*Applied Chemical Engineering (2024) Volume 7 Issue 1*
doi: 10.24294/ace.v7i1.3276

**ORIGINAL RESEARCH ARTICLE**

# A system dynamic modeling to evaluate fluidized bed dryers under tempering and recirculation strategies

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## ABSTRACT

Grain drying control strategies aim for a rational energy use and a final product with low breakage levels. However, an experimental approach may be prohibitive due to the costs, scale, and theoretical complexity of this operation. The simulation environment is suitable to design equipment's and plan operations strategies with low cost and high certainty. This work utilized system dynamics modelling to quantify the percentage of product breakage during drying in fluidized bed dryers under recirculation and tempering strategies. A sensitivity analysis of the model's input parameters including different fractions of recirculation was performed, showing their effects on drying and post-drying product quality. Finally, we present optimizations from different objectives of drying operations. The recirculation strategy worked as an attenuator to the drying rates and combined with tempering strategy reached a minimum breakage level.

***Keywords:*** intermittent drying; drying; quality; simulation, corn

**ARTICLE INFO**

Received: 14 November 2023
Accepted: 1 December 2023
Available online: 10 January 2024



## 1. Introduction

Drying is a well-known unitary operation. The drying objective is to remove humidity from a biological medium by a simultaneous heat and mass transfer process. The drying phenomenon is a subject of interest due to its impact on the environment and product quality. More specifically, the environmental impact caused by drying is associated with high-energy consumption and low energetic and exergetic efficiencies. However, conducting a drying operation searching for thermal efficiency may not represent an appropriate compromise with product quality.

Grain and food quality are still the subjects of intense research due to the development of thermal and hydro-sensitive stresses, and undesirable chemical and biochemical changes during drying. The inappropriate dryer setting points can significantly increase the level of breakage in grain drying[1].

Drying under traditional dryers' configurations such as counter-flow dryers[2], mixed-flow dryers[3], fixed-bed dryers[4] may expose the product into undesirable drying conditions that may result in thermal/mechanical damage and lower germination rates[5]. As an alternative to conventional dryers, the development of new dryers and new strategies have been developed aiming improve thermodynamic efficiency and product quality after drying[6,7]. Recently, Xu et al.[8] performed an analysis of a two-stage dryer. The dryer presented convincing results concerning product quality and thermal efficiency in drying operation.

The fluidized bed dryers are of special interest in this study. This type of dryer is associated to minimized levels of product mechanical damage[9]. However, the high drying rates used in fluidized bed dryers may affect product quality. So, the recirculation of exhausting air becomes an opportunity to increase thermal efficiency and investigate its impact on product quality[10].

The literature concerning fluidized bed dryers with recirculation and their thermal efficiencies is extensive[11–13]. Also, studies about drying impact on product quality. However, studies about drying impact on grain quality are still under investigation. Expressive results concerning the quality analysis under different drying strategies and dryer configurations were presented recently[6,14–17]. Additionally, was identified a lack of studies concerning the effect of the recirculation of exhaust air on product quality. In fact, this is highly associated with the difficulty in determining the dynamics of quality during drying.

Determining the dynamics of grain damage level during drying remains a topic of interest for researchers and practitioners in agricultural and food technology[18]. Traditional methods to determine the quality level can be time-consuming, costly, and destructive[19]. Moreover, the experimental analysis can be complex or prohibitive to determine the dynamics of quality during drying. Therefore, mathematical modeling emerges as an efficient tool to analyze drying operations and design efficient dryers at real scales.

The modeling of fluidized bed dryers is composed by balance equations, based on ordinary differential and algebraic equations, suitable for an approach by a System Dynamics Analysis and dynamical optimization methodology. System Dynamics (SD) is a methodology, developed by Jay Forrester in the 1950s, that allows the construction of models to analyze complex systems over time, through equations of finite differences or differentials. The models are built to analyze the different elements that compose it, their relationships and behavior[20].

In practice to determine and optimize the level of grain breakage during drying under recirculation and tempering strategies is complex. Accordingly, this study presents a novel, simple and validated simulation model by system dynamics methodology to quantify and optimize the level of product breakage during drying in fluidized bed dryers under recirculation and tempering strategies. Finally, a restricted and unrestricted optimization aiming to minimize the product losses during drying and tempering strategies were performed.

# 2. Materials and methods

## 2.1. Fluidized bed drying model

The lumped analysis of a fluidized bed drying model was performed. The presented model comprises a system of four nonlinear ordinary differential equations, specifically addressing mass and energy balance interactions between the grains and drying air. Additionally, it incorporates an empirical thin-layer drying equation. For a more detailed understanding of the model's development and underlying assumptions, readers can refer to Amantea et al.[21].

### 2.1.1. The continuity equation for air vapor

$$M_s \frac{\partial M}{\partial t} = m_a (W_1 - W_2) \tag{1}$$

### 2.1.2. Enthalpy equation for grain and air

$$m_s c_p \frac{\mathrm{d}\theta}{\mathrm{d}t} = m_a (c_a + W c_v)(T_1 - T_2) + h_v m_s \frac{\partial M}{\partial t} Q_{\mathrm{loss}} \tag{2}$$

### 2.1.3. Thin layer drying equation

In this study, the empirical single layer drying rate equation for corn is used[22].

$$\frac{\partial M}{\partial t}=\frac{M_e-M}{3600\left[A^2+\left(\frac{1}{900}\right)Bt\right]^{\frac{1}{2}}} \tag{3}$$

The empirical equation for the equilibrium moisture content values of shelled corn is used[22].

$$M_e=\left[\frac{\ln(1-rh)}{-0.688(T-227)}\right]^{\frac{1}{2}} \tag{4}$$

All the physical properties of corn kernel used in this work can be accessed in the study of Amantea et al.[21].

### 2.1.4. Recirculation

In a typical dryer with recirculation, there is a drying chamber where the drying air enters, flows through the grain bed and exits. At the chamber's outlet, a valve decides the fraction of exhaust air that will return to the drying chamber. A second valve composes the system and controls the inlet of fresh air to guarantee the system's drying capacity. Finally, the fractions of recirculated and fresh air are mixed and heated by a heat source and go to the drying chamber.

The drying air recirculation is a simple strategy and energetically efficient. Usually, the decisions concerning the recirculation fractions are made considering the relative humidity and temperature of the inlet air[23].

The mixture of one or more airflow rates with distinct temperature and humidity can be easily modeled by psychrometric principles. An airflow rate $m_3$ with humidity ratio $W_3$ is obtained by the mixture of two dry airflow rates $m_1$ and $m_2$ with respectively $W_1$ and $W_2$ humidity ratios[24]. Let *r* be the mass of dry air recycled. A mass balance over the air mixture yields,

$$W_3=W_1+(1-r)W_2 \tag{5}$$

The humidity ratio ($W_3$) is used to correct the air temperature after mixing the inflow and the fraction of exhaust airflow by[24],

$$T_3=\frac{T_1+T_2\left(\frac{W_3-W_1}{W_2-W_3}\right)\left(\frac{1.0048+1.88W_2}{1.0048+1.88W_1}\right)}{1+\left(\frac{W_2-W_1}{W_2-W_3}\right)\left(\frac{1.0048+1.88W_2}{1.0048+1.88W_1}\right)} \tag{6}$$

## 2.2. The causal diagram of fluidized bed drying

The drying condition was modeled considering the causal relationships among the variables associated with the drying process. The development and discussion of the following causal diagram can be accessed in the study of Amantea et al.[21].

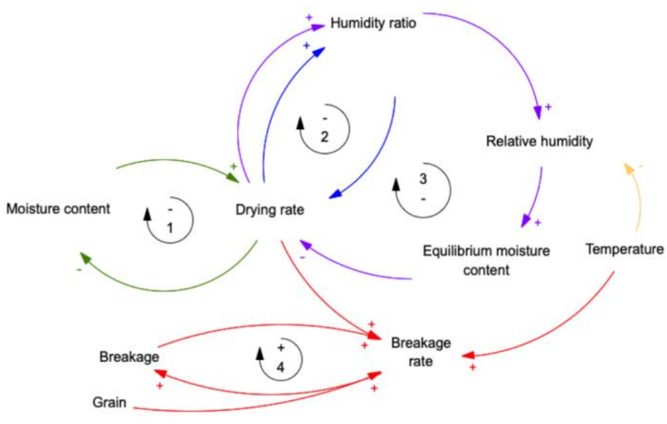


**Figure 1.** Causal diagram of the system dynamics breakage model[21].

**Figure 1** represents the interaction among key variables that compose the complex drying system. This depiction is a crucial step in dynamic modeling, allowing us to understand and plan how to optimize our actions in search of an improved operational point.

Essentially, two main systems interact: drying and quality. The negative cycles work to mitigate the damage generation caused by a positive cycle. The causal diagram presented was transcript to a stock and flow diagram and implemented in a system dynamics software (Anylogic Version 8.5 PLE)

### 2.3. Intermittent drying strategy

Intermittent drying is a strategy to manage the dryer energy source and consequently improve thermal efficiency. To simulate intermittent drying conditions a step function (Equation (13)) was inserted as initial condition for the Equation (8).

$$f(t) = \begin{cases} \text{Drying temperature}, & \text{turn on heater} \leq t < \text{turn off heater} \\ 30\ °C, & \text{turn off heater} \leq t < \text{turn on heater} \end{cases} \quad (7)$$

## 3. Results

### 3.1. Drying simulation parameters

The simulations were interrupted when the product moisture content reached 12% (dry bulb). The drying temperatures scenarios were simulated in range of 45–85 °C. The moisture content scenarios were simulated using initial moisture content range of 0.22–0.18 (dry bulb). The drying relative humidity was fixed in 5%.

### 3.2. Effect of initial grain water content

**Figure 2** illustrates the effect of initial water content on drying variables during drying.

The first effect of initial moisture content, and already expected, is the reduction in drying time. It is noteworthy that the drying time can be reduced by approximately 60%. The initial moisture content has a minimum effect under drying temperature. The breakage index was highly increased when the process was stated with a product with high water content. This fact is explained by the behavior of drying rates and product temperature. In another words a product with high initial water content will need more time to reach the final drying stage. Consequently, the breakage index will be higher than another drying conditions.

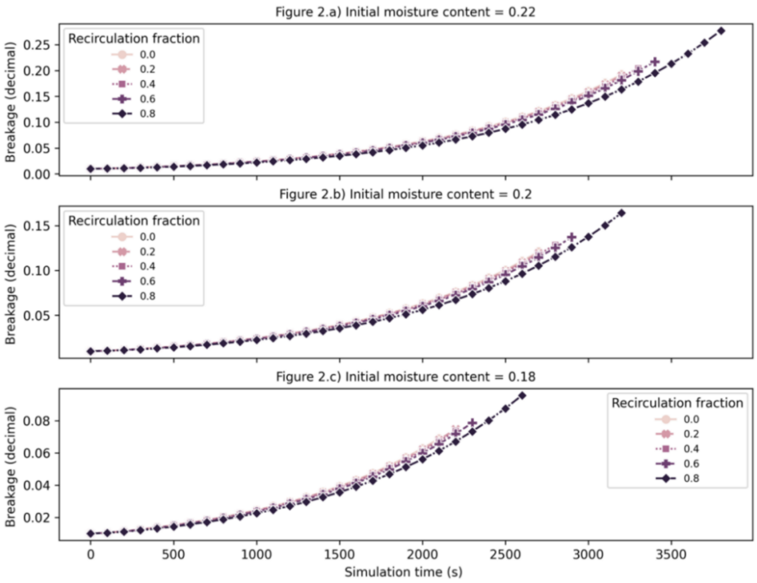


**Figure 2.** Effect of initial moisture content under breakage dynamics.

As expected, high recirculation fractions may reduce the drying temperature however the breakage index is slightly increased due to a gain in drying time.

### 3.3. Effect of drying temperature

**Figure 3** illustrates the effect of drying temperature drying variables during drying. Certainly, the drying temperature is the control variable that presents the greatest effect on product quality. As the drying temperature rises it can be noticed a loss of up to 10% by the breakage index during drying. However, from the quality point of view, the scenario with a lower drying temperature and maximum recirculation fraction is the most efficient. This fact is explained by the lower drying rates reached in a drying setup operation near the natural drying conditions. Thus, if the drying time is not under restriction this scenario should be taken.

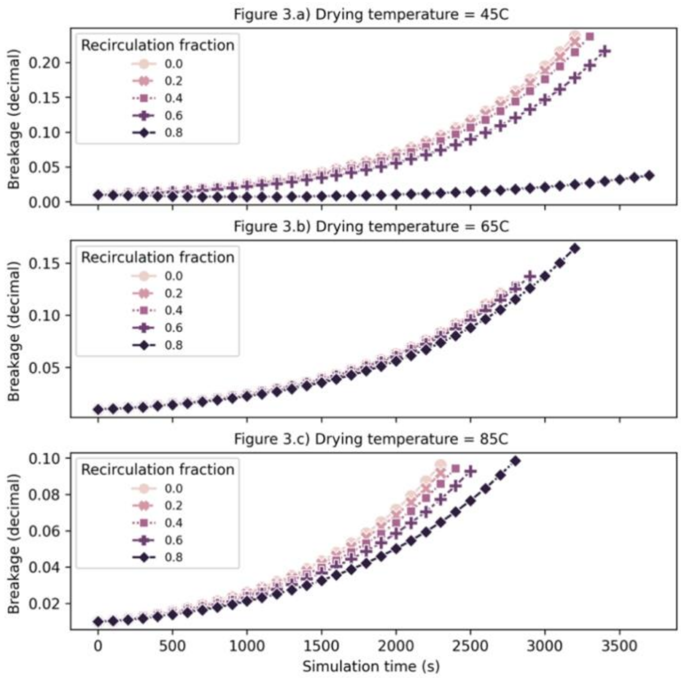


**Figure 3.** Effect of drying temperature on breakage dynamics.

### 3.4. Intermittent drying under recirculation

In this section, the effects of intermittent drying with recirculation under product quality is presented. The drying temperature was set to 85 °C. The heater and tempering times were set to 300 s.

The **Figure 4** shows the temporal profile for the average temperature and product breakage. Due to tempering strategy, the mean temperature during the process is lower than the continuous drying. This fact implies a reduction of ≈ 66% on breakage values. The tempering combined with a continuous recirculation of exhaust air improved the results. The scenarios where recirculation fractions practiced were between 0.25 and 0.5 presented breakage values of ≈ 2.5% without compromising the drying capacity.

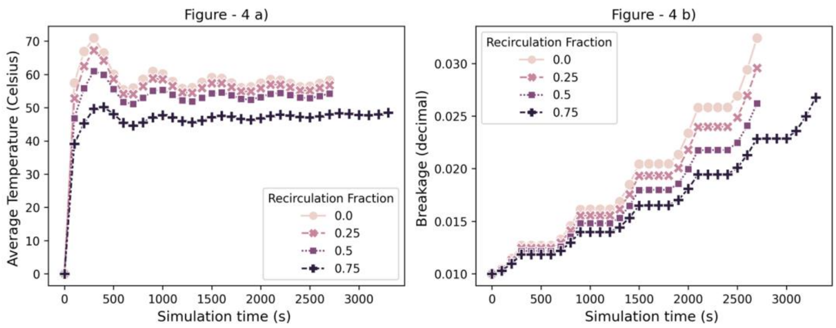


**Figure 4.** Time profiles for the intermittent drying experiment: **(a)** Average drying temperature temporal profile; **(b)** Product breakage temporal profile.

### 3.5. Process optimization

In order to find better operating points for the process, different conditions were created from different objectives and constraints.

Unrestricted optimization:

In this experiment the objective was to obtain the operating point that, at the end of the process, resulted in the lowest post-drying losses. Thus, the objective was formulated as minimizing the percentage of losses by allowing variation in drying temperature, initial water content of the product, recirculation fraction and tempering times. The initial moisture content was set to 20% (db). Notably, the drying time was not restricted. **Table 1** contains the initial drying parameters obtained and the percentage of breakages at the end of drying, after the optimization experiment.

**Table 1.** Simulation with unrestricted optimization.

| Drying temperature (°C) | Drying time (s) | Recirculation fraction | Heating time (s) | Tempering time (s) | Breakage |
|---|---|---|---|---|---|
| 85 | 3536 | 0.5 | 100 | 1200 | 1% |

The experiment shows that the use of high temperatures combined with high re-circulation fraction and long tempering times can lead to low breakage rates. Shortly, this is explained by the natural drying conditions used. However, the drying time may be prohibitive, because compared to traditional scenarios, the time obtained was exaggeratedly longer.

Optimization seeking specific breakage levels:

This was the last scenario proposed in this study. The objective was to search for the operating points that aimed to achieve the established percentage of breakage targets, allowing the input parameters to be varied. The results are shown in **Table 2**.

**Table 2.** Simulation for optimization seeking specific breakage levels.

| Drying time (s) | Drying temperature (°C) | Recirculation fraction | Heating time (s) | Tempering time (s) | Breakage |
|---|---|---|---|---|---|
| 2880 | 71.3 | 0.17 | 600 | 900 | Objective 5% |
| 2572 | 79.1 | 0.50 | - | - | Objective 10% |
| 2881 | 63.7 | 0.44 | - | - | Objective 15% |

The use of tempering strategy was suggested only in scenarios where the breakage level was equal to 5%. This fact was corroborated in the experiments performed suggesting that tempering and recirculation strategies reduce significantly the breakage levels during drying under recirculation.

The scenarios where the objective was a breakage level superior to 5% the recirculation strategy was always utilized but it is not mandatory. Similar results were obtained showing that there are multiple optimum solutions when there is no capacity constraint.

## 4. Conclusion

The proposed model was able to evaluate the impact of recirculation and tempering strategies on final product quality. It was verified that the recirculation strategy under different drying temperatures and initial moisture contents will affect the dryer capacity. High breakage levels were found under high initial water content and high drying temperatures. The recirculation works as a tool to attenuate the high drying rates. However, near the natural drying conditions may reduce expressively the dryer capacity.

The tempering strategy presented low levels of breakage during drying. Additionally, when combined with moderated recirculation fractions reached the lowest level of breakage without affecting the dryer capacity.

These results may suggest an outstanding energetic performance that should be investigated in future work.

Finally, as a suggestion to future works, this proposed methodology can be the basis to develop new drying control strategies concerning recirculation fraction and drying tempering aiming to dynamically maximize dryer energy efficiency and final product quality.

## Author contributions

Conceptualization, RPA; methodology, RPA; software, RPA; validation, RPA; formal analysis, RPA; investigation, RPA; resources, DS and GR; data curation, RPA; writing—original draft preparation, RPA; writing—review and editing, RPA, DS and GR; visualization, RPA; supervision, DS and GR; project administration, DS and GS; funding acquisition, GR and DS. All authors have read and agreed to the published version of the manuscript.

## Acknowledgments

The authors would like to thank the Department of Agriculture, Food, Environment and Forestry (DAGRI), from University of Florence for the lab structure.

## Conflict of interest

The authors declare no conflict of interest.

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