1. Introduction

Midrib components of tobacco leaves are used as lamínas and are indispensable in the manufacture of cigarettes in designing their smell and taste and making the cigarette feel firmer. Midribs shrunk by curing, a kind of drying unique to harvested tobacco, are moistened and flexibility increases on conditioning. They are shredded and dried to a prescribed water content in the manufacturing plant. Although midrib tissues expand somewhat in a series of conventional treatments, the resulting expansion is not sufficient when compared with its precured shape and size. The development of a new treatment that improves the expansion will be meaningful because it would lead to cost reduction of tobacco materials. In order that such treatment can be optimally designed, it is necessary to determine the prime factors responsible for the expansion and the main mechanism involved.

Expansion of the tobacco midrib is mainly influenced by the following two elements: (1) vaporization of water in the midrib tissues caused by drying; and (2) stress-strain characteristics of the tissues depending on its water content and temperature. The authors therefore consider that clarification of the drying process will be the first step in determining the factors and the mechanism of expansion. However, it is not easy to estimate drying curves of the midrib as its shape is not uniform.

In this paper, a simplified quantitative model that simulates changes in the water content and the temperature of a cylindrical plant material, tobacco midrib, which expands in air flow mixed with or without superheated steam. The model is characterized as follows: (1) mass and heat transfers in the midrib are described by one-dimensional diffusion based on conservation laws; (2) adsorption equilibrium of water is always achieved at a solid-gas interface, so that the internal movement of water is regulated as a rate-limiting step; and (3) transfer phenomena in the expanding diffusion field are simplified by defining the expanded maximum radius as a diffusion length. The curves of water content and temperature calculated by the model were in agreement with each experimental value under various drying conditions: air temperature of 373 to 473 K and flow rate of 10 to 20 m/s. The model also represented drastic rises in temperature caused by condensation heat of water vapor in the initial drying stage. It was therefore judged that the model has validity and can be applied to estimation of the drying curves in expanding diffusion systems for tobacco midribs.

Key words: tobacco midrib, expansion, drying, air, superheated steam.

2. Drying model

The following assumptions are applied to our model to simplify the drying phenomena and calculations:
1. A piece of tobacco midrib has a cylindrical shape and a homogeneous system.
2. Transfers of mass and heat in the midrib, which has a greater longitudinal length than a certain value, are described as radial diffusion, one-dimensional diffusion in the radial direction.
3. Water in the midrib vaporizes only at the solid–gas interface, the surface of the midrib.
the solid–gas interface. The water content of the surface can be obtained from Dubinin–Astakhov (DA) equation [1] that describes isotherms of water in the midrib. The parameters \( A_e, \ w_{\text{max}} \) and \( n \) are determined by fitting the isotherm to the equation.

Water vapor in the gas phase would condense instantly on the surface of the midrib under certain drying conditions, as soon as the midrib had been placed into the flow. In this case, we consider that the rate of condensation depends only on the energy balance and that condensation continues until the surface temperature of the midrib rises to the dew point of the gas. The water content of the surface is regulated as the maximum value, \( w_{\text{max}} \), given by the DA equation during condensation. The series of water transfers described above are specified as follows:

\[
\frac{\partial w}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r D_r \frac{\partial w}{\partial r} \right) (0 < r < r_{\text{max}})
\]

B. C.

\[
\frac{\partial w}{\partial r} = 0 \quad (r = 0)
\]

\[
\begin{align*}
\quad & \quad w = w_{\text{max}} \exp \left[ -\left( \frac{RT \ln \left( \frac{\rho}{\rho_0} \right)}{A_e} \right)^n \right] \quad (r = r_{\text{max}}) \\
\quad & \quad w = w_{\text{init}} \quad (0 \leq r \leq r_{\text{max}}, \quad t = 0)
\end{align*}
\]

I. C.

\[ T = T_{\text{init}} \quad (0 \leq r \leq r_{\text{max}}, \quad t = 0) \]

where \( r_{\text{max}} \) and \( \lambda \) represent the radius and the effective thermal conductivity of the expanded midrib, respectively.

Each partial differential equation of Eqs. 1, 2, 5, 6 and 7 is discretized, and an implicit method, the Gauss–Seidel method [3], is then used to determine numerical solutions to the simultaneous equations.

3. Experimental

3.1 Material

Pieces of 5±0.5 mm in width were sorted from the midribs of cured tobacco leaves and were cut into lengths of 30 mm. Volatile constituents in the midribs were removed in advance by drying under reduced pressure at 353 K for 8 h because the existence of their components could cause errors in the measurement of the water content as shown in next section 3.3. The dried midribs then were moistened under a relative humidity of 80% (hereafter abbreviated to %R.H.) at 295 K to adjust their water content.

3.2 Drying

A schema of the through–flow dryer is illustrated in Fig. 1. A piece of tobacco midrib (1) attached to an electrical slider (2) is inserted instantly into the central portion of a dryer pipe (3) with a volume of \( \pi \times 3000 \) mm and then dried for a prescribed period, while being placed perpendicular to the air flow. The flow coming into the pipe equipped with ribbon heaters (5) passes through straightening vanes (4) and then flows down to the midrib. Recording of drying processes with a digital camcorder (Sony, DCR-SC100, Tokyo, Japan) and measurement of surface temperatures with a radiation thermometer (TASCO, THI-301SL, Osaka, Japan) are carried out through a window made of barium fluoride (6). Differential pressure, temperature and velocity of the flow are also measured via taps (7) on the side walls of the pipe. The flow, having exited the pipe, circulates to a blower (8), and passes through a hygrometer (9), a heater (10) and a flowmeter (11) again. The mixing ratio or humidity of the flow is adjusted by both the flow rate of the exhaust gas and the injection of superheated steam between the blower and the hygrometer. The average velocity of the flow is set at a prescribed value by inverter control of the blower motor.
The moistened midrib was dried in the air flow whose mixing ratio had been adjusted to a prescribed value by mixing air with superheated steam. The air flow with a humidity 0.01 kg of H₂O/kg of dry air (hereafter abbreviated to kg-H₂O/kg-DA) without superheated steam was used in the temperature region of 373 to 473 K, while the temperature of the wet air flows mixed with the superheated steam was set at 423 to 473 K to avoid condensation of the steam introduced into the dryer. By injecting the superheated steam at a constant rate of 5.6 g/s and changing the flow rate of the exhaust gas, the mixing ratio of the wet air flows was adjusted to 0.27 and 2.48 kg-H₂O/kg-DA. The average velocity of the flows was set at 10 to 20 m/s.

### 3.3 Measurement of temperature, water content and shape

The temperature of the midrib surface was measured with the radiation thermometer during drying. After drying a piece of midrib in the flow for a prescribed period, the midrib was quickly removed from the dryer. The width of the midrib was then measured by a vernier caliper. The water content of the midrib was calculated from its weight reduction by hot-air drying at 373 K for 1 h. Drying curves were experimentally obtained by repeating the measurement of water content and temperature. In some experiments, expansion processes during drying were observed and recorded by the digital camcorder.

Images of the untreated and the dried midribs were taken by a digital microscope (Keyence, VHX, Osaka, Japan). The cross-section area and the width were measured for each midrib after the image magnified to ten diameters had been binarized. Circle-equivalent diameters were calculated from the cross-section areas.

### 4. Results and Discussion

The authors have performed preliminary expanding experiments with tobacco midribs of about 5 mm in initial diameter. As a result, it is confirmed that the dried cross-section enlarges or expands as its longitudinal length becomes longer in a range up to 10 mm in length, while its section and length remain almost constant for midribs longer than 10 mm. High resistance to internal movement of water along the longitudinal direction is considered to be the result of radial mass transfer acting as a prime pathway for such long midribs. Radial heat transfer would be another prime pathway in long cylindrical midribs because the heat quantity flowing into the inside through their side area increases. We therefore regarded the transfers of mass and heat as radial diffusion for 30 mm–long midribs.

Microscopic observation showed that the ratios of circle-equivalent diameter to width were almost constant at a mean value of 0.91 regardless of the degree of expansion, so that each equivalent diameter could be conveniently determined by multiplying each width measured with the vernier caliper by the mean ratio in the drying experiments that required many repeated runs.

Observations by the digital camcorder revealed that the shape of the midrib expands radially in air flows of temperatures higher than 403 K. Ratios of expanded maximum diameter to initial diameter and the rates of expansion with respect to time increased as the temperature of the flows became higher. As shown in Fig. 2, drastic expansion finished almost within 20 s under the drying conditions of a wet air flow of 473 K and 20 m/s, recording the fastest drying rate in our experiments, while it took the longest time of about 60 s for expansion under more moderate conditions with an air flow of 403 K and 10 m/s. Since expansion is complete in the early stage of drying compared with the total drying time, the expanded maximum radius is used as the diffusion limit.
length in the expanding system.

The effective diffusion coefficients of water in tobacco are expressed in the Arrhenius equation parameterizing frequency factors and activated energy as $D_e = D_0 \exp (-E_a/RT)$ [4]. The parameters, $D_0$ and $E_a$ for the midrib, determined by diffusion model [5] are used regardless of the degree of expansion.

The density of the expanded midrib is obtained from the ratio of maximum diameter, $d_{\text{max}}$, to the mean initial equivalent diameter, $d_{\text{init}}$, as $\rho_{\text{init}}/\left(d_{\text{max}}/d_{\text{init}}\right)^2$, as shown in Table 1 because the weight of air in the midrib is negligible.

The effective thermal conductivity of the untreated midrib is expressed as a function of the water content and the temperature [6]. All micro pores in the tobacco tissue are filled with water condensate at 80% R.H. [7]. Since the water is bound to the tissue [8], they can be regarded as a phase under the conditions of our experiments. We therefore apply the Maxwell–Eucken equation [9],

$\lambda = \lambda_{\text{m}} + \frac{2\lambda_{\text{m}} - 2\phi}{\lambda_{\text{m}} + 2\lambda_{\text{m}} + \phi} \left(\lambda_{\text{m}} - \lambda_{\text{w}}\right)$,

for a binary system (tobacco and bound water phase, and gas phase) to correct the thermal conductivity by expanding. Only the increased volume is defined as a void in the expanded one. This enables us to estimate the void ratio, $\phi$, to be \((d_{\text{max}}/d_{\text{init}})^2 - 1)/(d_{\text{max}}/d_{\text{init}})^2\).

The coefficients of water diffusion and thermal diffusivity described above are calculated by each time step and by each control volume in our drying model.

Curves of the water content and the temperature of tobacco midribs were calculated using such constants and parameters under various drying conditions. The drying curves with air and wet air flows are shown in Figs. 3 and 4, respectively. The unit of water content, kg of water/kg of dry material, is represented as kg/kg-DM in all figures. Differences between the experimental and the calculated surface temperature occur at the early drying stage in both figures. The differences would result from regulating the amount of water condensed on the surface only by the energy balance and the $w_{\text{max}}$, and fixing the diffusion field of mass and heat at the maximum radius. However, the curves simulated by the model are in total agreement with each experi-

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**Table 1** Dimensions of midribs changed by expansion

| Flow     | Temp. [K] | $d_{\text{init}}$ [mm] | $d_{\text{max}}$ [mm] | $\phi$ [-] | $\rho$ (1) [kg/m$^3$] |
|----------|-----------|-------------------------|------------------------|-------------|------------------------|
| Air (2)  | 273       | 4.6                     | 4.7                    | 0.04        | 644.7                  |
|          | 323       | 4.9                     | 7.9                    | 0.62        | 258.9                  |
|          | 373       | 4.6                     | 10.4                   | 0.80        | 131.7                  |
| Wet air (3) with steam | 323       | 5.1                     | 8.9                    | 0.07        | 221.0                  |
|          | 373       | 5.2                     | 11.4                   | 0.79        | 140.0                  |

(1) $\rho_{\text{init}}=673.0$ kg/m$^3$.
(2) Mixing ratio, 0.01 kg-H$_2$O/kg-DA; Velocity, 20 m/s.
(3) Mixing ratio, 2.48 kg-H$_2$O/kg-DA; Velocity, 10 m/s.

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Fig. 2 A piece of midrib expanding in a wet air flow.
Temperature of wet air, 473 K; Velocity, 20 m/s; Mixing ratio 2.48 kg-H$_2$O/kg-DA.
mental value in a wide range of 373 to 473 K and of 10 to 20 m/s in the flows.

The calculation enables us to estimate enthalpy change, that is, heat quantity that the midrib receives during drying. The curves of enthalpy change per unit weight with respect to the water content are shown in Fig. 5, in which the enthalpy of each untreated midrib is defined as zero. The curves are obtained by cumulating

**Fig. 3** Comparisons of calculated water content and surface temperature with experimental values (air flows). Velocity, 20 m/s; Volume ratio, 0.01 kg-H₂O/kg-DA. Circular symbols, Experimental; Solid lines, Calculated. The unit of water content, kg of water/kg of dry material, is represented as kg/kg-DM.

**Fig. 4** Comparisons of calculated water content and surface temperature with experimental values (wet air flows). Velocity, 10 m/s. Circular symbols, Experimental; Solid lines, Calculated.

**Fig. 5** Calculation of enthalpy change during drying.

[A] Air flows: Velocity, 20 m/s; Mixing ratio, 0.01 kg-H₂O/kg-DA; Temperature, 373, 423 and 473 K. [B] Wet air flows: Velocity, 10 m/s; Mixing ratio, 0.27 and 2.48 kg-H₂O/kg-DA; Temperature, 423 and 473 K.
differences in the enthalpy of wet midribs, \((C_{p, w} + C_{p, m})\)
\(\Delta H_{vap}\) : enthalpy of evaporation, J·kg\(^{-1}\)H\(_2\)O\(^{-1}\)
\(\epsilon\) : rate of emissivity (=0.93), –
\(\phi\) : void ratio, –
\(\lambda\) : thermal conductivity, W·m\(^{-1}\)·K\(^{-1}\)
\(\rho\) : density, kg·m\(^{-3}\)
\(\sigma\) : Stefan–Boltzmann constant, W·m\(^{-2}\)·K\(^{-4}\)

5. Conclusion

A drying system with a cylindrical tobacco midrib in which diffusion fields of mass and heat expand is simplified by the radial diffusion of mass and heat and by the fixation of expanding diffusion length. We concluded that this model has validity for simulation of drying curves because the calculated curves are in good agreement with the experimental values of water content and temperature of the midrib under various drying conditions. The model is a meaningful step for revealing the factors and the mechanisms of expansion of tobacco midrib.

**NOMENCLATURE**

\(A_e\) : constant in eq. 3 (=25.89), J·mol\(^{-1}\)
\(C_p\) : heat capacity, J·kg\(^{-1}\)·K\(^{-1}\)
\(D_e\) : effective diffusion coefficient, m\(^2\)·s\(^{-1}\)
\(D_o\) : frequency factor (=1.72×10\(^{-5}\)), m\(^2\)·s\(^{-1}\)
\(E_a\) : apparent activation energy (=4.15×10\(^4\)), J·mol\(^{-1}\)
\(d\) : diameter, m
\(n\) : constant in eq. 3 (=0.32), –

\(Nu\) : Nusselt number, –
\(p\) : vapor pressure, Pa
\(p^\circ\) : saturated vapor pressure, Pa
\(Pr\) : Prandtl number
\(q\) : heat flux, W·m\(^{-2}\)
\(R\) : gas constant, J·mol\(^{-1}\)·K\(^{-1}\)
\(Re_p\) : Reynolds number, –
\(r\) : radial coordinate, m
\(r_{max}\) : radius of expanded midrib, m
\(T\) : temperature, K
\(t\) : time, s
\(w\) : water content, kg-H\(_2\)O·kg-DM\(^{-1}\)

\(w_{max}\) : constant in eq. 3 (=5.40), kg-H\(_2\)O·kg-DM\(^{-1}\)
\(\alpha\) : thermal diffusivity, m\(^2\)·s\(^{-1}\)

**Subscript**

\(a\) : air
\(con\) : convection
\(init\) : initial value
\(m\) : midrib
\(rad\) : radiation
\(w\) : water
\(wall\) : wall

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気流により膨張するたばこ葉脈の乾燥モデル

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シガレットの香りや硬さを設計する際、たばこ葉脈は不可欠な原料として使用される。キュアリングとよばれる特殊な乾燥によって収縮したたばこ葉脈は、加水および乾燥処理により膨張する。コスト低減に寄与する本処理技術の合理設計には、膨張の主要機構の解明が必要である。著者らは、(1) 乾燥による葉脈内の水の気化、および(2) 含水率および温度依存性を示す葉脈組織の応力-歪み特性の2点が、膨張に影響を与える主要因子であると考えている。そこで、機構解明の第一段階として、葉脈の乾燥特性を明らかにする。本報では、空気流および熱水蒸気を混合した湿り空気流によって膨張するたばこ葉脈の含水率および温度を定量的に記述する乾燥モデルを示す。

予備検討により、長さ 10 mm 以上の葉脈では、半径方向の水および熱移動が主経路であると予想された。そこで、次の3つの仮定をモデルに導入し、不定形材料の乾燥現象を簡素化した。(1) たばこ葉脈は円筒形状をした均質材料である。(2) 長さ 10 mm 以上の葉脈内のある物質および熱移動は、半径方向の 1 次元拡散として記述される:および(3) 木の蒸発は固定面界（葉脈の表面）のみで生じ、さらに、観察の結果、乾燥の初期段階で膨張はほぼ終了することから、膨張した葉脈の円相当半径を拡散長として試験した。ある気流条件では、乾燥の初期に水蒸気が葉脈表面へ凝縮する。本モデルでは、凝縮はエネルギー収支のみにより決まり、表面温度が気流の凝点に達するまで凝縮するものとした。それら支配方程式を離散化し、Gauss-Seidel 法により数値解を求めた。

推算の際、乾燥による膨張の有無に関わらず、熱伝導係数および活性化エネルギー Ea をパラメータとする水の有効拡散係数 D = D exp(-Ea/RT) を内部移動に適用した。ここで、R および T は、それぞれ気体定数および温度である。乾燥実験を行った含水率領域では、葉脈中の吸着水は結合水として存在する。そこで、膨張した葉脈を 2 相（たばこと水の相、およびガス相）とみなし、膨張した葉脈の有効熱伝導度を Maxwell-Eucken の式により補正した。これら有効拡散係数および熱伝導度は、各 time step および control volume で求めた。

たばこ葉から幅 5±0.5 mm の葉脈を切り取り、長さ 30 mm に裁断した。初期含水率の調整のため、これら葉脈片を温度 295 K・相対湿度 80% で湿潤平衡にした。通風型乾燥機の電動スライダを取り付けた 1 本の葉脈片を気流に対して垂直に投入し、所定時間乾燥した。気流として、空気（温度 373-473 K、混合比 0.01 kg of water/kg of dry air（kg-H2O/kg-DA）、および湿り空気（温度 423, 473 K、混合比 0.27, 2.48 kg-H2O/kg-DA）を使用し、流速を 10 から 20 m/s とした。さらに、気流乾燥管の側面に設けたフッ化バリウム製の窓をとおして、放射温度計による葉脈表面温度の測定およびデジタルビデオカメラによる膨張過程の観察を行った。熱風乾燥（373 K, 1 h）により、乾燥葉脈の含水率を求めた。

推算値と実測値を比較すると、乾燥初期段階の表面温度にずれを生じた。この誤差は、(1) 熱収支と Wmax（Dubinik–Astahkov 式の最大含水率）のみで水蒸気の凝縮を規定したこと、および(2) 拡散長を最大半径に固定したことに関与したと考えられた。初期段階を除くと、温度および含水率の推算曲線は、それぞれの実測値にほぼ一致した。さらに、湿り空気の場合、モデルは、乾燥初期に生じるたばこ表面への水蒸気の凝縮および凝縮熱による急激な温度上昇を記述できた。

以上より、本実験条件で木乾燥モデルは妥当であり、膨張するたばこ葉脈の乾燥曲線の推算に適用できるものと判断した。