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Fixed-bed drying simulation with constant enthalpy, using the improved Michigan State University model

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ABSTRACT. Drying of agricultural products at high temperatures can be simulated by mathematical models, which intend to describe the drying process close to commercial patterns. They are based on simultaneous heat and mass transfer between the product that is losing moisture, and the air that is supplying energy to the process. All models use these balances, never allowing values of relative humidity of the air to be greater than 100%. However, it has not been common to evaluate air enthalpy, which should not have significant variation during the entire process, accepted as adiabatic. In this work, a mathematical model is proposed for fixed-bed corn (*Zea mays* L.) drying simulation, according to the Michigan State University (MSU) model. In the numerical solution, the enthalpy of the drying air was maintained constant as a quantitative physical indicator for correction of the heat and mass exchange in each step of the process, in order to obtain more real evaluations in all drying stages, and in the results for final moisture of the grain. As a result, greater space and time intervals for the simulation were possible. The simulation was validated by comparisons with literature results.

Keywords: high temperature, drying, enthalpy, simulation.

Simulação de secagem em camadas-fixas com entalpia constante, usando o modelo melhorado da Michigan State University

RESUMO. Os modelos matemáticos para simular secagem de produtos agrícolas em altas temperaturas se preocupam em descrever a secagem para se obter resultados próximos dos padrões comerciais. Eles são baseados nos balanços de energia e massa entre o produto que está perdendo umidade e o ar que está fornecendo energia para o processo. Todos os modelos baseiam-se nesses balanços, nunca, entretanto, permitindo valores da umidade relativa do ar superiores a 100%. Mas, não tem sido comum avaliar a entalpia do ar que, em processos de secagem, não deve ter variação significativa durante todo o período. Neste trabalho, propõe-se um modelo matemático para a simulação da secagem de milho (*Zea mays* L.), em camadas fixas, segundo o modelo de Michigan (MSU). Na simulação numérica, a entalpia do ar de secagem foi mantida constante como indicador físico quantitativo para correção dos balanços de energia e de massa, a cada passo evolutivo do processo, para se obter avaliações mais reais em todas as etapas de secagem e nos resultados para umidade final do produto agrícola. Constatou-se que é possível dispor de maior flexibilidade na definição dos intervalos de espaço e tempo para a simulação. Ela foi validada mediante comparações com resultados experimentais da literatura.

Palavras-chave: altas temperaturas, secagem, entalpia, simulação.

Introduction

Nowadays, seeds of agricultural products, in general, have received prominence for the countless processing possibilities for human feeding. It is essential (BROOKER et al., 1992) for the human beings to produce, preserve, and market seeds and grains. These three areas have received scientific attention due to their potential for providing healthy foods and in enough amounts for the people.

In the productive chain, the preservation and commercialization of agricultural products demand appropriate storage, which has, in the presence of water in those products, one of the main factors for its quality control. One of the first actions for preservation is drying, in order to leave the agricultural product with only enough moisture to allow appropriate storage for long-term durability until processing between harvests.

Drying is a crucial action, and there is consensus that, when inappropriate, it is the largest cause for deterioration of agricultural products in its chain of processing. Additionally, when compared with production and commercialization, drying is the stage where there is the largest consumption of energy, reaching up to 60% of the entire chain energy use (BROOKER et al., 1992). It must be understood then that the existent drying techniques need to be more and more suitable for the maintenance and preservation of the ecosystem. Drying needs to be accomplished within efficient patterns – that is, with safe knowledge of temperatures, moisture contents and amounts of air, promoting economy in the use of energy, and correct equipment size, particularly fans and air heaters. All of these factors lead to mathematical modeling of the drying process. Drying cannot be based only on experience, because it can become inefficient with climatic changes.

A way to improve that situation consists of allying technological and scientific knowledge with those who do the drying of agricultural products. In that aspect, process simulation has prominence, because it shortens the correct operational learning, avoiding inadequate and unnecessary operations which could lead to serious damages, besides giving safety to the procedure.

Numerical simulation for high temperature drying has become extremely viable, fast and effective, because computers are more powerful and at compatible prices with the agricultural economy, differently than when mathematical modeling began for drying of agricultural products. At that time, it demanded considerable amount of processing time and of computer memory. Moreover, the mathematical models for drying possessed unreal simplifications. Now, they are closer to reality, because they can provide results with better precision – that is, very close to the values stipulated for an agricultural product at the exit of a drying process.

Numerical simulation needs to develop even more, and to be optimized to become directly applicable to agricultural products drying processes, with fewer repeated field tests than nowadays. Furthermore, numerical simulation makes it possible to be a step from automatic drying control, a high energy consuming process which always needs to be efficient to become economically viable.

The mathematical models that describe the physical problem of drying are based on heat and mass balances between the product that is losing moisture and the drying air that is supplying energy. The consistency of the drying system is based on the reduction of the moisture from the product and of the temperature of the used air, and on the increase of the absolute humidity of that air and of the temperature of the product, never allowing values of the relative air humidity to be greater than 100%. Also, drying of agricultural products is accepted as a high quality process when the enthalpy of the drying air does not change significantly. Schematically, this can be seen in Figure 1. Ambient air (T_0) is heated to the drying air temperature (T_1), which reduces adiabatically during the drying process.

In this work, a mathematical simulation model for fixed-bed corn (*Zea mays* L.) drying is proposed, based on the new version (DALPASQUALE et al., 2009) of the Michigan State University (MSU) grain drying simulation model. It adds the concept of constant drying air enthalpy as a quantitative physical indicator for the adjustment of the heat and mass balances in each evolutionary step of the process. The main purpose is to obtain more realistic evaluations in all of the drying stages and in the results for final moisture of the agricultural product. The model solution follows the same procedures as the new version of the Michigan models (DALPASQUALE et al., 2009).

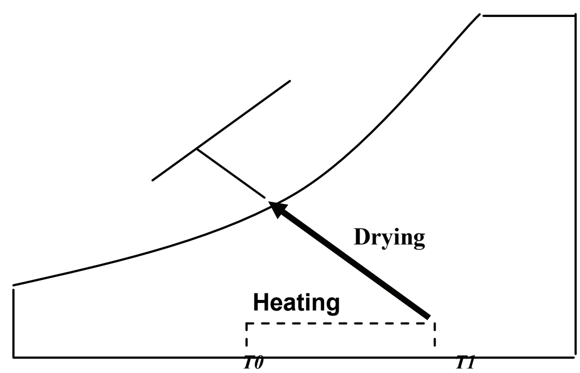

Figure 1. Representation of an efficient drying of agricultural products, with constant enthalpy, in a psychrometric chart.

Focusing on the constant enthalpy idea and new numeric solution method, the objectives of this work are:

1. to numerically simulate fixed-bed corn drying, applying the implicit/explicit method, based on backward finite differences, in order to numerically solve the proposed system of partial differential equations;
2. to apply constant enthalpy criteria during the drying process.

Material and methods

The new version of the Michigan State University grain drying simulation model - MSU1 is fully described in Dalpasquale et al. (2009). Details about its precision and flexibility about time and space increments are also discussed.

In this work, drying air enthalpy, as a function of air temperature and humidity ratio, is also included in that model to better use the adiabatic behavior of the drying process. Air enthalpy may be expressed by equation 1 (DALPASQUALE et al., 2009):

$$E = 1006.76T + W(2502086.97 + 1862.79T) \qquad (1)$$

E – air enthalpy, J kg^{-1} ºC;
W – air humidity ratio, kg_w $kg_{d.a.}$;
T – air temperature, ºC.

Which should stay constant, during the drying process, and equal to the conditions of the air entrance; that is, $E = E(T_0, W_0)$. Adding this condition to the new version of the Michigan State University grain drying simulation model results in:

$$\left\{\begin{array}{l} \dfrac{T_{ij} - T_{i-1,j}}{\Delta x} + \dfrac{ha(T_{ij} - \theta_{ij})}{G_a C_a + G_a C_v W_{ij}} = 0 \\ \dfrac{\theta_{ij} - \theta_{ij-1}}{\Delta t} - \dfrac{ha(T_{ij} - \theta_{ij})}{\rho_p C_p + \rho_p C_w U_{ij}} + \dfrac{\rho_p (h_{fg} + C_v (T_{ij} - \theta_{ij})) knt^{(n-1)} (U_{ij} - U_e)}{\rho_p C_p + \rho_p C_w U_{ij}} = 0 \\ \dfrac{W_{ij} - W_{i-1j}}{\Delta x} - \dfrac{\rho_p kn(j\Delta t)^{(n-1)} (U_{ij} - U_e)}{G_a} = 0 \\ U_{ij} - U_e - (U_0 - U_e) e^{(-k(j\Delta t)^n)} = 0, \\ E = 1006,76 T_{ij} + W_{ij} (2502086,97 + 1862,79 T_{ij}), \\ i = 1,2,3 \ldots NF \text{ e } j = 1,2,3 \ldots MF. \end{array}\right\} \qquad (2)$$

The numerical solution of system (2) – MSU2, like MSU1, requires the following sequence of steps:

1. Establish a rectangular mesh of knots to define the points where the moisture and the temperature of the product, as well as the temperature and the humidity ratio of the air, will be calculated for the fixed-bed of the product during drying, as illustrated in Figure 2. In the *x* direction, the bed is 0.8*m* high, which is subdivided in layers Δx deep, where the initial conditions of the product are at the knots, in the *x*-axis. The drying time, in the *t* direction, is divided in Δt time increments. The knots at the *t*-axis correspond to the boundary conditions of the air.

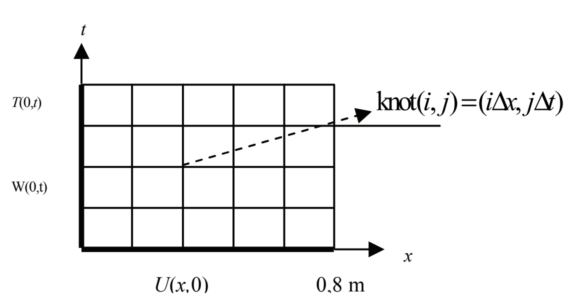

Figure 2. Structured mesh where moisture and temperature of the product, and temperature and humidity ratio of the air are calculated.

2. for I = 1,2,3….NF and j = 1,2,3…MF the T_{ij} (air temperature), θ_{ij} (product temperature), W_{ij} (air humidity ratio) and U_{ij} (product moisture content) values are calculated, solving the non-linear system composed by the first four equations in (2) through the Newton-Raphson method. Next, the W_{ij} ou T_{ij} values are adjusted through the enthalpy equation, allowing the correction of the U_{ij} value of the product moisture content.

In this work, results from MSU1 and MSU2 were investigated. Comparisons were made with those of Thompson's model, analyzing mathematical simulation of drying in the traditional form. In that case, care was taken so the relative humidity of the air did not exceed 100%, with no reference to the enthalpy of the air. Drying simulation results were generated for corn (*Zea mays* L.), initially at 20% moisture content, using a 0.4 m layer height. The simulation was conducted at 60ºC drying air temperature, using 0.25 m^3 s^{-1} m^{-2}, in an environment of 20ºC and absolute humidity of 0.012 kg_w $kg_{d.a}^{-1}$ (QUEIROZ et al., 1982). The system of equations (2) - MSU2, the improved formulation of the MSU grain drying simulation model, was solved using the methodology presented in Dalpasquale et al. (2008), methodology identical to solve MSU1, both models generating results from the same data as for Thompson's model.

The ability of MSU1 and MSU2 to simulate other experimental results of corn dried in 0.8m deep fixed-beds was also tested. Corn at 18, 25 and 35% initial moisture contents were dried at 40, 70 and 100ºC, each moisture at a different temperature. For all these tests, the amount of air used was 0.75 m^3 s^{-1}, from an environment at 22ºC and 60% air relative humidity (PORTELLA, 2001).

Results and discussion

Eight hours drying simulation results of Thompson's model, MSU1 and MSU2, are presented in Table 1.

Table 1. Average moisture content (%) simulated by Thompson's model, MSU1 and MSU2, using data by Queiroz et al. (1982).

Drying time (h)	Thompson's model	MSU1	MSU2
0.2	19.43	19.51	19.28
0.4	19.10	19.16	18.93
0.6	18.85	18.90	18.64
0.8	18.61	18.67	18.40
1.0	18.39	18.49	18.13
2.0	17.32	17.58	16.70
3.0	16.25	16.65	15.22
4.0	15.26	15.70	13.95
5.0	14.36	14.73	12.90
6.0	13.55	13.77	12.04
7.0	12.82	12.83	11.31
8.0	12.17	11.95	10.69

It is observed, in Table 1, that all simulated results maintained the negative logarithmic behavior, typical for describing drying of agricultural products. However, the estimates of MSU1 and MSU2 stayed always apart, initially in 0.23 percentage point, and 1.26 percentage point at the end, with Thompson's results in between, except for the last time.

Experimental value prediction ability of the two MSU models was also investigated.

The experimental results presented in Table 2 were simulated by the new version of the Michigan State University grain drying simulation model - MSU1. The time interval used was 1/20 of the total drying time. A similar approach was employed for space increment, which was also 1/20 of the thickness of the layer. These time and space increments made it possible to simulate the experimental moisture content values, but with some differences in drying time. The greater the drying rate, the larger the drying time differences between simulated and experimental results.

MSU2 had better performance. The time and space increments were *four times larger* than those of the previous model, and the results matched in moisture content and drying time, as shown in Table 3. The only difference was of 0.17 of an hour less simulation time for corn with 35% initial moisture content, dried at 100°C.

Table 2. Average experimental corn moisture content (%) in a 0.8 m-deep layer, and the corresponding MSU1 drying simulated results.

Moist(%)/Drying temp.(°C)	Drying t. (h) Exper.	Drying t. (h) MSU1	Moist. Cont. Exper. (%)	Moist. Cont. MSU1 (%)
35/100	5.78	6.25	12.98	12.98
25/70	5.32	5.76	12.98	12.99
18/40	6.23	6.75	12.70	12.71

Table 3. Average experimental corn moisture content in a 0.8 m-deep layer, and the corresponding MSU2 drying simulated results.

Moist(%)/Drying temp(°C)	Drying t. (h)	Drying t. (h) MSU2	Moist. Cont. Exper. (%)	Moist. Cont. MSU2 (%)
35/100	5.78	5.61	12.98	12.98
25/70	5.32	5.32	12.98	12.99
18/40	6.23	6.23	12.70	12.69

As seen in Tables 2 and 3, the use of constant enthalpy in the improved Michigan State University grain drying simulation model allows better matching results with less time. Maintaining constant enthalpy increases even more its performance, resulting in benefits such as: (1) desired product moisture content is reached in a faster way, because larger space and time increments may be used, with no interference in the quality of the final results; (2) no distortions should occur in the heat and mass balances between the product and drying air, once drying is conducted as the well accepted adiabatic process.

Conclusion

Drying simulation in corn fixed-beds proved to be highly effective when constant air enthalpy was maintained during the entire process. The improved Michigan State University grain drying simulation model brings drying simulation back to its desirable position, after almost two decades of little consideration. The new drying rate definition, originated from the well-known Page's thin-layer drying equation, led to a more coherent simulation model. Adding constant enthalpy in the drying simulation process made it possible to reach final results in less time, with high quality, more than simply checking for air relative humidity lower than 100%.

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