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Influence of Bed Geometry on the Drying of Skimmed Milk in a Spouted Bed

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Abstract

In this present work, the fluidynamic and drying process of skimmed milk in conical and conical-cylindrical spouted bed was analyzed as a function of different bed geometry and operating conditions. It used three internal cone angles (45˚, 60˚ and 75˚), different loads of inert particles (1.50, 3.00 and 4.50 kg) and a fixed static bed height (20.50 cm). Polyethylene particles of 4.38 mm of diameter and 930.50 ± 0.3 kg/m³ of specific mass were used as inert particles. An artificial neural network model was trained to predict the peak pressure drop and the minimum spout velocity from an experimental data bank. The experimental results showed a significant effect of geometric characteristics of the bed on fluidynamics parameters. It was also observed for the operating conditions that conical spouted bed and cone angle of 45˚ were more suitable for drying skimmed milk. The neural network provided predictions in good agreement with experimental data.

Keywords

Cone Angle, Bed Geometry, Bed Configuration, Inert Particles, Neural Network

1. Introduction

Several studies have been conducted to investigate the operating conditions on the fluidynamics and drying of pastes in a spouted bed. Mathur and Epstein [1] reported that the minimum fluid velocity at which a bed would remain in the spouted state depended on solid and fluid properties on the one hand and bed geometry on the other hand. Olazar *et al.* [2] conducted a study using contactors with different geometries, solids of different characteristics and with wide range of air velocity. The authors observed that there were limits for cone angle, D_o/D_i and D_o/d_p. From that, it was obtained the design parameters for the stable operation in a spouted bed. Olazar *et al.* [3] investigated the effect of the operating conditions (base angle, air inlet diameter, stagnant bed height, particle diameter and air velocity) on the fountain geometry. It was seen that the contactor base angle had a major

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incidence on the fountain geometry. San Jose *et al*. [4] reported that the angle cone had significant effect on the air velocity, the particles trajectory, and height of the font.

Pham [5] verified the existence of stagnant regions and the difficulty of particles circulation in the annular region with inserting pastes in bed. Thus, it was concluded that the pastes significantly changed the fluidynamics parameters as well as the solid and fluid circulation patterns. Medeiros *et al*. [6] investigated the influence of the chemical composition on the spouted bed performance in drying pulps of tropical fruits. The authors found that the presence of pulps with high concentrations of sugars provoked problems of instability in the spout, while the presence of fat favored the bed dynamic. Recently, Nascimento *et al*. [7] studied different concentrations of milk fat and found that the pulp composition also affected the process, since the absence of fat in skimmed milk caused significant changes in the flow of inert, and therefore provided increase expressive values of pressure drop.

The context presented shows that there are several factors affecting the fludynamic parameters and drying process in spout beds. However, it is difficult to get a good prediction of minimum spout velocity, pressure drop behavior and evaporation capacity of the equipment as a function of different experimental conditions once there are some gaps in the information provided by literature. In general, the analysis of the influence of bed geometry is done in dry beds and for operations using pastes the bed geometry was fixed. In order to improve knowledge in this subject, the experimental analysis was divided in three stages: first it was performed the determination of fludynamic parameters (peak pressure drop and minimum spouting velocity). In the wet experiments, distilled water was used as standard paste for being the constituent corresponding to 75% to 97% of the weight of real pastes. With knowledge from the previous steps, the drying of real pastes was done. According to Ochoa-Martinez *et al*. [8] and Nascimento *et al*. [7] the absence of fat in skimmed milk leads to difficulties in the circulation of the inert particles, accumulation of paste on the surface of inert particles, and consequently, an increase in the values of pressure drop. So, skimmed milk was used to show the potential improvement of drying with three different cone angles. In addition, a neural network was designed and trained with the data base to predict the minimum spouting velocity and the peak pressure drop on the spouted bed for the experimental conditions studied.

2. Materials and Methods

2.1. Equipment and Operations Conditions

The fluidynamics experiments were performed in a spouted bed consisting of an inox iron cylindrical vessel, with 120 cm of height, 30 cm of diameter, inlet diameter with 3 cm and three lower cone angles (45˚, 60˚ and 75˚). **Figure 1** shows the schematic diagram of the experimental setup.

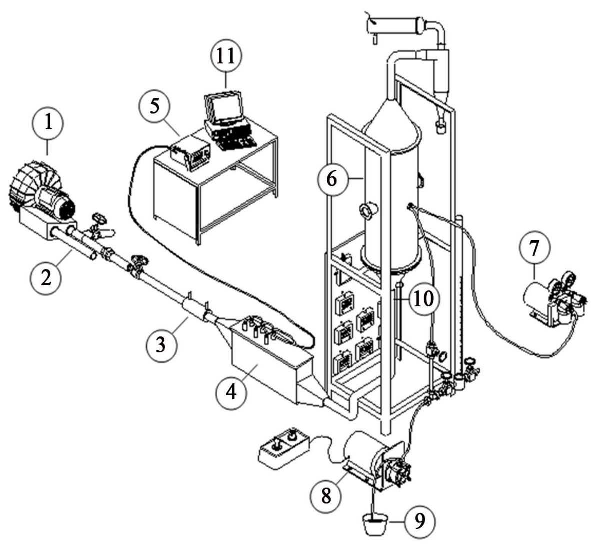


Figure 1. Schematic diagram of the experimental apparatus: (1) blower; (2) by-pass system; (3) Venture; (4) heat exchanger; (5) temperature controller; (6) drying chamber; (7) air compressor; (8) peristaltic pump; (9) paste reservoir; (10) inlet air nozzle; (11) acquisition unit.

Figure 2 presents the bed specifications used in this study and the bed dimensions are presented in **Table 1**.

A Venture nozzle is employed, whose geometric factors are defined in **Figure 3**.

Polyethylene particles of 4.38 mm of diameter and 930.50 ± 0.3 kg/m^3 of specific mass as inert particles were used in the experiments.

2.2. Experimental Description

Firstly the peak pressure drop characteristic and minimum spouting velocity in both conical and conical-cylindrical spouted beds were obtained based on the curve of the pressure drop versus the superficial air velocity from both increasing and decreasing the superficial air velocity, according to the methodology proposed by Mathur and Epstein [1]. The experimental operating conditions are summarized in **Table 2**. All measurements were triplicate in order to check the reproducibility of the data accuracy. The values of pressure drop are the measurements of empty bed pressure drop subtracted of the measurements of bed pressure drop with the load of particles.

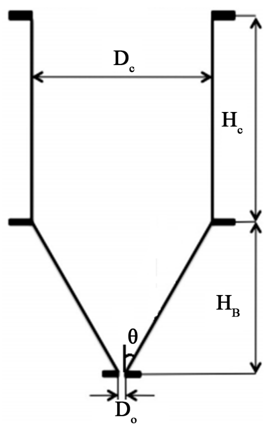


Figure 2. Bed specifications.

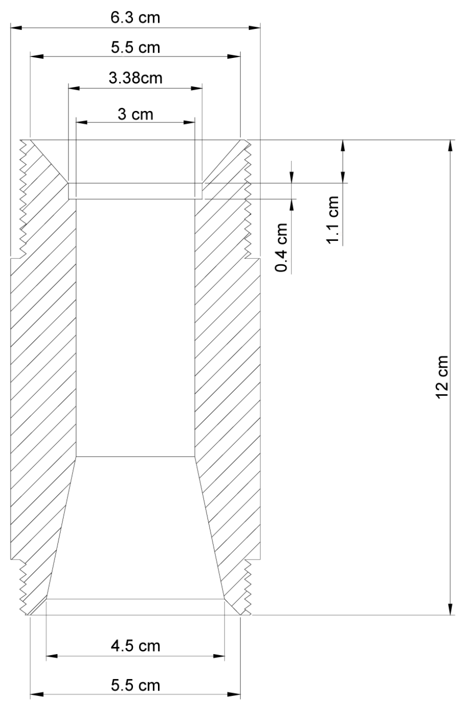


Figure 3. Inlet nozzle (Venture).

Table 1. Bed dimensions.

θ (˚)	H_B (cm)	D_c (cm)	H_c (cm)	D_0 (cm)
45	28.70	30	120	3
60	20.50	30	120	3
75	16.50	30	120	3

Table 2. Operating conditions.

Temperature (˚C)	θ (˚)	m_p (kg)	H_0 (cm)	Bed configuration
100	45	1.50	18.00	Conical
100	45	3.00	24.00	Conical
100	45	4.50	28.70	Conical
100	60	1.50	15.00	Conical
100	60	3.00	20.00	Conical
100	60	4.50	23.50	Conical-cylindrical
100	75	1.50	13.00	Conical
100	75	3.00	17.50	Conical-cylindrical
100	75	4.50	21.00	Conical-cylindrical
100	45	1.64	20.50	Conical
100	60	3.00	20.50	Conical
100	75	3.84	20.50	Conical-cylindrical

After that, the experiments that followed employed distilled water as standard paste in order to build an initial background on drying pastes. Finally, drying experiments using skimmed milk were carried out. Measurements of inlet air temperature and velocity, bed pressure drop, dry and wet bulb temperatures at the cyclone exhaust were available. Data was collected every 30 seconds by the acquisition system, 1024 points at a frequency of 500 Hz. Dry and wet bulb temperature measurements were converted to relative humidity values of the exhaust air. The inlet air temperature and inlet air velocity were at 100˚C and 1.30 u_{mj}, respectively.

2.3. Artificial Neural Networks

An artificial neural network (RNA) was proposed to predict the minimum spout velocity, pressure drop on the spouted bed for different cone angles and load of inert particles. The RNA can represent non-linear processes with complex structures and, in some cases, provide better results than empirical correlations [9], they may be an interesting and promising alternative to estimate fluidynamics parameters for different bed configurations. Another advantage to be highlighted and that fits the approach of this study is that neural networks are a simple alternative for processes that involve phenomena which are complex and of difficult mathematical description.

The neural network was developed using Neural Network Toolbox in MATLAB 2007 software. This was a three layer feedforward neural network, with one single hidden layer, two inputs and two outputs as shown in **Figure 4**.

The number of neurons in the hidden layer was chosen by trial and error, as suggested by Himmelblau [9], starting with 2 neurons and adding up some more until the network performance in estimating the correct output is satisfactory. The number of neurons for this study was 3. Backpropagation was used as learning method.

3. Results and Discussion

3.1. Minimum Spouting Velocity

Figure 5 shows the values of minimum spout velocity as a function of cone angle obtained for polyethylene particles, different load of inert material. The air temperature was keep at 100˚C. It is seen in **Figure 5** that, for the

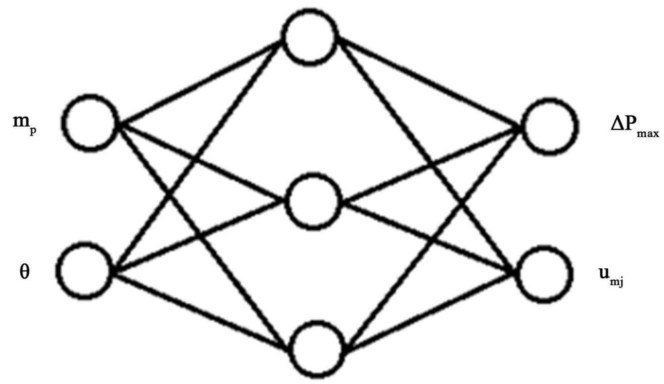


Figure 4. Schematic representation of the neural network used to estimate fludynamic parameters. Where, m_p is the load of inert material, θ is the cone angles, u_{mi} is the minimum spouting velocity and ΔP_{max} is the peak pressure drop.

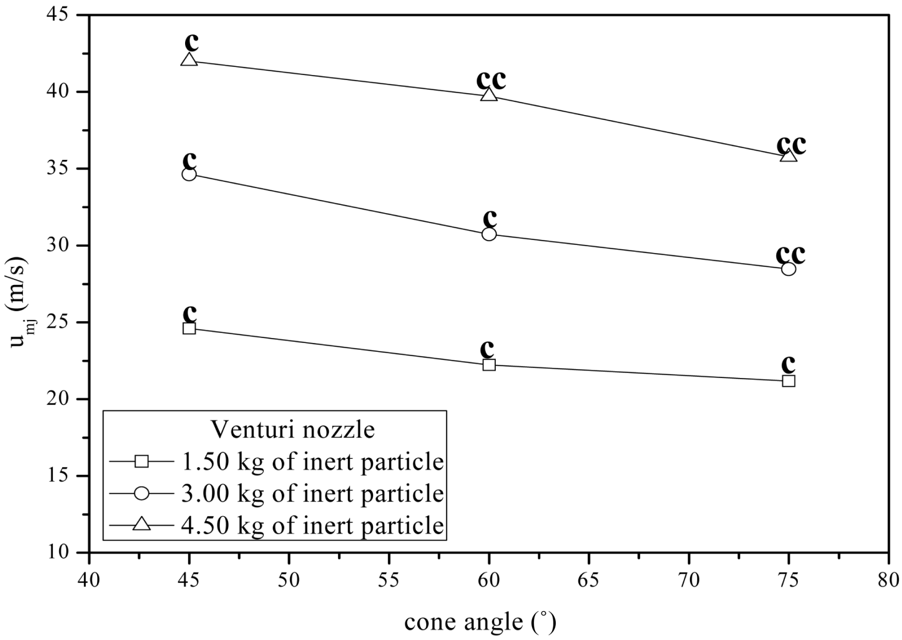


Figure 5. Minimum spout velocity as a function of cone angle obtained for different load of inert particle. *c-conical spouted bed, **cc-conical cylindrical spouted bed.

operational conditions employed, the minimum spouting velocity was influenced by the cone angle (θ) and by the load of inert particle (m_p). As it is seen in these results, a decrease in θ leads to higher values of u_{mj} for all values of m_p studied. This is due to the fact that for a fixed load of inert particles, increasing the cone angle decreases the static bed height, H_0, (**Figure 6**) and, consequently, smaller air velocity is needed to support the spouted state. In agreement with these results, Mathur and Epstein [1] reported that the minimum spouting velocity depends on the solid characteristics, fluid properties and bed geometry. Mathur and Epstein [1] also observed that for conical-cylindrical spouted bed the intensity of cone angle effect depending of other variable, as example, column diameter, D_c.

Another aspect that should be analyzed is the influence of cone angle on the fluidynamic for fixed static bed height. **Figure 7** presents the values of minimum spout velocity as a function of cone angle obtained for polyethylene particles, fixed static bed height and 100˚C.

It is shown in **Figure 7** that u_{mj} increases as θ is increased between 45˚ to 60˚, on the other hand, the minimum spouting velocity remains practically constant increases θ from 60˚ to 75˚. This is due to the fact that for a fixed static bed height (**Table 2**), increasing the cone angle from 45˚ to 60˚ the m_p difference was higher than

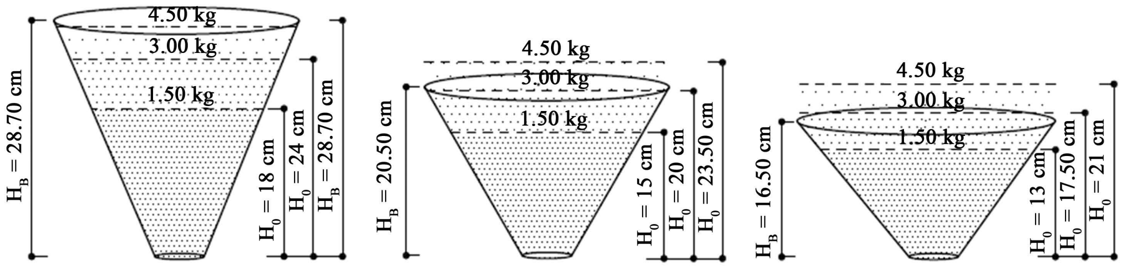


Figure 6. Static bed height for each base angle: (a) cone angle of 45˚; (b) cone angle of 60˚; (c) cone angle of 75˚.

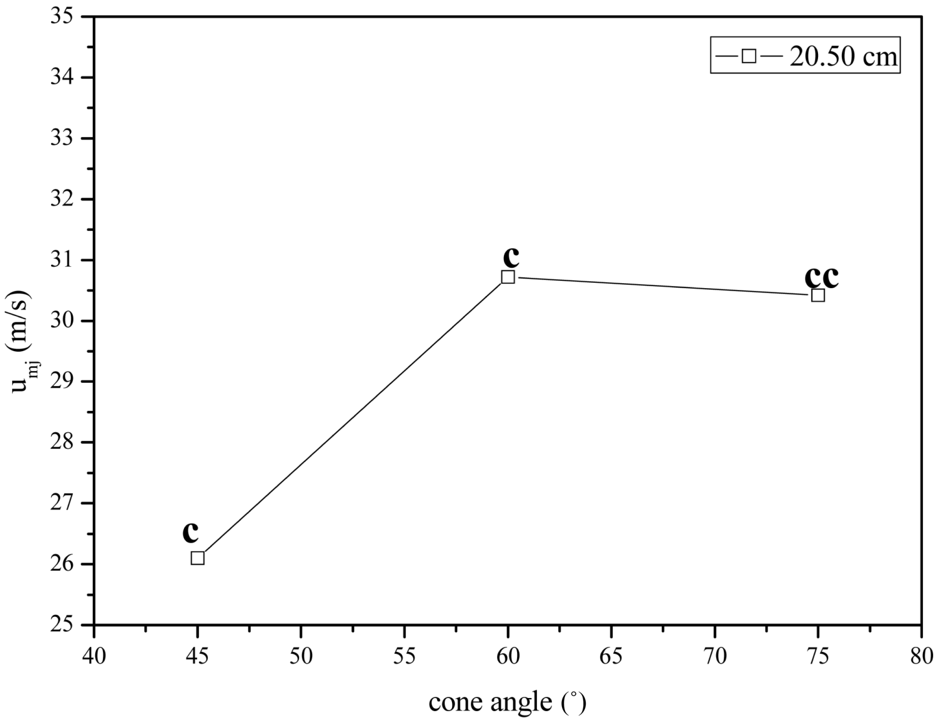


Figure 7. Minimum spouting velocity as a function of cone angle obtained for fixed static bed height. *c-conical spouted bed, **cc-conical cylindrical spouted bed.

varies cone angle form 60˚ to 75˚, 1.36 e 0.84 kg, respectively. Thus, a higher air velocity is required to maintain spouting regime increasing θ from 45 to 60˚.

Another aspect that must be taken into account is the bed configuration used. As one can observe in **Figure 7** it was used two distinct bed configurations: conical and conical-cylindrical spouted bed. According to Wang *et al.* [10], in conical spouted beds where the solids inventory is restrained within the conical region below the cylindrical section, the hydrodynamics of the conical spouted bed are quite different from that of the conventional cylindrical spouted beds. Kmiec [11] reported that the minimum spouting velocity in a conical spouted bed is more dependent on the bed height than the minimum spouting velocity in conical-cylindrical spouted beds. Mathur and Epstein [1] analyzed the data predict by the Mathur–Gisler Equation for different experimental data provided by literature for conical-cylindrical spouted bed bed. The authors observed that for columns up to 30.5 cm diameter the angle cone did not have significantly effect on the minimum spouting velocity. Although, in a 61 cm column, the spouting velocity for wheat was 10% higher with an 85˚ cone than with a 45˚ cone. It was also observed that the large column diameter, D_c, results were better correlated if the exponent to the ratio D_i/D_c was reduced to 0.23 for 45˚ and 60˚ cone angles and to 0.13 for 85˚. However, Olazar *et al.* [12] found that D_c should not be used in the correlation to predict u_{mj} in conical beds, because according to the authors this velocity will remain unchanged with variation in D_c as long as the bed remains entirely in the conical section.

Olazar *et al*. [2] conducted a study to delimit the application ranges of spouting regimes in conical contactors. The experiments were carried out with extension to solid of different characteristics, contactors with different geometry and with wide ranges of gas velocity. The authors found that particle diameter, d_p, had great effect, since there are restricted ranges of cone angles and inlet diameter for each values of d_p. This information indicates that this subject has to be treated with more care. The authors also observed that for high static bed height, the effect of the cone angle on the hydrodynamics it was more pronounced. Similar behavior was observed by Wang *et al*. [10].

3.2. Peak Pressure Drop

Figure 8 shows the values of peak pressure drop as a function of base angle obtained for polyethylene particles, different load of inert material and inlet air temperature of 100˚C. As observed in **Figure 8**, an increase in the cone angle decreases the peak pressure drop. As presented before in **Figure 6** for a given m_p, a decrease in θ increases in static bed height, H_0. Consequently, there is more air resistance and a higher pressure drop is required to break the bed and open the spout [13].

It was also observed that the effect of cone angle was less pronounced for 1.50 kg of inert particles. This is explained by the fact that was only used conical spouted bed and the m_p variation between for all cone angles studied was very similar. However, for 3.00 and 4.50 kg of inert particle it was used conical and conical-cylindrical spouted bed as showed in **Table 2**. These results showed that for higher load of inert particles the effect of the bed configuration was more pronounced. According to Mathur and Epstein [1] and Moustoufi, Kulah and Koksal [14], the hydrodynamics of conical spouted beds is significantly different from that of conventional spouted beds.

Another aspect studied in this work was the influence of cone angle on fluidynamic parameters for fixed bed height. There is a conflict between the information provided by literature. According to Bi [15], the Mukhlenov-Gorshtein [16] correlation predicts that $\Delta P_{máx}$ increases with increasing cone angle for given static bed height. The opposite is predicted by the correlations of Gelperin *et al.* [17] and Olazar *et al.* [18]. Wang *et al.* [10] did not observe a clear effect of cone angle on $\Delta P_{máx}$. In order to confirm this information, experiments were conducted using fixed static bed height and distinct cone angles, as shown in **Figure 9**.

Experimental evidences presented in **Figure 9** demonstrate the effect of cone angle on the peak pressure drop. It was observed for a fixed bed height, an increase in θ leads higher values of $\Delta P_{máx.}$ As shown in **Table 2**, for a fixed static bed height, the load of inert material increases as the cone angle is increased. Consequently, the

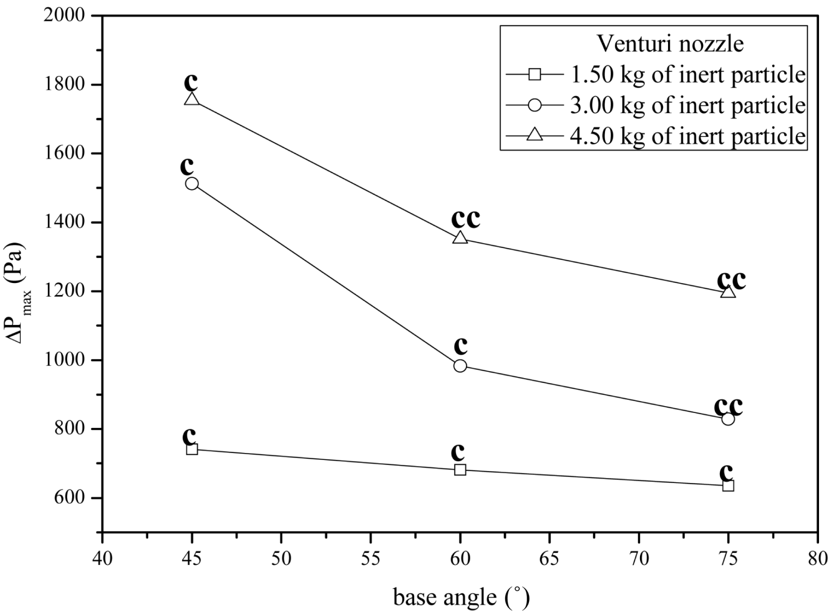


Figure 8. Peak pressure drop as a function of cone angle obtained for different load of inert particle. *c-conical spouted bed, **cc-conical cylindrical spouted bed.

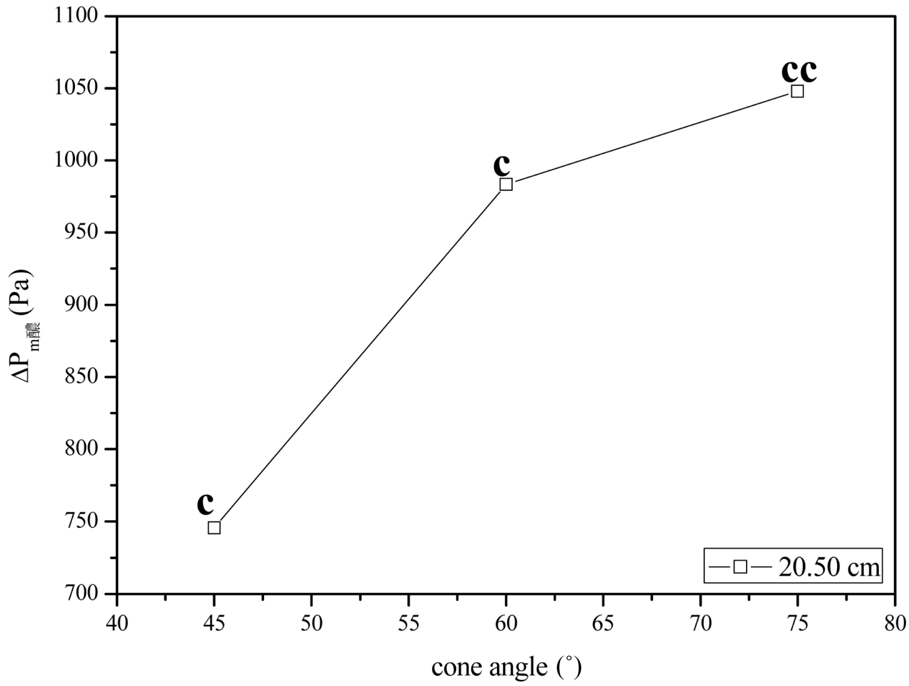


Figure 9. Peak pressure drop as a function of cone angle obtained for fixed static bed height. *c-conical spouted bed, **cc-conical cylindrical spouted bed.

measured values of $\Delta P_{máx}$ increases as the cone angles are increased. In the same way, it is observed that the effect of cone angle was more pronounced cone angles between 45˚ to 60˚ and 45 to 75˚. Whereas for θ from 60 to 75˚ the $\Delta P_{máx}$ variation is very small, since the m_p variation was not large to provoke a pronounced increase in $\Delta P_{máx}$. From **Figure 9**, it can be seen that the intensity of cone angle effect was dependent on the bed configuration.

The experimental results obtained in this work showed that the fluidynamic parameters of spouted bed were dependent on bed configuration, bed geometry and operating conditions. Thus, a confinable tool to predict the minimum spouting velocity and the peak pressure drop for different bed configuration is very useful and necessary.

3.3. Neural Network

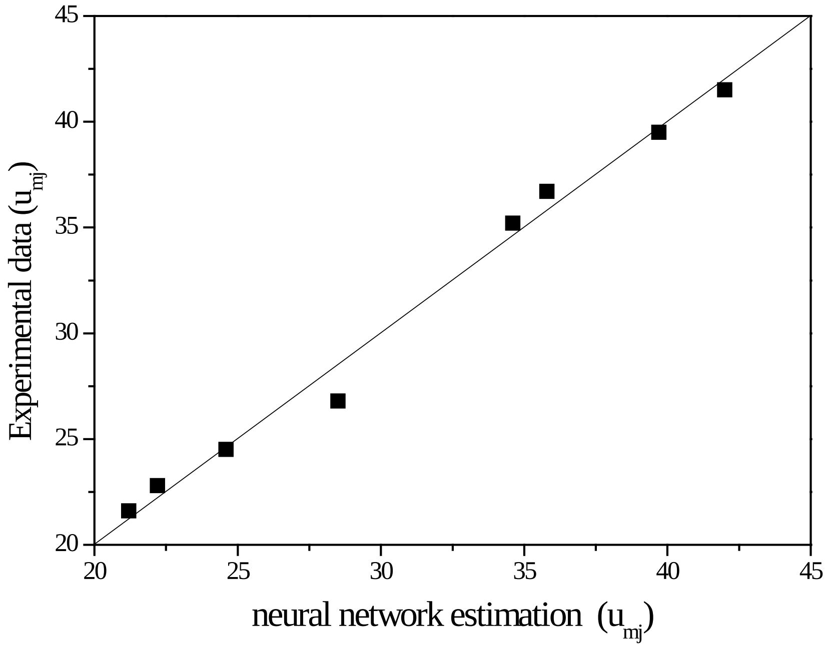
A neural network model was designed from experimental data to predict the minimum spouting velocity and peak pressure on the spouted bed for different cone angles and load of inert particle. **Figure 10(a)** and **Figure 10(b)** show the values of fluidynamic parameters provided by the neural networks and experimentally data obtained.

As observed in **Figure 10(a)** and **Figure 10(b)**, predictions by the neural network agree well with the experimental data, once the predicted values were close to 45˚ line. The results presented in **Figure 10(a)** and **Figure 10(b)** indicates that the RNA is useful method for predicting minimum spouting velocity and peak pressure drop of conical and conical-cylindrical spouted beds.

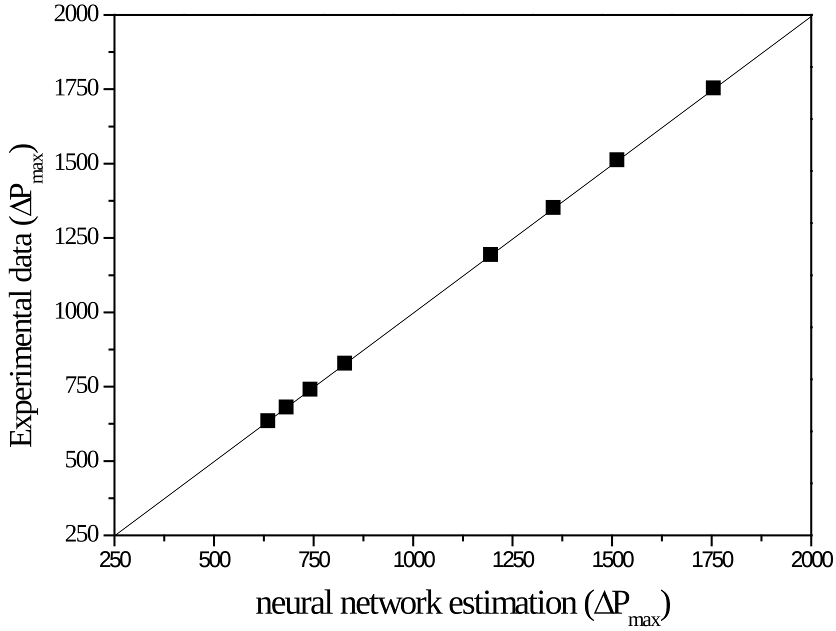
Neural network proposed in this work was trained and evaluated with experimental data for u_{mj} (30.72 m/s) and $\Delta P_{máx}$ (983.51 Pa) and it was obtained the respective values for u_{mj} (30.70 m/s) and for $\Delta P_{máx}$ (1027.60 Pa). It was observed that the network fitted best the measured values of minimum spouting velocity, since the error provided by the network is close to the experimental error.

3.4. Water Evaporation

The information obtained and discussed in the previous section were essential for to initiate the experimental runs using distilled water. **Table 3** shows the maximum capacity for evaporation water obtained from experimental measured for stable conditions.



(a)



(b)

Figure 10. Experimental and estimated data for the neural network: (a) u_{mj}; (b) ΔP_{max}.

Experimental investigation showed that the effect of m_p on maximum capacity for evaporation water, Q, was more pronounce than θ. As previously mentioned by Almeida *et al.* [19] the load of inert particles had a strong influence on the maximum allowable feed flow rate. This is because an increase in m_p increases the specific area of the bed. So, as evaporation occurs on the particles surface, an increase in the specific area increases the evaporation rate.

Referring to the effect of cone angle on maximum capacity for evaporation water, it was observed that Q had only an improvement of 5 ml/min. as θ varies from 75˚ to 60˚ or 75˚ to 45˚ for both load of inert particle available. Rodrigues [20] studied the effect of the cone angle on the maximum capacity for evaporating water. The author observed that the rate of water evaporation per unit of inert solid volume increases as θ varies from 60 to 30˚. It is also verified that the annulus aeration improves as θ decreases. However, this information cannot be compared, since the author used fixed bed height. So the author assigned this behavior to the fact that a higher in θ implies increasing in m_p, which consequently increases Q. It is noted that there is insufficient information about the effect of cone angle on maximum capacity for evaporation water mainly drying pastes provided by literature. The most researches analyze the inference of bed geometry of dry bed.

Referring to the effect of water on the fluidynamic behavior, **Figure 11** shows the dimensionless bed pressure drop as a function of time for 100˚C, $1.30u_{mj}$, 4.50 kg of inert particles and cone angle of 60˚.

As **Figure 11** shows the dimensionless bed pressure drop practically did not change for feed flow rates below 50 ml/min ($\Delta P_t/\Delta P_{t=o}$ close to 1). However, it decreased for feed flow rates above 55 ml/min. Similar results have been reported by Patel *et al.* [21], Schneider and Bridgwater [22], Almeida *et al.* [19] and Bitti *et al.* [23]. According to the abovementioned authors less air passes through the annulus as the amount of paste fed to the dryer is increased. The air main stream goes through the spout channel, reducing, in this way, the bed pressure drop. Another possible way to understand this phenomenon is that the presence of a liquid phase increases particle agglomeration, slowing down particle motion in the annulus. The same behavior was also observed for the other cone angles studied.

3.5. Drying of Skimmed Milk

Based on experimental results presented in **Table 3**, Q was obtained for 4.50 kg for all cone angles used. Thus, the drying experiments using skimmed milk were conducted for 4.50 kg, 1.30 u_{mj}, 100˚C and different cone angles. **Figures 12(a)-(c)** show the dimensionless bed pressure drop as a function of time for cone angles of 45˚, 60˚ and 75˚, respectively.

Despite cone angles did not had great effect on maximum capacity to evaporating water, **Figures 12(a)-(c)** showed the effect of dimensionless pressure drop during skimmed milk drying. By comparing **Figures 12(a)-(c)** it became clear that for the same operating conditions the dimensionless pressure drop had different behavior for θ = 60˚. The dimensionless pressure drop deviated from the straight line corresponding to $\Delta P_t/\Delta P_{t=o}$ = 1 for feed flow rates varying from 10 to 35 ml/min. Values of dimensionless pressure drop were higher than one for most feed flow rates employed. Similar behavior has been reported by Almeida *et al.* [19] and Nascimento *et al.* [7].

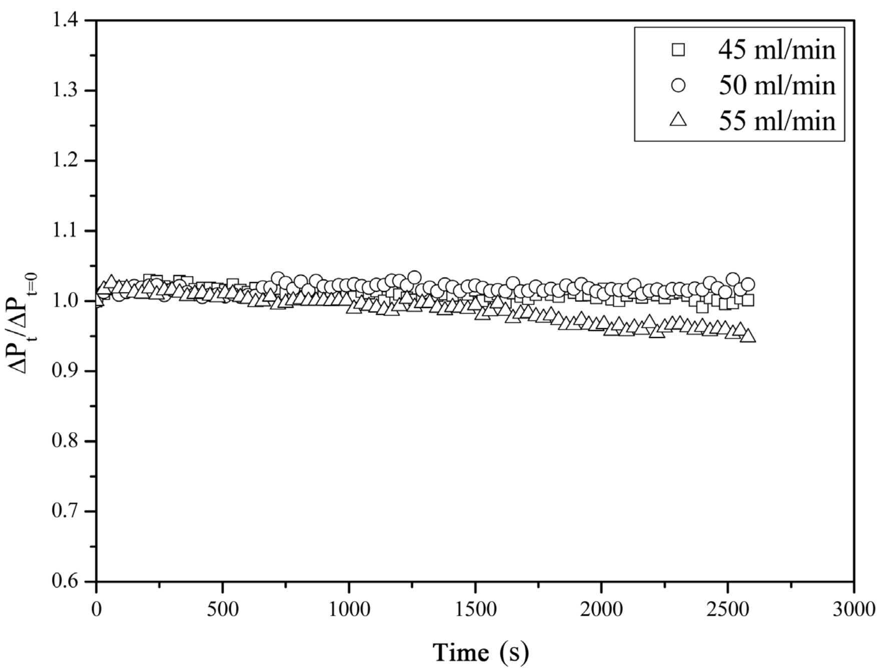


Figure 11. Dimensionless pressure drop as a function of time for T = 100˚C, mp = 4.5 kg and θ = 60˚, parametrizing Q.

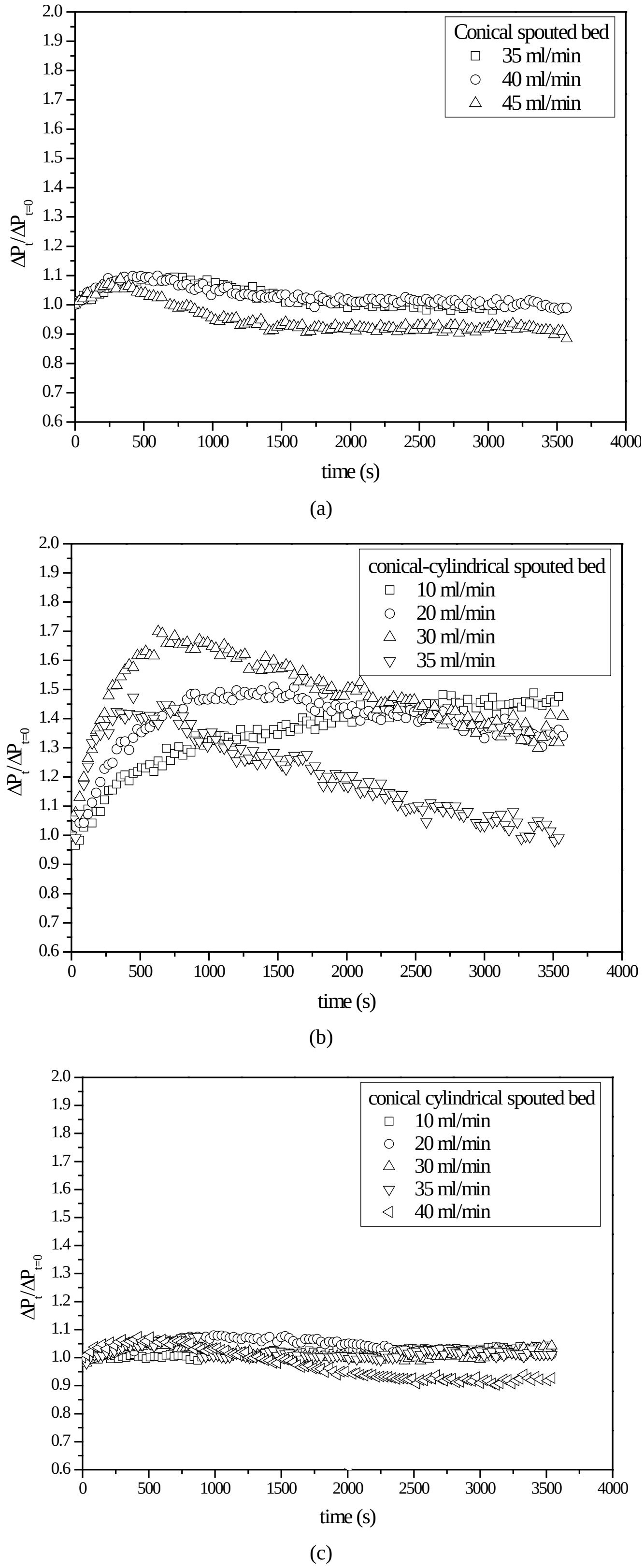


Figure 12. Dimensionless pressure drop as a function of time, parametrizing Q_{sm}: (a) cone angle of 45˚; (b) cone angle of 60˚ and (c) cone angle of 75˚.

Table 3. Maximum allowable water feed flow rates for different cone angles, 1.3 u_{mj} and 100˚C.

θ (˚)	m_p (kg)	Q (mL/min)
75	3.00	35
60	3.00	40
45	3.00	40
75	4.50	45
60	4.50	50
45	4.50	50

Comparing these figures was noteworthy that the dimensionless bed pressure drop practically did not change for feed flow rates below 45 ml/min ($\Delta P_t/\Delta P_{t=o}$ close to 1) for 45˚ and 40 ml/min for 75˚. However, it decreased for feed flow rates above 45 and 40 ml/min for cone angles 45 and 75˚, respectively. Similar results have been reported using water as paste by Almeida *et al*. [19], Patel *et al*. [21], Schneider and Bridgwater [22] and Bitti *et al*. [23].

The experimental evidences indicated that dimensionless pressure drop for skimmed milk had similar behavior when it was used distilled water for cone angles of 45˚ and 75˚, as observed comparing **Figure 11**, **Figure 12(a)** and **Figure 12(c)**. One can be said that the bed did not "feel" the presence of the paste. However, it was also observed that the feed flow rate of skimmed milk was smaller than water, as shown in **Table 4**. Similar results have been reported by Almeida *et al*. [19] and Nascimento *et al*. [7].

An aspect that must be taken into account is the bed configuration used in this work (conical and conical-cylindrical spouted bed). According to Olazar *et al*. [12], for conical spouted beds, cone angles higher than 60˚ are not recommended because the solid circulation rate is very low. Elperin *et al.* [24] reported that a cone angle of 40˚ - 45˚ was the optimum for maximizing solids circulation rate. Thus, the stable values of $\Delta P_t/\Delta P_{t=o}$ for conical spouted bed and cone angle of 45˚ can be related to the high circulation of the inert particles, which minimized the effect of paste adhesion as related by Nascimento *et al*. [7]. On the other hand, the lower limit of cone angle for conical beds is 28˚, as the bed is unavoidably unstable for lower angles [12].

The high values of dimensionless pressure drop using cone angle of 60˚ can be a consequence of dead zone (zone of stagnant solids) that is formed near the inlet orifice for high values of cone angles [25]-[27]. Moreover, the absence of fat in skimmed milk provokes difficults in the particles circulation [7]. The dead zone reduces solid circulation and is not recommended for drying of pastes. However, **Figure 12(c)** showed that cone angle of 75˚ was more stable than 60˚ (**Figure 12(b)**). In both cases it was used conical-cylindrical spouted beds. According to Mathur and Epstein [1] for conical-cylindrical beds, an increase in cone angle leads increases in the cross flow rate in the upper region of the bed. Thus, there was more solid circulation using the cone angle of 75˚, which favored the drying of skimmed milk.

The analysis of the three steps: fludynamic without paste, water evaporation and drying paste showed that the spouted bed technique was complex and one should be taken into account several factors to understand them. For instance, cone angle had not great effect on fludynamic using water, although it was observed a significant inference by using a real paste (skimmed milk).

4. Conclusions

From the results of this study, it was found that fluidynamic parameters and maximum capacity of water evaporation were influenced by both cone angles and load of inert particle in the range of operating conditions analysed. It was also found that the effect of load of inert material on water evaporation was more pronounced than cone angle. The neural network was a good tool for prediction when you had a data bank.

Drying experiments showed that the cone angle had significant effect on the dimensionless pressure drop. The evidences show that a conical spouted bed with cone angle of 45˚ is recommended to drying skimmed milk.

Table 4. Maximum flow rate of distilled water and skimmed milk in spouted bed: 1.30 u_{mj}, 100˚C.

θ (˚)	m_p (kg)	Q (mL/min)	Q_{sm} (mL/min)
75	4.50	45	35
60	4.50	50	30
45	4.50	50	40

Acknowledgements

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Nomenclature

D_0	Diameter of the inlet	cm
D_c	Diameter of the column	cm
D_i	Diameter of the bed bottom	cm
H_0	Static bed height	cm
H_B	Cone height	cm
H_c	Column height	cm
m_p	Load of inert	kg
$P_{máx}$	Peak pressure drop	Pa
Q	Maximum feed flow rate of distilled water	mL/min
Q_{sm}	Maximum feed flow rate of skimmed milk	mL/min
u_{mj}	Minimum spouting velocity	m/s

Greek Letters

θ	Cone angle	˚
Δ	Difference	-