Summary

The mass transfer coefficient is a basic parameter in the project and analysis of industrial soybean meal dryers. The aim of this work was to determine a model to estimate the soybean meal mass transfer coefficient (K). Experimental data on the drying kinetics were obtained in a bench scale tray dryer at different temperatures and air speeds. It was observed that the air temperature and moisture content of the soybean meal exerted a significant influence on the value for K and that the limiting step for mass transfer occurred in the interior of the particle. A model was developed to evaluate K, which could be used in the project, analysis, modeling, simulation, optimization and control of any soybean meal dryer on an industrial scale.

Key words: Drying kinetics; Soybean meal; Mass transfer coefficient; Model.
1 Introduction

The basic objective of soybean meal production is to obtain a product with the best quality at the lowest possible cost. The operation is characterized by high energy consumption (JONGENEELEN, 1976) and there are energy losses to the environment, increasing production costs. In order to maintain the final quality of the soybean meal high, but at low cost, it is necessary to establish strategies to optimize the drying, which can be done using mathematical techniques.

The mathematical modeling of a dryer is based on differential energy and mass equations, empirical and complementary equations. The numerical solution of the differential equations depends on knowledge of the mass transfer coefficient, which can be estimated according to the diffusion equation given by Fick’s law, or using dimensionless numbers (STRUMILLO and KUDRA, 1986). Another alternative used to estimate this coefficient is from the models resulting from the fitting of experimental data (IGUAZ et al., 2003; KROKIDA et al., 2004).

In order to contribute to the design and optimization of soybean meal dryers, the present work proposed to determine a model based on experimental the mass transfer coefficient in the soybean meal drying process.

2 Material and methods

2.1 Material

The samples of desolventized soybean meal were collected at the inlet of the rotary dryer of a vegetable oil extraction industry located in the southern region of Brazil (Agroindustrial Cooperative, COAMO). The particles of soybean meal were laminated and presented a moisture content of 0.22 kg H₂O/kg dry solid.

The samples were dried in a tray dryer, as shown in Figure 1. The equipment consisted of an air blower, duct with electric resistances and a plenum.

The air was inserted into the system by the fan and the flow was controlled by a butterfly valve. Afterwards went through the heating system, through the plenum and through the sieves that supported the soybean meal. To ensure constant airflow during the drying process, measurements were realized periodically at the blower inlet and sieve outlets, using an anemometer. The air temperature was adjusted by controlling the power dissipated by electrical resistances, and measured manually using thermocouples.

The upper part of the plenum was a perforated plate with the tray placed on it. Two sieves with meshes of 200 and 270 were used to support the soybean meal.

A digital psychrometer was used to measure the relative humidity and the temperature of the ambient air. An analytical balance was used to weigh the sample until it reached constant weight. The time interval between successive weighings was measured using a chronometer and the sample was weighed quickly (about 3 s) to minimize moisture loss from the soybean meal to the environment. A hothouse was used to determine the dry weight of the soybean meal sample.

Tyler sieves with meshes of 7, 8, 10, 14 and 20, plus a semi-analytical balance, a chronometer and a mechanical shaker of the sieves containing the samples of soybean meal were used to determine the particle size distribution.

2.2 Experimental setup

2.2.1 Data acquisition methodology to determine the particle size distribution of the soybean meal

The average size of the particles in the soybean meal was determined using the particle-size distribution technique shown in Gomide (1983), Freire et al. (1986) and Luz (2006).

2.2.2 Data acquisition methodology to obtain the soybean meal drying kinetics

The procedure for data acquisition is described below:

1) Initial reading of the temperature and relative humidity of the air in the laboratory;
2) Adjustment of the air temperature to 50 °C and the airflow speed to 1.1 m.s⁻¹;
3) After weighing, a 30.0 g sample of wet soybean meal was placed on the sieves, giving a height of 5 mm;
4) Weighing of the samples during the drying process after 0.5, 1, 1.5, 2, 3, 4, 5 and 6 min, and then each 2 min until the material reached constant weight;
Scientific note: mass transfer coefficient in the drying of soybean meal

LUZ, G. R. et al.

5) Estimation of the drying rate, \( R_w \), from the data obtained in item 4, using Equation 1 (GEANKOPLIS, 1993);

\[
R_w = \frac{\Delta X}{\Delta t}
\]

6) Repetition of the steps above (1 to 5) using temperatures of 74, 85, and 97 °C, maintaining the air speed constant at 1.1 m.s\(^{-1}\);

7) After changing the air speed to 2.5 m.s\(^{-1}\), the experimental data were obtained again for the drying of the soybean meal at 50, 74, 85 and 97 °C;

8) Determination of the dry weight of the soybean meal sample in a hothouse at 105 ± 2 °C for 24 h.

2.2.3 Methodology used to calculate the soybean meal mass transfer coefficient

The mass transfer coefficients, \( K \), were calculated according to Equation 2 as presented by Welty et al. (2001), applying the data for moisture content, \( X_s \), and drying rate, \( R_w \), for each combination of air speed and air temperature. The equilibrium moisture content, \( X_e \), corresponds to the final value of the moisture content in the sample under each condition.

\[
K = \frac{R_w}{(X_s - X_e)}
\]

3 Results and discussion

3.1 Particle size distribution of the soybean meal

Figure 2 presents the results for the particle size distribution of the soybean meal with the following average diameters: 3.4, 2.6, 2.0, 1.4 and <1.0 mm and the respective percents of the total mass: 18.2, 10.5, 30.9, 14.8, 19.2, 6.4.

Figure 2 shows that the majority of the particles had a diameter of 2.0 mm. The size data were then fitted to various distribution models such as GGS (GATES–GAUDIN–SCHUMANN), RRB (ROBIN–RAMMLER–BENNET) and LOG–NORMAL (LN), Freire et al. (1986). The best fit was obtained with the LOG–NORMAL model, yielding an average diameter of 1.5 mm and standard deviation of 0.04 mm.

3.2 Drying kinetics of the soybean meal

The experimental drying and drying rate curves for the soybean meal with different air speeds and air temperatures, are presented in Figure 3.

It is clear from Figures 3 and 4 that the air temperature exerted a significant influence on the drying rate, but that the influence of the airflow rate was minimum in the range of temperatures from 50 to 97 °C. Moreover, two periods of decreasing drying rate can be observed,

![Figure 3. Drying curves for the soybean meal.](image-url)

![Figure 4. Drying rate curves for the soybean meal.](image-url)
which varied with the air temperature, indicating that the limiting step for mass transfer occurred in the interior of the particle.

3.3 Mass transfer coefficient

It is crucial to find a mathematical model to estimate K, which can be used to resolve the set of equations developed for the rotary industrial dryer of soybean meal.

As observed previously, only the air temperature influenced the mass transfer process in the soybean meal and therefore soybean meal drying is only controlled by diffusion. Thus one can consider that the coefficient is only related to the moisture content of the solid and the air temperature. So the average moisture content of the product and the average drying rate were calculated for each temperature and the coefficients calculated according to Equation 2 and presented in Table 1.

Initially, the experimental values for K were fitted to the polynomial models using the software Statistica®, considering only the moisture content data for a given air temperature. The best fit was obtained with the quadratic equation represented by Equation 3.

\[
K = a_1 X^2 \pm b_1 X + c_1
\]  

The fitting and correlation parameters calculated for Equation 3, are shown in Table 2 and Figure 5 presents the graphical results. Equation 4 was used to evaluate the fitting for the K values.

\[
\Phi = \sum_{i=1}^{n} (K_{exp} - K_{cal})^2
\]

However, it was necessary to find a model that also included the air temperature in order to estimate the mass transfer coefficient.

In the fitting process, several models were tested and the model that showed the best result was represented by Equation 5. Further details can be verified in Luz (2006).

\[
K = (-0.0047 T_{air} + 0.7668) X_s^2 + (0.0022 T_{air} - 0.2515) X_s + 0.0027 \exp(71.8130 / T_{air})
\]  

The quality of the fitted empirical model represented by Equation 5 is shown in Figure 6, making it evident that this model satisfactorily represented \( R^2 = 0.98 \) the experimental data K in the range of conditions explored.
Scientific note: mass transfer coefficient in the drying of soybean meal
LUZ, G. R. et al.

Figure 6. Fitting of K as a function of $X_s$ and $T_{air}$.

4 Conclusions

There are two periods of decreasing drying rate during the industrial drying of soybean meal, and the air temperature significantly influences this rate.

The air temperature and the moisture content of the soybean meal exerted significant influences on the mass transfer coefficient.

The limiting step for mass transfer during the drying of soybean meal is in the interior of the particles.

Equation 5 satisfactorily represented ($R^2 = 0.98$) the experimental data for K in the range of experimental conditions explored.

Nomenclature

- $X_{av}$: Average moisture content in the soybean meal (kg H$_2$O/kg dry matter)
- $X_{in}$: Initial moisture content in the soybean meal (kg H$_2$O/kg dry matter)
- $X_s$: Moisture content in the soybean meal (kg H$_2$O/kg dry matter)
- $X_e$: Equilibrium moisture in the soybean meal (kg H$_2$O/kg dry matter)
- $v_{air}$: Air Speed (m/s)
- $\Delta t$: Variation of time (s)
- $\Delta X$: Variation of moisture content (kg H$_2$O/kg dry matter)
- $\Phi$: Summation of the average quadratic deviations

References


