Heat penetration into small rectangular alfalfa/bromegrass bales for insect disinfestation

A. Opoku[1], S. Sokhansanj[1], W.J. Crerar[1], G.J. Schoenau[2] and H.C. Wood[3]

Departments of [1]Agricultural and Bioresource Engineering, [2]Mechanical Engineering, and [3]Electrical Engineering, University of Saskatchewan, 57 Campus Dr., Saskatoon, Saskatchewan, Canada S7N 5A9.

Opoku, A., Sokhansanj, S., Crerar, W.J., Schoenau, G.J. and Wood, H.C. 2001. **Heat penetration into small rectangular alfalfa/ bromegrass bales for insect disinfestation**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **43**: 3.31-3.38. The Hessian fly insect (*Mayetiola destructor* (Say)) uses young cereal plants that volunteer in hay crops as its host to lay its eggs. To prevent the spread of Hessian fly to other cereal growing regions, quarantine regulations require that compressed hay bales sold commercially be either inspected for host plants or disinfested. One means of disinfestation is thermal treatment to 60°C for a minimum of 3 min. A thermal treatment unit was constructed for baled hay heat penetration studies. Heat penetration tests were conducted on small rectangular bales of hay (mixture of alfalfa and bromegrass) of varying density from 95.5 to 235.0 kg/m^3 and moisture content from 7.3 to 17.7%. The treatment temperature ranged from 64.0 to 90.0°C, relative humidity ranged from 6 to 75%, and airflow ranged from 0.12 to 0.38 m/s. The bales were oriented on the cut-edge during the heat treatments. To reduce the heating time and achieve uniform bale heating, drying of the bale should be prevented. Increasing air relative humidity, velocity and temperature reduced the heating time to reach the efficacy temperature of 60°C. The fastest heating time was 5.0 minutes and it was achieved at air temperature, relative humidity and velocity of 76°C, 50%, and 0.33 m/s, respectively. **Keywords**: Hessian fly, alfalfa, forage, grass, bale, disinfestation, thermal treatment, heat penetration, quarantine.

Les repousses de céréales dans les champs de foin servent de plante hôte à la mouche de Hesse (*Mayetiola destructor* Say)) qui y pond ses oeufs. Pour empêcher que la mouche de Hesse ne se répande à d'autres régions où l'on cultive des céréales, la réglementation phytosanitaire impose que les bottes de foin qui sont vendues soient inspectées pour y détecter la présence de plantes hôtes ou désinfectées. Le traitement thermique des bottes à 60°C durant au moins 3 minutes est une des méthodes de désinfection préconisées. On a construit une unité de traitement thermique pour étudier la pénétration de la chaleur dans les bottes de foin. Les tests de pénétration de chaleur ont été faits sur de petites bottes de foin rectangulaires (mélange de luzerne et de Brome) dont la densité variaient de 95.5 à 235 kg/m^3, et la teneur en eau de 7.3 à 17.7 %. Les températures de traitement s'échelonnaient de 64 à 90°C, l'humidité relative de 6 à 75 %, et le débit d'air de 0.2 à 0.38 m/s. Durant le traitement, les bottes étaient placées du côté tranché. Afin de réduire le temps de chauffage, et obtenir une répartition uniforme de la chaleur, il faudrait empêcher que les bottes ne sèchent durant le traitement. Le temps pour atteindre la température efficace de 60°C a été réduit en augmentant l'humidité relative, le débit d'air et la température de traitement. Le temps de chauffage le plus court était de 5 minutes et fut atteint lorsque la température de traitement était de 76°C, l'humidité relative de 50 % et le débit d'air de 0.33 m/s. **Mots clés**: mouche de Hesse, luzerne, fourrage, herbage, désinfection, traitement thermique, pénétration de la chaleur, quarantaine.

INTRODUCTION

Hessian fly (*Mayetiola destructor* (Say)) uses young volunteer cereal plants as its host to lay eggs. The insect survives and thrives in the puparium stage in the lower parts of the plant. The infested plants growing in forage fields as weeds may be introduced into hay at the time of cutting and baling, and be distributed to other cereal growing regions.

To protect against the spread of the Hessian fly, some hay importing countries, such as Japan, require that hay be either inspected for host plants or disinfested. Methods such as heat treatment, fumigation, hay compression, and a combination of fumigation and hay compression have been explored by researchers to destroy the insect in hay bales. Yokoyama et al. (1993a, 1993b, 1996) investigated the use of fumigation, hay compression, and a combination of fumigation and hay compression. They indicated that a combination of fumigation using 2.12 g/m^3 aluminium phosphide for 7 days at 22°C followed by hay compression using a pressure $\geq$8 MPa was more effective in controlling the insect than fumigation or hay compression alone.

The use of heat treatment to control fruit-flies and micro-organisms has also been investigated by Gaffney and Armstrong (1990), Gaffney et al. (1990), Sharp et al. (1991), Shellie et al. (1993), Mangan and Ingle (1994), and Neven et al. (1996).

Sokhansanj (1994) and Sokhansanj et al. (1990, 1992, 1993) studied the use of heat treatment to disinfest hay of Hessian fly insects. From time-temperature mortality tests, they indicated that a temperature of 60°C or above for 3 min was sufficient to kill all stages of the insect. Experimental and simulation studies conducted on thermal treatment and disinfestation of Hessian fly insects mixed with chopped hay in a laboratory rotary drum unit showed that humid air between 80 and 90% relative humidity and 60°C temperature, with an exposure time of 3 min resulted in a total kill of the pupae stage of the insect.

Sokhansanj et al. (1997) investigated methods of heat treatment of baled hay for destruction of Hessian flies. They found that heat penetration into the baled hay was often incomplete, mainly due to variation in bale density. Field tests using a commercial baled hay dryer (Sokhansanj 1998) were not successful in complete killing of the flies. It was speculated that uneven heat distribution in bales during heat treatment might have been responsible for the failure to kill the insects.

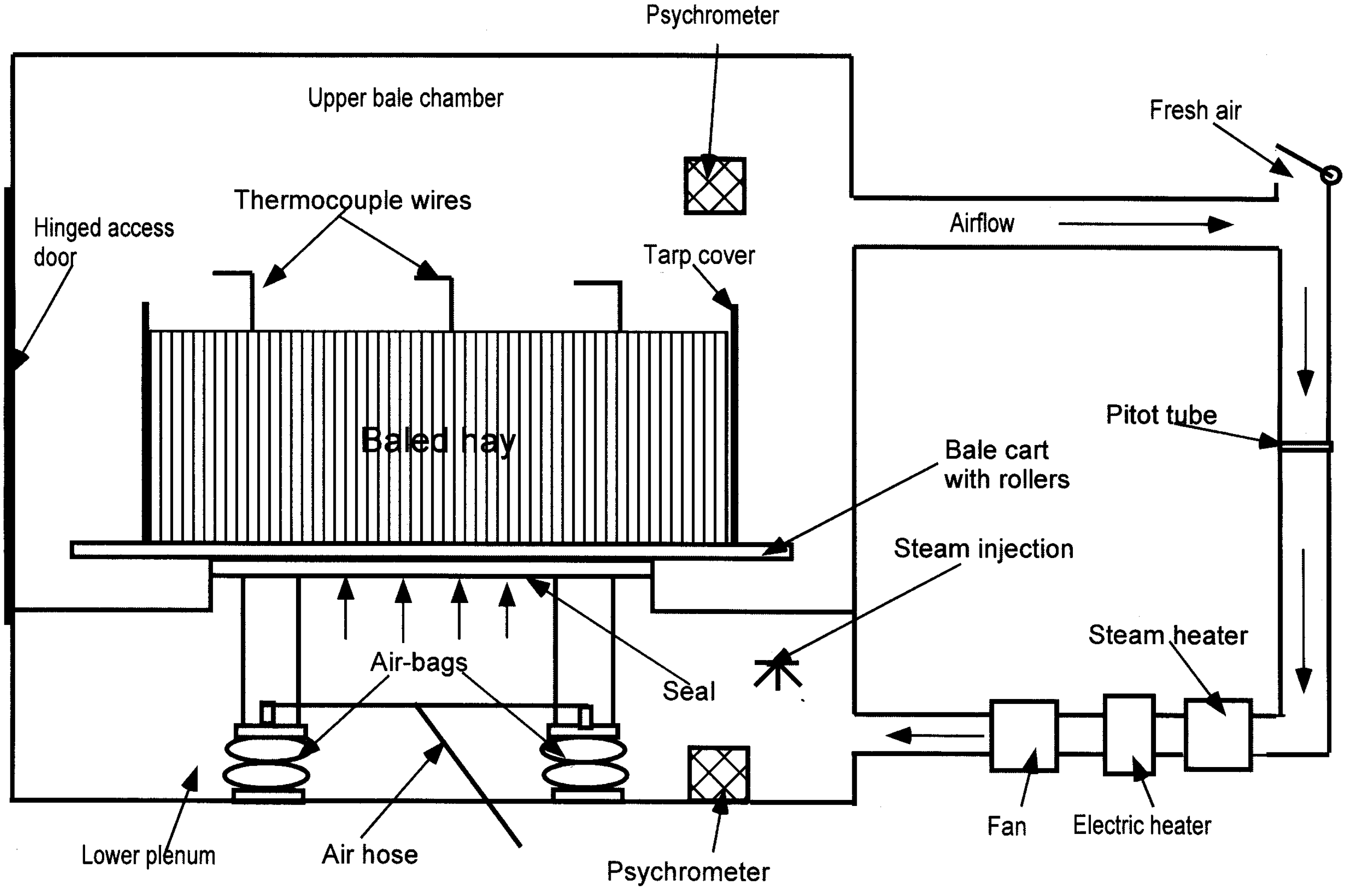


Fig. 1. Schematic diagram of the thermal treatment unit when the bale is in the chamber and the sealing unit is pushed against the bottom of the bale cart

OBJECTIVES

The objective of this research was to determine experimentally the optimum conditions for an effective heat penetration into hay bales. Specifically:

1. to conduct heat penetration tests on baled hay of varying bulk density and moisture content, and
2. to determine the air temperature, relative humidity, and airflow that would minimize the time required for uniform heating of baled hay. The results should help in the design of commercial heat treatment equipment.

MATERIALS and METHODS

An experimental thermal treatment apparatus for small rectangular baled hay (350 x 460 mm) heat penetration studies was constructed. Figure 1 shows a schematic diagram of the equipment that consisted of a sealed chamber, a centrifugal fan, steam heat exchanger, electrical heaters, steam injection, instrumentation, and data acquisition system.

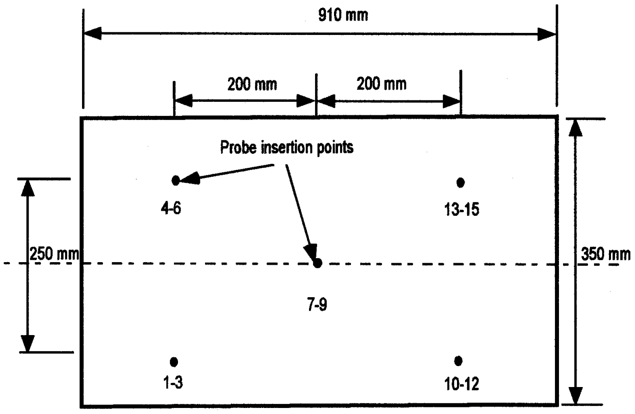
The treatment chamber, 1.78 m long, 0.83 m wide, and 1.8 m high, was constructed from 12.7 mm thick plywood reinforced by a steel frame. The chamber was insulated with 25.4 mm thick styrofoam sheets. The seams were sealed with silicone sealant. The chamber was divided into a lower plenum and an upper bale chamber. The dividing platform had a 1.02 x 0.51 m opening in the centre. A rolling cart consisting of a 1.21 x 0.82 m plywood board with 0.66 x 0.25 m opening at the centre was used to transfer the instrumented test bale into the bale chamber. Four casters were fitted under the cart to roll the loaded cart in and out of the chamber. A ratchet and locking tie-down straps were used to tie a tarpaulin around the sides of the test bale to reduce air leakage around the bale.

A variable-speed centrifugal fan capable of delivering air at a maximum volume airflow of 0.41 m^3/s and at a static pressure of 4.49 kPa was used to circulate air through the bale and the chamber. The air was heated by a steam-to-air heat exchanger. Additional heat was provided by an electrical heater. Steam was added to the air to increase the humidity of the incoming heated air.

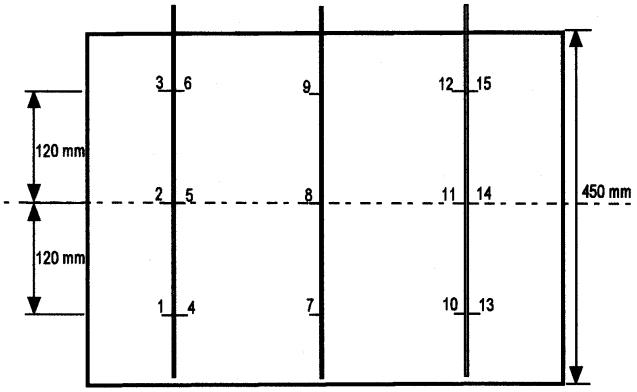
Instrumentation

Type T thermocouples were used to measure the temperature in the lower plenum and the upper bale chamber, and in the air circulation duct before and after the heaters. Two motorised aspirated psychrometers, consisting of fans, type T thermocouples, cotton wicks, and water storage containers to wet the wicks were constructed. One was installed in the lower plenum and the other in the upper bale chamber to measure the wet and dry bulb temperatures.

Three type T thermocouples were attached to a 3.2 mm diameter fibreglass rod with sensor tips spaced 120 mm apart.



Top view of baled hay



Side view of baled hay

Fig. 2. Thermocouple probes insertion and temperature measuring points within a hay bale, cut edge along the length of the bale (not to scale).

A heat shrink tube secured the thermocouple sensors onto the rod. Five rod assemblies were prepared. Figure 2 shows the temperature probe insertion points to determine the temperature of the lower, middle, and upper parts of the bale. For a 450 mm high bale, the vertical temperature sampling points were 105, 225, and 345 mm from the bottom of the bale.

Pressure taps were placed in the lower plenum and in the upper bale chamber to measure the air pressure drop across the test bale. Flexible plastic tubing with internal diameter of 3.2 mm connected the taps to a digital manometer to measure the pressure drop across the bale. An averaging pitot-tube assembly measured the average speed of air through the circulating pipes. For some tests, a 25.4 mm pipe was placed on top of the bale and airflow through the bale was measured using a hot-wire anemometer. Airflow through the bale also was estimated using the measured pressure drop across the bale and VanDuyne and Kjelgaard (1964) relationship. A data logging unit (Model 8082A, Sciemetric Instruments Inc., Manotick, ON) was used to record all the output signals from the sensors. The data were displayed on a monitor and stored on the hard drive disk for further analysis.

Test procedure

The hay bales (mixture of alfalfa and bromegrass) used in these experiments were obtained from a hay shed at the University of Saskatchewan. The hay was cut, baled, and stored in the hay shed for less than 8 months. To not disturb the internal configuration of a bale before a heat penetration test, approximately 100 g samples were removed from outside of the bale from top, middle, and bottom for moisture measurement. Earlier moisture measurements indicated the bales were in moisture equilibrium and the moisture contents did not vary significantly from outside of the bale to the interior. Each bale was weighed and its dimensions (length, width, height) were measured. The bulk density of each bale was calculated from the measured bale mass and the volume calculated from the bale dimensions. After the heat treatment, the bale was weighed and another set of hay samples taken for moisture measurement. Moisture contents were determined by the oven method according to the ASAE Standard S358.2 (ASAE 1998). Moisture tests were carried out in duplicates and expressed in per cent wet basis (w.b.).

To do a heat penetration test, a bale was placed on the cut edge over the cart. Temperature probes were inserted into the bale at points shown in Fig. 2. The tarpaulin was wrapped around the bale. It took up to 30 min to bring the chamber to the desired temperature and relative humidity. Once equilibrium was reached, the chamber door was opened and the instrumented bale was rolled into the chamber.

The data were recorded at 30 s intervals until the temperature of the slowest thermocouple in the bale reached 60°C. The test continued for three more minutes before turning off the steam supply and the fan. The bale was then removed from the chamber. The heating time was determined as the time required for the slowest heating spot to reach a temperature of 60°C. The fastest and slowest heating locations within the bale were monitored by the thermocouple sensors (Fig. 2). The number of times these different thermocouple locations within the bale were the fastest or slowest heating spots was statistically determined and their frequencies tabulated. Change in moisture content was determined from the initial and the final moisture contents of the bale. The air temperature, relative humidity, pressure drop across the bale, and airflow readings were averaged over each test run.

Altogether 103 heat penetration tests were conducted. Each test was done on a different bale. Uncontrolled variables were bale size, mass, and initial moisture content. The controlled variables were supply air temperature, air relative humidity, and airflow. Fourteen tests were conducted with no recirculation of the air, and eleven tests with the bale ties removed prior to the heat treatment.

RESULTS

Test conditions

Table 1 summarises the dimensions, mass, density, and initial and final moisture contents of 103 bales tested. The dimensions of the bales ranged from 910 to 1085 mm for the length, 449 to 484 mm for the height, and 342 to 375 mm for the width. The cut edge facing the airflow was the length and width (average 978 x 357 mm). The heaviest bale tested was 38.0 kg and the

Table 1. Summary of dimensions, mass, bulk density, and initial and final moisture contents of 103 hay bales tested in the chamber.

	Length (mm)	Width (mm)	Height (mm)	Mass (kg)	Density (kg/m^3)	Moisture content (% w.b.)	
						Initial	Final
Average	978	357	456	24.2	149.0	12.0	9.0
Std. dev.	37	7	6	5.6	35.7	3.0	3.9
Maximum	1085	375	484	38.0	235.0	17.7	17.6
Minimum	907	342	449	15.7	95.5	7.3	1.9

lightest bale was 15.7 kg. The density of the bales varied from 95.5 to 235.0 kg/m^3. The initial moisture content for the bales ranged from 7.6 to 17.7%.

Table 2 lists about 25% of the data selected randomly. The data consist of bale height which was the length of air travel through the bale, bale density, average air relative humidity, and temperature measured at the lower plenum before entering the bale, pressure drop across the bale, air velocity through the bale, air recycled or not, bale with ties or not, moisture content of the bale before and after the test, moisture content change and the time for the coldest spot in the bale to reach 60°C.

Table 3 shows the range of average temperature, relative humidity, static pressure, and velocity combinations and variations that were used in the tests. The temperatures used for testing ranged from 64 to 90°C and relative humidity ranged from 6 to 75%. These maxima or minima values belong to different test runs. The effects of combined temperature and relative humidity on the degree of heat penetration are discussed later.

Temperature

Figure 3 shows a typical temperature-time relationship during a heat penetration test. The inlet temperature increased by 7-8°C

Table 2. Typical experimental data.

Run No.	Height (mm)	Density (kg/m^3)	Ø* (%)	Temp* (°C)	ΔP (Pa)	Air velocity (m/s)	R*/ties (Y/N*)	Moisture content (% w.b.)			Heat time (min)
								Initial	Final	Δmc	
1	470	156	8	64	139	0.16	N/Y	15.9	2.9	-13.0	274.0
5	460	152	20	79	319	0.27	N/Y	14.7	3.5	-11.2	70.0
9	460	145	14	76	73	0.12	Y/Y	14.5	2.2	-12.3	226.0
13	460	158	24	78	134	0.15	Y/Y	15.1	3.6	-11.5	174.0
17	470	120	48	71	75	0.16	Y/Y	14.9	7.6	-7.3	195.0
21	480	127	43	78	77	0.15	Y/Y	15.7	16.4	0.7	10.0
25	470	135	45	84	84	0.15	Y/Y	16.5	13.8	-2.7	53.0
29	460	121	7	84	105	0.19	Y/Y	15.8	4.1	-11.7	66.0
33	460	114	21	77	100	0.20	Y/Y	14.4	6.5	-7.9	118.0
37	470	119	26	90	120	0.21	Y/Y	13.5	6.1	-7.4	84.0
41	450	134	41	80	105	0.16	Y/Y	13.4	12.5	-0.9	14.0
45	460	117	20	87	79	0.16	N/Y	13.7	3.6	-10.1	135.0
49	470	118	59	68	107	0.18	Y/Y	8.5	10.0	1.5	15.0
53	460	117	49	75	100	0.17	Y/Y	7.9	10.8	2.9	9.0
57	470	117	43	83	89	0.16	Y/Y	7.6	9.7	2.1	6.0
61	460	121	45	76	79	0.14	Y/Y	7.9	9.1	1.2	7.0
65	460	122	51	81	177	0.23	Y/Y	8.2	7.0	-1.2	2.7
69	460	122	45	72	170	0.23	Y/Y	9.5	7.4	-2.1	7.0
73	460	168	59	75	257	0.19	Y/Y	8.6	12.2	3.6	7.7
77	470	171	75	67	439	0.27	Y/Y	11.5	12.4	0.9	5.7
81	470	163	52	75	356	0.26	Y/Y	13.5	12.6	-0.9	9.0
85	470	159	57	75	563	0.34	Y/Y	10.8	10.6	-0.2	4.7
89	460	183	56	76	481	0.26	Y/N	12.3	12.6	0.3	4.0
93	450	235	56	77	613	0.20	Y/Y	8.8	13.0	4.2	14.7
97	470	222	69	74	414	0.17	Y/N	9.1	10.8	1.7	7.7
101	470	218	28	80	338	0.16	N/Y	12.5	10.9	-1.6	37.0

Ø* = average inlet air relative humidity. Temp* = average inlet air temperature.
R*/ties = air fully recycled/bale with ties. Y/N* = yes/no

Table 3. Summary of temperature, relative humidity, and air velocity for testing 103 hay bales.

	Temperature (°C)	Relative humidity (%)	Airflow	
			Static pressure (Pa)	Velocity, Eq. 1 (m/s)
Average	77	40	215	0.19
Std. dev.	6	18	171	0.05
Maximum	90	75	686	0.38
Minimum	64	6	65	0.12

during the 12 minute heating cycle. Location 15 was the slowest heating point in this test, where it took about one minute before the temperature started to rise. It took almost 5 minutes for this temperature to reach 60°C. The lower plenum temperature normally cooled slightly during loading. It regained heat quickly after the bale was rolled in and the door was closed tightly.

The temperatures at the lower parts of the bale, on the inlet side of the heated air, rose rapidly before asymptotically approaching the temperature of the inlet air. The temperature difference between the fastest and the slowest spots was large. The longer it took for the slowest heating point to reach 60°C, the longer the lower parts were exposed to high temperatures.

Table 4 lists the fastest and the slowest heating spots and their frequencies for 63 tests. The sensor at location 9 (see Fig. 2) had the highest frequency (24 times) of the slowest spot followed by location 15 (11 times). There were instances that the slowest spots occurred in the middle parts of the bale, when the air was recirculated, as indicated for sensors at positions 2, 8, 11, and 14. Generally locations at the bottom were the fastest heating spots. The sensors at locations 13 and 1 (the two ends of the bale) were among the fastest heating spots within the bale to reach a temperature of 60°C, and their frequencies were 16 and 15, respectively.

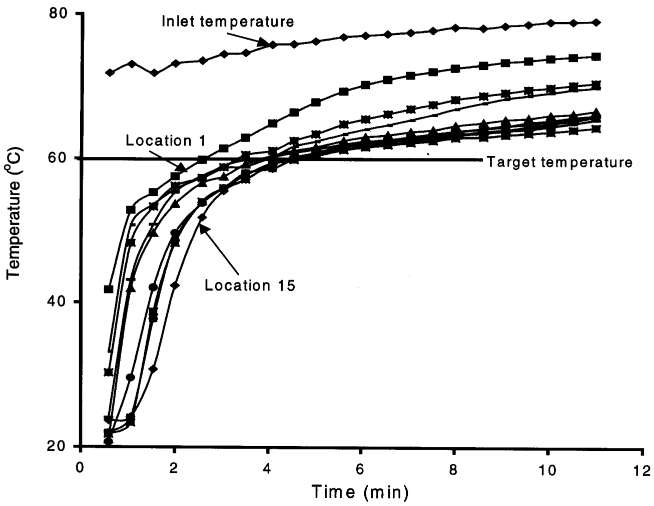


Fig. 3. Typical temperature history of 9 points within a hay bale at an average inlet air temperature of 76°C and relative humidity of 50%. See Fig. 2. for location positions.

Moisture content

The heating time was correlated with the moisture loss or gain with an r-squared of 0.76. Figure 4 plots bale moisture gain or loss versus heating time. Greater moisture loss increased the time for the slowest heating point to reach a temperature of 60°C. The data show wide variations in the heating times. In general, for shorter heating times the bale gained moisture, and for longer heating times, the bale lost moisture.

Heating time was longer when the inlet air had lower relative humidity. The heating time decreased with an increased relative humidity. The drop in moisture content was greatest at the lower relative humidity and the heating time was longer. The latent heat released during evaporation at the low relative humidity reduced the bale interior temperature thereby prolonging the heating time. When inlet air humidity was high, any condensation that might have occurred on the hay surfaces increased the heat transferred to the hay surfaces resulting in reduction in the heating time. The latent heat transferred to the hay surfaces and the resulting condensation of moisture on the hay surfaces increased the hay mass and moisture content.

Airflow

The airflows used in these tests varied from 0.081 to 0.168 m^3/s. Table 5 lists the average and standard deviation of about 25 measured air velocities on top of the bales. The air velocities reported in Table 2, 3, and 5 were estimated from pressure drop across the bale using an equation developed by VanDuyne and Kjelgaard (1964). The average measured air velocities ranged from a minimum of 0.12 m/s to a maximum of 0.33 m/s. Using the VanDuyne and Kjelgaard equation, the average estimated air velocity facing the bale was 0.19 m/s with a minimum of 0.12 m/s to a maximum of 0.38 m/s. The air velocities obtained

Table 4. Number of times thermocouple locations within the bale indicated the fastest or slowest heating spots to reach the target temperature of 60°C among 63 tests.

	Frequency of occurrence	
Sensor location	Fastest location	Slowest location
1	15	0
2	0	1
3	0	6
4	12	0
5	0	0
6	0	7
7	7	0
8	0	2
9	0	24
10	13	0
11	0	1
12	0	9
13	16	0
14	0	2
15	0	11

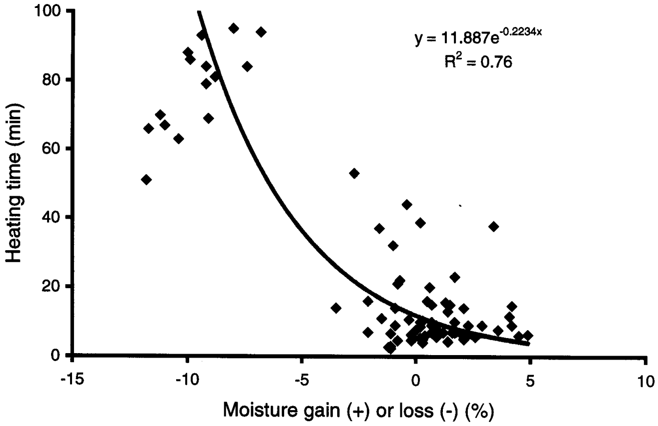


Fig. 4. Moisture gain or loss by bale versus heating time to reach 60°C for the coldest point in the bale.

using the VanDuyne and Kjelgaard (1964) equation were close to or within the range of the measured values. The VanDuyne and Kjelgaard (1964) equation is:

$$\frac{dP}{dL} = 0.072 B^{2.31} V^{1.60} \tag{1}$$

where:

B = dry matter density (kg/m^3),
dP = pressure drop (Pa),
dL = length of air travel (m), and
V = velocity (m/s).

Bale density

Table 2 shows that a bale with a density of 183 kg/m^3 took 4.0 min to reach 60°C while a bale with a density of 235 kg/m^3 took 14.7 min. The temperatures and relative humidities used in these two tests were almost the same. This result suggests that density of a bale plays an important role in the movement of air through the bale and in the transfer of heat. Greater bale density increases the pressure drop across the bale and thus reduces the amount of air passing through it. This reduces the heat that is available for transfer to the bale. If bale density is high, more heat energy will be required to produce a change in temperature than if bale density is low. Thus for a constant heat energy, the temperature of a low density bale will reach the desired temperature faster than a high density bale.

Tests also were conducted to determine the effect of bales with ties and without ties on the heating time. The result indicated the heating time for untied bales was shorter than tied bales (Table 2). The densities of the bales without ties were not measured, however it was observed that the compressed bale loosened up when the ties were cut. In this relaxed state, more heat might have passed through the bale to heat it in a shorter time.

Functional relationship

Similitude analysis was used to relate the treatment time to test variables. Table 1 and 2 list the variables used in the analysis. The functional relationship developed is:

$$\left(\frac{tV}{L}\right) = a_0 \left(\frac{M_i}{\phi}\right) * \left(\frac{T_0 + 273}{T + 273}\right)^{a_2} * \left(\frac{\rho}{\Delta\rho}\right)^{a_3} \tag{2}$$

Table 5. Average and standard deviation of measured and estimated airflow through the bale.

Run No.	Air velocity Average measured (m/s)	Standard deviation (m/s)	Eq. 1 (m/s)
79	0.20	0.04	0.24
80	0.15	0.03	0.25
81	0.16	0.01	0.26
82	0.16	0.01	0.29
83	0.25	0.11	0.25
84	0.23	0.03	0.27
85	0.24	0.05	0.34
86	0.26	0.02	0.32
87	0.25	0.09	0.24
88	0.20	0.13	0.23
89	0.33	0.10	0.26
90	0.19	0.07	0.20
91	0.22	0.03	0.21
92	0.22	0.11	0.22
93	0.18	0.02	0.20
94	0.13	0.02	0.19
95	0.17	0.03	0.22
96	0.12	0.01	0.18
97	0.14	0.01	0.17
98	0.16	0.01	0.24
99	0.16	0.05	0.21
100	0.15	0.04	0.17
101	0.13	0.03	0.16
102	0.18	0.03	0.15
103	0.17	0.02	0.17

where:

t = treatment time, time for the slowest heating spot to reach 60°C (s),
V = average air velocity through bale (m/s),
L = bale height (m),
M_i = initial moisture content (%, w.b.),
ϕ = average air relative humidity (%),
T = average inlet air temperature (°C),
T_o = initial bale temperature (°C),
ρ = dry bale bulk density (kg dry matter/m^3), and
$\Delta\rho$ = local variation or standard deviation in the bulk density (kg dry matter/m^3).

The group of variables within a parenthesis is dimensionless obeying the laws of the π theorem (Murphy 1950). All variables, except $\Delta\rho$, are well defined and can be quantified easily. The local variations of bulk density within a bale is not easily quantifiable. The standard deviation of bulk density for the entire 103 bales was used as an estimate of $\Delta\rho$. Future experiments should address methods for quantifying $\Delta\rho$ for individual bales.

Table 6. Estimated coefficients and standard deviations for Eq. 2.

	Estimated coefficients	Standard deviation
a_0	14.3853	4.1069
a_1	1.2504	0.1364
a_2	10.5099	6.6975
a_3	-0.0651	0.4961
R^2	0.67	
F-statistics	31.14	
Comparing Eq. 2 to the data		
Mean sum of square of residuals	1.3315	
Mean absolute residuals	0.7634	
Mean sum of relative absolute residuals	0.7812	

The coefficients a_0, a_1, a_2, and a_3 were estimated by taking the natural logarithm from both sides of Eq. 2. The 103 data sets were divided into two groups of 52 and 51. The linear regression program LINEST function in Microsoft® EXCEL was used to fit the transformed equation to the first data set (52 data). Table 6 presents the estimated parameters, their standard error of estimates, R^2, and F statistics.

The fit was not very good (R^2=0.67). The F statistics (F=31.14) indicated that all of the terms were significant at 5% significant level ($F_{\alpha= 0.05,\ df1=51,\ df2=4} = 5.67$). The mean sum of absolute residuals (0.7634) was close to the mean sum of relative residuals (residuals divided by the dependent variable, 0.7812). This indicated that the magnitude of residuals was of the order of the magnitude of the dependent variables. Figure 5 plots the residuals (predicted- experimental) values for Eq. 2 for heating time periods up to 40 minutes. The residuals are positive for heating periods of up to 10-12 minutes. For the remaining heating periods the residuals are randomly distributed around the zero line. Equation 2 should be improved once a better value for $\Delta\rho$ is developed.

CONCLUSIONS

Heat penetration experiments using heated air were conducted on 103 bales in a heat treatment test chamber. Moisture contents and temperatures of the bales were measured. The following conclusions can be drawn:

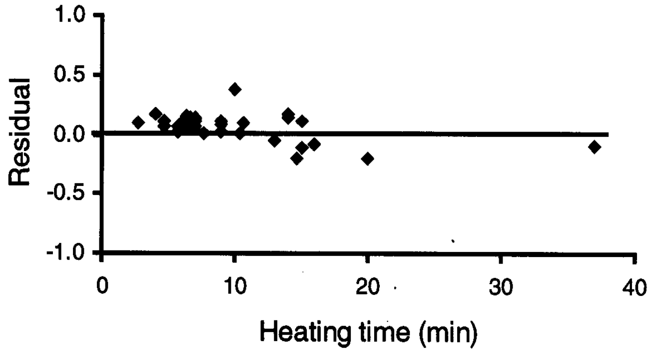


Fig. 5. Residuals (predicted-experimental) dimensionless time ratio for Eq. 2.

1. Drying of the product should be prevented for a faster, uniform baled hay heating.
2. Increasing the relative humidity, temperature, and air velocity reduced the heating time for the bale to reach 60°C. The heating time was reduced from 226.0 min at inlet air temperature of 76°C, air relative humidity of 14%, and air velocity of 0.12 m/s to 10.0 min at inlet air temperature of 78°C, air relative humidity of 43%, and air velocity of 0.15 m/s.
3. The top and centre parts of the bale were the slowest spots within the bale to reach 60°C compared to the bottom parts as indicated in Table 4.
4. The fastest heating time was 5.0 min and it was achieved at air temperature, relative humidity, and velocity of 76°C, 50%, and 0.33 m/s, respectively.

REFERENCES

ASAE. 1998. ASAE Standard S358.2 - Moisture measurement-forages. In *ASAE Standards 1998*, 553. St. Joseph, MI:ASAE

Gaffney, J.J. and J.W. Armstrong. 1990. High-temperature forced-air research facility for heating fruits for insect quarantine treatments. *Journal of Economic Entomology* 83(5):1959-1964.

Gaffney, J.J., G.J. Hallman and J.L. Sharp. 1990. Vapor heat research unit for insect quarantine treatments. *Journal of Economic Entomology* 83(5):1965-1971.

Mangan, R.L. and S.J. Ingle. 1994. Forced hot-air quarantine treatment for grapefruit infested with Mexican fruit fly (Diptera: Tephritidae). *Journal of Economic Entomology* 87(6):1574-1579.

Murphy, G. 1950. *Similitude in Engineering*. New York, NY: The Ronald Press Company.

Neven, L.G., L.M. Rehfield and K.C. Shellie. 1996. Moist and vapor forced air treatments of apples and pears: Effects on the mortality of fifth instar codling moth (*Lepidoptera: Tortricdae*). *Journal of Economic Entomology* 89(3):700-704.

Sharp, J.L., J.J. Gaffney, J.I. Moss and W.P. Gould. 1991. Hot-air treatment device for quarantine research. *Journal of Economic Entomology* 84(2):520-527.

Shellie, K.C., M.J. Firko and R.L. Mangan. 1993. Phytotoxic response of 'Dancy' tangerine to high-temperature, moist, forced-air treatment for fruit fly disinfestation. *Journal of the American Society of Horticultural Science* 118(4):481-485.

Sokhansanj, S. 1994. Heat treatment of baled hay for elimination of Hessian fly (Mayetiola Destructor (Say)). A special report prepared and submitted to Agriculture and Agrifood Canada. Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, Canada.

Sokhansanj, S. 1998. Thermal kill of Hessian fly (Mayetiola Destructor (Say)) pupae in baled Timothy (Phloem pratense L.) in a commercial forage dryer. In *Drying '98*, ed. A.S. Mujumdar, 1995-2001.

Sokhansanj, S., H.C. Wood and V.S. Venkatesam. 1990. Simulation of thermal disinfestaton of hay in rotary drum dryers. *Transactions of the ASAE* 33(5):1647-1651.

Sokhansanj, S., V.S. Venkatesam, H.C. Wood, J.F. Doane and D.T. Spurr. 1992. Thermal kill of wheat midge and Hessian fly. *Postharvest Biology and Technology* 2:65-71.

Sokhansanj, S. H.C. Wood, J.W. Whistlecraft and G.A. Koivisto. 1993. Thermal disinfestation of hay to eliminate contamination with Hessian fly (*Mayetiola Destructor* (Say)). *Postharvest Biology and Technology* 3:165-172.

Sokhansanj, S., E.A. Arinze, H.C. Wood and G.J. Schoenau. 1997. Temperature response of baled hay. ASAE Paper No. 97-6002. St. Joseph, MI: ASAE.

VanDuyne, D.A. and W.L. Kjelgaard. 1964. Air-flow resistance of baled alfalfa and clover hay. *Transactions of the ASAE* 7(3):267-270.

Yokoyama, V.Y., J.H. Hachett and G.T. Miller. 1993a. Hessian fly (*Diptera: Cecidomyiidae*) control by hydrogen phosphide fumigation and compression of hay for export to Japan. *Journal of Economic Entomology* 86(1):76-85.

Yokoyama, V.Y., J.H. Hachett and G.T. Miller. 1993b. Hessian fly (*Diptera: Cecidomyiidae*) control by compression of hay for export to Japan. *Journal of Economic Entomology* 86(3):803-808.

Yokoyama, V.Y., G.T. Miller, P.L. Hartsell and J.H. Hachett. 1996. Complete mortality of Hessian fly (*Diptera: Cecidomyiidae*) puparia in two large scale tests to confirm the efficacy of a multiple quarantine treatment for compressed hay exported to Japan. *Journal of Economic Entomology* 89(3):705-711.