Drying of large round hay bales

G.C. MISENER1, C.D. MCLEOD1, C.A. ESAU2 and W.A. GERBER1

1 Agriculture Canada Research Station, Fredericton, NB, Canada E3B 4Z7; and 2 Nova Scotia Department of Agriculture and Marketing, Truro, NS, Canada B2N 5E3. Received 13 March 1989; accepted 12 April 1990.

The airflow inlet configuration did not influence the drying rate of the soft core bales but did affect the drying rate of the uniform density bales. Experiments were conducted to determine the effect of two bale types and three airflow inlet configurations to the bales on the drying rate of the bales. Soft core bales dried more evenly than uniform density bales where a higher moisture content was retained in the top outer portion. The airflow inlet configuration did not influence the drying rate of the soft core bales but did affect the drying rate of the uniform density bales.

INTRODUCTION

Large round bales have been developed to mechanize hay harvesting and handling and they are a one-person forage system with relatively low equipment investments. When covered storage and long distance hauling are needed, the cost of the system increases. The labour required from harvesting to feeding is approximately 0.17, 0.12, and 0.09 person hours per tonne for 360, 550, and 900 kg round bales, respectively (ANON 1978). In eastern Canada, hay harvested at the optimum stage of maturity must be field dried for up to three days before it is suitable for storage. This long period on the field often leaves the hay exposed to rain. Baling hay at a moisture content of 30 to 35% reduces the field curing time and the risk of inclement weather while also reducing leaf losses which result from harvesting a dry crop (MacDonald and Clark 1987). Artificial drying is needed to lower the moisture content of large round bales to less than 18% thereby preventing heat and mould growth within the bale. It is necessary to provide an external source of heat to dry large round bales whereas no external heat is necessary to dry conventional square bales. In both cases, part of the energy required to evaporate the water is provided by the hay itself (Wood and Parker 1971). However, with more mass and longer moisture migration paths in the large bales, the moisture reduction is slower. This combination of high moisture for longer times provides conditions suitable for moulds and secondary chemical and biological reactions. Also, Collins et al. (1987) suggested that the storage method significantly affects dry matter and the quality of alfalfa hay in round bales.

The two types of bales most commonly used in eastern Canada are bales with either an expandable chamber or bales with a fixed chamber. The expandable chamber machine produces a relatively uniform density bale and the fixed chamber machine forms a variable density bale with a lower density core. Bledsoe et al. (1985) suggested that the effect of dry matter density on drying rate is critical for a given bale size. Marchant (1976), using equations describing the flow of air through porous agricultural materials, investigated the resistance to airflow through hay packaged in large round bales. VanDuyne and Kjelgaard (1964) found the resistance to airflow varied exponentially with dry matter density. Bledsoe and Hitch (1986) used finite element analysis to predict the effect of bale, duct, and air inlet/outlet characteristics on airflow through large bales. They concluded that dry matter density and its distribution within the bale were the key factors that determined the drying rates. Désilets (1976) suggested that the end of a uniform density bale opposite to the air entrance was nearly impossible to dry even when an air distributor was inserted longitudinally in the bale centre.

The objective of the study reported in this paper was to determine the effect of components for directing airflow through bales and of bale type on dryer performance.

REVIEW OF LITERATURE

Henry (1977) suggested that the minimum airflow rate required for drying large round bales was 16 m³/min per tonne of hay. Bledsoe et al. (1981) used 34.5 m³/min per package while Garthe (1985) used 22 m³/min in his experiments. Frisby et al. (1985) measured airflow rates of 38.4 m³/min at a static pressure of 831 Pa in an experiment with a uniform density bale and of 57 m³/min at a static pressure of 498 Pa with a soft core bale. The static pressure decreased during drying (Garthe 1985), which suggested that the airflow rate from a well selected fan will increase as the drying progresses.

There is some variation in the estimated power requirements as Bledsoe et al. (1981) used a 2.2 kW motor for a four bale dryer and Morrison and Shove (1981) installed a 0.75 kW motor on a one bale dryer. Frisby et al. (1985) powered the fan with a 1.1 kW electric motor on a single bale dryer. Désilets (1976) used a 2.2 kW electric motor to power an axial flow fan on a two bale dryer.

With the higher resistance to moisture migration encountered when drying large bales, the heat produced by the hay is not sufficient. Therefore, a supplemental heat source is required. Henry (1977) and others did extensive studies of solar collectors for this particular application and Garthe (1985) used a wood stove. Morrison and Shove (1981) measured energy consumptions of 6.2 and 8.7 kWh per percentage point of moisture removed during experiments with a solar collector and airflow rates of 36.6 m³/min per bale operated intermittently and 39.6 m³/min per bale operated continuously. Frisby et al. (1985) measured the energy consumption of the electric motor in two experiments (uniform density and soft core bales); their figures were 5.4 kWh per percentage point of
moisture removed from the uniform density bale and 3.2 kWh per point of moisture removed from the soft core bale. The bale dry matter masses were 620.5 kg and 603.3 kg, respectively.

DESCRIPTION OF DRYER

Facility

The dryer was designed to dry up to nine bales simultaneously with a configuration that facilitates comparison among treatments including field treatments, airflow rates, and drying temperatures. Air is distributed to three separate bale sets by three ducts located in the concrete floor. A damper was installed in each duct to individually control the airflow rate. The ducts have a square cross-section 0.6x0.6 m with three 0.6 m diameter holes equally spaced for directing airflow into three bales. The ducts are insulated with 50 mm thick styrofoam. Each bale is placed in a plywood and steel frame that is suspended from a load cell during drying and is connected to the duct with a flexible tube.

One duct is equipped with a 50 kW electrical resistance heater while the other two ducts have 24 kW heaters. To accommodate the range of power and flows previously reported, each duct is equipped with a 3.73 kW electric motor driven fan (Delhi B1-18).

A roof over the facility provides protection from rain and a support structure from which to suspend the bales.

Instrumentation

Parameters that were monitored during the drying process and the sensors required were as follows:

- bale temperatures (type T thermocouples)
- ambient temperatures (RTD sensors and thermocouples)
- ambient humidity (capacitive type humidity sensor)
- duct humidity (capacitive type humidity sensor)
- duct temperatures (RTD sensors and thermocouples)
- duct pressures (pressure transducer with amplifier)
- bale weights (strain gauge type load cells)

A multichannel data logger with a tape drive for data storage was used to record these parameters. The data logger, a

Fluke Model 2280B, was programmed to accept voltage input from type T thermocouples and the signal was conditioned by using the data tables available on the data logger. Signal conditioning was not required for either the humidity-temperature sensors or the pressure sensors. Conditioning for the strain gauge sensors was obtained by a conditioning unit that provided excitation voltages and sensor amplification. Fig. 1 shows the various locations of the sensors within the drying facility. Table I lists the type and accuracy of the sensors used in the facility.

Scaling is provided for the humidity, RTD, pressure, and strain gauge sensors to give output readings in the appropriate SI units. Data are stored on an on-board tape drive unit capable of holding up to 500 kbytes of formatted data. Data are transferred from the tape drive through an RS232C serial port and downloaded onto a microcomputer for further analysis.

The thermocouples were thermoelectric type T, connected with 16 gauge extension wire with PVC jacketing and shielding. The conductors were twisted internally to minimize electromagnetic pickup. Other temperature sensors were part of the humidity sensor and consisted of a temperature dependent resistor whose voltage drop was linearized by the sensor linearizing circuit to give an output of 50 mV/°C.

Fig. 1. Schematic diagram of drying facility with instrumentation and method of bale - duct inlet configuration.
Pressure readings were obtained using Sensotec TJE/83, 0-3.4 kPa pressure transducers. An internal amplifier was included to give a full scale output of 2.9 V/kPa and to provide ratiometric excitation voltages. The duct pressures of the three systems were monitored and reinitialized every 15 minutes to account for changes in atmospheric pressure.

Relative humidity readings were taken with a Vaisala capacitive sensor humidity probe outside the ducts for ambient conditions and inside the ducts for predrying conditions.

Individual bale weights were determined by transducers (tension) manufactured by Transducers Inc. with a maximum capacity of 900 kg. The sensor signals from the load cells were conditioned by a Sensotec Strain Gauge Amplifier. The amplifier provided excitation voltages of 10 Vdc and amplified the sensor output to 5 Vdc. A shunt calibration resistor was included to provide linear calibration of the output. The amplifier is field programmable for various types of input levels as well as full scale and zero adjustments.

Temperatures were monitored at the fan inlet (ambient), the fan outlet, the heater exhaust, and points along the duct. These established the base temperatures of the overall system. Thermocouples were also placed in various locations within the bales to obtain a temperature-time profile from each bale.

MATERIALS AND METHODS

Three trials were conducted to determine the effect of components for directing airflow through bales and of bale type on dryer performance.

Alfalfa was mowed and conditioned in the morning and was tedded and raked the following day. Nine bales were made during each of three trials with either a baler with a variable chamber or one with a fixed chamber. The bales were 1.2 m wide and 1.5 m in diameter. They were transported to the dryer, weighed, and sampled to determine the initial moisture content. The nine bales were then placed on the dryer according to the arrangements presented in Table II with three bales on each duct. The nine bales were dried simultaneously. This arrangement allowed three treatments (inlet configuration) and three replications of each treatment.

Each bale placed on duct I was penetrated by a cylindrical steel ring, 0.15 m high and 1.1 m in diameter. The ring was attached symmetrically to a frame base made from plywood 1.8 m in diameter with a 0.9 m circular hole similar to the arrangement used by Bledsoe et al. (1981). The ring penetrated the bale end to ensure that an air seal was obtained between the plywood base and the large bale. The frame and bale were then suspended over the duct outlet and were connected to the outlet with a flexible vinyl tube. There were three frames with mounted bales connected to duct I.

Bales were suspended over duct II outlets by using straps under the bales instead of plywood frame bases. The exterior of each bale was wrapped with plastic film and the bales were connected to the duct outlet with flexible tapered vinyl tubes. This maximized the airflow area through the bales and prevented air from escaping out the sides of the bales.

The bales on duct III were placed on plywood bases, similar to those on duct I except the steel ring was not used and the circular hole in the plywood was only 0.6 m in diameter.

Table II. Mean drying characteristics\(^1\) of bales

<table>
<thead>
<tr>
<th></th>
<th>Trial I</th>
<th>Trial II</th>
<th>Trial III</th>
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<tbody>
<tr>
<td></td>
<td>Duct I Soft</td>
<td>Duct II Uniform</td>
<td>Duct III Soft</td>
</tr>
<tr>
<td>Original moisture, %</td>
<td>44.0</td>
<td>41.1</td>
<td>43.7</td>
</tr>
<tr>
<td>(wet basis)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final moisture, %</td>
<td>19.4</td>
<td>22.7</td>
<td>19.4</td>
</tr>
<tr>
<td>(wet basis)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original weight, kg</td>
<td>588.4</td>
<td>910.9</td>
<td>578.9</td>
</tr>
<tr>
<td>Dry weight, kg</td>
<td>329.1</td>
<td>536.8</td>
<td>325.7</td>
</tr>
<tr>
<td>Airflow/bale, m(^3)/sec</td>
<td>0.43</td>
<td>0.21</td>
<td>0.39</td>
</tr>
<tr>
<td>Static pressure in duct, Pa at time = 0</td>
<td>1020.2</td>
<td>1082.5</td>
<td>1032.7</td>
</tr>
<tr>
<td>Drying time, h</td>
<td>116.0</td>
<td>116.0</td>
<td>116.0</td>
</tr>
<tr>
<td>Average water removal, kg/h</td>
<td>1.6a</td>
<td>1.9a</td>
<td>1.5a</td>
</tr>
<tr>
<td>Mean drying rate(^2), %/day</td>
<td>5.10a</td>
<td>3.80b</td>
<td>5.03a</td>
</tr>
</tbody>
</table>

\(^1\) All parameters listed are means of the three bales placed on the individual ducts.

\(^2\) Averaged rate over drying period.

\(^a\) Means followed by the same letter in rows within the trials are not significantly different at 0.05 level as measured by the Duncan's Multiple Range Test.
As a result of a recommendation by Morrison and Shove (1981), 1.2 m diameter plywood covers were placed on the top of the bales on ducts I and III during the drying process. Four thermocouples were inserted into each bale at the top and bottom core, as well as the top and bottom exterior. The temperature of the bales was monitored hourly. Four samples were taken from each bale daily with a powered probe at the top and bottom core and the top and bottom exterior. The samples were then oven dried to determine the moisture content.

All fans were turned on and the thermostats on the heaters were set to maintain a duct temperature of 26.7 °C. Individual bale weights were monitored hourly as well as duct pressures as outlined by the instruments described earlier.

RESULTS AND DISCUSSION

Figs. 2 to 4 show the decline in the average moisture content of the bales during drying for each trial. The initial moisture content was higher than expected due to inclement weather conditions before baling in 1988. However, most bales reached an average moisture content that was less than the 20 percent (wet basis) objective originally established as the maximum acceptable. The drying rates obtained in this study were similar to the values reported by Morrison and Shove (1981) and Frisby et al. (1985) and are summarized in Table II.

The mean drying rates from each trial were compared to determine the relative effect that airflow directing devices and bale types had on the rates. In trial I, the mean drying rates for the soft-core bales were significantly higher than the mean rates for the uniform density bales. The drying rates appeared to be reduced by the higher density of the uniform bale type. However, there was no significant difference in the average absolute rate of water removed from the bales. The drying rates of the soft-core bales did not differ with different bale inlet configurations. This trend is also shown in Fig. 2 where the initial moisture contents of the soft-core bales were higher than the uniform density bales.

In trial II, where the uniform density bales were made with a density less than that in trial I, the drying rates approached those of the soft-core bales (Fig. 3). The drying rate of the uniform density bales (wrapped with plastic film) on duct II, was significantly higher than that of the uniform density bales on duct I. The evaporation rate of water was significantly higher for the uniform density bales than the soft-core bale.

In trial III, (nine uniform density bales) the inlet configura-
The static pressure in the ducts during drying was higher than that from the bales on ducts I and III. The average evaporation rate of water from the bales varied. In trial I, the caps were not held in place tightly and the moisture content of the outer top portion of the bales did not dry to a satisfactory level (Fig. 6). This is consistent with Bledsoe et al. (1985) who also found it difficult to achieve uniform drying, especially in the top outside sections of uniform density bales. It appears that insufficient airflow is produced within the bales as well as the weight of the bales. The static pressure in the air ducts dropped as the bales were dried from their initial to final moisture levels. The static pressure in the ducts during drying was higher than the static pressures measured by Frisby et al. (1985). As shown in Table III, duct static pressures dropped as the bales were dried. Morrison and Shove (1981) indicated that static pressures measured under the bales dropped an average of 14 percent as the bales were dried from their initial to final moisture levels.

CONCLUSIONS

An experimental drying facility for large round bales was designed and constructed, and during the initial trials, it operated within expectations. The facility has the capability of drying nine bales simultaneously with three drying parameter treatments and three replications of each treatment. The dryer is equipped with instruments to monitor the psychrometric properties of the air entering the bales as well as the weight of the bales.

The drying rates of uniform density bales were affected by the method used to direct air through the bale. Bales wrapped with a plastic film dried faster than those placed on plywood that had either a simple 0.6 m diameter hole or a hole surrounded by a 1.1 m diameter ring to prevent leakage. The final moisture content varied less within soft-core bales than it did within uniform density bales. However, snugly fitted caps were required to dry the outer top portion of the bales during the time that the bale average was dried to the desired moisture content. The top portion of the uniform density bales did not dry below 20 percent.

The static pressure in the air ducts dropped as the bales were dried from their initial to final moisture levels. The soft core bales produced a lower static pressure than the uniform density bales.

ACKNOWLEDGEMENT

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REFERENCES


Table III. Static pressure* in air ducts

<table>
<thead>
<tr>
<th>Bale Moisture (wet basis)</th>
<th>Soft Core</th>
<th>Uniform Density</th>
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<tbody>
<tr>
<td></td>
<td>Static Pressure, Pa</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>25.0</td>
<td>943.8</td>
<td>54.4</td>
</tr>
<tr>
<td>30.0</td>
<td>968.5</td>
<td>59.5</td>
</tr>
<tr>
<td>35.0</td>
<td>993.3</td>
<td>64.5</td>
</tr>
<tr>
<td>40.0</td>
<td>1018.1</td>
<td>69.5</td>
</tr>
</tbody>
</table>

* Values were determined from regression equations with static pressure as a function of bale moisture content.

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