

EXPERIMENTAL STUDY AND SIMULATION OF MASS DISTRIBUTION OF THE COVERING LAYER OF SOYBEAN SEEDS COATED IN A SPOUTED BED

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Abstract - In previous work, it was observed that the covering of soybean seeds with bacteria and micronutrients enhances vigorous growth of the plant thereby avoiding use of ammoniacal fertilizers. In the spouted bed covering can be done by pulverization of the coater slurry on the soybean seeds using a pneumatic atomizer. The optimum thickness of the cover allows the fundamental gaseous interchanges for germination and provides the ideal conditions for bacterium activity. The objective of this work was to study the influence of the process variables on thickness of the cover. A simulation of the mass distribution of seeds was obtained using a population balance model. Through the results obtained the operational conditions under which the coating layer distribution were determined has the greatest uniformity.

Keywords: population balance model, coating, soybean seeds, spouted bed.

INTRODUCTION

The coating technique can be used in covering the seeds of agricultural products, with the objective of achieving adherence of macro and micronutrients, inoculants (bacteria), fungicides to their surfaces or modifying their format and size with inert material. The use of spouted beds in the coating of soybean seeds with micronutrients and inoculants offers several advantages, mainly taking into account the characteristics and properties of soybeans (Lucas, 2000):

- 1) rational dosage of micronutrients;
- 2) decrease in the leaching of micronutrients;
- 3) reduction in fuel and labor expenses;
- 4) optimization of the use of nitrogen fertilizers.

The inoculation process permits nitrogen fixation, so some part of the soybeans needs can be obtained

from the air, minimizing the use of ammoniacal fertilizers. The process consists in adherence of the nitrogen-fixing *Bradyrhizobium* bacterium to the seed surface. The bacteria will adhere to the plant roots as a nodule and convert the nitrogen in air to meet the plant's needs.

The inoculant is mixed with water and also with molybdenum and cobalt micronutrients, which are important in the process of nitrogen fixation as a consequence of the nodulation of roots, but are found at low concentrations in Brazilian soil. This slurry is used to coat the seeds and the result of the increased nitrogen fixation is more vigorous plants.

Figure 1 shows the presence of nodules on the roots of plants from seeds submitted to this process.

The effects of the process of soybean seed inoculation with *Bradyrhizobium* measured in terms of the index of germination, vigor, appearance and

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fissures of seeds and number of nodules on the roots was evaluated by Lucas (2000). The results proved the effectiveness of the use of the spouted bed for soybean seed inoculation.

Lucas (2000) showed that the final quality of the soybean seeds as well as the efficiency of the process is strongly related to the operational variables. However, it is important not only to evaluate the total amount of covering adhering to the seeds, but also to study the coating mass distribution on the soybean seeds.

Besides the total amount of coating on the seeds, the coating mass distribution is of primary importance. Layer thickness must assure germination of the seeds and also the bacteria activity. This means it must provide the ideal gaseous interchanges, the fixation of nitrogen and the correct concentration of micronutrients, because very thick layers impair germination of seeds by impeding gaseous interchanges, while very thin ones do not

assure the ideal activity of the bacterium in the process of nitrogen fixation and may not contain the ideal amount of micronutrients.

Liu and Lister (1992) observed relationship between coating mass and *in natura* seed mass in several types of seeds coated in a spouted bed (see Figure 2). They observed that two soybean seeds with the same mass *in natura* can have different coating masses. It is worth noting that the coating mass may be not proportional to the *in natura* seed mass.

The objective of this work was to identify the conditions under which the mass distribution of the coating layer has the greatest uniformity. In order to understand the influence of the main operational variables of the covering process, a simplified mathematical model based on population balance was developed. The model was validated with experimental values obtained by analysis using the image technique.

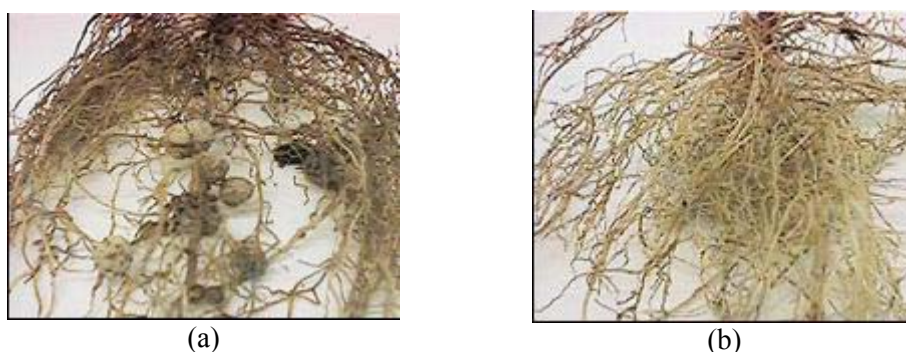


Figure 1: Roots of soybean plants with inoculum (a) and without inoculum (b)

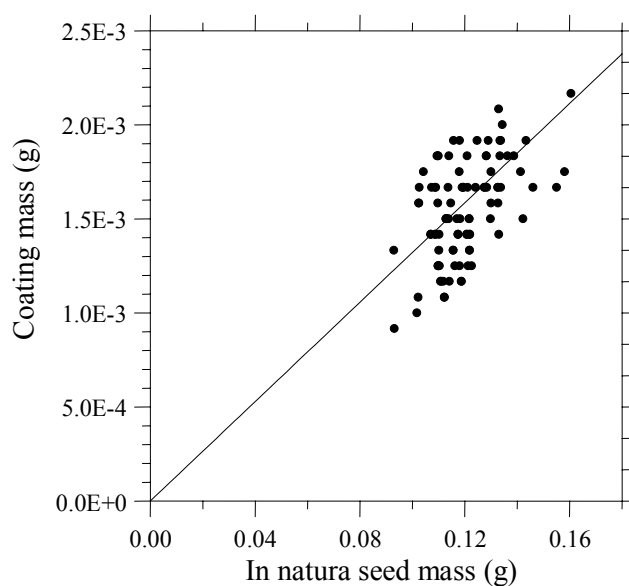


Figure 2: Coating mass versus *in natura* seed mass

MATERIALS AND METHODS

Materials

The *Vencedora* variety of soybeans used in the experiments has a germination rate of around 90%. The concentration of the coating slurry (C_S) was 0.13 g solids/ml of slurry, with 95% micronutrients and 5% inoculum. The commercial product used as micronutrient was *Nodulus* (supplied by Bio-Soja Ltd.), which contains 1% cobalt and 10% molybdenum. The inoculum was *Emerge Wetttable Powder* (supplied by Milenia Agrociências S/A), which contains *Bradyrhizobium* bacterium. Table 1 shows the properties of the soybean seeds used in this work.

Experimental Apparatus and Operational Conditions

Figure 3 shows a scheme of the experimental apparatus. Air was impelled by a 7.5 HP blower (1), and its flow rate was adjusted by gate valves and one bypass (2). The air was heated by electrical resistances (3) connected to a voltage variation device (4). Temperature was adjusted

by a double-pipe heat exchanger (5). A Pitot tube (6) calibrated with a hot wire anemometer was used to measure of the spouted air flow rate. Pressure drop was measured with a micromanometer (7). Air temperature was measured using a constantan-copper thermocouple (8) located at the inlet of the spouted bed (9). The spouted bed was made of stainless steel with the following dimensions: diameter of the cylindrical part, 0.21m; diameter of the base, 0.035 m and cone angle 60°. The spouted bed was equipped with a glass window (10) for observation of the atomization system. The slurry (11) was agitated and heated by a plate (12) and it was fed into a double-fluid atomizing nozzle (14) by a peristaltic pump (13). The atomization air flow rate was adjusted with a rotameter (15).

The spouted air temperature was not allowed to go above 39°C due to the presence of the bacterium. The initial seed mass was 2500g and the coating process time was 20min. At the end of this time, a random sample of 100 seeds was removed and the seeds individually weighed with and without coating.

Table 1: Physical properties of soybean seeds of the *Vencedora* variety

ρ_s (kg/m ³)	ϕ	dp (m)
$1.17 \cdot 10^3$	0.9	$6 \cdot 10^{-3}$

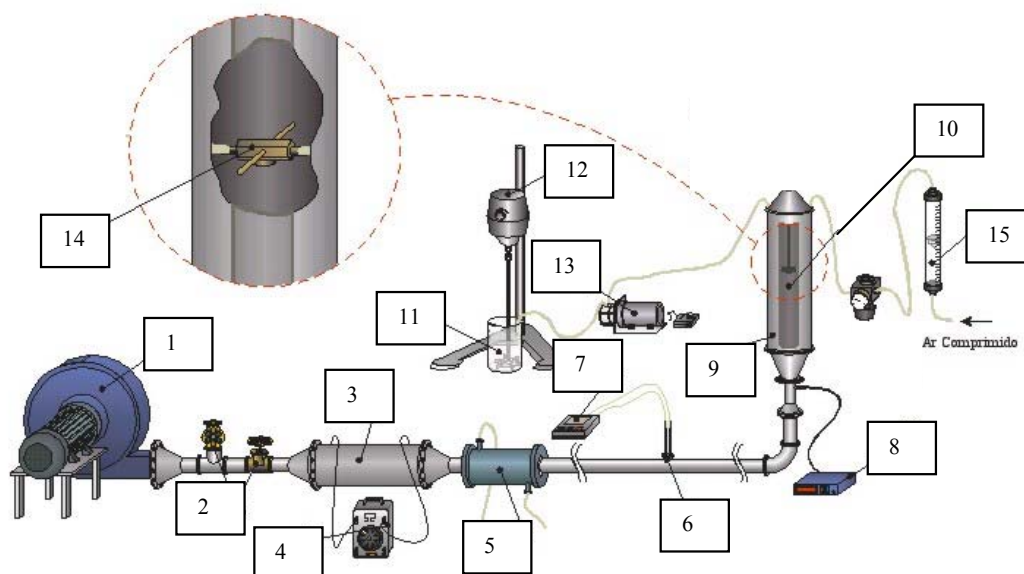


Figure 3: Experimental apparatus

Determination of the Dispersion Index

The dispersion index (DI) is a dimensionless value related to the degree of uniformity of the seeds. It is defined as the slope of the straight lines parallel to the central line shown in Figure 4. These upper and lower lines intercept the respective outlier points of the central line.

Image Analysis

Coating thickness was calculated as the difference between the average diameter of the coated soybean (Figure 6) and the diameter of the soybean whose coating had been mechanically removed (Figure 7). The diameter was measured with the image analysis technique (Figure 5) using a digital photographic camera Sony /Mavica MVC-FD73 and software for image processing tasks (Global Lab - Image). The image was calibrated with a steel sphere with a diameter of 9.5 mm.

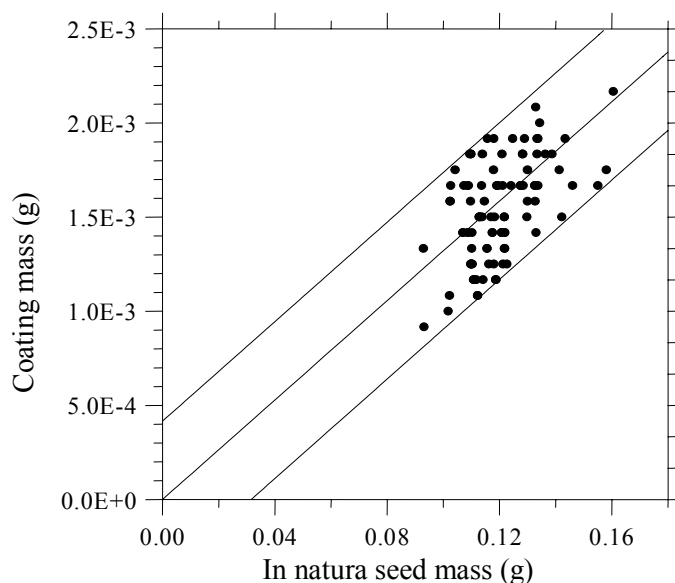


Figure 4: Graph of determination of the dispersion index

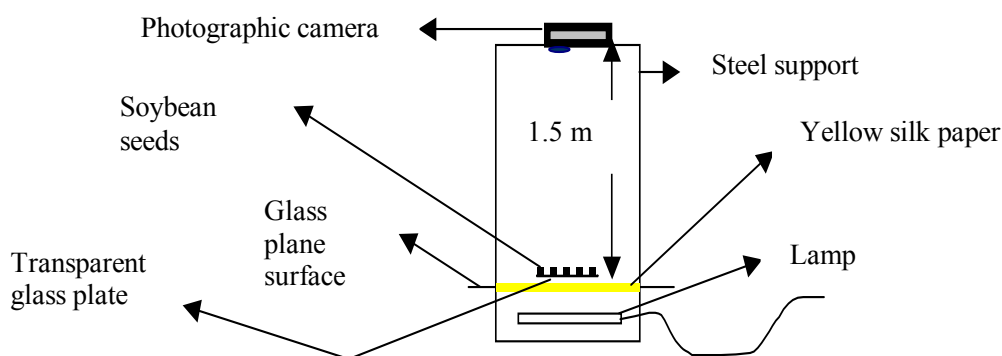


Figure 5: Apparatus used to capture the images

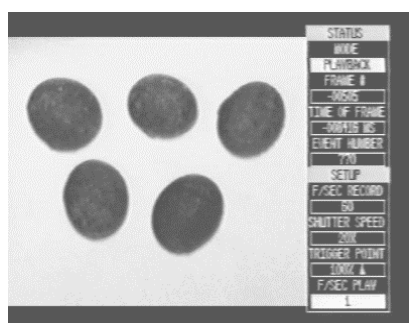


Figure 6: Coated soybean seeds

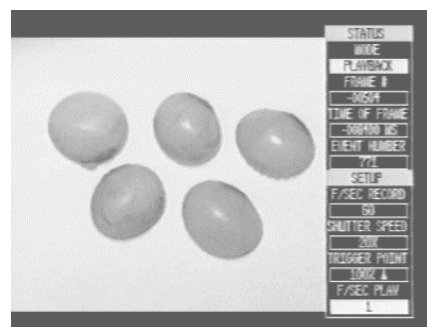


Figure 7: Soybean seeds after removal of coating

Efficiency and Thickness

The objective of this stage of this work was to verify the influence of the process variables on efficiency (η) and coating thickness (E). The variables studied were flow rates of the spouted air, atomization air and slurry. The values of these variables were defined by the central composed design technique.

Model Description

The general population balance equation given by Equation (1) comes from the continuity equation applied to a small element of arbitrary volume, R.

$$\frac{d}{dt} \int_R \psi dR = \int_R (B - D) dR \quad (1)$$

where B and D are the appearance and disappearance rates of new particles respectively and ψ is a general density function distribution.

In this work ψ is the function distribution of seed mass, $Nf(m)$, where the state coordinate is the mass of soybean seeds. So, using the treatment proposed by Liu and Lister (1992) and neglecting the agglomeration and fragmentation phenomena, Equation (1) can be rewritten as

$$\frac{\partial}{\partial t} (Nf(m)) + \frac{\partial}{\partial m} (G(m)Nf(m)) + D - B = 0 \quad (2)$$

In coating soybean seeds the main mechanism is growth by layer, and thus Equation (2) can be reduced to

$$\frac{\partial}{\partial t} (Nf(m)) = -\frac{\partial}{\partial m} (G(m)Nf(m)) \quad (3)$$

According to Liu and Lister (1992), the growth rate can be given by

$$G(m) = \frac{dm}{dt} = Km \quad (4)$$

where the proportionality coefficient K can be obtained for some time T from the following mass balance:

$$\int_{m_{\min}}^{m_{\max}} Nf(m)G(m)dm = Q_s C_s \eta \quad (5)$$

where Q_s is the slurry flow rate, C_s the slurry concentration, η the process efficiency, m_{\min} the minimum value of seed mass and m_{\max} the maximum value of raw soybean seed mass.

The discretized form of Equation (5) (Liu and Lister, 1992, Hounslow et al., 1988) for mass-dependent growth is given by Equation (6):

$$\frac{dN_i}{dt} = \frac{1}{m_i} (aG_{i-1}N_{i-1} + bG_iN_i + cG_{i+1}N_{i+1}) \quad (6)$$

where m_i is the smallest value of mass in interval i and coefficients a, b, and c are solutions of the zero-, first- and second-order moments given by Equation (7)

$$a = \frac{2r}{(1+r)(r^2-1)}, b = \frac{2}{1+r}, c = \frac{-2r}{(1+r)(r^2-1)} \quad (7)$$

where r is $\frac{m_{i+1}}{m_i}$, i.e., the ratio between the largest

and the smallest limit in each interval.

The growth rate in discretized form is given by Equation (8):

$$G_i = \frac{\eta Q_s C_s \bar{m}_i}{\sum_{j=1}^{\infty} N_j \bar{m}_j} \quad (8)$$

where \bar{m}_i is the mean value of mass in the discrete interval i and N_j represents the total number of seeds in the interval. The efficiency of coating η as a function of the operational variables: spouted air flow rate, atomization air flow rate and slurry flow rate was obtained empirically by the response surface technique.

The model was solved using a specific code developed in Maple V[®]. This software was chosen because it enables the combination of symbolic and numerical tools, useful in the automatic generation of the equations and in the analytic and numeric solutions of the model.

Hounslow et al. (1988) reported oscillations resulting from the application of the 4th order Runge-Kutta method in the solution of the balance equations for the particular case where the growth rate, G , was assumed to be constant, probably due to the lack of particles in the first intervals. Under the conditions established in this study this possibility is avoided.

RESULTS

Dispersion Index

The operational conditions and spouted bed configuration able to minimize the dispersion index were obtained by a two levels factorial design technique (Box et al. 1978). The following qualitative variables were considered: use of internal tube (X_{q1}), radial location of the nozzle atomizer (X_{q2}) and size of seeds (X_{q3}). Table 2 shows the variables and their respective levels, where “sieves” 11 and 13 are commercial terms that correspond to seeds with medium diameters of 6.5 and 5.5 mm, respectively.

Table 3 contains the dispersion index values (DI) obtained from various experiments. The significance level of each variable (effect) is shown in Table 4. It can be observed that DI is influenced in the order X_{q1} , X_{q3} and X_{q2} and that there is an interaction between X_{q1} and X_{q2} . The best condition (the highest degree of uniformity) was obtained with the use of the internal tube and with the radial position for the nozzle atomizer off center.

The minimization of coating nonuniformity when the internal tube is used in the spouted bed may be associated not only with the increased regularity in the time associated with each seed trajectory but also with the number of times that the seed follows this trajectory. The radial position of the nozzle atomizer off center (0.66R) atomizer avoids a greater elutriation of the atomized material. These conditions guarantee the lowest dispersion index and were used to determine both coating thickness and efficiency.

Efficiency and Thickness

Table 5 contains the experimental results on efficiency and coating thickness as well as the operational conditions for each experiment.

The empirical models obtained for efficiency and coating thickness, containing only parameters with significance levels lower than 5% with correlation coefficients of 94.2% and 98.3%, respectively, and with random independently distributed residues, are given by Equations (9) and (10):

$$\eta = 77.96 - 5.142X_1 + 1.720 X_2 + 6.150 X_3 - 3.598X_1^2 - 2.408X_3^2 + 2.385X_1X_3 \quad (9)$$

$$E = 0.026 - 0.0028X_1 + 0.0050X_2 + 0.0047X_3 - 0.0011X_1^2 - 0.0018X_1X_2 - 0.0029X_1X_3 \quad (10)$$

where X_1 , X_2 and X_3 are dimensionless variables given by Equations (11) to (13), related to the spouted air flow rate Q_{SA} (L/s), the atomization air flow rate Q_{AT} (L/s) and the slurry flow rate Q_S (L/s), respectively,

$$X_1 = \frac{Q_{SA} - 32.9}{2.5} \quad (11)$$

$$X_2 = \frac{Q_{AT} - 0.42}{0.12} \quad (12)$$

$$X_3 = \frac{Q_S - 0.25}{0.05} \quad (13)$$

Table 2: Qualitative variable levels

Variable	Level = 1	Level = -1
X_{q1}	with internal tube	without internal tube
X_{q2}	Nozzle at center	Nozzle at 0.66R
X_{q3}	50% “Sieve” 11 and 50% “Sieve” 13	100% “Sieve” 13

Table 3: Dispersion index results for different experimental conditions

X_{q1}	X_{q2}	X_{q3}	DI (10^4)
1	1	1	6.42
1	1	-1	7.18
1	-1	1	6.46
1	-1	-1	7.18
-1	1	1	11.11
-1	1	-1	12.74
-1	-1	1	7.79
-1	-1	-1	8.87

Table 4: Results of the calculated effects of the dispersion index

Effect	Value (10^4)	Significance Level (10^3)
X_{q1}	-1.7	0.55
X_{q2}	0.9	3,40
X_{q3}	-0.5	15.00
$X_{q1}X_{q2}$	-0.9	3.30

Table 5: Experimental values for efficiency (η) and coating thickness (E)

Exp.	Q_{AJ} (L/s)	Q_{AT} (L/s)	Q_{SUS} (L/s) (10^3)	η (%)	E(m) (10^5)
1	35.4	0.53	0.30	78.70	3.35
2	30.4	0.53	0.30	86.40	4.26
3	35.4	0.31	0.30	70.30	1.97
4	30.4	0.31	0.30	76.40	2.44
5	35.4	0.53	0.20	62.00	1.84
6	30.4	0.53	0.20	68.52	2.74
7	35.4	0.31	0.20	55.60	1.95
8	30.4	0.31	0.20	75.60	1.80
9	32.9	0.42	0.25	77.23	2.53
10	32.9	0.42	0.25	77.93	2.63
11	37.3	0.42	0.25	57.80	1.67
12	28.4	0.42	0.25	76.40	2.74
13	32.9	0.61	0.25	80.62	3.51
14	32.9	0.22	0.25	76.80	1.74
15	32.9	0.42	0.34	81.40	3.33
16	32.9	0.42	0.16	60.20	1.66

Response surfaces were obtained from equations 9 and 10. Figure 8 shows the response surface that relates coating thickness to the dimensionless variables X_1 and X_3 . The value of the other variable (V_{AT}) was fixed at the central point ($X_2=0$). The greatest thickness was obtained for the lowest spouted air flow rates (X_1) and highest slurry flow rates (X_3).

Figure 9 shows that thickness may increase with an increase in the atomization air flow rate (X_2) or a decrease in the spouted air flow rate (X_1), as a consequence of the elutriation process. The same analysis can be applied to the process efficiency curves.

Simulation Results

Figure 10 contains a comparison of simulated model results and the experimental data. This figure shows good agreement between the experimental and simulated mass distribution of seeds for two standard experiments, conducted at different slurry flow rates and with similar raw seed distributions and efficiency. It can be verified that the increase in the slurry flow rate causes an increase in the coating mass of the same seed.

The mean deviation between the experimental and simulated values of the total mass of coated seeds for all 16 experiments was 0.35% with a 95% confidence level for the interval from 0.27% to 0.42%. These values confirm the prediction of coating layer distribution obtained by the method described in this paper.

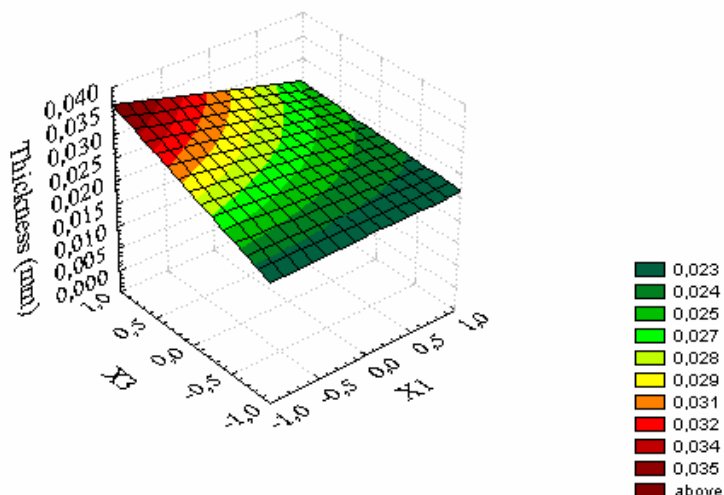


Figure 8: Response surface for the coating thickness with $X_2 = 0$

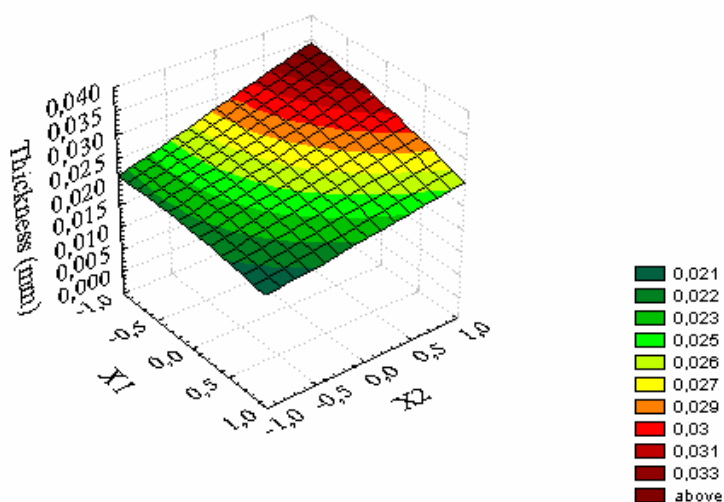


Figure 9: Response surface for the coating thickness with $X_3 = 0$

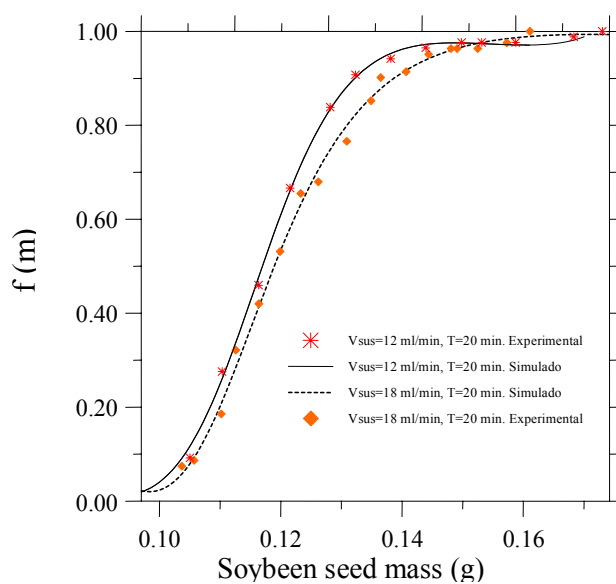


Figure 10: Experimental and simulated mass distributions: effect of slurry flow

CONCLUSIONS

The lowest dispersion index and the most uniform distribution of coating thickness are consequences of the use of an internal tube in the spouted bed and of location of the nozzle in a radial position of 0.66R.

The simulation based on a population balance showed that the model was able to predict the mass of coated seeds in the spouted bed with an error of around 0.3%.

NOMENCLATURE

B	rate of appearance of new particles for a range of state properties	
C _S	concentration of solids in the coating slurry,	Kg/m ³
D	rate of disappearance of new particles	
f(m)	normalized density function	
G(m)	growth rate,	Kg/s
K	growth rate constant,	s ⁻¹
\bar{m}	mean mass,	Kg
N	total number of soybean seeds	
Q _{SA}	spouted air flow rate,	L/s
Q _{AT}	atomization air flow rate,	L/s
Q _S	slurry flow rate,	L/s
R	region where the entity ψ is valid	
t	time,	s
T	total time of the experiment,	s
V _x ,	velocity in x,	m/s
V _y	velocity in y,	m/s
V _z ,	velocity in z,	m/s
Xq ₁	codified spouted air flow rate	
Xq ₂	codified atomization air flow rate	
Xq ₃	codified slurry flow rate x,y and z - space coordinates,	m

Greek Symbols

η	process efficiency
ξ	any state property
$\bar{\psi}$	general density function distribution

Subscripts

s	solid (slurry)
SA	spouted air
AT	atomization air

REFERENCES

- Box, M.J., Hunter, W.G. and Hunter, J.S., Statistics for Experimenters. An Introduction to Design, Data Analysis, and Model Building; John Wiley and Sons, New York (1978).
- Duarte, C. R. et al., The Use of the Population Balance Model in the Study of Coating of the Soybean Seeds in a Spouted Bed, Proceedings of the XXIX ENEMP (CD-ROM), São João Del Rei, MG (2001).
- Freire, J.T. and Oliveira, W.P., Technological Aspects of the Processes of Particles Covering, Special Topics in Drying, UFSCar Graphic, São Carlos-SP, Brazil, Vol. 1, pp. 253-293 (1992).
- Hounslow, M.J., Ryall, R.L. and Marshall, V. R., A Discretized Population Balance for Nucleation, Growth, and Aggregation, *AIChE Journal*, Vol. 34, pp. 1821-1832 (1988).
- Hounslow, M.J. and Wynn, J.W, Short-Cut Models For Particulate Process, *AIChE Journal*, Vol. 17, pp. 505-516 (1993).
- Liu, L.X. and Lister, J.D., Spouted Bed Seed Coating: The Effect of Process Variables on Maximum Coating Rate and Elutriation, *Powder Technology*, Vol. 74, pp. 215-230 (1993).
- Liu, L.X. and Lister, J.D., Coating Mass Distribution from a Spouted Bed Seed Coater: Experimental and Modeling Studies, *Powder Technology*, Vol. 74, pp. 259-270 (1992).
- Lucas, K.B.C., Soybean Inoculation and Covering with Micronutrients in a Spouted Bed, Master's thesis, Federal University of Uberlândia, Uberlândia - MG (2000).
- Randolph, A.D. and Larson, M.A., Theory of Particulate Processes, Department of Chemical Engineering, University of Arizona, Tucson (1988).