Simulation of baled hay drying with airflow inversion and exhaust air recirculation

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Morissette, R. and Savoie, P. 2008. **Simulation of baled hay drying with airflow inversion and exhaust air recirculation**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **50**: 3.9–3.19. A multiple thin-layer approach was developed using LabVIEW software to simulate artificial drying of baled hay. The model assumed batch drying of a stack of bales with vertical airflow across the product; simulated controls included air temperature, airflow inversion, exhaust air recirculation and cool air tempering at the end of drying. A laboratory dryer was used to generate new data to estimate empirical equations of moisture transfer coefficient and equilibrium moisture content for grass hay. Total drying cost included variable costs (propane, electricity, labour), fixed costs of dryer, and a weight loss function due to overdrying below the target of 12% final moisture content on a wet basis (wb). For hay initially at a moisture content of 26% wb, the least-cost drying air temperature was 45°C in the range of 40 to 60°C. A single airflow inversion after 3 h improved final moisture homogeneity and reduced the drying cost by $10/t dry matter (DM) compared with no inversion. Partial exhaust airflow recirculation (typical ratio of 0.3) slightly improved the final moisture content homogeneity and energy efficiency but provided little cost reduction due to a longer drying time. A forced-air cooling period at the end of drying recuperated sensible heat in the bales, allowed the reduction of the heating period by about 15 min, and provided a slight economic gain ($1/t DM). Overall drying costs of hay from 26 to 12% dry basis (db) were decreased from $44 to $30/t DM by selecting improved values for control parameters. Such a predictive model could be integrated into a control system for commercial hay drying to enhance thermal efficiency and to reach the targeted final moisture content at reduced cost. By modifying the empirical equations of moisture transfer coefficient and equilibrium moisture content, other baled biomasses such as corn stover or cereal straw could also be modelled to identify improved drying scenarios. **Keywords:** Hay, biomass, bale, drying, simulation, moisture, thin layer.

Un modèle de prédiction basé sur la théorie des couches minces a été développé avec le logiciel LabVIEW afin de simuler le séchage du foin en balles. Le programme simule le séchage en lot avec un flux d'air vertical à travers le foin; les variables contrôlables incluent la température de l'air, l'inversion du flux d'air, la recirculation partielle de l'air sortant du séchoir et la ventilation à l'air ambiant en fin de séchage. Un séchoir de laboratoire a servi à générer de nouvelles données et à estimer des équations empiriques de transfert d'humidité et de teneur en eau à l'équilibre pour du foin de graminées. Le coût total de séchage incluait les charges variables (propane, électricité, main-d'œuvre), les charges fixes et les pertes de masse de foin lors du surséchage sous le seuil de 12% de teneur en eau sur une base humide (b.h.). Le foin initialement à 26% b.h. avait une température optimale de l'air de 45°C dans la plage 40 à 60°C. Une inversion du flux d'air après 3 h améliorait l'homogénéité de la teneur en eau finale et réduisait le coût de séchage de 10 $/t de matière sèche (MS) comparativement à aucune inversion. Une recirculation partielle de l'air (avec un ratio type de 0,3) améliorait légèrement l'homogénéité de la teneur en eau dans le foin et l'efficacité énergétique mais elle avait peu d'effet sur le coût total à cause d'un temps de séchage plus long. Une période de refroidissement à la fin récupérait la chaleur sensible et réduisait de 15 minutes la période de combustion du propane, avec une économie faible (1 $/t MS). Globalement, les coûts pour sécher le foin de 26 à 12% b.h. passaient de 44 à 30 $/t MS grâce à la sélection de paramètres de contrôle améliorés. Un tel modèle pourrait être intégré dans un système de contrôle d'un séchoir commercial pour améliorer l'efficacité thermique et atteindre les cibles de séchage au moindre coût. En modifiant les équations empiriques de transfert d'humidité et de teneur en eau à l'équilibre, le modèle pourrait aussi servir à réduire le coût de séchage d'autres biomasses en balles comme la fibre de maïs ou les pailles de céréales. **Mots-clés:** foin, biomasse, balle, séchage, simulation, teneur en eau, couche mince.

INTRODUCTION

The development of sustainable markets of hay and biomass (e.g. corn stover, cereal straw) generally requires high quality, high density and high volume. High-quality hay is already used for horse and cattle feeding, and corn stover and straw could potentially be used to produce energy by direct combustion or to provide fibre for products such as oriented strand board (OSB). Moisture content (MC) should be as low as 12% on a wet basis (wb) to avoid mould development in hay (Savoie and Joannis 2006) and as low as 10% wb to ensure high energy efficiency for biomass combustion (Mani et al. 2006). In practice, these low MC levels are difficult to reach with traditional field drying techniques for hay, straw or corn stover. Artificial drying of baled products is one way to control the final MC (Descôteaux and Savoie 2006).

Artificial drying of baled products is influenced by air temperature, air velocity, dryer configuration and hygroscopic properties of the biomass, among other factors. Arinze et al. (1994) reported that MC heterogeneity and over-drying were common problems in a batch drying process. Reduced heating, partial air recirculation and airflow inversion could improve the thermal efficiency of large bale drying (Descôteaux and Savoie 2003a). O'Callaghan et al. (1971) and Arinze et al. (1994) recommended that warm hay bales should be cooled with ambient air before leaving the dryer to rehydrate over-dried zones, dehydrate wetter zones, and reduce the occurrence of hay spoilage after drying. A simulation model could contribute to better understand these phenomena and to identify optimal drying scenarios.

The main objectives of this study were: (1) to develop a mathematical model for artificial drying of hay bales using controllable airflow conditions such as temperature, inversion, recirculation and cooling; (2) to validate the model with experimental data; and (3) to identify the best economic operating conditions from a set of simulation runs.

MATERIALS and METHODS

Model development

Four differential equations based on a model proposed by Sokhansanj and Wood (1991) were used to describe heat and moisture transfer between the crop and the flowing air. The four equations represent heat balance of air (1), heat balance of hay (2), moisture balance of air (3) and moisture balance of hay (4):

$$\frac{\partial T_a}{\partial x} = \frac{-h_c a(T_a - T_p) - (h_{fg} + c_v(T_a - T_p))\rho_a v_a \dfrac{\partial H}{\partial x}}{\rho_a v_a(c_a + c_v H)} \tag{1}$$

$$\frac{\partial T_p}{\partial t} = \frac{h_c a + c_w \rho_a v_a \dfrac{\partial H}{\partial x}}{\rho_p(c_p + c_w M)}(T_a - T_p) \tag{2}$$

$$\frac{\partial H}{\partial x} = -\frac{\rho_p}{\rho_a v_a}\frac{\partial M}{\partial t} \tag{3}$$

$$\frac{\partial M}{\partial t} = -k(M - M_e) \tag{4}$$

The thermal properties of air were obtained from Spencer (1969) in the case of convective heat transfer coefficient ($h_c a$) and from Opoku et al. (2004) in the case of specific heat of hay (c_p).

$$h_c a = 256800\left[\frac{\rho_a v_a(T_a - 273)}{P_{atm}}\right]^{0.6011} \tag{5}$$

$$c_p = 2666.243 + 10.288T_p + 3691\left(\frac{M}{1 + M}\right) - 7.836\rho_p \tag{6}$$

The differential equations were converted into finite difference equations and programmed with LabVIEW software (version 7.1, National Instruments, Austin, TX). The overall model considered several superimposed thin layers to simulate drying of thick hay bales, with typical numerical integration in 0.01 m thick increments and time steps of 10 s. The detailed model is described by Morissette (2006). Moisture content of hay was expressed on a dry matter (DM) basis (e.g. 20% wb is equivalent to 0.25 g of water/g DM or simply 0.25 g/g).

Experiments to estimate drying parameters

In Eq. (4), the moisture transfer coefficient (*k*) and the equilibrium moisture content (M_e) are crop specific and need to be estimated with experimental data. Since information on equilibrium moisture content of baled hay is rather limited (ASABE 2008), three laboratory experiments were carried out to generate new desorption (or drying) and adsorption (or rehumidification) data. Timothy grass was wilted to a moisture content ranging between 0.17 and 0.55 g/g (15 to 36% wb), and then placed in 10 superimposed trays of 50 mm thickness in the laboratory. Trays had a horizontal section of 286 mm × 286 mm; hay was compressed at an average density of 100 kg DM/m^3 (about 409 g DM per tray). A first experiment was unidirectional airflow at three initial air drying temperatures: 30, 45 and 60°C. The second experiment was based on bidirectional airflow with air initially at 60°C and inversion periods of 30, 60 and 120 min. The third experiment used high relative humidity air at three consecutive temperatures of 25, 30 and 35°C. Experiment 1 was replicated three times; experiments 2 and 3 were replicated twice. Each layer was weighed regularly (15 min intervals for the first hour, 30 min intervals for the next two hours, 1 h intervals thereafter). Drying stopped when evaporation of each individual layer was less than 2 g/h. Data for each layer were grouped for two or more drying intervals as long as air temperature and relative humidity were relatively constant (less than 3°C between maximum and minimum temperature; less than 0.10 in relative humidity range). One data set therefore included three or more pairs of moisture content and time for a single layer under constant temperature and relative humidity. Parameters *k* and M_e were estimated for each data set by solving simultaneously for best fit (Solver function in Excel analytical tools). For parameter M_e, three prediction equations (Henderson, Chung-Pfost, and Oswin equations as described in ASABE 2008) were then compared as a function of air temperature and relative humidity. For parameter *k*, six prediction models (linear, exponential, and logarithmic, with or without air temperature and humidity, and initial moisture content) were also compared.

In general, moisture transfers from the hay to the flowing air (desorption). However, in some circumstances, moisture transfer can be reversed, flowing from moist air to a relatively dry crop (adsorption). Because of hysteresis, equilibrium moisture content in desorption ($M_{e,des}$) is equal to or slightly higher than equilibrium moisture content in adsorption ($M_{e,ads}$).

Control decision criteria for simulation model

When simulating baled hay drying, four important control points were identified: (1) the time to terminate drying; (2) the time to switch the direction of airflow across the bale (i.e. time of inversion); (3) the fraction of exhaust air recirculated into the dryer; and (4) the time to turn off heat while maintaining airflow for final cooling of bales. Each of these actions was programmed according to specific decision criteria.

Time to terminate drying For all simulation tests, drying was terminated when two conditions were met: (1) the average MC of all layers was below the target average final MC (0.136 g/g or 12% wb) because this is a common standard in the commercial hay industry; and (2) the MC in any single layer was below the maximum acceptable MC (0.176 g/g or 15% wb), a generally accepted level under which very little mould growth will occur.

Time to invert air flow For unidirectional drying, air flowed continuously through the hay in the same direction until the end. When bidirectional drying was considered, airflow direction was changed according to a set of rules. The simplest rule was to invert airflow cyclically after a fixed period of time. Other inversion rules could analyze the spread of MC in various layers during drying and trigger inversion when MC in the driest layer was near the lowest desired MC level. Only the fixed-period inversion rule was considered in the present simulation runs.

Fraction of air recirculation Exhaust air from the dryer could be partially recirculated. A mass and energy balance determined the mixed air properties according to ASHRAE (1997). Mixing was assumed to occur just before the air was heated by the propane gas burner. In the present model, the fraction of exhaust air recirculated was adjusted according to two approaches: (1) by setting a constant recirculation fraction for the entire duration of drying; (2) by setting two different recirculation fractions: one before the first airflow inversion and another after the first inversion until the end of drying. The best level of recirculation was determined by simulation.

Time to cool bales with forced-air ventilation The time to stop heating and proceed with cooling was studied iteratively. First, drying was simulated with continuous air heating until the two final MC criteria were met (average below 0.136 g/g; every layer below 0.176 g/g). Then, for the following simulations, heating was stopped a short time (defined by the user) before the drying time found previously. Drying continued with ambient air only until the two MC criteria were met. The time for cooling bales and lowering MC to the required level was slightly longer than the time cut from the first simulation when heating was used continuously.

Drying cost estimation

The total drying cost was determined by estimating and adding three partial costs: (1) the capital cost of the dryer (depreciation, interests, insurance, etc.), which was an annual fixed cost; (2) the variable cost, which included energy (propane gas for the burner and electricity for the blower) and labour (time to load and unload the dryer, and general supervision of the process); and (3) a hay loss value (also called a market price penalty), which was 0 if the whole hay batch was dried perfectly homogeneously to the target (12% wb). The first two costs were estimated according to standard engineering cost methods (ASABE 2006). The actual price parameters are described below in the simulation scenarios and in Table 1.

The third cost represented a market penalty due to overdrying; it increased when the final MC across the hay layers was more heterogeneous. It was calculated as follows:

$$MP = p_p(M_{ref} - M_f) \tag{7}$$

Table 1. Values of variables used in simulation.

Dryer characteristics	
Floor dimensions:	8 drying cells of 2.13 m × 7.29 m
Total floor area:	124.2 m^2
Stack height:	0.89 m
Volumetric capacity:	110.5 m^3 per batch
Operation:	60 days per year, 24 h/day
Fan power:	2 fans of 33 kW each
Heating power:	2 propane burners of 293 kW each
Total dryer cost:	$300,000
Machine life:	20 years
Interest:	6% per year of average value
Tax and insurance:	1.75% per year of purchase price
Repair and maintenance:	1.25% per year of purchase price
Hay characteristics	
Hay density:	185 kg DM/m^3
Mass capacity:	20.45 t DM per batch
Initial MC:	0.25, 0.35 or 0.45 db (20, 26 or 31% wb)
Hay initial temperature:	15 or 25°C (depending on scenario)
Targeted mean final MC:	0.136 g/g (12% wb)
Targeted maximum MC:	0.176 g/g (15% wb)
Market price of hay:	$150/t wet matter (at 12% wb or 0.136 g/g)
Energy cost	
Propane (for air heater):	$19/GJ
Electricity (for fans):	$0.05/kWh
Labour	
Labour charge:	$15/h
Time to load dryer:	60 min
Time to unload dryer:	60 min
Employees:	1 full time employee and 1 part time to load and unload the dryer
Air conditions	
Outdoor air temperature:	15 or 25°C (depending on scenario properties)
Outdoor air relative humidity:	0.45 (decimal)
Air velocity:	0.25 m/s
Drying air temperature:	40 to 60°C

where MP is a market penalty or income loss ($/t DM) due to weight loss as a result of overdrying below the target or reference MC (M_{ref}) expressed on a dry basis and typically 0.136 g/g (12% wb). The final average MC (M_f, db) is always less than or equal to the target because this is a constraint in the drying process. The price of the product (p_p) is the market price for hay at the reference MC ($/t wet matter). Another useful comparison criterion was the specific energy consumption (SEC), i.e. the ratio of total energy from propane and electricity divided by the net amount of water evaporated.

Model validation

The model was tested by comparing simulation results with laboratory measurements from Morissette (2006) and previous experimental data from Descôteaux et al. (2002). The main variable for comparison was the moisture content over time for several layers (typically 50 mm thick under experimental conditions).

In total, 25 experimental runs were used for the validation. The drying air temperature varied from 24.7 to 60.0°C, air RH varied from 0.05 to 0.45 (dec.), air velocity varied from 0.12 to 0.37 m/s, initial MC varied from 0.15 to 0.47 g/g, hay density varied from 103 to 243 kg DM/m^3, and total drying time varied from 300 to 1020 min. Twenty-one runs were dried with unidirectional airflow and four runs were dried with bidirectional airflow with inversion periods of 30, 60 or 120 min.

Simulation scenarios

Simulated dryer characteristics The simulated hay dryer described in Table 1 had a floor area of 124 m^2 which is about 12 times greater than a pilot-scale dryer described by Descôteaux and Savoie (2006). The dryer could receive a stack of bales of rectangular form, either small (typically 0.35 m × 0.445 m × 0.80 m) or large (typically 0.80 m × 0.89 m × 2.10 m). The drying model assumed uniform vertical airflow across the hay stack; hay density was the main characteristic to affect heat and mass transfer rates besides airflow conditions. The propane was assumed to be used for direct air heating; the added humidity from combustion was not included in the mixed air as it represented less than a 6% change in absolute humidity at maximum power. The simulated dryer had several control options, such as adjustable air temperature, airflow inversion capability, variable exhaust air recirculation and bale cooling. Other operational and economic characteristics are described in Table 1.

Simulation procedure All characteristics were held constant except the control variables, which were changed according to a four-step procedure. In step 1, drying air temperature was varied from 40 to 60°C by 5°C increments with unidirectional airflow. This range of temperature was chosen for two reasons: (1) it corresponded to the range of variables in the empirical moisture transfer equations; (2) preliminary analysis at lower drying air temperatures indicated poor economic results because of relatively slow drying and high fixed costs per tonne. The temperature from step 1 that resulted in the least-cost scenario was chosen for the next step. In step 2, airflow inversion was added as a control variable, periodically 2, 3 or 4 h after the start of drying. In step 3, various air recirculation ratios were considered: a constant ratio between 0.3 and 0.9, in 0.2 increments; no recirculation before the first inversion and 0.3 to 0.9, in 0.2 increments, after inversion; 0.3 before the first inversion and 0.5 to 0.9 thereafter, in 0.2 increments. In step 4**,** the previous best scenario had its total drying time shortened by 10, 15, or 20 min and replaced with cool air ventilation without heat. This cool air ventilation was continued until the two drying criteria were met (average MC below 0.136 g/g; no layer wetter than 0.176 g/g).

Sets of simulation scenarios Three sets of simulation scenarios were analyzed. The first was a detailed step-by-step series of simulations with fixed hay and air conditions: initial MC of hay at 0.35 g/g, and ambient air at 25°C. The second set was also a step-by-step analysis that considered three levels of hay initial MC (0.25, 0.35 and 0.45 g/g). The third set looked into the effect of ambient air temperature (15 or 25°C) on the drying process.

RESULTS and DISCUSSION

Experimental drying results and estimation of M_e and k

Drying data from three experiments with timothy in the laboratory resulted in 157 sets of values in desorption and 26 sets of values in adsorption for M_e and k as a function of air temperature (T_a), air relative humidity (RH), and initial hay moisture content (M_i). Because of the limited number of adsorption data, equilibrium moisture content data in adsorption published by Bakker-Arkema et al. (1962) were also used to predict $M_{e,ads}$.

Parameters for equilibrium moisture content When a single equation to predict $M_{e,ads}$ was tested in the full range of temperature and humidity, poor R^2 values were estimated (0.484 for Henderson model, 0.424 for Chung-Pfost model and 0.520 for Oswin model). The prediction model for $M_{e,ads}$ was therefore segmented into four ranges of relative humidity. In the range $0.10 \leq \mathrm{RH} < 0.60$, $\mathrm{M_{e,ads}}$ was predicted to be:

$$\mathrm{M_{e,ads}} = 0.04618 + 0.08240\mathrm{RH} + 0.1342\mathrm{RH}^2 - 30.56 \times 10^{-6}\ \mathrm{T_a} - 0.9051 \times 10^{-3}\mathrm{RH\ T_a} \tag{8}$$

In the range $0.60 \leq \mathrm{RH} \leq 0.90$, $M_{e,ads}$ was predicted to be:

$$\mathrm{M_{e,ads}} = 0.3358 - 1.003\mathrm{RH} + 1.139\mathrm{RH}^2 + 3.327 \times 10^{-3}\ \mathrm{T_a} - 6.502 \times 10^{-3}\ \mathrm{RH\ T_a} \tag{9}$$

For $\mathrm{RH} < 0.10$, $M_{e,ads}$ was interpolated between 0 and the value at $\mathrm{RH} = 0.10$. For $\mathrm{RH} > 0.90$, values were extrapolated between the value at $\mathrm{RH} = 0.9$ and a maximum increment of 0.67 g/g based on data of Bakker-Arkema et al. (1962) at very high RH.

The equilibrium moisture content in desorption was estimated by empirical Eq. 10 obtained by regression with the 157 sets of values for grass hay. The overall coefficient of determination (R^2) was 0.827.

$$M_{e,des} = M_{e,ads} + 0.01172\,\exp(4.638RH^{2.532}) \times \left(\frac{15.6}{T_a}\right)^{1.431RH} \tag{10}$$

Data used to estimate parameters in Eq. 10 ranged between 22 and 62°C for air temperature, and between 0.05 and 0.85 for air relative humidity. Fig. 1 illustrates the relationship between predicted and empirical values of $M_{e,des}$.

Parameters for moisture transfer coefficient The new experimental data for timothy hay were used to estimate two models of the moisture transfer coefficient (k), one in desorption, the other in adsorption. After comparing six prediction models including exponential, logarithmic and linear terms with air temperature, air humidity and initial moisture content, Eq. 11 was selected to predict the desorption coefficient (k_{des}, s^{-1}):

$$k_{des} = 83.33 \times 10^{-6} + (69.96 \times 10^{-6} M_i + 5.720 \times 10^{-6}) \times (T_a - 25) \tag{11}$$

Equation 11 had an R^2 of 0.62. It was valid in the air temperature range between 25 and 62°C. For lower air temperatures, k_{des} was interpolated between the value estimated at 25°C and 0 at 0°C. Fig. 2 shows the relationship between predicted and experimental drying rate coefficients.

Five other models were compared to predict the adsorption coefficient (k_{ads}, s^{-1}). Equation 12 was selected to predict moisture adsorption in the range of RH between 0.6 and 1.0:

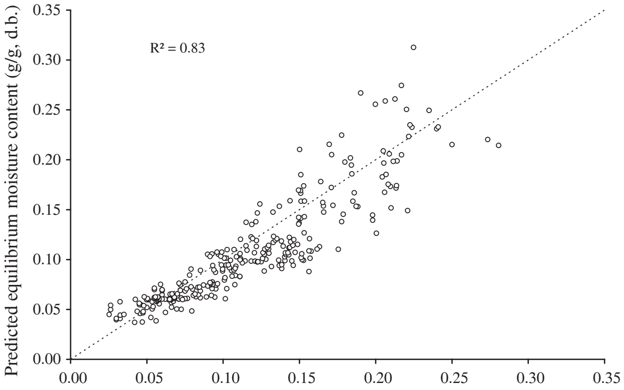

Fig. 1. Predicted equilibrium moisture content in desorption ($M_{e,des}$; Eq. 10) versus experimental data ($n = 157$ data sets).

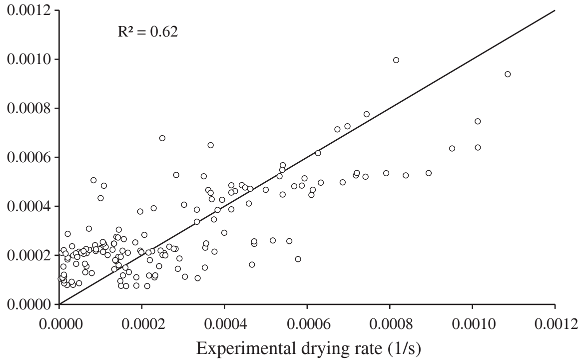

Fig. 2. Predicted drying rate (k_{des}; Eq. 11) versus experimental data ($n = 157$ data sets).

$$k_{ads} = 41.67 \times 10^{-6} + (3.992 \times 10^{-3} \exp(-6.286\,M_i)) \times (RH - 0.60) \tag{12}$$

Equation 12 had an R^2 of 0.46. For RH values below 0.60, k_{ads} was interpolated between a value of 0 at 0.00 RH and the value estimated at 0.60 RH. To determine whether moisture transfer was in desorption or adsorption, the two equilibrium MC were estimated from Eqs. 8, 9, or 10. If the hay layer moisture content was below $M_{e,ads}$, then adsorption would occur at rate k_{ads}. If the hay layer moisture content was above $M_{e,des}$, then desoprtion would occur at rate k_{des}. If the hay layer moisture content was between $M_{e,ads}$ and $M_{e,des}$, then no moisture exchange between air and hay was assumed.

Validation

The model predicted MC with reasonable accuracy over time (average $R^2 = 0.96$, lowest $R^2 = 0.81$) for 25 validation tests of 10 layers each. Fig. 3 illustrates an example of experimental MC versus simulated MC over time. The difference between experimental and simulated final MC ranged from −0.027 and 0.066 g/g with an average of 0.008 g/g. At air temperatures below 28°C, the model slightly underestimated the equilibrium MC.

The time to reach the target MC of 0.136 g/g ranged from 2 to 802 min (average 170 min) experimentally and from 4 to 678 min (average 167 min) by simulation. The relative difference with regard to time averaged −20%. Fig. 4 shows an example of simulated moisture content over time for different positions in the haystack when incoming air was heated at 60°C with ambient air at 25°C and 0.45 RH, airflow at 0.20 m/s across the stack, initial hay temperature at 25°C and a stack density of 185 kg DM/m^3. In this example, the time to reach the target MC ranged from 20 to 240 min depending on position in the stack.

The model underestimated adsorption rate after inversion. This was due to an underestimation of $M_{e,ads}$. The model could be improved by further calibration of empirical equations. At this stage, the model was considered to be satisfactory for simulation.

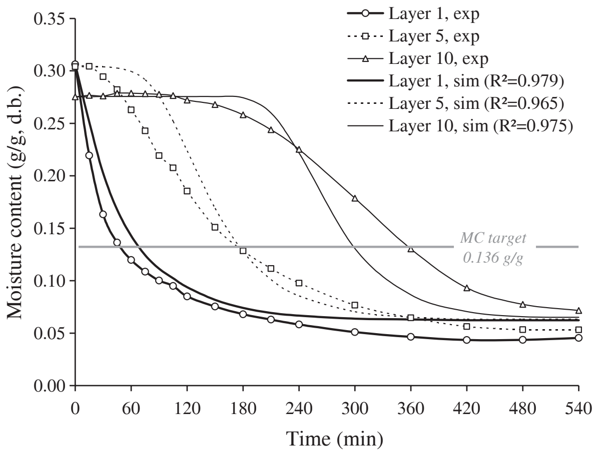

Fig. 3. Example of validation for unidirectional drying of ten 50-mm-thick layers of hay with heated air at 44.7°C. Layer 1 was closest to incoming heated air; layer 10, farthest.

Simulation with constant hay initial conditions

Step 1 (varying air temperatures) The step-by-step simulation procedure was carried out with the basic initial conditions: hay with MC of 0.35 g/g and temperature of 25°C; ambient air temperature at 25°C with a RH of 0.45. Table 2 shows results for each of the four steps where the four control variables (temperature, inversion, recirculation, and cooling time) were varied successively.

In step 1, five scenarios simulated drying at air temperatures between 40 and 60°C for unidirectional airflow only, without recirculation or cooling. The first scenario of step 1 (air temperature of 40°C) resulted in a final average MC of 0.088 g/g with a standard deviation (SD) of 0.027 g/g. This batch required 448 min total time in the dryer. The specific energy consumption (SEC) was 3121 kJ/kg of water evaporated, which is relatively efficient because the minimum energy for evaporation (enthalpy) is about 2400 kJ/kg (77% efficiency). However, the relatively long drying time implied a low dryer capacity (estimated at 152 batches per year based on 60 available work days and a total cycle of drying time plus 120 min per batch to load and unload). The fixed costs were constant on an annual basis: 11% (5% for depreciation on purchase price, 6% for interest on average value over 20 yr, which is equivalent to 3% of purchase price per year, and 3% for other fixed costs) of $300,000 i.e. $33,000 per year. They were not constant on a unit mass basis because the annual capacity of the dryer varied depending on scenarios. A slow drying scenario resulted in higher fixed costs per unit mass than a fast drying scenario. For scenario 1, the other costs (variable and market penalty due to weight loss) were relatively low because of a high thermal efficiency and a final MC about 0.05 g/g below the target of 0.136 g/g. The total cost for drying and weight loss was estimated at $41.31/t DM.

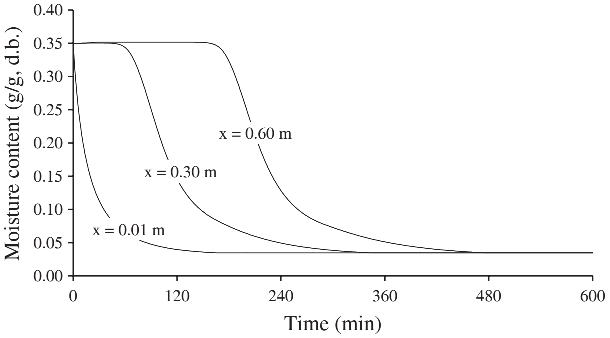

Fig. 4. Simulated moisture content in a hay stack as a function of time and distance from incoming heated air at 60°C.

The high-temperature scenario 5 (60°C) resulted in more over-drying (0.07 g/g below target) than the low-temperature scenario 1 (40°C). It also had the highest total cost ($44.17/t DM) because of a high SEC. Meanwhile, a 45°C air temperature (scenario 2) showed the lowest total drying cost ($41.24/t DM). The SEC was improved considerably (3325 kJ/kg vs. 3719 kJ/kg for scenario 5) and the variable cost (mainly energy) was reduced by more than $2/t DM. However, scenario 2 did not prevent over-drying (final mean MC: 0.083 g/g). Least-cost scenario 2 of step 1 (45°C heated air) was retained for step 2. Scenarios 1 and 3 (air temperatures of 40°C and 50°C) were almost as good as scenario 2; the total cost difference was less than $0.14/t DM.

Step 2 (varying airflow inversion periods) In step 2, three levels of airflow inversion (after 2, 3 or 4 h) were compared. Over-drying was significantly reduced (final average MC of 0.125 g/g, only 0.011 g/g below target) with airflow inversion after 3 h. Compared to the best unidirectional drying (scenario 2 of step 1), the best bidirectional drying (scenario 2 of step 2) reduced drying and weight loss cost by $10 to a total $31.23/t DM. The drying cost reduction is explained primarily by the lower market price penalty (63% of total reduced cost), the lower energy cost (28% of reduction) and the shorter drying time (fixed costs contributing to 9% of reduction). A shorter airflow inversion period (2 h with scenario 1) did not decrease the total cost as much as a 3-h airflow inversion period. A longer 4-h inversion period (scenario 3) was too late to prevent over-drying (final MC of 0.116 g/g) and moisture heterogeneity (MC standard deviation of 0.035 g/g). The simulated results agree with experimental observations by Descôteaux and Savoie (2003b) concerning the need to find an optimal time to apply inversion. Scenario 2 from step 2 (inversion after 3 h) was retained for the next step of simulation.

Step 3 (varying exhaust air recirculation ratios) In step 3, scenario 5 (no recirculation for first 3 h until inversion and 0.3 recirculation afterwards) resulted in the least cost ($31.10/t DM). This was only $0.13/t DM less than the drying cost without any air recirculation (best scenario of step 2). Recirculation barely improved final MC (0.009 g/g below target compared with 0.011 g/g without recirculation). Scenario 4 with 0.9 exhaust air recirculation resulted

Table 2. Simulation results with four-step cost reduction for a batch of hay at 0.35 g/g initial MC with ambient air temperature of 25°C and RH of 0.45.

Scenario	Moisture content final	Moisture content S.D.	Moisture content max	Drying time	SEC*	Batches per	Variable cost	Market price penalty	Fixed cost	Total cost
	(g/g, dry basis)			(min)	(kJ/kg)	year	$/t DM			
Step 1 (varying air temperatures, T_a)										
1 (40°C)	0.088	0.027	0.176	448	3121	152	23.50	7.20	10.61	41.31
2 (45°C)	0.083	0.028	0.176	376	3325	174	24.04	7.95	9.25	41.24
3 (50°C)	0.079	0.028	0.176	325	3487	194	24.53	8.55	8.30	41.38
4 (55°C)	0.074	0.030	0.176	289	3618	211	25.16	9.30	7.64	42.10
5 (60°C)	0.064	0.035	0.176	267	3719	224	26.15	10.80	7.22	44.17
Step 2 ($T_a = 45$°C; varying airflow inversion periods)										
1 (2 h)	0.118	0.035	0.176	351	3582	183	22.66	2.70	8.80	34.16
2 (3 h)	0.125	0.033	0.176	326	3423	194	21.25	1.65	8.33	31.23
3 (4 h)	0.116	0.035	0.176	327	3312	193	21.30	3.00	8.34	32.64
Step 3 ($T_a = 45$°C, inversion period = 3 h; varying exhaust air recirculation ratios before/after first inversion)										
1 (0.3/0.3)	0.128	0.034	0.176	355	3561	182	21.97	1.20	8.87	32.04
2 (0.5/0.5)	0.121	0.030	0.176	417	3693	161	23.71	2.25	10.02	35.98
3 (0.7/0.7)	0.125	0.031	0.176	494	3798	141	24.73	1.65	11.47	37.85
4 (0.9/0.9)	0.136	0.020	0.176	793	4045	95	28.28	0.00	17.04	45.32
5 (0.0/0.3)	0.127	0.033	0.176	337	3417	189	21.21	1.35	8.54	31.10
6 (0.0/0.5)	0.128	0.033	0.176	352	3432	183	21.33	1.20	8.81	31.34
7 (0.0/0.7)	0.127	0.030	0.176	396	3437	168	21.93	1.35	9.63	32.91
8 (0.0/0.9)	0.133	0.023	0.176	484	3484	143	22.70	0.45	11.29	34.44
9 (0.3/0.5)	0.125	0.033	0.176	386	3584	171	22.57	1.65	9.45	33.67
10(0.3/0.7)	0.124	0.028	0.176	433	3607	156	23.29	1.80	10.32	35.41
11(0.3/0.9)	0.136	0.025	0.176	526	3659	134	23.73	0.00	12.07	35.80
Step 4 ($T_a = 45$°C, inversion time = 3 h, air recirculation ratio of 0.3 after 3 h; varying cooling times)										
1 (10 min)	0.128	0.033	0.176	337	3343	189	20.83	1.20	8.54	30.57
2 (15 min)	0.129	0.032	0.176	339	3314	188	20.66	1.05	8.57	30.28
3 (20 min)	0.130	0.031	0.176	350	3291	184	20.65	0.90	8.78	30.33

*The specific energy consumption (SEC) is the propane and electrical energy used to extract 1 kg of water from hay.

in a mean final MC exactly on target (0.136 g/g) and a very homogenous hay MC (SD of 0.02 g/g). However, this scenario meant high air RH, very slow drying (793 min per batch), low dryer capacity (95 batches per year) and high fixed costs per unit mass. Drying cost was actually the highest ($45.32/t DM) at 0.9 air recirculation and unsatisfactory.

Step 4 (varying cooling periods) In step 4, cooling periods were considered to start 10, 15 or 20 min before the normal ending time estimated in the best previous scenario (Step 3, scenario 5: 337 min drying time). Such a cooling period was intended to recuperate the sensible heat in the bales to remove the last units of moisture to reach the target. The 15-min period without heating (scenario 2) provided the overall least-cost drying ($30.28/t DM) and saved an extra $0.82/t DM compared with the best scenario without cooling in step 3. The final MC (0.129 g/g) was closer to the mean final MC criterion and the uniformity was slightly improved (SD of 0.031 g/g). Scenarios 1 and 3 (10 and 20 min of heating time reduction followed by cooling) did almost as well as 15 min. Total cost was decreased by $0.53 and $0.77/t DM, respectively, compared with no cooling.

The overall least cost scenario was based, therefore, on drying at an air temperature of 45°C, with a single airflow inversion after 3 h, two successive exhaust air recirculation ratios (0 initially and 0.3 after inversion) and a cooling period starting 15 min before the estimated total drying time with heating only (i.e., 337-15 = 322 min to start cooling, which actually lasted 17 min to reach the MC targets). This least-cost scenario was obtained for a haystack of 0.89 m height and 0.35 g/g initial MC with air velocity of 0.25 m/s, ambient air temperature of 25°C and RH of 0.45. Fig. 5 shows the MC distribution within the hay stack at different drying times for this scenario.

Simulation results at different initial moisture contents

The same step-by-step simulation procedure was performed with two other initial MC: 0.25 g/g (or 20% wb) and 0.45 g/g (or 31% wb). With hay MC initially at 0.25 g/g, the least-cost scenario included a drying air temperature of 40°C, a 2-h airflow inversion period and a 15-min heating time reduction at the end of drying; total drying time was 222 min. Recirculation was not economical. With an initial MC of 0.35 g/g, the optimized conditions were a drying air temperature of 45°C, an airflow inversion period of 3 h, recirculation ratios of 0 and 0.3, and a 15-min heating time reduction; total drying time was 339 min. With an initial MC of 0.45 g/g, the optimized conditions were a drying air temperature of 50°C with an airflow inversion period of 4 h, successive recirculation ratios of 0 and 0.7, and a 20-min heating time reduction; total drying time was 445 min, twice the time for drier hay at initial MC of 0.25 g/g (222 min).

From these results, the best drying air temperature, recirculation ratio, and inversion period are seen to increase with initial MC. A single inversion was sufficient to reach the MC criteria for all initial MC in the range of 0.25 to 0.45 g/g. Multiple inversions would be necessary only if a high proportion of exhaust air was recirculated, but this was not economical mainly because a high recirculation ratio slowed drying and increased the capital cost per unit tonne of hay. Fig. 6 shows the drying costs for the three initial MC. Totals drying costs were about $19, $30 and $40/t DM for hay at initial MC of 0.25, 0.35 and 0.45 g/g, respectively.

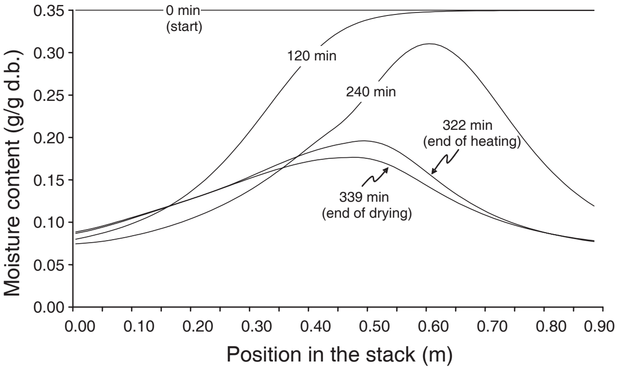

Fig. 5. MC distribution as a function of vertical position in the hay stack and time for least-cost drying scenario with airflow inversion at 180 min.

Effect of different ambient air temperatures

The effect of a lower ambient air temperature (15°C) was simulated and compared with results previously found for an ambient air temperature of 25°C. Ambient air RH was considered constant at 0.45. Lower ambient temperature was representative of a cool summer night.

With ambient air temperature at 15°C, the least-cost scenario retained was a drying air temperature of 40°C, an airflow inversion period of 3 h, a recirculation ratio of 0.5 after the first inversion, and a heating time reduction of 15 min at the end of drying. The final MC was 0.134 g/g (SD of 0.029 g/g). Thus, over-drying was nearly eliminated as a result of a cooler ambient air temperature (15 vs. 25°C).

The SEC was nearly 30% higher at a low ambient air temperature of 15° compared with a warmer, 25°C, ambient temperature (Fig. 7). The step-by-step optimization with ambient air at 15°C reduced the SEC by 8.1%, from 4525 kJ/kg of water evaporated (step 1) to 4185 kJ/kg (step 4). This reduction was more significant than the one observed with an ambient air temperature of 25°C. The economic criterion used for reducing cost was more important than the energy efficiency criterion when inversion was introduced (step 2) at 25°C ambient temperature.

The simulated drying cost was higher with ambient air at 15°C compared with 25°C ($33.40 vs $30.28/t DM). This increase was mostly due to higher variable costs ($24.15 vs. $20.66/t DM). When outdoor air conditions were cool, more energy was required to dry hay but a side benefit was reduced over-drying.

The model is useful to understand baled hay drying under a wide range of controlled factors (air temperature, inversion, recirculation, cooling) and uncontrolled factors (ambient temperature and initial hay moisture content,

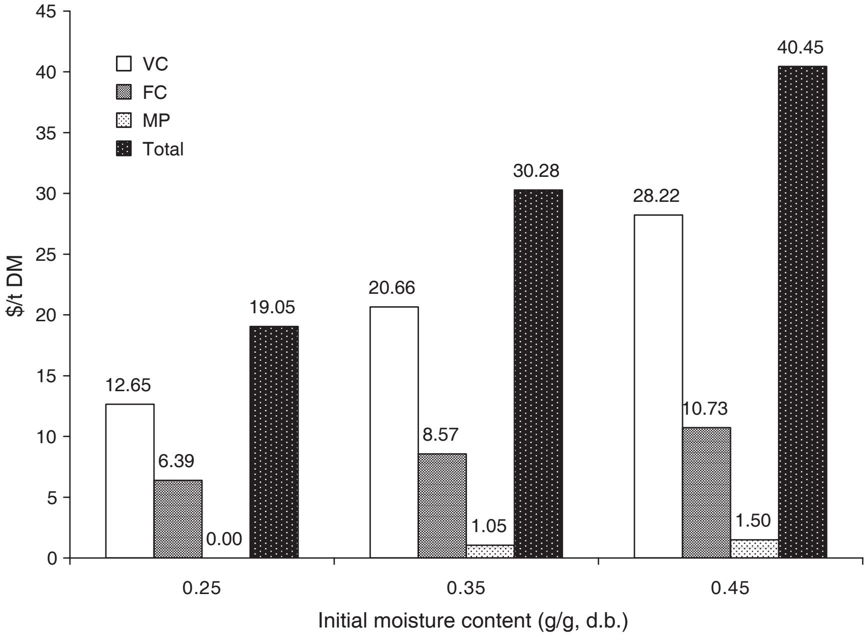

Fig. 6. Variable costs (VC), fixed costs (FC), market penalty (MP) due to over-drying, and total costs of drying scenarios at hay initial moisture contents of 0.25, 0.35 and 0.45 g/g on a dry basis.

notably). It has the potential to predict drying behaviour very precisely and to interface with a control system to optimize drying in real time. The model offers other possibilities to simulate artificial drying of biomasses such as corn stover or straw when market conditions become favourable for their use in high volumes.

CONCLUSION

A computerized program was developed to predict hay batch drying based on thin-layer theory. New empirical equations to predict equilibrium moisture content and moisture transfer rate, for both desorption and adsorption, were developed because of limited information in the current literature on baled hay drying.

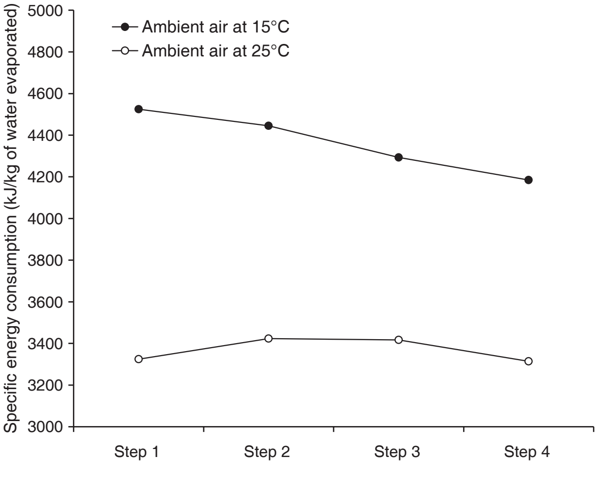

Fig. 7. Specific energy consumption (SEC) at each simulation step for drying with ambient air temperature of 15°C or 25°C.

The model predicted moisture content with reasonable accuracy over time (average $R^2 = 0.96$) for 25 validation tests, which consisted of ten 50-mm-thick layers drying for periods between 300 and 1020 min each. The time to reach the target moisture content of 0.136 g/g (12% wb) ranged from 2 to 802 min (average 170 min) experimentally, and from 4 to 678 min (average 167 min) by simulation. The model overestimated time to reach the target moisture content, especially for rapid drying. The model underestimated the equilibrium moisture content in adsorption, a phenomenon that can occur when humid air comes into contact with relatively dry hay.

With the current simulation model, control parameters were varied to estimate the least-cost scenario according to an economic function that included fixed dryer cost, variable drying cost (propane gas, electricity, labour) and a weight loss function when hay was overdried below the target moisture content. With hay bales initially at 0.35 g/g moisture content and stacked at 0.89 m vertical height, the least-cost drying conditions were heated air at 45°C, one airflow inversion after 3 h, no air recirculation prior to inversion and a ratio of 0.3 thereafter, and a final cooling period of 17 min (between 322 and 339 min from start) to reach a double target of average moisture below 0.136 g/g and all layers below 0.176 g/g. Total drying cost was \$30.28/t DM compared with as high as \$44.17/t DM for a less optimal combination.

When hay was at a lower initial MC (0.25 g/g), the least-cost drying air temperature was lower (40°C) than with initially wetter hay; less time was required to dry (222 min) and the drying cost was lower (\$19.05/t DM). When hay was at a higher initial MC (0.45 g/g), the least-cost drying air temperature was higher (50°C) than with initially drier hay, more time was required to dry (445 min) and drying cost was higher (\$40.45/t DM).

Generally, drying air temperature and airflow inversion contributed most to cost reduction while air recirculation and forced-air cooling had a smaller effect. The predictive algorithm could be integrated in a commercial hay batch dryer and interact with different control parameters. Empirical equations could be changed to model the drying of other types of bales such as corn stover or cereal straw. The predictive model should be further validated and calibrated with new drying data to increase its reliability. This approach could contribute to the production of high quality dried biomass and enhance thermal efficiency at the least cost possible.

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LIST of SYMBOLS

c	specific heat (J/kg•°C)
DM	dry matter
H	air moisture ratio ($kg_{water}/kg_{dry\text{-}air}$)
h_ca	volumetric convective heat transfer coefficient (J/m^3•°C•s)
h_{fg}	water enthalpy (fluid to gas) (J/kg)
k	moisture transfer rate coefficient (s^{-1})
M	moisture content on a dry basis (g of water/g of dry matter)
MP	market penalty ($/t DM)
p	product price ($/t as is, wet matter)
P	pressure (Pa)
RH	relative humidity (decimal)
SEC	specific Energy Consumption (kJ/kg_{water})
T	temperature (°C)
t	time (s)
v	air velocity (m/s)
x	hay layer thickness (m)
δ	local derivative
ρ	density (kg/m^3)
Subscripts	
a	air
ads	adsorption
atm	atmospheric
des	desorption
e	equilibrium
f	final
i	initial
p	product (hay)
ref	reference
v	water vapour
w	water