MASS-TRANSFER CHARACTERISTICS OF TOBACCO LEAVES

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Analytical results are presented on the mass-transfer characteristics of tobacco leaves.

Water transport is inseparable from heat transport, and the two have to be considered essentially together [1].

The treatment of tobacco leaves may be otpimized if one knows the mass-transfer characteristics; a tobacco leaf has a highly developed capillary structure and a large surface of contact with the air, which means that water can be taken up rapidly.

The mode of binding of the water to the material varies from one part of the isotherm to another, so it is not possible to describe the isotherm by a single equation [2], and so the experimental evidence is described by an empirical formula relating the equilibrium water content to the relative humidity of the air.

Absorption isotherms recorded by tensimetric methods [3] have given a straight-line relation for adsorbed water, viz.,

$$U = a\varphi + b, \tag{1}$$

while for the curvilinear part, which represents capillary-bound and osmotic water, the two-constant empirical formula is

$$U = \frac{K\varphi}{B - \varphi}. \tag{2}$$

Least-squares fitting for the isotherms for a particular type of tobacco leaf has given

$$U = 0.129\varphi + 0.025, \quad 0{,}1 \leqslant \varphi < 0.5, \tag{3}$$

$$U = \frac{0.102\varphi}{1.056 - \varphi}, \quad 0.5 \leqslant \varphi \leqslant 0.9. \tag{4}$$

If (3) and (4) are considered as a single curve, then the latter has a discontinuity at $\varphi = 0.5$; as the isotherm should be continuous, we eliminate the discontinuity by continuing curve (4) to the left to the point where it meets (3). This gives $\varphi = 0.484$.

With these revised boundaries, (3) and (4) become

$$U = 0.129\varphi + 0.025, \quad 0.1 \leqslant \varphi \leqslant 0.484, \tag{5}$$

$$U = \frac{0.102\varphi}{1.056 - \varphi}, \quad 0.484 \leqslant \varphi \leqslant 0.9. \tag{6}$$

The point $\varphi = 0.484$ is the junction between the two parts, at which the derivative has a discontinuity, and therefore $\varphi = 0.484$ is a singular point. This characterizes approximately the transition from one form of water binding to another.

The transport potential for water vapor in moist air is a chemical potential dependent on temperature, the partial pressure of the water vapor, and the water content of the material; the binding energy for water in the hygroscopic region (for $U < U_h$) is [2, 4] equal in magnitude to the chemical potential for mass transport, i.e., $E \equiv |\mu|$,

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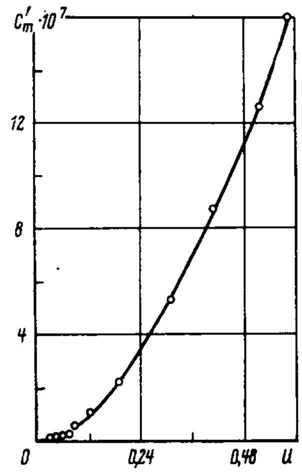

Fig. 1. Dependence of c'_m in kmole/J on water content U in kg/kg.

$$\mu = RT \ln \varphi. \tag{7}$$

One of the basic thermodynamic characteristics is the true (local) specific isothermal water capacity c'_m, and by the method of [4, 5] we determine this quantity as

$$c'_m = \left(\frac{\partial U}{\partial \mu}\right)_T \tag{8}$$

and the mean value $\bar{c}'_m$ for the range in φ from 0.1 to 0.9 at 293°K.

Much published evidence [2, 4, 5, 6] indicates that c'_m should be determined in the hygroscopic region as the slope of the tangent to the plot of U against μ for T = const, which results in some discrepancy from calculations, since graphical differentiation is of restricted accuracy even in skilled hands, and is also laborious.

Here we replace graphical differentiation in the determination of c'_m by the derivative of the function $U = f(\varphi)$ with respect to μ.

From (7), φ is expressed in terms of μ by

$$\varphi = \exp\frac{\mu}{RT}. \tag{9}$$

We substitute (9) into (5) and (6) to get

$$U = 0.129 \exp\frac{\mu}{RT} + 0.025, \quad 0.1 \leqslant \varphi \leqslant 0.484, \tag{10}$$

$$U = \frac{0.102 \exp\frac{\mu}{RT}}{1.056 - \exp\frac{\mu}{RT}}, \quad 0.484 \leqslant \varphi \leqslant 0.9. \tag{11}$$

We differentiate (10) and (11) with respect to μ to get

$$\frac{\partial U}{\partial \mu} = 0.129 \frac{1}{RT} \exp\frac{\mu}{RT}, \quad 0.1 \leqslant \varphi \leqslant 0.484, \tag{12}$$

TABLE 1. Thermodynamic and Physical Constants of Leaf Tobacco

Parameters	Rel. air humidity								
	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
Water content U in kg/kg of dry material	0,038	0,050	0,062	0,074	0,092	0,134	0,200	0,319	0,589
Mass-transport potential $\mu \cdot 10^{-5}$ J/mole	56,091	39,206	29,329	22,321	16,885	12,444	8,689	5,436	2,566
Specific isothermal mass capacity c'm in 10^{-7} mole/J									
analytical differentiation	0,052	0,103	0,155	0,206	0,697	1,244	2,381	5,261	15,939
graphical differentiation	0,069	0,135	0,180	0,220	0,0675	1,320	2,250	5,65	12,300

$$\frac{\partial U}{\partial \mu} = \frac{0,102\frac{1}{RT}\exp\frac{\mu}{RT}\left(1,056-\exp\frac{\mu}{RT}\right)+0.102\frac{1}{RT}\left(\exp\frac{\mu}{RT}\right)^2}{\left(1,056-\exp\frac{\mu}{RT}\right)^2}, \tag{13}$$

$$0,484 \leqslant \varphi \leqslant 0.9.$$

Various steps using (9) and $1/RT = 4 \cdot 10^{-7}$ cause (12) and (13) to become

$$\frac{\partial U}{\partial \mu} = 0.516 \cdot 10^{-7}\varphi, \quad 0,1 \leqslant \varphi \leqslant 0.484, \tag{14}$$

$$\frac{\partial U}{\partial \mu} = \frac{0.431 \cdot 10^{-7}\varphi}{(1,056-\varphi)^2}, \quad 0,484 \leqslant \varphi \leqslant 0.9. \tag{15}$$

The values of $\mu = RT\ln\varphi$ derived from (7) and of $c'_m = \frac{\partial U}{\partial \mu}$ derived from (12) and (13) are given in Table 1, while c'_m is also given in Fig. 1.

Table 1 shows that the value of c'_m found by graphical differentiation is substantially different from the c'_m found graphically in the parts that asymptotically approach the coordination axes; the value of c'_m at the singular point (φ = 0.484) we now determine from the following formulas, which are the limits to left and right as φ tends to 0.484:

$$\lim_{\varphi \to 0,484-0} c'_m \cdot 10^7 = 0,516 \cdot 0,484 = 0,250,$$

$$\lim_{\varphi \to 0.484+0} c'_m \cdot 10^7 = \frac{0,431 \cdot 0,484}{(1,056-0,484)^2} = 0,638.$$

The quantity $c'_m \cdot 10^7$ has a discontinuity at the singular point (Fig. 1), whose magnitude is 0.638−0.250 = 0.388.

Values have been given [5] for $\bar{c}'_m$ for moist materials in the hygroscopic region as derived from the chemical potential for mass transport, and this is a thermodynamic parameter that can be used in practical recommendations on the choice of processes for obtaining the optimum hygroscopic parameters in materials. Also, $\bar{c}'_m$ can be used in solving the inverse problem: to determine the methods and modes of treatment in such a way as to obtain the optimum water-accumulating capacity in tobacco leaves.

The following formula [4] gives $\bar{c}'_m$ for the range for φ from 0.1 to 0.9:

$$\bar{c}'_m = \frac{(U)_{\varphi=0.9}-(U)_{\varphi=0.1}}{(\mu)_{\varphi=0.1}-(\mu)_{\varphi=0.9}} = \frac{0.589-0.038}{(56.031-2.566)\cdot 10^5} = 1.028 \cdot 10^{-7}. \tag{16}$$

When one has data on the mean mass capacity of tobacco leaves in the hygroscopic region, one can perform calculations on the mass transfer between the material and the air [5].

As an example we consider the uptake of water by tobacco leaves from the surrounding air [3] under the following conditions: initial water content of the leaves $U_1 = 0.134$ kg/kg, mass $P_1 = 20$ kg, transport chemical potential $\mu_1 = -12.444 \cdot 10^5$ J/mole ($\varphi = 0.6$). Uptake of water vapor from the air causes the chemical potential of the leaves to rise to $\mu_2 = -2.566 \cdot 10^5$ J/mole ($\varphi = 0.9$). We now determine the amount of water taken up by the material and the specific water content at the end of the process.

By analogy with elementary relations in thermodynamics, the amount of water entering the tobacco leaves from the air is [5]

$$\Delta M = \bar{c}'_m G_d(\mu_2 - \mu_1) = 4.606 \cdot 10^7 \cdot 17.64\,(12.444 - 2.566) \cdot 10^5 = 8.025 \text{ kg}. \quad (17)$$

The mass of the absolutely dry tobacco is

$$G_d = \frac{P_1}{1 + U_1} = 17.64 \text{ kg}, \quad (18)$$

where $\bar{c}'_m$ is the mean value for φ between 0.6 and 0.9 as given by (16):

$$\bar{c}'_m = \frac{(U)_{\varphi=0.9} - (U)_{\varphi=0.6}}{(\mu)_{\varphi=0.6} - (\mu)_{\varphi=0.9}} = \frac{0.589 - 0.134}{(12.444 - 2.566)10^5} = 4.606 \cdot 10^{-7} \text{ mole/J}.$$

The final mass of the material is

$$P_2 = P_1 + \Delta M = 20 + 8{,}025 = 28{,}025 \text{ kg}.$$

The specific water content at the end of the process is found from (18) as $U_2 = 0.588$ kg/kg.

This result differs from the data given by the sorption isotherms by about 0.2%, which is quite adequate for practical calculations.

NOTATION

U	is the water content;
φ	is the relative humidity;
μ	is the transport chemical potential;
R	is the universal gas constant;
c'_m, $\bar{c}'_m$	are the true and mean isothermal specific mass capacities, respectively;
T	is the absolute temperature.

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