Moisture Permeability of Cured Tobacco Epidermis

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The mechanism of moisture transfer into the cured tobacco leaf was investigated in connection with the moistening processes during cigarette manufacturing. The moisture was sorbed through three pathways: through the upper epidermis, lower epidermis and the cut face. For laminar tobacco larger than about 5.0 mm in width, most moisture was sorbed through the epidermes, with nearly equal flux through the upper and lower epidermes. The permeability of the cuticular layer was the limiting factor to moisture transfer rate into the cured laminar tobacco through the epidermis, and the moisture transfer through the stomata was negligible as compared with that through the cuticular layer. An empirical kinetic model is presented to describe the entire moisture sorption process through cured tobacco epidermis, together with the values of the parameters involved. Rational moisture control of the cured laminar tobacco will be possible on the basis of this analysis.

Many physical properties of tobacco are highly sensitive to its moisture content, and the control of moisture content of tobacco is a matter of primary concern in the tobacco industry. Moisture is added to, and removed from, the tobacco several times during processing depending on the type of operation, changing the moisture content in the range from ca. 5% to ca. 40% on a dry basis. However, the mechanism of moisture transfer into and out of the cured tobacco has not yet been satisfactorily studied.

Chen et al. and Shimizu have studied the rates of moisture desorption in tobacco during the curing process, using leaves with a 100~400% moisture content on a dry basis. Kamei et al. have analyzed the rates of sorption and desorption of moisture in cured tobacco, but they used the whole leaf without separating the midrib. In cigarette manufacturing, the drying and the moistening operations are conducted mainly with laminar or shredded tobacco.

In order to develop a rational moistening criterion for the cured laminar tobacco with less than 50% moisture content on a dry basis, the mechanism of moisture transfer into cured tobacco was investigated in this paper.

MATERIALS AND METHODS

Tobacco. Flue cured tobacco (BY-4) and air cured tobacco (Burley-21) were used, since their porous structures and moisture sorption capacities were quite different as previously reported.

Microscopic observation. The surface and the stomata of the cured tobacco leaf were observed with a scanning electron microscope (Nihon-Denshi JEM 100B and ASID).

Physical properties. True and apparent densities, \( \rho \) and \( \rho' \): True density, \( \rho \), was measured with a Toshiba-Beckman Air Pycnometer using ground tobacco. Apparent density, \( \rho' \), was calculated from Eq. (1).

\[
\rho' = 1/(1/\rho + V_p) \quad (g\cdot cm^{-3})
\] (1)

Pore volume, \( V_p \) (cm\(^3\)·g\(^{-1}\)): Total lacunal volume in the...
Fig. 1. Three Fluxes of Moisture Sorption into a Cured Tobacco Leaf.

Pu, Pl and Pc: Fluxes through the upper leaf epidermis, lower leaf epidermis and cut faces, respectively.

texture of tobacco was measured on shredded tobacco by means of the Solution-Impregnation Method. Specific leaf-surface area, $A$ (cm$^2$·g$^{-1}$): This was calculated from the average weight of twenty laminae, the surface area of each being 72 cm$^2$ (6 cm x 6 cm x 2).

Leaf thickness, $d$: This was calculated from Eq. (2). The calculated thickness was in good agreement with the measured mean values.

$$d = 2(\sqrt{p + V_p})/A \text{ (cm)} \quad (2)$$

Rate of sorption. The laminar tobacco was fixed with fine brass wire to avoid deformation, and the shredded tobacco was placed on, or between, brass wire nets. These samples were hung from a balance in a room where the temperature, humidity and air velocity were controlled at experimental conditions. The changes in weight were measured by stopping the air flow. Three fluxes of moisture sorption were considered as Fig. 1 shows: the fluxes through the upper epidermis, lower epidermis and the cut face. Each flux was measured by sealing the others with paraffin.

Moisture transfer coefficient of cured tobacco epidermis. The moisture transfer coefficient through cured tobacco epidermis, $K_s$, was calculated from Eq. (3).

$$\frac{M}{A} \cdot \frac{d\bar{W}}{dt} = K_s(\bar{W}_e - \bar{W})^n \quad (\text{mg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}) \quad (3)$$

where

- $K_s$: moisture transfer coefficient through the epidermis (mg·cm$^{-2}$·s$^{-1}$)
- $\bar{W}_e$: equilibrium moisture content on a dry basis under the experimental conditions (%)
- $\bar{W}$: average moisture content on a dry basis, at time $t$ (%)
- $n$: empirical constant (--)
Moisture Sorption in Tobacco

Fig. 2. Influence of Shred Width on Total Moisture Sorption Rates at 23°C, 80%RH and W of 10%.

--- , sorption rate through the upper and lower leaf epidermes. The cut faces were sealed with paraffin.

the moisture content is controlled for both the laminar and shredded tobacco leaves. The moisture transfer through the leaf epidermis and cut faces should, therefore, be separately estimated for rational moisture control. The moisture transfer through the leaf epidermis was studied in this paper. The moisture control for shredded tobacco will be discussed in the next paper.

3) Mechanism of moisture transfer through the cured tobacco epidermis

Two pathways can be considered for moisture transfer through the leaf epidermis, that is, through the stomata and cuticular layers. Electron microscopic observation showed that almost all the stomata of cured tobacco leaf were closed as Fig. 3 indicates, although the airtightness of closed stomata may not be complete. The size of the stoma in the upper and lower leaf surface was nearly equal. However, the number of stoma in the lower leaf surface was about 3 times as many as in the upper leaf surface. If the moisture was mainly transferred through the stomata, the upper and lower leaf epidermes would have different permeabilities to moisture. By sealing one side of a leaf with paraffin, the rate of moisture sorption through the other side of the leaf was measured and the values compared with each other as Fig. 4 shows. In Fig. 4, the value of We was determined after the sorption equilibrium had been reached. The moisture sorption rate through the lower leaf epidermis was only slightly larger than that through the upper leaf epidermis. Since the area occupied by stomata was less than 1% of the total leaf-surface, it was assumed in the following analysis that the moisture transfer through the stomata was negligible as compared with the moisture transfer through the cuticular layer.

After removing the cuticular layers with chroloform, the rate of moisture sorption
Fig. 5. Rates of Moisture Sorption through the Leaf Epidermis and the Influence of Cuticular Layer Removal. (30°C, 75%RH)

O—— , intact BY-4; □—— , cuticular layer removed BY-4; A—— , intact Burley-21.

Table II. Values of $K_s$ and $n$ in Eq. (3)

<table>
<thead>
<tr>
<th>Tobacco</th>
<th>$K_s$ (mg·cm$^{-2}$·s$^{-1}$)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BY-4</td>
<td>$6.19 \times 10^{-6}$</td>
<td>1.15</td>
</tr>
<tr>
<td>Burley-21</td>
<td>$4.04 \times 10^{-6}$</td>
<td>1.37</td>
</tr>
</tbody>
</table>

markedly increased as Fig. 5 shows. This result indicates that the permeability of the cuticular layer is the limiting factor to the moisture transfer rate through cured tobacco epidermis.

Figure 5 also shows the linear relationship between $\log(\frac{W_e - \bar{W}}{A \cdot d\bar{W}/dt})$, according to Eq. (3), for the intact BY-4 and Burley-21. The values of $K_s$ and $n$ in Eq. (3) were determined as shown in Table II.

4) Influence of temperature and relative humidity on the moisture sorption rate parameters

Figure 6 shows the influence of temperature and relative humidity on the values of $K_s$ and $n$ in the kinetic model of Eq. (3). The values of $K_s$ and $n$ were not affected by the relative humidity as shown by the solid symbols in Fig. 6. The values of $W_e$ at 70, 80 and 87% relative humidities, at 23°C, were 20.1, 31.8 and 40.7%

on a dry basis, respectively. The value of $n$, which is the slope of the straight lines in Fig. 6, was also independent of temperature. The semi-logarithmic plots of $K_s$ vs. $1/T$, the reciprocal of the absolute temperature, fell on a straight line as Fig. 7 shows. Therefore, assuming Arrhenius’ relationship in Eq. (4), the activation energy was estimated to be 57.3 kJ per mol.
\[ K_s = K_{s0} \cdot e^{-E/RT} \text{ (mg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}) \]  

(4)

where

- \( K_{s0} \): constant (mg \cdot \text{cm}^{-2} \cdot \text{s}^{-1})
- \( R \): ideal gas constant (kJ \cdot \text{mol}^{-1} \cdot \text{K}^{-1})
- \( E \): energy of activation (kJ \cdot \text{mol}^{-1})
- \( T \): absolute temperature (K)

The temperature dependence of the moisture permeability for several polymer films has been determined by Doty et al., with results showing a wide range of behavior in this respect. The activation energy of moisture permeability for cured tobacco epidermis was approximately equal to that of plofilm. Thus, the empirical model of Eq. (3) was proved to be suitable for describing the moisture transfer through the cured tobacco epidermis.

Since the moisture of tobacco is controlled on the basis of \( W \), the integration of Eq. (3), shown as Eq. (5), can be used to predict the time–moisture content relationship for laminar tobaccos.

\[ t = \frac{M}{K_s \cdot A} \cdot \frac{(W_e - \bar{W})^{1-n} - (W_e - \bar{W})_0^{1-n}}{n-1} \]  

(5)

where

- \((W_e - \bar{W})_0\) is the value of \( W_e - \bar{W} \) at \( t = 0 \) (%)

Values for the parameters in Eq. (5) are already summarized in Tables I and II. In Eq. (5), the values of \( K_s \) and \( n \) are not very different for the flue cured and the air cured tobaccos, but the values of \( A \) are quite different. Therefore, the time necessary to reach the equal moisture content, \( \bar{W} \), will be quite different for flue cured and the air cured tobaccos.

The moisture control of shredded tobacco will be discussed in the next paper.

REFERENCES