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Study on the general dynamic model of biomass drying processes

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Abstract

Nowadays most studies of drying processes dynamics are established on empirical models without clear physical meanings, which could not predict the drying characteristic on different dryers. In order to describe the change of temperature and water content in the cut tobacco in different dryers, a mathematical model based on heat and mass transfer phenomena was developed, and the model employed the relationship of equilibrium moisture content and air humidity as basis, the difference of moisture between biomass and wet air as mass transfer driver, and the difference of temperature between biomass and wet air as heat transfer driver. The drying experiments under different air temperature and humidity are carried out on the batch rotary dryer, and the variance of temperature and moisture content in the biomass is obtained by using infrared thermometer and oven. The model is validated by two parameters with experiment data under each condition of air temperature and humidity. The results show that the drying dynamic model is well on accuracy and universality, and it could be applied on different drying device to predict the characteristic of kinds of drying processes.

Keywords: *cut tobacco; drying dynamics; equilibrium moisture content; heat transfer; mass transfer.*

1. Introduction

Drying is an important operation to manufacture many products that benefit mankind being drying technology more widely used in biomass, such as drying of grains, seeds, fruits, vegetables, fodder, woody particles, tobacco, and so on.

Measuring the drying process of each individual particle or fiber is almost impossible, but many researchers prefer to gain understanding of the processes in the most comprehensive way as possible. Mohammad et al. (2016) applied the eXtended Discrete Element Method (XDEM) to simulate the temperature, moisture content and drying rate of woody particles during drying in a circulating cylinder. Koji et al. (2014) investigated a simplified quantitative model that simulates changes in the water content and the temperature of the tobacco midrib, and the validity of the model is examined. Zhu et al. (2015) introduced a two-stage convective drying strategy for cut tobacco drying, and the temperature and moisture evolution of cut tobacco were simulated by developed heat and mass transfer models. The above results indicate that obtaining the material's temperature and water content changes in detail under different operating conditions and fitting of measured data with an appropriate drying model can help us to set the optimum operation condition, as well as improve the quality of material in drying process.

Drying process of biomass using the rotary dryer is the one of important process in cigarette factory. Rotary dryers are designed so as to force the drying material to circulate along the unit while in contact with the air, in such way the best mass and heat exchange is attained. Good control scheme may further help improve the intrinsic quality and external quality of tobacco production. Thus a comprehensive understanding of the process characteristics of tobacco water content and surface temperature in the rotary dryer are useful information for setting up suitable control schemes. So the present work has been undertaken to study the drying characteristics of cut tobacco by using a specially designed rotary dryer. A dynamic model has been implemented and found to be satisfactory. The temperature and water content evolution of the cut tobacco as biomass at different drying temperatures were calculated and compared with the results of the experimental investigation.

2. Materials and methods

Cut tobacco was used in this study，which was produced in the Fujian Province of China. Before each experiment, water contents of the cut tobacco samples were adjusted to 22.5±0.1 % by adding calculated amounts of water to the cut tobacco samples respectively.

In order to obtain real time drying characteristics of the material in the dryer, a laboratory rotary dryer was purposely designed in the principle shown in Fig 1.

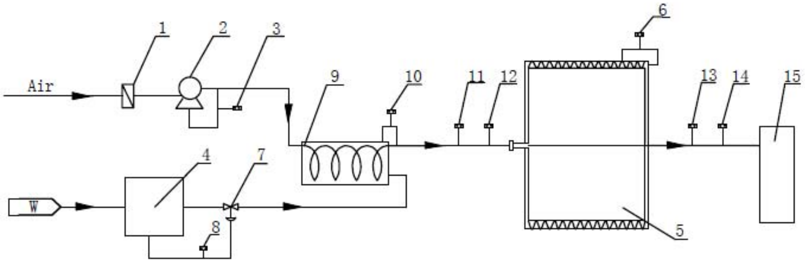


Fig. 1. Schematic diagram of the laboratory scale rotary dryer: (1)air filter, (2)blower, (3)air flow meter, (4)steam generator, (5)drying chamber, (6)chamber temperature controller, (7)electrical valve, (8)vapor flow meter, (9)mixing chamber with electrical heater, (10) air temperature controller, (11)inlet air temperature and humidity recorder, (12)inlet air flow meter, (13)outlet air temperature recorder, (14)outlet air humid recorder, (15)drain

The length of the laboratory dryer is just 1.0 meter, and its diameter has maintained the same diameter as industrial rotary dryer about 1.9 meters. During the experiments, the, inlet humidity and temperature can be controlled to any practical value as the inducstrial dryer by mixing air with the superheated steam, while the average velocity of the flow was also set at a prescribed value. By detecting the water contents and temperatures of the cut tobacco sample at different drying moments, we can simulate the whole drying process with this laboratory rotary dryer.

The drying experiments were carried out in the laboratory drying chamber. The inlet temperature was respectively set to 338, 358, 378, 398 and 418 K, while the average velocity of the flow was kept to 0.067 ms^{-1}, and only the compressed air from atmospheric environment (28 ℃ and RH 0.77) was used without inducing the steam in the current study.

During the drying process, the sampling interval was set to 30 seconds, and the sampling groove was quickly pulled out from the chamber. The temperature of the cut tobacco samples in the groove was quickly measured by an infrared thermal imaging device within 2 seconds, and simultaneously cut tobacco samples were taken to offline to measure the water contents separately by weight loss method. The each sample amount taken away for weight analysis was 10 g approximately, which is 0.5 % of the total 2 kg.

3. Mathematical model

In order to simulate the mass transfer process, we assume that on the surface of biomass, there exists a film of wet air, which is equilibrium with water content in the biomass. The relationship of equilibrium can be written as

$$RH_e = 1 - \exp\left(-ATX^B\right) \tag{1}$$

where RH_e represents the relative humidity of the film, T denotes the temperature of biomass, the parameter A and B indicate the drying characteristic of biomass.

According to the Antoine equation, the vapor pressure of the film can be expressed as the product of saturated vapor pressure and relative humidity, which is

$$p_e = 1.1939 \times 10^{10} \exp\left(-\frac{3826.36}{T - 45.47}\right) RH_e \tag{2}$$

where p_e is the vapor pressure of the film with Pa.

Using the state equation of ideal gas, we can get the concentration of vapor in the film as

$$C_e = \frac{1.1939 \times 10^{10} \exp\left(-\frac{3826.36}{T - 45.47}\right)\left(1 - \exp\left(-ATX^B\right)\right)}{RT} \tag{3}$$

where C_e represents the concentration of vapor in the film with unit mol.m^{-3}.

Meanwhile, the vapor concentration in the bulk surrouding the biomass, which indicates dry air, can be express as

$$C_b = \frac{1.1939 \times 10^{10} \exp\left(-\frac{3826.36}{T_b - 45.47}\right) RH}{RT_b} \tag{4}$$

where C_b represents the vapor concentration in the bulk with unit mol.m^{-3}, and T_b is the temperature in the bulk, which is equal to the temperature of the rotary dryer wall.

In order to obtain the mass transfer equation of drying process, we assume that only the convective mass transfer occurs but the diffusion is ignored, so the rate of mass transfer can be written as the product of the convective mass transfer coefficient and driver of mass transfer, which is expressed as the difference of vapor concentration in common. The above statement can be translated as the following formula

$$N = h_m A_m \Delta C \tag{5}$$

where $h_m A_m$ is convective mass transfer coefficient including the mass transfer surface area.

So the drying process of biomass per kilogram can be gotten as the following differential equation

$$\frac{1}{M_{H_2O}}\frac{dX}{dt} = N \tag{6}$$

where X is the dry base moisture content of biomass with unit kg.kg^{-1}, M_{H_2O} is molecular mass of water, and its unit is kg.mol^{-1}.

On the other hand, the heat transfer equation of drying process is not difficult to describe. Since the change of temperature of biomass can be contributed to two facts, the one is convective heat transfer from the hot air, the other is endothermic vaporization during the drying of cut tobacco. So the heat transfer equation can be written as

$$\left(XC_{p,w} + C_{p,t}\right)\frac{dT}{dt} = hA_m(T_b - T) + \Delta H_w \frac{dX}{dt}$$

where hA_m denotes the convective heat transfer coefficient combined with inseparable heat transfer area, ΔH_w is the latent heat of vaporization of water, $C_{p,w}$ is the specific heat capacity of the water with unit J·m^{-3}·K^{-1} and $C_{p,t}$ is the specific heat capacity of cut tobacco with unit J·m^{-3}·K^{-1}.

For the integrity of the heat transfer equation, the latent heat of vaporization and the specific heat equation of water are functions of bulk temperature, and they can be expressed as

$$\Delta H_w = 2891833\left(1 - \frac{T_b}{647.13}\right)^{0.321}$$

$$C_{p,w} = 1.459\times10^{-6}T_b^4 - 1.971\times10^{-3}T_b^3 + 1.005\times T_b^2 - 228.7T + 23750$$

But the specific heat capacity of cut tobacco is remained constant for simplication of the mathematical model, which is obtained as the following value as

$$C_{p,t} = 1.4286\times10^3$$

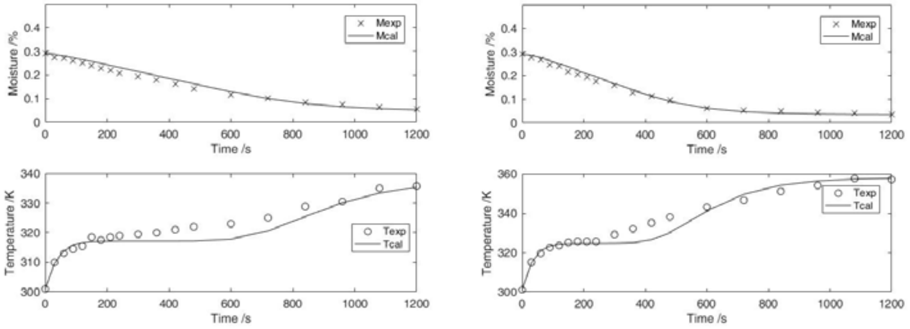
In summary, the mass transfer equation and the heat transfer equation are clearly shown, which is the govering equations of the drying process. In the mathematical model, the two parameters A and B is related to the properties of biomass, and the convective mass and heat transfer coefficients are the key factors of the model, which are determined by the operation conditions such as inlet velocity of hot air. The two coefficients can not be accurayly obtained before the drying experiments or by other independent experiments, but they could be fitted by the temperature and moisture curves of biomass during drying process.

4. Results and discussion

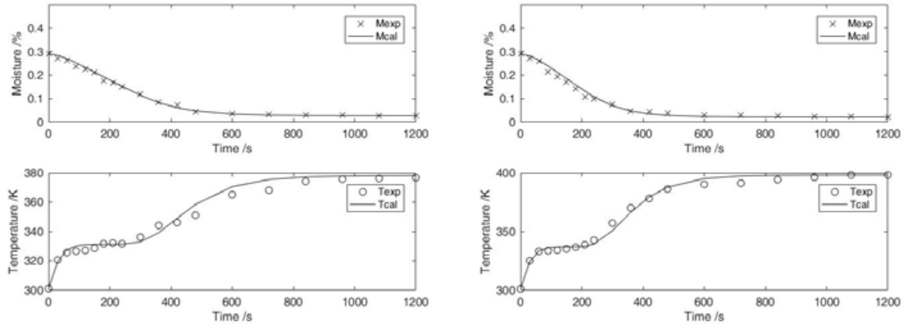
The mathematical model was fitted by using the functions ode45 and lsqnonlin on MATLAB® 2017a to get the heat transfer and mass transfer coefficients, where the function ode45 is used for solving the ordinary differential equations by 4 order Runge-Kutta methods, and the function lsqnonlin is used for exploring the optical parameters by nonlinear least squares method. Through the experiment data at different dryer temperature, the heat transfer coeffiecient is 31.2245 with unit $W \cdot m^{-3} \cdot K^{-1}$ and the mass transfer coeffiecient is 0.0651 with unit $kg \cdot m^{-3} \cdot K^{-1}$. It is obvious that the two most important parameters keep constant for all the drying conditions at different inlet temperature.

Figure 2 shows the temperature and moisture content of cut tobacco in the rotary dryer at different inlet temperature range from 338K to 418K. It can be seen that the simulated curves of water content and temperature are well consistent with the experiment data at each time. It is mean that the mathematical model with only two coefficients can reveal the main mechanism of the drying processing in the labarotary rotary dryer.

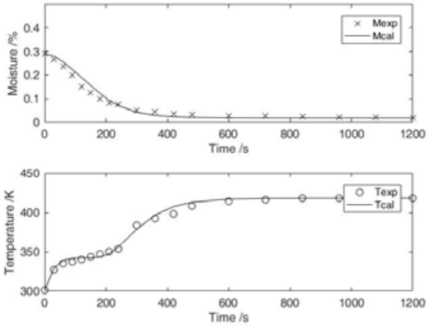
It is easy to see that the moisture content of cut tobacco decreases with time and the temperature of cut tobacco increases with time. Moreover, the variance of both moisture content and temperature can be separated into three stages. At the initial stage, the temperature rises up fastly but the moisture content goes down slowly, then the temperature remains stable and the moisture content falls down with constant drying rate at the medium stage, finaly at the last stage the temperature of cut tobacco grows up distinctly but the sample moisture content slightly decreases for a long time. We also can find that when the inlet temperature increases, the first stage almostly keeps unchanged, and the medium stage continues a short time period, but the last stage occupies a long time.



(a) 338K (b)358K



(c) 378K (d) 398K



(e) 418K

Fig. 2. the Comparsion of experiment data and simulated data of moisture content and temperature with inlet temperature range from 338K to 418K

5. Conclusions

A laboratory rotary dryer was designed to simulate the drying process of biomass. The evolutions of the water content and surface temperature of cut tobacco at different drying temperatures were investigated. The determination of heat and mass transfer coefficients by calculating from the experimental data of temperature and water content appears as a more convenient method. The mathematical model with equilibrium relationship of moisture content could represent the drying characteristics of cut tobacco accurately. Moreover, the current work provides the essential basis for the future computational fluid-dynamic (CFD) simulation of tobacco drying in industry production line.

6. References

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