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HEAT AND MASS BALANCE OF AN INDUSTRIAL SCALE BIG BALE HAY DRYER

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***Abstract*.** A bidirectional airflow hay dryer was built in 2007 and operated in 2008 in St-Alexandre de Kamouraska (Québec) to dry large rectangular bales. The dryer circulated heated air alternately from the top to the bottom or from the bottom to the top of the hay stack. The bidirectional dryer also included exhaust air recirculation. A second dryer was operated with unidirectional airflow without air recirculation. Six batches of big bales were monitored during a complete drying cycle. Each batch was composed of 72 bales with mean dimensions of 0.8 m x 0.9 m x 2.1 m and average mass of 348 kg per bale. Bales were stacked to a height of 1.8 m, within four drying cells holding 18 bales each. The initial mean moisture content (MC) at harvest time was between 18.8 and 30.1%, while the final mean MC after drying was between 10.7 and 19.8%. Drying time and propane cost were low for a small reduction of MC: 18 h and $14.82/t of dry matter (DM) to dry hay from 26.2 to 19.8%; 13 h and $11.15/t DM to dry hay from 18.8 to 11.6%. However, drying time and propane cost were high for important MC reductions: 58 h and $43.50/t DM to reduce MC from 30.0 to 11.2%; 58 h and $54.23/t DM to reduce MC from 30.1 to 10.7%. The bidirectional dryer was more energy efficient than the unidirectional dryer, mainly because of exhaust air recirculation. The measurement of MC was compared between a standard method (oven-dried samples over a 24 h period at 103°C) and an electronic probe (Delmhorst). Results indicated that the probe was not reliable to estimate the absolute MC accurately.

Keywords. Hay, dryer, moisture content, energy, recirculation, airflow inversion

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Introduction

Bidirectional drying of hay bales was proposed by Savoie and Descôteaux (2006) to improve thermal efficiency and final moisture uniformity in hay stacks. The principle consists in circulating heated air alternately from the top to the bottom and from the bottom to the top of the hay stack with the use of controllable air duct valves. In 2007, an industrial scale hay dryer was built in Saint-Alexandre de Kamouraska (QC) according to the principle of bidirectional airflow. It had a surface area twelve times greater than the original experimental prototype (Descôteaux and Savoie 2006). Preliminary results obtained in 2007 indicated that the industrial scale dryer could dry small and big hay bales from 30 to 12% moisture content (MC), but drying time was sometimes longer than 48 h. More hay batches had to be dried to better monitor the thermal efficiency and the MC throughout the bales.

In 2008, several drying batches were planned with the objective of improving thermal efficiency. More systematic monitoring was scheduled to obtain precise heat and mass balances. The main drying parameters were the proportion of exhaust air recirculation, the frequency of airflow inversion and the drying air temperature. Each parameter was selected depending on hay characteristics at the time of harvest. During these experiments, the packaged hay was in the form of large rectangular bales.

Dryer description

Two dryers were built side by side under the same roof (Fig 1). The first dryer was designed for bidirectional airflow, with heated air circulating alternatively from the top to the bottom of the hay stack and from the bottom to the top. A variable fraction of the exhaust air could also be reused in this dryer (Fig. 2). The second dryer was designed with unidirectional air flow; the heated air always circulated from the top to the bottom of the stack; it had no provisions for exhaust air recirculation.

Each dryer included four drying cells of 2.1 m x 7.3 m (7 ft x 24 ft) separated by a flexible curtain wall. A mobile wagon was placed in each cell with either one row of 9 big bales (0.9 m high) or two rows of 18 bales (1.8 m high). Individual bales measured 0.8 m x 0.9 m x 2.1 m (32 in x 36 in x 84 in). The four cells in each dryer contained 36 or 72 big bales of approximately 350 kg for a maximum capacity of 25.2 t (hay at 25 % MC). The two dryers were operated independently so up to 144 big bales could be dried simultaneously.

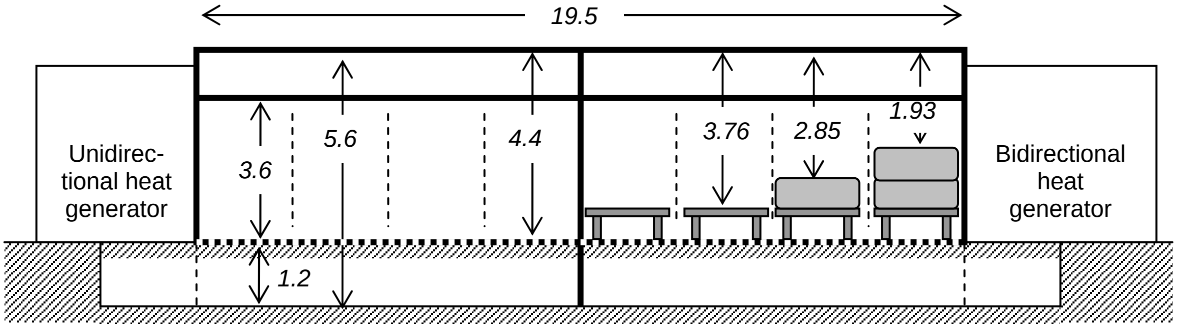
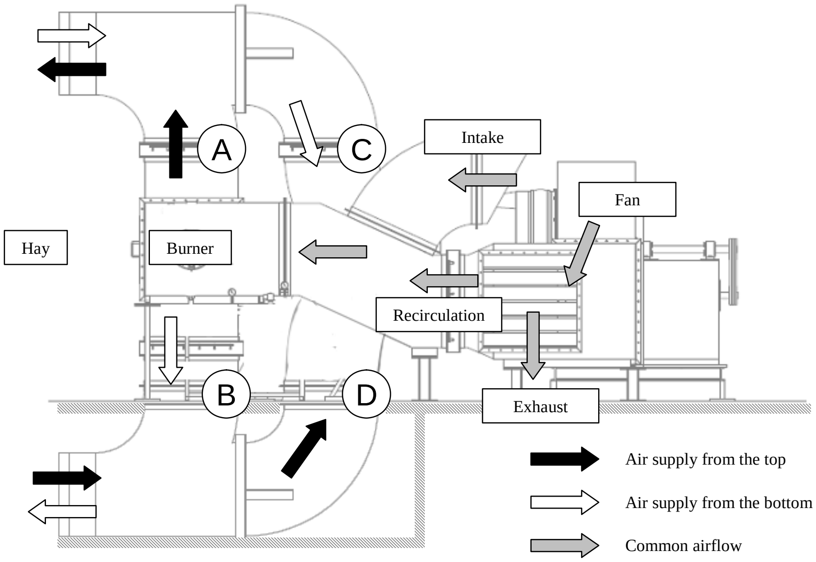


Figure 1. Elevation view of the empty unidirectional dryer (left) and of the bidirectional dryer with wagons (right) (dimensions are in meters).

Each dryer was equipped with a 440 kW (1.5 MBTU/h) direct-fired propane burner. Fans were selected with a mean airflow rate of 10.4 m³/s (22 000 CFM) and 7.1 m³/s (15000 CFM) for the bidirectional dryer and the unidirectional dryer, respectively. Both dryers were controlled independently with a semi-automatic programmable controller (fan and burner start/stop, drying air temperature, airflow inversion, recirculation rate and overall drying time).



Air supply from the top (black arrows)
- Dampers A and D opened
- Dampers C and B closed

Air supply from the bottom (white arrows)
- Dampers C and B opened
- Dampers A and D closed

Figure 2. Bidirectional airflow scheme for air supply from the top or from the bottom.

Objectives

The main research objective was to validate a protocol for drying parameters of big hay bales based on initial conditions. Three sub-objectives were as follows: 1) to enhance the thermal efficiency during drying; 2) to measure the impact of airflow inversion and recirculation; 3) to compare MC measuring techniques for big bales before and after the drying process.

Materials and method

Drying protocol

A drying protocol was developed within the constraint of commercial hay production and harvest variations. Controlled drying parameters were drying air temperature, airflow inversion cycle and exhaust air recirculation rate. Initial hay MC was usually between 20 and 30%; it depended on climate and hay making conditions. The batch drying process was stopped when the hay MC reached an average of 12% and the MC was relatively uniform (generally ± 3 % from the average).

For the unidirectional dryer, three levels of temperature were set: 1) 45°C all the time; 2) 60°C all the time; 3) 60°C from 0 to 50% of the predicted drying time and 45°C until the end. For the bidirectional dryer, two levels of temperature were set: 1) 45°C all the time; 2) 60°C all the time. The two temperature levels in the bidirectional dryer were combined with two exhaust air reuse sequences: 1) 50% recirculation all the time; 2) 25% recirculation from 0 to 50% of the predicted drying time and 75% recirculation until the end of drying. In the bidirectional drying, airflow was inverted at 50% of the estimated drying time. When drying was prolonged beyond the predicted time (because average MC was still above 12% or the range was greater than ± 3% of average), another airflow inversion was done at 100 % of the predicted drying time. Four replications were planned for each set of variables for a total of 12 and 16 batches for the unidirectional dryer and the bidirectional dryer, respectively.

Drying parameters were selected according to the initial mean MC and the available time before the next batch. For example, if the time ahead was long enough (> 24 h) or the initial MC was relatively low, the drying air temperature was set to 45°C. On the opposite, for a shorter time period before the next batch and a higher initial MC, a higher drying temperature was selected (60°C). Table 1 shows the drying parameter selection criteria.

Table 1. Drying air temperature selection according to available time period and initial MC.

Case	Nb of batches on site	Available time period	Initial MC	Drying air temperature
1	1	12 to 16 h	All MC	60°C
2	1	24 h	< 18 %	45 °C
			> 18 %	60°C
3	1	48 h	< 25 %	45 or 60°C
			> 25 %	60°C
4	1	More than 48 h	All MC	45°C
5	2 (1 in the dryer, 1 waiting)	No matter	All MC	1st batch : 60°C 2nd batch : Ref. case 1, 2, 3 or 4

Moisture content measurement

Hay bales were sampled before, during and after the drying process to measure MC. In each dryer, eight bales within a single cell were sampled. Each bale was weighted and measured for dimensions and volume. A Delmhorst electronic probe was used to measure MC at 15 locations uniformly distributed on the longest vertical side of the bale. Three samples were taken with a core drill (upper-left, centre-middle and lower-right) and dried in an oven for MC determination (ASABE, 2006). Before and after each drying batch, individual wagons were weighed on a truck scale. During drying, only the wagon containing sampled bales was weighed.

Process parameters measurement

Air temperature, air relative humidity and absolute static pressure were measured in each plenum (upper and lower) and outside the dryer. Upstream static pressure of the fan was also measured. These data were logged every 30 s by a LabVIEW-driven data acquisition system (National Instrument, Austin, TX). Intake and exhaust airflows as well as air ducts differential static pressure and propane used were measured periodically.

Results

Mass balance validation

While 28 batches were planned for the 2008 experiments, only 6 batches were completed according to the drying protocol. Two hay fires disrupted dryer operations in 2008. However, relevant data were obtained from the six batches that were monitored during a complete drying cycle. The following analysis is based on the results from these six batches.

In Table 2, initial and final masses were obtained from the truck scale. The final DM was calculated with the final mass and the final oven measured MC. The calculated initial MC is the difference between the initial mass and the dry matter, divided by the initial mass. Differences between calculated and measured MC ranged from -1.7 and 2.0% (absolute). This is equivalent to relative differences in MC between -9.2 and 7.7% with an average of -0.7%. With such a small deviation, the sampling method with the oven was considered good enough to characterize the average MC before as well as after the drying process.

Table 2. Measured MC by oven drying of hay samples taken prior to drying (initial) and after drying (final) compared to calculated initial MC based on final MC and mass balance of total evaporation.

Batch	Mass of the batch (kg)			**Oven** moisture content (%)				
	Initial	Final	DM (final)	Final measured	Initial calculated	Initial measured	Absolute difference	Relative difference
3	24480	21920	17573	19.8	28.2	26.2	2.0	7.7
4	25800	21120	18678	11.6	27.6	27.5	0.1	0.4
5	26600	22000	19485	11.4	26.7	27.2	-0.5	-1.8
6	25960	20720	18395	11.2	29.1	30.0	-0.9	-2.9
7	26240	20400	18219	10.7	30.6	30.1	0.5	1.5
8	21120	19800	17511	11.6	17.1	18.8	-1.7	-9.2
							Average:	-0.7

Table 3. Measured MC by an electronic sensor (Delmhorst) of hay samples taken prior to drying (initial) and after drying (final) compared to calculated initial MC based on final MC and mass balance.

Batch	Mass of the batch (kg)			**Delmhorst** moisture content (%)				
	Initial	Final	DM (final)	Final measured	Initial calculated	Initial measured	Absolute difference	Relative difference
3	24480	21920	17663	19.4	28.2	20.4	7.8	38.5
4	25800	21120	17539	17.0	32.0	26.7	5.3	20.0
5	26600	22000	18189	17.3	31.6	28.6	3.0	10.5
6	25960	20720	17615	15.0	32.1	30.0	2.1	7.0
7	26240	20400	17872	12.4	31.9	30.9	1.0	3.3
8	21120	19800	17383	12.2	17.7	15.7	2.0	12.6
							Average:	15.0

In Table 3, a mass balance based on the Delmhorst moisture measurements showed a greater difference between measured and calculated initial MC. These differences ranged between 1.0 and 7.8% (absolute) or between 3.3 and 38.5% relatively to the initial MC measured with the Delmhorst. The relative difference averaged 15.0%. Thus, the electronic probe was not adequately calibrated and should be used with caution to predict MC of hay samples.

Heat and mass balances of drying batches

Each one of the six batches analysed in 2008 was composed of 72 big bales placed on 2 rows. The targeted average MC at the end of drying was 12 % with a maximum at 15 %. Tables 4 and 5 summarize experimental results for batches 3 to 8 (batches 1 and 2 were not completed)

Table 4. Drying conditions and moisture content for batches no. 3 to 8

BATCH NO.	**3**	**4***	**5***	**6****	**7****	**8**
Date (2008)	07-30	07-31	07-31	08-06	08-06	08-17
Dryer	Bidir	Bidir	Unidir	Bidir	Unidir	Bidir
Drying conditions						
Planned treatment						
Estimated drying time (h)	24	36	36	38	38	10
Air flow supply (T:top, B:bottom)	T-B	T-B	T	T-B	T	T-B
Exhaust air recirculation (%)	50	25-75	-	25-75	-	50
Drying air temperature (°C)	45	60	60	45	45	45
Effective treatment						
Drying time (h)	18	50	50	58	58	13
Air flow supply for each cycle	T-B	T-B-T	T	T-B-T	T	T-B
Recirculation rate for each cycle (%)	39-44	15-62-66	-	25-68-65	-	59-52
Ambiant air temperature (°C)	19.8	13.3	13.3	12.3	12.3	14.3
Drying air temperature (°C)	44.4	52.5	52.0	46.0	45.7	46.3
Air flow within hay (m^3/s)	10.64	9.90	7.23	10.61	7.18	10.59
Air velocity within hay (m/s)	0.17	0.16	0.12	0.17	0.12	0.17
CHARATERIZATION OF THE BALES WITHIN A CELL (8 over 18 bales were sampled)						
Initial						
Mean MC, oven method (%)	26.2	27.5	27.2	30.0	30.1	18.8
Mean std dev MC, oven method (%)	3.4	4.4	5.1	4.7	4.5	1.4
Max MC, oven method (%)	34.1	33.8	34.3	37.7	36.8	21.6
Mean MC, Delmhorst (%)	20.4	26.7	28.6	30.0	30.9	15.7
Mean std dev MC, Delmhorst (%)	6.6	4.1	5.2	4.4	4.3	1.2
Max MC, Delmhorst (%)	32.0	33.1	36.8	38.1	37.3	16.8
Total hay mass (kg)	6120	6450	6650	6490	6560	5280

Total hay dry matter (kg)	4517	4677	4838	4543	4585	4286
Bale length (m)	2.19	2.20	2.17	2.19	2.17	2.19
Wet hay density (kg/m³)	209.3	217.4	232.2	224.5	225.5	170.4
Dry matter density (kg DM/m³)	154.1	157.5	168.5	157.0	157.5	138.3
Final						
Mean MC, oven method (%)	19.8	11.6	11.4	11.2	10.7	11.6
Mean std dev MC, oven method (%)	5.7	4.7	3.1	3.3	4.0	2.6
Max MC, oven method (%)	27.2	21.6	16.0	16.4	17.3	16.5
Mean MC, Delmhorst (%)	19.4	17.0	17.3	15.0	12.4	12.2
Mean std dev MC, Delmhorst (%)	7.6	10.4	4.6	6.9	5.7	2.1
Max MC, Delmhorst (%)	36.7	38.6	25.5	27.5	22.1	16.1
Total hay mass (kg)	5480	5280	5500	5180	5100	4950

Batches 4 and 5 (*) and 6 and 7 (**) were dried simultaneously and had similar initial characteristics.

Table 5. Heat and mass balance for batches no. 3 to 8

BATCH NO.	**3**	**4***	**5***	**6****	**7****	**8**
MASS BALANCE (based on hay weighing)						
Initial batch mass (kg)	24480	25800	26600	25960	26240	21120
Initial batch dry matter (kg)	18068	18708	19353	18172	18338	17146
Evaporation to reach 12% MC (kg)	3948	4541	4608	5310	5401	1636
Final hay mass (kg)	21920	21120	22000	20720	20400	19800
Actual water evaporated (kg)	2560	4680	4600	5240	5840	1320
Energy and power						
Propane consumption (L)	383	1093	1339	1129	1421	273
Energy consumption (MJ)	14986	42818	52452	44245	55664	10705
Specific energy (MJ/L)	39.2	39.2	39.2	39.2	39.2	39.2
Evaporation energy (MJ/kg water)	6400	11700	11500	13100	14600	3300
Burner power (kW)	231	238	291	212	267	229
RECIRCULATION CONTRIBUTION						
Mass air flow (kg/s)	12.1	11.2	-	12.1	-	12.0
Heating power (kW)	299	443	-	408	-	387
Burner power (kW)	238	238	-	212	-	248
Recirculation contribution (kW)	61	205	-	196	-	138
Recirculation contribution (%)	19	45	-	46.2	-	35.3
Dryer performance						
Drying capacity (t DM/day)	24.1	9.0	9.3	7.5	7.6	31.7

Drying capacity (t /day)	32.6	12.4	12.8	10.7	10.9	39.0
Mean evaporation rate (kg/h)	142.2	93.6	92.0	90.3	100.7	101.5
Drying energy (MJ/kg evaporated)	6.07	11.19	14.44	9.30	11.63	8.23
Consumption per hour (L/h)	21.25	21.86	26.78	19.47	24.50	21.02
Consumption per hour (MJ/h)	832.6	856.4	1049.0	762.9	959.7	823.4
Balanced evaporation efficiency (%)	42.7	24.7	21.7	28.0	26.2	30.7
DRYING COST						
$ propane / L	0.70	0.70	0.70	0.70	0.70	0.70
$ propane / batch	267.76	765.03	937.16	790.53	994.54	191.26
$ propane / t DM	14.82	40.89	48.42	43.50	54.23	11.15
$ propane / t at final MC	12.22	36.22	42.60	38.15	48.75	9.66
$ propane / kg water evaporated	0.23	0.62	0.81	0.50	0.62	0.29

Batches 4 and 5 (*) and 6 and 7 (**) were dried simultaneously and had similar initial characteristics.

For batch no.3 (bidirectional dryer), the planned treatment was a drying air temperature of 45°C, a 50% recirculation rate at all time and an airflow inversion after 12h of drying. After a first 12-hour cycle with warm air coming from the top, hay was sampled for mass and MC; the remaining drying time was estimated. In the second drying cycle, warm air was supplied from the bottom. A 30-min period of ambient air ventilation was done at the very end of the process. Hay dried from 26.2 to 19.8% MC within 17.5 h. Thus, 2560 kg of water were evaporated by using 383 liters of propane. This batch was interrupted before reaching the final MC criteria (mean MC at 12% with a maximum at 15%) partly because of a wrong initial and final MC estimation. However, balanced evaporation efficiency was good (42.7%) despite the low recirculation contribution (61 kW of the 299 kW available to the hay). With a propane cost of 0.70 $/l, drying cost (only for propane) was about 14.82 $/t DM or 12.22 $/t at the final MC estimated by the mass balance (17.6%).

For batches 4 and 5, initial MC was around 27% and hay dried to 11.5% after 50 h instead of the 36 h estimated initially. The bidirectional dryer (batch 4) and the unidirectional dryer (batch 5) both evaporated about 4600 kg even if the airflow through the bidirectional dryer was higher (9.9 vs 7.2 m^3/s). However, less propane was consumed by batch 4 (1093 vs 1339 l) for a higher efficiency (11.2 vs 14.4 MJ/kg of water evaporated). Such a higher efficiency was provided by the exhaust airflow recirculation adjusted at consecutive ratio: 15, 62 and 66 % for the 1st, 2nd and 3rd inversion cycle respectively (balanced average was 46 %). The higher air flow rate of the bidirectional dryer decreased the potential to enhance the thermal efficiency because more propane than necessary was consumed to heat air without any water evaporation improvement. The propane cost for the bidirectional dryer was lower than the unidirectional dryer (40.89 vs 48.42 $/t DM). The air flow inversion was not significant on the MC homogeneity improvement (standard deviation on the final MC of 4.7% and 3.1% for the bidirectional and unidirectional dryer respectively).

Batches 6 and 7 were initially about 30% MC with a sampled maximum at 37.7%. After a 58-h drying period at 46°C, mean final MC were similar for both batches: 11.2 and 10.7% for batch 6 (bidirectional dryer) and batch 7 (unidirectional dryer), respectively. The bidirectional dryer evaporated less water (5240 kg vs 5840 kg) and consumed less propane (1129 vs 1421 l) than the unidirectional dryer. A recirculation ratio of 53% improved the efficiency (9.3 MJ/kg vs 11.6 MJ/kg) and supplied half the energy used for drying. The balanced evaporation efficiencies were about the same for both batches (28 and 26%). However, the bidirectional dryer was more efficient when hay became drier (26.6 and 22.0% for 2nd and 3rd cycle, respectively) compared to the unidirectional dryer (24.3 and 13.7% for 2nd and 3rd cycle, respectively). This could be explained by the reuse of exhaust air with low moisture content. Propane costs were 43.50 and 54.23 $/t DM for batches 6 and 7, respectively. Compared to batches 4 and 5, the final MC was more uniform for the bidirectional dryer than the unidirectional (standard deviation of 3.3 vs 4.0%, respectively) but this slight difference was not significant and did not show that air flow inversion improved the final homogeneity.

The batch 8 was processed by the bidirectional dryer. The drying air temperature was 45°C and a recirculation ratio of 50 % was maintained for the complete duration of the process. Hay dried from 18.8 to 11.6% within a 12-h period with warm air and an extra hour with ambient air ventilation. A single airflow inversion was performed after 5 h. Thus, 1320 kg of water were removed from the hay by using 273 l of propane. The average air flow rate was 10.6 m^3/s. The drying cost was lowest for all batches measured: 11.15 $/t DM or 9.66 $/t of hay at 12% MC. The balanced evaporation efficiency of 30.7% was relatively good. Airflow recirculation contributed to 35% of the drying energy with a volumetric recirculation ratio of 55%. This batch showed the importance to harvest hay as dry as possible (with initial MC lower than 20%) to achieve low drying cost and high drying capacity. Indeed, this study showed that the drying time would be divided by four when hay was harvested at 19 % (13 h) instead of 27 % (50 h for batches 4 and 5). A low initial MC also resulted in a lower specific energy need (8 MJ/kg of water evaporated compared to 9 to 14 MJ/kg for wetter batches 4 to 7).

Conclusion

Six batches of large rectangular hay bales were monitored during complete drying cycles in two dryer in the summer of 2008. Each batch was composed of 72 big bales (mean dimension of 0.8 m x 0.9 m x 2.1m with an average mass of 348 kg) stacked 2 rows high (1.8 m height) within 4 cells of 18 bales each. Initial MC at baling ranged between 18.8 and 30.1%. MC varied between 10.7 and 19.8% after artificial drying. Drying time and propane cost were relatively low for a reduction of 6 to 7 units of MC: 18 h and 14.82 $/DM t to reduce MC from 26.2 to 19.8 % (batch 3) or 13 h and 11.15 $/DM t to reduce MC from 18.8 to 11.6% (batch 8). On the opposite, drying time and propane cost were higher when drying required the removal of nearly 20 units of MC: 58 h and 43.50 $/DM t to reduce MC from 30.0 to 11.2% (batch 6) or 58 h and 54.23 $/DM t to reduce MC from 30.1 to 10.7% (batch 7). The bidirectional dryer was slightly more efficient than the unidirectional dryer, mainly because of the exhaust air recirculation system. A drying air temperature of 45°C (batches 6 and 7) improved the overall thermal efficiency and provided a similar evaporation rate (90 to 100 kg of water per hour) to drying with air at 60°C (batches 6 and 7). Moisture content measurement comparisons between the standard method (oven at 103°C for 24 h) and a Delmhorst electronic probe showed large variations. The electronic probe requires regular calibration and should be used with caution to estimate an absolute value of MC for freshly harvested hay or dried bales. The core sampling method with standard oven-dried MC determinations provided good estimates of the initial and final mean MC when compared to a mass balance based on actual evaporated water from the hay batch.

Perspectives

The thermal efficiency of the industrial scale dryer was about 30%. This low efficiency limited the dryer capacity and consequently the harvest capacity when hay had to be artificially dried. Wrapping of hay bales at low moisture content (< 20 %) could be appropriate to store temporarily a high volume. Drying could be done after the harvesting period. Another perspective could be to decentralize industrial hay drying sites by using several farm-scale dryers that supply a distribution network.

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