Diffusion of Moisture from Burley Tobacco Leaves During Curing

Linus R. Walton, Mark E. Casada, Wiley H. Henson, Jr.,
MEMBER ASAE   MEMBER ASAE
Larry D. Swetnam, James H. Casada
ASSOC. MEMBER ASAE   MEMBER ASAE

ABSTRACT

THE whole leaf diffusion model, derived from the vapor diffusion equation, was shown to be applicable to the drying of burley leaves during the cure. The diffusion models accurately described the drying of whole burley leaves. The exponential model, which was used as a standard of comparison, was better at describing the drying of the separated leaf components, lamina and midrib, than were the diffusion models, but was very poor at describing the drying of whole leaves. The whole leaf diffusion model physically explained the transfer of moisture from the midrib to the lamina of the intact leaf by effectively increasing and reducing the modified diffusion coefficients of the midrib and lamina, respectively, compared with those of the separated lamina and midrib in which no moisture was transferred between these leaf components.

INTRODUCTION

Curing of burley tobacco is characterized physically by a loss of moisture and continuous color change of the leaf from green to yellow to brown (Walton and Henson, 1971). The chemical composition of the leaf is altered greatly during curing (Tso, 1972). The principal enzymatic reactions that occur during air curing are the hydrolytic breakdown of large molecules, such as protein, starch, nucleic acids, etc. and the oxidative reactions that convert amino acids, carbohydrates, etc. from the breakdown of the large molecules to organic acids, carbon dioxide, ammonia, water and other compounds. About 15 to 20 percent of the dry weight of the leaf is lost by these reactions. The principal factors which control these essential biochemical processes are temperature and moisture content of the leaf. So the rates of moisture loss and chemical changes must be compatible to cure good quality burley tobacco. From a drying standpoint, the problem is to maintain a leaf moisture content which will enhance desirable chemical and biological changes in the leaf.

Article was submitted for publication in May 1981; reviewed and approved for publication by the Electric Power and Processing Division of ASAE in February 1982. Presented as ASAE Paper No. 80-3549.

The investigation reported in this paper (No. 80-2-254) is in connection with a joint project of the Southern Region, USDA-ARS, and the Agricultural Experiment Station, College of Agriculture, University of Kentucky, and is published with the approval of the Director of the Station.

The authors are: LINUS R. WALTON, Associate Professor, MARK E. CASADA, Agricultural Engineer, WILEY H. HENSON, JR., Agricultural Engineer, USDA-ARS, Southern Region, Mid-Atlantic Area; LARRY D. SWETNAM, Agricultural Engineer, and JAMES H. CASADA, Research Specialist, Agricultural Engineering Dept., University of Kentucky, Lexington, KY.

The exchange of moisture between the curing leaf and its environment is in response to a vapor pressure difference between the interior of the leaf and the ambient environment with the moisture diffusion in the direction of the lower vapor pressure. Experience indicates that the thin lamina dries faster than the thicker midrib. Thus, the condition may occur that causes moisture to diffuse to the lamina and away from the midrib. Three environmental factors—airflow, temperature and humidity—affect diffusion of moisture between the leaf and the ambient environment because of their relationship to convective mass transfer coefficient, the mass diffusivity, and the vapor pressure gradient. Before the environment can be controlled to provide improved curing, the response of tobacco to be a given environment must be known.

Drying curves for tobacco have been experimentally determined by several investigators (Humphries, 1963; Chang and Johnson, 1971; Bunn and Henson, 1968; Bunn et al., 1972; Parups and Hoffman, 1964; Stinson et al., 1974; and Walton et al., 1976). The last three studies were on drying of the cured leaf rather than drying of the leaf during curing. Bunn et al. (1972) used a modified hyperbolic equation to empirically describe the drying of high moisture materials, including the drying of whole burley plants. Bunn and Henson (1968) had previously used an exponential equation to describe the drying of burley leaves. Humphries (1963) devised an experimental technique for determining the resistance of the epidermal layers of the tobacco leaf to the diffusion of moisture during yellowing of flue-cured tobacco.

Walton et al. (1976) derived diffusion models for the lamina and midrib of the cured leaf which are based on diffusion theory and the geometry of the leaf components. The objective of this paper was to determine the applicability of these mathematical models of diffusion of moisture to the drying of burley leaves during the cure. The evaluation of applicability was based on accuracy and the ability of the models to physically explain the dynamics of the drying process.

MATHEMATICAL MODELS

The lamina and midrib are the two primary components of the burley leaf. The thickness, shape and physical structure of the lamina differ greatly from that of the midrib. Walton et al. (1976) showed that the lamina and midrib of the cured leaf differ greatly. Visual observation indicated a similar difference during curing of burley tobacco. Thus, models were required for both the lamina and midrib and were derived by Walton (1974). Geometric models of the lamina and midrib were determined as the first step of the model development.

Since lamina is the thin broad portion of the leaf with a very small thickness to surface area ratio, the infinite thin sheet was chosen as the geometric model to represent the lamina.

The midrib, central vein of the leaf, has a diameter of about 1.5 to 2.0 cm near the stalk, and is tapered toward the tip. The cross section appears to be a circle with a segment removed on the top side of the leaf. The infinitely long circular cylinder was chosen as the geometric model of the midrib because of the very high length to diameter ratio of the midrib and because the circular cross section more nearly approximates the cross section of the midrib than any of the classical shapes.

The governing equation was the vapor diffusion equation with the assumption that the surface of the tobacco leaf instantaneously reached equilibrium with its environment. The model for the moisture content of the lamina was derived as a function of time and the distance from the center of the lamina. This equation was integrated over the thickness of the lamina to yield an equation (Walton, 1974) for the average moisture content of the lamina as a function of time:

$$\theta_L(t) = \sum_{n=0}^{\infty} \frac{2}{(\lambda_n L)^2} e^{-(D/L^2)(\lambda_n L)^2 t} \quad \text{[1]}$$

where

θ = $M - M_e/M_o - M_e$
M = Moisture content at time t, dry basis, percent
M_e = Equilibrium moisture content, percent
M_o = Initial moisture contnent
L = Half thickness of the lamina, cm
$\lambda_n L$ = $(2n + 1)\pi/2$
n = 0, 1, 2 . . .,
D = Mass diffusion coefficient based on the mass of water per unit mass of solid, cm^2/h
t = time, h
(D/L^2) = Modified mass diffusion coefficient for the lamina, h^{-1}

The model for the midrib was derived as a function of time and the radial coordinate and then integrated over the radius to yield a mathematical model (Walton, 1974) for the average moisture content of the midrib as a function of time:

$$\theta_M(t) = \sum_{n=1}^{\infty} \frac{4}{(\beta_n R)^2} e^{-(D/R^2)(\beta_n R)^2 t} \quad \text{[2]}$$

where

$\beta_n R$ = nth positive root of $J_o(\beta_n R) = 0$
$J_o(\beta_n R)$ = Bessell function of order zero
R = Radius of midrib, cm
(D/R^2) = Modified mass diffusion coefficient for the midrib, h^{-1}

The exponential equation was used as the standard of comparison in evaluating the aucuracy of equations [1] and [2] as applied to drying of the lamina, midrib, and whole leaf.

$$\theta(t) = e^{-kt} \quad \text{[3]}$$

where

k = drying constant, h^{-1}

The modified mass diffusion coefficients and drying constant are constants only for a given temperature and humidity. Determination of the effect of temperature and humidity on these constants is beyond the scope of this research.

EXPERIMENTAL PROCEDURE

Drying curves for the lamina, midrib, and whole leaf were required. Eight plants of burley variety KY-14 were harvested at optimum maturity and separated into two groups of four plants for curing of the leaves at temperature and relative humidity combinations of 29 °C, 43 percent and 24 °C, 65 percent. Four consecutive leaves were removed from the middle stalk position of each plant. The top and bottom-most of the four leaves were separated into their lamina and midrib components. The two middle leaves were left intact for curing. The wounded edge of both the lamina and midrib were coated with paraffin to prevent moisture loss from the severed edge. The sample size was thus two intact leaves and two leaves separated into their leaf components (lamina and midrib). There were four replications of each sample.

The specimens were placed in chambers with temperature and relative humidity control. The relative humidity was maintained by saturated salt solution. Uniformity of conditions was maintained in each chamber by circulation of air. The specimens were weighed using 454 g load cells at about 12-h intervals over the first 60 h, at least daily through 200 h of curing, and at the end of the cure (equilibrium weight).

Equations [1] and [2] were fitted to the desorption data using the method of Marquardt (1966) of minimizing the sum of square of the differences between observed and predicted values of moisture ratio, $\theta(t)$, through an iterative process. The computed parameters were the

TABLE 1. STANDARD ERROR OF THE LAMINA MODEL (EQUATION (1), MIDRIB MODEL (EQUATION (2), AND THE EXPONENTIAL MODEL (EQUATION (3) WHEN APPLIED TO THE SEPARATED LAMINA AND MIDRIB OF THE LEAF

Environmental conditions			Standard error of $\theta(t) \times 10^2$			
			Lamina		Midrib	
Temperature, °C	Relative humidity, %	Plant number	Lamina model	Exponential model	Midrib model	Exponential model
29	43	1	1.39	1.32	3.24	4.12
		2	1.98	0.62	1.78	3.40
		3	1.51	0.86	2.92	3.21
		4	1.89	0.58	3.61	1.87
24	65	1	2.88	0.68	3.13	3.69
		2	3.31	0.64	2.59	2.70
		3	2.35	1.31	2.90	2.70
		4	3.22	0.92	2.95	3.72

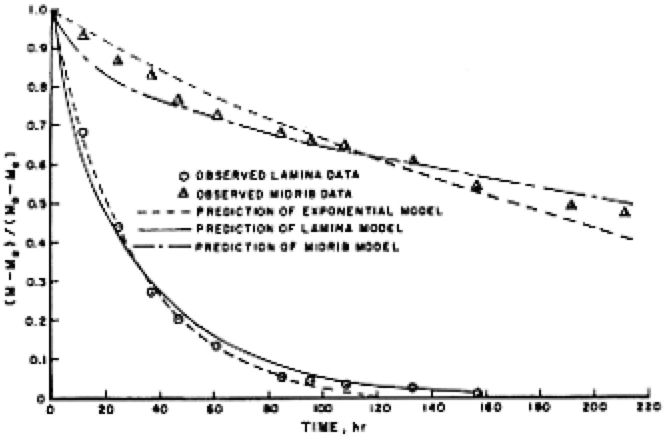

FIG. 1 Observed and predicted lamina and midrib moisture ratio by the exponential model and the lamina and midrib diffusion models at 24 °C and 65 percent R.H.

mass diffusion coefficient and the drying constant that gave the best fit of equations [1], [2], and [3] to the experimental data.

The fitting of equation [3] to the experimental data was straightforward, but the fitting of the lamina and midrib models was more involved. Equations [1] and [2] were fitted to the data for the separated components of the leaf, the lamina and midrib, respectively. The model for the whole leaf was the sum of the weighed average of the lamina and midrib models using weights of the components from the same plant as the whole leaves:

$$\theta_W(t) = \frac{(W_o - W_e)_L}{(W_o - W_e)_W}\,\theta_L(t) + \frac{(W_o - W_e)_M}{(W_o - W_e)_W}\,\theta_M(t) \quad \ldots\ldots\ldots [4]$$

where

$\theta_w(t)$ = θ of whole leaf
W_o = Initial weight, g
W_e = Equilibrium weight, g
L = Subscript denoting lamina
M = Subscript denoting midrib
W = Subscript denoting whole leaf
$(W_o - W_e)_W = (W_o - W_e)_M + (W_o - W_e)_L$

The mathematical models of the midrib given by equations [1] and [2] were derived from an analysis of the diffusion of moisture from the cured leaf. The experiment just described was designed to determine the applicability of these models to the diffusion of moisture from the leaf during curing.

RESULTS AND DISCUSSION

The standard error of the lamina model (equations [1]), midrib model (equation [2]), and the exponential model (equation [3]), when applied to the separated lamina and midrib of the leaf, is shown in Table 1. The exponential model was far superior to the lamina model in describing the drying of the lamina when separated from the midrib. However, the midrib model was slightly better than the exponential model in describing the drying of the midrib when separated from the lamina.

The lamina and midrib models were based on the consideration of internal resistance to diffusion of moisture (the external resistance was assumed to be negligible compared to the internal resistance). The exponential model is not based on internal resistance to diffusion of moisture, and thus, is most applicable when internal moisture gradients are small. Therefore, the exponential model was expected to apply better to the drying of the lamina with its small thickness than to the drying of the midrib with its larger radius and was expected to have its best opportunity of exceeding the diffusion models in accuracy when applied to the drying of the separated lamina.

The modified mass diffusion coefficients from equations [1] and [2] and drying constants from equation [3] for the separated lamina and midrib of the leaf are shown in Table 2. A comparison of the lamina and midrib data showed that the lamina data were much more consistent than the midrib data. The comparison also showed that the lamina dried much faster than the midrib as the relative dimensions of the components would lead one to expect. Lamina and midrib drying data along with the prediction curves from the lamina, midrib, and exponential models are shown in Fig. 1. The half life [$\theta(t) = 0.5$] of the lamina was 20 h compared to 186 h for the midrib of Fig. 1.

The standard error of the whole leaf diffusion model (equation [4]) and the exponential model (equation [3]), when applied to whole leaf drying, is shown in Table 3. The standard error showed that the whole leaf diffusion model described the drying of the whole leaf much better than did the exponential model. The diffusion model described the drying of the whole leaf as well as it described the drying of the lamina and better than it described the drying of the midrib (Table 1). The exponential model did not describe the drying of the whole leaf nearly as well as it described the drying of the lamina or midrib (Table 1). Since the exponential did a good job of describing the drying of the leaf components, one would not expect it to describe the drying of the whole leaf equally well because the sum of two exponentials cannot be described very well by a single exponential. However, the objective of this paper was to evaluate the

TABLE 2. MODIFIED MASS DIFFUSION COEFFICIENTS FROM EQUATIONS [1] AND [2] AND DRYING CONSTANTS FROM EQUATION [3] FOR THE SEPARATED LAMINA AND MIDRIB OF THE LEAF

Environmental conditions			Modified Diffusion coefficients		Drying constants	
Temperature, °C	Relative humidity, %	Plant number	Lamina $(D/L^2) \times 10^2$	Midrib $(D/R^2) \times 10^4$	Lamina $k \times 10^2$	Midrib $k \times 10^3$
29	43	1	1.648	7.958	4.942	8.391
		2	1.688	1.852	5.036	3.274
		3	1.515	3.454	4.550	4.794
		4	1.815	2.139	5.391	3.601
24	65	1	1.126	2.921	3.419	4.111
		2	1.059	1.492	3.220	2.740
		3	1.173	1.841	3.577	3.103
		4	0.818	3.393	2.512	4.519

TABLE 3. STANDARD ERROR OF THE WHOLE LEAF DIFFUSION MODEL (EQUATION [4]) AND THE EXPONENTIAL MODEL (EQUATION [3]) WHEN APPLIED TO WHOLE LEAF DRYING

Environmental conditions			Standard error of $\theta(t) \times 10^2$	
Temperature, °C	Relative humidity, %	Plant number	Diffusion model	Exponential model
29	43	1	1.72	7.18
		2	1.88	9.87
		3	1.36	9.89
		4	2.06	9.47
24	65	1	2.71	6.03
		2	3.12	4.92
		3	2.88	4.84
		4	3.31	3.61

diffusion models. Using the exponential model as the standard of comparison, the whole leaf model (equation [4]) was concluded to have sufficient accuracy to be considered valid.

The modified mass diffusion coefficients from equation [4] and the drying constants from equation [3] for drying of the whole leaf are shown in Table 4. Observation of the curing tobacco showed that the lamina of the whole leaves dried rapidly compared to the midrib with the exception of a small area of lamina adjacent to the midrib that acts as a fin to transfer moisture from the midrib. The effect of this localized moisture transfer on the whole leaf diffusion model was shown by comparing the modified mass diffusion coefficients of Table 4 to those of Table 2. The values for the lamina and midrib from the whole leaf were lower and higher, respectively, than that of the separated lamina and midrib as was expected since the drying of the lamina was retarded and the drying of the midrib enhanced by the localized moisture transfer from the midrib to the lamina. An example of whole leaf drying data along with the prediction curves of the whole leaf diffusion model and the exponential model is shown in Fig. 2. The diffusion model had its greatest error during the first 24 h but provided an excellent description of the data thereafter. The exponential model gave a poor description of the data.

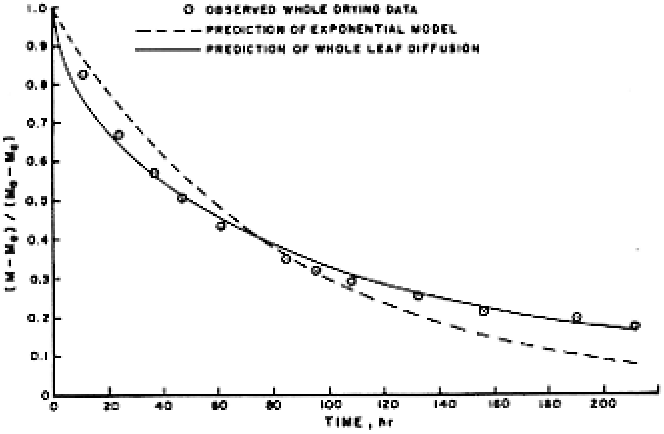

FIG. 2 Observed and predicted moisture ratio of whole leaf by the exponential model and the whole leaf diffusion model at 24 °C and 65 percent R.H.

CONCLUSIONS

The conclusions formulated from the results of this research were as follows:

1 The whole leaf diffusion model (equation [4]) accurately described drying of whole burley leaves.

2 The exponential model (equation [3]) was better at describing the drying of the separated lamina than was the diffusion model of the lamina (equation [1]).

3 The diffusion model (equation [2]) of the midrib was slightly better at describing the drying of the separated midrib than was the exponential model (equation [3]).

4 The whole leaf diffusion model physically explained the transfer of moisture from the midrib to the lamina of the intact leaf by effectively increasing and reducing the modified diffusion coefficients of the midrib and lamina, respectively, compared with those of the separated lamina and midrib in which no moisture was transferred between these leaf components.

5 The whole leaf diffusion model (equation [4]) is applicable to the drying of burley leaves during the cure.

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TABLE 4. MODIFIED MASS DIFFUSION COEFFICIENTS FROM EQUATION [4] AND DRYING CONSTANTS FROM EQUATION [3] FOR DRYING OF THE WHOLE LEAF

Environmental Conditions			Modified Diffusion coefficients		Drying
Temperature, °C	Relative humidity, %	Plant number	Lamina $(D/L^2) \times 10^2$	Midrib $(D/R^2) \times 10^4$	constant $k \times 10^2$
29	43	1	0.9586	7.510	1.477
		2	1.4254	5.944	1.429
		3	1.4034	6.026	1.507
		4	1.3607	6.308	1.436
24	65	1	0.6233	7.164	1.205
		2	0.4245	7.028	0.999
		3	0.4405	7.983	1.066
		4	0.2939	7.045	0.857