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ANIBAL JOSÉ BARRIOS QUANT[1]
JOSE ANDRÉS PEREZ MENDOZA[1]
JOHN TELOTTE[2]

[1]Chemical Engineering Department, Universidad del Atlántico, Km 7, Puerto Colombia, Atlántico, Colombia
[2]Department of Chemical and Biomedical Engineering, FAMU-FSU College of Engineering, Florida State University, Tallahassee, FL, USA

SCIENTIFIC PAPER

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A COMPREHENSIVE ANALYSIS OF CRITICAL VARIABLES USED TO DESIGN A SPRAY DRYER OF WHEY PROTEIN CONCENTRATES

Article Highlights

- Results showed specific responses for each model
- Mujumdar responses offered three different kinds of spray flow
- Dimensional variables were not affected over denaturation conditions
- Models analyzed presented different behaviors

Abstract

Five models of a spray dryer design for a whey protein process were analyzed in this study. These models include first principle approaches and empirical correlations. From a large set of given design specifications (inlet and outlet moisture contents, inlet air conditions and residence time), the physical size of the spray drying system was determined from their correlations. Then, the designs were compared to both industry heuristics for size ratios and dryer performance (when possible) to assess the validity of these models. Specific consideration was given to the correlation between the systems that met design heuristics and those that produced a usable product.

Keywords: spray dryer, design, sizing, dimensional analysis, critical variables, whey protein.

In the whey industry, large quantities of whey proteins such as whey protein concentrate, and whey protein isolates are produced (WPI) [1,2]. Spray-dried whey protein powders are usually used in sports nutrition formulas, dietary supplements and many other food products [3,4].

Spray drying is a complex, multiphase, flow phenomenon which includes a gas phase (air drying), liquid phase (droplets), and a solid phase (particles) [5]. Designing a spray dryer is a complex task due to the transport phenomena present in the design and particle formation [6]. Additionally, multiple variables such as viscosity, conductivity, heat capacity, and humidity, force the designer to solve the Navier-Stokes equations [7]. To design spray dryers with less complexity, designers have developed assumptions based on variables that allow an easier design process for spray dryers [8].

Each model design has been developed from knowledge and experience of the researcher [9]. The focus of this study is to find the common variables in four different design models and evaluate how these variables affect the sizing of the spray dryer [10].

DESIGN MODELS

Mathematical modeling is a powerful tool in physics, chemistry, and engineering for interpretation and prediction of natural phenomena and experimental results [11]. A mathematical model of spray drying process is a simplification of the phenomenon based on material and energy balances [12].

Published theoretical models of droplet drying kinetics can be subdivided into the following two categories: 1) empirical models and 2) models based on semi-empirical approaches that utilize the concept of characteristic drying curves (CDC) [13].

The models of Mujumdar [4] Suryanarayana [15], Gluckert [16] and Masters [17] described the dimensional structure of a spray dryer. These were

Correspondence: A.J. Barrios Quant, Chemical Engineering Department, Universidad del Atlántico, Km 7, Puerto Colombia, Atlántico, Colombia.
E-mail: abarriosquant@fsu.edu
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selected in this study according to the impact they had in the development of research in the spray dryer field, to analyze their design and sizing methodologies.

The analysis of these models focused on the structure of each and the variables that significantly influenced the design and sizing of a spray dryer. The equations below show only the diameter, length, and volume of each model. The complete structure of each model is available as supplementary material.

Mujumdar model [14]:

$$D = \sqrt{\frac{4G}{3600\pi\, ju}}$$
$$L = \frac{4V}{\pi D^2} \tag{1}$$
$$V = \frac{\tau F_2}{Hp_{whey}}$$

Suryanarayana model [15]:

$$D_{spray} = \frac{\sqrt{4A_c}}{\pi}$$
$$L = 0.6D_{spray} \tag{2}$$
$$V = G_s V_{avg} t_d$$

Gluckert model [16]:

$$D = 2\sqrt{(T_t 2.24V_{res}(b(\frac{D_r}{2})^{12} + (\frac{D_r}{4})}$$
$$L = 1.5D_{spray} \tag{3}$$
$$V = G_s V_{avg} t_d$$

Masters model [17]:

$$Dvs = \frac{14000Q10.24}{nh012Nd0.6}$$
$$L = 1.5D_{spray} \tag{4}$$
$$V = \frac{1}{4}\pi D_i 2h_{spray}$$

The influence of the common variables in each model was tested by the variation of the model in a specific and known range, based on avoidance of whey protein denaturation. The common variables were called critical variables and the values reported in the literature are shown in Table 1.

Variables and treatments evaluation

The analysis was evaluated by the effect of the variables on the responses obtained in the models and the relation between the size and the different values that were applied to the models.

The treatments were organized by considering the main factor of protein denaturation. These were classified in two levels: low damage treatment and high damage treatment, according the expected protein condition outcome of this treatment. The purpose of labeling was to analyze the responses of the models in two conditions, denaturation (De) and non-denaturation (NDe) variables.

Variable analysis

The variables were organized randomly and set to obtain thirty-two responses. The treatments were classified into two groups: size rule and construction cost. The analysis was carried out using two values for each of the five independent variables (Table 1). The treatments terminology was used to explain the thirty-two possible variables used on this study to determine the value of the responses (spray diameter, length and volume) in each particular model. The complete list of treatments in the models can be found in the supplementary information.

The different values that were used in the analysis were selected depending on the denaturation suffered by whey proteins in the atomization process. This was associated with the impact of the process variables such as humidity content, inlet and outlet dryer temperatures, air velocity, air flow, whey outlet humidity and residence time on the quality of whey protein powders.

Taking into consideration the protein denaturation as an undesirable result in the whey protein process, it is necessary to set up the values of the variables to estimate the damage suffered by proteins

Table 1. Critical variables used to standardize the models to design a spray dryer of whey protein concentrates

Variable	Values		Dimension of variable	Reference
Humidity content of the liquid whey	0.60	0.90	kg/kg	[18-20]
Inlet air temperature	85	180	°C	[21-23]
Outlet air temperature	80	120	°C	[24-26]
Whey outlet humidity	0.05	0.10	kg/kg	[27-29]
Air flow	123	288	m^3/s	[30-32]
Residence time	3	10	s	[33-35]
Air velocity	0.5	0.7	m/s	[36-38]

in the spray process. The effects of the humidity content, inlet air temperature, outlet air temperature, air velocity, air flow, outlet whey humidity and residence time were used as inputs to get responses of the spray diameter, length, and volume (Table 1).

Geometric restrictions

Mujumdar [14] suggested that when building a spray dryer there are three conditions with a range of acceptable values based on the length (L), diameter (D), volume (V) and number of blades (nf), in order to make a well distributed spray dryer [14]:

$$\begin{aligned} &0.02 < L / D < 0.20 \\ &0.02 < L / V < 0.15 \\ &5 < nf / D < 15 \end{aligned} \tag{5}$$

The last restriction was not taken in consideration into the development of this study due to the conditions of Mujumdar [14], which were designed for a rotary dryer and adjusted for a spray dryer [21].

Masters [17] proposed similar restrictions where an idealistic relationship (L/D) was created based on the flow pattern of spray dryer and the type of atomizer utilized on the atomization process (Table 2). Such restrictions were employed to compare the responses of L/D on all the treatments of the four models, obtaining the flow type/atomizer that was fitted to the value of the ratio L/D.

Table 2. Relationship between configuration systems and dimensions of the spray dryer, from the Spray Drying Handbook, Masters (1979)

Spray dryer / atomizer	Length:diameter
Parallel flow / rotatory	0.6:1
Parallel flow / top atomizer	4:1
Co-current flow / rotatory	5:1
Mixed flow / top atomizer	1.5:1
Fluidized bed	0.4:1

Powder characteristics

The powder characteristics were adjusted by Masters (Table 3) [17] to determine the minimum diameter needed by the spray chamber. According the thickness of the powder produced, the powder characteristics also suggest an approximate powder flow as an estimation of the spray process taking into consideration the drop diameter [17].

Table 3. Relationship between the powder characteristics of the whey liquid flow and diameter, from the Spray Drying Handbook, Masters (1979)

Spray drop type	Drop diameter μm	Minimum diameter, m	Approximate powder flow, kg/h
Very thin	20-40	1.5	20
Thin	40-80	2	150
Medium	80-100	4	1000
Thick	100-150	6	1500

New model proposition (Barrios-Quant model)

Barrios-Quant *et al.* (2019) proposed a new model based on the comprehensive analysis of the critical variables that were used in the other four models. The critical variables selected to standardize the four models, were used as the main variables to design the model. These variables defined as humidity content of the liquid whey, inlet air temperature, outlet air temperature, whey outlet humidity, air flow, and residence time. The model established by Barrios *et al.* (2019), is an empirical model that describes the dimensional structure of a spray dryer based on the main three-dimensional variables (length, diameter and volume). The main characteristic of the Barrios model is that they used the most common variables employed in the four models (Mujumdar, Suryanarayana, Gluckert and Masters) and set them in equations which derivate in the dimensional variables of the spray dryer.

The equations below show only the diameter, length and volume of the Barrios model. The complete structure of each model is available as supplementary material.

Barrios-Quant model:

$$\begin{aligned} &D = \sqrt{\frac{4G}{3600\pi ju}} \\ &L = \frac{4V}{\pi D^2} \\ &V = G_s V_{avg} t_d \end{aligned} \tag{6}$$

The analysis of the Barrios-Quant model won't be included in the analysis of the models to size and design a spray dryer based on the structure of each and the variables that significantly influenced the design and sizing of a spray dryer.

RESULTS AND DISCUSSION

Depending on the modeling and their boundary conditions, variations in dimensional parameters (diameter, length and volume) were obtained in the design models. When the models of Mujumdar [14], Suryanarayana [15], Gluckert [16] and Masters [17] were analyzed using the residence time and air velocity levels (high and low) as variables, only four responses of the possible thirty-two were obtained for the models of Mujumdar, Suryanarayana and Gluckert [14-16] and one of thirty-two for Masters [17].

The responses were limited when the time of residence and air velocity were used in the set of critical variables. Generally, these variables are used by designers in the mass and heat balances. However, they did not have a considerable effect on the four models. This could be attributed to the fact that each model responds independently to a specific group of variables. Therefore, these variables were replaced by the inlet air flow and the whey outlet humidity. In this case, the responses were increased in sixteen of thirty-two for the models of Mujumdar [14], Suryanarayana [15] and Gluckert [16] and one of thirty-two for Masters [17].

Model responses

The different values that were used to analyze the design and sizing of each spray dryer model were selected depending on the denaturation issue suffered by whey proteins in the atomization process, associated with the impact of the process variables such as humidity content, inlet and outlet dryer temperatures, air velocity, air flow, whey outlet humidity and residence time on the quality of whey protein powders.

Taking into consideration the protein denaturation such as undesirable result in the whey protein processing (Krešić *et al.,* 2008), it is necessary to set up the values of the variables to estimate the damage suffered by proteins in the spray process. This conversion process of protein solutions into dry powder is complex because of their sensitivity to heat, especially when they are still in solution (Abdul-Fattah *et al.*, 2007; Qi *et al.*, 2011). A considerable amount of protein is inactivated or denatured due to thermal as well as air interface-related stresses; these stresses cause irreversible damage of the secondary structure such as α-helix, β-sheet, and random coil (Ameri and Maa, 2006; Li-Chan *et al.*, 2018; Sadek *et al.*, 2013).

The most common factors affecting denaturation of proteins are solvent conditions, temperature, and surface interactions (Crillo *et al.*, 2015; Griffiths, 2010) All these factors are relevant to protein drying, solvent conditions such as humidity, atomization, and the air-water interface parameters: the inlet and outlet air temperatures and surface parameters with air, such as air velocity and residence time (Anandharamakrishnan *et al.*, 2015) which were also adjusted to the study.

The responses of the models (Figure 1) were calculated by the combination of the five variables selected for this study in the two levels chosen. This procedure showed 32 responses for each dimensional variable (diameter, length and volume) over every model; the average responses of each model were compared to see the behavior of each model over the same operational conditions. It is pertinent to highlight that the “T” in top of the bars in the graph means the average value conquered.

The results showed particular responses for each model without any tendency in general, which confirmed that every model responds in a different path over the same operational conditions. The values obtained in the process listed in Table 4 were divided on maximum and minimum responses, trying to analyze the patterns on the responses. The model of Gluckert demonstrated the maximum values on Diameter and Length responses, the Masters' model demonstrated the maximum value on Volume, and the minimum values all belonged to the Suryanarayana model.

Following the data in Table 5, it was possible to determine the effect of the diameter on the powder characteristics, according to (Masters, 1979). The thickness of the whey powders, delivered by the models of Mujumdar, Suryanarayana, and Masters, the spray followed the very thin powder type (20-40 μm),

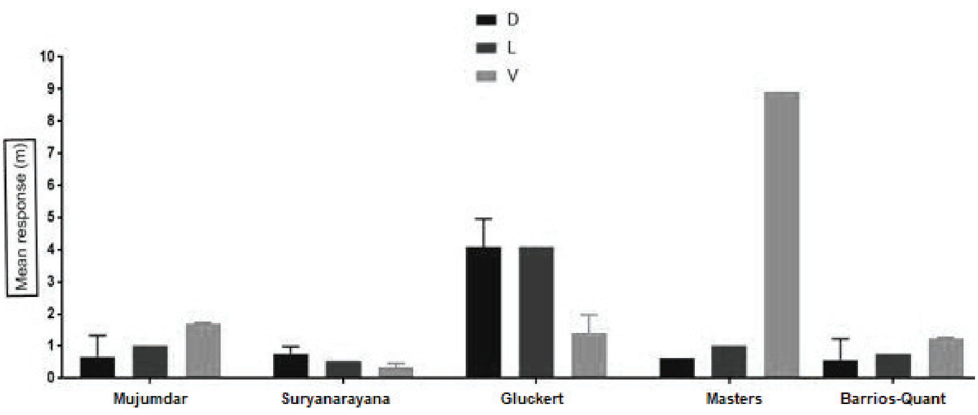

Figure 1. Responses of the dimensional variables of the spray dryer in the four models.

Table 4. Boundary values of dimensional variables used to design the spray dryer of whey protein concentrates

Model	*D* (m)		*L* (m)		*V* (m^3)	
	Max	Min	Max	Min	Max	Min
Mujumdar	1.936	0.352	2.667	0.126	1.730	1.651
Suryanarayana	1.151	0.454	0.794	0.313	0.489	0.168
Gluckert	5.302	3.075	7.953	4.612	2.137	0.759
Masters	0.6328	0.6328	1.024	1.024	20.91[a]	8.930
Barrios-Quant	1.756	0.5241	2.368	1.298	2.419	0.783

[a]This value was excluded of the plot, considered to be an outlier

Table 5. Variables present in the model of Mujumdar and their influence on the dimensional responses; the symbols (+) and (-) describe the relationship between the variable and the response, directly proportional or inversely proportional, respectively; (N/E) means no effect over the response

Variable	*D*	*L*	*V*
Inlet air temperature	+	+	N/E
Outlet air temperature	+	+	N/E
Wet bulb temperature	+	+	N/E
Protein temperature	+	+	N/E
Air velocity	-	+	N/E
Residence time	N/E	+	+
Whey flow	+	N/E	+
Inlet whey humidity	+	-	N/E
Outlet whey humidity	-	+	+
Whey temperature	-	+	N/E
Heat losses	+	-	N/E
Total heat transfer to whey powder	+	-	N/E

whereas the model of Gluckert presented the same proportion for medium (80-100 μm) and thin (100-150 μm) powders.; this behavior was attributed to the bigger range of diameters ($P > 0.05$) obtained in the Gluckert model. Also, this pattern will be linked to the model correlation to determine the diameter (Gluckert model) due to the fact that this equation was based on a semi-empirical model related to air velocity and drop properties, which was not evaluated on this study.

An interesting concern related to the powder characteristics of (Masters, 1979), was the whey protein flow. Masters suggested that depending on the conditions of the powder, the diameter should exhibit an approximate whey protein flow. For this study, we adjusted a liquid whey inlet flow of 50 kg/h obtaining 12 kg/h of whey protein. Following this data, every spray produced for the different models should have shown a very thin powder pattern. Nevertheless, the study obtained thin and medium powder responses which represented that there should also exist whey powder flows of 150 and 1000 kg/h which have no accordance with the operational conditions. This issue will be attributed to the specific experimental conditions utilized by Masters.

The treatments used in this research were not shown in the data analysis due to practical purposes. The treatments were organized in low and high damage treatments, Figure 2. To observe if the final and desired conditions of whey protein powder had an influence over the design and sizing of the spray dryer, the dimensional responses of the whole models were organized in the two treatment conditions and then were analyzed. The average was obtained of each variable.

The results show that there were not significant differences ($P < 0.05$) between low and high damage treatments, which supposes that the denaturation conditions will be not a when designing a spray dryer. Nevertheless, this pattern set a precedent to study in advance the relationship between the whey protein powder conditions and the dimensional variables of spray dryers.

Mujumdar

This model is empirical and was established on mass and energy balances. The responses of this model were calculated by the interactions of 10 variables, as shown in Table 5, established by the author.

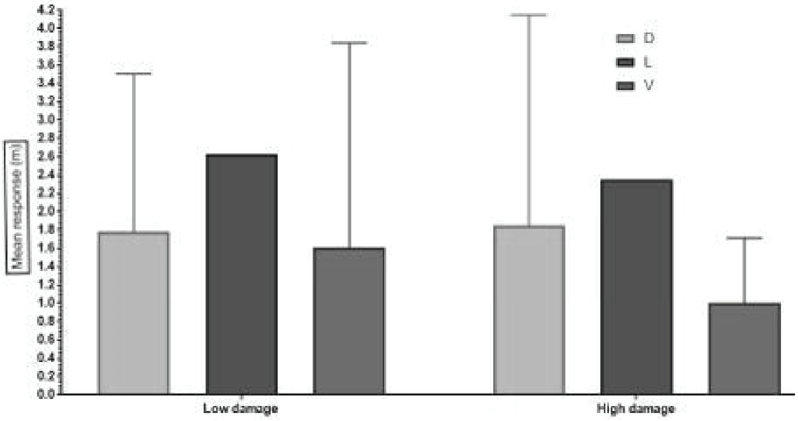

Figure 2. Treatment conditions responses for the two levels selected to standardize the models to design a spray drying of whey protein concentrates.

The humidity content and the outlet whey humidity affected the total heat transfer, the inlet and outlet temperature, and the air flow required. The air velocity had an effect in the diameter. The residence time and air flow impacted the volume. Finally, the length was calculated by a relationship between the volume and the diameter.

In this model, the relative humidity (*RH*) played an important role in the determination of the wet bulb temperature, and in the capacity of the air to be able to remove enough water from the whey. The study chose the *RH* on 79% (kg/kg dry base, Schuck *et al.*, 2008; Behboudi-Jobbehdar *et al.*, 2013), and the air temperature gradient, affected the spray diameter directly. The whey flow presented an interesting pattern at the moment to make variations in the values inside the model. This variable only affected the diameter and the volume of the dryer. Which means that at a nanoscale flow (1e-24 kg/h), and bulk flow (1e+24 kg/h), the length is the same. The air flow has not influenced this model because it was calculated inside the model.

The diameter and the length in this model were affected with the variance of the humidity, and the inlet and outlet air temperatures. However, when the treatment presented repetition of these conditions, the variance of the residence time was not changed in the response. The model had only two different spray volumes (1.6509 and 1.7295 m^3), because the volume only variated with the total whey outlet flow.

The 30% of the responses in this model follow the geometric restrictions of (Mujumdar, 2013, the diameter being bigger than the length). Almost 46% have bigger lengths, and the other 24% do not apply. These percentages are presented in Figure 3. The same pattern occurred with the treatment numbers (1), (2), (9) and (10), characterized per volume bigger than the length, Figure 4. Also, this model only accomplished the 8% of the geometric restrictions of the treatments even though the author was the original creator of this rule. According to the geometric restriction of (Masters, 1979), this rule is not trustworthy at the moment in designing a spray dryer.

The treatments of Mujumdar showed positive responses to the geometric restrictions in treatments (1), (2), (9) and (10). This behavior is attributed to the variables used in those treatments at 85 and 80 °C, adjusted to inlet and outlet air temperatures, respect-

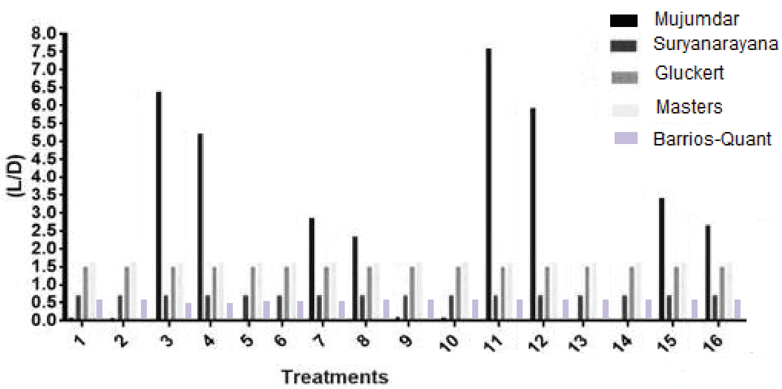

Figure 3. Responses of the four models of the dimensional variables length and diameter.

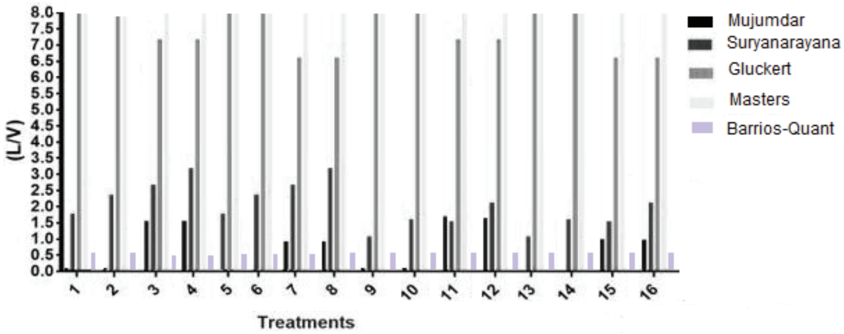

Figure 4. Responses of the four models of the dimensional variables length and volume.

ively. The inlet humidity was changed from 0.60 kg/kg dry basis to 0.90 kg/kg dry basis, and the outlet humidity content from 0.05 kg/kg dry basis to 0.10 kg/kg dry basis. The air flow had no effect in the responses and belonged to the low damage treatments.

The spray dryers which followed the geometric restriction according to (Mujumdar, 2013) were not dimensionally possible in pilot scale, with dimensions in treatments (1), (2), (9) and (10) of diameter - length being (1.5815–0.1260 m, 1.958–0.1262 m, 1.5180–-0.1433 m and 1.884–0.1395 m, respectively.

The treatments of Suryanarayana showed negative answers to the geometric restrictions of (Mujumdar, 2013) in all treatments in the *L*/*D* and *L*/*V* relations. This behavior could be attributed to the correlations of the model that produced responses with differences no bigger than 0.3566 cm between diameter and length, Figure 3, and relation no smaller than 0.752 cm between the length and the volume, Figure 4.

The treatments of Gluckert showed negative answers to the geometric restrictions in all treatments in the *L*/*D* and *L*/*V* relations, Figures 3 and 4. This behavior could be attributed to the correlations of the model that produce responses with differences no bigger than 0.654 cm between diameter and length, and relation no smaller than 5.942 cm between the length and the volume.

The treatments of Masters showed positive responses to the geometric restrictions in all treatments in the *L*/*D* and *L*/*V* relations, Figures 3 and 4. This behavior could be attributed to correlations that are specifically designed to respond to the atomizer variables, which were not considered in this study, because they give the same response in diameter, length and volume for all the treatments.

The treatments which did not follow the geometric restrictions of (Mujumdar, 2013) showed the same kind of response of not being able to be built on a pilot scale. The relation between length and the diameter was inverted, length being bigger than the diameter.

The model of Mujumdar presented a variation on the kinds of systems (flow/atomizer type) which should integrate the spray dryer, according to (Masters, 1979) who adjusted a geometric restriction depending on the relationship *L*/*D*, Figure 5. The responses of Mujumdar presented a huge range of possible systems to assemble the spray dryer due to the responses, with 30% of diameters bigger than the lengths and 46% of lengths bigger than thediameters, which fit on the different patterns adjusted by (Masters, 1979).

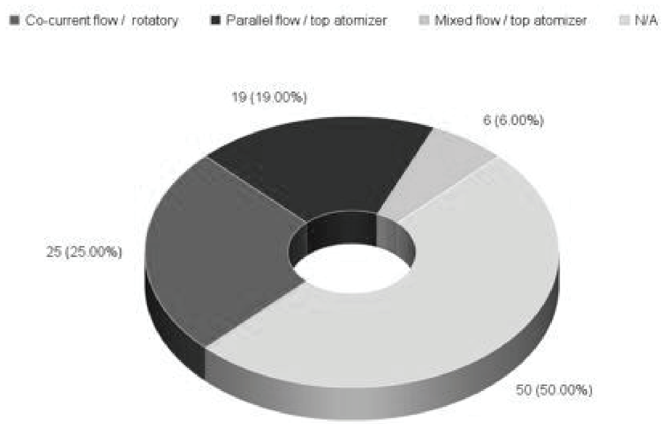

Figure 5. Responses of the four models of the dimensional variables length and diameter according Masters geometric restrictions.

Suryanarayana

This model is an empirical model and was based on empirical suppositions based on the fluid mechanics inside the spray drier, the settlement velocity, and Reynolds number (Re) interaction. The dimensional variables (diameter length and volume) showed that the dimensions of diameter and length decrease when the flow inside the spray chamber was more turbulent. The Re had not had a direct relation with the spray volume over the different flow patterns: laminar (Re ≤ 2100), transitional (2100 ≤ Re ≤ 4000) and turbulent (Re ≥ 4000).

The responses of this model were calculated by the interactions of six variables, as shown in Table 6. All these variables are directly linked with the heat and mass transfer processes and with the temperatures of the air. This model did not take into consideration any of the temperatures presented in the study related to air or whey to calculate the dimensional variables.

In this model, the air density impacted all the variables in a positive way. However, this was limited by the air temperature and the whey density. The air density cannot be higher than the whey density. Furthermore, the spray volume showed high sensitivity on air density changes: at 85 °C, 1 atm and 0.8510 kg/m^3, the volume was 290.87 m^3, whereas at 180 °C, 1 atm and 0.7788 kg/m^3, the volume was 238.457 m^3. This demonstrated the linear relation between air density and spray volume.

The particle size had a direct (+) influence over all the dimensional variables. This is an undesirable effect on the final whey protein powder, because having a big particle size could result in difficulties at the time of dissolution in water (José Toro-Sierra *et al.*, 2013; Chegini *et al.*, 2014; Haque *et al.*, 2015). This variable should not be considered when making bigger changes and getting a specific spray dimension.

The models of Surayanarayana, Gluckert and Masters presented the same pattern: 100% of (parallel flow/ top atomizer) and (mixed flow/ top atomizer) to the last two, respectively. According to (Masters, 1979), who adjusted a geometric restriction depending on the relationship *L*/*D*, this behavior was attributed to the relationship between *L*/*D* in all the treatments; it was (0.6:1) to Suryanarayana and (1.5:1) to Gluckert and Masters.

Gluckert

This model is a semi-empirical model and was based on the drop properties, in which this model responded to the inlet and outlet temperatures, as shown in Table 7. The humidity had no effect in the model. The residence time had no effect in the model, because the residence time was calculated inside the model and was linked to the air temperatures. The humidity had a minimum effect in the residence time calculation also.

Even when this semi-empirical model was based on the drop properties, none of the drop characteristics influenced the dimensional responses of the spray. This behavior is attributed to drop kinetics. Usually the drop patterns are employed to describe the final particle size and the temperature distribution inside the spray chamber. However, there has not been enough attention in the relationship between drop patterns and the dimensions of the spray, (Kuhnhenn *et al.*, 2018).

If the size of the diameter increases to fit 95% of drops from the cloud, then the length and volume should also increase. This phenomenon was attributed to the increase in the space needed for the drops to dry. The diameter in this model depends on the residence time, the diameter of the atomizer, and the air velocity. The length was calculated by the factor of the diameter, and the volume was determined with the air flow and the residence time.

Table 6. Variables present in the model of Suryanayana and their influence on the dimensional responses; the symbols (+) and (-) describe the relationship between the variable and the response, directly proportional or inversely proportional, respectively; (N/E) means no effect over the response

Variable	*D*	*L*	*V*
Air flow	+	+	+
Air density	+	+	+
Air Viscosity	+	+	N/E
Whey density	+	+	+
Whey concentration	N/E	N/E	+
Particle diameter	+	+	+
Operation velocity	-	-	N/E
Settlement velocity	-	-	N/E
Residence time	N/E	N/E	+

Table 7. Variables present in the model of Gluckert and their influence on the dimensional responses; the symbols (+) and (-) describe the relationship between the variable and the response, directly proportional or inversely proportional, respectively; (N/E) means no effect over the response

Variable	D	L	V
Dry solids flow	N/E	N/E	+
Whey inlet humidity	N/E	N/E	+
Whey outlet humidity	N/E	N/E	+
Whey density	N/E	N/E	-
Air flow	N/E	N/E	+
Air inlet humidity	N/E	N/E	-
Air outlet humidity	N/E	N/E	-
Air inlet temperature	N/E	N/E	-
Air outlet temperature	N/E	N/E	+
Wet bulb temperature	N/E	N/E	-
Inlet air enthalpy	N/E	N/E	N/E
Outlet air enthalpy	N/E	N/E	N/E
Transfer velocity	N/E	N/E	-
Latent heat of vaporization	N/E	N/E	+
Drop temperature	N/E	N/E	+
Thermal conductivity	N/E	N/E	-
Solids concentration	N/E	N/E	-
Water mass per drop	N/E	N/E	-
Film conductivity around the drop	N/E	N/E	-
Initial mass of solids by drop	N/E	N/E	+
Atomizer diameter	-	-	+
Atomizer velocity	-	-	N/E
Holes number	-	-	N/E
Holes length	-	-	N/E
Residence time	N/E	N/E	+

Masters

The model of Masters is a semi-empirical model and was based on whey properties specifying drop skill, air conditions and atomizer characteristics. This model obtained the same responses in all the treatments because variables utilized in the analysis had no impact on the modeling. This model's only responses to the atomization characteristics, atomizer type and operation velocity, number of holes, drop size, drop temperature, drop diameter were not included in the first analysis in order to get the same responses for all the treatments, as shown in Table 8.

If more water is removed in the drops in the overall spray process of the first and second drying time, the volume of the dyer will be greater. When 8.62 e-8 kg of water evaporated from the whey per drop, the total residence time was 6.06 s, while when 12.65 e-8 kg of water evaporated in the whole process, the total residence time was 10.47 s, which demonstrated the relationship between volume, evaporated water and residence time.

Table 8. Variables present in the model of Masters and their influence on the dimensional responses;The symbols (+) and (-) describe the relationship between the variable and the response, directly proportional or inversely proportional, respectively; (N/E) means no effect over the response

Variable	*D*	*L*	*V*
Sauter diameter	+	+	+
95% drops cloud	+	+	+
Drop humidity removed	N/E	N/E	N/E
Remain drop humidity	N/E	N/E	N/E
Drop humidity at critical point	N/E	N/E	N/E
Drop surface temperature	N/E	N/E	N/E
Atomizer diameter	+	+	N/E
Atomizer velocity	-	-	-
Air flow	N/E	N/E	+
Air thermal conductivity	-	-	-
Latent heat of air vaporization	+	+	+
Whey density	-	-	-
Inlet whey humidity	+	+	+
Outlet whey humidity	-	-	-
Relative drop velocity	+	+	N/E
Drying time in constant velocity	+	+	+
Drying time in decreasing period	+	+	+
Residence time	+	+	+
Drop travel time	N/E	N/E	N/E

Barrios-Quant

The Barrios-Quant model is an empirical model and was established based on the mass and energy balances of a spray dyer for the production of whey protein concentrates. The responses of this model were calculated by the interactions of 10 variables, as shown in Table 9. The residence time which is usually estimated in the other models, was calculated as the sum of time that the liquid whey stays in the reservoir plus the time that the air remains in the gas chamber divided by the inlet flow, assuming that the reservoir is in equilibrium.

The whey flow had a direct (+) influence over all the dimensional variables. This phenomenon was attributed to the space that is needed to hold the quantity of whey liquid that is getting into the spray chamber. The residence had an effect over the diameter and the length in this model. The responses showed that the dimensions of diameter and length increased when the residence time and whey humidity decreased. The values (1.756 m, 2.368 m and 2.419 m^3) of the dimensional variables (diameter, length and volume) were respectively more suitable than the data delivered by other models (data from Table 4). This may work better for designing a spray dryer than the models of Mujumdar, Suryanarayana, Gluckert and Masters.

Table 9. Variables present in the model of Barrios-Quant and their influence on the dimensional responses; the symbols (+) and (-) describe the relationship between the variable and the response, directly proportional or inversely proportional, respectively; (N/E) means no effect over the response

Variable	*D*	*L*	*V*
Whey flow	+	+	+
Inlet whey humidity	+	+	N/E
Outlet whey humidity	+	+	N/E
Whey temperature	+	+	N/E
Air flow	-	+	-
Air velocity	N/E	+	+
Air inlet temperature	+	N/E	-
Air outlet temperature	+	-	N/E
Inlet air humidity	-	+	+
Outlet air humidity	+	+	N/E

In this model, as well as the Mujumdar model, the inlet air relative humidity (*RH*) plays an important role in the determination of properties such as wet bulb temperature, enthalpy, and specific volume, and in the capacity of the air to be able to remove enough water from the whey.

CONCLUSIONS

The models analyzed in this study presented different behaviors when evaluated in the same operational conditions. This is because the creator of each model used different mathematical correlations to describe the same phenomenon. This resulted in different responses in the spray dryer dimensional variables (diameter, length and volume), which showed that there was no convergence on which simplified models are the most predictive.

This study offers guidance for new designers for four different kinds of models, each one with specific critical variables and responses. Mujumdar [14] should be chosen if the designer considers the air properties. Suryanarayana [15] may be useful for specific whey characteristics. Gluckert [16] should be considered when only the desired air temperatures and whey protein conditions are available. Masters [17] may be useful if the designer wishes to emphasize the atomizer characteristics. By analyzing the critical variables for each model, this study delivers a wide range of design opportunities for a spray dryer depending on the variables important to the designer.

Supplementary material

Additional data are available from the corresponding author upon request.

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Nomenclature

A Antoine constant, -
b Parameter, -
D Spray diameter, m
d Disc atomizer diameter, m
D_c Critic diameter, m
D_i Cylinder diameter, m
D_r Atomizer diameter, m
D_g Spray diameter, m
D_v Sauter diameter, m
e Capital recovery factor, m
F_1 Whey inlet flow, L/h
F_2 Whey outlet flow, kg/h
F_g Whey outlet flow, kg/h
G Air flow,
G_g Parameter, -
H Blades length, m
h Antoine constant, -
H_1 Air inlet humidity
H_2 Air inlet humidity, kg/kg
j Parameter, -
L Length, m
n Blades number, m
N Atomizer velocity, m/s
N' Time of the loan, year
ρ_{whey} Whey density, kg/m^3
Q Whey flow, kg/h
T Residence time, s
t_d Residence time, s
t_T Total residence time, s
u Parameter, -
V Volume, m^3
V_{avg} Average air density, kg/m^3
V_t Total camera volume, m^3

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ANIBAL JOSÉ BARRIOS QUANT[1]
JOSE ANDRÉS PEREZ MENDOZA[1]
JOHN TELOTTE[2]

[1]Chemical Engineering Department, Universidad del Atlántico, Km 7, Puerto Colombia, Atlántico, Colombia
[2]Department of Chemical and Biomedical Engineering, FAMU-FSU College of Engineering, Florida State University, Tallahassee, FL, USA

NAUČNI RAD

KOMPLETNA ANALIZA KRITIČNIH PROMENLJIVIH KORIŠĆENIH ZA PROJEKTOVANJE SPRAJ SUŠARE KONCENTRATA PROTEINA SURUTKE

U ovom istraživanju je analizirano pet modela sušara za raspršivanje proteina surutke. Ovi modeli uključuju pristupa prvog principa i empirijske korelacije. Od velikog broja zadatih projektnih specifikacija (ulazni i izlazni sadržaj vlage, uslovi ulaznog vazduha i vreme zadržavanja), fizička veličina sistema za sušenje raspršivanjem određena je iz njihovih korelacija. Zatim, projektna rešenja upoređena sa obe industrijskom heuristikom vezano za odnose veličina i performanse sušara (kada je to moguće) da bi se procenila valjanost ovih modela. Posebno je razmotrena povezanost između sistema koji su zadovoljavali projektnu heuristiku i onih koji su proizveli proizvod koji se može koristiti.

Ključne reči: sprej sušara, dizajn, dimenzionisanje, dimenzionalna analiza, kritične promenljive, proteini surutke.