50, D90 were particle sizes for 10%, 50% and 90% cumulative mass respectively.

2.3.3 Morphology

Morphologies of the PCSD and SD egg white powders were analyzed using the SU-1510 Scanning Electron Microscopy (Hitachi, Japan). Samples were prepared on the aluminum SEM stubs. The mounted powders were sputter-coated with gold–palladium, achieving a coating thickness of approximately 15 nm. The electron micrographs were produced by the SEM in secondary electron mode with an operating voltage of 5 keV. A range of 50 to 1500 magnification was used in the images.

2.3.4 Components

The main food components are water, protein, fat and carbohydrate. The above components of the PCSD powders were also measured in this work. The water content, M_w, was measured using the traditional drying oven method. The mass fraction of total protein, M_p, was measured using the Kjeldahl determination method according to the Chinese national standard (GB/T5009.5-2010). The mass fraction of the total fat, M_f, was measured using Soxhlet extraction method according to the Chinese national standard (GB/T 1477.2-2008). The concentration of carbohydrate, M_c, was calculated by the equation (1)

$$M_c = 1 - M_w - M_P - M_f \tag{1}$$

2.3.5 Proteins denaturation

The protein denaturation level of the egg white powders was determined using a differential scanning calorimetry (DSC) method on a DSC204 FI differential scanning calorimeter (Netzsch, German). Samples of 8.7 mg egg white powders were loaded in hermetically sealed aluminum pans using a pipette. An empty pan was used as reference. Samples were first equilibrated at 30 ^{O}C for 5 min and then, the temperature was raised to 150 ^{O}C at a speed of 5 ^{O}C/min. The DSC curves were obtained (shown in Figure 7) and total denaturation enthalpies were calculated from the DSC curves. The degree of denaturation in percentage relative to the low temperature hot air dried (LHAD) sample (assigned 0% denaturation) was calculated in this work.

2.3.6 Foaming ability and foam stability

Foaming ability (FA) and foam stability (FS) are two important functions of egg white proteins in the manufacture of the bakery products. In this work, FA and FS were measured using the method described in the references (Lechevalier et al 2007; Manzocco et al 2013). First, a certain egg white powder was mixed with distilled water to form a 0.4% mass fraction egg white solution. Next, a 25 ml egg white solution was taken in a cylinder and its pH value was adjusted to 8. The solution was then homogenized using an emulsification machine at the speed 14000 min^{-1} during 2 minutes and after emulsification, its volume was written down immediately, V_0. After a standing of 30 minutes, the new volume was recorded, V_{30}. The FA and FS are calculated using the following equations (2) and (3) respectively.

$$FA = \frac{V_0 - V_{\text{int}}}{V_{\text{int}}} \times 100\% \quad (2)$$

$$FS = \frac{V_{30} - V_{\text{int}}}{V_0 - V_{\text{int}}} \times 100\% \quad (3)$$

Where, V_{int}, is the initial volume of the solution, 25 ml.

2.3.7 Gelling properties

Egg white gels were prepared by heating 300 ml of the egg white solution with a 11% protein concentration in plastic tubes in a water bath at 80^{O}C for 1h, and subsequently cooled at room temperature for at least 4h. After removing the tubes, cylindrical samples (3 cm diameter, 2 cm high) were cut using two parallel metal wires. The texture of the gel samples was measured using a TA-XT2 texture analyzer (Stable Micro System Ltd, UK). A 20 mm diameter plate probe was used a texture profile analysis (TPA) in a double compression test to penetrate to 50% depth at a penetration speed of 2 mm/s. The gel hardness and springiness were calculated from the TPA system.

2.3.8 Statistical Analysis

In this work, the measurement of product colors were repeated four times and three samples were analyzed for other product properties. The data were processed to obtain the maximum, minimum, mean value, standard deviation, and range as shown in Tables 2-4.

3 RESULTS AND DISCUSSION

3.1 PC Drying Process

Table 1 summarizes the operation data obtained for the PCSD process of egg white. From Table 1, it can been seen that when the PC dryer operated in a heat load of 24.32 kw (80% of its design capability), the dryer can reduce the moisture content of the egg white from its initial 86.96% to the final 8.11% in a feeding rate of 0.6 kg/min. In this condition, the evaporation rate of the PC spray dryer was calculated to be 33.62 kg water/hr (84% of its designed capability) and the produce capability was 36 kg liquid egg white /hr. The energy consumption was calculated to be 2604 kw/kg water evaporated, which is slightly higher than the water evaporation latent heat of 2258 kJ/kg. Compared with the traditional spray dryers with energy consumptions of 4500-11500 kJ/kg (Zibcinski, 2002; Wu and Mujumdar, 2006b), the PCSD dyer has a very low energy consumption and high energy efficiency.

The high energy efficiency is one distinctive merit of the PCSD dryers which were also observed in PCSD drying of other materials. In the sequent PCSD drying of other materials, a similar high drying energy efficiency was obtained: the energy consumption was 2974.7 kJ/kg when drying the skim milk from its initial moisture content of 93.13% to final 11.3%, 3317.3 kJ/kg when drying the TiO_2 solution from 75% to 5% (Wu et al, 2014). Kudra and Mujumdar(2001) reported a energy consumption of 4187 kJ/kg when PC drying food waste from 45% to 10%. Benali and Legros (2004) carried out an experimental study on thermal drying of clean sands on a valved pulse combustion unit. The heating time of sand particles in the pulsed system was found shorter than the one observed when operating with a conventional burner under the same conditions, resulting in a 25.5% reduction of natural gas consumption.

The high energy efficiency can be explained by the reasons that the high temperature and high velocity oscillating gas generated by pulse combustion enhanced the mass and heat transfer rates between the egg white and drying gas. The enhanced mass and heat transfer rates increased the drying rate and shortened the drying time of the egg white. The increased drying rate in the PC dryer may be due to the reasons that (1): a higher drying gas temperature. Higher drying gas temperature causes a higher drying drive force and thus increases the drying rate. In this case, the drying gas temperature in the PC dryer reaches 326.6 ^{O}C while traditional spray dryers use a drying gas temperature of 110-150 ^{O}C for heat sensitive food materials. (2): a smaller particle diameter. As shown in Figure 6, the PCSD dried egg white powders have a smaller mean particle diameter than the traditional SD dried ones. A smaller particle diameter means a bigger surface area/volume ratio of the egg white. Thus, the egg white has bigger contact surface with the drying gas in the PC dryer, which is useful to increase drying rate. (3) a highly turbulent flow field in the drying chamber. The pulsating exhaust gas flow causes a highly turbulent flow field in the PC drying chamber, which will improve the heat and mass transfer coefficient between the drying gas and the egg white powders and eventually, to increase the drying rate.

Table 1 shows that 60.28% dry solid feed was collected from the cyclone and 13.24% dry solid was collected from the drying chamber wall blowdown at the end of the pilot test. The total yield of the egg white dry solid feed is about 73.52%. In the experiment, it was observed that the egg white powders deposited on the chamber wall can be easily blown down using the compressed air. The fact means that the wall deposit of egg white powders was minor in the PC spray dryer. About 26.48 % dry solid feed was lost due to the possible deposition in the baghouse or escaping into the environment of smaller egg white powders. The multi-purpose cyclone of the pilot dryer is not efficient for egg white powder collection.

Table 1

3.2 Product Properties

3.2.1 Product color

Figure 5 shows the PC spray dried and traditional spray dried egg white powders. The PCSD powders have a white color while the SD powders have a pale yellow color. When measured using the DC-P3 colorimeter, the PCSD powders had a mean *L* value of 79.87, *a* of -4.96 and *b* of 8.60. While the SD powders had a mean *L* value of 77.91, *a* of -6.21 and *b* of 10.33. Ma et al (2013) reported a mean *L* value of 99.25, *a* of 0.83, and *b* of 14.27 for SD dried egg white powders in a optimum experimental drying conditions of spraying flow of 22 mL/min, feeding temperature of 39.8 ^{O}C and inlet air temperature of 178.2 ^{O}C. The color change of the egg white powders are complex and one reason may be due to the oxidization reaction occurring in the drying process. In PC dryer, the powders had a shorter residence time due to increased egg white drying rate. Also, the oxygen concentration in the flue gas of pulse combustor is lower than the that in the hot air used in traditional spray dryers. In this condition, the oxidization reaction of egg white is minor in the PC dryer and thus, the egg white powders can keep its white color.

Figure 5

3.2.2 Particle size

Figure 6 show the size distributions of PCSD and SD egg white powders. From Figure 6, it was found that compared with SD powders, the PCSD powders had a smaller mean diameter and tighter size distribution. The D50 diameter of the PCSD powders was 20.15 μm while the SD powders had a D50 diameter of 54.74 μm. The RSF parameters, which is used to express the particle size uniformity, are 2.71 for the PCSD powders and 3.42 for the SD powders respectively, showing the PCSD powders had a more consistent particle size. This can be explained by that when the nozzles or rotary disks begin to wear on a traditional spray dryer, the dynamics of atomization change, and the particle size changes with it. While in the PC dryer, there are no parts to wear out; every droplet sees the same atomization energy and the same differential temperature. Thus, dried particle size distributions tend to be tighter than those obtained from a traditional spray dryer.

Figure 6

3.2.3 Morphology

Figure 7 shows the SEM images of PCSD and SD egg white powders. From Figure 7, it can be seen that the PCSD powders had a superior particle surface characteristics. The SEM images showed that most PCSD powders were single and disperse ones which had a sphere shape and smooth surface. By contrast, the SD powders easily aggregated to form bigger particles that had various shapes and coarse surface. In Figure 7, it was interesting to note that PCSD powders had a hollow structure while SD powders had a dense solid structure. This hollow structure may be caused by fast drying rate of the egg white in the PC dryer. The fast drying rate means a short drying time and in the PC dryer, the drying time is so short that the droplet does not have enough time to shrink fully. Thus, the hollow structure will form for the PCSD powders. While in the traditional spray dryers, the drying rate is moderate due to the low drying air temperature and the egg white droplet have enough time to shrink fully.

So, a dense solid structure was observed for the SD powders.

Figure 7

3.2.4 Components and protein denaturation

The initial liquid egg white comprises of 10.87% protein, almost 0.0% total fat, 2.17% total carbohydrate, 86.96% water. After PC drying, the liquid egg white becomes powders which comprise of 8.11±0.13% water, 73.97±1.45% protein, 0.18±0.03% total fat, 13.17% total carbohydrate and 4.57% ash. The above experimental data showed that the PCSD powders are a material with high protein content. However, protein is a heat-sensitive material and denaturation may occur in its high temperature thermal treatment. Denatured protein powders not only alter the functionality, such as foaming and gelling compared to their native undenatured form, but also sometimes results in their malfunctioning in living systems.

Literatures reviews shown that the egg white protein denaturation easily occur in the spray drying process due to usage of the high temperature hot air (Lechevalier et al 2007; Rao and Labuza, 2012; Ma et al, 2013). Hence, it is imperative to know how much the egg white protein will denature in the PC drying, where a hot oscillating gas of 326.6 ^{O}C was even used. In this work, the protein denaturation degree of the PCSD egg white powder was determined in percentage relative to the low temperature hot air dried (LHAD) sample (0% denaturation assumed). The LHAD sample was obtained by drying the initial liquid egg white to a dry solid with final moisture of 8% in a hot air convective drying oven using a drying air temperature of 40 ^{O}C. Since the drying temperature is far smaller than the egg white protein denaturation temperature (89 ^{O}C) shown in Figure 8, thus a 0% denaturation was assumed for the LHAD sample.

Figure 8

Figure 8 show the DSC curves for the PCSD powders and LHAD sample. From Figure 8, it can be seen that the egg white protein denaturation temperature was about 89 ^{O}C. By calculating and comparing the total denaturation enthalpies using the DSC curves shown in Figure 8, the protein denaturation degree of the PCSD powder relative to the LHAD sample was determined to be 98.4%, indicating that little protein denaturation occurs in the PC drying process. This can be explained by a short residence time of the egg white in the PC dryer due to its high drying rate. Because of the short residence time (sometimes lees than 1s, see the reference (Swientek, 1989)), the egg white temperature hasn't even risen to the protein denaturation temperature at the end of drying and this can be verified by the gas temperature of 76.6 ^{O}C at the drying chamber outlet shown in Table 1. Also in the short residence time, the egg white protein done not have enough time to denature completely.

3.2.5 Foaming and gelling properties

Egg white powders are a desirable ingredient for many foods such as bakery products, meringues and meat products, because of its excellent foaming and gelling properties. Tables 3-4 show the measured foaming and gelling properties of the PCSD, Kangde ™ SD and LHAD egg white powders. In Table 3, it can be seen that the Kangde ™ SD powders had the best foaming ability of 37.73±0.8% and foam stability of 96.46±1.0%. The LHAD sample had a similar foaming ability but its foam stability was low (79.56±10.5%). The PCSD powders had a good foam stability but a low foaming ability (26.27±3.2%). In Table 4, the LHAD sample has the best gelling properties with a hardness of 1080.4±135.8 g. Compared with the LHAD sample, there is a slight reduction of 11.3% for the PCSD powder but a drastic reduction of 55% in hardness for the Kangde ™ SD powders. From Table 4, it can be concluded that PCSD techniques had a better performance in maintaining the gelling properties than traditional SD operations.

Generally, the spray drying process definitely causes a harmful effect of the foaming and gelling properties of the egg white (Mine, 1995; Mine, 1996; Lechevalier et al 2007). This can be verified by the reduced foaming ability of the PCSD powders and the decreased gel hardness of the Kangde™ SD powders compared with the LHAD sample. Heating of egg white powders at 75-80 ^{O}C for 10-15 days is widely used in industry to offset the property losses resulting from the spray-drying process: both gelling and foaming properties (Kato et al, 2002; Tanlansier et al, 2009). The foaming ability of the PCSD powders may be improved further by such dry-heating treatment or addition of food agents which have a strong foaming ability, such as sodium lauryl sulfate .

Table 3

Table 4

4 CONCLUSIONS

In this paper, the PC spray drying of egg white was conducted and selected product properties of the PCSD powders has been measured and compared with the SD powders. Compared with traditional SD techniques, the following conclusions can be drawn for the PCSD techniques.

(1) PCSD technique had a high dryer energy efficiency. In this work, the energy consumption of 2604 kJ/kg water evaporated was achieved for PCSD drying of the egg white.

(2) PCSD technique produced powders with superior surface characteristics, smaller mean particle diameter and more homogeneous size distribution. In this work, the PCSD powders had a uniform sphere shape and smooth surface, a D50 diameter of 20.15 μm and RSF parameter of 2.71. By contrast, the SD powders had a coarse surface, a D50 diameter of 54.74 μm and RSF parameter of 3.42.

(3) The protein denaturation was minor in PCSD drying of egg white even when a hot drying temperature of 326.6 ^{O}C was used.

(4) PCSD technique maintained a good gelling property of the egg white powders.

The experimental results showed PCSD techniques are superior in both energy efficiency and product quality than traditional SD techniques. Thus, there is a promising application potential in drying of egg white. With more pilot tests, PCSD may be widely applied in drying of heat-sensitive food and bio-materials

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Feed rate of the liquid egg white	0.6 kg/min
Initial moisture content	86.96%
Heat release of PC combustor	24.32 kw
Gas temperature at the feeding point	326.6
Gas temperature at the drying chamber outlet	76.6
Ambient air temperature	25.0
Running time	28 min
Dry solids fed during run	2.19 kg
Powders from cyclone	1.32 kg (60.28%)
Powders from chamber wall blowdown	0.29 kg (13.24%)
Powders from chamber wall brushdown	-
Powder from baghouse	-
Total yield	73.52 %
Final moisture content of powders	8.11%
Water evaporation rate	33.62 kg water /hr
Volume evaporation rate	8.41 kg water /hr
Energy consumption	2604 kJ/kg water evaporated

Table 1 Operation data for the PC spray drying process of the egg white

Items	Maximum	minimum	Mean	Standard Deviation	Range
PCSD powders					
L	79.90	79.86	79.88	0.02	0.04
a	-4.98	-4.94	-4.96	0.02	0.04
b	8.62	8.60	8.61	0.01	0.02
SD powders					
L	77.92	77.91	77.91	0.01	0.01
a	-6.23	-6.20	-6.21	0.01	0.03
b	10.42	10.31	10.35	0.05	0.11

Table 2 Statistics of the color parameters for PCSD and Kangde ™ SD egg white powders

Items	Maximum	minimum	Mean	Standard Deviation	Range
Foaming ability (%)					
PCSD	28.0	24.8	26.3	1.3	3.2
SD	38.0	37.2	37.7	0.4	0.8
LHAD	38.0	32.0	36.0	2.8	6
Foam stability (%)					
PCSD	96.9	88.7	92.8	3.4	8.2
SD	96.8	95.8	96.5	0.5	1
LHAD	84.2	73.7	79.7	4.4	10.5

Table 3 Statistics of the foaming properties for PCSD, Kangde ™ SD egg white powders and LHAD sample

Items	Maximum	minimum	Mean	Standard Deviation	Range
Hardness (g)					
PCSD	1082.3	900.0	957.6	88.3	182.3
SD	520.7	450.6	486.5	28.7	70.1
LHAD	1120.4	984.6	1080.4	68.1	135.8
Springiness (%)					
PCSD	96.1	91.5	94.1	1.9	4.6
SD	90.3	83.7	85.1	3.8	6.6
LHAD	92.4	82.8	88.3	4.1	9.6

Table 4 Statistics of the gelling properties for PCSD, Kangde ™ SD egg white powders and LHAD sample

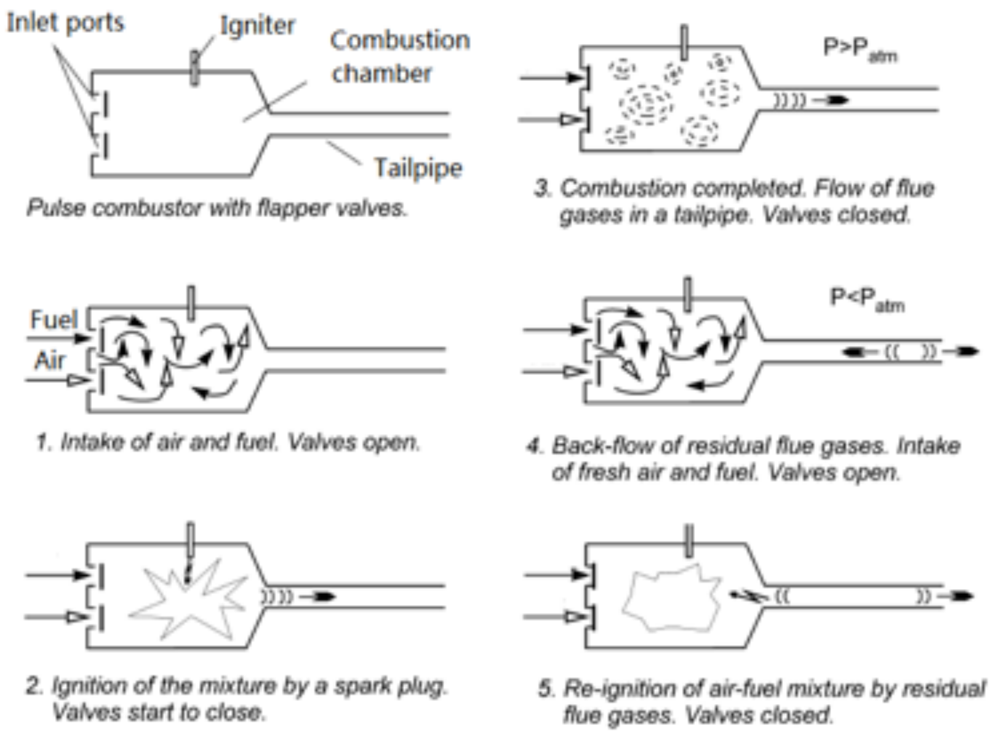


Figure 1 The operation principle of a Helmholtz type pulse combustor with flapper valves

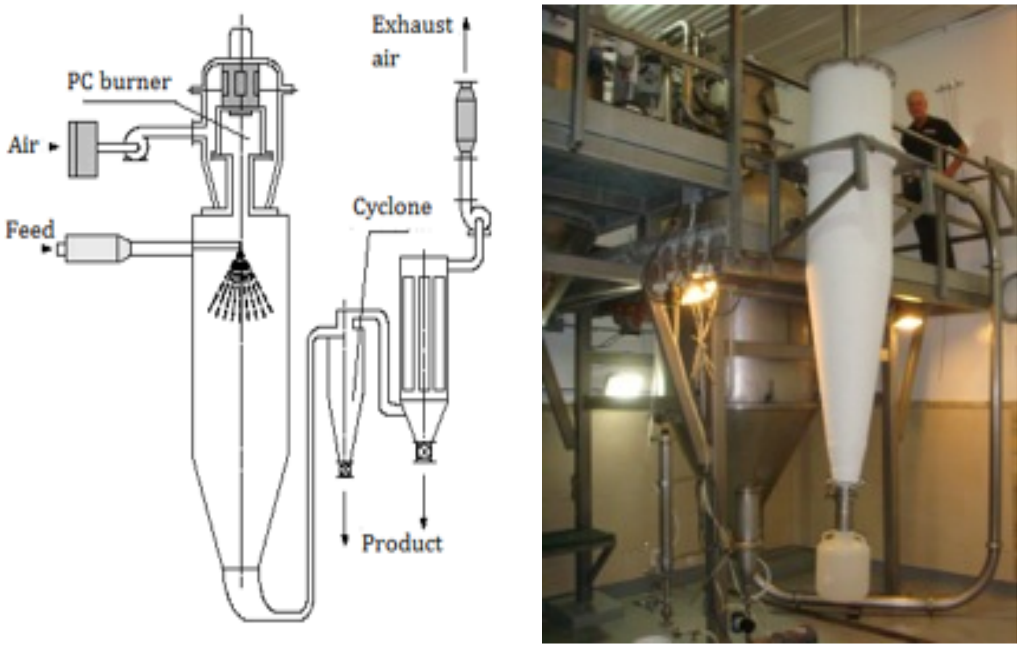


Figure 2 The pilot PC spray dryer (left: flowchart; right: Photo of experimental setup)

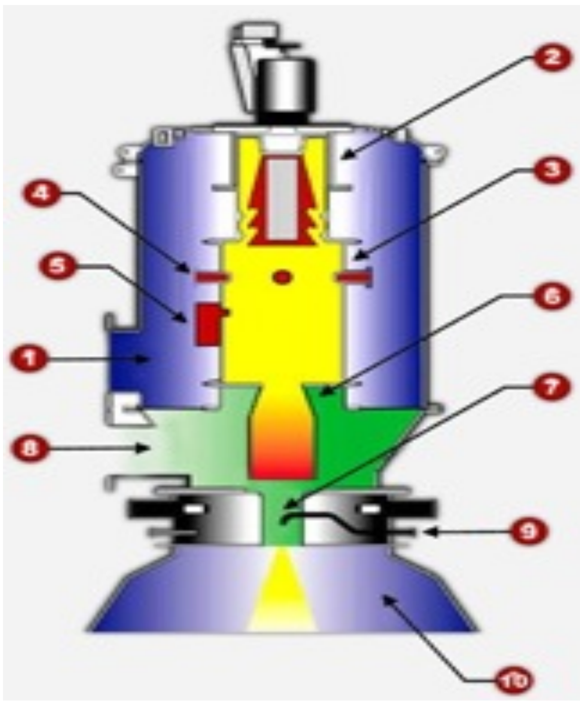


Figure 3 Schematics of PC liquid atomizer
((1: Air; 2: unidirectional air valve; 3: Combustion chamber; 4, Fuel; 5, Pilot; 6, Tailpipe; 7, Atomizer; 8, Quench air; 9, Liquid; 10, Drying chamber)

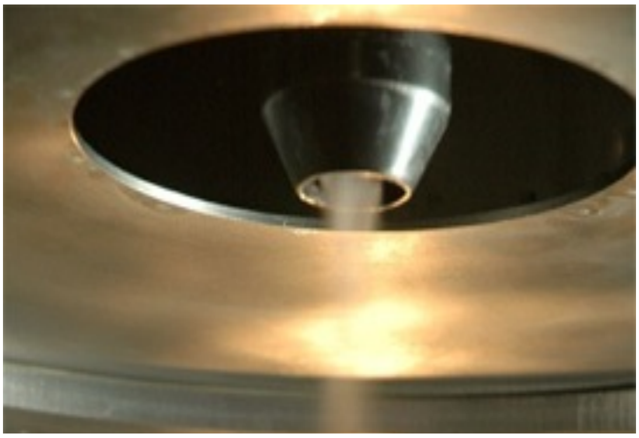


Figure 4 Snapshot of liquid atomization process by PC exhaust gas

(a) PCSD powders

(b) Kangde ™ SD powders

Figure 5 PC spray dried (a) and traditional spray dried (b) egg white powders

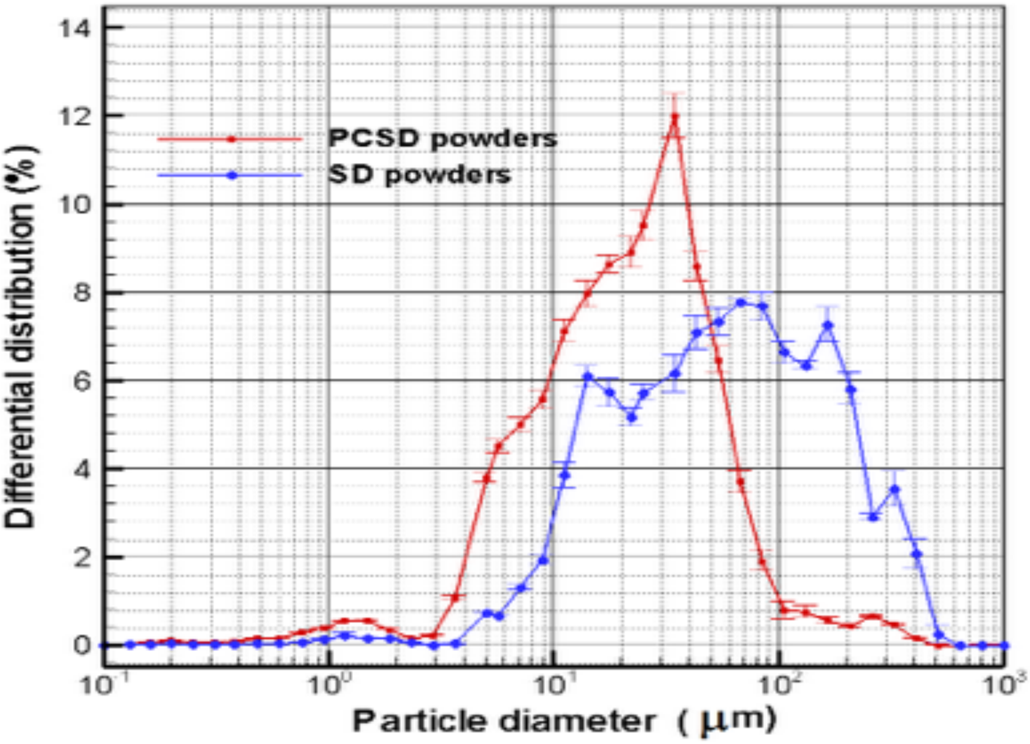
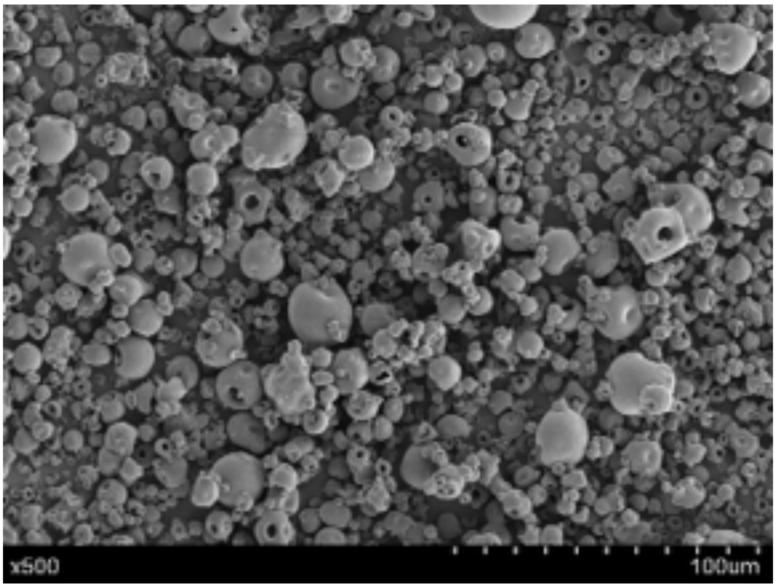
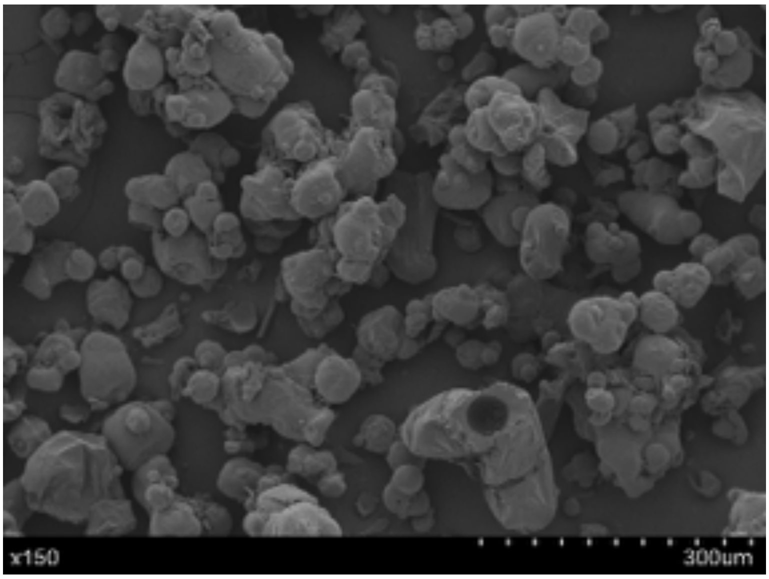


Figure 6 The size distributions of PCSD and Kangde ™ SD egg white powders



(a) PCSD powders



(b) Kangde ™ SD powders

Figure 7 SEM images of PCSD and Kangde ™ SD egg white powders

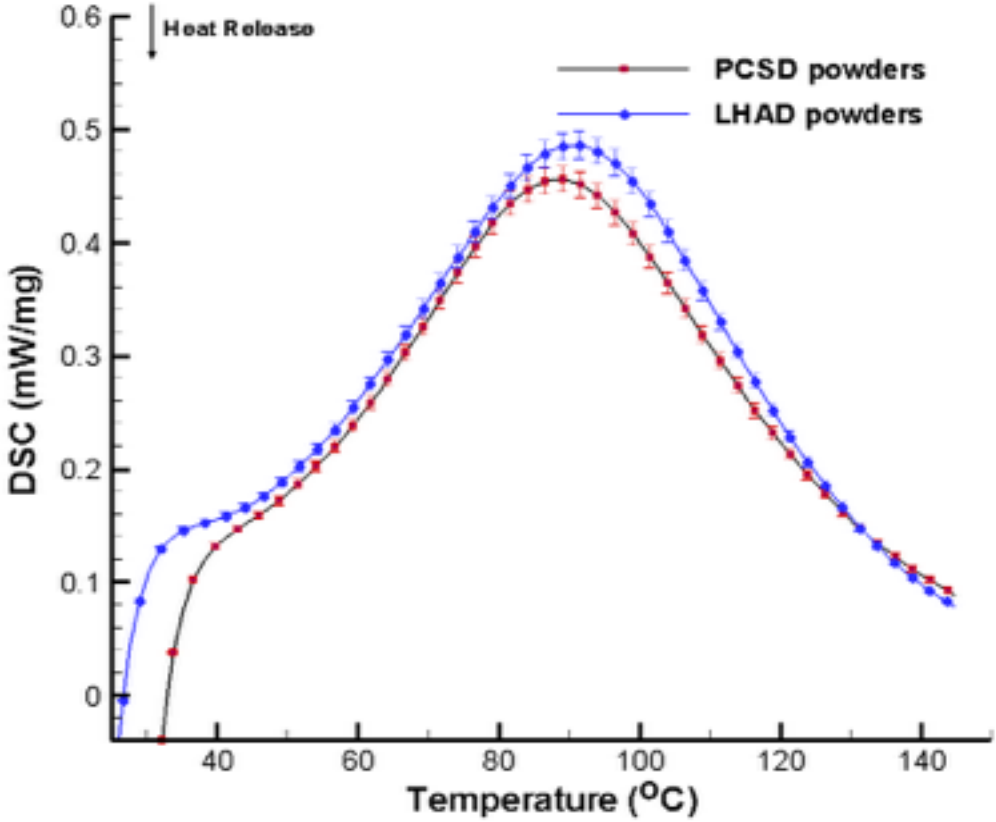


Figure 8 The DSC curves for the PCSD powders and LHAD sample