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OPTIMIZATION OF THE DRYING PROCESS OF TEXTURED SOY PROTEIN

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Abstract. Textured soy proteins (TSP) have been used for many years as a substitute of animal protein. In recent times, since the discovery of its beneficial health effects, TSP also became an important functional ingredient in several food applications. The process of TSP involves a drying step, which is one of the most relevant and challenging processes in manufacturing food product. In this study, the drying process of TSP was optimized in order to determine the optimal system operating conditions (drying air temperature, drying air velocity, and height of product layer) minimizing the drying time and the energy consumption of the drying process. The problem was formulated as a multi-objective optimization and was solved by the ε-Constraint method. The optimization was based on the drying model and on the energy consumption model previously obtained by Cassini (2004). The Pareto curve obtained for the proposed problem lies on the maximum allowed drying air temperature and on the minimum height of the product layer, remaining the drying air velocity as the weight variable for the optimal point. To minimize the energy consumption the drying air velocity lies on its lower bound. When the main objective is to minimize the process time, the drying air velocity lies on its upper bound.

Keywords: Textured Soy Protein, Drying, Multi-objective Optimization.

1. Introduction

The proteins are essential components of the cells, being in the central point of biological processes. They exert important regulatory functions, controlling the intra- and extra-cellular conditions and providing information to other components of the cell.

Around 1950, the nutritional importance of protein and the high content of this nutrient in the soybean (soybean contains about 40% of vegetable protein) were discovered. Based on it, the food industries started the production of defatted soybean flour designated to human feed. This production increases everyday and, nowadays, more than 1.5 million ton of defatted meal are produced worldwide (Bunge, 2001). As a consequence of their great applicability in the food industry, this product gave origin to other ones, like textured, concentrated, and isolated soy protein.

At the present time, the use of TSP as meat extenders in meat processed products is very common. Studies proving the relationship of soy protein consumption to cholesterol reduction and heart diseases prevention increased the interest of the whole food industry to develop products using soy as ingredient. As a consequence, the range of new soy protein applications increased as well. Nutritional bars, beverages, cereals,

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biscuits, sauces, chocolates, snacks, among many others, are some examples of food products that use soy protein as a functional ingredient.

The main functions of the use of TSP in a food product may include: increase water and protein content of this food, reduce product cost, enhance texture and hardness of the product and replace a portion of the meat keeping the original protein content of the product.

In the production of TSP, one of the main steps is the drying process, which is necessary to decrease the product moisture content until the required level. The objective of dehydration in foods is diminishing its degradation caused by the growth of bacteria, yeasts, and molds. Moreover, undesirable chemical and biochemical reactions – which also are responsible for product degradation and shelf life time reduction – are affected by moisture decrease.

Drying is a very complex process since it involves simultaneous heat, mass, and momentum transfer in which moisture is removed from food material and carried out by hot air. This operation may also be accompanied by chemical and biochemical reactions, phase change, and shrinkage of the food product (Baker, 1997). This process is mainly affected by its parameters (type of dryer, system pressure, drying air temperature, velocity, and relative humidity) and the product nature (superficial area, orientation of constituents, and type and concentration of solutes) (Barbosa & Vega, 1996).

The optimization of the drying process can be achieved by the variation of the listed parameters, decreasing the product residence time inside the dryer and increasing, therefore, the plant productivity. However, these parameters cannot be varied indefinitely: the increase in the drying air temperature, for instance, facilitates the migration of water molecules inside the product, speeding up its drying rate; on the other hand, as the temperature increase, depending on the food characteristics, undesired chemical and physical reaction can be started (such as vitamins loss, color change, undesired flavors, solubility modifications, and essential amino-acids loss) and excessive surface hardening can be achieved.

Another issue – and, in fact, one of the most important for industrial processes – that must be considered during drying optimization is the energy consumption and, consequently, the overall drying cost. The higher the drying air temperature and velocity used, the faster the drying; however, the power used to heat and to circulate the air increases.

Therefore, as energy is a proportional function of used power and process time, both conditions should be used to optimize the drying process. Higher drying air temperatures and velocities use more power, but through a shorter time; on the other hand, lower temperatures and velocities increase the drying time and decrease the used power.

Optimization of the drying process may be considered as an indispensable tool for industrial process, because it is performed to ensure rapid processing conditions yielding an acceptable quality product and a high throughput capacity (Madamba, 2002).

The objective of the present study is the optimization of the drying process of a commercial type of textured soy protein, through the formulation of a multi-objective optimization problem. The goal is to determine the optimal system operating conditions (drying air temperature, drying air velocity, and height of product layer) minimizing the drying time (ensuring that the maximum moisture content allowed by legislation may be attained in the TSP commercialization) and the energy consumption of the drying process.

2. Theoretical Fundaments

In many decision-make problems, several criteria are involved and must be balanced and, consequently, the formulation of a single constrained objective function may not represent the problem satisfactorily. Subsequently, multi-objective optimization methods appeared in order to solve problems involving more than one objective function (Secchi, 2001 and Ticona, 2003).

A multi-objective problem may be written in following general form:

$$\min_{x \in K} F(x) = [F_1(x)\ F_2(x) \ldots F_q(x)]^T$$

subjected to:

$$\begin{aligned} h_j(x) &= 0, \quad j = 1, 2, \ldots, m \\ g_j(x) &\leq 0, \quad j = 1, 2, \ldots, p \end{aligned}$$

where F(x) is the vector of objective functions to be minimized, h(x) is the vector of equality constraints, and g(x) is the vector of inequality constraints. If any of the components of F(x) are competing, then there is no unique solution to this problem.

Different strategies could be used to solve this optimization problem, depending on its characteristics, such as weighted sum, ε-constraint, and goal attainment strategies. The ε-constraint strategy, used in this work, consists of the optimization of only one objective function and the expression of the others as inequality constraints (= ε). As a consequence, the generated problem becomes:

$$\min_{x \in K} F_r(x)$$

subjected to:

$$\begin{aligned} h_j(x) &= 0, \quad j = 1, 2, \ldots, m \\ g_j(x) &\leq 0, \quad j = 1, 2, \ldots, p \\ F_i(x) &\leq \varepsilon_i, \quad i = 1, 2, \ldots, q, \quad i \neq r \end{aligned}$$

This method can be used whether the feasible region is convex, non-convex, or discrete, being able to solve non-convex problems, identifying non-inferior points inside the non-convex region. This methods, however, depends on the choice of the objective function to be optimized and on the definition of the constraints that must be applied to the other functions.

Independent of the chosen method, the main characteristic of a multi-objective optimization problem is the non-uniquely of the solution. That is, the optimum of a given objective function is different from the optimum of another one. Therefore, the solution of a multi-objective optimization problem is not a single point, but a region, which is known as the Pareto region, or the subset of non-inferior solutions (Collischonn & Tucci, 2002). In this region, the improvement in one objective function causes the degradation of another (Secchi, 2001).

3. Materials and methods

In the present study, the drying process of a commercial type of TSP was optimized. The medium equivalent diameter presented by the samples of this type of TSP was 1.98 cm and it contained about 50% of protein, 20% of sugars, 20% of fiber, 3-5% of ashes, and 0% of fat.

The model capable to predict the drying curves of this type of TSP, presented in Eq. 1, was previously developed by Cassini (2004) and relates the moisture content of the product with the process parameters and the drying time.

$$\left(\frac{X-X_{eq}}{X_0-X_{eq}}\right)=\exp\left(-\left(\begin{array}{l}k_1+k_2\,T+k_3\,v+k_4\,h+k_5\,T^2+k_6\,v^2+\\+k_7\,T\,v+k_8\,T\,h+k_9\,v\,h+k_{10}\,T\,v\,h\end{array}\right)t\right) \qquad (1)$$

In this equation, X (kg water/kg dm) is the moisture content in time t (s), X_0 and X_{eq} are, respectively, the initial and the equilibrium moisture content, T (ºC) is the drying air temperature, v (cm/s) is the drying air velocity, h (cm) is the height of product layer, and k_1 to k_{10} are the constants of the model. The X_0 and X_{eq} values obtained for this type of TSP were, respectively, 0.278 and 0.0036 kg water/kg dm. Table 1 presents the values of the constants k of Eq. 1.

Table 1: Constants of the model (Eq. 1) for the studied TSP.

k_1	-0.0161945	k_6	-0.0000005
k_2	0.0000850	k_7	-0.0000005
k_3	0.0001970	k_8	-0.0000322
k_4	0.0029925	k_9	-0.0000217
k_5	0.0000002	k_{10}	0.0000002

The model capable to predict the energy consumption of the equipment used in the drying experiments considers the energy consumption as a function of the equipment operation time and the process parameters (drying air temperature and velocity), as can be seen in Eq. 2.

$$E=t\left(c_1+c_2T+c_3v+c_4T^2+c_5v^2+c_6Tv\right) \qquad (2)$$

where E (J) is the energy consumption, c_1 to c_6 are the constants of the model, presented in Table 2.

Table 2: Constants of the energy consumption model (Eq. 2).

c_1	-1131.92095	c_4	0.23268
c_2	-42.30554	c_5	-0.19787
c_3	55.09535	c_6	0.13927

From these two models it is possible to formulate the objective functions to be minimized: the process time, and the energy consumption. This optimization problem is under some constraints related to the process parameters and the final moisture content to be reached by the product. The optimal drying air temperature (T*) must lie between 90 and 130°C; the drying air velocity must lie between 100 and 150 cm/s; the height of product layer must lie between 2.5 and 5 cm; and the final moisture content of TSP must lie between 0.065 and 0.08 kg water/kg dm. These values constitute the validity domain of the model established in previous work (Cassini, 2004) and the TSP maximum moisture content allowed by legislation of Brazil (Resolution CNNPA n° 14/78 of the Health Office).

Therefore, the formulation of the optimization problem becomes:

$$\min_{x \in K} F(x) = [F_1(x) \;\; F_2(x)]^T$$

where:

$$F_1(x) = E = t\left(c_1 + c_2 T + c_3 v + c_4 T^2 + c_5 v^2 + c_6 T\, v\right)$$

$$F_2(x) = t = t_f = \frac{\ln\left(\dfrac{X_0 - X_{eq}}{X - X_{eq}}\right)}{\left(k_1 + k_2 T + k_3 v + k_4 h + k_5 T^2 + k_6 v^2 + k_7 T\, v + k_8 T\, h + k_9\, v\, h + k_{10} T\, v\, h\right)}$$

subjected to: $90 = T = 130$
$100 = v = 150$
$2.5 = h = 5$
$0.065 = X_f = 0.08$

where t_f is the final process time and X_f is the product moisture content at t_f.

To solve this multi-objective optimization problem, the ε-constraint strategy was used and the minimization of the energy consumption (and, consequently, the operational cost) was preferred, having the process time constrained under different ε values. The optimization problem was solved by the SQP method, using the BFGS approximation for the Hessian matrix and a cubic polynomial in the linesearch procedure (Secchi, 2001).

4. Results and Discussions

Figures 1 and 2 present the influence of the drying air temperature, T, and the drying air velocity, v, in the functions to be minimized. Figure 1 presents the T and v influence in the final process time (t final), when h is equal to 2.5 cm, and Figure 2 presents the influence of these parameters in the energy consumption of the equipment (Pot, in Watt).

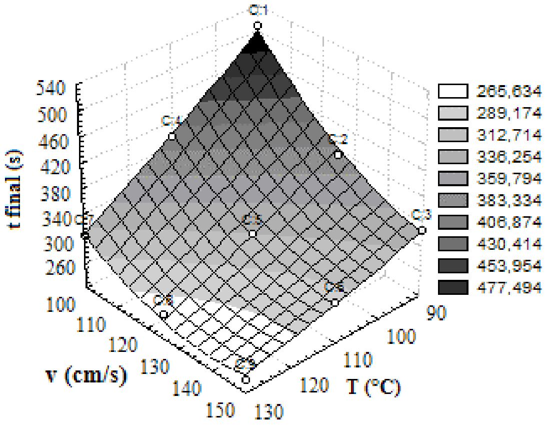

Fig. 1: Influence of T and v in the final drying process time.

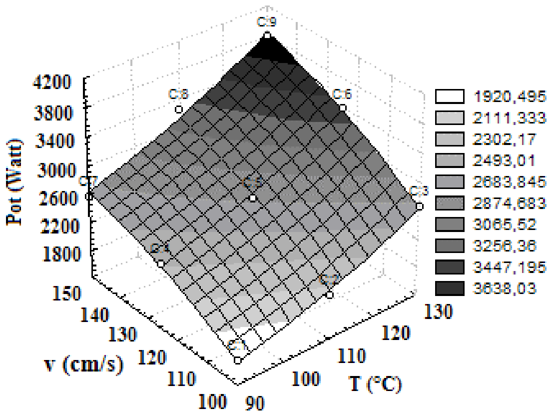

Fig. 2: Influence of T and v in the power consumption of drying equipment.

It can be seen from these figures that the higher the drying air temperature and velocity, the higher the energy consumed by the drying equipment to reach these conditions, and the shorter the final process time.

As mentioned earlier, the optimization problem was solved with the ε-constraint strategy, minimizing the energy consumption and limiting the final process time under different ε values. Besides that, the problem resolution was repeated with various initial guessed values for T, v, and h. This procedure, however, did not cause any variation in the obtained results.

In Table 4, it can be observed that, for any tested ε value, the optimal drying air temperature T* and height of product layer h* found by the optimization program (developed with Matlab 5.3 software) were constants and equal to 130°C and 2.5 cm, respectively. The optimal point obtained for drying air velocity v*, however, varied as a function of the ε values. Table 4 also presents the objective function E* and the final process time t_f*.

Table 4: Result of the optimization problem solved by the ε-constraint strategy.

ε (s)	T* (°C)	v* (cm/s)	h* (cm)	E* (J)	t_f* (s)
250	130	134.02	2.5	889295.35	250
260	130	123.81	2.5	865965.65	260
270	130	116.63	2.5	849617.81	270
280	130	110.98	2.5	836467.74	280
290	130	106.28	2.5	825200.17	290
300	130	102.26	2.5	815181.71	300
302	130	101.53	2.5	813293.48	302
304	130	100.81	2.5	811438.40	304
306	130	100.11	2.5	809614.57	306
500	130	100	2.5	809330.11	306.31
1000	130	100	2.5	809330.11	306.31
1500	130	100	2.5	809330.11	306.31
2000	130	100	2.5	809330.11	306.31

From Table 4 it also can be observed that the optimal solution converge to a point characterized by the lower energy consumption and a relatively short final process time. At this point, the drying air temperature is equal to 130°C and the drying air velocity assumes its lower value (100 cm/s). As the final process time is restricted to values lower than 306 s, the optimal value of the drying air velocity starts to grow up in order to reach the process time that respects the imposed constraint. As a consequence, the energy consumption of the equipment also grows up.

Relating these results with figures 1 and 2, it can be observed that the drying air temperature affects the drying time more effectively than the drying air velocity; the influence of these parameters in power consumption is, however, very similar. These evidences explain the settling of the drying air temperature in its maximum value and the varying drying air velocity as a function of the constraint imposed to the final process time.

Figure 3 presents the Pareto region, or non-inferior solutions, for the studied objective-functions (t_f and E) obtained trough the resolution of the proposed problem with the ε-constraint strategy.

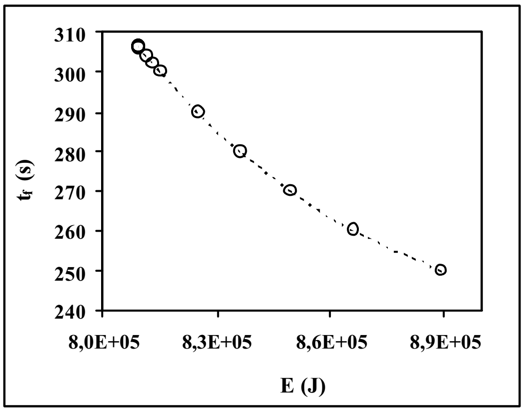

Fig. 3: Pareto region for the studied objective functions t_f and E.

On the Pareto region, any reduction in t_f* will result in an increase of E*, and vice-versa. It is important to point out that this region correspond to the optimal conditions of T, v, and h obtained by the optimization program, and the convex characteristic of it may not be maintained for other conditions.

Through data presented in Table 4 and the Pareto region of Fig. 3, it is possible to observe the variation showed by the studied objective functions during the resolution of the optimization problem. While the final process time varies between 250 and 306.31 s – a 56.31 s variation – the variation of the energy consumption is about 80,000 J – between 889,295 J and 809,330 J. Considering the cost of the electrical energy as R$0.09 per kWh (approximated electrical energy cost for this kind of industry), the process operational cost can be estimated.

The energy consumption presented in Table 3 was used to dry 400 g of TSP, the approximated mass of product used experimentally by Cassini (2004) to reach a height of product layer of 2.5 cm. Table 5 presents the drying process cost estimation as a function of its energy consumption. In this table, the column R$/ton presents the drying cost of one ton of TSP and the last column presents an annual estimation of TSP drying cost, considering an annual production of 40,000 ton.

In Table 5, it can be observed that, if the minimization of time is the priority, an annual cost about R$2,200,000.00 may be expected for the drying process of this type of TSP. However, a small adjustment in the process parameters – or, in this case, a reduction in the drying air velocity – may result in a slower but more economic process.

Table 5: Drying process cost estimation as a function of its energy consumption.

ε	v* (cm/s)	t_f*(s)	E* (J)	E* (kWh)	Drying cost (R$/ton)	Drying cost (R$/year)
250	134.02	250	889295.35	0.247	55.17	2206617.09
260	123.81	260	865965.65	0.241	53.72	2148728.88
270	116.63	270	849617.81	0.236	52.70	2108164.83
280	110.98	280	836467.74	0.232	51.89	2075535.43
290	106.28	290	825200.17	0.229	51.19	2047577.10
300	102.26	300	815181.71	0.226	50.57	2022718.20
302	101.53	302	813293.48	0.226	50.45	2018032.92
304	100.81	304	811438.40	0.225	50.34	2013429.89
306	100.11	306	809614.57	0.225	50.22	2008904.40
500	100	306.31	809330.11	0.225	50.20	2008198.57
1000	100	306.31	809330.11	0.225	50.20	2008198.57
1500	100	306.31	809330.11	0.225	50.20	2008198.57
2000	100	306.31	809330.11	0.225	50.20	2008198.57

Accordingly to Table 5, if the drying air velocity of 100 cm/s is used, the drying process annual cost may be estimated in approximately R$2,000,000.00; this represents an economy of about R$200,000.00 – or 10% of the drying cost – per year in the drying process of this type of TSP. As a consequence, an increase in the final process time in less than 1 minute means almost nothing if compared to the financial benefit obtained.

The results described above were obtained considering the electrical energy as the source energy consumed by the equipment. Industrially, however, it is more usual the use of steam as thermal energy source. Thus, considering that each ton of steam (at 10 bar of pressure and operating at 190°C of temperature) generates about 778 kWh of energy and costs approximately R$45.00, an economy of about R$130,000.00 may be estimated if the process drying air velocity is set to its minimal value (100 cm/s).

6. Conclusions

Through the resolution of the multi-objective optimization problem, which aimed the minimization of the final drying process time and the energy consumption, it was possible to identify the Pareto subset of non-inferior solutions correspondent to the optimum system process parameters (drying air temperature and velocity and height of product layer).

The ε-constraint strategy presented a good performance obtaining the optimum solution of the proposed problem.

The results indicated that the optimum region is composed by the maximum value for the drying air temperature and by the minimum value for the height of product layer. The drying air velocity varied accordingly to the constraints or priorities imposed in objective functions, being set to the maximum when the final process time was prioritized and to the minimum when the energy consumption was more important.

Through the drying operational cost estimation as a function of the energy consumption, it was possible to realize that using the lower drying air velocity allowed – 100 cm/s – could generate an annual cost reduction around R$200,000.00 without increasing the process time dramatically (less than 1 minute increase), being the most indicated set for this parameter.

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