Steam-jet agglomeration of skim milk powders: Influence of process parameters

Mathieu Persona\textsuperscript{a,b}, Bernard Cuq\textsuperscript{b}, Agnès Duri\textsuperscript{b}, Cécile Le Floch-Fouéré\textsuperscript{c}, Romain Jeantet\textsuperscript{a}, and Pierre Schuck\textsuperscript{a}

\textsuperscript{a}STLO, UMR1253, INRA, Agrocampus Ouest, Rennes, France; \textsuperscript{b}IATE, UMR1208, INRA, Montpellier Supagro, Université Montpellier 2, Montpellier, France

ABSTRACT
Steam-jet agglomeration consists in steam–wetting of the surface of fine primary particles, colliding the sticky particles and consolidating the agglomerates by drying in order to obtain the desired properties. The aim of this work was to evaluate the influence of the steam/powder ratio and drying time on growth mechanisms and skim milk agglomerate properties. We demonstrated a predominant influence of the steam/powder ratio on the growth mechanisms and agglomerate properties due to the contribution of the steam flow rate. Moreover, the drying time was identified as a key process parameter to control the final water content, rehydration and mechanical properties of the agglomerates.

Highlights
• A steam-jet agglomeration pilot plant was developed to study the agglomeration of skim-milk powders.
• The growth mechanisms and agglomerates properties depended on the steam/powder ratio, through the contribution of the steam flow rate.
• The drying time was identified as a key process parameter to control the final water content, rehydration and mechanical properties of the agglomerates.

Introduction
Agglomeration processes consist in combining fine primary particles to form larger ones with modified improved properties (e.g., size, density, structure, or functional properties). Different processes and technologies (agglomeration during drying, fluid-bed agglomeration, steam-jet agglomeration, high shear agglomeration, or pressure agglomeration processes) are used by the industry to agglomerate powders, depending on the powder types and the target properties.\cite{1} For example, properties such as fast rehydration may be desirable for specific applications like cocoa powders or milk powders.\cite{2-4} Such properties can be designed using an agglomeration process.\cite{5,6}

When compared to the conventional wet agglomeration processes, steam-jet agglomeration appears to be a suitable technology for producing agglomerates with high porosity and a high dissolution rate.\cite{7,8} During steam-jet agglomeration of amorphous water-soluble particles, water condenses on the particle surface and promotes an increase of the particle surface temperature up to 80–90°C. Consequently, the glass transition of the amorphous components occurs and the local viscosity decreases leading to a sticky particle surface.\cite{9,10} Random collisions between particles then lead to the formation of liquid and viscous bridges, which are further solidified by water evaporation during a drying step, promoting the strengthening of the agglomerates. The adhesion forces between sticky particles depend on several parameters: surface viscosity, contact angle of the liquid/solid system, surface tension of the liquid at the particle surface, contact time and the kinetic energy of the particles.\cite{11} The agglomerate strength has to be high enough to prevent erosion during transportation or dispensing. Despite the industrial importance of steam-jet agglomeration for skim milk powders, this technology has not yet really been considered in scientific studies.

The main objectives of the present research were to study the steam-jet agglomeration of skim milk powders and to evaluate the effects of some process parameters on the growth mechanisms of the agglomeration and on the properties (size, shape, mechanical strength, water content, and wetting time) of the final agglomerates. A specific steam-jet pilot plant was developed and characterized for this purpose.
Material and methods

Materials

Skim milk powder was used as raw material. It was obtained by spray drying using a pilot plant facility (Bionov, France). The water content of the native skim milk powder (2.82 ± 0.21 g.100 g⁻¹ dry matter) was measured by weighing after oven drying at 102°C for 5 h.¹¹ The Feret diameter ($d_{50} = 105.9 ± 6.3 \mu m$) and the spread of size distribution (span = 1.09 ± 0.03) of the native particles was measured by an optical granulomorphometer analyzer (Qicpic, Sympatec GmbH, Germany). The powder sample was pneumatically conveyed to the optical bench at a pressure of 50 kPa and the image of each particle was captured by a camera. Further analysis made it possible to determine the shape factors and the corresponding particle size distribution of the powders. The Feret diameter is deducted from the projected area of the particles using a slide gauge. In general, it is defined as the distance between two parallel tangents of the particle at an arbitrary angle. An industrial agglomerated skim milk powder was used as the reference.

Equipment

A steam-jet agglomeration pilot plant was built for the present study (Figure 1). It consists of a vertical cylindrical tube with an internal cross-section of 76 mm. The skim milk powder was introduced at the top of the tube by means of a volumetric feeder (Gericke, Switzerland; type: GAC), and then fell gravimetrically inside the vertical tube. Steam was generated by a classical boiler (Collard-Trolart, France) and introduced into the vertical tube at 18.5 cm from the top. Different powder feed rates (2.6, 3.2, and 4.1 kg.h⁻¹) and steam flow rates (1.3, 1.7, and 2.1 kg.h⁻¹) were tested. The process conditions were characterized by the ratio of the steam flow rate to the powder feed rate (kg.h⁻¹ steam/kg.h⁻¹ powder). The powder was moistened by the steam flow inside the tube and agglomerated during its fall. The wet agglomerates were collected at the bottom end of the tube. They were immediately spread as a thin layer (thickness of approximately 20 mm) over a stainless steel plate and introduced into a static oven (Memmert GmbH, Germany) at 90°C for the drying stage. Different drying times (5, 10, and 15 min) were tested. The dried agglomerates were collected and immediately sieved over a column of two metallic sieves of decreasing mesh (4 and 0.4 mm). Sieving was conducted at ambient temperature for 2 min with an amplitude of 0.2 mm. The weight of each collected fraction of grains was measured. The mesh size range was determined with regard to the values classically used in the milk powder agglomeration industry. The agglomerates that were collected over the 0.4-mm sieve were immediately sampled and stored inside hermetically-sealed plastic cups until characterization.

Effects of the process variables

Two factorial experimental designs ($2^2$ plus one center point) were considered to determine the effects of two process parameters (Table 1): the steam/powder ratio (0.41, 0.53, or 0.65) and drying time (5, 10, or 15 min).
Each experimental design was performed in triplicate. The first experimental design was built with different values of the steam flow rate (1.3, 1.7, or 2.1 kg h\(^{-1}\)) and a constant value of the powder feed rate (3.2 kg h\(^{-1}\)). The second experimental design was built with different values of the powder feed rate (2.6, 3.2, or 4.1 kg h\(^{-1}\)) and a constant value of the steam flow rate (1.7 kg h\(^{-1}\)) in order to obtain similar steam/powder ratio values like in the first experimental design. The measured responses were: the mass fractions of the fines particles (\(d<0.4\) mm), agglomerates (0.4 mm <\(d<4\) mm) and oversize grains (4 mm <\(d\)), the Feret diameter, the circularity, the mechanical strength, the water content and the wetting time of the agglomerates. The results were analyzed using R software (version 3.3.3).\[12\] The effects of the process variables on the responses were obtained after standardization of the data. The significance was evaluated at a 95% confidence level.

### Characterization of the agglomerates

The water content of the dried agglomerates was measured by weighing a small sample (1 g) after oven drying at 102°C for 5 h.\[11\]

Samples of agglomerates were used to determine the Feret diameter using FIJI analysis software.\[13\] Particle size distributions were characterized by the median value of the Feret diameter (\(d_{50}\)) of a small sample (approximately 5 g) of agglomerates (representing between 200 and 600 agglomerates). Measurements were conducted in triplicate. The sphericity of the dried agglomerates was determined using ImageJ software. Sphericity is a measurement of the length/width particle relationship and therefore ranges between 0 (needle shaped object) and 1 (perfect circle).

The mechanical strength of the dried agglomerates was measured using a texture analyzer (TA1 Texture Analyzer, AMETEK Lloyd Instruments, USA). The agglomerate strength was defined as the force needed to compress a powder bed (22 mm in diameter and 8 mm in height) of agglomerates at 50% of the initial height, using a cylindrical metallic probe (diameter: 12 mm). A 5N load cell was used with a compressive probe operating at 0.08 mm s\(^{-1}\). Mean values were determined from two measurements.

The external microstructure of the agglomerates was observed using a DS-Ri1 camera (color mode: RGB; 16 bits per channel; 1280 × 1024 pixels) mounted on an AZ100 macroscope (Nikon, Japan) (magnifications from 1–40) in light reflection mode. For each slide position, series of 15–17 images with different focal planes were taken in order to compose an extended focus image (image composed of the sharpest pixels between the Z-series). In addition, mosaic images were assembled by reconstructing 2 × 2 extended focus images using NIS-Elements imaging software (Nikon, Japan) operating on the AZ100 system.

The wetting time of the dried agglomerates was determined by measuring the time required for 5 g of powder to completely sink across the free surface of 100 mL of water at 20°C contained in a 400-mL beaker (diameter of 70 mm; height of 135 mm).\[11\] Mean values were determined from two measurements.

### Experimental results

**Agglomeration experiments at the pilot scale**

The microstructure of the initial particles and final agglomerates was observed by optical microscopy and compared to those of industrial agglomerated skim milk powder (Figure 2). The pilot plant agglomerates were characterized by a very porous structure with an irregular shape. Some initial particles were still visible at the surface. The agglomerates were not dense objects

| Trials | Steam rate | Powder rate | Steam/powder ratio | Drying time |
|--------|------------|-------------|-------------------|------------|
| 1      | −1         | 0           | −1                | −1         |
| 2      | −1         | 0           | −1                | +1         |
| 3 (center point) | 0         | 0           | 0                 | 0          |
| 4      | +1         | 0           | +1                | +1         |
| 5      | +1         | 0           | +1                | −1         |
| 6      | 0          | +1          | −1                | +1         |
| 7      | 0          | +1          | −1                | −1         |
| 8 (center point) | 0      | 0           | 0                 | 0          |
| 9      | 0          | −1          | +1                | −1         |
| 10     | 0          | −1          | +1                | +1         |

*Table 1. Values and levels used in the two factorial experimental designs.*
since internal porosity between initial particles could be observed, demonstrating that complete solid fusion between the native skim milk powder particles had not occurred. On the other hand, the industrial agglomerates were characterized by a more spherical shape and regular surface. They represented relatively dense objects since only little internal porosity could be observed. This difference between the pilot plant and industrial agglomerates could be partly explained by the difference in the drying step. Static drying was applied in the present study, whereas fluid-bed drying is generally used in the industrial process, leading to the formation of more compact agglomerates due to collisions between wet agglomerates on the fluid bed.

The steam-jet agglomeration pilot made it possible to obtain agglomerates of skim milk powder, regardless of the experimental conditions (Table 2). Satisfactory reproducibility of the measured responses was obtained. Only three experimental combinations (within the framework of trials 2, 4, and 5, respectively; Table 2) were characterized by a relatively high standard deviation (variation coefficient >30%) for the measured values of the mass fractions of the fines and oversize particles. These experiments were not considered for the statistical analysis.

The changes in the process parameters (steam/powder ratio and drying time) significantly affected the agglomeration yield in fines, agglomerates and oversize particle fractions, and the measured properties of the dried agglomerate fractions (Table 2). The measured mass fraction of the fines, agglomerates and oversize particles ranged between 27–72, 18–32, and 9–50%, respectively. The measured values of the circularity, Feret diameter, mechanical strength, water content and wetting time of the dried agglomerates were in the range of 0.69–0.77, 1.50–2.30 mm, 0.31–1.07 N, 4.0–6.0 g.100 g$^{-1}$, and 12–24 s, respectively.

When compared to the industrial product, the measured values of the water content (5.32 g.100 g$^{-1}$) were almost similar, the wetting time (7.7 s) was slightly lower and the Feret diameter (2.93 mm) and circularity (0.785) were slightly greater. The mechanical strength of the industrial product was found to be greater than 5 N (the limit of the load cell). Given its more compact and regular structure, the Feret diameter, circularity and mechanical strength of the industrial product were therefore significantly superior to the pilot plant agglomerates properties.

**Influence of process parameters on agglomeration yields**

The effect of the process parameters on the agglomeration yields was investigated using the two experimental designs. The mass fraction corresponds to the agglomeration process yields in fines, agglomerates and oversize particles. Physicochemical properties were measured on the agglomerate fraction alone. Values between brackets are standard deviations from the mean of three replications.

### Table 2. Results of the two experimental designs. The mass fraction corresponds to the agglomeration process yields in fines, agglomerates and oversize particles. Physicochemical properties were measured on the agglomerate fraction alone. Values between brackets are standard deviations from the mean of three replications.

| Trials | Mass fraction | Circularity | Feret diameter | Mechanical strength | Water content | Wetting time |
|--------|----------------|-------------|----------------|---------------------|--------------|---------------|
|        | Fines (%) | Agglomerates (%) | Oversize (%) | (−) | (mm) | (N) | (g.100 g$^{-1}$) | (s) |
| 1      | 72.3 (±8.5) | 18.7 (±4.0) | 9.0 (±4.4) | 0.743 (±0.015) | 1.55 (±0.20) | 0.740 (±0.141) | 5.23 (±0.18) | 12.5 (±0.9) |
| 2      | 53.7 (±8.0) | 28.0 (±3.5) | 18.3 (±9.0) | 0.767 (±0.021) | 1.76 (±0.07) | 0.312 (±0.015) | 4.08 (±0.05) | 14.5 (±1.8) |
| 3      | 46.7 (±7.5) | 31.0 (±1.7) | 22.3 (±7.0) | 0.770 (±0.040) | 1.90 (±0.13) | 0.675 (±0.156) | 4.76 (±0.12) | 15.8 (±1.3) |
| 4      | 27.7 (±14.6) | 22.3 (±3.5) | 50.0 (±15.5) | 0.693 (±0.040) | 1.99 (±0.32) | 1.077 (±0.283) | 6.01 (±0.30) | 16.2 (±1.9) |
| 5      | 31.0 (±3.5) | 25.7 (±4.2) | 43.0 (±7.9) | 0.713 (±0.012) | 2.30 (±0.14) | 0.557 (±0.180) | 4.45 (±0.27) | 24.0 (±2.6) |
| 6      | 41.6 (±6.4) | 27.8 (±1.2) | 30.6 (±6.8) | 0.715 (±0.025) | 2.15 (±0.29) | 0.636 (±0.118) | 6.10 (±0.09) | 12.5 (±0.5) |
| 7      | 46.7 (±3.6) | 28.0 (±2.2) | 25.3 (±4.8) | 0.737 (±0.030) | 1.98 (±0.32) | 0.391 (±0.053) | 5.14 (±0.30) | 14.5 (±1.0) |
| 8      | 39.6 (±7.4) | 28.4 (±1.1) | 32.0 (±4.3) | 0.716 (±0.012) | 2.10 (±0.13) | 0.492 (±0.070) | 5.49 (±0.36) | 14.2 (±1.8) |
| 9      | 35.1 (±4.0) | 32.8 (±2.7) | 32.2 (±6.5) | 0.730 (±0.029) | 1.88 (±0.17) | 0.382 (±0.116) | 5.94 (±0.13) | 11.7 (±0.3) |
| 10     | 40.4 (±1.3) | 29.8 (±1.4) | 29.9 (±2.3) | 0.714 (±0.031) | 2.06 (±0.19) | 0.475 (±0.157) | 5.00 (±0.51) | 14.3 (±1.5) |
| Industrial | – | – | – | 0.785 (±0.037) | 2.93 (±0.20) | – | 5.32 (±0.09) | 7.7 (±0.6) |
designs (Table 3). When modifying the steam flow rate (first experimental design), the steam/powder ratio was negatively correlated \( (R^2 = 0.915) \) with the mass fraction of the fines particles and positively correlated \( (R^2 = 0.810) \) with the mass fraction of the oversize particles. On the other hand, there was no significant effect of the steam/powder ratio on the mass fraction of the agglomerates. A similar trend was observed when modifying the powder feed rate (second experimental design): the steam/powder ratio was negatively correlated \( (R^2 = 0.447) \) with the mass fraction of the oversize particles. This is consistent with the class by class growth mechanism reported by Barkouti [3] during the fluid-bed agglomeration of skim and whole milk powders, with first the association of initial particles to form intermediate structures, and in a second time, the association of these structures into larger agglomerates. Increasing the steam/powder ratio thus favors the agglomeration mechanisms, mostly by the increase of the steam flow rate according to the higher values of the correlation coefficients. Indeed, a higher steam flow rate should increase the exposure, of the powder surface to steam, promoting the formation of liquid and viscous bridges between the native particles, stickiness, and growth mechanisms. Regardless of the experimental design, the results did not demonstrate a significant effect of the drying time on the agglomeration yields. The agglomeration yields are thus mainly linked to the agglomeration stage. The drying time does not affect the agglomeration mechanisms or the mass proportion of the different classes of agglomerates within the range of the parameters tested in this study.

### Influence of process parameters on agglomerate properties

The effects of the process parameters on the properties of the dried agglomerates investigated in the two experimental designs are presented in Table 4. When modifying the steam flow rate (first experimental design), the steam/powder ratio was correlated with all the agglomerate properties. Increasing the steam flow rate inside the agglomeration tube resulted in an increase in contact density between the steam and the surface of the native particles. This affects the extent of agglomeration by increasing the occurrence of liquid

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**Table 3.** Effects of the process variables on the agglomeration yields for the two experimental designs. Values consist of the estimated coefficient of the linear model. Significant differences are indicated \( p < 0.05 \) (*), \( p < 0.01 \) (**), \( p < 0.001 \) (***)

| Responses                                      | Steam/Powder Ratio \((-)\) | Drying time (min) | Interaction | \( R^2 \) |
|------------------------------------------------|----------------------------|-------------------|-------------|---------|
| **First experimental design (effect of steam flow rate)** |                            |                   |             |         |
| Weight fraction of fines particles (%)        | -0.868***                  | -0.066            | 0.356**     | 0.915   |
| Weight fraction of agglomerates (%)          | -0.015                     | 0.403             | -0.167      | 0.194   |
| Weight fraction of oversize grains (%)       | 0.843***                   | -0.053            | -0.303      | 0.810   |
| **Second experimental design (effect of powder feed rate)** |                            |                   |             |         |
| Weight fraction of fines particles (%)       | -0.517*                    | 0.423             | 0.006       | 0.446   |
| Weight fraction of agglomerates (%)          | 0.636**                    | -0.264            | -0.280      | 0.566   |
| Weight fraction of oversize grains (%)       | 0.249                      | -0.306            | 0.112       | 0.170   |

**Table 4.** Effects of the process variables on the agglomerates properties for the two experimental designs. Values consist of the estimated coefficient of the linear model. Significant differences are indicated \( p < 0.05 \) (*), \( p < 0.01 \) (**), \( p < 0.001 \) (***)

| Responses                                      | Steam/Powder Ratio \((-)\) | Drying time (min) | Interaction | \( R^2 \) |
|------------------------------------------------|----------------------------|-------------------|-------------|---------|
| **First experimental design (effect of steam flow rate)** |                            |                   |             |         |
| Circularity (-)                                | -0.693*                    | 0.331             | 0.020       | 0.543   |
| Feret diameter (mm)                            | 0.797**                    | 0.230             | 0.101       | 0.740   |
| Mechanical strength (N)                        | 0.420*                     | -0.794**          | 0.056       | 0.741   |
| Water content (g.100 g\(^{-1}\))              | 0.355*                     | -0.913***         | -0.100      | 0.907   |
| Wetting time (s)                               | 0.674***                   | 0.480**           | 0.339**     | 0.901   |
| **Second experimental design (effect of powder feed rate)** |                            |                   |             |         |
| Circularity (-)                                | -0.066                     | 0.060             | -0.331      | 0.136   |
| Feret diameter (mm)                            | -0.195                     | 0.011             | 0.345       | 0.177   |
| Mechanical strength (N)                        | -0.298                     | -0.266            | 0.548*      | 0.510   |
| Water content (g.100 g\(^{-1}\))              | -0.132                     | -0.846***         | 0.012       | 0.734   |
| Wetting time (s)                               | -0.151                     | 0.704**           | 0.093       | 0.529   |
bridges, as well as the structure and properties of the agglomerates. Increasing the steam availability resulted in larger and less spherical agglomerates with increased water content and mechanical strength and poorer wetting properties. A similar positive relationship between steam pressure and mean particle diameter was reported by Vissotto et al.\(^2\) during the steam-jet agglomeration of cocoa beverage powder formulated with crystal or granulated sugars. Takeiti et al.\(^{14}\) also reported a significant effect of the steam pressure on the optimum dissolution time of maltodextrin powders agglomerated using steam-jet agglomeration. On the other hand, no significant effect of the steam/powder ratio on the properties of the dried agglomerates could be observed when modifying the powder feed rate (second experimental design). These results demonstrated that the steam flow rate is the limiting factor of the process in the range of experimental conditions studied here. On the contrary, Takeiti et al.\(^{14}\) reported a slight but significant effect of powder feed rate on the optimum dissolution time, and Vissotto et al.\(^2\) reported a negative influence of the powder feed rate on the mean particle diameter.

As expected, the drying step affected the water content of the dried agglomerates. Controlling the water content of the final agglomerates is essential in order to avoid caking and microorganism development during storage of the agglomerates. Regardless of the experimental design, the drying time was negatively correlated with the water content (\(R^2 = 0.907\) and 0.734 for the first and second experimental designs, respectively), and positively correlated with the wetting time (\(R^2 = 0.901\) and 0.529) of the final dried agglomerates. A strong influence of the drying time on the mechanical strength of the agglomerates was also observed in the first experimental design. Our results demonstrate that the drying step significantly influenced the characteristics of the final agglomerates, with adverse changes in their wetting properties. The drying stage at 90°C can lead to modifications of the structure of the agglomerates, e.g., by decreasing the mechanical strength, as observed in the first experimental design. For coarse particles, increasing liquid content generally increases granule strength through capillary forces up to the saturation state.\(^{15,16}\) Moreover, the modifications of the physicochemical state of the dairy components directly affect the rehydration kinetics of the material\(^{17}\) e.g., as a consequence of the partial crystallization of lactose also observed during the fluid-bed drying of milk powder by Yazdanpanah and Langrish.\(^{18}\) Similarly, considering the solubility of the agglomerates, Takeiti et al.\(^{14}\) observed a significant positive correlation of the drying temperature with the dissolution time of maltodextrin powders, and Vissotto et al.\(^2\) reported a significant positive correlation of the drying temperature with the insolubility of cocoa beverage powder. These authors showed a significant positive effect of the drying temperature on the mean particle diameter.\(^2\)

### Correlations between agglomerates properties

Table 5 gives the values of the linear correlation coefficients between the different measured responses considering the whole set of experiments from the two experimental designs. A strong negative correlation between the mass fractions of the fines particles and oversize particles was obtained (\(R = -0.944\)). This correlation showed that a more intense agglomeration process led to the formation of larger structures from the smaller ones, except for the agglomerate mass fraction, which remained constant. As expected, a strong negative correlation between the Feret diameter and the circularity of the agglomerates was observed (\(R = -0.662\)). These two structural properties were correlated in an opposite way with the mass fractions of the fines and oversize particles. Obtaining larger amounts of the oversize fraction led to larger and less spherical agglomerates.

Concerning the wetting properties of the agglomerates, we demonstrated a significant negative correlation.

### Table 5. Linear correlation coefficients of the linear regression for the responses measured during the two experimental designs. Values are given as the correlation coefficient. Significant linear regressions are indicated (\(p < 0.05\) (*)), \(p < 0.01\) (**), \(p < 0.001\) (***)

|                         | Fines particles (%) | Agglomerates (%) | Oversize grains (%) | Circularity (−) | Feret diameter (mm) | Mechanical strength (N) | Water content (g.100 g\(^{-1}\)) | Wetting time (s) |
|-------------------------|---------------------|------------------|---------------------|----------------|---------------------|----------------------------|------------------------|----------------|
| Fines particles (%)     | −0.086              | −                  | −                   | −              | −                   | −                          | −                      | −              |
| Agglomerates (%)        | −0.945***           | −0.246            | −                   | −              | −                   | −                          | −                      | −              |
| Oversize grains (%)     | −0.542***           | 0.120             | −0.567***           | −              | −                   | −                          | −                      | −              |
| Circularity (−)         | −0.528**            | −0.067            | 0.536***            | −              | −                   | −                          | −                      | −              |
| Feret diameter (mm)     | −0.151              | −0.378            | 0.270               | −0.189         | 0.022               | −                          | −                      | −              |
| Mechanical strength (N) | −0.249              | −0.043            | 0.257               | −0.372         | 0.144               | 0.301                      | −                      | −              |
| Water content (g.100 g\(^{-1}\)) | −0.282          | −0.137            | 0.318               | −0.108         | 0.413*              | 0.074                      | −0.535**              | −              |
| Wetting time (s)        | −0.120              | −                  | −                   | −              | −                   | −                          | −                      | −              |
(R = −0.535) between the water content and the wetting time of the agglomerates. On the other hand, Gabbott et al. [19] found that agglomerate water content had no effect on the dissolution rate of the drug substance in the wet agglomeration of pharmaceutical compounds during tablet production. We also observed a slight positive correlation (R = 0.413) between the Feret diameter and the wetting time, which is not classically reported in the literature.[2,20]

Obtaining large and dry agglomerates could be a disadvantage for the wetting properties of the agglomerates.

Conclusion

The steam-jet agglomeration pilot plant designed in this study made it possible to study the agglomeration of skim milk powder and to evaluate the influence of process parameters on the agglomerate growth mechanisms and properties. An increase in the steam/powder ratio resulted in a decrease in the proportion of the small agglomerates due to more intense agglomeration mechanisms. The agglomeration growth was controlled by the exchange surface between the steam and the native skim milk particles. Changes in the steam flow rate led to a greater impact on the extent of agglomeration than changes in the powder feed rate within the range of the process parameters investigated.

The final agglomerate properties strongly depended on the agglomeration growth. The structures of the final agglomerates were affected by the changes in the steam flow rate. An increase in the drying time also led to a significant reduction in the water content and an increase in the wetting time of the agglomerates. The stabilization of the agglomerates and the wetting properties are influenced by the agglomeration step as well as the drying step of the steam-jet agglomeration process. Therefore, the control of agglomeration and the drying step should be considered together.

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