Bidirectional drying of baled hay with air recirculation and cooling

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Savoie, P. and Joannis, H. 2006. **Bidirectional drying of baled hay with air recirculation and cooling.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 3.53 - 3.59. Twelve batches of 60 small rectangular hay bales were dried artificially in a prototype dryer with air heated at 60ºC. Bales were dried according to four treatments: I) unidirectional flow with 50% air recirculation; II) bidirectional flow with 50% air recirculation; III) bidirectional flow with 50% air recirculation plus a 30-min cooling period; IV) bidirectional flow with 90% air recirculation plus a 30-min cooling period. Bidirectional flow was applied by reversing airflow direction once during a drying cycle after 2/3 of the planned propane gas had been combusted. There were two drying cycles, an A-drying period when 100% thermal efficiency was assumed (average time in dryer between 2.5 and 3.5 h) and a B-drying period when the actual efficiency of the previous drying cycle was assumed (average time in dryer between 3.9 and 5.1 h). There was no significant difference between the four airflow treatments in terms of moisture content reduction, bale mass reduction, and thermal efficiency. Overall for 720 bales, the average moisture content was reduced from 24.0% initially at baling to 20.1% after A-drying period, 15.8% after B-drying period, and 12.6% after six weeks of storage. On average, 35 L of propane were required to dry a tonne of hay (874 kg dry matter) from the initial moisture content of 24%. The average time in the dryer was 6.8 h. Average bale masses were 31.1 kg at baling, 29.6 kg after A-drying, 28.0 kg after B-drying and 27.0 kg after storage. The thermal efficiency averaged 41.6% during period A and 26.7% during period B. Treatment IV with high air recirculation and cooling tended to have higher thermal efficiencies (45.3 and 30.2% for A and B periods, respectively) than the three other treatments. High density bales dried significantly more slowly ($p = 0.028$) than low density bales in the range of 161 to 182 kg (dry matter)/m³. Bales should therefore be grouped as much as possible in a homogeneous batch, both in terms of density and initial moisture. Moisture content distribution was very homogeneous within individual bales after a 10-week storage period. The dryer could produce high quality hay bales for the commercial market. However, further analysis and experimentation are required to determine the optimal conditions for air velocity and temperature, time of drying, and cycles of air inversions. **Keywords**: drying, hay, bale, airflow, moisture.

Douze lots de 60 petites balles de foin rectangulaires ont été séchés dans un séchoir prototype avec de l'air chauffé à 60ºC. Les balles étaient séchées selon quatre traitements : I) flux d'air unidirectionnel avec 50% de recirculation; II) flux d'air bidirectionnel avec 50% de recirculation; III) flux d'air bidirectionnel avec 50% de recirculation et refroidissement de 30 min; IV) flux d'air bidirectionnel avec 90% de recirculation et refroidissement de 30 min. Un flux d'air bidirectionnel était appliqué en inversant la direction de l'air une fois après la combustion des 2/3 du gaz propane prévu dans un cycle de séchage. Il y avait deux cycles de séchage : une période de séchage A pendant laquelle on supposait une efficacité thermique de 100% (durée de séchage entre 2,5 et 3,5 h) et une période de séchage B pendant laquelle on supposait l'efficacité thermique de la période précédente (durée de séchage entre 3,9 et 5,1 h). Il n'y a pas eu de différence significative entre les quatre traitements de circulation d'air au niveau de la réduction de la teneur en eau et de la masse des balles, ni au niveau de l'efficacité thermique. Globalement pour les 720 balles séchées, la teneur en eau est passée de 24,0% à la récolte à 20,1% après le séchage A, 15,8% après le séchage B et 12,8% après six semaines d'entreposage. En moyenne, il a fallu 35 L de propane pour sécher une tonne de foin (874 kg de matière sèche) à partir de la teneur en au initiale de 24%. Le temps moyen de séjour dans le séchoir était de 6,8 h. Les masses moyennes des balles sont passées de 31,1 kg à la récolte, à 29,6 kg après le séchage A, 28,0 kg après le séchage B et 27,0 kg après l'entreposage. Les efficacités thermiques moyennes étaient de 41,6% pour la période A et 26,7% pour la période B. Le traitement IV avec un haut niveau d'air recirculé et un refroidissement avait tendance à être plus efficace (45,3% et 30,2% pour les périodes A et B, respectivement) que les trois autres traitements. Des balles à haute densité ont séché plus lentement de façon significative ($p = 0,028$) que des balles à basse densité dans la plage de 161 à 182 kg (matière sèche)/m³. Les balles devraient donc être regroupées dans des lots homogènes au niveau de la densité et de la teneur en eau. La distribution de la teneur en eau dans des balles individuelles était très homogène après dix semaines d'entreposage. Le séchoir pouvait donc servir à produire des balles de foin de haute qualité pour le marché du foin de commerce. Toutefois, d'autres analyses et expérimentations sont requises pour déterminer les conditions optimales pour la vitesse et la température de l'air, la durée du séchage et les cycles d'inversion d'air. **Mots clés**: séchage, foin, balle, flux d'air, teneur en eau.

INTRODUCTION

The production of good quality commercial hay requires a precise control of the moisture level. Field drying can remove a large proportion of excess water from the fresh crop, but in most climatic zones, weather variations result in variable moisture content at baling. For this reason, several researchers and commercial companies have proposed artificial drying with heated air to better control the final moisture of baled hay (Parker et al 1992; Arinze et al. 1994; Inventagri 2005). These processes generally work with unidirectional flow of air and can result in over-drying of bales first in contact with heated air.

Precise control of moisture in hay bales is not always clearly defined. The moisture content needs to be low enough to avoid the development of mold during storage. However, moisture content should not be too low because hay is generally sold on a wet basis; over-dried hay will result in an economic loss due to weight loss and wasted energy. An industry guideline for a safe moisture content level is below 12% (Personal Communication: R. Knitel, Green Prairie Products, Lethbridge,

Fig. 1. **Air flow system with propane gas burner, four gate valves for directional change, blower pulling air in negative pressure, and two louvers to control recirculation.**

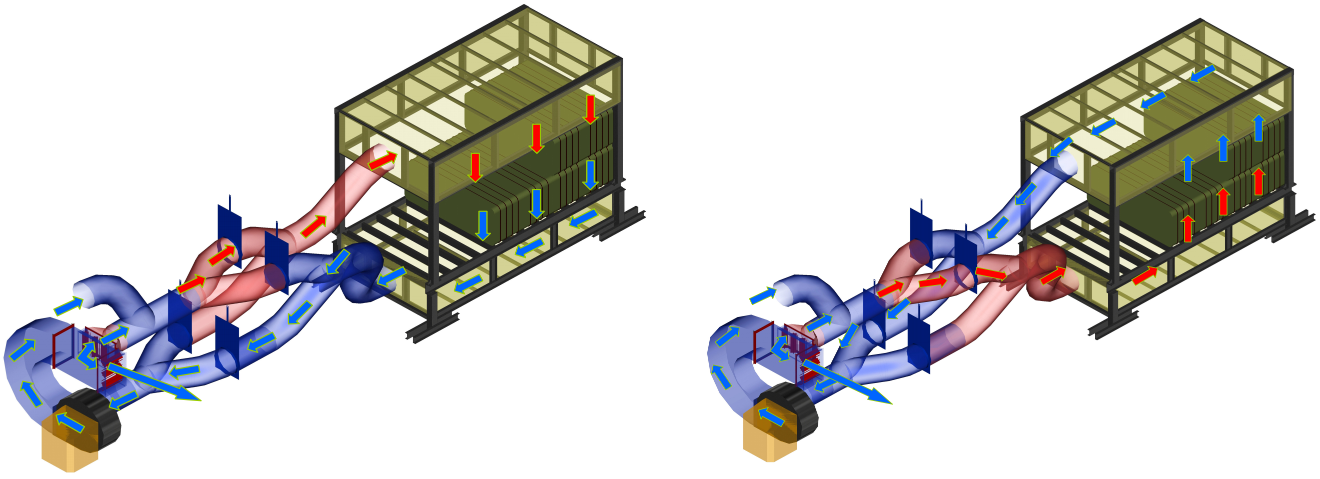
AB). Couture et al. (2002) measured microscopic mold in petri dishes with hay at various levels of moisture content between 10 and 25%. Over an 8-week period, they observed no mold development in alfalfa below 14% moisture content and in timothy below 11% moisture content. Above these moisture levels, the colonized area increased and represented as much as 70 to 80% of hay area when moisture content was 25%.

Another important characteristic of commercial hay is the density. A high density is desirable to reduce transportation cost. High densities in the order of 300 to 400 kg DM (dry matter)/m³ may be reached with hay cubes and pellets. Densification of these products is done after artificial drying of chopped forage to about 10% moisture (Berney 1991). However, baled hay is usually packaged in the field at moisture contents much higher than 10 to 12%. For this reason, small hay bales are often packed loosely at low densities, typically in the order of 100 to 140 kg DM/m³ to facilitate forced ambient air drying (House and Stone 1988). Unfortunately, the dried bales have a low density and are not suitable for transport over long distances.

A dryer was developed to extract water from high density bales of biomass such as corn stover (Savoie and Descôteaux 2004) and hay (Descôteaux and Savoie 2006). An original characteristic of the dryer is bidirectional airflow, i.e. the capability to move air alternately upward and downward across the bales (Savoie and Descôteaux 2006). This novelty was integrated in the dryer to minimize over-drying and produce bales with relatively uniform final moisture. The objective of the present experiment was to evaluate different airflow treatments comparing unidirectional and bidirectional flow, two levels of air recirculation, and the option of air cooling at the end of drying. The pilot scale dryer was used to dry small rectangular hay bales which were grouped in different classes of dry matter density.

METHODOLOGY

A prototype bidirectional hay dryer was designed and constructed at the Normandin Research Farm in 2002-2003. The dryer was described in detail in Descôteaux and Savoie (2006) and Savoie and Descôteaux (2006) and previously used to dry mid-size hay bales and corn stover bales. Bidirectional airflow was obtained by opening or closing synchronously four gate valves (Figs. 1, 2a, 2b). The energy source to heat air was propane gas fed to a burner of 102 kW maximum power. The blower placed at the end of the air circulation system pulled air in negative pressure across the bales and was operated by an electric motor (11.2 kW). A polyethylene film located between the upper and lower plenums surrounded the bales and created an excellent seal under suction during drying (Fig. 3). The perforated floor had a total area of 4.88 by 2.44 m. Two sets of louvers at the end of the air duct regulated the amount of exhaust air blown outside the system and the amount of exhaust



(a) (b)

Fig. 2. **Bidirectional dryer: (a) with two gate valves opened to direct heated airflow to upper plenum; (b) with two alternate gate valves opened to direct heated airflow to lower plenum.**

Fig. 3. Drying chamber with 60 small hay bales over two levels between the upper and lower plenums. Door is closed and polyethylene adheres to bales during drying under suction.

air recirculated and mixed with ambient air just prior to heating by the gas burner.

The experiment was set up to compare four airflow treatments (Table 1). Airflow was initially upward across the bales for all treatments. When inversion was applied, air flow direction was reversed once (downward) after 2/3 of the planned amount of propane gas had been used (see below for the method for estimating propane used per drying period). The rate of air recirculation was constant throughout the drying period (at 50 or 90%). Air recirculation was calibrated by measuring volumetric flow in the fresh air intake duct and in the exhaust air outlet duct with a hot-wire anemometer and a 10-point grid. When a cooling period was part of the treatment, the hay bales remained an extra 30 min in the dryer after the heated-air drying period was completed; the same airflow was maintained for 30 min without heating. The heated air temperature was set at 60ºC for all four treatments so the burner adjusted the rate of propane combustion to maintain this temperature. The blower was set at constant speed for all four treatments (with an average airflow of 3.4 m³/s). The actual airflow varied slightly from one batch to the other because of small changes in the hay stack density and initial moisture content (airflow ranged between 2.9 and 4.0 m³/s with a standard deviation of 0.31 m³/s). The average air velocity was 0.38 m/s and the average pressure drop was 14 mm of water across the hay stack of 0.91 m thickness.

Each treatment was replicated three times. One replication consisted in drying a batch of 60 small bales placed in two layers of 30 bales covering a floor area of about 2.1 by 4.3 m. Each bale measured on average 0.356 by 0.457 by 0.867 m.

Hay bales were harvested at three dates (June 20, June 24, and July 7, 2005) during the first growth cycle of a permanent grass field composed mainly of timothy. Grass was generally mowed between 36 and 54 h prior to baling, left to dry in a wide swath, tedded, and raked. At each harvest date, more than 240 bales were harvested, individually identified, weighed, and measured circumferentially to estimate volume and density. After eliminating broken bales, exactly 240 bales were retained. The retained bales were classified into six groups according to density. Ten bales from each density group were selected for each replication (60 bales) and placed in six rows of homogeneous density; each row was 4.3 m long, 0.36 m wide, and 0.91 m high (five bales at the bottom, five bales at the top). The six 10-bale rows of relatively homogeneous density were placed randomly across the width of the dryer floor.

Table 1. Drying treatments applied to batches of 60 small hay bales.

Treatment	Airflow inversion	Rate of air recirculation (%)	Cooling after drying
I	no	50	no
II	yes	50	no
III	yes	50	yes
IV	yes	90	yes

All drying treatments were carried out in two phases, an A-drying period and a B-drying period. The A-drying period started just after harvest. Each treatment required about 4 h in the dryer and an extra 2 h for loading and unloading. The four treatments were applied randomly and were completed generally within 48 h. The amount of water to be evaporated during the A-drying period was calculated from the estimated moisture at baling and the goal of reaching 12% final moisture content. The amount of propane used in the A-drying period was calculated by assuming nearly 100% thermal efficiency, i.e. the amount of water to be evaporated (kg) multiplied by the theoretical enthalpy of evaporation of water (2.5 MJ/kg) and divided by the combustion energy of propane (93.8 MJ/m³ of gas or 24.9 MJ/L of liquid). After the first drying period, all bales were weighed again and the exact amount of water evaporated was calculated. The thermal efficiency of the A-drying period was estimated as the ratio of enthalpy of water evaporated over the energy provided by the propane.

After each treatment had dried for the A-period, the 60 corresponding bales were set aside until the three other treatments had dried. The same 60 bales for each treatment were then dried for the B-period (usually after a wait of 24 to 48 h during which it was assumed that drying did not take place). The amount of water to be evaporated in B-period was calculated from the difference between moisture content after A-period and the goal of 12% final moisture. The amount of propane used in B-drying period was again based on the theoretical combustion energy of propane (93.8 MJ/m³) to evaporate the estimated water above 12% moisture (2.5 MJ/kg of water), but this time augmented by taking into account the thermal efficiency estimated in A-period. At the end of B-drying, all bales were again individually weighed and placed into a barn with only natural aeration. After six weeks of storage, all bales were again weighed.

Just prior to baling at each date, four grab samples of forage were taken in the windrows to estimate the initial moisture content of bales by a rapid (30-min) method of estimation (Koster Tester). After B-drying period, 24 bales out of 60 from each batch were opened up and sampled at two sections, one at 50 mm from the end of the bale and the other near the centre at 425 mm from the end. Of 24 bales sampled, 12 were taken randomly from the bottom layer and 12 were taken from the upper layer. The samples were oven dried for 24 h at 103ºC to

Table 2. Initial moisture content (IMC) and density of bales at harvest with average values and standard deviation. Density is expressed on a wet, as is, or dry basis.

Harvest date	Batch No.	Treatment	IMC Average (%)	IMC SD (%)	Density Wet average (kg/m^3)	Density Wet SD (kg/m^3)	Density Dry average (kg/m^3)
June 20	1	III	25.6	3.2	244	12.0	182
	2	II	25.8	2.3	244	11.9	181
	3	I	25.6	2.6	244	11.9	181
June 24	5	IV	24.6	2.3	230	13.1	174
	6	I	24.6	2.5	230	12.9	174
	7	IV	24.3	2.0	231	12.5	175
	8	III	24.4	2.6	231	12.7	175
	9	II	24..2	2.8	231	12.6	175
July 7	10	II	22.3	2.7	208	12.8	162
	11	I	21.1	2.3	208	12.8	164
	12	IV	22.8	2.2	208	12.9	161
	13	III	22.3	2.7	208	12.9	162

estimate moisture content according to ASAE standard S358.2 (ASAE 2002). After storage, another 24 bales were sampled in the same way to estimate average moisture content per bale. Initial moisture content and moisture content after A-drying reported in the paper were calculated from bale weight loss and the 48 subsequent moisture samples from the same bales (24 after B-drying and 24 after storage).

Four other bales per batch were stored an extra four weeks (10 weeks total) and sampled at 23 points to assess internal moisture variability. The bale was cut with a band-saw. All samples were taken at mid-height (228 mm) of each bale. Each sample had a section of 75 by 75 mm, over a height of 150 mm; volume was about 0.84 L and mass 125 g. Twelve samples were on the periphery (0 to 75 mm from the outside), eight samples were median samples (75 to 150 mm from the outside) and three samples were near the centre (150 mm from the outside).

Analysis of variance was carried out to compare the four treatments of Table 1 (with 3 replications per treatment). The main variables analysed were bale moisture content, bale mass change, total water evaporated, rate of water evaporation, and thermal efficiency.

RESULTS and DISCUSSION

As planned, more than 240 bales were harvested at each baling date (259, 319, and 261 bales on June 20, June 24, and July 7, respectively). The wet mass of bales retained for the drying experiments averaged 32.8, 32.2, and 28.4 kg at the three dates, respectively, with ranges: 27.9 to 38.7 kg, 25.0 to 40.2 kg and 24.3 to 34.5 kg. The initial moisture content of bales was on average higher at the first harvest date (25.7%) than at the two other dates (24.4% and 22.1%, respectively). Similarly, average wet density was higher at the first date (244 kg/m^3) than at the two other dates (231 and 208 kg/m^3, respectively). Dry matter (DM) density, i.e. adjusted for 0% moisture content, also declined at the three dates (181, 175, and 162 kg DM/m^3).

Table 2 shows average values and standard deviations of initial moisture content and density of bales for all twelve batches of hay. During the first harvest date, the fourth treatment could not be dried immediately due to a power failure and need to refill the propane reservoir. This was compensated for by drying treatment IV twice with bales from the second harvest date and using 300 bales instead of 240 as initially planned, as implied in Table 2. All four treatments were therefore replicated three times as planned, but treatment IV was slightly biased compared to the three other treatments because it was not applied with the first set of wetter bales (although the second set of bales was almost as wet as the first set initially). No statistical correction was attempted because of the limited number of replications (3) and it was not physically possible to consider a fourth replication as the grass crop was too mature after July 7.

Wetter and denser bales resulted in a heavier load in the dryer at the first date (1970 kg wet mass on average per batch) than at the second date (1934 kg) and third date (1701 kg). Another factor that influenced total mass per load of 60 bales was the variation in bale length observed at the three harvest dates: 0.828, 0.859, and 0.838 m, respectively. To reach the objective of a final moisture content of 12%, the amount of water to be removed per batch was on average 306, 273, and 196 kg, respectively, at each harvest date.

Table 3 shows the actual amounts of water evaporated and propane gas used during each drying period and for each batch. By the end of the B-drying period, an average of 177, 208, and 166 kg of water had evaporated at each of the three dates, respectively. These levels of evaporation represented 58, 76, and 85% of the water that should have been removed to reach a final moisture content of 12%. The thermal efficiency ranged between 33 and 65% (average of 43%) for the A-drying period and between 18 and 41% (average of 28%) for the B-drying period. The lower thermal efficiency in the second drying period reflects the greater difficulty to remove moisture as hay bales become drier. Average propane consumption per unit water evaporated was 0.065 L/kg in period A and 0.102 L/kg in period B.

To carry out statistical comparisons, results were grouped per treatment with three replications each. Figure 4 shows the wet mass of bales initially, after A-drying, after B-drying, and after storage for each of the four treatments (average of three replications and 60 bales weighed per replication). There was no significant difference between the mass of bales used initially for the four treatments, as expected (average of 31.1 kg, $p = 0.99$). The bales were therefore evenly spread out among treatments in terms of initial mass variation. The differences of bale mass between the four treatments remained non-significant ($p > 0.99$) at the three other stages of weighing (average wet mass of 29.6 kg after A-drying, 28.0 kg after B-drying, and

Table 3. Water evaporated, propane used, and thermal efficiency for each drying period and each batch.

Harvest date	Batch No.	Treatment	A-drying period			B-drying period			Combined
			Evaporation (kg)	Propane (m^3)	Efficiency (%)	Evaporation (kg)	Propane (m^3)	Efficiency (%)	Efficiency (%)
June 20	1	III	109.4	6.61	44.1	60.5	9.12	17.7	28.7
	2	II	86.2	6.70	34.3	101.6	13.18	20.5	25.2
	3	I	96.7	6.60	39.1	75.6	10.95	18.4	26.0
June 24	5	IV	97.2	6.49	39.9	114.7	10.26	29.8	33.7
	6	I	105.0	6.46	43.3	98.6	8.10	32.4	37.3
	7	IV	91.0	6.50	37.3	129.0	11.90	28.9	31.9
	8	III	80.9	6.52	33.1	124.2	13.77	24.0	26.9
	9	II	98.1	7.14	36.6	99.9	10.40	25.6	30.1
July 7	10	II	63.3	4.41	38.3	112.1	9.03	33.1	34.8
	11	I	85.5	4.39	52.0	92.5	6.03	40.9	45.5
	12	IV	108.3	4.44	65.0	52.3	4.01	34.8	50.6
	13	III	79.0	4.39	47.9	71.0	6.99	27.1	35.1

27.0 kg after storage). As a result, the average water evaporation per bale was 1.5 kg during A-drying, 1.6 kg during B-drying, and 1.0 kg during storage without any difference between the four airflow treatments. Similarly, there were no differences between moisture contents of the four treatments at the various stages of bale processing (Table 4). The average moisture content of bales was 24.0% at baling, 20.1% after A-drying period, 15.8% after B-drying period, and 12.6% after storage. It is noteworthy that after the 6-week storage period, the objective of moisture removal had been reached at levels of 87.6, 100.8, and 97.3% for the three dates of harvest, respectively. It is therefore important to consider both the drying process and subsequent storage to produce high quality hay at the desired moisture level. The average amount of propane used to dry one tonne of hay at 12.6% (874 kg DM) from the initial moisture of 24.0% was a total of 35.2 L/t subdivided as 13.7 L/t for the A-drying period, 21.5 L/t for the B-drying period, and no energy cost during storage when 25% of the water evaporation occurred.

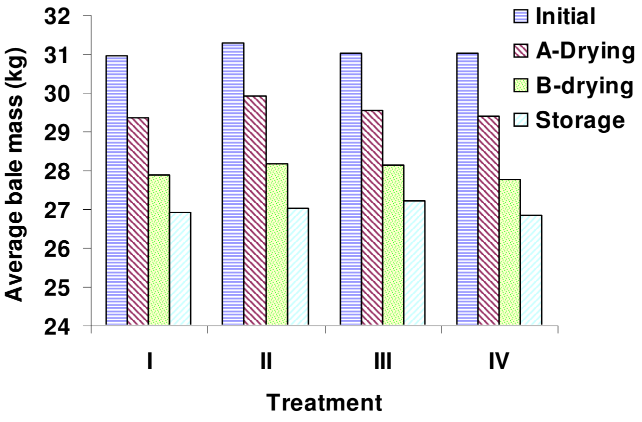


Fig. 4. **Bale mass initially at harvest, after period A drying, after period B drying and after six weeks of storage. Mass is averaged for three replications of 60-bale drying batches for each treatment.**

The time required for drying is illustrated in Table 5. The total drying time during periods A and B was practically the same at 6.8 h for treatments I and II (unidirectional and bidirectional airflow with the same proportion of air recirculation, 50%). When two 30-min cooling periods were added at the same rate of air recirculation, the total time in the dryer increased by practically an hour to 7.7 h for treatment III. In the case of treatment IV, air recirculation was increased to 90%, thereby reducing the gas burning power required to maintain a constant air temperature but increasing the total time for drying to an average of 8.6 h. Thus, almost an extra hour in the dryer was due to the higher air recirculation.

The rates of evaporation were estimated as the total water evaporated divided by the total time in the dryer, including the cooling time for treatments III and IV. There was no statistical difference between the four treatments for either A ($p = 0.707$) or B ($p = 0.338$) drying periods, but there was a trend for slower average drying rates with the cooling periods (e.g. 34.1, 32.6, 30.2, and 29.1 kg/h for period A for the four treatments, respectively). The average drying rate of period A (31.5 kg/h) was significantly higher ($p < 0.001$) than the rate of evaporation during period B (21.7 kg/h).

The average burner power reported in Table 6 is based on the time the burner was on, i.e. excluding the cooling time for treatments III and IV. The average power was reduced in treatment IV as a higher proportion of air was recirculated.

The thermal efficiency during period A averaged 41.6% (SD of 9.0%). The difference was not statistically significant between the four airflow treatments ($p = 0.53$). The highest efficiency was for treatment IV (45.3%) suggesting a benefit from recirculating a high proportion of exhaust air. However, this treatment required a longer drying time. The second highest efficiency (43.9%) during A-drying was observed with the unidirectional airflow treatment I. During period B, the thermal efficiency was again not significantly different ($p = 0.49$) between the four airflow treatments with an average of 26.7%

Table 4. Average moisture content (MC) and standard deviation (SD) of bales initially at harvest, after drying periods A and B, and after 6-week storage.

	Treatment I		Treatment II		Treatment III		Treatment IV	
	MC* (%)	SD (%)	MC (%)	SD (%)	MC (%)	SD (%)	MC (%)	SD (%)
Initial	23.7	2.5	24.1	2.6	24.1	2.8	23.9	2.2
After A-drying	19.6	2.5	20.7	2.5	20.4	2.6	19.7	2.4
After B-drying	15.3	2.9	15.7	2.9	17.2	2.9	15.1	2.8
After storage	12.7	1.1	12.8	1.0	12.6	1.0	12.4	1.1

* MC and SD on wet basis

Table 5. Time in dryer (h) for each treatment during drying periods A and B (averaged over three replications).

	Treatment I		Treatment II		Treatment III		Treatment IV	
	A	B	A	B	A	B	A	B
Upward flow	2.86	3.93	1.84	3.28	1.99	3.19	1.94	2.78
Downward flow	0.00	0.00	0.68	0.98	0.54	0.96	1.08	1.81
Cooling	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50
Total	2.86	3.93	2.52	4.26	3.03	4.65	3.52	5.09
Total A+B	6.79		6.78		7.68		8.61	

(SD of 7.0%). The two highest efficiencies during B-drying were again for treatment IV (30.2%) and treatment I (28.2%).

The bidirectional airflow treatments (II, III, and IV) were not always superior to unidirectional airflow treatment (I) in terms of thermal efficiency, perhaps because of a possible water condensation. Immediately after airflow inversion, the heated air circulated through moist bales and subsequently moved into dryer bales. If air became saturated and the drier bales were at a temperature slightly lower than the air temperature, some condensation would occur. This phenomenon would not last very long nor represent much moisture but it would likely reduce the thermal efficiency as more heat was required later to remove the condensate. Condensation might be avoided by applying inversion sooner than after 2/3 of gas consumption or by using a higher air temperature immediately after inversion. Modeling and more precise analysis of this phenomenon is required to optimize the process of inversion.

Figure 5 illustrates the proportion of water evaporated from the lower and upper 30-bale layers for the four treatments and two drying periods. Unidirectional drying (treatment I) tended to result in a higher evaporation from the lower layer which was always the first in contact with heated air than from the upper layer ($p = 0.058$). The three other treatments, all with air inversion, showed no significant difference in evaporation between the lower and upper layer ($p > 0.47$).

Density of bales had a significant effect ($p = 0.028$) on the moisture content at the end of the B-drying period (Fig. 6). The higher density bales ended with a higher final moisture content than the lower density bales. This can be explained by the fact that all bales in a batch remained the same amount of time and the higher density bales contained more water initially; therefore, they also contained more water at the end of drying. Bales should be grouped as much as possible in a homogeneous batch, both in terms of density and initial moisture. Otherwise, the lighter and initially drier bales will need to be overdried to ensure that the heavier and initially wetter bales reach a target final moisture content.

After a total of 10 weeks of storage, four bales per drying batch were brought to the laboratory to be cut up into 23 pieces as described in the Methodology section. There was no significant difference ($p > 0.31$) in the moisture content between the different positions. The average moisture content was 14.2% (SD = 1.3%). The final moisture of bales after this 10-week storage period was considered relatively homogeneous (CV = 9.4%). The average moisture after 10 weeks of storage was slightly higher than moisture content estimated after six weeks of storage (average of 12.6%, Table 4). Storage certainly

Table 6. Water evaporated per 60-bale batch, use of propane, and thermal efficiency for each treatment during drying periods A and B (average over three replications).

	Treatment I		Treatment II		Treatment III		Treatment IV	
	A	B	A	B	A	B	A	B
Water evaporated (kg)	95.8	88.4	82.5	104.5	89.7	85.0	98.8	98.7
Rate of evaporation (kg/h)	33.5	22.5	32.7	24.5	29.6	18.3	28.1	19.4
Propane (m^3)	5.82	8.36	6.08	10.87	5.84	9.96	5.81	8.72
Burner power (kW)	53.0	55.4	62.9	66.5	60.1	62.5	50.1	49.5
Efficiency (%)	43.9	28.2	36.2	25.6	41.0	22.8	45.3	30.2
Efficiency A+B (%)	34.6		29.4		29.5		36.2	

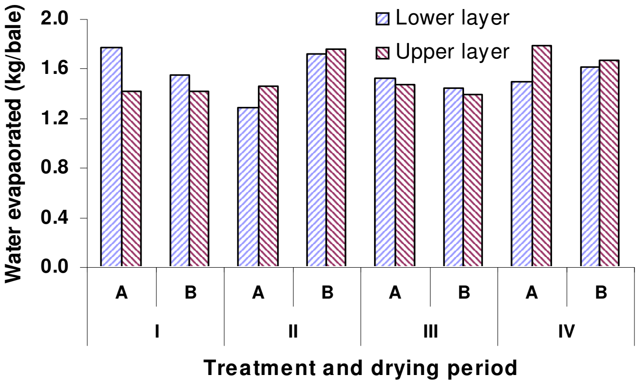


Fig. 5. Average water evaporated per bale in the lower 30-bale layer and the upper 30-bale layer for each drying period A and B and each treatment I to IV.

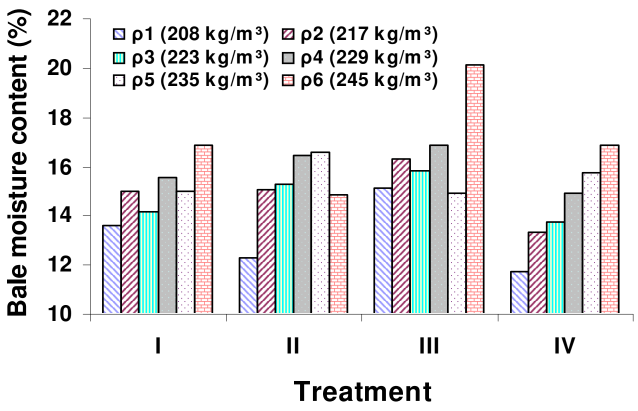


Fig. 6. Average bale moisture after B-drying as a function of wet density averaged over 10 bales per batch and three replications. Each batch (60 bales) was composed of six rows of 10 bales with homogeneous wet density, ρ (average values in legend).

contributed to some moisture migration and homogenization within bales. Further analysis would be necessary over a longer period of time and over various storage seasons, since the current storage periods (6 or 10 weeks) were in summer (July, August, and early September) when ambient weather was relatively warm (daytime temperature generally greater than 20ºC). Over a longer period of storage and under colder temperatures in fall and winter, the moisture distribution and absolute level of moisture may be different.

CONCLUSIONS

Four different hay bale drying treatments comparing unidirectional and bidirectional airflow, two levels of air recirculation (50% or 90%), and a cooling period did not show any significant difference in terms of total moisture removal, change in bale mass, and thermal efficiency when a similar amount of propane gas was used. However, a higher air recirculation tended to result in higher thermal efficiency while requiring more time in the dryer because less combustion power was needed to maintain a constant air temperature (60ºC).

The evaporation rate was significantly higher in a first drying period (from 24.0 to 20.1% average moisture content during a period ranging from 2.5 to 3.5 h) than during a second drying period (from 20.1 to 15.8% average moisture content during a period ranging from 3.9 to 5.1 h). After a six-week storage period, bales had an average moisture content of 12.6%.

High density bales required more time to dry than low density bales (in the range of 161 to 182 kg DM/m³). Bales should therefore be grouped in homogeneous batches in terms of density and initial moisture to avoid overdrying or wet pockets of moisture.

More experimentation, analysis, and simulation would be useful to optimize the drying process of hay bales in terms of thermal efficiency, interaction with the storage period, and cost.

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