Diffusion of Moisture in Burley Tobacco Bales During Storage

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ABSTRACT

A model to describe long-term moisture diffusion in burley tobacco bales was developed from the vapor diffusion equation. The model agreed better with experimental results when the initial moisture content was at the high and normal level than when the initial bale moisture contents were low. When the initial moisture content was low the bale was subjected to both significant wetting and drying conditions during the day from the diurnal variation of the ambient relative humidity. Moisture loss from bales was predicted to be 0.4, 7.2, and 11.7% of initial bale weight for bales at low, normal, and high initial moisture contents, respectively, after one year in storage. Diffusion of moisture perpendicular to the leaf lamina was negligible as predicted by the model.

INTRODUCTION

Burley tobacco producers are currently marketing their tobacco in a relative new package, in which roughly 34 kg of cured burley tobacco leaves are packed into a .3 m × .9 m × .6 m high bale. A surplus of burley tobacco from one crop year may result in a substantial number of bales being stored over the summer to be sold during the next year's marketing sessions. Because of the bale's short time in usage, little is known about the storage characteristics of burley tobacco bales. The loss of moisture from the bales during storage is of particular importance to farmers and tobacco producers.

The diffusion coefficients in the bale must be known to evaluate moisture loss from bales. Walton et al. (1976) determined diffusion coefficients of individual cured burley leaves; however, these values do not apply to the semiporous media that exists in the bale. Stinson et al. (1974) found diffusion coefficients for dense packages of flue-cured tobacco, but diffusion coefficients for flue-cured tobacco are not directly applicable to burley tobacco. Swetnam and Walton (1984) validated a mathematical model derived from the vapor diffusion equation and determined diffusion coefficients for densely packed burley tobacco leaves, which are directly applicable to burley tobacco bales. They presented diffusion coefficients for densely packed burley tobacco leaves, which are directly applicable to burley tobacco bales. Their diffusion coefficients were presented as a function of direction of diffusion, initial moisture content, stalk position, and temperature.

The results from Swetnam and Walton (1984) showed that the diffusion of moisture was strongly dependent on direction of diffusion relative to the leaf lamina. The mass diffusivities parallel to the leaf lamina were much larger than those perpendicular to the lamina because of a continuous pore space in the bale for diffusion parallel to the lamina, as opposed to the high resistance of moisture diffusion offered by multiple layers of leaves in the perpendicular direction. Therefore, a model of moisture diffusion in the bale must account for the anisotropism of the diffusion coefficient. Because of the lack of a continuous pore space path in the perpendicular direction, as exists in typical porous media, we have referred to the bale as a semiporous media.

In long-term (1 year) storage of tobacco bales the boundary conditions will vary with humidity and temperature (Jeffrey, 1940; Locklair et al., 1957), which in turn vary with time. Also, the diffusion coefficients will vary with temperature (Swetnam and Walton, 1984), and thus, also vary with time. The variation in these factors must be accounted for in any effective long-term model of moisture diffusion in burley tobacco bales.

The objective of this study was to develop a model for long-term moisture diffusion in burley tobacco bales that accounts for the variation of the diffusion coefficient with direction and temperature and for the time varying boundary conditions.

MATHEMATICAL DEVELOPMENT

The governing equation was the vapor diffusion equation (Swetnam and Walton, 1984) with negligible surface resistance applied to an anisotropic media,

$$\frac{\partial \theta}{\partial t} = D'_x(t)\frac{d^2\theta}{\partial x^2} + D'_y(t)\frac{\partial^2\theta}{\partial y^2} + D'_z(t)\frac{\partial^2\theta}{\partial z^2} \quad \ldots\ldots [1]$$

where $\theta = M - M_o$,

$D'(t) = \frac{D(t)}{\rho\beta}$ = time dependent directional modified diffusion coefficient

ρ = dry matter bulk density of tobacco

β = slope of moisture content—water vapor density equilibrium isotherm

M = moisture content at time t, dry basis, %

M_o = initial moisture content, dry basis, %

Article was submitted for publication in June, 1987; reviewed and approved for publication by the Food Process and Engineering Institute in August, 1987.

The investigation reported in this paper (82-2-292) is in connection with a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director of the Station.

This research was funded in part by a grant from the Agricultural Research Service, United States Department of Agriculture through Cooperative Agreement Number 58-7B30-187.

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$D(t)$ = time dependent directional diffusion coefficient
t = time
x, y, z = the three axes.

Since the ambient conditions that gave the boundary conditions (Q) were a function of time only, we expressed the boundary and initial conditions as

$$\theta(a, y, z, t) = Q(t) \qquad \frac{\partial\theta}{\partial x}(0, y, z, t) = 0$$

$$\theta(x, b, z, t) = Q(t) \qquad \frac{\partial\theta}{\partial y}(x, 0, z, t) = 0$$

$$\theta(x, y, c, t) = Q(t) \qquad \frac{\partial\theta}{\partial z}(x, y, 0, t) = 0$$

$$\theta(x, y, z, 0) = 0$$

Solving equation [1] with these time dependent boundary conditions was done using Duhamel's Theorem (Arpaci, 1966).

$$\theta(x, y, z, t) = \sum_{n=1}^{N} \gamma(x, y, z, t - \tau_i)\, \Delta M_i \quad \ldots\ldots\ldots [2]$$

where $\gamma(x, y, z, t)$ is the response of the corresponding linear homogeneous system to a single unit step input and τ_i is the time of the step change. ΔM_i. Equation [2] reflects our assumption that Q(t) consists entirely of step changes, which results from using the average monthly humidity to determine the boundary conditions. The usual integral term (Arpaci, 1966) could also have been included in equation [2] if a general function, Q(t), were to be used.

Letting,

$$\beta(x,y,z,t) = \gamma - 1 = U(x,t) * V(y,t) * W(z,t) \quad \ldots\ldots [3]$$

to make the boundary conditions homogeneous and then to separate the problem into three one-dimensional problems left,

$$D'_x(t)\frac{\partial^2 U}{\partial x^2} = \frac{\partial U}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots [4]$$

with boundary conditions

$$U(a,t) = 0$$

$$\frac{\partial U}{\partial x}(0,t) = 0$$

and the initial condition

$$U(x,0) = -1$$

and two identical sets of equations in V(y, t) and W(z, t).

With the three modified diffusion coefficients now separated we applied the method of Crank (1956) to account for the time dependent modified diffusion coefficients; functions of time only, because they are functions of temperature, which is a function of time only. Letting $dT = D'_x(t)dt$ gave

$$T = \int_0^t D'_x(s)\, ds \quad \ldots\ldots\ldots\ldots\ldots\ldots [5]$$

Substituting equation [5] into equation [4] resulted in

$$\frac{\partial^2 U}{\partial x^2} = \frac{\partial U}{\partial T} \quad \ldots\ldots\ldots\ldots\ldots\ldots [6]$$

with boundary conditions

$$U(a,T) = 0$$

$$\frac{\partial U}{\partial x}(0,T) = 0$$

and the initial condition

$$U(x,0) = -1$$

Again, there were identical equations in V(y, T) and W(z, T).

Equation [6] was solved by separation of variables leaving the final solution of equation (1) as

$$\theta(x,y,z,t) = \sum_{i=1}^{N} [1 + G(x, T-\theta_i) * G(y, T-\theta_i) * G(z, T-\theta_i)]\, \Delta M_i \quad \ldots\ldots\ldots\ldots [7]$$

where

$$G(\alpha, T-\theta_i) = \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{(2n+1)} \cos(\lambda_\alpha \alpha) \exp[-\lambda_\alpha (T-\theta_i)],$$

$$T = \int_0^t D'_\alpha(s)\, ds$$

$$\theta_i = \int_0^{\tau_i} D'_\alpha(s)\, ds$$

ΔM_i = monthly step changes in M
M = moisture content, dry basis, %
τ_i = time of the step change, ΔM_i
N = number of months
$D_\alpha(t)$ = monthly step function for modified diffusion coefficients
λ_α = $\frac{2(n+1)\pi}{2d_\alpha}$, n = 0, 1, 2, . . . , and
d_α = a, b, c,
for α = x, y, and z.

METHODS

The modified diffusion coefficients used in equation [7] were those reported by Swetnam and Walton (1984). Values were calculated by linear interpolation and by linear extrapolation for temperatures below 5.6°C. The extrapolation gave negative values for a few low temperature modified diffusion coefficients in the perpendicular direction. These were taken to be zero.

Equation [5] was integrated numerically by

$$T = \sum_{i=1}^{N} D'_x(i) * t_m \quad \ldots\ldots\ldots\ldots\ldots\ldots [8]$$

where, $D_x(i)$ = modified diffusion coefficient for month i

t_m = 1 month = 730 h

Due to the symmetry of the problem, only one-eighth of the bale needed to be evaluated by equation [7] to describe the drying characteristics of the entire bale. This eighth of the bale was evaluated at 125 points at each time interval to obtain the concentration gradients. The points of evaluation were at distances $0.1d_\alpha$, $0.3d_\alpha$, $0.7d_\alpha$, and $0.9d_\alpha$ from the bale center were d_α = a, b, c for α = x, y, z. The resulting 125 values for moisture content were averaged to obtain the bale moisture content, thus, effectively numerically integrating equation [7]. The assumed dimensions for calculations in an average year were 2a = 89.0 cm, 2b = 56.0 cm, and 2c = 30.5 cm.

The model, equation [7], was compared to moisture content data from an experiment designed to evaluate storage of burley tobacco in bales from spring to fall using three stalk positions (bottom, middle, and top), three leaf moisture levels (low, normal, and high) and two replications.

Burley variety KY 14 was grown using recommended cultural practices. The tobacco was harvested and cured in the conventional manner. The tobacco was removed from the barn and stripped into three farm grades (top, middle and bottom of the stalk) when the natural weather conditions created a leaf moisture content corresponding to the high moisture level. Two-thirds of the stripped leaf was then placed into conditioning chambers for drying to the two remaining moisture levels. The average initial moisture content for the low, normal, and high moisture levels were 17.4, 23.0, and 31.7% d.b.

Bales were formed using methods and equipment recommended by Duncan and Smiley (1980). Bales were approximately 0.3 m × 0.9 m × 0.6 m and weighed about 31, 37 and 43 kg at low, normal, and high moisture, respectively. The leaves were oriented parallel to the 0.3 m × 0.9 m surfaces, i.e., the top and bottom of the bale, with the leaf midribs parallel to the 0.9 m dimension. The butts of the midribs were placed at the ends of the bale with the tips of the leaves overlapping in the center of the bale. The leaves were compressed vertically parallel to the 0.6 m dimension under 5 kN of force.

The bales were stored in a well-ventilated barn for about 8 months from spring to fall. All bales were sampled by coring to obtain moisture contents initially, and at 1, 3.5, 6, and 7.5 months. A 2.5 cm diameter core was taken from the top to the center of the bale. Moisture content determinations were made on the combined lamina and midrib by oven drying at 70°C for 72 h.

A simultaneous but separate experiment was being conducted on these bales to determine the physical and chemical changes of the tobacco during storage. In general, the same sampling was used for chemical determinations as well as moisture content determinations for this study. However, special sampling of the high and low moisture content bales of the middle stalk position for tar determinations resulted in so many corings in these bales that corings could not be confined to the center portion of the bale and were, thus, useless for the purpose of this study. Observed moisture loss of the fourteen remaining bales of burley tobacco was compared to the moisture loss predicted by the mathematical model (equation [7]). A standard error of prediction, defined as,

$$S.E. = \frac{\sum_{i=1}^{n} (Y_a - Y_p)^2}{n-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots [9]$$

where,
S.E. = standard error of prediction
Y_a = observed moisture content
Y_p = predicted moisture content
n = number of observations,
was used to compare equation [7] to the observed bale moisture contents.

The comparison of the moisture loss predicted by the model to the actual measured moisture loss of the 14 bales was for a specific year. The question quite naturally arises as to the amount of moisture loss that the producer can theoretically expect during 12 months of storage in an average meteorological year. The average monthly temperatures and humidities for average year calculations were taken from typical meteorological year (TMY) data (National Climatic Center, 1981) for Lexington, KY and are shown in Table 1. The average monthly relative humidity was calculated from the average monthly dry bulb and dewpoint temperatures. The equilibrium moisture contents and, thus, the boundary conditions for the monthly humidities were taken from the combined data of Jeffrey (1940) and Locklair et al. (1957). These equilibrium moisture contents are also given in Table 1.

RESULTS AND DISCUSSION

The standard errors of prediction for the moisture loss predicted by equation [7] for the 14 bales that were stored for eight months are shown in Table 2. The model predicted higher final moisture contents than were

TABLE 1. AVERAGE MONTHLY AMBIENT CONDITIONS FOR LEXINGTON, KENTUCKY FROM TMY DATA (NATIONAL CLIMATIC CENTER, 1981).

Month	Temperature °C	Relative humidity, %	Equilibrium moisture content, % d.b.
November	7.3	73.6	20.9
December	3.3	76.5	23.7
January	−0.5	77.6	25.0
February	1.5	66.3	15.3
March	6.3	67.8	16.3
April	14.0	52.8	9.7
May	17.0	66.2	15.2
June	22.6	67.7	14.8
July	24.1	78.1	22.6
August	23.0	76.7	21.6
September	21.0	74.4	20.3
October	14.2	66.2	15.3

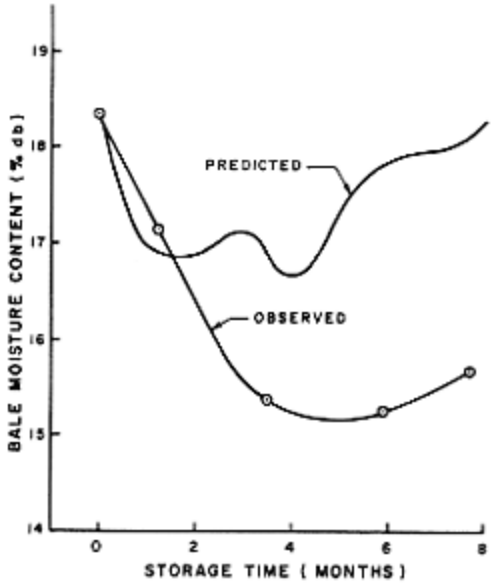

Fig. 1—Observed and predicted moisture content of experimental low initial moisture content bale during eight-month storage period.

actually observed for bales with average initial moisture contents of 23% d.b. and below. It predicted lower than observed final moisture contents for bales with average initial moisture contents greater than 23% d.b. Fig. 1 through 3 show the moisture content histories, both predicted and observed, for a typical low, normal, and high initial moisture content bale, respectively. For the low moisture bale, in Fig. 1, both the predicted and observed moisture content curves have essentially reached equilibrium during the last few months; but, the equilibrium moisture contents used to predict the moisture content history of the bale in Fig. 1 (as well as

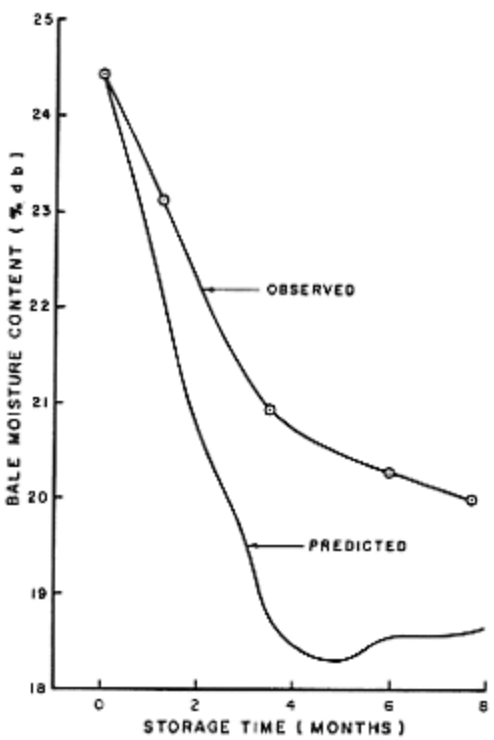

Fig. 2—Observed and predicted moisture content of experimental normal initial moisture content bale during eight-month storage period.

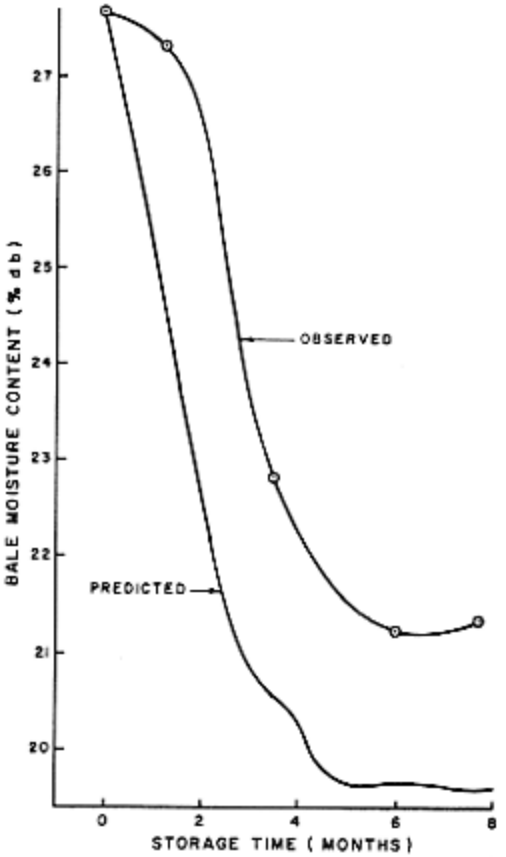

Fig. 3—Observed and predicted moisture content of experimental high initial moisture content bale during eight-month storage period.

the rest of the low moisture bales) are, apparently, higher than the actual equilibrium moisture contents experienced by the bale. The cause of this discrepancy appears to be the diurnal variation of the relative humidity, and, subsequently, of the ambient equilibrium moisture content, combined with the hysteresis exhibited by burley tobacco leaves for moisture sorption as compared to desorption.

The diurnal variation of the ambient equilibrium moisture content conditions is shown in Fig. 4 for one day averaged over the month of July, 1982. Walton et al. (1976) showed that individual burley tobacco leaves exhibited significant hysteresis during sorption of

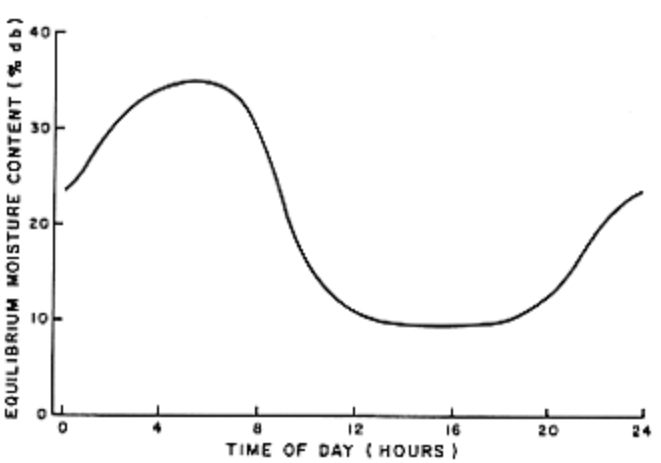

Fig. 4—Average diurnal variation of equilibrium moisture content for Lexington, Kentucky, during July 1982.

moisture as compared to desorption. The diffusion coefficients for sorption in individual leaves were an order of magnitude smaller than for desorption in the range of 13°C (55°F) to 24°C (75°F), although the effect did decrease with decreasing temperature through this range. Some hysteresis should carry over to the baled leaves, but no data is available to accurately show the magnitude of the hysteresis in burley tobacco bales. The diurnal variation of the equilibrium moisture content seen in Fig. 4 causes error in the moisture contents predicted by equation [7] because they subject the bales to both sorption and desorption gradients during a typical day. When the average daily equilibrium moisture content is used with the desorption diffusion coefficient of Swetnam and Walton (1984), it is implicitly assumed that all moisture diffusion takes place at the rate indicated by these desorption diffusion coefficients. Actually, though, the high equilibrium moisture contents at night cause very little sorption of moisture since the diffusion coefficients for moisture sorption are so much smaller than those for desorption. As a result, the model predicted an increase in moisture content during storage while it actually dried, as shown in Fig. 1.

The problem of the model predicting too much moisture sorption with the desorption diffusion coefficients was compensated for by calculating the monthly average equilibrium moisture contents from the monthly average temperature and humidity, given in Table 1. The equilibrium moisture content is a nonlinear function of humidity (Jeffrey, 1940, and Locklair et al., 1957), thus, the equilibrium moisture contents found from the average relative humidity for each month were lower than would have been obtained by calculating the equilibrium moisture content at every time that the relative humidity is available from the weather data during the month (i.e. every third hour of the day), and then averaging these equilibrium moisture contents over the whole month. The data in Table 2 show that the standard errors are evenly distributed between high and low and thereby indicate that these average equilibrium moisture contents compensate to some extent for the high night time equilibrium moisture contents that actually do not cause as much moisture sorption as their magnitude indicates. The higher initial moisture content bales, i.e. those above 24% d.b., had predicted moisture contents that were lower than observed because, at their higher moisture contents, they were subject to less night time sorption gradients than were the lower initial moisture content bales, and, thus, they had less error for predicting too much sorption at night. The prediction of the model cannot be improved with the diffusion coefficient data available. Diffusion coefficients for moisture sorption in densely packed burley leaves must be determined before the prediction of the model can be improved.

The data shown in Table 2 and Figs. 1, 2, and 3 were for a particular year. The question naturally arises as to what can be expected in an average year if bales of burley tobacco must be held over for next years sale because of exceeding quota. Table 3 shows the theoretically predicted weight loss due to moisture loss during an average year predicted by equation [7] for burley tobacco bales stored from November 1 to October 31 of the next year. Average weight losses were 0.11 kg, 2.46 kg, and 4.70 kg for low, normal and high initial moisture content bales, respectively. These values corresponded to weight losses of 0.4%, 7.2%, and 11.7% of the initial bale weight for low, normal, and high initial moisture contents. The lack of sufficiently large drying gradients

TABLE 2. STANDARD ERROR OF PREDICTION FOR 14 EXPERIMENTAL BALES.

	Initial moisture content	Stalk position	Rep.	Standard error*, % d.b.	% S.E.† / avg. m.c.
Low	15.5	Bottom	1	+3.66	25.0%
	16.4	Bottom	2	+3.68	24.0%
	19.8	Top	1	+2.33	14.0%
	18.3	Top	2	+2.29	14.0%
Normal	20.1	Bottom	1	+2.21	12.7%
	19.8	Bottom	2	+2.65	15.5%
	23.0	Middle	1	+0.44	2.2%
	25.1	Middle	2	−2.04	9.0%
	25.5	Top	1	−2.89	12.4%
	24.4	Top	2	−1.70	7.8%
High	41.8	Bottom‡	1	(−9.22)	(24.7%)
	29.0	Bottom	2	−1.51	6.8%
	28.3	Top	1	−3.84	16.0%
	27.7	Top	2	−1.81	7.5%

*The (+) or (−) indicates whether the predicted final moisture content was higher or lower than observed, respectively.

† = 100 x (Standard Error)/(Average observed moisture content).

‡Unusually high density bale: diffusion coefficients from the literature are not actually applicable.

TABLE 3. PREDICTED WEIGHT LOSS OF TYPICAL BURLEY TOBACCO BALES AFTER ONE YEAR IN STORAGE.

Initial moisture content*	Stalk position	Final moisture content, % d.b.	Assumed initial bale weight, kg	Predicted final bale weight, kg	Moisture weight loss, kg
Low	Bottom	17.58	27.22	27.03	0.19
Low	Middle	18.20	27.22	27.17	0.05
Low	Top	17.99	27.22	27.12	0.10
Normal	Bottom	18.33	34.02	31.46	2.57
Normal	Middle	19.02	34.02	31.63	2.39
Normal	Top	18.89	34.02	31.60	2.42
High	Bottom	18.37	40.82	35.77	5.05
High	Middle	19.98	40.82	36.26	4.56
High	Top	19.29	40.82	36.05	4.77

*Low, 18.4% d.b.; 28.0% d.b.; High, 35.1% d.b.

TABLE 4. COMPARISON OF MOISTURE CONTENT BY TWO-DIMENSIONAL AND THREE-DIMENSIONAL MODELS.

Initial moisture content*	stalk position	Month	3-d model average moisture content, % d.b.	2-d model average moisture content, % d.b.	Percentage points difference
Low	Bottom	6	15.83	16.08	0.25
Low	Middle	7	16.33	16.47	0.14
Low	Top	6	16.36	16.49	0.13
Normal	Bottom	7	17.88	18.04	0.16
Normal	Middle	9	18.91	18.99	0.08
Normal	Top	7	19.58	19.81	0.23
High	Bottom	6	21.84	22.29	0.45
High	Middle	8	21.25	21.65	0.40
High	Top	5	25.45	26.14	0.69
				Average =	0.28

*Low, 18.4% d.b.; Normal, 28.0% d.b.; High, 35.1% d.b.

to cause much drying during December and January for normal and high moisture content bales, minimizes any error that may have resulted from extrapolating the diffusion coefficients for these low temperature months.

The difference between the magnitude of the diffusion coefficients in the parallel and perpendicular directions (Swetnam and Walton, 1984) suggests that it may be possible to neglect diffusion perpendicular to the leaf lamina, thus, using only a two-dimensional model, without introducing appreciable error. The model predicted that drying penetrated only a short distance into the bale in the perpendicular direction. The average bale moisture contents were recalculated assuming that the moisture contents in the interior of the bale, which were not affected by diffusion in the perpendicular direction, extended to the surface of the bale, as would be the case if there were no diffusion in that direction. The resulting moisture contents, at the worst month for the particular bale, are compared to those predicted by the three-dimensional model in Table 4.

Table 4 shows that the average difference between the prediction of the two and three-dimensional models was 0.28 percentage points, d.b. This translated to a 0.07 kg difference for an average bale, or 0.21% of the total bale weight. Such a small error would not be significant compared to the errors that simply result from variation between samples of such biological materials.

The assumption during the mathematical development that the surface resistance to moisture diffusion is negligible followed from assuming that the bales are separated during storage, and that they are in an environment, such as a barn, where there will be at least a small continuous air flow over them. Theoretical calculations showed that the error in the λ_s values in equation [7] was about 1 percent for airflows of 15.2 m/s. Since even higher airflows are common in burley tobacco barns, this assumption was very reasonable.

Because no penalties are applied for moisture content when tobacco is sold, unless it is so wet as to be in danger of spoiling, it is usually profitable for the farmer to bale tobacco at a relatively high moisture content, and thus, increase the total weight sold. The small difference in final moisture contents in Table 3 indicates that there is little advantage to baling tobacco at high moisture content if it is to be stored for a long period of time. The small increase in final moisture content does not justify the risk of spoilage that may occur (Bunn and Henson, 1978) while the tobacco is at high moisture content.

The mathematical model derived using time varying boundary conditions showed promise, but its ability to accurately predict the moisture content history of burley tobacco bales was severly limited by the lack of proper input parameters. Diffusion coefficients for sorption and the hysteresis of equilibrium moisture contents are needed to improve the prediction accuracy of the model.

CONCLUSIONS

The following conclusions were formulated from the results of this study:

1. The model of equation [7] generally predicted a higher final moisture content than observed for a low initial moisture content and a lower final moisture content than observed for a high initial moisture content.
2. The model agreed better with experimental results when the initial moisture content was at the high and normal level than when the initial bale moisture content was so low that the bale was subjected to both wetting and drying conditions caused by diurnal variations of ambient relative humidity.
3. The predicted weight loss caused by moisture loss from burley tobacco bales stored for one year in an open environment was 0.4, 7.2, and 11.7% of the initial bale weight for low, normal, and high initial moisture contents, respectively.
4. A 0.21% error in moisture content prediction resulted from assuming that moisture diffusion perpendicular to the leaf lamina was negligible.
5. There is little advantage to baling tobacco at high moisture content if the bales are to be stored for about 1 year before being sold.
6. Using the average monthly temperature and humidity to obtain the equilibrium moisture content compensated to some extent for the model's tendency to overestimate moisture sorption at night.

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