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SHORT COMMUNICATION

RECONSTITUTE TOBACCO PRODUCT DRYING MODEL

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Abstract – Drying is one of the most energy-intensive and frequently used processes in the tobacco industry. In the present work, heat and mass transfer phenomena in drying sheet materials with impinging air flow are analyzed. A blended leaf (BL) drying model is developed and validated to predict the drying behavior of the reconstitute tobacco product. A numerical method of line technique [Schiesser, 1991] was used to solve the coupled differential equations governing the drying process. This model has been successfully applied to simulate BL drying processes in the pilot plant and the BL plant. The present model provides a relatively fast and efficient way to improve process performance, increase plant productivity, and optimize energy utilization. With this model, the number of trials necessary to achieve the objectives is reduced, in other words, a large amount of time, money, and manpower is saved. The model results are also helpful in studying the drying behavior of reconstitute tobacco products and understanding the effect of dryer profiles on the sheet strength and subjective results.

Key words: Reconstitute Tobacco, Drying, Mathematical Model

INTRODUCTION

BL is a reconstitute tobacco product. In BL manufacturing, finely ground production dust and stems are mixed with binders to form a slurry material, after a certain aging time the slurry is cast into flat sheets and dried to the 15% oven volatiles (OV[1]) level. Since the drying operation has a great impact on product quality and subjective acceptance, a great amount of effort has been continuously made. In order to optimize the current BL drying process for improved sheet quality, increased productivity, and reduce operation cost, and to develop new qualified products, it is desirable to develop a predictive mathematical model to simulate the pilot plant and BL plant dryers and determine the dryer profiles for improving the performance of the current process and developing new products, such as new blended leaf (NBL) and cast sheet products.

The objective of the present work is to develop a BL drying model to simulate the pilot plant and BL plant dryers and optimize the BL drying process. In order to validate the drying model for the BL plant use, a dryer characterization study was carried out [McFadden and Chen, 1992]. In that study, the real temperature profiles and the gas velocities in each zone were measured in the BL plant. The model was then validated to simulate the drying operation in the BL plant. The model results agree well with the measured main dryer exit OVs for all three lines. From then, the model has been successfully applied to provide dryer profiles of various trials in the pilot plant and the BL plant.

MATHEMATICAL MODEL DESCRIPTION

Drying of BL involves thin sheet materials with high initial moisture content and simultaneous conductive and convective heating by the impinging air flow. The present BL drying model is based on the drying model developed by [Chen and Schmit, 1990], which has been successfully used to predict drying of wool veneer, polymer pellets, activated alumina, gypsum boards, and food products.

The physical model for the analysis is shown in Fig. 1. The slurry is assumed to have uniform initial temperature of 328-339 K and 18-21% solid content, and is exposed to a impinging air flow of temperature T_a and relative humidity Ψ. Since tobacco contains bound water, the slurry material contains both free water and bound water. During drying in a main dryer, most of the free water is removed from the material. In this

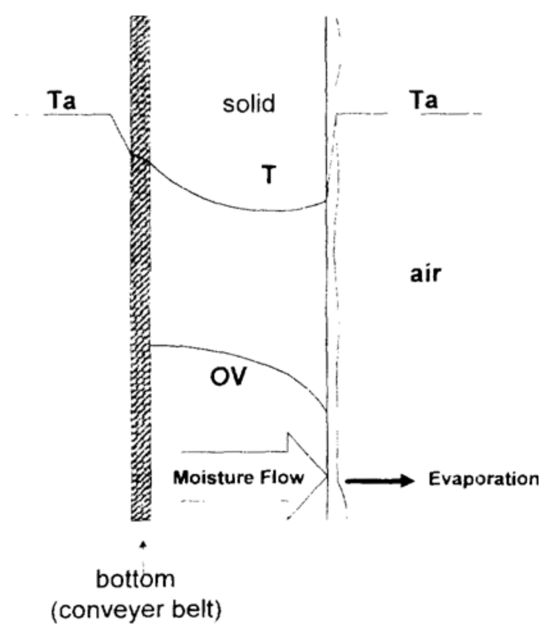

Fig. 1. Physical model of BL drying.

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[1]Those volatiles in tobacco that are evolved by treatment in a forced draft oven at a prescribed temperature for a standard period of time.

case, the governing equations for the BL drying process can be written as;

$$\frac{\partial X}{\partial t} = \nabla(D_L \nabla X) + \nabla(D_T \nabla \ln T) \quad (1)$$

$$(\rho c_p)\frac{\partial T}{\partial t} = \nabla(k_{eff} \nabla T) \quad (2)$$

where D_L is the internal moisture diffusion coefficient and D_T is so-called the effective thermo-diffusion coefficient. The first term on the right side of Eq. (1) reflects capillary flow of water and the second term reflects the liquid flow driven by temperature gradient which causes a gas phase pressure gradient. k_{eff} is the effective thermal conductivity which is a function of temperature and moisture content.

The initial conditions for temperature and moisture content are:

$$T = T_0 \quad (3)$$

$$X = X_0 \quad (4)$$

The boundary conditions at the top surface are different from that at the bottom surface, since the top surface is exposed to air and the bottom is contacting the steel belt. At the top surface x=L.

$$k_{eff} \left.\frac{\partial T}{\partial \chi}\right|_L = h(T_a - T_L) - \phi_{mL}\,\Delta h_v \quad (5)$$

$$-\rho_0 D_L \left.\frac{\partial X}{\partial \chi}\right|_L - \rho_0 D_T \left.\frac{\partial \ln T}{\partial \chi}\right|_L = \phi_{mL} = \frac{h_m M}{RT_a}(P_{vL} - P_{va}) \quad (6)$$

At the bottom surface x = 0:

$$k_{eff} \left.\frac{\partial T}{\partial \chi}\right|_0 = h_b(T_a - T_b) \quad (7)$$

$$-\rho_0 D_L \left.\frac{\partial X}{\partial \chi}\right|_0 - \rho_0 D_T \left.\frac{\partial \ln T}{\partial \chi}\right|_0 = 0 \quad (8)$$

where P_{va} is the partial pressure of water vapor in the circulating air stream. h, h_m are the heat and mass transfer coefficients at the top surface, while h_b is the overall heat transfer coefficient at the bottom. So long as the moisture content at the surface is higher than a criterion X_{fcr}, the values of h and h_m remain constant and they are determined by the following expression [Arganbright, Resch, and Olson, 1979],

$$Nu_b = \frac{hB}{k_a} = 0.049\, Re_{exit}^{0.797} \left(\frac{L_t}{B}\right)^{-0.275} \quad (9)$$

$$Sh_b = \frac{h_m B}{D_a} = 0.97 * Nu_b \quad (10)$$

where

$$Re_{exit} = \frac{vB}{\nu} \quad (11)$$

The above equation is good for the slot impinging nozzles. Here, the nozzle width B=0.0064 m, the nozzle spacing L_t=0.2 m, and the distance between nozzle exit and sheet surface is 0.0057 m, as built in the pilot plant dryer. For the round nozzle in the BL plant dryer, a correction factor is used in the equation. The impinging gas velocity v is a function of damper setting for each zone of the main dryer, but there is no such relationship provided by the vendor. Therefore, the gas velocities with different damper settings should be measured to find the relationship.

During drying, the heat and mass transfer coefficients also vary with time. When the free moisture content at the surface drops to a critical value, typically 30-40% of the saturated value, the heat and mass transfer coefficients become functions of the free moisture content at surface. In the present model, only mass transfer coefficient is assumed to decrease linearly with the free moisture content at surface:

$$h_m = h_{m0}(0.3 + 0.7 * \frac{X_{fL}}{X_{fcr}}) \qquad (0<X_{fL}<X_{fcr}=2.46) \quad (12)$$

The physical properties of BL, such as equilibrium desorption, density, specific heat, and thermal conductivity in the model were correlated based on the previous experiment data of [Browne, 1990], as shown in Table 1. Linear relationships were used to re-correlated the experimental data. The moisture transfer coefficients and dependence on moisture content (OV) and temperature will be back-estimated through the fitting of the experimental data.

A numerical method of line technique was used to solve the above partial differential equations (pde's). This scheme is based on the solution of a set of initial value ordinary differential equations (ode's). These ode's are obtained from the pde boundary value problem of interest by discretizing the pde's in the spatial dimensions. This yields a set of ode's with time as the independent variable. A suitable ode solver is then used to integrate the system of equations in time to yield the required results. The ode solver chosen in this work is LSODE a widely available software package developed at LLNL by [Hindmarsh, 1980]. Important parameters specified in the model, such as

Table 1. Physical properties of BL

Properties	BL	Unit
Initial OV	81.5	%
Measured exit OV	45	%
Thickness L	0.25	mm
Porosity ε	(1.46 − X)*0.3438 for X<2.46	
Density ρ_0	512 (for X<2.46)	kg/m^3
Specific heat c_p	1.12 − 3.06*OV	kJ/kgK
Conductivity k	.324+.281*OV	W/mK
Equilibrium desorption (X_{eq} vs. RH) for BL X_{eq}=0.618*RH − 1.70*RH^2+1.71*RH^3		

X---moisture content (kg water/kg solid), OV=X/(1+X); RH---relative humidity.

equilibrium desorption of BL, density, specific heat, and thermal conductivity are shown in Table 1. The mass transfer coefficients were estimated and expected to be within an order magnitude of the true value.

The computer code for the model is written in FORTRAN language and can be run on an IBM PC. The model inputs include air velocities, humidities, and temperatures in each zone of the dryer, slurry solid content (OV) and temperature, sheet thickness, sheet density, and belt speed. Typical running time is less than the real drying time, i.e. the sheet residence time in the dryer.

MODEL APPLICATIONS AND DISCUSSIONS

1. Dryer Simulations for Pilot Plant

The pilot plant main dryer has four drying zones and a total drying section length of 12.2 m, i.e., 3.05 m for each zone. The slurry after an aging process (18.5-21 % solids, 344 K) is spread onto a 0.0038 m wide steel belt which passes through the dryer. The belt velocity is adjustable from about 0.1 m/s to 0.38 m/s. In the each drying zone, heat is supplied by a gas burner to maintain the zone temperature. The circulating hot gas flows through a series of impinging slots to heat the sheet material from the top and bottom, the gas velocity can be adjusted by setting the damper opening level. Part of the circulating air goes to the exhaust pipe which indicates a fresh air flow for each zone. Since only the top surface of the slurry on the belt is open to air, moisture is limited to be removed at the top surface. The heating by the impinging air at the bottom is usually kept at maximum to build a temperature gradient across the sheet which will drive liquid moisture to move towards the top surface and enhance the drying process.

In order to validate the model for the simulation of BL drying process at the pilot plant, the actual air temperatures and nozzle exit velocities in each zone of the main dryer were measured. The relationship between damper opening level and nozzle exit velocity is shown in Fig. 2. The measured drying conditions, dryer exit OVs, and typical model results for drying BL in the pilot plant are listed in Table 2. In the calculation, the fresh air flow rate was assumed to be 0.42 kg/s for each zone. As can be seen from these tables, the model results of the dryer exit OV agree well with experimental data.

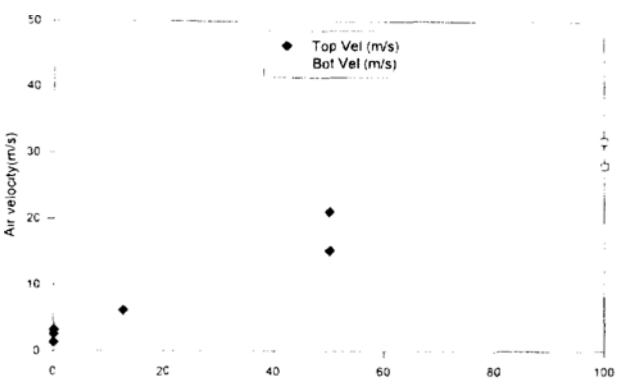

Fig. 2. Air velocity vs damper opening (pilot plant).

Table 2. Modeling BL drying in pilot plant

Exp. no.	BL-01	BL-02
Slurry solids (%)	18.5	18.5
Belt speed (m/s)	0.279	0.279
Thickness (mm)	0.17	0.23
Sheet wt (kg/m^2)	0.136	0.133
Measured exit OV (%)	43.8/48.1	36.8
Predicted exit OV (%)	46.3	37.2

2. Dryer Simulations for Main Plant

The main dryers in the BL plant are some how similar to the main dryer in the pilot plant, but each dryer has nine drying zones and a total length of 54.9 m, i.e., 6.1 m for each zone. The steel belt width is 1.5 m. Moreover, round nozzles are equipped for the impinging air flow.

A dryer characterization study was carried out to validate the developed drying model for the BL plant use [McFadden and Chen, 1992]. In that study, the real temperature profiles and the gas velocities in each zone were measured in the BL Plant, as shown in Tables 3 and 4. The drying conditions for BL were also measured in the characterization study: 19 % slurry

Table 3. BL plant dryer characterization (I. Temperature)

Dryer	Line 1		Line 2		Line 3	
	Setting	Measured left/right	Setting	Measured left/right	Setting	Measured left/right
Zone 1	630	627/616	616	616	617	610/656
Zone 2	631	615/616	616	616	616	616/615
Zone 3	630	619/617	616	616	616	615/594
Zone 4	561	539/549	561	561	546	547/543
Zone 5	547	544/541	532	532	547	552/523
Zone 6	532	527/525	491	491	533	525/506
Zone 7	464	464/460	450	450	464	461/441
Zone 8	427	426/426	408	408	436	437/429
Zone 9	408	406/406	394	394	408	407/386
Entering slurry		329		331		331

Table 4. BL plant dryer characterization (II. Gas Velocity)

Dryer	Line 1		Line 2		Line 3	
	Upper	Lower	Upper	Lower	Upper	Lower
Zone 1	22.86	23.88	14.22	24.89	12.70	24.38
Zone 2	15.24	24.89	17.78	27.43	13.97	25.15
Zone 3	24.64	23.37	12.70	28.45	15.24	27.53
Zone 4	23.37	24.89	23.34	22.10	23.88	23.37
Zone 5	22.10	23.88	24.38	22.86	27.69	23.88
Zone 6	20.83	22.61	24.38	23.88	29.21	21.34
Zone 7	25.40	23.88	25.40	23.38	29.46	15.49
Zone 8	23.37	22.86	22.86	23.88	31.50	16.51
Zone 9	27.69	23.88	26.67	26.42	30.23	15.24

Table 5. Model results and measured process variables

Properties	Line 1	Line 2	Line 3
Initial OV (%)	81	81	81
Slurry temp. (K)	329.26	330.93	330.93
Thickness L (cm)	0.0251	0.0241	0.0246
Density ρ (kg/m^3)	519.6	519.6	519.6
Sheet wt (kg/m^2)	0.138	0.132	0.135
Measured exit OV (%)	48.4	49.6	50
Predicted exit OV (%)	(48.4)	(50.0)	(50.4)

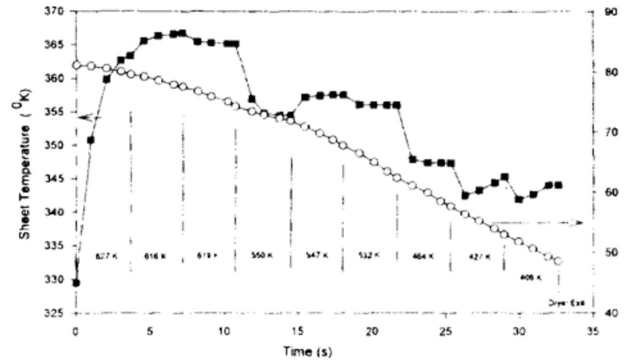

Fig. 3. Simulation results for BL drying model (Line 1).

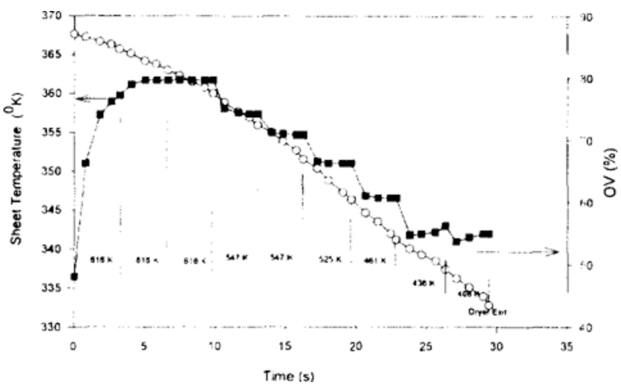

Fig. 4. Simulation results for BL drying model (Line 2).

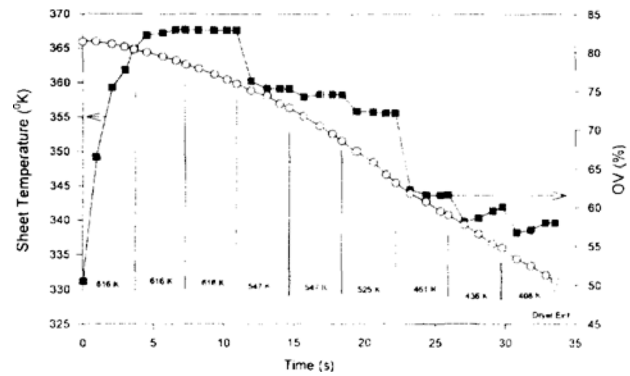

Fig. 5. Simulation results for BL drying model (Line 3).

solid content, 0.000254 m sheet thickness, and 1.68 m/s line speed. The fresh air flow rate was assumed to be 0.84 kg/s for each zone in the calculation. The model results agree well with the measured main dryer exit OVs in all lines, as shown in Table 5. Figs. 3-5 show the simulated temperature and OV profiles for each dryer line.

The model also predicted that, by increasing the starting slurry solid content only and without changing zone temperatures and sheet weights, the dryer throughput for BL drying operations will be increased.

CONCLUSIONS

The BL drying model is developed and validated to predict the drying behavior of NBL products. The model has been successfully applied to simulate BL drying process in the pilot plant and BL plant. Also, the model helped us understand the effect of dryer profiles on the sheet strength and subjective results. The use of the model in the pilot and BL plant trials reduces the number of trials necessary to achieve our objects.

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NOMENCLATURE

B : nozzle width or diameter [m]
BL : blended leaf
c_p : specific heat [J/kg K]
D : moisture diffusion coefficient [m^2/s]
k_{eff} : effective thermal conductivity of cigarette column [W/m K]
k : thermal conductivity [W/m K]
h : surface heat transfer coefficient [W/m^2 K]
h_m : surface mass transfer coefficient [m/s]
L : sheet thickness [m]
L_t : nozzle spacing [m]
M : molecular weight of water [kg/kgmol]
NBL : new blended leaf
OV : oven volatiles
P_v : vapor pressure [N/m^2]
R : gas constant [J/kgmol K]
RH : relative humidity
Re : Reynolds number
Sh : Sherwood number
T : temperature [K]
t : time [s]
v : impinging velocity [m/s]
X : moisture content in tobacco [kg H_2O/kg tobacco]
x : thickness coordinate [m]

Greek Letters

ε : porosity
Ψ : relative humidity
ϕ_{ml} : drying rate at the surface x=L [kg/m^2 s]
ν : kinematic viscosity [m^2/s]
ρ : solid density [kg/m^3]

Subscripts

0 : initial value
a : air
b : bottom
cr : critical
f : free moisture
L : liquid
T : thermal

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