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Review

Spray drying: An overview on wall deposition, process and modeling

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ABSTRACT

The spray drying process is considered a conventional method to convert liquids to powders with some but at an acceptable level of degradation and oxidation of volatile compounds. Spray drying is based on the preparation, homogenization, atomization, dispersion and subsequently dehydration of the solution. Wall deposition is a key processing problem in the spray dryer particles that indirectly affects the quality and quantity of the product. The degree of wall deposition is affected by several factors including operating parameters, type and size of spray dryer and the spray dryer wall properties. The development of wall depositions in the spray dryer deteriorates the yield of the products and hence increases the costs of manufacturing and maintenance. And constructive models are very resourceful in understanding the mechanism of wall deposition which will result in direct economic benefits to the food industry. The aim of this review is to give a physical and chemical description of the wall deposition mechanism and introduce the classified models to simulate and visualize this behavior in spray dryers.

Contents

1. Introduction

Spray drying is a process that transforms feedstock from a fluid state to a dried particle form by spraying the feed into a hot drying medium (Masters, 1994). The feeding can either be in solution, suspension, emulsion or paste form. The properties of the dried product depend on the physical and chemical properties of the feed and the dryer design, and the operation. The industrial application of the spray drying technique in the milk and detergent industries began in the 1920s. However, Samuel Percy (Percy, 1872) was the first person who patented it entitled "Improvements in drying and concentrating liquid substances by atomizing" (Masters, 1994). Nowadays, the application of the spray drying technique has been expanded to various types of food production such as egg products, beverages, vegetable proteins, fruit and vegetable extract, carbohydrates, tea extracts, yogurt and many other products in powder

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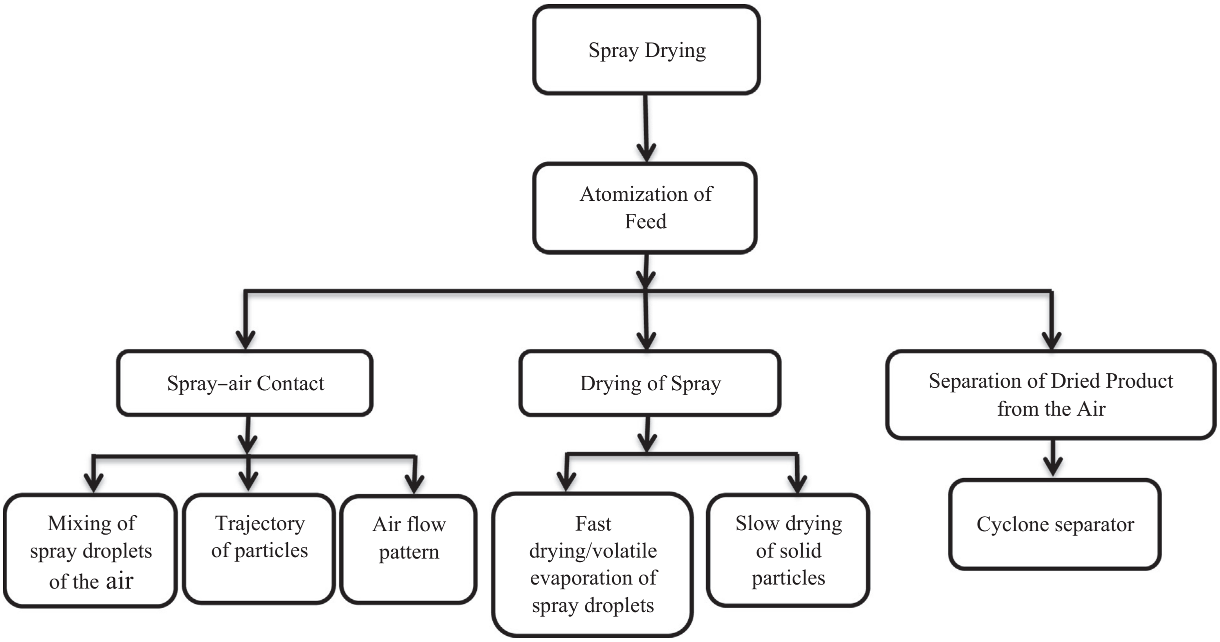

Fig. 1. Schematic diagrams of spray drying process.

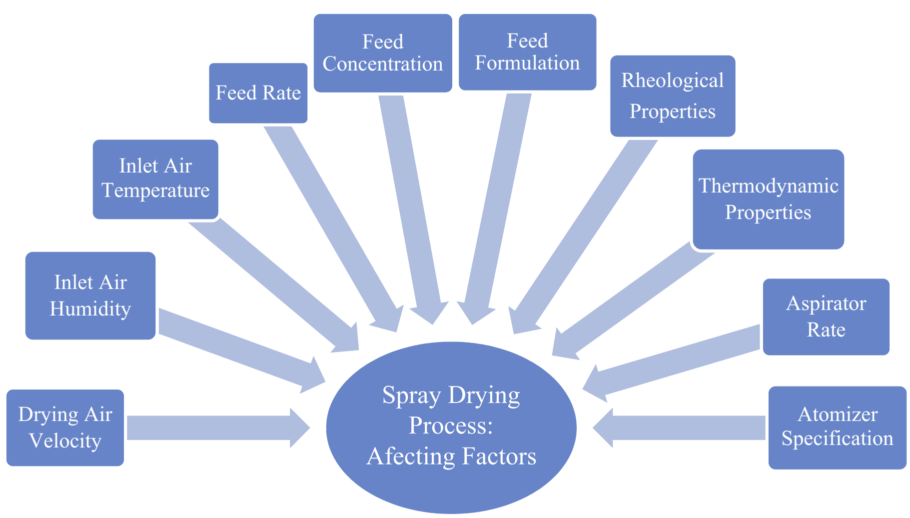

Fig. 2. Schematic diagrams of affecting factor on spray drying process.

form. Some of the previous works on spray drying and the additives used (carriers) are tabulated in Table 1.

The benefits of the spray drying technique include the ability to produce powders of a specific particle size and moisture content, irrespective of the dryer capacity. It is a continuous and easy operation which is fully automatically controlled with a quick response time, and is also applicable to both heat sensitive and heat-resistant materials. Essentially, the spray drying process is a continuous drying operation which combines several stages in the process as presented in Fig. 1 (Masters, 1994):

Each stage is carried out according to the dryer design and operation setting, which determine the characteristics of the dried products. The atomizing stage must create a spray for optimum evaporation conditions in order to achieve an economic production of the desired products (Masters, 1994). Spray-air contact is determined by the position of the atomizer in relation to the drying air inlet. In a co-current flow design, spray evaporation is rapid and as the drying air cools, accordingly the evaporation time is shortened. The product is not subject to heat degradation. When the spray comes into contact with the drying air, evaporation takes place in the droplets until the moisture content becomes too low to diffuse through the dried droplet surface. Finally, the recovery of dried powder is carried out either in the cyclone, filter bag or electrostatic precipitator (Keshani, 2013).

The spray drying process is mainly affected by several parameters as presented in Fig. 2. Since spray drying is usually the end-point of a process that also influences the quality of the final product, it has attracted more attention over the last two decades. A key processing problem in spray dryers is the wall deposition of particles that indirectly affects the quality of the product through the degradation of the deposited particles and the resulting pollution of the main product. Its understanding provides guidance in the selection of the operating conditions of the spray dryers that

Table 1
Selected previous researches carried out on spray drying process.

Raw material	Carriers/wall materials	Type of spray dryer	Inlet/outlet temperature	References
Acai (*EuterpeoleraceaeMart*)	Maltodextrin	Mini spray dryer	138–202 °C/82–114 °C	Tonon et al. (2008)
Lemon myrtle oil	Modified starch + maltodextrin, whey protein + maltodextrin	Pilot spray dryer	180 °C/60–70 °C	Huynh et al. (2008)
Mandarin oil	Gum arabic, 20 DE maltodextrin		160–200 °C/80–100 °C	Bringas-Lantigua et al. (2011)
Red-freshed pitaya (*Hylocereuspolyrhizus*) Seed Oil	Sodium caseinate, whey protein, gum arabic	Mini spray dryer	150 °C/77 °C	Lim et al. (2012)
Mountain tea (*Sideritisstricta*)	β-Cyclodextrin, maltodextrins, gum arabic	Mini spray dryer	145–165 °C/75 °C	Nadeem et al. (2011)
Lactose	Maltodextrin	Pilot scale co-current spray dryer	140–180 °C/95 °C	Keshani et al. (2012)
Sugars (sucrose, glucose, fructose) and citric acid	Maltodextrin	Anhydro lab scale spray dryer	150 °C/65 °C	Bhandari et al. (1997)
Raisin juice	Maltodextrin	Bench –top lab scale spray dryer	110 °C/77 °C	Papadakis et al. (2006)
Sucrose	Maltodextrin	-cylinder- on- cone spray dryer	120–190 °C/95–97.5 °C	Woo et al. (2007a)
Honey	Maltodextrin/whey protein isolate	Mini spray dryer	150 °C/85 °C	Shi et al. (2013)

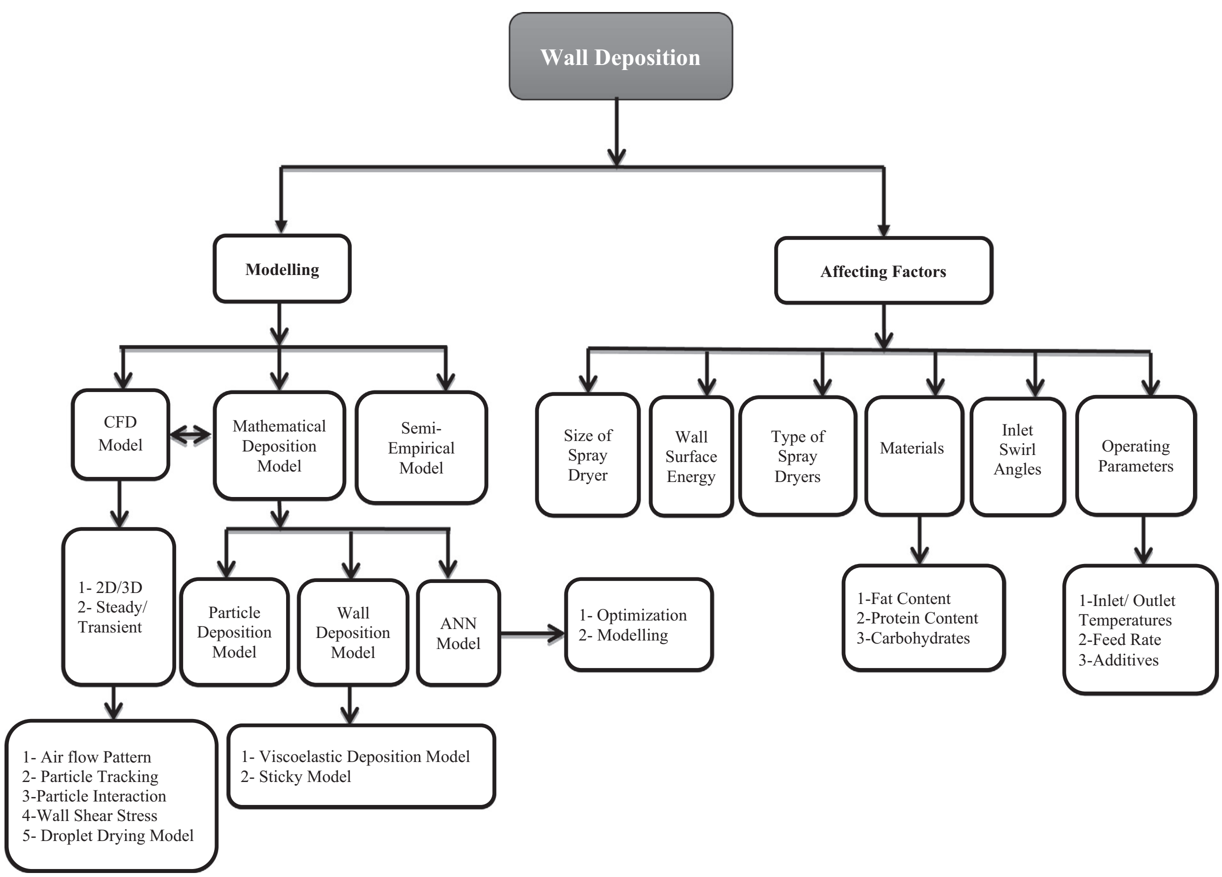

Fig. 3. Schematic diagrams of wall deposition area on spray dryer.

will minimize wall deposition and hence help to improve the quality of the product. A schematic diagram of the works done on the wall deposition in a spray dryer is presented in Fig. 3. Currently, the main challenges in the production of powders in spray dryers are the development of the desired powder properties and the costs. It is therefore important to identify the optimum operating criteria and processing conditions to ensure the preservation or enhancement of the quality of the dried products during the spray drying processes.

2. Particle wall deposition

The main thrust of recent works is to understand the mechanism of particle deposition on the surfaces of the inner walls of the spray dryer. Large drying chambers reduce wall deposition by setting the walls out of the range of most particle trajectories (Masters, 1994; Oakley, 1994). A brief description of the advantages and disadvantages of wall deposition are provided in Table 2. The affecting factors on wall deposition are as shown in Table 3.

Table 2
Advantages and disadvantages of wall deposition.

Advantages of wall deposition	Disadvantages of wall deposition
Product quality • Sufficient moisture evaporation • Using drying agents for improving powder hygroscopicity • Decrease stickness temperature	• Variable quality, influence of room temperature • Lead to a buildup of large amounts of product on the dryer
Desired powder properties • Small particle size • Low bulk density	• Occurred at high temperature because temperature of deposition particle is above *Tg* and sticky point temperature
Preservation • Enhancement of quality of dried product	• Affected on internal gas flow patterns
Low cost	• Stop dryer and removal of wall deposition
Safety fire hazard	• Spray drying is not operated properly • Dangerous when wall deposition feels cause damage to containers

The properties of the wall of the dryer in which deposition occurs also play a significant role in the mechanism of product deposition. It is well known that the adhesion of liquids onto walls depends on the wall properties (Bhandari and Howes, 2005). Recent experimental works by Kota and Langrish (2006), showed that nylon exhibited a lesser deposition rate due to the non-sticky nature of the nylon compared to stainless steel. They showed that less stickiness may lead to more bouncing or sliding on the nylon and therefore appeared less adhesive compared with the stainless steel. Further work by Woo et al. (2009a,b) showed that different wall materials affect the deposition rate of rubbery particles significantly. A Teflon surface with less surface energy has a less deposition flux compared to a stainless steel surface that has a higher surface energy. A higher wall temperature also increases the deposition flux (Woo et al., 2007b). Adhikari and co-workers (2007) showed that Teflon is generally less "sticky" when compared to stainless steel (S-S) by using an *in-situ* tack method for relatively large droplets.

One of the factors that influence the quality of the product and wall deposition is the chamber geometries or spray dryer types. The chamber geometry directly changes the air flow pattern and consequently influences the behavior and flow pattern of the particle within the dryer (Huang et al., 2003b). Several researchers have studied other possible chamber geometries such as pure conical, lantern and hour-glass geometry (Huang et al., 2003a,b), horizontal configuration (Huang and Mujumdar, 2006) and parabolic geometry(Keshani et al., 2014), as the spray drying chamber. It should be noted that not only the cylinder geometry but the duration of the particle residence in the drying chamber as well as overall chamber volume can impact drying performance. A work by Huang and Mujumdar incorporated a horizontal spray dryer to study wall depositions. They reported that the deposit on the bottom part of spray dryer is significant even in the presence of the fluid bed. This is due to the air flow that passes at low velocity through the small opening.

Swirling flow patterns in a spray dryer can be typically classified into two types: inlet vane (or direction) induced swirls and atomizer-induced swirls. Many experimental measurements and observations have been undertaken for inlet-induced swirls. This is coupled with detailed numerical studies which highlighted the unsteady and oscillatory behavior of such flows (Langrish et al., 2004; Lebarbier et al., 2001). A work by Langrish et al. (2004) studied the effects of change in flow features that was observed at three inlet swirl angles of no swirl, 15° and 25°. A high inlet swirl angle would occur due to this flow behavior, but as seen in the velocity contour map, the chances of wall deposition are greater here than with no swirls, due to the larger velocities at the walls. Previous experimental data (Ozmen and Langrish, 2003; Southwell and Langrish, 2001) indicated that the wall deposition was minimized for no swirl, but that evaporation was still adequate.

Several authors have attributed product deposition in spray dryers to product stickiness. Particles deposit on the wall by sticking to it, which is due to the sticky particle which occurs above the glass transition temperature, *Tg* (Roos, 2009; Shrestha et al., 2008). Spray drying produces dry amorphous powders that are thermoplastic due to heating or exposure to high humidity, resulting in water sorption and thermal plasticization of the particle surfaces (Roos and Karel, 1991). At temperatures above *Tg*, amorphous structures are in a rubbery state where the polymer molecules become softer and more flexible because of greater molecular mobility. The temperature of the surface of the product such as amorphous sugar should not reach more than 10–20 °C above *Tg* during spray drying to avoid substantial product stickiness, especially in low molecular weight carbohydrates (Aguilera and Lillford, 2007; Bhandari et al., 1997; Roos and Karel, 1991; Woo et al., 2009a). This is due to the greater molecular mobility of the amorphous components in a highly viscous flow between the particle surfaces, making the powder more cohesive (Aguilera and Lillford, 2007). At temperatures below *Tg*, the amorphous parts of the materials are in a glassy state where the polymer molecules have no segmental motion but vibrate slightly (Brennan et al., 1971). Ozmen and Langrish (2003) observed that when the wall deposition temperature is below the sticky point temperature, there is less wall deposition. When the feed flow rate increases, larger droplets are formed and the evaporation rate is lower. This is caused by the larger amounts of water introduced into the dryer. Moreover, increasing the feed flow rate results in higher residual moisture content. There was a corresponding visual increase in deposits on the wall of the drying chamber. The deposition in this case is high because of the higher feed flow rate. Ozmen and Langrish (2003) observed that the rate of adhesion of milk powder to the walls was different from the rate of cohesion of milk particles to other particles on the walls. This means that the rate of adhesion of the first layer was different compared to that of other layers when particles cohere to the adhered particles. Chegini and Ghobadian reported that at a constant air inlet temperature, increasing the feed flow rate increased the wall deposition (Chegini and Ghobadian, 2007). When more feed was atomized into the chamber, the residence time of the particles was shorter and the drying time was reduced, resulting in wetter particles. In this condition, the particles were more cohesive which caused the deposition rate to increase and the yield to decrease. The work by Keshani et al. (2012) reported that the effect of additive as a drying aid is more significant in reducing the deposition fluxes. The additives added to the sugar-rich feed, increased its molecular weight and hence its glass transition temperature *Tg*, which consequently reduced the particle stickiness and wall deposition in the spray drying (Adhikari et al., 2004; Roos and Karel, 1991). The work by Adhikari et al. (2009a,b) studied on application of proteins (WPI and sodium caseinate) on minimizing the stickiness of sugar-rich

Table 3
Affecting factors on wall deposition.

	Factors		Advantages/disadvantages	References
Process based factors	Wall properties material (wall surface energy)	S-S	• Low cost • High wall deposition	Bhandari and Howes (2005), Keshani et al. (2012), Woo et al. (2009a,b)
		Teflon	• Low wall deposition • High cost	Keshani et al. (2013), Woo et al. (2009a,b)
		Nylon	• Less wall deposition	Kota and Langrish (2006)
	Spray dryer types	Conical	• High wall deposition	Keshani et al. (2012, 2013)
		Parabolic	• Less wall deposition	Keshani et al. (2014)
		Horizontal	• Flow pattern is not optimal for spray drying since the main air inlet is located at a corner of the chamber	Cakaloz et al. (1997), Huang and Mujumdar (2006)
	Inlet swirl angles	No swirl	• Less deposition	Langrish et al. (2004), Ozmen and Langrish (2003), Southwell and Langrish (2001)
		High swirl	• High wall deposition	Huang and Mujumdar (2006) [20]
	Operating parameters	Inlet temperature	• Low product moisture • High wall deposition • Less deposition below sticky point temperature	Keshani et al. (2012), Woo et al. (2007a, 2010c))
		Feed rate	• Low evaporation rate • Reduce during time • Short residence Time • Rubbery wall deposition • Dripping wall deposition • Product moisture high • High wall deposition • Less yield	Chegini and Ghobadian (2007), Jumah et al. (2000), Keshani et al. (2012), Masters (1994)
Material based factors	Material	Additive	• Reduce deposition rate • Increase moisture content • Increase molecular weight • Increase *Tg* • Reduce thermoplasticity/ hygroscopicity • Segregate the droplets during spray drying and form a skin	Adhikari et al. (2004), Bhandari et al. (1997), Brennan et al. (1971), Goula and Adamopoulos (2010), Keshani et al. (2012), Kim et al. (2003), Meerdink and van't Riet (1995), Papadakis et al. (2006), Roos (2009), Roos and Karel (1991), Roustapour et al. (2006), Wang and Langrish (2009)
		Fat content	• Relatively high wall deposition	Keshani et al. (2013) Paterson et al. (2007)
		Protein content	• Less wall deposition	Keshani et al. (2013), Kota and Langrish (2006), Langrish et al. (2007)
		Carbohydrate content	• High deposition	Keshani et al. (2012)

foods using surface active proteins and the effect of a small amount of low molecular surfactants (LMS) in preventing the surface migration of proteins (and producing non-sticky film). They found that in the absence of LMS, the proteins increased the powder recovery due to the formation of a glassy protein-rich film and the reduction of surface stickiness of sucrose droplets. However, in the presence of LMS recovery, dropped significantly. Jayasundera et al. (2010) investigated the effect of low-molecular-weight surfactants and sodium caseinate on spray drying of sugar-rich foods. Later on, Jayasundera et al. (2011a,b) studied the effect of protein types and low molecular weight surfactants on spray drying of sugar-rich foods using sucrose as a model sugar and sodium caseinate and pea protein isolate (PPI) as model proteins. They reported that the amount of protein required for successful spray drying of sucrose–protein solutions depends on the amount of proteins present on the droplet surface but not on the bulk concentration. Stickiness is also due to the hygroscopicity of non-crystalline sugars (Roos, 2009) and their thermoplasticity (Brennan et al., 1971). Maltodextrin as a drying aid is added to produce a powder product by reducing the thermoplasticity and hygroscopicity as well as the stickiness and product deposition. The particle stickiness on the wall is due to the molecular mobility of the amorphous powders as a highly viscous surface layer that produced more powders that are cohesive. Several researchers (Bhandari et al., 1997; Kim et al., 2003; Meerdink and van't Riet, 1995; Wang and Langrish, 2009) have observed that there is strong evidence that additives segregate to the surface of the droplets during spray drying and form a skin with a higher *Tg* around the droplets. Kieviet noted that wall deposition affected the residence time distribution of the particles, and particularly that an important factor in determining residence times with high wall deposition rates was the time taken by the particles to slide down the conical wall of a spray dryer(Kieviet et al., 1997). The sticking of particles to the walls and to each other, and the sliding of wall deposits are therefore important issues.

The presence of lactose and protein on the surface could have made the particle surface more rigid due to the high glass transition point (Woo et al., 2008). On the other hand, another possibility is that the presence of lactose and protein could have made the particle surface more hydrophilic. The work by Keshani et al. reported that the presence of a high proportion of protein on the surface, however, led to significant reduction in the adhesion rate at the cone of the spray dryer (Keshani et al., 2013). Although a higher proportion of fat is expected on the surface of whey protein, the protein is dominant in making the surface hydrophobic. A similar trend observed for full cream milk particle is more distinct than for whey protein particle. Whey protein powder was shown to be very hydrophobic when compared with skim milk which also contains some proportion of protein (which could contain both whey and casein) on the surface; resisting wetting by water (Gaiani et al., 2009; Kim et al., 2002). In whey protein particles, the deposition reduction is more significant in the adhesion rate at the bottom plate. The whey protein particles exhibited a sudden decrease in cohesion rate when compared to the initial adhesion rate. The effect of fat content on wall deposition and caking properties of powder and its mechanism is different from

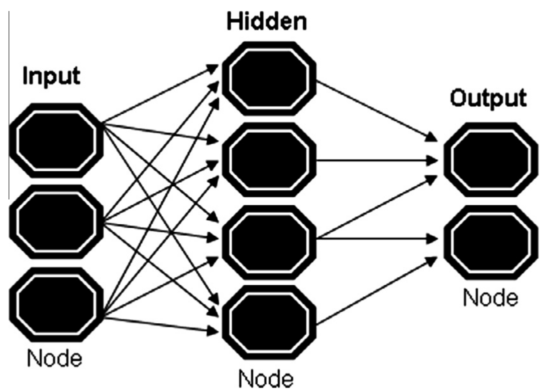

Fig. 4. Schematic representation of a multilayer perceptron feed-forward network.

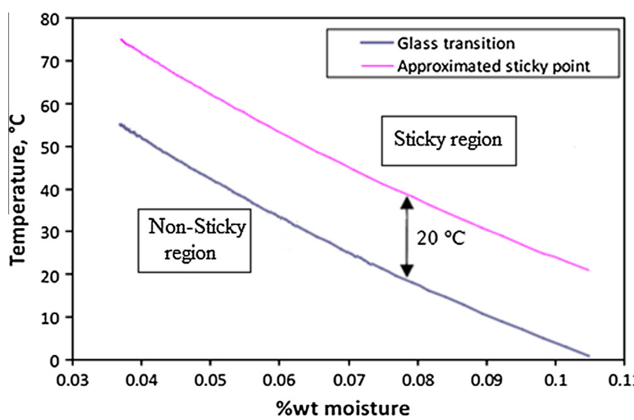

Fig. 5. Typical glass transition and approximated sticky point curve for lactose (Woo et al. 2010a).

carbohydrates (Foster et al., 2005; Paterson et al., 2007). The usage of a lower chamber wall surface energy reduces the adhesion rate of the particles. This reduction is more significant for the more hydrophobic whey particles compared to the fat containing particle surfaces.

Many researchers have found that some deposition flux curves closely resemble linear lines rather than significantly curved nonlinear lines (Keshani et al., 2012; Kota and Langrish, 2006; Woo et al., 2007a). They attributed this behavior to the small differences between the adhesion and cohesion rates of the particles. It is also well known in the mechanism of product deposition that the adhesion of liquids onto walls depends on properties of the dryer walls (Bhandari and Howes, 2005). Accordingly, Ozmen and Langrish (2003) observed that the rate of adhesion of milk powder to the walls was different from the cohesion of milk particles to other particles on the walls. This means that the rate of adhesion of the first layer might be different compared to that of other layers when particles cohere to the adhered particles.

3. Modeling

Artificial neural network (ANN) is a valuable instrument in the design and optimization of processes. A properly trained ANN links input and output parameters without the need for fundamental models. ANN does not require prior knowledge about the structure and relation-ships that exist between variables and this is useful in where the complexity of the mechanisms is high. But unlike the fundamental models it is lack of physical concept. Computational fluid dynamics (CFD), is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows.

3.1. Application of artificial neural networks (ANN) in spray drying process

Artificial neural network (ANN) is a mathematical or computational model that simulates the biology of the human brain. The ANN predicts values of unmeasured goal parameters using the correlation between measured parameters and the target parameters. The ANN models have been successfully used in the prediction of problems in bio-processing and chemical engineering (Movagharnejad and Nikzad, 2007; Nourouzi et al., 2012).

A typical ANN system has three layers of neurons: input layer, one hidden layer and an output layer. Each layer has its corresponding units (neurons or nodes) and weighted connections. The connections can be feed-forward or feedback. Each unit receives the sum of its weighted inputs and passes the results through a nonlinear activation function (transfer function) such as the sigmoid (logistic) function. The activation function acts on the weighted sum of the unit's inputs. The outputs feed through the network to optimize the weights between the units. The optimum point is found by minimizing the error during the training or learning phase where the learning of the mathematical relationship between input variables and corresponding outputs occurs. The ANN changes the value of the weighted links to reduce the difference between the predicted and target (observed) values. This process is repeated across many training cycles (iteration or epoch) until a specified level of accuracy is obtained. The scheme of feed-forward multilayer perceptron network is shown in Fig. 4 (Rosenblatt, 1958).

In the field of drying, the ANN is a better alternative to conventional empirical and semi-empirical modeling based on polynomial and linear regressions especially for problems involving many parameters such as spray drying. The ANN models have been developed and tested for the drying of various materials. Hussain and Rahman developed a model consisting of a hybrid ANN that included a polynomial regression model and a standard ANN for the prediction of porosity in eleven types of fruits and vegetables during drying (Hussain et al., 2002). Other researchers developed ANN models for the modeling of drying of potato slices (Islam et al., 2003); ginseng (Martynenko and Yang, 2006), carrots (Cubillos and Reyes, 2003), tomatoes (Movagharnejad and Nikzad, 2007), grains (Farkas et al., 2000); *Echinacea angustifolia* (Erenturk et al., 2004) and apples (freeze drying) (Menlik et al., 2010). The ANN has been used in the prediction of thermal properties such as the thermal conductivity of food as a function of temperature, moisture content and apparent porosity (Sablani and Rahman, 2003), heat and mass transfer coefficients of cassava and mango (Hernández-Pérez et al., 2004), and the physical property changes of dried carrots as a function of fractal dimension and moisture content (Kerdpiboon et al., 2006). ANN are also effective for optimization, modeling, and process control (Erenturk and Erenturk, 2007; Koc et al., 2007; Zhang et al., 2002). Keshani and team carried out a work on the optimization and modeling of lactose powder wall deposition rate in spray dryers (Keshani et al., 2012). The ANN is able to predict the optimal parameters of rough rice drying (Zhang et al., 2002) and the process and quality parameters of spray-dried orange and pomegranate juice (Chegini et al., 2008; Youssefi et al., 2009).

3.2. Mathematical deposition model

The mathematical model of particle deposition is an important step in developing and validating spray drying. Wall particle depositions can recycle into the chamber, making the deposition

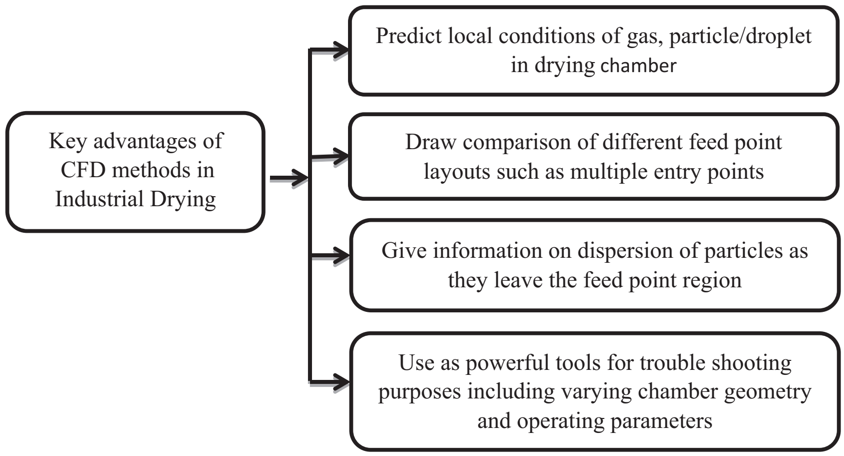

Fig. 6. Schematic diagrams of key advantages of CFD methods.

Table 4
CFD modeling of a spray dryer.

No.	Dimension	Code	Objects	References
1	2D/3D	FLUENT	2D model is suitable for fast and low-resource consumption; numerical calculations with reasonable accuracy	Mezhericher et al. (2009)
2	3D	FLUENT	3D CFD models are presented in terms of the velocity magnitudes, velocity components, temperature profiles and particle trajectories with rotating disc spray dryers	Huang et al. (2004a)
3	2D	FLUENT	The transient simulations with droplet–droplet interactions showed that insulation of the spray dryer substantially affects the patterns of temperature and vapor mass fraction, whereas the influence on velocity flow fields is less considerable	Mezhericher et al. (2008)
4	2D	FLUENT	REA model was applied in a CFD simulation of an industrial scale dryer providing quite good prediction on the outlet particle moisture	Jin and Chen (2009a)
5	3D	FLUENT	Gas/particle interaction plays an important role in modern spray dryers and may have influences on wall deposition, agglomeration and powder degradation. The gas/particle interactions in this large dryer are studied using numerical results	Jin and Chen (2009b)
6	3D	FLUENT	A new deposition model is developed and implemented in the CFD software	Jin and Chen (2010)
7	3D	STAR-CD	Drying model is incorporated into the CFD calculations	Lo (2005)
8	3D	FLUENT	The effect of chamber diameter and operating conditions on flow stability without the inclusion of droplet injection are investigated	Woo et al. (2009b)
9	3D	FLUENT	A new empirical drying model is developed in CFD simulations	Ullum et al. (2010)
10	2D/3D	FLUENT	CFD simulations performed for a continuous phase to predict the hydrodynamics of drying air, flow path and velocity vectors	Wawrzyniak et al. (2012)
11	2D	-	The developed drying model, DrySim is very suitable to make low cost calculations for the food industry	Straatsma et al. (1999)
12	3D	FLUENT	A CFD model is used to simulate momentum, heat and mass transfers between the discrete phase of droplets and the continuous gas phase	Huang et al. (2005))
13	3D	FLUENT	A CFD simulation is carried out to compare the gas flow and temperature patterns as well as particle trajectories in different chamber geometries	Huang et al. (2003b)
14	3D	FLUENT	Simulation of the temperature and moisture content of a single milk particle as a function of its residence time in the spray drier and the drying mechanism	Birchal et al. (2006)
15	2D	FLOW3D	CFD simulations of gas turbulence and validation results	Oakley (1994)
16	3D	CFX5	CFD simulation of the effects on inlet swirl on gas flow patterns	Langrish et al. (2004)
17	3D	CFX4.3	A CFD simulation is performed with a tall form spray dryer to examine the characteristics of the flows that exist within these complex devices	Harvie et al. (2002)
18	3D	CFX4.3	A numerical investigation of the gas flow patterns existing inside a pilot-scale tall-form counter current dryer is made	Harvie et al. (2001)
19	2D	FLUENT	CFD simulation is carried out for predicting the gas flow pattern, gas temperature and humidity distribution, and heat and mass transfer characteristics of a pulsating flow spray-drying chamber	Wu and Mujumdar (2006)
20	2D	FLUENT	A CFD simulation is carried out to investigate airflow pattern, temperature and humidity profile at different levels in the drying chamber	Huang et al. (2003a)
21	2D	FLUENT	CFD simulation of the effects of low humidity and temperature on the gas flow patterns, droplet trajectories and overall dryer performance	Huang and Mujumdar (2007a)
22	3D	FLUENT	A CFD model is carried out to predict the gas flow field, gas temperature, gas water content, particle paths and evaporation from wet particles	Ullum (2006)
23	3D	FLUENT	CFD study is carried out to investigate the possibility of multi-functional applications for a specific spray dryer chamber	Huang et al. (2006)
24	2D	–	Gas flow behavior in a co-current spray dryer is investigated	Sano (1993)
25	2D	FLUENT	CFD simulation of the spray drying process in a two-stage horizontal chamber is investigated	Huang and Mujumdar (2006)
26	3D	CFX	The comparison of the predictions of two different turbulence simulation approaches SST and SAS models, for the simulation of the gas flow	Fletcher and Langrish (2009)
27	3D	CFX4.4	The extent to which water droplets spread out in the drying chamber is affected by the amount of swirl in the inlet air	Guo et al. (2003)
28	2D	FLUENT	CFD simulation of the effects of low inlet air humidity and temperature on the gas flow patterns, droplet trajectories and overall dryer performance are investigated	Huang and Mujumdar (2007b)
29	3D	FLOW3D	The modeling of the air flow pattern and temperature are investigated	Kieviet and Kerkhof (1995), Kieviet et al. (1997)

Table 5
CFD applications in wall deposition.

CFD application in wall deposition	References
The numerical simulation is investigated with regards to the changes in wall deposition rate	Langrish and Zbicinski (1994))
The wall deposition is predicted using superheated steam instead of air in the spray dryer	Frydman et al. (1998, 1999)
The developments in understanding in the assessment of spray dryers, focussing on wall deposition problem	Langrish and Fletcher (2003)
The developments in predicting Flow patterns in a spray dryer	Cakaloz et al. (1997), Guo et al. (2003), Harvie et al. (2001), Langrish (2007), Langrish and Fletcher (2001); Langrish et al. (2004), Lebarbier et al. (2001), Southwell and Langrish (2000, 2001)
In the CFD model, the counter-current spray drying processes are identified, i.e., the regions of particle agglomeration and wall deposition in spray drying	Zbicinski and Zietara (2004)
The CFD simulation is investigated to reduce the wall deposition rate and thermal degradation for particles by modifying the air inlet geometry	Langrish (2007)
The CFD simulation of a spray dryer based on mathematical modeling and experimental trials for predicting and measuring the wall deposition	Langrish and Zbicinski (1994), Sadripour et al. (2012)
The effects of turbulence and droplet size in a relatively simple geometrical configuration, with the aim being to assess the ability of a CFD simulation to predict the actual wall deposition fluxes and the trends in these fluxes in such geometry	Langrish and Kota (2007)
A study of the precession of the central jet of air inside spray dryer, where this central jet may be connected to the occurrence of wall deposits inside this equipment	Lebarbier et al. (2001)
The predictions of deposition patterns using CFD simulations based on transient-flow behavior	Kota and Langrish (2007a)
The particle deposition behavior in a conical section of the spray dryer is predicted using simple correlations for particle depositions in pips	Kota and Langrish (2007b)
The different levels and scales of mathematical modeling are applied to spray dryers. These scales ranged from the whole dryer level (coarsest scale), through plug-flow reactor approximations, to the finest scale, computational fluid dynamics (CFD)	Langrish (2009)
The mathematical model of particle deposition is developed and implemented in the CFD software	Jin and Chen (2010)

phenomenon even more complicated. Cleaver and Yates studied recycling particle and deposition rates (Cleaver and Yates, 1976). They showed that wall shear stress is a key parameter of particle recycling. The deposition varies linearly with time because it is below a critical value, and the deposited particles can re-enter the dryer. The measurement of the critical wall shear stress is a helpful experiment in physicochemical problems such as re-deposition where the dynamic force of adhesion controls the phenomena (Cleaver and Yates, 1976).

The wall deposition model determines the destiny of the particles, when they are tracked and reach the wall. A suitable wall deposition model will affect the prediction of both the yield and then final product moisture. Several researchers (Huang et al., 2004b; Langrish and Zbicinski, 1994; Mezhericher et al., 2008) have utilized the stick-on-contact approach as reported in literature. In theory, it is assumed that a number of particles will touch the boundary wall; these will adhere and will be removed from the simulation. One major drawback of the stick-on-contact deposition model based on the glass transition temperature *Tg*, is its over-prediction of deposition rates. This is due to neglecting the effects of particle rigidity and velocity as well as the angle of the collision (Woo et al., 2010a). The work by Bhandari and his co-workers indicated that increasing the rigidity of the particles increases the yield from the spray drying process (Adhikari et al., 2005; Bhandari et al., 1997). Ozman & Langrish investigated this effect in a pilot scale spray dryer unit and developed a deposition model based on the Glass Transition – Sticky Point concept. Fig. 5 shows the typical glass transition curve of lactose as predicted by the Gordon–Taylor correlation (Ozmen and Langrish, 2003). From Fig. 5, the glass transition temperature and the corresponding sticky point temperature are the critical function of the particle moisture. At higher moisture contents, the sticky point declines and vice versa. If the particle temperature exceeds the sticky point, the particle becomes sticky and will adhere to the walls. It is included that the sticky point of the material is taken as the cut-off point in determining whether or not a particle sticks to the wall. With application to amorphous carbohydrates, it is common to take the sticky point as 20–25 °C higher than the glass transition point (Woo et al., 2010b). Aside from product stickiness and *Tg*, a new deposition mechanism is proposed based on the collision of viscoelastic amorphous food particles with the wall (Woo et al., 2010a). Murti et al. applied particle gun experiments and showed that the velocity and angle of the striking particle affect the deposition of skim milk powders (Murti et al., 2006). A higher striking velocity causes a higher critical *T*–*Tg* value, which leads to a lower tendency to adhere. In addition, it was also found that at a lower the critical *T*–*Tg* value, a smaller striking angle reduces the dependency of the particle stickiness on temperature. Therefore, the particle impacting momentum does affect the deposition outcome. In order to address these aspects of the deposition modeling, a recent work involved the development of a rheology based deposition model (Woo et al., 2010a). The premise of this model is based on the viscoelastic property of the amorphous particles often encountered in spray drying (Palzer, 2005). The effect of velocity, particle size and particle rigidity on particle deposition can be determined by using time the temperature superposition technique. Case studies of past data showed good qualitative agreement with the model that warrants further work in the future (Woo et al., 2010a).

4. CFD applications in wall deposition of spray drying system

The CFD techniques used to study and solve complex engineering applications includes fluid flow and heat and mass transfer problems. There are some key advantages that CFD methods can offer to the drying industry as presented in Fig. 6. Table 4 summarizes the CFD modeling of the spray dryer from 1993 to 2012.

A key issue in wall deposition for spray dryers is particle stickiness, since this has an important bearing on whether or not the particles that hit the walls stay there and for how long. The collision flux of particles with the wall is a function of the fluid flow patterns in the dryers, and CFD can offer guidance in this area (Langrish, 2005). The application of CFD simulations and experimental work in the study of wall deposition help to understand the spray pattern and process parameters which control the feed water composition and flow rate, the hot air temperature and flow rate and the droplet size from the atomizer (Langrish and Fletcher, 2001; Masters, 1994; Schuck et al., 2005). However, the flow patterns of both gas and particles (droplets and dry particles) inside the spray dryer and the mechanism of particle deposition on the walls are highly complex, which makes the understanding of the underlying processes difficult. An accurate prediction of wall deposition for droplets depends on having sufficient resolution of the near-wall turbulent behavior of the flow. Matida et al. suggest that optimizing the parameters in the RANS equations to give accurate near-wall turbulence statistics for the primary flow may improve this situation for wall deposition, without significantly affecting the prediction of the bulk flows (Matida et al., 2000). From an operational point of view, operating the spray dryer within a narrow optimum range of operating parameters, which must be determined empirically for each spray dryers, can avoid wet products and significant product deposition on the walls (Woo et al., 2007b). In the following sections, the applications of CFD in wall depositions are tabulated in Table 5.

5. Conclusion

The significant impact of wall deposition and the complexity of its underlying mechanisms have resulted in a considerable number of research works, either experimental or theoretical. This review addresses various aspects of wall deposition such as the application of CFD, ANN based techniques and several mathematical models. After conducting this research it is clear that wall deposition modeling has been developed as a tool to evaluate the experimental results and to reach the reliable conclusions. Furthermore, the effects of various parameters such as primary conditions (inlet–outlet temperature, air flow rate, feed rate, feed concentration and wall material, air flow pattern in chamber geometry, type and size of spray dryer and spray dryer wall properties on wall deposition were presented and discussed.

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