Climate effect on strategy sellection and energy consumption for in-bin drying of corn with natural air/low temperature

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Abstract: This is a general study about the performance and energy requirement for NA/LT in-bin drying of corn at 10 different locations in Argentina. The goals of this study were to use the PHAST-FDM simulation model and historical weather data to study the performance of four NA/LT in-bin drying strategies for drying corn with different airflow rates (1 to 2 $m^3\ min^{-1}\ t^{-1}$) and from different initial moisture contents (MC) (17 and 20%) in terms of drying time, final moisture content and dry matter loss, among other parameters. Additionally, the electrical and caloric energy consumption was also estimated. The most successful strategy across locations was the intelligent strategy (a model based strategy). The appropriate specific airflow rate was 2 $m^3\ min^{-1}\ t^{-1}$ in North Argentina and 1 $m^3\ min^{-1}\ t^{-1}$ in the South Argentina. In some locations with warm weather, no NA/LT in-bin drying strategy succeeded in drying corn with initial MC of 20% or superior under the airflow rates ranges investigated in this study, mostly due to excessive dry matter loss. The location with the coldest weather (Balcarce) resulted with the highest total energy consumption per point of moisture extracted and per ton of grain, (35.5 and 25.1 kWh for 17% and 20% initial MC, respectively). On the contrary, the location with the warmest weather (Saenz Peña) resulted with the lowest total energy consumption, with 9.4 and 10.7 kWh per point of moisture extracted and per ton, for 17% and 20% initial MC, respectively.

Keywords: in-bin drying, natural air / low temperature; drying strategies; climate effect; simulation; dry matter loss; energy consumption

Citation: Diego de la Torre, and Ricardo Bartosik. 2013. Climate effect on strategy sellection and energy consumption for in-bin drying of corn with natural air/low temperature. Agric Eng Int: CIGR Journal, 15(2): 304−317.

1 Introduction

The primary alternative drying process to achieve the best food corn quality is natural air / low temperature (NA/LT) in-bin drying. This involves in-bin drying of corn using airflow rates of 1.1 to 2.2 $m^3\ min^{-1}\ t^{-1}$ and natural air, or air heated by only 3℃ to 8℃.

The advantages of NA/LT in-bin drying systems are the uniform final moisture content (MC_f) of the grain bulk, the low drying temperature and the possibility to store the grain in the same bin used to dry. The disadvantages of NA/LT in-bin drying systems are that they are more challenging to operate than high temperature dryers, can cause over-drying of the grain bottom layer, are weather dependent (could result with excessively extended drying time), and have low drying capacity ($t\ h^{-1}$) compared to high temperature systems (Bartosik, 2005).

Morey et al. (1979) reported that specific NA/LT in-bin drying strategies must be established for each location. These strategies consist of different approaches to use fan and burner throughout the drying cycle.

Bartosik and Maier (2004) developed a strategy that would regulate the amount of supplemental heat according to the current weather condition. Later, Bartosik (2005) developed a model based self adapting variable heat strategy. This strategy incorporated the Thompson Equilibrium model to predict the drying progress, which allowed use of fan and burner more or

Received date: 2013-01-15 **Accepted date:** 2013-04-13
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less aggressively based not only in the current weather conditions, but also in the predicted grain MC. The Purdue University Post Harvest Aeration and Storage Simulation Tool – Finite Difference Method (PHAST-FDM) simulation model and historical weather data was used to evaluate this strategy for different U.S. Midwestern locations and concluded that the model based strategy outperformed all the other evaluated strategies (continuous natural air, equilibrium moisture content window, and continuous constant heat). Finally, Bartosik and Maier (2007) implemented the model-based strategy in a series of NA/LT in-bin drying field test in the U.S. Midwestern Corn Belt for drying food grade corn with satisfactory results regarding to drying time, total energy consumption (EC_t) and MC_f.

A similar model-based and variable heat strategy, named intelligent strategy, was developed and tested by simulation in three locations of Argentina (de la Torre et al., 2008). Simulation results confirmed that, the intelligent strategy outperformed all the other strategies evaluated. Later, a prototype of NA/LT in-bin drying system was constructed and field tested for drying popcorn with the Intelligent strategy (de la Torre et al., 2011), and it was concluded that NA/LT in-bin drying with the Intelligent strategy has a great potential for optimizing popcorn quality and reducing drying energy consumption.

Based on research results, it seems that NA/LT in-bin drying with the intelligent strategy could be a major improvement for Argentine farmers and processors of specialty corns. However, in order to help farmers and processor to adopt this technology, additional information is required regarding how the Intelligent strategy would perform, in comparison to more simple strategies, in the different weather conditions of Argentina corn production areas. In term of the system operation, more information is required regarding the expected drying time and maximum initial MC for the different regions, and in terms of system design, more information is required regarding the optimal airflow rate for different regions.

Other useful information for investing in NA/LT in-bin drying systems is for estimation of operational drying cost. The operational drying cost is calculated by the amount of energy demanded by the drying operation and the price of the energy. The amount of energy demanded depends on the fan run hours (FRH) and the burner run hours (BRH), which are greatly affected by the weather conditions (Bartosik and Maier, 2004). Still is not fully understood how the climatic variables (i.e.: ambient temperature) affect drying performance and energy consumption (EC). Thus, it is not reliable to extrapolate EC and drying costs of NA/LT system from one location to another if weather conditions are different, and a site specific analysis should be performed instead.

The goal of this research was to use the PHAST-FDM simulation model and historical weather data of 10 locations throughout the corn production area of Argentina to study the performance of four NA/LT in-bin drying strategies for drying corn with different airflow rates and from different MC_i. The specifics objectives were 1) to study the effect of weather conditions on different NA/LT in-bin drying strategies; 2) to select the best NA/LT in-bin drying strategy for drying corn in each location; 3) to determine the optimal airflow rate for each location and MC_i combinations; 4) to determine the average drying time for each location and MC_i combination; 5) to determine the effect of the average ambient temperature of the drying month on airflow, dry matter loss (DML) and drying time and 6) to obtain the electrical, caloric and total energy consumption for NA/LT in-bin drying in each location.

2 Materials and methods

Ten locations were selected representing several Argentinean regions with a wide range of agro-climatic conditions where corn is produced and dried. The PHAST-FDM simulation model and historical weather data (hourly ambient temperature and RH) were used.

The PHAST-FDM simulation model was previously validated and extensively used for simulating in-bin drying and aeration processes (Zink, 1998; Montross and Maier, 2000; Bartosik and Maier, 2004; Bartosik and Maier, 2007; Berruto et al., 2011). This mathematical model assumed that the drying and rewetting (reconditioning) process occurs over a series of time steps. The grain bed is modeled as a number of layers and a set of heat and mass balance equations predicts the changes in the conditions of the grain in different layers and the air passing through them.

The Thompson (1972) equilibrium model was used to predict the MC changes of a deep layer of corn. This model assumes that the drying air leaves the layer at thermal and moisture equilibrium conditions with the grain of that layer. No thin-layer drying or rewetting equations are needed, but a reliable equilibrium relative humidity / equilibrium moisture content (ERH/EMC) model is of primary importance for the Thompson equilibrium drying model.

The required inputs for the model are ambient air temperature and RH for each time step, and initial temperature and MC of the grain. The heat and mass balances were done on the basis of 1 kg of dry air. The physical and thermal properties of corn were obtained from the ASAE Standards D241.4 and D243.4, respectively. The properties of the moist air were computed on the basis of the equations and parameters of ASAE Standard D271.2, and the ERH equation and parameters were taken from ASAE Standard D245.5.

The PHAST model was solved using the finite difference method and it was first written in FORTRAN platform, and then converted into Visual Basic. An extensive description of the model could be fount in Bartosik (2005).

Before the simulation started, a weather database was created including hourly ambient temperature and RH of each location considered (Table 1).

Table 1 List of the locations considered in this study, period of time with weather data, latitude and longitude, average corn harvest date, average ambient temperature and ambient RH of the harvest month

Locations. Province.	Period of time with weather data	Lat.	Long.	Harvest date	Average ambient temperature/℃	Average RH/%
Saenz Peña. Chaco	01/1999 to 12/2006	-26.87	-60.45	1-Feb	26.1	70.0
Cerro Azul. Misiones	1/1991 to 12/1998	-27.65	-55.43	1-Mar	23.6	73.0
Bella Vista. Corrientes	1/1992 to 12/2002	-28.43	-58.92	1-Mar	24.5	74.0
Reconquista. Santa Fe	05/1991 to 07/2001	-29.18	-59.7	1-Mar	23.1	78.0
Manfredi. Córdoba	08/2000 to 01/2005	-31.82	-63.77	15-Abr	15.8	71.2
Oliveros. Santa Fe	08/1990 to 12/1995	-32.55	-60.85	15-Mar	22.2	76.0
Pergamino. Bs. As.	01/2001 to 12/2006	-33.93	-60.55	15-Mar	20.3	72.2
Castelar. Bs. As.	01/1990 to 12/2004	-34.67	-58.65	15-Mar	21.4	64.0
Anguil. La Pampa	10/1990 to 06/2007	-36.5	-63.98	1-May	11.2	76.5
Balcarce. Bs. As.	05/1991 to 12/2004	-37.75	-58.3	15-May	14.3	83.4

The weather data was obtained from agricultural research stations of INTA (in Spanish: National Institute of Agricultural Technology). The data was checked and corrected from errors and/or missing data.

Four NA/LT in-bin drying strategies were evaluated for each location to dry yellow dent corn from 17 and 20% MC_i to 14.5% MC_f with three airflow rates (1, 1.5 and 2 $m^3 min^{-1} t^{-1}$). A typical farm bin of 5 m high and 8 m diameter, flat floor, holding approximately 172 t of corn, was considered.

The starting drying date was the typical corn harvest date for each location, and the initial grain temperature was considered to be the same as the average ambient temperature of the month (Table 1).

According to Bartosik and Maier (2006), the concentration of fine material at the center of the grain mass causes a non-uniform airflow rate in the bin. For instance, if the average airflow rate is 1 $m^3 min^{-1} t^{-1}$, the typical distribution will be 85% (0.85 $m^3 min^{-1} t^{-1}$) of the average airflow through the center of the grain mass and 115% (1.15 $m^3 min^{-1} t^{-1}$) through the periphery. Thus, this study considered the non-uniform distribution reported by Bartosik and Maier (2006).

The PHAST-FDM uses the Modified Chung-Pfost EMC equation (standard of the ASAE D245.5), and the corn parameters determined by Bartosik and Maier (2007).

2.1 Drying strategies

The NA/LT in-bin drying strategies included in this research are shown in Table 2.

Table 2 Fan and burner operation mode and drying air temperature for the four strategies considered in this study

Strategy	Fan operation	Burner operation	Drying temperature
CNA	Continuous since start drying date to end drying date	No supplemental heat	Ambient temperature + Fan pre warming
CH3	Continuous since start drying date to end drying date	Continuous since start drying date to end drying date	Fixed in 3℃ above ambient temperature
Window	Intermittent according to ambient EMC and prescribed limits	No supplemental heat	Ambient temperature + Fan pre warming
Intelligent	Intermittent according to drying progress and ambient EMC	Intermittent according to drying progress and ambient EMC	Variable according to ambient EMC

Continuous Natural Air (CNA): the fan is turned "on" when the bin was filled and it is turned "off" when the grain mass completes drying. The fan remains "on" without interruption, regardless of weather conditions.

Continuous Constant Heat (CH3): the fan and the burner are turned "on" when the bin is filled and turned "off" when the grain mass completes drying. Both, fan and burner work without interruption, regardless of weather conditions. The burner is regulated to increase the ambient temperature at 3℃.

Window (W): the ambient EMC is calculated based on the ambient temperature and RH. Maximum and minimum EMC limits are set (i.e. 12% and 17%, respectively). When the EMC is between these limits the fan is turned "on", otherwise the fan is turned "off". The intermittent operation of the fan continues until the grain mass completes drying. This strategy does not use the burner, so it does not condition the drying air.

Intelligent strategy: this is a model based proprietary strategy. The entire grain mass is assumed to consist of layers of grain. The Thompson Equilibrium model is incorporated to compute the drying progress of the different grain layers throughout the drying operation. In order to predict drying, the model uses the ambient temperature and RH data, and the bin airflow rate. The goal of the intelligent strategy is to maintain the bottom grain layer between a minimum and a maximum MC during the entire drying period (i.e., 14% to15%). The minimum MC limit is progressively increased by the control strategy during the drying period based on the drying progress. The air exhausting the bottom layer of grain is in equilibrium (temperature and equilibrium RH) with the conditions of the grain in this first layer. The grain in the second layer will eventually equilibrate with the conditions of the air exhausting the first layer of grain (14% to15% MC). Subsequently, layer by layer, the grain in the entire grain bulk will tend to equilibrate to the same conditions as the grain in the first layer (Figure 1). Thus, by controlling the MC of the grain in the bottom layer, the intelligent strategy is able to achieve a uniform final MC of the grain in the entire bulk. In addition to the MC change in the different layers the model estimates the time left to finish drying. Based on the results of the prediction model (grain MC for the different layers) and the weather information (ambient temperature and RH) the intelligent strategy uses the fan and the burner more or less aggressively. Additionally, if air conditioning is needed, variable supplemental heat is provided according to the weather condition. A detailed description of this strategy could be found in Bartosik (2005).

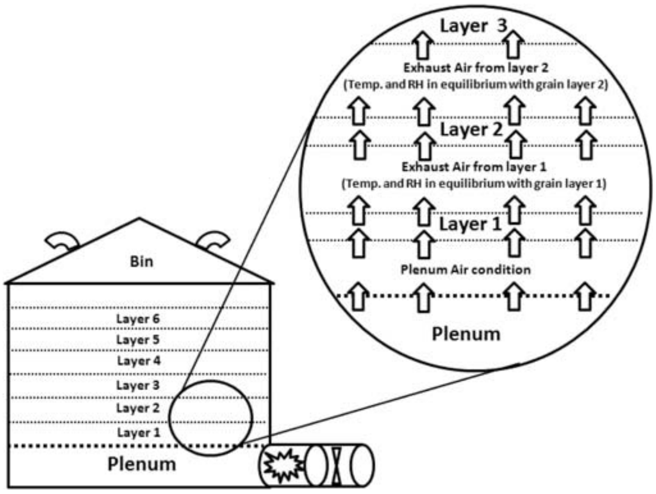

Figure 1 Schematics of the grain layers and the equilibrium conditions between air and grain while the air pass across grain mass

For all the strategies grain was considered dried when the average MC dropped below 14.5 %, and the maximum MC dropped below 15.5 %.

2.2 Fan and burner run hours

The simulation was performed in hourly time steps. For each hour, the simulation model checks the weather data (temperature and relative humidity) and, based on the operational conditions of the in-bin drying strategy selected (Table 2), determines whether the fan and the burner should be "on" or "off". At the end of the drying period the model computes the accumulated FRH and BRH for that particular run.

2.3 Energy consumption

The total energy consumption (EC_t, Equation (1)) for NA/LT drying was the sum of the electrical power required by the fan (EC_e) and the caloric energy required by the burner (EC_c).

$$EC_t\ (kWh) = EC_e\ (kWh) + EC_c\ (kWh) \tag{1}$$

FRH, BRH and drying temperature set point are the key variables to calculate the EC during drying. Table 2 indicates the operation of the fan and burner for the four NA/LT in-bin drying strategies.

The PHAST-FDM simulation model computes both the fan and burner EC for each hour in which the fan and burner are "on" during the entire drying process.

2.4 Fan energy consumption

The fan EC_e (Equation (2)) was calculated based on the FRH and the fan power (kW) as follows:

$$EC_e\ (kWh) = Fan\ Run\ Hours\ (h) \times Fan\ Power\ (kW) \tag{2}$$

The characteristics of the fans used for the simulation were selected using the AireAR software (Bartosik et al., 2009), according to the three different airflow rates considered (Table 3).

Table 3 Specific airflow rate, total airflow, static pressure, and fan pre-warming and fan power estimated by the AireAr software for in-bin drying of corn

Specific airflow rate /m³ min⁻¹ t⁻¹	Total airflow /m³ min⁻¹	Static pressure/Pa	Fan pre-warming /℃	Fan power /kW
1.0	172	335.0	0.46	3.72
1.5	258	591.4	0.82	7.5
2.0	344	900.0	1.25	14.9

2.5 Fan temperature increase

When the ambient air passes through the fan there is a temperature increase due to the air friction loss (pressure drop) and heat loss from the motor. The temperature increase due to the fan friction is presented in Table 3 and was computed as following Equation (3) (Noyes and Navarro, 2002):

$$Fan\ Temp\ (°\mathrm{C}) = \frac{St\ Pressure\,(\mathrm{kPa})}{\rho(\frac{\mathrm{kg}}{\mathrm{m}^3}) \times c(\frac{\mathrm{kJ}}{\mathrm{kg}\,°\mathrm{C}}) \times \varepsilon} \tag{3}$$

where, *Fan Temp* is the temperature increase in the air due to fan (℃); *St Pressure* is the static pressure of the system in kPa (Table 3); ρ is the air density (kg m^{-3}, a value of 1.2 kg m^{-3} was used), c is the specific heat of air (kJ kg^{-1} $℃^{-1}$, a value of 1 kJ kg^{-1} $℃^{-1}$ was used) and ε is the total fan efficiency (decimal, a value of 0.60 was used).

2.6 Burner energy consumption

The burner operation varied according to the NA/LT drying strategy implemented (Table 2). The CNA and the W strategies do not use supplemental heat, so no EC_c was considered. The CH3 strategy considers a constant increase of 3℃ in the ambient air temperature since the start drying date to the end drying date. The intelligent strategy runs the burner intermittently, and also changes the drying temperature according to the drying progress and the weather condition (de la Torre, 2010). This implies that the burner should add a variable amount of heat to the ambient air and, hence, that the burner consumption varies according to the weather condition.

The EC_c for each hour in which the burner was "on" was computed according to the enthalpy increase of the air after the fan (including the fan pre-warming) and the enthalpy of the drying air (after the burner) (Figure 2).

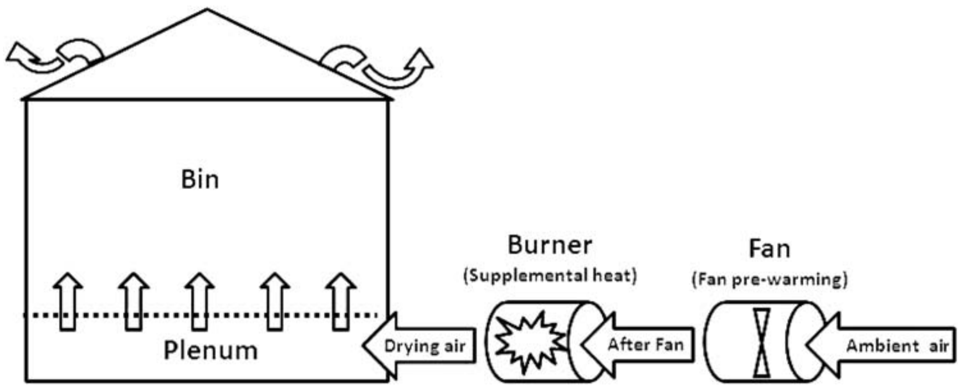

Figure 2 Schematics of the components of NA/LT in-bin drying system, the airflow direction and the different air temperatures considered for computing the burner energy consumption

The enthalpy of the air (kJ kg^{-1} of dry air) was computed according to the psychrometric ASAE Standard (ASAE D 271.2, 1979).

The EC_c was computed using the enthalpy increase and the total airflow, adjusted by the burner efficiency. For each hour of drying, the air specific volume (m^3 kg^{-1}) was computed according the ASAE D271.2 standard (1979) using the ambient temperature and RH. The total airflow (Table 3) was converted from m^3 min^{-1} to kg min^{-1} using the air specific volume. A burner efficiency of 85% was considered (Bartosik, 2003). The final expression for computing EC_c was as follows (Equation (4)):

$$EC_c\ (\text{kWh}) = \textit{Enthalpy Increase}\ (\frac{\text{kJ}}{\text{kg air}}) \times \textit{Total Airflow}\ (\frac{\text{m}^3}{\text{min}}) \times \frac{1}{\textit{Air Specific Volume}\ (\frac{\text{m}^3}{\text{kg}})} \times 60\ (\frac{\text{min}}{\text{hour}}) \times \frac{1}{\textit{Burner Efficiency}} \times 0.000278 \frac{\text{kW}}{\text{kJ}} \quad (4)$$

where, EC_c is the caloric energy consumed by the burner (kWh); *Enthalpy Increase* is the difference in enthalpy between the drying air and the air after the fan (kJ kg^{-1} dry air); *Total Airflow* is the total airflow provided by the fan (m^3 min^{-1}); *Air Specific Volume* is the specific volume of the ambient air (m^3 kg^{-1}); and *Burner Efficiency* is the efficiency of the burner to convert the fuel in heat (decimal).

2.7 Specific energy consumption

A typical problem for comparing energy consumption of different dryers is that the energy consumption varies with the amount of tones (weight) being dried and the amount of moisture removed. To make easier the comparison the EC was divided by the number of tones of the in-bin drying batch (172 tones) and the number of points of moisture removed from the MC_i of 17% or 20% to the MC_f, obtaining the specific energy consumption (*SEC*) parameter as follows (Equation (5)):

$$SEC\ (\frac{kWh}{p\ t}) = \frac{EC(kWh)}{(MC_i - MC_f) \times 172t} \quad (5)$$

2.8 Selecting the best drying strategy for each location

The best strategy for each location was selected according to a combination of the maximum DML, drying time, over-drying risk and EC_t.

DML is defined as the loss of physical mass of grain due to seed respiration and fungi growth (Wilcke et al., 1998). The PHAST-FDM model computes the accumulated DML for each grain layer according to the procedure of Saul and Steele (1966). The equations of the model were referred from the papers published by Thompson (1972); Brook (1987); and Stroshine and Yang (1990).

The DML is a consequence of the respiration of microorganism and the grain, so it is and indicator of the biological activity in the grain mass. Bern et al. (2002) determined that when the DML accumulated is superior to 0.5% the commercial quality of the grain falls to a lower quality category. Grain quality loss during drying is not acceptable, so those strategies that at the end of the drying time had a maximum DML superior to 0.5% were discarded (since the top grain layer is the last to be dried, the accumulated DML is usually the highest in this layer).

Over-drying occurs when the grain is dried beyond the desired MC_f (14.5%). When over-drying occurs there is a quantitative loss of grain weight and a monetary loss for the grain seller. The over-drying was estimated as the difference between the average MC_f of the grain mass at the end of the drying period and the desired MC_f of 14.5%.

For each location the PHAST-FDM model ran several years for each combination of strategy, MC_i and airflow rate (Table 1). The average and standard deviation values of the following parameters were obtained for each set of runs: MC_f, maximum *DML*, EC_e, EC_c, EC_t and drying time.

Sometimes the average value of a parameter is not appropriate to select a suitable drying strategy. For instance, if for a given strategy the 10 year average DML is 0.5%, it means that half of the years the DML would be above the limit (unacceptable spoilage risk). Thus, another parameter should be used to take into account the year to year variability.

For each set of simulation runs the maximum DML likely to occur once every 10 years was computed (DML_{90}) using the normal probability distribution, the average value and the standard deviations of the maximum DML (Bartosik and Maier, 2004). This meant that 90% of the time the expected maximum DML would be equal or lower to the DML_{90}. This procedure was followed also to compute the maximum drying time (drying $time_{90}$), maximum caloric energy consumption ($EC_{c.90}$), maximum electric energy consumption ($EC_{e.90}$), maximum total energy consumption ($EC_{t.90}$), maximum fan run hours (FRH_{90}) and maximum burner run hours (BRH_{90}).

Finally, a ranking was made for each location and combination of strategies, airflow rate and MC_i based on three criteria: DML_{90}, drying $time_{90}$ and $EC_{t.90}$.

2.9 Criteria for selecting the best strategy

For a given location, all the combinations were ordered by increasing DML_{90}, rejecting all combination with DML_{90} higher than 0.5%. Then, the remaining combinations were ordered by increasing drying $time_{90}$, rejecting all those combinations with drying $time_{90}$ longer than 60 days. Finally, the remaining combinations were ordered by increasing EC_{t90}, and the strategy resulting with the lowest energy consumption was selected. However, if this strategy resulted with an over-drying risk higher than 0.5% (MC_f lower than 14%), the next strategy in the list was selected instead. Table 4, shows an example of the selecting procedure for Balcarce. The detailed information regarding the selection of the best strategy for each location considered could be found in de la Torre (2010).

Table 4 Results of the corn drying simulations for Balcarce, example for selecting the optimal strategy and airflow rate combination

Treatment			MC_f[1] /%	DML_{90}[2] /%	EC_{c90}[3] /kWh	EC_{e90}[4] /kWh	EC_{t90}[5] /kWh	drying time $_{90}$[6] /Days	
MC_i /%	Airflow rate/m^3 min^{-1} t^{-1}	Strategy							
*17	1	Intelligent	14.2	0.10	13 523	3 505	17 028	39	
17	1.5	Intelligent	14.2	0.07	14 725	4 840	19 565	27	
17	2	Intelligent	14.2	0.06	13 409	6 901	20 310	20	
*20	1	Intelligent	14.2	0.35	19 205	5 040	24 205	57	
20	1.5	Intelligent	14.1	0.26	18 502	6 653	25 154	37	
20	2	Intelligent	14.1	0.21	19 131	9 856	28 987	28	60 Days[8]
17	2	CH3	14.5	0.11	42 720	31 151	73 871	87	
17	1.5	CH3	14.5	0.13	39 137	19 134	58 271	106	
20	2	CH3	14.4	0.27	49 770	38 181	87 951	107	
17	2	EMC window	14.0	0.20	0	7 533	7 533	111	
20	1.5	CH3	14.5	0.32	39 678	20 430	60 108	113	
20	1	CH3	14.5	0.41	30 441	11 657	42 098	131	
17	1	CH3	14.5	0.18	32 372	11 779	44 152	132	
17	1.5	EMC window	13.9	0.25	0	5 088	5 088	134	
17	1	EMC window	13.7	0.37	0	3 749	3 749	180	0.5 %DML[7]
17	2	CNA	14.4	0.68	0	88 014	88 014	246	
20	2	EMC window	13.7	0.71	0	10 239	10 239	141	
17	1.5	CNA	14.4	0.73	0	48 534	48 534	270	
20	2	CNA	14.4	0.76	0	88 166	88 166	247	
20	1.5	CNA	14.4	0.87	0	46 809	46 809	260	
20	1.5	EMC window	13.6	0.89	0	6 699	6 699	169	
20	1	CNA	14.3	0.99	0	24 134	24 134	270	
17	1	CNA	14.4	1.19	0	49 320	49 320	552	
20	1	EMC window	13.4	1.31	0	4 773	4 773	216	

Note: * Selected treatment (strategy and airflow rate combination).

[1] Final average moisture content of the grain.

[2] Maximum dry mater loss with 90 % probability of occurrence.

[3] Maximum caloric energy consumption with 90 % probability of occurrence.

[4] Maximum electric energy consumption with 90 % probability of occurrence.

[5] Total energy consumption with 90 % probability of occurrence.

[6] Maximum drying time with 90 % probability of occurrence.

[7] 0.5 % dry matter loss threshold (treatments with higher values were discarded).

[8] 60 days drying time threshold (treatments above this threshold were discarded).

3 Results and discussion

3.1 Effect of weather on the performance of the NA/LT in-bin drying strategy

Table 5 summarizes the percentages and causes of rejection of the four strategies across all the locations.

Table 5 Percentage of rejection by cause (excessive dry matter loss, excessive drying time. over-drying risk) and total rejection for the four in-bin drying strategies across all locations

	DML_{90}	Drying tim$_{90}$	Over-drying risk	Total
Strategy	/> 0.5%	/> 60 days	/MC_f < 14%	
CNA	72	87	27	97
CH3	23	17	80	97
W	62	78	88	100
Intelligent	23	5	22	37

The CNA strategy was rejected 97% of the time, due mainly to excessive drying time$_{90}$ (87% of the time). This is a limitation in terms of the logistic for the drying operation and the drying cost (large FRH). The second source of rejection was the excessive DML_{90} (72% of the time), implying that when CNA strategy is implemented, there is an important risk that the top grain layer results with spoilage (DML_{90} > 0.5%). Over-drying risk was not critical for the CNA strategy, since it occurred only 27% of the time. Thus, the overall analysis across all locations showed that this is not a recommended strategy to implement with NA/LT in-bin drying.

The CH3 strategy was rejected 97% of the time, mainly due to excessive over-drying risk (80% of the time). The second source of rejection was the excessive DML_{90}, although only with the 23%. The drying time$_{90}$ was not an important source of rejection for the CH3 strategy, since it occurred only 17% of the time i. If increase in lower temperature be considered (i.e. 2℃ instead of 3℃), a lower rejection percentage by over drying risk is obtained, but an increase in the rejection due to DML_{90} and drying time$_{90}$ should be expected. However this strategy, with a moderate amount of supplementary heat, could be suitable for some locations.

The W strategy was always rejected in all locations (100% of the time). The main source of rejection was over-drying risk (88% of the time). The second source of rejection was the excessive drying time$_{90}$ (78% of the time). The third cause of rejection, but not less important (62% of the time), was the DML_{90}. Increasing the low EMC limit (i.e. from 12% to 13%) would reduce the rejection due to over-drying risk; however it would certainly increase the rejection due to DML_{90} and drying time$_{90}$. Thus, this strategy seems to be inappropriate to implement for NA/LT in-bin drying.

The Intelligent strategy was rejected only 37% of the times, being the main sources of rejection the DML_{90} (23% of the time). The second source of rejection was the over-drying risk (22% of the time). The third cause of rejection, with only 5% of the time, was the drying time$_{90}$. Clearly, the intelligent strategy was the most suitable strategy (less rejected) across all the locations for NA/LT in-bin drying.

3.2 Optimized strategy

Table 6 represents the optimal combination of strategy and airflow rate selected for each location and MC_i.

The Intelligent strategy was the most suitable strategy for the majority of the locations in this study. In a similar study, Bartosik (2005) determined that the SAVH (an equivalent strategy to the intelligent strategy) was the best option in the Midwestern U.S. Corn Belt, outperforming the CNA, W and CH strategies.

The intelligent strategy was outperformed for the CH3 only in Reconquista when the MC_i was of 20% (although over-drying risk was detected), and by the CNA strategy in Pergamino and Saenz Peña (but only for 17% MC_i). In Bella Vista, a warm and humid location, non strategy was able to accomplish drying without incurring in severe DML when the MC_i was of 20%.

Based on these observations the recommended alternatives for such warm weather conditions are: dry with intermediate temperature systems (increasing over-drying risk), increase airflow rate (however, increasing airflow rate beyond 2 m^3 min^{-1} t^{-1} would result in substantial increase of EC_e), incorporate stirring devices, or reduce MC_i. The implementation of one of these alternatives (or a combination of them) would reduce the drying time and the DML.

Table 6 Combination of strategy and specific airflow rate selected for each location and average values of final moisture content (MC_f), dry matter loss (DML_{90}), drying time (DT_{90}), fan run hour (FRH_{90}), burner run hour (BRH_{90}), specific caloric energy consumption (SECc), specific electrical energy consumption (SECe) and specific total energy consumption (SECt)

Location	MC_i /%	Selected Strategy	Airflow /$m^3\ min^{-1}\ t^{-1}$	MC_f /%	DML_{90} /%	Drying time$_{90}$ /days	FRH_{90} /hours	BRH_{90} /hours	SECc /$kWh\ p^{-1}\ t^{-1}$	SECc /%	SECe /$kWh\ p^{-1}\ t^{-1}$	SECe /%	SECt /$kWh\ p^{-1}\ t^{-1}$
Saenz Peña	17 b	CNA	1	13.7	0.34	37	897	0	0.0	0	5.9	100	5.9
	20 b	Intelligent	2	13.8	0.48	33	529	154	3.3	31	7.4	69	10.7
Cerro Azul	17	Intelligent	1.5	14.0	0.18	23	518	289	11.6	61	7.5	39	19.1
	20 b	Intelligent	2	13.9	0.47	26	570	356	8.9	52	8.2	48	17.1
Bella Vista	17	Intelligent	1	14.0	0.30	32	757	322	7.2	70	3.1	30	10.3
	20 a	-	-	-	-	-	-	-	-	-	-	-	-
Reconquista	17	Intelligent	1	14.1	0.28	34	791	443	12.9	69	5.8	31	18.7
	20 b	CH3	2	13.4	0.49	22	540	540	8.8	55	7.0	45	15.8
Manfredi	17	Intelligent	1.5	14.2	0.08	25	582	363	21.1	70	9.0	30	30.2
	20	Intelligent	1.5	14.1	0.31	35	832	585	15.1	71	6.1	29	21.2
Oliveros	17	Intelligent	1.5	14.0	0.19	22	536	308	13.3	63	7.7	37	21.0
	20	Intelligent	1.5	14.1	0.49	37	825	514	11.0	64	6.1	36	17.1
Pergamino	17	CNA	1.5	14.3	0.18	45	1085	0	0.0	0	17.5	100	17.5
	20	Intelligent	1	14.0	0.44	54	1194	570	8.4	66	4.3	34	12.7
Castelar	17	Intelligent	1	14.0	0.23	34	814	413	11.4	66	5.8	34	17.2
	20	Intelligent	1.5	14.0	0.44	36	813	468	9.5	62	5.9	38	15.4
Anguil	17	Intelligent	1	14.4	0.09	38	896	594	22.8	75	7.5	25	30.2
	20	Intelligent	1	14.5	0.30	53	1274	865	15.2	86	2.6	14	17.7
Balcarce	17	Intelligent	1	14.2	0.10	39	942	811	28.2	79	7.3	21	35.5
	20	Intelligent	1	14.2	0.35	57	1344	1179	19.1	79	5.0	21	24.1
Average	17	-	-	14.1	0.2	33.1	781,8	354,4	12.9		7.7		20.6
	20	-	-	14.0	0.4	39.2	880,1	581,2	11.0		5.8		16.9

Note: a No combination of strategy and airflow rate is recommended in this location due to spoilage risk (DML > 0.5% at the end of the drying process).
b Over-drying risk (final MC < 14.0%).

3.3 Airflow rate

Table 6 shows that, in general, drying 17% MC_i corn required airflow rates from 1 to 1.5 $m^3\ min^{-1}\ t^{-1}$ and drying 20% MC_i required higher airflow rates, from 1.5 to 2 $m^3\ min^{-1}\ t^{-1}$. These results agree with those of Wilcke et al. (1993), which suggested that to succeed in NA/LT in-bin drying of corn the airflow rate must be raised when the MC_i increases.

For 17% MC_i there was a trend to reduce the optimized airflow rate in those locations with higher ambient temperature during drying. This can be explained because at 17% MC_i the grain has little risk of spoilage, and a rise in the ambient temperature increases the drying capacity. On the other hand, at 20% MC_i there was a trend to increase the optimized airflow rate in locations with higher ambient temperature during drying. This is because at 20% MC_i the grain is in serious risk of spoilage, which increases with the rise of the ambient temperature. As a consequence, in order to avoid spoilage, airflow rate must be increased to dry faster as ambient temperature increases. Bartosik (2003) studied the feasibility of implementing NA/LT in-bin drying systems for drying 22% MC_i corn in different locations of the Midwestern U.S. The authors reported that in warm locations (i.e. Little Rock, AK) it was not possible to achieve drying with an airflow rate of 1.67 $m^3\ min^{-1}\ t^{-1}$ before significant DML would occur. Contrastingly, in colder locations this airflow rate was suitable for safe drying of corn.

3.4 Drying time

The average drying time for 17% MC_i was 33.1 days and for 20% MC_i was 39.2 days (Table 6). The longest drying time was in Balcarce (cold location) for 20% MC_i (57 days) and the shortest drying time was in Reconquista (warm location) for 17% MC_i (22 days).

3.5 Final moisture content and over-drying risk

Table 6 shows that in all locations the MC_f was equal or lower to the desired MC_f of 14.5%. The average MC_f

(across locations) for 17% MC_i was 14.1 (0.4% of over-drying) and for 20% MC_i was 14 % (0.5% of over-drying). Even though there was no a clear relationship between the ambient temperature during the drying period and the over-drying risk, the most severe over-drying was observed in the warmer locations. For instance, in Reconquista and Cerro Azul (for 20 % MC_i) and in Saenz Peña (for both MC_i) the MC_f was lower than 14% (more than 0.5% of over-drying). In these locations, over-drying could be reduced incorporating a grain stirring device to the bin. This device mixes the upper and bottom grain layers increasing the MC uniformity and reducing the over-drying risk (Mwaura, 1981).

3.6 Dry matter loss

Table 6 shows that, across locations, the average DML_{90} for 20% MC_i was twice the DML_{90} for 17% MC_i (0.4 and 0.2%, respectively). The highest DML_{90} (but below the limit of 0.5%) was observed for 20% MC_i in the warm locations of Oliveros, Reconquista and Cerro Azul (0.49, 0.49 and 0.47%, respectively). On the other hand, the lowest DML_{90} was observed for 17% MC_i and the cold locations of Balcarce, Anguil and Manfredi (0.1, 0.09 and 0.08%, respectively). In general, for the same MC_i, there was a trend to increase the DML_{90} with the increase of the ambient temperature during the drying period.

3.7 Fan and burner run hours

The average expected FRH_{90} across all locations for drying 17% MC_i corn was 781.8 h (Table 6). Drying 20% MC_i corn took in average only 12% more hours (880.1 hs), but the optimized average airflow rate for the wetter corn was higher. The longest FRH_{90} for 17% MC_i was for Pergamino with the CNA strategy and 1.5 m^3 min^{-1} t^{-1} of airflow (1,085 h), while for 20% MC_i the longest FRH_{90} was in Balcarce with the intelligent strategy and 1.0 m^3 min^{-1} t^{-1} of airflow (1,344 h). The shortest FRH_{90} for drying 17% MC_i corn was 518 h for Cerro Azul with the Intelligent strategy and 1.5 m^3 min^{-1} t^{-1} of airflow rate, and for 20% MC_i corn was 529 h for Sáenz Peña with the intelligent strategy and 2 m^3 min^{-1} t^{-1} of airflow rate.

The average expected BRH_{90} across all locations for drying 17% MC_i corn was 354.4 h. Drying 20% MC_i corn took 64% more hours (581.2 hs) in average, implying that drying wetter corn required a significantly larger burner use. The longest BRH_{90} for 17% and 20% MC_i were for Balcarce with the intelligent strategy, 811 h 1179 h, respectively, while the shortest BRH_{90} for 17% MC_i were 0 h for Pergamino and Saenz Peña with the CNA strategy and for 20% MC_i was 154 h for Saénz Peña with the Intelligent strategy.

3.8 Energy consumption

Table 6 shows that the average SEC_t for drying 20% MC_i corn was 16.9 kWh p^{-1} t^{-1} and for 17% MC_i was 20.6 kWh p^{-1} t^{-1}. These results are similar to those obtained in a preliminary study (de la Torre et al., 2008) were the average SEC_t were 19.0 and 25.1 kWh p^{-1} t^{-1} for 20% and 17% MC_i, respectively.

More energy was required (per percentage point of MC removed and per ton of grain) in Balcarce than in any other location to dry corn with 17% or 20% MC_i (35.5 kWh p^{-1} t^{-1} and 24.1 kWh p^{-1} t^{-1}, respectively). On the other hand, in Saenz Peña the energy requirement was lower than any other location (5.9 and 10.7 kWh p^{-1} t^{-1} for 17 and 20% MC_i, respectively).

Figure 3a shows that there was no relationship among the average ambient temperature during drying and the SEC_e, either for 17 or 20% MC_i, being in general in between 5 and 8 kWh p^{-1} t^{-1}. Coincidently, Bartosik and Maier (2007) studied NA/LT in-bin drying for several U.S. Midwestern locations and fount similar SEC_e (from 6.0 to 7.1 kWh p^{-1} t^{-1}) in weathers substantially colder than those explored in this study.

The SEC_c was from 0 kWh p^{-1} t^{-1} (CNA strategy) to 28.2 kWh p^{-1} t^{-1}. There was a trend to increase the SEC_c in those locations with colder ambient temperature. This implies that as the ambient air during drying cools down, the caloric energy required to heat the air to a suitable drying condition increased (Figure 3b), as well as the total energy (electric plus caloric energy) (Figure 3c). Additionally, the increase was higher for 20% than for 17% MC_i. As a result, drying in cold weather resulted with higher SEC_t than drying in warm weather (15-16 kWh p^{-1} t^{-1} and 20-27 kWh p^{-1} t^{-1} for 24℃ and 12℃ of ambient temperature, respectively).

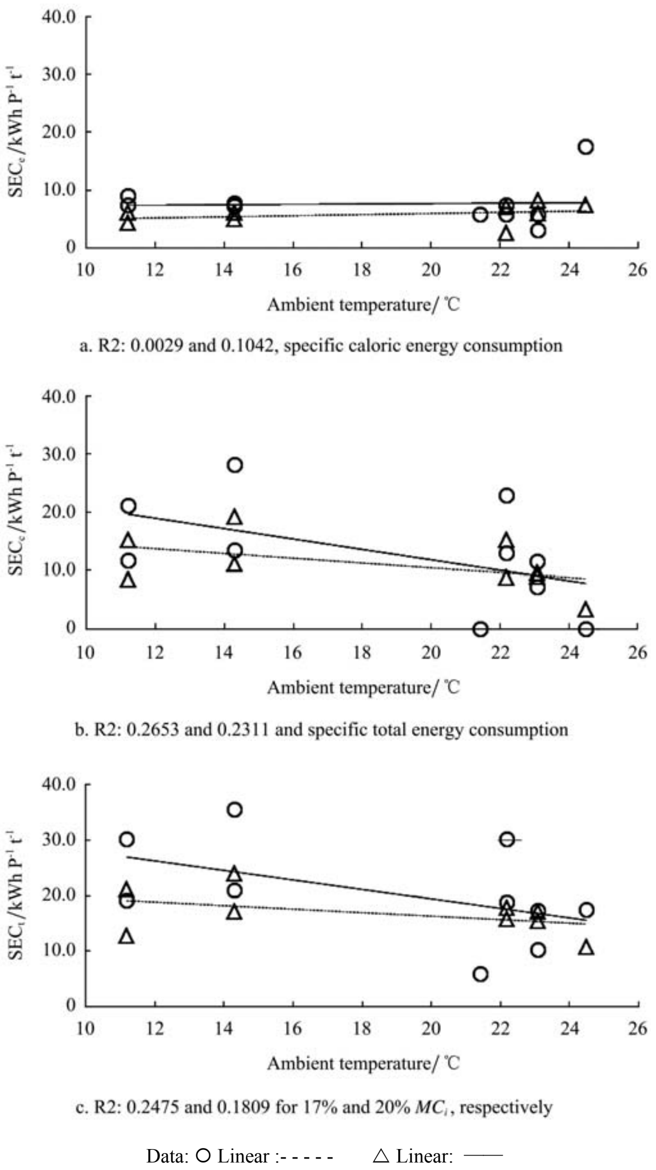

Figure 3 Relationship (linear regression) between average ambient temperature of the harvest month and specific electrical energy consumption

The ambient temperature during drying affected not only the total amount of energy but also the relative composition. In Balcarce (cold weather) more caloric energy was required proportionally than electrical energy (79% and 21%, respectively), while in Saenz Peña (warm weather) the proportion of electrical energy was substantially higher (100% and 69% of the total energy for 17% and 20% MC_i, respectively) (Table 6). This implies that the strategies and airflow rates selected for drying in warm weather conditions (i.e. Saenz Peña) do not require much fuel to heat the air, but a high airflow rate is required instead to reduce drying time and avoid grain spoilage.

4 Summary and conclusion

The most successful strategy was the intelligent strategy (a model-based fan and burner control strategy), which outperformed the continuous natural air, the continuous constant heat and the EMC windows strategies across all locations.

There was a trend to increase the airflow rate with the initial moisture content (MC_i). For 17% MC_i, a relatively low airflow rate could be recommended either for cold or warm regions (1 to 1.5 m^3 min^{-1} t^{-1}), but for 20% MC_i the recommended airflow rate went from 1 m^3 min^{-1} t^{-1} in cold locations to 2 m^3 min^{-1} t^{-1} in warm locations.

In some locations with warm weather, no NA/LT in-bin drying strategy succeeded in drying corn with MC_i of 20% under the airflow rates ranges investigated in this study (excessive DML).

The average drying time for 17 % MC_i was 33.1 days and for 20% MC_i was 39.2 days.

The average DML for 20% MC_i was twice the DML for 17% MC_i (0.4 and 0.2 %, respectively) and there was a positive relationship between ambient temperature and DML for both MC_i.

The average fan run hour (FRH_{90}) for drying 17% MC_i corn was 718.8 h, wile for drying 20% MC_i was 880.1 h, only 12% more. On the other hand, the average burner run hour (BRH_{90}) was of 354.4 h for 17% MC_i and of 581.2 h for 20% MC_i, 64% more. This implies that the MC_i has a substantial effect of the caloric energy demanded for NA/LT drying.

The average specific caloric energy consumption (SEC_c) was of 12.9 and 11.0 kWh per point of moisture extracted and per tonne, for 17% and 20% MC_i, respectively. There was a trend to increase the caloric energy consumption in those locations with colder temperature.

The specific electrical energy consumption (SEC_e) either for 17 or 20% MC_i, was in between 5 and 8 kWh p^{-1} t^{-1}, and no relation was found between ambient temperature and electrical power consumption.

The average total specific energy consumption was of 20.6 and 16.9 kWh per point of moisture extracted and per ton, for 17% and 20% MC_i, respectively.

Acknowledgment

The authors want to thank to the National Institute of Agricultural Technology (INTA) of Argentina for the financial support of this research.

Notation:

BRH burner run hours, hours

CNA continuous natural air in-bin drying strategy

CH3 continuous constant heat with 3°C increase in-bin drying strategy

DML dry matter loss /%

EC energy consumption /kWh

EMC equilibrium moisture content /% w.b

FRH fan run hours /h

MC moisture content /% w.b

NA/LT natural air/low temperature

RH relative humidity /%

ERH equilibrium relative humidity /%

SEC specific energy consumption /kWh per percentage point and per ton

W equilibrium moisture content based with 12 and 17% lower and upper operational limits in-bin drying strategy

Subscripts:

c caloric energy consumed by the burner

e electrical power energy consumed by the fan

f final value (after drying)

i initial value (before drying)

t total energy consumed by the fan and the burner

90 maximum value likely to occur once every 10 years (90% of probability)

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