Effect of site specific weather conditions on the energy consumption of a high temperature continuous flow corn dryer

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Abstract: The estimation of drying energy consumption is important for grain elevators and the grain processing industry in order to compute the drying cost and also for properly planning the energy supply during the drying season. It is also important for making energy policies related to agriculture. Locations with different weather should have different drying performances but this effect was not sufficiently studied in previous research. The main goal of this study was to determine the energy requirement for drying yellow dent corn with a continuous flow high temperature dryer for ten locations in Argentina with different weather conditions. The study was carried out using historical weather data of ten locations scattered through the corn producing region of Argentina, and a mathematical model to simulate the drying conditions of corn from 17 and 20% initial moisture content (m.c.$_i$) to 15% final moisture content (m.c.$_f$). The specific total energy consumption for drying corn from 17% m.c.$_i$ was 8,207 kJ per kg of water evaporated (kg$_w^{-1}$) and for 20% m.c.$_i$ was 5,535 kJ/kg$_w$ on average across locations, resulting in an average drying efficiency of 31% for 17% m.c.$_i$ and 46% for 20% m.c.$_i$. The specific convective heat losses to the ambient under the average weather condition of the locations considered were 196 kJ/kg$_w$ for 17% m.c.$_i$, and 136 kJ/kg$_w$ for 20% m.c.$_i$, less than 3% of the total drying energy. The ambient temperature affected the total drying energy, which, in general, decreased about 1.25% per each ℃ of ambient temperature increase. Drying energy efficiency could be improved by selecting ambient temperature conditions.

Keywords: grain drying, simulation, energy balance, energy losses, ambient temperature, specific energy consumption

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1 Introduction

The drying operation is the process that consumes more energy in the grain postharvest system. In Argentina, as in many grain producing countries, corn is the crop that demands most of the drying capacity, about 70% to 80% of the corn must be dried before storage, being the typical harvest moisture content (m.c.) range from 17% to 22%.

Since most of the drying capacity in Argentina is based on high temperature continuous flow drying, the energy consumed is mostly fossil fuel energy (natural gas, GLP, and diesel oil). The estimation of the drying energy consumption is important for grain elevators and the grain processing industry in order to better compute the drying cost and also for properly planning the energy supply during the drying season. Additionally, a good estimation of the drying energy consumption is important for making energy policies. In current days the ambient impact of fossil fuels burning is a major concern, efficient energy management of all process (including grain drying) is under the spot light as it was in the 70' due to economic reasons (Young and Dickens, 1975).

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Today it is well known that the energy consumption and overall efficiency of high temperature drying is affected by type of grain, grain hybrid or variety, grain condition, initial and final grain m.c., foreign matter presence, dryer type (e.g. column or mixed flow), dryer design characteristics (e.g. column dimensions and airflow) and operation modality (e.g. grain flow and drying air temperature) (Morey et al., 1976; Olesen, 1987; Brooker et al., 1992; Maier and Bakker-Arkema, 2002). The weather conditions (ambient temperature and relative humidity (RH)) and grain temperature also affect the dryer efficiency (Morey et al., 1976; Olesen, 1987; Brooker et al., 1992). Morey et al. (1976) concluded that the energy efficiency of drying is complex and many of the recommendations to increase it depend on climate and location.

Figure 1 shows the energy balance of a continuous flow high temperature grain dryer that helps to understand the complexity of the system and the effect of climatic conditions on the energy requirements. The energy inputs to the drying system are provided by the specific grain initial enthalpy (*Qg*), the specific enthalpy of ambient air (*Qa*) and the specific energy supplied by the burner to increase ambient air temperature (*Qb*). This last one is the major source of energy from these three components (Olesen, 1987).

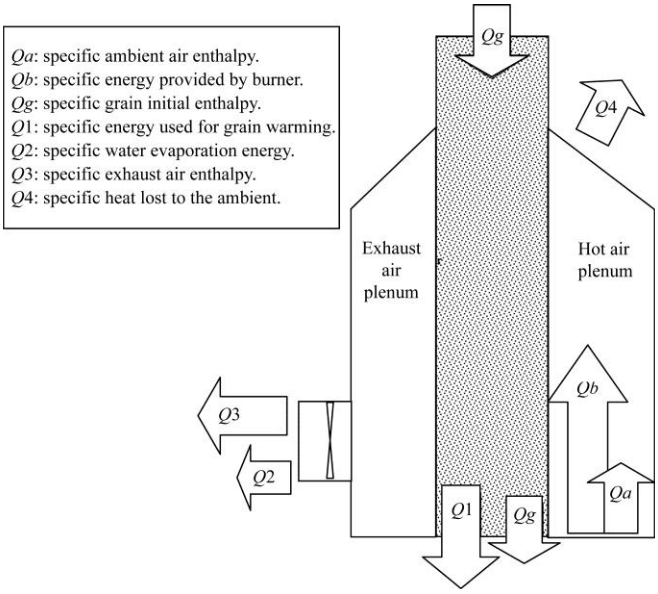

Figure 1 Schematics of the specific energy balance of a continuous flow high temperature grain dryer (cross flow dryer). The size of the arrows indicates the relative magnitude of the energy gain and loss

The total energy of the system has four main destinations, named *Q*1: specific heat used for increasing the grain temperature, *Q*2: specific energy consumed for evaporating water from the grain (useful drying energy), *Q*3: specific exhaust air heat loss (warm air exiting the dryer), and *Q*4: specific heat loss to the ambient air by convection from the metal sheet of the dryer plenum. As *Q*2 is the only useful energy for drying, energy used for grain warming, exhaust air heat and convective heat lost to the ambient represent energy losses that reduce the efficiency. Drying efficiency (*Eff*) can be defined as the ratio between the mean grain latent heat of vaporization (2,512 kJ/kg) and the energy consumed by the dryer to evaporate one kg of water from de grain (Olesen, 1987).

Convective heat loss to the ambient is the lowest of the three drying energy losses components, at least for temperate to warm weather conditions (De Dios, 2000). Thus, the efforts to increase drying efficiency are focused on reducing exhaust air heat losses by re-engineering dryers design (e.g. recovering and reusing unsaturated exhaust air) (Olesen, 1987) and using the sensible heat of the grain for completing drying in the bin with aeration (dryeration system) (Foster, 1973; Brooker et al., 1992; Gely and Giner, 2002). In Argentina (temperate to sub-tropical country) the heat loss to the ambient air due to poor dryer insulation could be presumably low, but it was never studied. Its magnitude depends on the dryer design (e.g. insulation and heat exchange surface), the operational conditions of the dryer (temperature of the drying air) and the weather condition during drying.

The drying capacity of the air depends mostly on the air temperature and, to a lesser extent, on the absolute humidity. Typically, high temperature dryers operate with very low drying air RH, less than 8%, regardless the ambient air RH. For instance, when drying with ambient air conditions of 20 ℃ and 95% RH, the RH in the plenum drops to 7% when the drying air is heated up to 70 ℃. With the same ambient air and drying air temperatures (20 ℃ and 70 ℃, respectively) but with an ambient RH of 50%, the RH in the plenum would be close to 4%. Even though it could be an effect of the ambient air RH on the drying efficiency, this effect is low. The amount of energy required to increase the air temperature from the ambient temperature to a given drying temperature depends mostly on the ambient temperature. As the ambient temperature decreases, the energy requirement to heat up the drying air to a given temperature increases more than the drying capacity (Olesen, 1987).

The drying capacity, the energy consumption and the cost of the drying operation depend on the weather conditions during the drying period, thus, locations with different weather pattern should have different drying performances (Morey et al., 1976). There is information available in the literature regarding the effect of the different weather conditions in the performance of natural air / low temperature in-bin drying systems (Bartosik and Maier, 2004; de la Torre and Bartosik, 2013). However, there is a lack of information in the literature about the effect of different weather conditions on the performance of continuous flow high temperature drying operation.

The main goal of this study was to determine, using simulation, the energy requirement for drying yellow dent corn with a continuous flow high temperature dryer for ten locations in Argentina with different weather conditions. The specific objectives were: 1) to estimate the range of energy consumption for drying corn from two different initial moisture contents; 2) to make a heat balance of the dryer and estimate the heat losses due to convective heat transfer from the dryer to the ambient air; and 3) to establish a relationship between the ambient air temperature, energy consumption and drying efficiency.

2 Methodology

The total energy demanded by the drying operation includes the combustion energy (required by the burner to heat up the air to a certain temperature) and the electrical energy (required by the fans to generate the appropriated airflow for drying).

The estimation of the energy required by the burner (combustion energy) was carried out using weather data of ten locations scattered through the corn producing region of Argentina (Figure 2). Two procedures were implemented. On one hand, a mathematical model was used to estimate the drying time, dryer capacity and the energy consumption for each location. On the other hand, convective heat loss to the ambient was estimated and the energy consumption was adjusted by adding this value for each location.

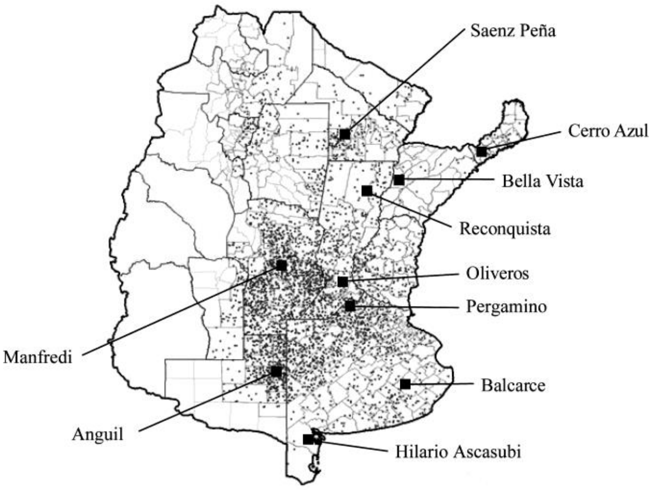

Figure 2 Map of the Central and Northern provinces of Argentina showing the corn producing areas and the distribution of the ten locations evaluated in this study. Each grey dot represents 1000 hectares (SAGPyA, 2006)

2.1 Simulation model

The simulations were carried out with a cross flow drying mathematical model (non-equilibrium model for the variables: grain temperature and m.c., drying air temperature and humidity). The model was derived from a model developed for simulating wheat drying (Giner et al., 1996) and adapted for corn.

Table 1 shows the parameters considered for the drying simulations of yellow dent corn.

Table 1 Model parameters used for the simulation of cross flow drying for yellow dent corn

Parameter	Value	Source
Voids (decimal)	0.42	ASABE Standard: ANSI/ASAE D241.4 OCT1992 (R2012)
Specific heat of wet bulk grain (kJ/kg/k)	1.465+0.0356MC MC in % wb	ASABE Standard: ASAE D243.4 MAY2003 (R2012)
Wet bulk density (kg/m^3)	$701.9+16.76MC-1.1598MC^2+0.018240MC^3$ m.c. (%, wb)	ASABE Standard: ANSI/ASAE D241.4 OCT1992 (R2012)
Modified Chung-Pfost Em.c. parameters	A=374.34 B=0.18662 C=31.696	ASABE Standard: SAE D245.6 OCT2007 (R2012)
Convective heat transfer coefficient – α (kJ/C/m/h)	5+3.4Ws 4.187 (when Ws<5 m/s) $6.14Ws^{0.78}$ 4.187 (when Ws>5 m/s) Ws:wind speed (m/s)	Sokhansanj and Bruce (1987)

The thin layer drying was solved with the diffusion equation proposed by Becker (1959), using the specific area computed with the dimensions proposed by

Muthukumarappan and Guanasekaran (1990) and the bulk moisture diffusion coefficient of Parti and Dugmanics (1990).

The modeled drier had six columns, being the dimensions of each column of 20 m tall, 2 m wide and 0.3 m deep, having a static capacity of 49 t with corn at 20% m.c. (72 m^3) and 52 t for 17% m.c.. This would be a typical dryer of a commercial grain elevator facility in Argentina.

The dryer had a specific airflow of 70 m^3/min/t and the drying air temperature was set to 90℃. The dryer was operated at full heat mode, meaning that the entire column was used for drying (no cooling section was considered). This is a frequent dryer operation in Argentina.

The total electrical energy required to provide the prescribed airflow by the fans and the electrical energy required for the grain discharging mechanism was estimated in 50 HP (37 kW). The electrical energy demand (kWh) for each location and m.c. was estimated multiplying the installed power (37 kW) and the drying time (hours) estimated by the model. The values were then transformed to kJ in order to compare with energy demanded by the burner.

Drying simulation was performed for the typical corn harvest month of each location. The harvest date was determined based on the information provided by the Extension Service of the National Institute of Agricultural Technology (INTA) of Argentina (Table 2).

Table 2 Geographic coordinates, harvest month, average temperature, relative humidity and wind speed of the harvest month for the ten locations considered in this study. Average wind speed (Ws) of the harvest month measured at 10 m above the ground

Location	lat	long	Harvest month	Ta, ℃	RH, %	Ws, m/s
HilarioAscasubi, Bs. As.	-39.00	-62.00	May	11	73	3
Balcarce, Bs. As.	-37.75	-58.30	May	14	84	3
Anguil, La Pampa	-36.50	-63.98	May	11	77	2
Pergamino, Bs. As.	-33.93	-60.55	March	20	72	3
Oliveros, Santa Fe	-32.55	-60.85	March	22	76	2
Manfredi, Córdoba	-31.82	-63.77	April	16	90	2
Reconquista, Santa Fe	-29.18	-59.70	March	23	80	2
Bella Vista, Corrientes	-28.43	-58.92	March	25	76	2
Cerro Azul, Misiones	-27.65	-55.43	March	24	74	2
Saenz Peña, Chaco	-26.87	-60.45	February	26	73	1

The incoming grain temperature was set equal to the average ambient temperature of the harvest month of each location (Table 2).

The average ambient temperature and RH of the harvest month were set as the conditions at which the air entered into the dryer. Then, it was considered that the air was heated up to 90℃ after passing through the burner. Additionally, the ambient air temperature and the wind velocity determined the convection heat losses of the dryer to the environment.

Two initial moisture contents ($m.c._i$) were considered for each location (17% and 20%) to capture the range of m.c. at which most of the corn is harvested in Argentina. The m.c. after drying ($m.c._f$) was 15.5%, 1% point above the commercial (and safe storage) m.c. in Argentina (14.5%). Drying to 15.5% instead of 14.5% is a common procedure in which the dryer is operated with the full heat mode (cooling section transformed into drying section) and the corn is transferred from the drier to a bin with a temperature higher than 45℃ and a m.c. of 15.5%. The final cooling and drying (about 1% point) is achieved with the aeration system in the storage bin, as a sort of "dryeration" presses. The in-bin cooling and final drying were not considered in this study.

The inputs and out puts parameters of each simulation run are presented in Table 3.

Table 3 Inputs and outputs parameters of the high temperature drying simulation

Inputs			Outputs		
Parameter	Symbol	Unit	Parameter	Symbol	Unit
Ambient temperature	Ta	℃	Drying time	Dt	h
Ambient relative humidity	RH	%	Dryer capacity	R	t/h
Grain initial temperature	Tg_i	℃	Final grain temperature	Tg_f	℃
Grain initial moisture content	$m.c._i$	%	Specific drying energy	Qs	kJ/kg_w
Grain final moisture content	$m.c._f$	%			
Drying air temperature	-	℃			
Airflow	-	m^3/min/t			
Column width	-	m			
Column height	-	m			
Columns quantity	-	-			
Column thickness	-	m			

2.2 Heat and energy demand

Many times it is difficult to make comparisons between different drying experiments or simulation studies because only the total energy consumption is reported. The total energy consumption largely depends on the size of the dryer and the initial and final grain m.c., among other factors. One solution for this limitation is to report the energy consumption data in relation to the amount of water removed (specific energy consumption). According to the energy balance of Figure 1, Qd represents the specific heat required to increase the grain temperature, the specific heat required for removing moisture from the grain and the specific heat loss with the exhaust air. Correspondingly, Qd represents the enthalpy increase of the drying air compared with the ambient air. This drying heat is related to the amount of water removed from the grain (Equation (1)).

$$Qd = Q1 + Q2 + Q3 \tag{1}$$

where, Qd: specific drying heat (kJ/kg$_w$); $Q1$: specific energy used for grain warming (kJ/kg$_w$); $Q2$: specific water evaporation energy (kJ/kg$_w$); $Q3$: specific exhaust air heat loss (kJ/kg$_w$).

The simulation model computed the specific drying heat (Qd) by psychrometry, considering the energy required to increase the temperature from ambient conditions (Table 2) to the drying air conditions, i.e. 90 ℃, and the same absolute humidity as the ambient air condition (de la Torre, 2010).

The heat loss of the dryer (high temperature plenum) to the ambient air through the metal sheet occurs before the drying air enters in contact with the grain, so it is considered an energy loss that affects the drying performance. In this study only the convective losses were considered.

The equation proposed by Dubbel (1946) to estimate forced heat convection through flat surfaces was used to estimate the convection losses from the hot air plenum (Equation (2)). The hot air plenum surface of the drier was estimated in 100 m^2 based on dimensions of commercial dryers with similar characteristics to the one proposed in this study. The temperature of the ambient air was considered the same as the average temperature of the harvest month for each location (Table 2), and the metal sheet temperature was set in 90 ℃, same as the drying air.

$$Q4t = \alpha \times A \times (Tm - Ta) \tag{2}$$

where, $Q4t$: total convective heat loss to the ambient air through the metal sheet of the hot air plenum (kJ/h); α: convective heat transfer coefficient (kJ/ ℃/m^2/h); A: exposed surface of the hot air plenum of the dryer (m^2); Tm: metal sheet temperature (℃); Ta: ambient air temperature (℃).

The convective heat transfer coefficient depends on the wind speed of the cold air in contact with the hot surface of the dryer. In this study it was used the average wind speed of the harvest month for each location (Table 1).

The total amount of water removed from each tone of grain through the drying process was calculated with Equation 3, being 17.75 kg/t for 17% m.c.$_i$ and 53.25 kg/t for 20% m.c.$_i$.

$$Kg_W = \left(\frac{1000 \times MC_i}{100}\right) - \left(\frac{DM \times MC_f}{100 - MC_f}\right) \tag{3}$$

where, kg_w: kg of water evaporated from each tone of wet grain (kg/t); 1000: (kg/t); DM: dry matter of each tone of wet grain (kg/t); $m.c._i$: initial grain m.c. (%); $m.c._f$: final grain m.c. (%)

For each location, the specific heat loss to the ambient through the hot air plenum of the dryer ($Q4$) was calculated with the drying capacity (R, t/h) obtained from the simulation, the total convection losses from the hot air plenum ($Q4t$) obtained from Equation (2) and the kg of evaporated water per each tone that passes through the dryer, as shown in Equation (4).

$$Q4 = \frac{Q4t}{R \times kg_w} \tag{4}$$

where, $Q4$: specific convective heat loss to the ambient air through the metal sheet of the hot air plenum (kJ/kg$_w$); $Q4t$: total convective heat loss to the ambient air through the metal sheet of the hot air plenum (kJ/h); R: dryer capacity (t/h); kg_w: kg of water evaporated from each tone of wet grain, Equation (3) (kg/t)

Since the study assumed that the drying temperature in each location was maintained fixed in 90 ℃, in order to obtain the specific heat provided by the burner to dry corn (Qb), the specific convective heat loss to the ambient air through the metal sheet of the hot air plenum ($Q4$) should be added to the specific drying heat consumption (Qd) (Equation (5)).

$$Qb = Qd + Q4 \tag{5}$$

where, Qb: specific heat provided by the burner to dry corn (kJ/kgw); Qd: specific drying heat, Equation (1) (kJ/kgw); *Q*4: specific convective heat loss to the ambient air, through the metal sheet of the hot air plenum, Equation (4) (kJ/kgw).

The specific electrical energy demanded was calculated with the total electrical power installed in the dryer (e.g. electric fan motors and the motors that move the mechanical part that regulates the flow of grain), 50 HP; the drying capacity for each location and the amount of water removed (Equation (6)).

$$Ee = \frac{Pi \times 0.735 \times 3600}{R \times kg_w} \quad (6)$$

where, *Ee*: specific electrical energy consumption (kJ/kg$_w$); 0.735: conversion factor from HP to kW (kW/HP); *Pi*: total electrical power installed in the dryer (HP); *R*: dryer capacity (t/h); *kg$_w$*: kg of water evaporated from each tone of wet grain, Equation (3) (kg/t); 3600: conversion factor from kWh to kJ (kJ/kWh).

The total energy consumption to dry corn was computed adding the thermal energy and the electrical energy (Equation (7)).

$$Et = Qb + Ee \quad (7)$$

where, *Et*: specific total drying energy (kJ/kg$_w$); *Qb*: specific heat provided by the burner to dry corn, Equation (5) (kJ/kg$_w$); *Ee*: specific electrical energy consumption, Equation (6) (kJ/kg$_w$).

The total drying energy was converted into drying efficiency, taking as reference the mean grain latent heat of vaporization, i.e. 2,512 kJ/kg$_w$ (600 kcal/kg$_w$; Olesen, 1987) (Equation (8)):

$$Eff = \frac{2512}{Et} \times 100 \quad (8)$$

where, *Eff*: drying efficiency (%); 2512: mean grain latent heat of vaporization (kJ/kg$_w$); *Et*: specific total drying energy, Equation (7) (kJ/kg$_w$).

The energy demanded to increase the grain temperature (*Q*1) was calculated according to the ASABE standard D 243.4 Equation (9):

$$Q1 = \frac{(1.465 + 0.0356 \times (MC_f + MC_i)/2) \times (\mathrm{Tg}_f - Tg_i) \times 1000}{kg_w} \quad (9)$$

where, *Q*1: specific energy used for grain warming (kJ/kg$_w$); *m.c.$_i$*: initial grain m.c. (%); *m.c.$_f$*: final grain m.c. (%) –obtained from drying simulation; *Tg$_i$*: grain initial temperature (℃); *Tg$_f$*: grain final temperature (℃) –obtained from drying simulation; *kg$_w$*: kg of water evaporated from each tone of wet grain, Equation (3) (kg/t); 1000: conversion factor from kg to tone (kg/t).

The heat lost with the exhaust air was estimated as the difference between the heat source (*Qd*) and the other heat losses as Equation (10):

$$Q3 = Qd - (Q1 + Q2) \quad (10)$$

where, *Q*3: specific exhaust air heat loss (kJ/kg$_w$); *Qd*: specific drying heat, Equation (1) (kJ/kg$_w$); *Q*1: specific energy used for grain warming, Equation (9) (kJ/kg$_w$); *Q*2: specific water evaporation energy (kJ/kg$_w$).

3 Results and disucussion

The simulation results for ten locations are presented in Table 4 for 17% m.c.$_i$ and in Table 5 for 20% m.c.$_i$. In each table the locations are ordered by increasing total energy consumption.

Table 4 Drying time (*Dt*), dryer capacity (*R*), specific convective heat losses to the ambient air (*Q*4), specific heat provided by the burner for drying (*Qb*), specific electrical energy (*Ee*) and specific total energy required for drying (*Et*) for drying corn from 17% m.c.i. Average values and standard deviation (*S*)

Location	*Dt*, min	*R*, t/h	*Q*4, kJ/kg$_w$	*Qb*, kJ/kg$_w$	*Ee*, kJ/kg$_w$	*Et*, kJ/kg$_w$	*Eff*, %
Saenz Peña	28	114	126	7084	66	7151	35
Bella Vista	28	113	184	7360	67	7423	34
Cerro Azul	28	113	155	7436	67	7503	33
Reconquista	29	110	180	7758	68	7825	32
Oliveros	29	111	155	7758	68	7829	32
Pergamino	29	111	205	8030	68	8097	31
Manfredi	30	108	214	8742	70	8813	29
Balcarce	29	109	243	8905	69	8972	28
Anguil	29	110	214	9127	68	9194	27
Hilario Ascasubi	29	110	281	9198	68	9265	27
Average	29	111	196	8140	68	8207	31
S	<1	2	46	786	1	787	3

Table 5 Drying time (*Dt*), dryer capacity (*R*), specific convective heat losses to the ambient air (*Q*4), specific heat provided by the burner for drying (*Qb*), specific electrical energy (*Ee*) and specific total energy required for drying (*Et*) for drying corn from 20% m.c.i. Average values and standard deviation (*S*)

Location	*Dt*, min	*R*, t/h	*Q*4, kJ/kg$_w$	*Qb*, kJ/kg$_w$	*Ee*, kJ/kg$_w$	*Et*, kJ/kg$_w$	*Eff*, %
Saenz Peña	59	52	92	4970	47	5016	50
Bella Vista	59	53	134	5108	48	5154	49
Cerro Azul	59	53	109	5137	47	5183	48
Reconquista	59	53	126	5242	47	5288	48
Oliveros	59	53	109	5280	47	5326	47
Pergamino	58	53	142	5426	47	5472	46
Manfredi	59	53	142	5753	47	5799	43
Balcarce	58	53	163	5878	47	5924	42
Anguil	58	54	147	6029	46	6075	41
Hilario Ascasubi	58	54	193	6071	46	6117	41
Average	59	53	136	5489	47	5535	46
S	<1	<1	29	408	<1	408	3

3.1 Drying time and capacity

The drying time for 17% m.c.$_i$ was from 28 to 30 minutes, while for 20% m.c.$_i$ was about double, from 58 to 59 minutes. The low variation in drying time across locations can be explained by the uniform drying temperature, which was set in 90℃. However, the difference will be noticed in the amount energy required to reach the prescribed temperature in the different locations.

When drying from 17% m.c.i the drying capacity was, on average, 111 t/h, while when the m.c.$_i$ was 20%, the drying capacity was almost half, 53 t/h on average. Similar to drying time, the drying capacity had a very low variability across locations (Standard deviation (S): one or less).

3.2 Convective heat losses

The convective heat lost to the ambient was, on overage, 196 kJ/kg$_w$ for 17% m.c.$_i$, and substantially lower for 20% m.c.$_i$ (136 kJ/kg$_w$). However, in both drying condition the heat losses were less than 3% of total drying energy. Although there was variability across locations (S between 29 and 46 kJ/kg$_w$), the impact in the total energy consumption was rather minor. One speculation could be that the weather conditions considered were not challenging enough to cause an important heat loss. Figure 3 shows the predicted effect of ambient temperatures on convective heat lost to the ambient, where it can be noticed that very low temperatures, e.g. 0℃, could cause a heat loss of about 260 kJ/kg$_w$. Figure 4 shows that extremely high wind velocity (e.g. 20 m/s), could cause a potential convective heat lost to the ambient of about 955 kJ/kg$_w$. Both extreme ambient conditions resulted with a heat loss much higher than those estimated for the typical drying condition considered in this study. Thus, under certain extreme conditions (low temperatures and high wind velocities), convective heat loss to the ambient could be a substantial part of the total energy demanded by the drying operation, being probably convenient to insulate the dryer if those weather condition were frequents.

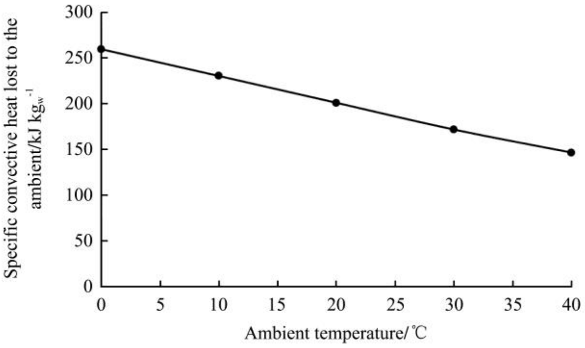

Figure 3 Effect of ambient temperature on the specific convective heat losses of the dryer (*Q*4) for a dryer temperature of 90℃ and wind velocity of 3 m/s

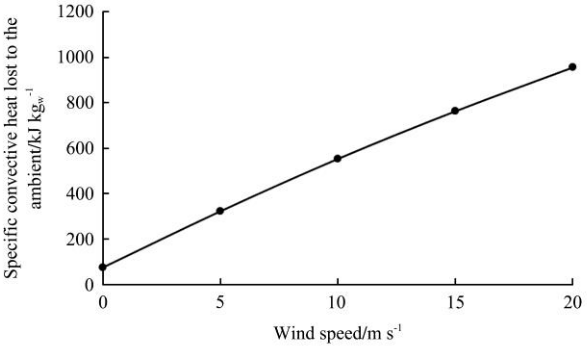

Figure 4 Effect of the wind velocity on the specific convective heat losses of the dryer (*Q*4) for an ambient temperature of 11℃ and a dryer temperature of 90℃

3.3 Fuel, electrical and total energy

The specific energy provided by burner (*Qb*) was of 8,140 kJ/kg$_w$ for 17% m.c.$_i$ and of 5,489 kJ/kg$_w$ for 20% m.c.$_i$. On the other hand, the electrical energy consumption was of 68 kJ/kg$_w$ for 17 and 47 kJ/kg$_w$ for 20% m.c.$_i$, respectively (0.3 and 0.7 kWh/t) and no difference across locations was expected in this parameter (Tables 4 and Table 5).

The total drying energy for 17% m.c.$_i$ was 8,207 kJ/kg$_w$ on average, while for 20% m.c.$_i$ was 5,535 kJ/kg$_w$. There was variability across locations, being the standard deviation of 787 and 408 kJ/kg$_w$ for 17 and 20% m.c.i, respectively. These results are between 3,000 and 10,500 kJ/kg$_w$, the range of energy consumption reported in the literature for high temperature drying (Frisen, 1980; Rodriguez, 1982; Maier and Bakker-Arkema, 2002; Donato, 2007).

Considering that the energy required to evaporate 1 kg of water from grain is 2,512 kJ, the drying efficiency for 17% m.c.$_i$ was of 31%, while for 20% m.c.$_i$ was higher, 45%.

3.4 Energy balance

More than half (57%) of the total energy required for drying corn from 17% m.c.$_i$ corresponded to the energy used for grain warming (Table 6), water evaporation energy was 31% and exhaust air heat loss, 9% of the total drying energy. This implies that an important energy saving could be achieved by using the sensible heat of the grain for a dryeration process (recovering part of the energy used for grain warming). The second source of energy saving could be achieved by recovering part of the drying capacity of the exhaust air, but in this case only 9% of improvement could be achieved at the most.

Table 6 Energy partition (kJ/kgw), on average for all locations, for drying corn from 17 and 20% m.c.i.

Energy destination	17% m.c.$_i$	%	20% m.c.$_i$	%
Q1 (specific grain warming energy)	4672	57	1964	35
Q2 (specific water evaporation heat)	2512	31	2512	45
Q3 (specific exhaust air energy loss)	762	9	879	16
Q4 (specific heat lost to the ambient)	196	2	136	2
Qb (specific burner energy)	8140	99	5489	99
Ee (specific electrical energy consumption)	68	1	47	1
Et (specific total drying energy)	8207	100	5535	100

When drying corn from 20% m.c.$_i$ about 35% of the total energy was used for grain warming, and around 16% was for exhaust air heat loss, while water evaporation energy was the biggest proportion, about 45%.

The main difference of drying corn from 17% or 20% m.c.$_i$ was the energy used for grain warming. Even though the final average grain temperature was higher for 20% than for 17% m.c.$_i$ (69℃ and 60℃, respectively) and, hence, the total energy used for increasing the grain temperature was higher for the higher m.c., the amount of moisture removed was much higher at 20% m.c.$_i$ than at 17%, resulting drying from 20% with less proportional energy used for grain warming.

The specific energy provided by burner (Qb) represented 99% of the total energy required for drying and, correspondingly, the electrical energy consumption accounted for only 1% of the total drying energy. This implies that the electrical energy has a negligible effect on the high temperature drying cost.

3.5 Effect of ambient temperature

The ambient temperature affected the total energy consumption. Figure 5 shows that drying corn from 17% m.c.$_i$ with an ambient temperature of 11℃ had a total energy consumption of about 9,265 kJ/kg$_w$, while when the ambient temperature was of 26℃ the total energy consumption dropped to 7,150 kJ/kg$_w$ (23% reduction), with a decreasing consumption rate of 141 kJ/℃ of temperature increase (1.5%/℃). Drying corn from 20% m.c.$_i$ had a similar trend. When the ambient temperature was of 11℃ the total energy consumption was of about 6,116 kJ/kg$_w$, being reduced to 5,016 kJ/kg$_w$ with ambient temperature of 26℃ (18% reduction), with a decreasing consumption rate of 73,3 kJ/℃ of temperature increase (1.2%/℃).

Based on these data, by selecting warm harvest weather instead of cold harvest weather, farmers could obtain important savings in the drying operation. For example farmers could select the warmer hours of the day, or dismiss the coolest ones, for harvest, if grain conditions and logistic of the farm and the grain elevator allow it. Today, with the available weather forecast system, selecting harvest days with suitable temperature for drying could be fairly simple to implement.

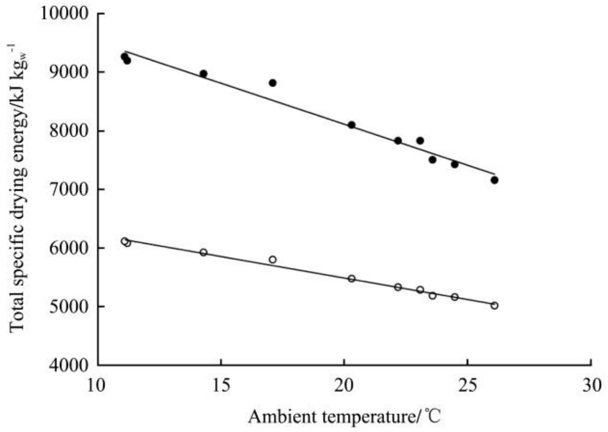

Figure 5 Average ambient temperature of the location and total energy consumption for drying corn in a continuous flow-high temperature dryer from 17 and 20% m.c.$_i$. Ref: ● = 17% m.c.$_i$ (lineal regression $y = -33.277x + 2604.2$; $R^2 = 0.9693$); ○= 20% m.c.$_i$ (lineal regression $y = -17.396x + 1658.9$; $R^2 = 0.9884$)

Many grain buyer companies have several grain elevators distributed across the country, in locations with different temperature patterns. Often, these companies have a fixed drying fare among elevators, which could be adjusted by the average ambient temperature of the location during the drying season based on the relationship of Figure 5.

De la Torre and Bartosik (2013) investigated the effect of weather conditions on the energy required for drying corn with natural air/low temperature (NA/LT) in-bin drying systems for the same locations and m.c.$_i$ considered in the present study. In comparison with NA/LT, high temperature drying energy consumption for 17% m.c.$_i$ was between 18% lower and 147% higher (NA/LT energy consumption was 7,151 and 8,972 kJ/kg$_w$, for Saenz Peña and Balcarce, respectively), while for 20% m.c.$_i$ was 23% lower for cold locations (e.g. NA/LT energy consumption for Balcarce was 5,924 kJ/kgw) to 52% higher for warm locations (e.g. NA/LT energy consumption for Saenz Peña was 5016 kJ/kgw). This would indicate that, in terms of energy consumption, NA/LT in-bin drying systems are more affected than high temperature drying systems by weather conditions. Additionally, NA/LT would consume less energy than high temperature drying under warm weather conditions, but more energy under cold weather conditions (Table 7). When comparing high temperature drying and NA/LT drying other important difference is the type of energy required for drying. While high temperature drying consumes more than 99% of fuel energy and less than 1% of electrical energy, NA/LT in-bin drying system consumes about 60% of fuel energy (from 0 to 86%, according to the drying strategy and weather condition) and 40% of electrical energy. Thus, the final cost of drying will depend not only on the drying efficiency in terms of energy, but also on the relative cost of the fuel and the electrical energy, being the final cost more variable for NA/LT drying than for high temperature drying systems.

Table 7 Total energy consumption for drying corn from 17 and 20% m.c.i with natural air / low temperature in-bin drying systems and high temperature continuous flow drying system for Balcarce (cold location) and Saenz Peña (warm location)

Location	NA/LT*		High Temperature		Difference	
	17% m.c.$_i$	20% m.c.$_i$	17% m.c.$_i$	20% m.c.$_i$	17% m.c.$_i$	20% m.c.$_i$
	kJ/kg$_w$	kJ/kg$_w$	kJ/kg$_w$	kJ/kg$_w$	% difference	% difference
Balcarce	10928	7725	8972	5924	-18%	-23%
Saenz Peña	2893	3295	7151	5016	147%	52%

Note: * Data from de la Torre and Bartosik (2013).

4 Conclusions

The specific total energy consumption for drying corn from 17% m.c.$_i$ was from 7,151 kJ/kg$_w$ in the warmest location to 9,265 kJ/kgw in the coldest location (8,206 kJ/kg$_w$ on average), while for 20% m.c.$_i$ was 5,016 kJ/kg$_w$ in the warmest location to 6,117 kJ/kg$_w$ in the coldest location (5,535 kJ/kg$_w$ on average), resulting in an average drying efficiency of 31% for 17% m.c.$_i$ and 46% for 20% m.c.$_i$.

The caloric energy consumption (fuel) accounted for more than 99% of the total energy, being the electrical energy consumption less than 1%.

The specific convective heat losses ($Q4$) under the average weather condition of the locations considered were 196 kJ/kg$_w$ for 17% m.c.$_i$, and 136 kJ/kg$_w$ for 20%

m.c.$_i$, less than 3% of the total drying energy. However, under more challenging weather conditions (low temperature and high wind speed) this heat loss could be up to 955 kJ/kg$_w$.

When drying corn from 17% m.c.$_i$, about half of the total energy (57%) was used for increasing the grain temperature during the drying process ($Q1$). The evaporation heat ($Q2$) represented 31% and the heat lost with the exhaust air ($Q3$) about 9% of the total energy. When drying corn from 20% m.c.i 35% of the total energy was used for increasing the grain temperature ($Q1$), and about 16% was lost in the exhaust air ($Q3$). The evaporation heat was the biggest proportion, about 45% ($Q2$). This implies that an important energy saving could be achieved by using the sensible heat of the grain in a subsequent dryeration process and/or implementing a recirculation system of the exhaust air that still has drying potential.

The ambient temperature affected the total energy consumption. Drying corn from 17% m.c.$_i$ with an ambient temperature of 11 ℃ had a total energy consumption of 9,265 kJ/kg$_w$, while when the ambient temperature was of 26 ℃ the total energy consumption dropped to 7,150 kJ/kgw (23% reduction). Drying corn from 20% m.c.$_i$ had a similar trend, from 6,116 kJ/kgw when the ambient temperature was of 11 ℃, to 5,016 kJ/kgw with ambient temperature of 26 ℃ (18% reduction). In general, the energy consumption dropped about 1.35 %/ ℃ of ambient temperature increase. Drying energy efficiency (and drying cost) could be improved by selecting warmer ambient temperature conditions, if grain conditions and logistic of the farm and the grain elevator allow it.

Nomenclature

kg_w: kg of water evaporated from each tone of wet grain (kg/t).
DM: dry matter of each tone of wet grain (kg/t).
$m.c.$: moisture content (%, wet based).
$m.c._i$: initial moisture content (%, wet based).
$m.c._f$: final moisture content (%, wet based).
Qa: specific enthalpy of ambient air (kJ/kg$_w$).
Qb: specific energy provided by burner (kJ/kg$_w$).
Qd: specific drying heat (kJ/kg$_w$).
Qg: specific grain initial enthalpy (kJ/kg$_w$).
$Q1$: specific energy used for grain warming (kJ/kg$_w$).
$Q2$: specific water evaporation energy (kJ/kg$_w$).
$Q3$: specific exhaust air heat loss (kJ/kg$_w$).
$Q4$: specific convective heat lost to the ambient (kJ/kg$_w$).
$Q4t$: total convective heat loss to the ambient air through the metal sheet of the hot air plenum (kJ/h).
Ee: specific electrical energy consumption (kJ/kg$_w$).
Eff: drying efficiency (%).
Et: total specific drying energy (kJ/kg$_w$).
Pi: total electrical power installed (HP).
RH: relative humidity (%).
Ta: ambient temperature (℃).
Tm: metal sheet temperature (℃).
Ws: wind speed (m/s).
α: Convective heat transfer coefficient (kJ/ ℃/m^2/h).
Tg_i: grain initial temperature (℃).
Tg_f: grain final temperature (℃).
Dt: drying time (h).
R: dryer capacity (t/h).
A: exposed surface of the hot air plenum of the dryer (m^2).
S: standard deviation.

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