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LINSEC - The software for modeling and simulation of grain drying systems[1]

LINSEC - Programa computacional para modelagem e simulação de sistemas de secagem de grãos

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ABSTRACT - Considering the importance of mathematical models in the development and analysis of grain drying systems, and understanding the need to develop interfaces that will improve the accessibility of these models, this work aimed to: a) implement the Thompson model to simulate grain drying at high temperatures; b) develop an appropriate language to generate drying models; and c) develop a graphical interface with the goal of facilitating user understanding. Thus the computational program LINSEC that was created using the programming language Visual Basic 6.0. LINSEC was highly effective for the modeling and simulation of drying systems and in providing simulated values close to reality. LINSEC is highly flexible and user-friendly during the modeling of several types of dryers.

Key words: Grain dryer. Mathematical models. Thompson's model.

RESUMO - Tendo em vista a importância dos modelos matemáticos no desenvolvimento e análise de sistemas de secagem, além do conhecimento e necessidade de desenvolver interfaces de modo a aprimorar a acessibilidade e uso destes modelos, este trabalho visou: a) implementar o modelo de Thompson de modo a simular a secagem de grãos a altas temperaturas; b) desenvolver uma linguagem apropriada para gerar sistemas de secagem; e c) desenvolver uma interface gráfica com o objetivo de facilitar o entendimento do usuário, utilizando-se a linguagem Visual Basic 6.0. O programa computacional LINSEC, demonstrou uma alta efetividade na simulação de secagem, fornecendo valores próximos à realidade. É flexível e de fácil utilização pelo usuário durante a simulação para diferentes tipos de secadores.

Palavras-chave: Secadores de grãos. Modelos matemáticos. Modelo de Thompson.

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INTRODUCTION

Artificial drying of agricultural products is a technology which usually utilizes high cost equipment with high energy consumption in order to heat the air used for drying (REINATO *et al*., 2002; SHARMA; CHEN; LAN, 2009). Among drying modalities, drying at high temperatures is the most commonly used technology in commercial grain storage facilities (LUANGMALAWAT *et al*., 2007). This technology generates a gradient of humidity which accelerates the drying process, extends the shelf life of agricultural products (ERENTURK; ERENTURK; TABIL, 2004) and prevents losses due to the low water activity achieved (ULLMANN *et al*., 2010). However, it also creates conditions that can cause discoloration, cracks and fissures on the grains (BUNYAWANICHAKUL *et al*., 2007; LUANGMALAWAT *et al*., 2007; NISHIYAMA; ZAO; LI., 2005; RAO; BAL; GOSWAMI, 2006). In this case, the equipment must be designed in order to prevent these changes, preserve product quality and maximize dryer efficiency.

The main goal of drying is to remove excess water from the product until it reaches the ideal level of moisture content. This level is required in order to store, process and commercialize grain in a safe mode (JAYAS; WHITE, 2003; LIU *et al*., 2007; OLIVEIRA *et al*., 2010). To achieve this objective on a commercial scale, the use of high-capacity dryers that employ high drying-air temperature is recommended. These dryer systems generally imply high acquisition cost, heating energy consumption, and electrical energy usage (REINATO *et al*., 2002; SHARMA; CHEN; LAN, 2009).

Generally, drying mathematical models are used to predict final moisture content and output product temperature of products and drying time (DALPASQUALE *et al*., 2007). The mathematical model consists of heat and mass transfer interaction between the product and drying air. Even though empirical equations provide very accurate results for each specific experiment, they are not valid for other conditions. Simulation models are therefore recommended for describing the drying process (MOVAGHARNEJAD; NIKZAD, 2007).

Thompson's model is one of the most rewarding options for simulating grain drying at high temperatures, because of its lower requirement for computational resources and accuracy in estimating the output variables. This model is based on energy and mass transfer laws and an empirical equation of thin-layer drying of grain (DALPASQUALE; SPERANDIO, 2010). It was formulated considering the thin layer concept, with a simultaneous change of moisture content, air and grain temperature, and relative humidity (SOUZA; QUEIROZ; LACERDA FILHO, 2002).

It has been proved that mathematical modeling and simulation are important tools in the development, design and analysis of grain drying systems. These activities normally require programming language skills. Therefore, this scenario indicates the need to develop graphical interfaces that can aid modeling and simulation of drying systems. Therefore, this work presents a computational toolset that provides modeling and simulation drying systems with a graphical interface.

MATERIAL AND METHODS

A computational program known as LINSEC was implemented through the use of the program Visual Basic, version 6.0. It is a graphically oriented simulation toolset that allows the assemblage of computational models of grain dryers and simulation of the drying process according to Thompson's model. The organized block structure of the model permits the modeling and simulation of several types of grain drying systems.

The blocks are related to air, products and dryers. Each block represents an integral specific part of the drying system. LINSEC disposes of fifteen blocks. In order to model a dryer system, users need to select blocks according to dryer configuration.

LINSEC works in the following way: (a) the blocks that represent the drying system parts are inserted in the workspace; (b) the blocks are connected accordingly to the logic that governs the drying systems, leading to the flow sheet of air and product movement; (c) an instructional code of LINSEC language is generated; and (d) LINSEC compiles the language and simulates the drying on the basis proposed by Thompson, Peart e Foster (1968). The conceptual model related to the modeling of drying systems using LINSEC can be seen in Figure 1.

The drying process was divided into several subprocesses. The grain bed was considered as several layers with reduced thickness, placed upon each other. The variations in the conditions of air and grain in each layer were calculated based on small increments of time. All steps and equations are presented by Souza, Queiroz and Lacerda Filho (2002) and Dalpasquale and Sperandio (2010).

Tables 1, 2 and 3 contain, respectively, information about blocks related to drying air, product properties and dryer configuration.

Figure 1 - Conceptual model related to the modeling of drying systems using LINSEC

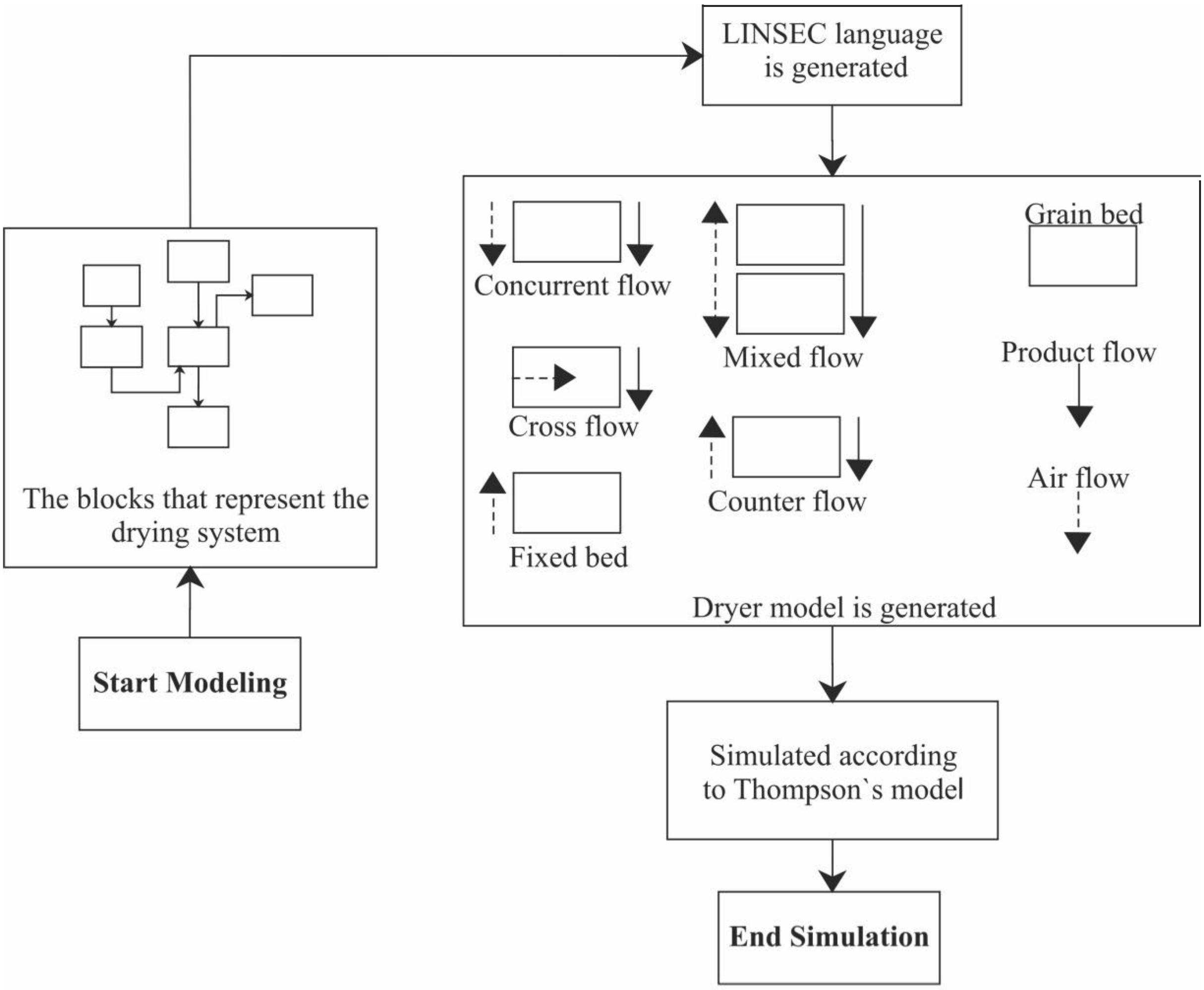


Table 1 - Blocks related to drying air

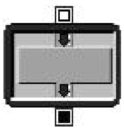
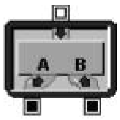
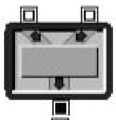
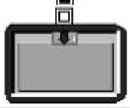
Block Name	Graphic Symbol	Description
Air source		Used for defining inlet air conditions such as: air temperature (ºC), relative humidity (%), and volumetric flow rate ($m^3\ s^{-1}$)
Heating system		Characterizes heater system according to the following information: air outlet temperature (ºC), heater system efficiency (%), and energy consumption ($kJ\ s^{-1}$)
Air divider		Divides airflow in two outlets. User needs to inform percentage of air flow for which outlets
Air mixer		Used for modeling mixing of two airstreams
Air exhaust storage		Monitors the outlet airstreams conditions. During simulation it reports: average air temperature (ºC), relative humidity (%) and air volume (m^3)

Table 2 - Blocks related to product properties

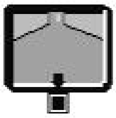
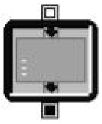
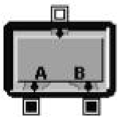
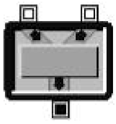
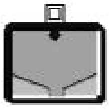
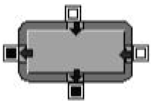
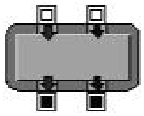
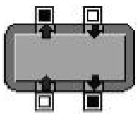
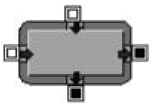
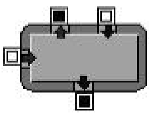
Block Name	Graphic Symbol	Description
Product inlet		Used for defining initial grain properties: type (corn, soybean, wheat or rice), moisture content (% w.b.), temperature (^{o}C), specific mass (kg m^{-3}) and product flow (kg s^{-1})
Storage section		Sets up a grain holding bin: requires volume (m^3)
Product divider		Divides grains flow in two. User needs to inform which percentage will flow by outlet "A"
Product mixing		Represents the mixing of two grain flows
Product outlet		Reports final moisture content of the product

Table 3 - Blocks related to dryer configuration

Block Name	Graphic Symbol	Description
Cross flow section		Sets up grain columns. Circular shape requires: inner and external diameter (m) and height (m). Rectangular shape requires: length, width and height columns. Both cases need to define the airflow direction
Concurrent flow section		Defines section area (m^2) and height of dryer chamber in concurrent flow dryer
Counter flow section		Establishes section area (m^2) and height of dryer chamber in counter flow dryer
Mixed flow section		Defines configuration of a mixed flow drying section and the following data is required: distance between the alternate rows of inlet and exhaust air ducts (m), cross-sectional area of the dryer (m^2), cross-sectional area of the ducts (m^2), number of rows of inlet air ducts, number of rows of outlet air ducts, number of ducts in each row, and airflow direction
Fixed bed section		If drying chamber is horizontal, the user needs to define: cross sectional area of the drying chamber (m^2) and height of grain column (m). If drying chamber is vertical and circular with inlet drying air duct in the center, it is necessary to enter the inner and outer diameter and the height of the drying chamber

In order to test LINSEC, two different sets of data related to the corn drying were employed: (i) the first one refers to a fixed bed dryer designed by Silva (1980), and (ii) the second to a concurrent flow dryer developed by Queiroz *et al*. (1988).

Fixed bed dryer modeling

Figure 2 shows a flowchart that represents the fixed bed dryer under the same experimental conditions carried out by Silva (1980).

The drying chamber of a fixed bed dryer was modeled with a cross section of 1.0 m^2, and column height of 0.305 m grain. The experimental data of nine drying tests accomplished by Silva (1980) is presented in Table 4.

Concurrent flow dryer modeling

The Figure 3 presents the flowchart that represents the concurrent flow dryer under the same experimental conditions conducted by Queiroz *et al*. (1988).

Figure 2 - (a) Conceptual model that represents the fixed bed dryer and (b) model that represents the fixed bed dryer in the LINSEC under the same experimental conditions specified by Silva (1980)

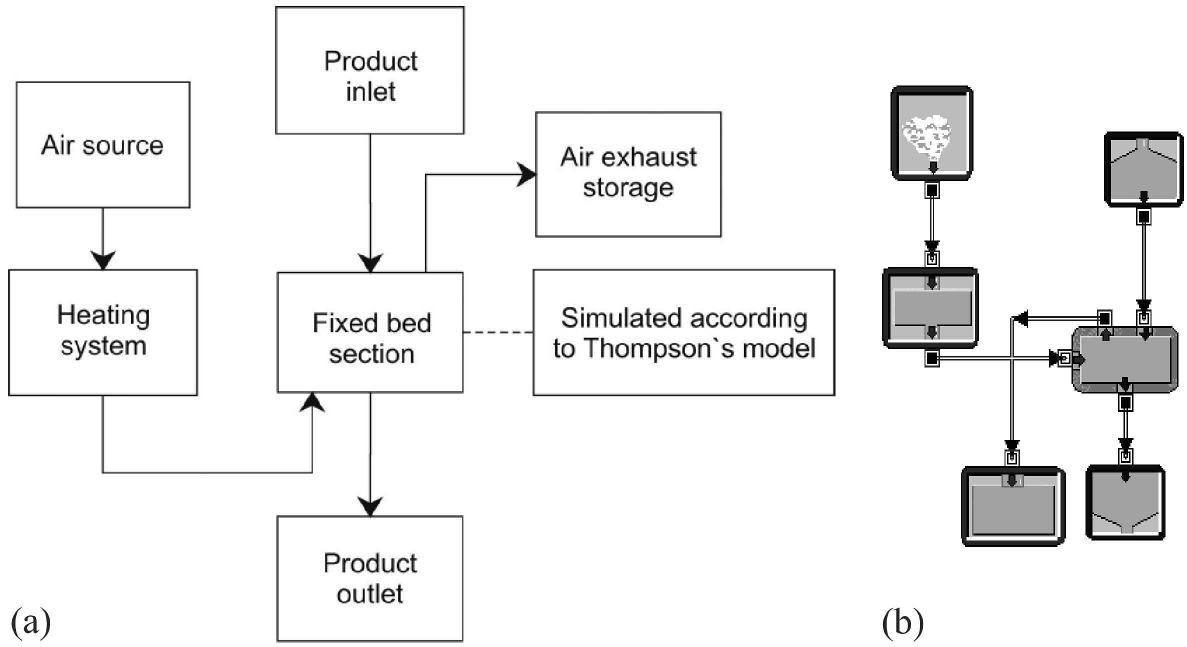
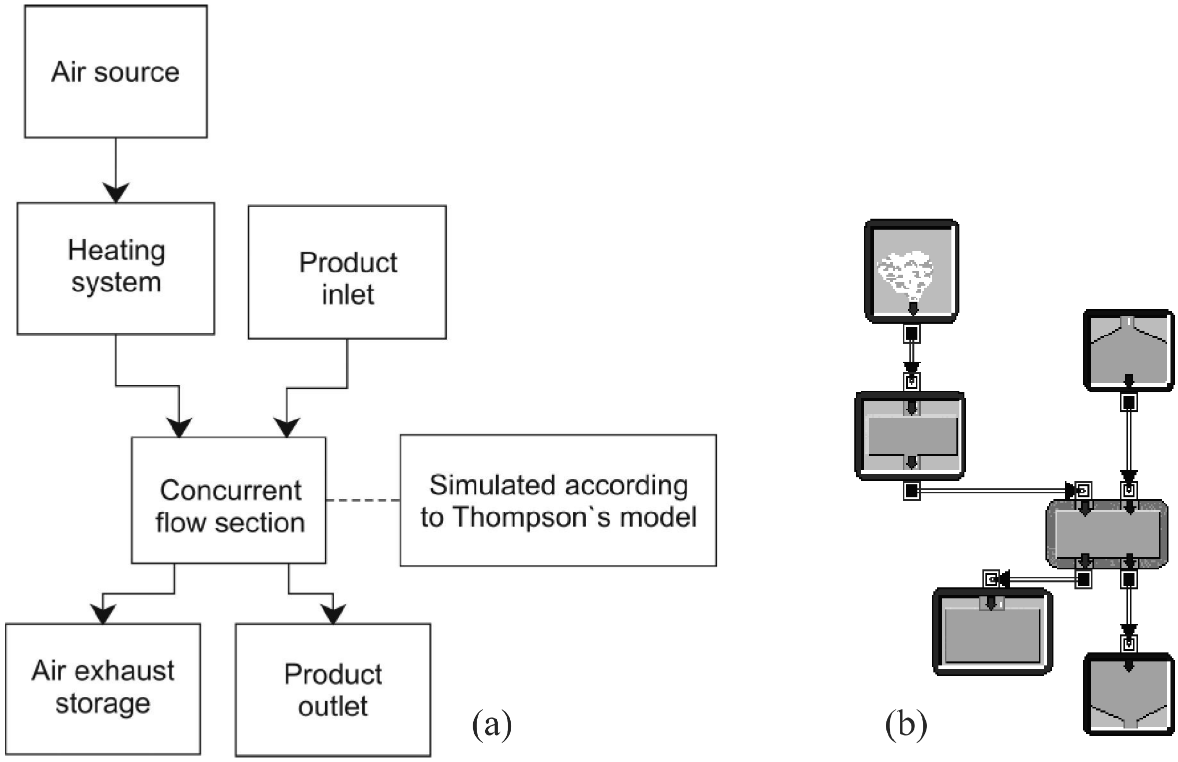


Table 4 - Drying conditions used in the experimental tests conducted by Silva (1980) and implemented in LINSEC in order to run simulations in the fixed bed dryer for corn

Drying conditions	Test								
	1	2	3	4	5	6	7	8	9
MCi (% w.b.)[1]	28.57	28.57	27.90	26.90	24.70	24.01	24.81	25.98	35.69
Tpi (ºC)[2]	18.75	17.95	7.95	8.15	12.55	11.65	10.95	9.95	12.25
Td (ºC)[3]	90.95	94.45	99.45	86.65	98.15	103.85	99.95	100.55	99.45
Te (ºC)[4]	21.25	10.65	2.85	4.85	12.65	11.15	10.15	6.85	12.55
RH (%)[5]	55	68	81	58	60	71	2	50	60
t (s)[6]	1764	1548	1296	1044	612	1116	288	3600	5688
G (m^3 s^{-1})[7]	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332

1/ MCi, initial moisture content of the product; 2/ Tpi, initial temperature of the product; 3/ Td, drying air temperature; 4/ Te, environment air temperature; 5/ RH, relative humidity; 6/ t, drying time; 7/ G, airflow

Figure 3 - (a) Conceptual model that represents the concurrent flow dryer and (b) model that represents the concurrent flow dryer in the LINSEC under the same experimental conditions conducted by Queiroz *et al.* (1988)



The dryer dimensions are: chamber cross section of 0.25 m² and grain bed height of 0.60 m. The experimental data of the nine tests conducted by Queiroz *et al*. (1988) are presented in Table 5.

Table 5 - Experimental conditions of the drying tests performed by Queiroz *et al.* (1988) and implemented in LINSEC for simulating the corn drying process in the concurrent flow dryer

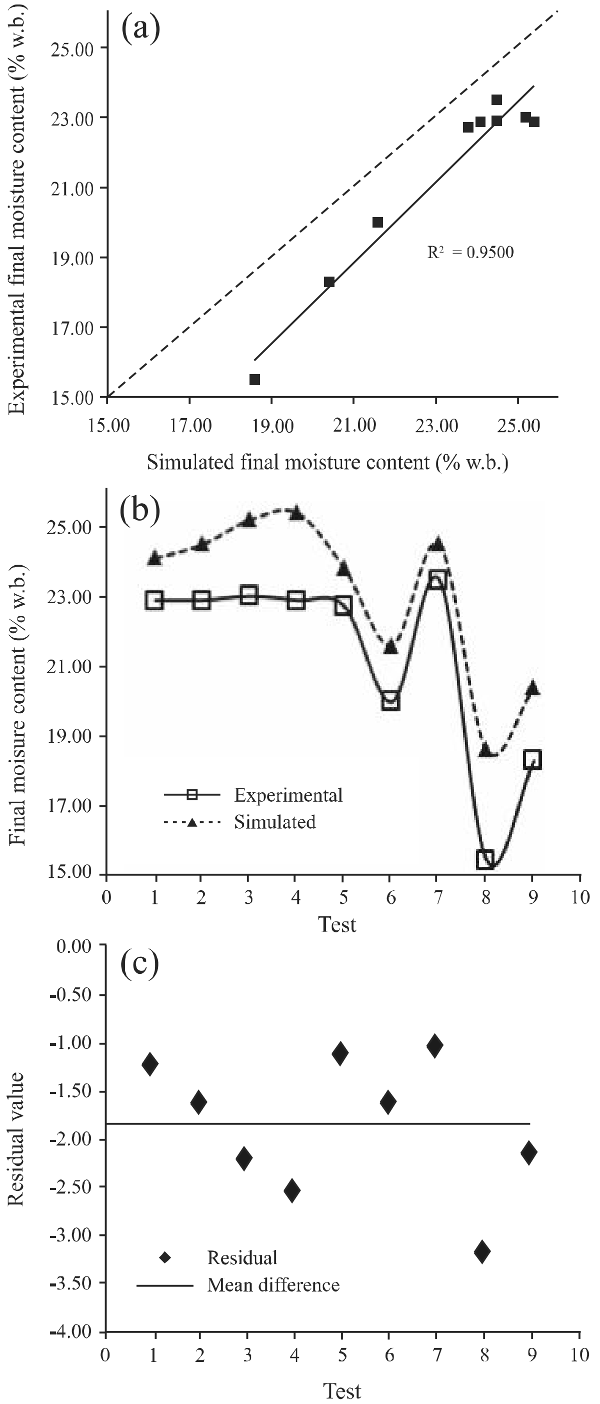
Drying conditions	Test								
	1	2	3	4	5	6	7	8	9
MCi (% w.b.)[1]	15.87	14.92	16.78	17.10	17.52	17.46	19.12	18.93	17.59
Tpi (ºC)[2]	26.00	29.40	29.00	29.60	27.50	30.00	28.50	28.90	27.70
Td (ºC)[3]	130.30	130.50	169.60	160.40	150.50	170.20	140.20	140.50	157.20
Te (ºC)[4]	20.90	27.40	25.10	28.50	20.00	26.70	27.20	21.80	27.60
RH (%)[5]	72	58	59	59	79	63	58	72	59
t (s)[6]	12600	14400	11700	10800	11700	11700	10800	13500	11700
G ($m^3 s^{-1}$)[7]	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332	0.5332
Lr ($kg s^{-1}$)[8]	0.0943	0.0658	0.0948	0.1315	0.0930	0.0975	0.0968	0.0695	0.1325

[1/] MCi, initial moisture content of the product; [2]/Tpi, initial temperature of the product; [3]/ Td, drying air temperature; [4]/ Te, environment air temperature; [5]/RH, relative humidity; [6]/ t, drying time; [7]/ G, airflow; [8]/ Lr, loading rate

RESULTS AND DISCUSSION

Figure 4 shows the results of the average final moisture content simulated by LINSEC and experimental data obtained by Silva (1980).

Figure 4 - (a) Simulated values of final moisture content *versus* experimental data obtained by Silva (1980), (b) comparison of simulated and experimental final moisture content in each test and (c) tendency of residual distribution values



As can be seen in Figure 4, the final moisture content simulated by LINSEC was higher than the experimental data. The mean and maximum absolute differences between simulated and experimental moisture contents were 1.82% w.b. and 3.13% w.b., respectively. Martins *et al*. (1982) performed the same comparative test using the MSU (Michigan State University) simulated and experimental data and obtained the mean and maximum differences of 0.88% w.b. and 3.45% w.b., respectively. As showed in Figure 4, the residual values demonstrate that simulated data presented a stochastic distribution and a systematic mean error.

Figure 5 presents the results of the water removed from the grains in the simulated tests *versus* experimental tests carried out by Silva (1980).

Figure 5 shows that simulated values of the amount of water removed from the grains were underestimated in relation to the experimental values. The mean and maximum absolute differences between the simulated and experimental data were 2.16% and 3.37%, respectively. As showed in Figure 5, the residual distribution values demonstrate that simulation results presented stochastically distributed and systematic mean error. The correlation coefficient was 0.9840.

The results of the average final moisture content simulated by LINSEC and experimentally obtained data by Queiroz *et al*. (1988) can be seen in Figure 6.

According to Figure 6 final moisture content simulated by LINSEC was higher than results obtained by Queiroz *et al*. (1988). The mean and maximum absolute differences between simulated and experimental final moisture content were 1.05% w.b. and 1.63% w.b., respectively. Queiroz *et al*. (1988), in the same comparison, using the MSU model, obtained the mean and maximum differences of 0.35% w.b. and 0.70% w.b., respectively. The largest error observed in this study probably could have been caused by lower accuracy in the Thompsons's model for drying temperatures above 100 °C, as shown in Table 5. In this case, the Michigan model has better accuracy.

Figure 7 shows the results of water removed from the grains in the simulated tests *versus* the experimental tests obtained by Queiroz *et al*. (1988).

According to Figure 7 one can conclude that the amount of water removed from the grains in the simulation was underestimated in relation to the experimental values. The mean and maximum absolute differences between the simulated and experimental water removed from the grains were 1.18 and 1.78%, respectively. Complementing the Figure 7 information, one can conclude that residual distribution values of simulated results present trend

Figure 5 - (a) Water removed from the grains simulated test *versus* experimental values obtained by Silva (1980), (b) comparison of simulated and experimental water removed from grains in each test, and (c) tendency of residual distribution values

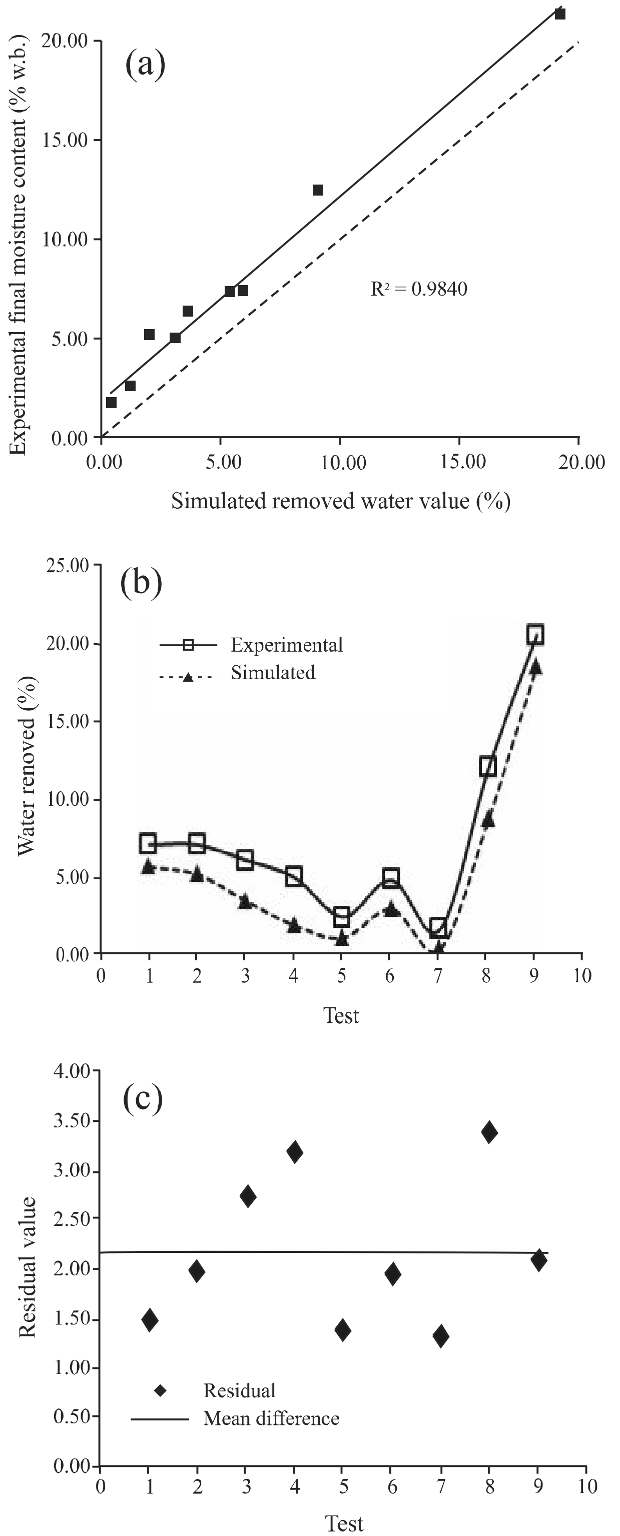


Figure 6 - (a) Simulated final moisture content *versus* experimental final moisture content obtained by Queiroz *et al.* (1988), (b) comparison of simulated and experimental final moisture content in each test and (c) tendency of residual distribution values

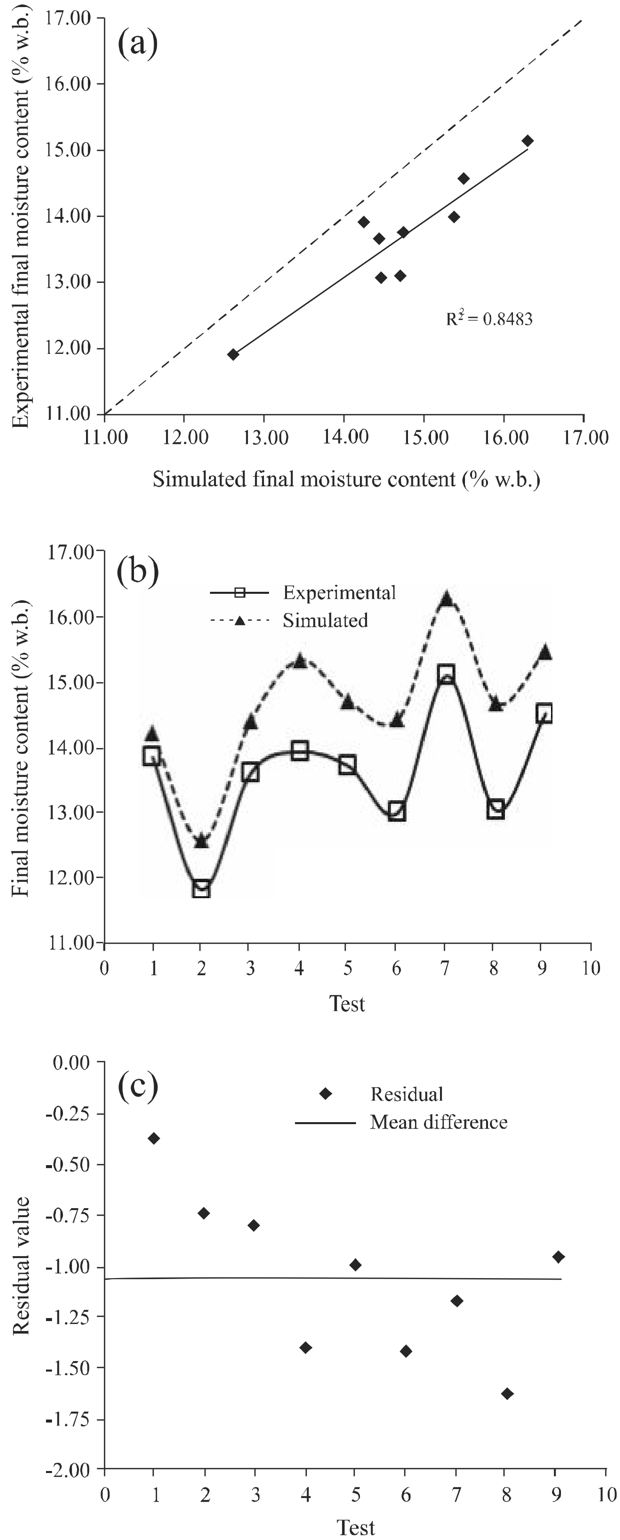
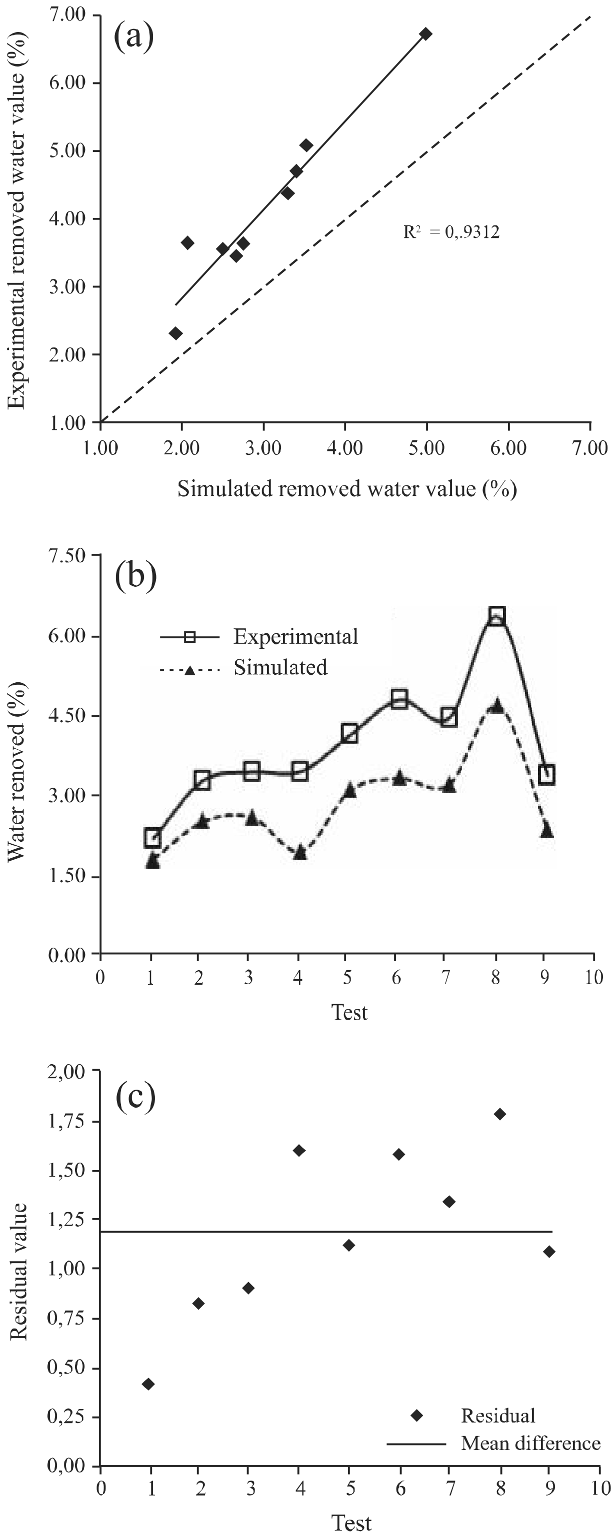


Figure 7 - (a) Water content removed from the grains by simulation *versus* experimental values of water removed obtained by Queiroz et al. (1988), (b) comparison of simulated and experimental water removed from the grains in each test and (c) Tendency of the residual distribution values



distribution and systematic mean error, and there is increasing tendency of error according to increasing amounts of water removed from grains.

CONCLUSIONS

1. According to the test procedures, LINSEC, a toolset for modeling grain dryers, can be used for modeling and simulating a concurrent flow drier and fixed bed dryer, with the great advantage of not demanding user knowledge of programming languages;
2. Modeling drying systems using LINSEC is an easy procedure that offers a large number of users the opportunity to use simulation at the development, design, evaluation and analysis of drying systems.

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