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Modeling and simulation of drying characteristics on flexible filamentous particles in rotary dryers

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Abstract−Experiments were conducted to demonstrate the effects of the drum wall temperature on the heat and mass transfer in rotary dryers. The drying characteristics of flexible filamentous particles in rotary dryers were further explored. In addition, the inlet and outlet temperatures and moisture contents of granular particles were measured. As a result, the good agreement between the simulations and experiments verified the rationale and feasibility of the numerical method. Therefore, the approach was adopted to evaluate the temperature and moisture content of wet granular particles in a rotary dryer in different conditions, for instance, drum wall temperature and rotational speed. The results revealed that the higher drum wall temperature led to hotter particles with lower outlet moisture content. Conversely, the higher rotational speed resulted in cooler particles with higher outlet moisture content due to the decrease of residence time in the rotary dryer.

Keywords: Flexible Filamentous Particles, Heat and Mass Transfer, Experimental Model, Numerical Simulation, Rotary Dryers

INTRODUCTION

Drying technology is traditional method abundantly applied to the fields of the cement, lime, coal, flour, pharmaceuticals, ceramics, energy, tobacco, food and chemical industries. It is commonly known that heat and mass transfer occur simultaneously during the drying process in a rotary dryer. The heat and mass transfer of wet granular particles play an extremely important role during the drying process [1,2]. The heat is transferred from materials of higher temperature to those of lower temperature, such as wet granular particles, by conduction, convection and radiation heat transfer. Heat is used to vaporize the surface moisture of particles. Generally, the mass transfer occurs during the drying process due to the pressure difference between the steam partial pressure on the surface of the particles and the surrounding atmosphere. Furthermore, the drying process is usually affected by the state, vaporization rate at the surface and the internal moisture diffusion rate of the particles. The general drying equipment, including fixed bed, fluidized bed, rotary and microwave dryers, has been employed to deal with particles in different operational conditions [3,4]. With the advent of computer technology, numerical simulation can be an effective way to solve several problems associated with drying process. However, it is still difficult to handle promptly by experimental methods, especially the heat and mass transfer on wet granular particles in rotary dryers [5,6]. A non-equilibrium distributed parameter model was used to describe the coupling of heat and mass transfer with the movement of particles in a rotary dryer [7-9]. The temperature of particles obtained by the discrete element method was higher than the experimental results due to the negligible contact heat transfer among particles in a fluidized bed [10-12]. A theoretical model for the evaporation of microparticle and nanosized solution droplet was developed to predict whether the particles produced via spray drying and pyrolysis were fully filled or not. The particle characteristics were numerically studied under different conditions by the emulsion combustion method [31-33]. For reference, the drying process of lignite was taken. The temperature distribution of lignite particles, air humidity and mean residence time along the length of no-flight rotary dryers were measured. The moisture content of particles and temperature of the drying gas play a significant role in the mean residence time and residence time distribution of the particles according to numerous experimental studies [13,14]. The thermal particle dynamics (TPD) model was processed based on the assumption that the gas flow among particles was stationary and the heat transfer of the gas phase could be neglected [15]. Particles and gas flow were treated as porous media, and the thermal conductivity was experimentally measured based on the percolation theory. The results showed that the fractal dimension of granular particles played a key role in their thermal conductivity within the temperature range of 50 °C to 600 °C according to the thermal conduction mechanism of fluid in pores. The influence on convective heat transfer could be neglected in bulk pores for granular particles with a diam-

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eter below 4 mm [18]. The experts tried to develop an appropriate model for flexible filamentous particles, such as cut-tobacco particles, by assuming that they were neutrally buoyant chains of rigid bodies connected through ball and socket joints. At the same time, the heat and mass transfer of granular particles in rotary dryers were simulated [16,17]. The movement behavior of cut-tobacco particles in rotary dryers was experimentally studied. The influence on the flow direction of gas and cut-tobacco particles was also researched, and the result demonstrated that particles could be fully dried in cocurrent rotary dryers [35,36]. The relation between surface temperature and moisture content of cut-tobacco particles during the drying processes in rotary dryers was experimentally investigated [37].

In practice, previous production operations are quite dependent on experience due to the limitations of traditional experiments, such as heavy workload, high cost and long period of duration. Therefore, the heat and mass transfer of wet flexible filamentous particles in rotary dryers are studied by a combination of experimental and numerical methods. The wet tobacco particles were used as the experimental material. The temperature and moisture content of particles in different conditions, including the rotary drum wall temperature, particles mass flow and hot gas temperature, were experimentally investigated during the drying process. The outlet temperature and moisture content of material particles are directly influenced by the drying operational conditions. An appropriate model for those granular particles is developed in this study. The rotary dryer is divided into several isometric units and a series of equations is used to describe the heat and mass transfer between particles and gas flow in each unit. The output temperature and moisture content of particles in a unit are calculated, which are used as the input parameters for the next unit and so on. Visual Basic codes for particles are used to solve the equations of the heat and mass transfer. As a result, the temperature and moisture content of particles along the rotary dryer are identified. The inlet and outlet temperatures and moisture contents of granular particles estimated by numerical method agreed well with the experimental data. The results verified the rationale and feasibility of the numerical approach. Accordingly, the above results not only can provide many references for actual production processes, but also are absolutely useful to improve drying efficiency. Research on drying process of wet particles in a rotary dryer has demonstrated significant academic value and great application potential.

EXPERIMENTAL MATERIALS AND METHODS

The experimental apparatus consists of a rotary dryer, heating system and fans. The drum wall of a rotary dryer is indirectly heated via the oil bath inside the drum wall. The gas flow is heated before going into the rotary dryer through a fan, which is used to enhance the drying process. The wet cut-tobacco particles are fed into the rotary dryer through a slot in the vibration. Meanwhile, the movement performance of particles in the rotary dryer is affected by flights. As a result, these particles are being dried and migrated from one end of the rotary drum to the other end caused by lifting and cascading by these flights in a rotary dryer with a slope. However, it is quite difficult to directly detect the moisture content and temperature of particles during the drying process inside the rotary dryer considering the industrial-scale complexity of the drying system and the limitations of the measuring equipment [19]. Therefore, moisture detection and thermocouples were set up at the inlet and outlet of the rotary dryer. Meanwhile, the temperature and moisture content of flexible filamentous particles could be collected by a computer. The temperature and humidity of air could be also obtained by such approach.

The wet cut-tobacco particles were used as experimental material, which resulted in a moisture content of 20% after balancing the moisture content in a room at constant temperature and humidity. Furthermore, the temperature of granular particles was measured by thermocouples, and particles at the inlet and outlet could be fast obtained and stored in air tight container, and then the moisture content of particles at the inlet and outlet was accurately measured by the oven method [30]. A rotary speed of 11 r/min, a gas velocity of 0.2 m/s in the rotary dryer and the mass flow of particles were strictly controlled by the vibration slot. Three kinds of rotary dryers with different sizes and shapes were used in these experiments. The experimental atmosphere inside the rotary dryer had to be kept at a steady state for 30 min until the following experiment started. Moreover, the feed rate of particles, gas velocity, temperature and moisture content of the gas had to be consistent.

Table 1. Physical and numerical parameters of four conditions used in the model

Properties	Sample 1	Sample 2	Sample 3	Sample 4
Length of rotary dryer, mm	8800	8800	5000	8000
Diameter, mm	1850	1850	2050	1700
Mass flow of particles, kg/h	5000	5000	5000	4500
Height of flights,mm	300	300	450	410
Number of flights	12	12	12	12
Velocity of gas, m/s	0.2	0.2	0.2	0.2
Temperature of gas, °C	85.6	95	93.4	95
Temperature of drum wall, °C	140	150	148	150
Inlet moisture of particles, kg/kg	0.185	0.193	0.19	0.2
Outlet moisture of particles,kg/kg	0.128	0.128	0.127	0.13
Inlet temperature of particles, °C	28	28	28	28

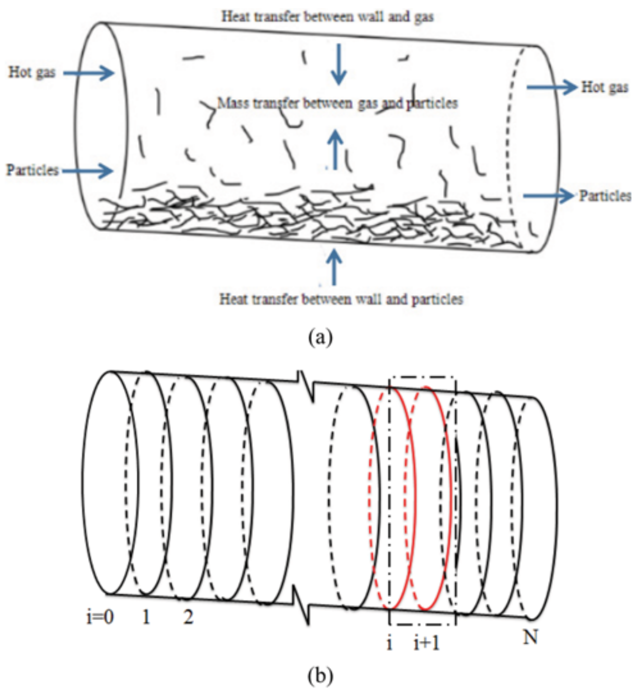

Fig. 1. The heat and mass transfer in a rotary dryer.

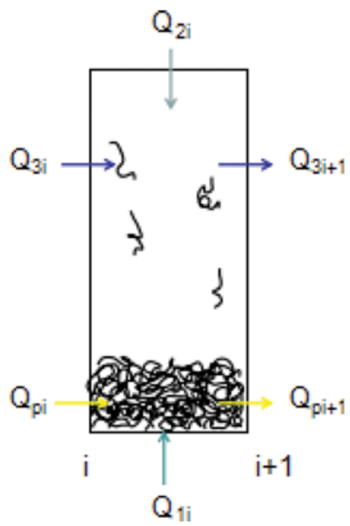

Fig. 2. The heat and mass balance in a control volume i.

Each experiment was repeated four times to verify the results and obtain the mean values of temperature and moisture content of particles. As a consequence, the mean values of the temperature and moisture content were obtained. The properties of the geometric parameters are listed in Table 1.

SIMULATION METHODS

The heat and mass transfer on wet particles occur in the rotary dryers during the drying process. In this study, the rotary dryer was divided into several volumes with each having the same length as the others. The heat and mass transfer equations were developed in each volume. A schematic of the control volume, which clearly describes the heat and mass transfer in a rotary dryer, is shown in Fig. 1. Generally, the wet particles are in direct contact with the drum wall when moving to the bottom in rotary dryers. Meanwhile, the heat conduction between wet particles and drum wall takes place caused by the temperature difference. In general, the mean residence time of particles plays a significant role on the heat and mass transfer. Hence, the mean residence time can be calculated based on Eq. (14). It is assumed that the residence time in each control volume is the same. The heat convective heat and mass transfer take place during the dropping process by flights. The residence time of dropping can also be obtained and applied to the convective heat and mass transfer. Typically, the operating temperature of rotary dryers is below 150 °C; therefore the radiation heat transfer can be ignored due to negligible heat transfer rate in this temperature [20]. Considering that cut-tobacco particles were used as experimental material, thermal conductivity and mass transfer still occurred among particles because of the inhomogeneity of temperature and moisture content.

A suitable mathematical model for the simulation of wet particles drying characteristics in a rotary dryer was developed. To develop such a mathematical model, the total length of the drum is divided into several isometric elementary control volumes. Additionally, the temperature and moisture content of the particles are obtained by the equations based on the laws of conservation of mass and energy. The type of rotary dryer used is cocurrent, namely, gas flow has the same direction as the particles. The heat and mass balance in a control volume i are shown in Fig. 2. The following assumptions were made to simplify the model:

(1) The drying process in each elementary control volume is steady.

(2) The variation of the parameters within the rotary drum can be summarized as a one-dimensional model. Furthermore, moisture content of the particles and humidity of the air flow changes only along the longitudinal direction of the drum.

(3) The drying process generally occurs in the falling drying rate period [28]. At the falling drying rate period, the moisture transmission rate from inner to surface in a particle is lower than the rate at constant drying rate period. Moreover, there is lack of enough moisture to be evaporated; however, the heat from the rotary drum (heat source) is constant. Therefore, the excess heat is used to raise the temperature of the particles. The moisture content of particles experiences a significant drop and the temperature increases during the falling drying rate period.

(4) The structure change of the particles within the rotary dryer is ignored during the drying process.

1. Heat Transfer Equations

The heat of wet particles is mainly obtained from the thermal conductivity of the drum wall and the convection of the hot air flow. The relation between enthalpy and heat transfer is established in steady-state conditions. Hence, the rate of inlet heat is equal to that of the outlet heat within each elementary control volume in a unit time. The general equations for heat transfer in the particles are as follows:

$$Q_{1i}+Q_{2i}+H_{pi}+H_{gi}=H_{pi+1}+H_{gi+1} \tag{1}$$

$$Q_{1i}=a_1F_1(T_w-T_{pi}) \tag{2}$$

$$Q_{2i}=\alpha_2F_2(T_w-T_{gi}) \tag{3}$$

$$H_{pi}=W_{dp}(C_{dp}+X_iC_{H_2O})(T_{pi}-T_{ref}) \tag{4}$$

$$H_{gi}=W_{dg}(C_{dg}+Y_iC_V)(T_{gi}-T_{ref})+W_{dg}Y_ir \tag{5}$$

Based on Eq. (2), Eq. (3), Eq. (4) and Eq. (5), Eq. (1) can be simplified as:

$$\begin{aligned}&T_{pi}[W_{dp}(C_{dp}+X_iC_{H_2O})-\alpha_1F_1]+T_{gi}[W_{dg}(C_{dg}+Y_iC_V)-\alpha_2F_2]\\&-T_{pi+1}W_{dp}(C_{dp}+X_{i+1}C_{H_2O})-T_{gi+1}W_{dg}(C_{dg}+Y_{i+1}C_V)\\&=T_{ref}[W_{dp}C_{H_2O}(X_i-X_{i+1})+W_{dg}C_V(Y_i-Y_{i+1})]\\&+W_{dg}r(Y_{i+1}-Y_i)-T_w(\alpha_2F_2+\alpha_1F_1)\end{aligned} \tag{6}$$

In equations above, Q_{1i} represents the heat transfer rate between the drum wall and the cut-tobacco particles, and Q_{2i} corresponds to the connective heat transfer rate between the drum and hot gas flow. H_p and H_g are the enthalpies of particles and gas flow respectively. α_1 is the heat transfer coefficient between the drum and the cut-tobacco particles, which can be calculated by a correlation $\alpha_1=0.394(W_{dg}/F_1)^{0.289}(W_{dp}/F_1)^{0.541}$. α_2 is the convective heat transfer coefficient between the drum and the hot gas, $\alpha_2=0.022(W_{dg}/F_2)^{0.879}$ [28]. F_1 is the contact area between particles and drum in each elementary control volume. F_1 is determined by a large number of factors, such as structure of flights, rotational speed, mass flow rate of particles. Therefore, F_1 is investigated based on empirical formula in tobacco industry, 1/2 to 2/3rds of total superficial area of a rotary dryer. In this paper, 60 percent of total superficial area is taken as the contact area. F_2 is the contact area between drum and hot gas. According to the method as below, F_2 is always determined by 1/3 to 1/2 of total superficial area of a rotary dryer. 45 percent of total superficial area is taken as the contact area between gas flow and drum. In Eqs. (2) and (3), T_w is the temperature of drum wall. T_{gi} and T_{pi} represent the temperature of gas flow and particle respectively. In Eqs. (4) and (5), T_{ref} is the reference temperature equivalent to 273 K. W_{dp} is mass flow of dry cut-tobacco particles and W_{dg} is the dry air. X_i is the moisture of particles in elementary control volume i and Y_i is the humidity of gas flow. In Eq. (6), r is the latent heat of vaporization. C_v, C_{dp}, C_{dg} and C_{H_2O} represent specific heat of vapor, dry particle, gas flow and water, respectively.

Additionally, the heat gained by cut-tobacco particles was from drum wall and hot gas flow. As a result, it led to the increase in the temperature of the particles and evaporation of the water within particles. The heat transfer equations applied to the particles and gas flow are written as follows:

$$Q_{1i}+Q_{3i}=Q_{ph}+Q_v+Q_{hv} \tag{7}$$

$$Q_{3i}=\alpha_3F_3(T_{gi}-T_{pi}) \tag{8}$$

$$Q_{ph}=W_{dp}(C_{dp}+X_{i+1}C_{H_2O})(T_{pi+1}-T_{pi}) \tag{9}$$

$$Q_v=W_{dp}(X_i-X_{i+1})r \tag{10}$$

$$Q_{hv}=W_{dp}(X_i-X_{i+1})C_v(T_{gi+1}-T_{pi}) \tag{11}$$

where, Q_{3i} is the connective heat between the gas flow and the particles, α_3 is the convective heat transfer coefficient between cut-tobacco particles and hot gas. F_3 is the contact area between gas flow and particles, which is equal to F_m. Q_{ph} represents the heat that causes the increase in the temperature of the particles. Q_{hv} is the heat for the vaporization of water and Q_v is the latent heat of vaporization.

The aforementioned parameters that utilized in the energy balance equations can be set from several data tables [21]. The physical parameters of the cut-tobacco particles remain unchanged because changes in temperature during the drying process are negligible. It is extremely difficult to clearly ascertain the heat transfer coefficient and area, which are affected by the motion state, moisture content, velocity of gas flow, particle filler content in the rotary dryer and rotational speed. Generally, several methods are employed, including numerical simulation, experimental correlation and semi-empirical, to study the drying behavior of particles along the length of the rotary drum [22,23].

2. Mass Transfer Equations

In the preheating period, the flexible filamentous particles may obtain moisture if the steam pressure of gas flow (P_{gv}) is larger than the surface steam pressure of particles (P_{pv}). The steam pressure of gas flow and particles could be investigated, respectively, as follows:

$$P_{gv}=\frac{101300Y}{0.622+Y} \tag{12}$$

$$P_{pv}=\exp\left(27.486-\frac{6580}{41+T_p}\right) \tag{13}$$

The gas flow could gradually obtain moisture from flexible filamentous particles during drying process in a rotary dryer due to the difference of surface steam pressure. The moisture lost by cut-tobacco particles is equal to the moisture gained from the hot gas flow. The rate of mass transfer is equal to the moisture lost by cut-tobacco particles. According to the law of conservation of mass, the equations for each elementary control volume per unit time were developed as follows:

$$W_{dp}(X_i-X_{i+1})=W_{dg}(Y_{i+1}-Y_i) \tag{14}$$

$$M_i=k_mF_m(c_{gi}-c_{pi})M_r \tag{15}$$

$$M_i=-W_{dg}dY \tag{16}$$

$$c_i=\frac{p_i}{RT_i} \tag{17}$$

where, k_m denotes the interfacial convective mass transfer coefficient, which is affected by the gas-solid relative velocity, temperature and humidity of the gas flow, and temperature and moisture content of particles. Various factors can lead to the changes of contact area F_m; for instance, the shape of the particles, the filler content, the structure of the flights and the rotational speed. M_i represents the convective mass transfer rate in volume i. c_{gi} and c_{pi}, respectively, are the substrate concentration of steam in gas flow and particles. p_i and T_i represent, respectively, the pressure and temperature of steam. R is molar gas constant. The above parameters can be calculated, by a supercomputer [24].

The correlation on the mean residence time of granular particles in a rotary dryer is given by [27]

$$\tau=L\cdot\left[\frac{0.3344}{SN^{0.9}D}\pm\frac{0.6085G}{S_Sd_p^{0.5}}\right] \tag{18}$$

$$v_p = \frac{L}{\tau} \tag{19}$$

where, τ represents the residence time of granular particles (s), L describes the length of rotary dryer (m), S indicates the slope of rotary dryer (°), N is the rotational speed (rev/s), D represents the diameter of dryer (m), G and S_s describe gas flow rate per cross section area (kg/(m^2·s)) and solid rate per cross section area (kg/(m^2·s)), respectively. d_p and v_p, respectively, suggest the diameter of particle (m). Furthermore, the negative sign in Eq. (18) is applied for cocurrent flows, which means the gas flow has the opposite direction to solids phase and the negative is for cocurrent flows, which means the gas flow has the same direction as solids phase. The heat transfer factor and mass transfer factor are described by j factor as follows:

$$j_H = \mathrm{St}\,\mathrm{Pr}^{2/3} \tag{20}$$

$$j_M = \left(\frac{k_m}{\mu\rho}\right)\mathrm{Sc}^{2/3} \tag{21}$$

The convective mass transfer coefficient k_m is investigated based on the correlation of $j_H = j_M$, which is applied to rotary dryers [34]. Usually, the contact area F_m between particles and gas flow is quite difficult to measure by experimental and numerical methods. Meanwhile, cut-tobacco particles fully contact with gas flow during the drying period in rotary dryers and the contact area when particles are dropped from flights is much larger than the area when they are in the flights. Therefore, it is assumed that all cut-tobacco particles are contacted with gas flow and the contact area F_m is determined by the mass flow rate and density of particles.

The inlet and outlet moisture content of the particles are usually identified for practical production. Thus, the temperature and moisture content of the cut-tobacco particles and the gas flow were solved numerically and programmed by using Visual Basic method.

3. Comparison between Experimental and Numerical Results

The numerical simulation system was performed with an industrial-scale drum. However, according to the operating conditions, the temperature and moisture content of particles in the axial section of rotary dryers are particularly difficult to obtain by approximate approaches [25,26]. In addition, the measurements from inside the rotary dryer are not available. For this reason, a numerical mathematical model was developed to estimate the temperature and moisture content of particles inside the rotary dryer. The inlet and outlet experimental data were measured and obtained, and then compared with simulation results. The simulated and

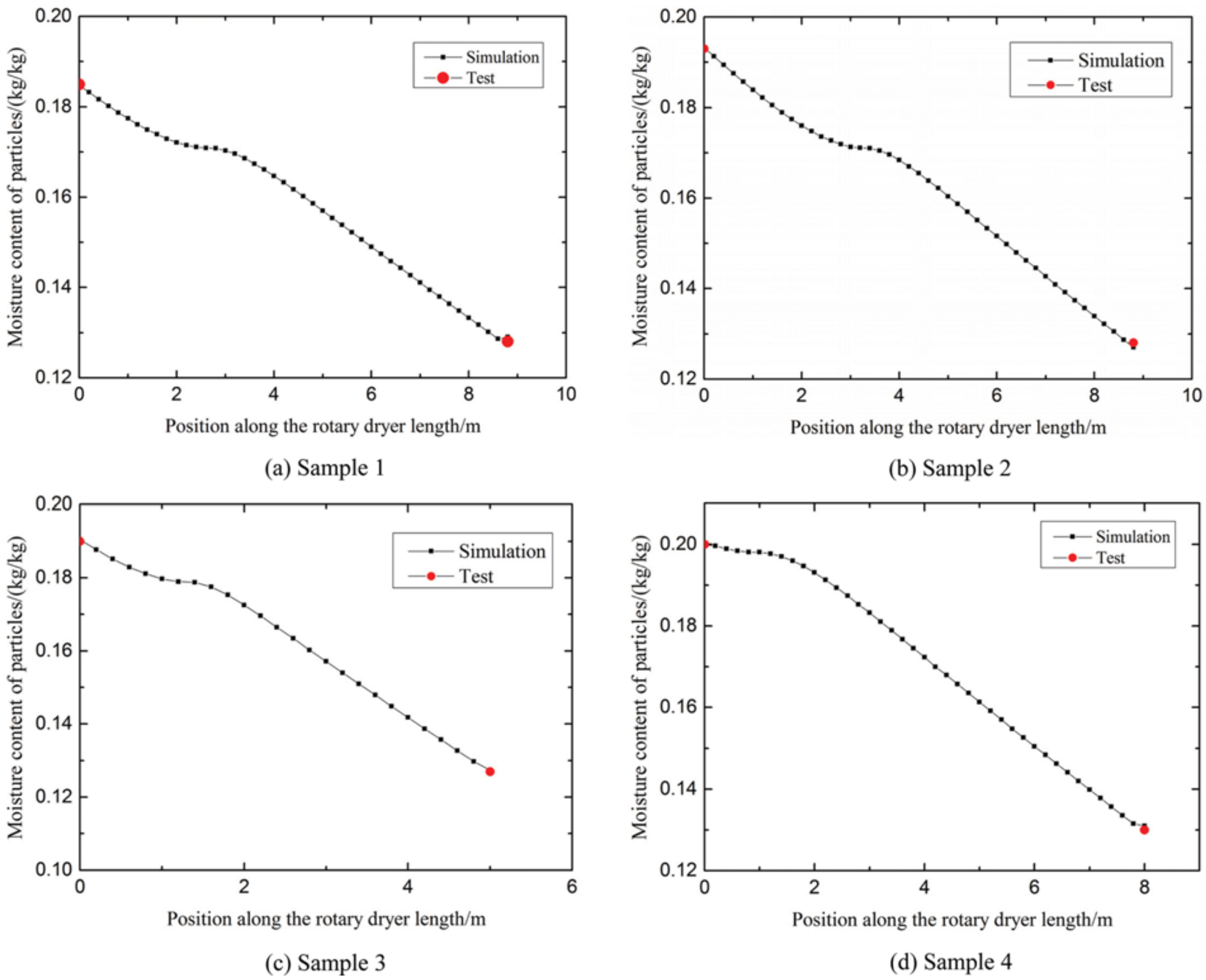

Fig. 3. Simulated and measured cut-tobacco particles moisture content along the rotary dryer under four different conditions.

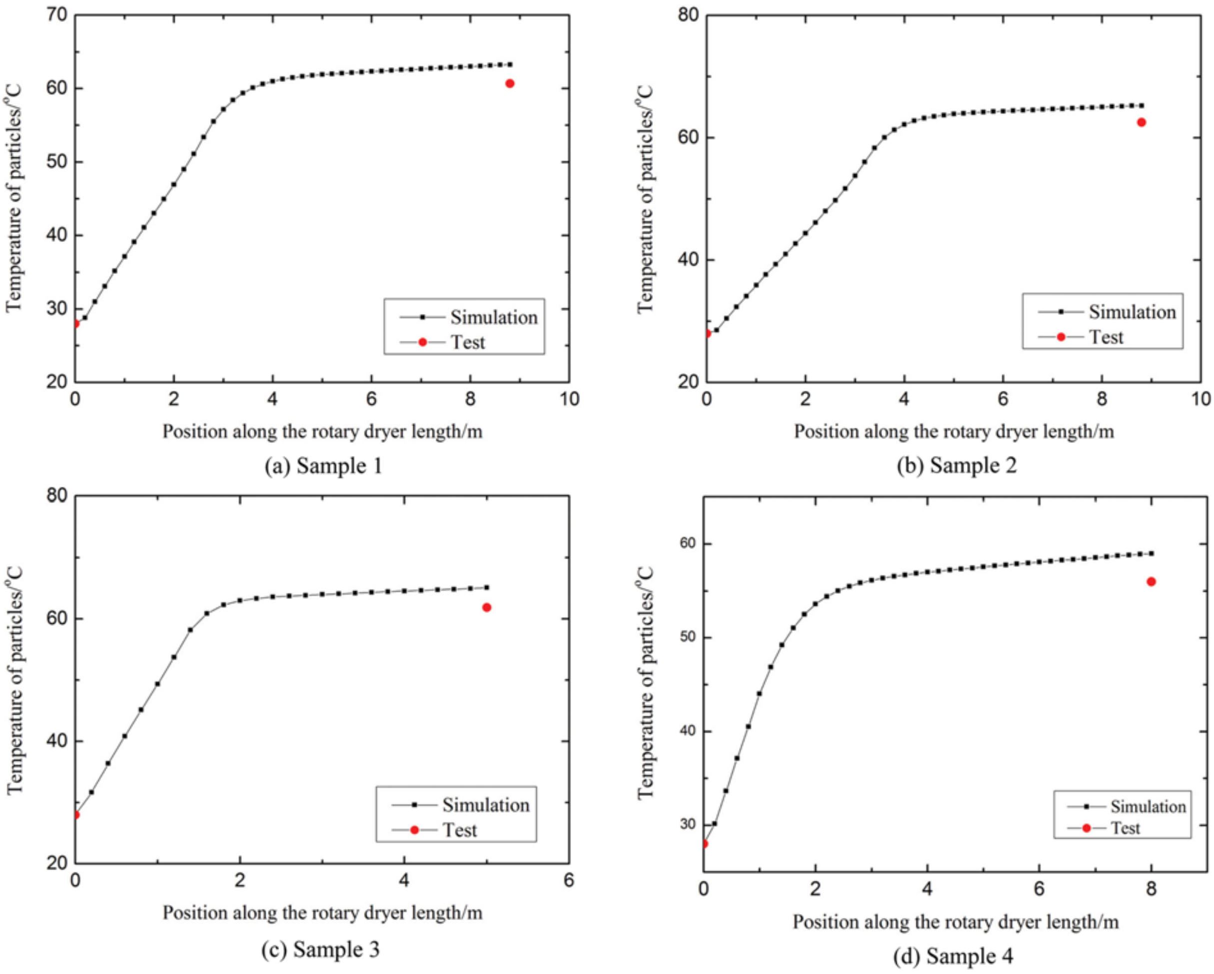

Fig. 4. Simulated and measured cut-tobacco particles temperature along the rotary dryer under four different conditions.

measured moisture content and temperature of the cut-tobacco particles along the length of the rotary dryer in four different conditions are shown in Fig. 3 and Fig. 4.

A comparison of the numerical simulation results with experimental data in four different drying conditions revealed that the moisture content of the particles changed slightly in the beginning. A large amount of heat was used to heat particles during the preheating period. Accordingly, the temperature of the particles significantly increased. Moreover, the temperature of the particles underwent a slight change and the surface water vapor pressure was higher than that of the hot gas flow. It resulted in the movement of moisture from inner to the outer space. Thus, the surface moisture that was vaporized brought about a quick increase in the evaporation rate and a reduction in the moisture content of the particles. The simulated temperature at the exit was higher than that of the experimental data due to the gas exhaustion at the end of the drying process. First, in general, a moisture exhaust system was set up at the exit of each rotary dryer, which was used to exhaust the excess moisture of flexible filamentous particles. Meanwhile, a bit of heat could be also taken away by the moisture exhaust system during experimental drying processes. Therefore, the temperature of particles was marginally influenced and the temperatures of particles investigated by simulation method were higher than the experimental results. Second, the temperature of particles obtained by the discrete element method was higher than the experimental results due to the negligible contact heat transfer among particles in rotary dryers. The cut-tobacco particles were dried from 19% (initial moisture content) to around 13%, and heated from 28 °C to 65 °C (target temperature) at the exit of the rotary dryer. The simulation results of the particle temperature were higher than the experimental data due to the gas exhaustion during the drainage period. Hence, it led to the decline in the temperature of the particles. The results indicated that the deviation of the moisture content was less than 1% and that of the temperature was less than 10%. It illustrated that the simulation results agreed well with the experimental data. The numerical mathematical model was feasible and effective for predicting the temperature and moisture content of the particles inside the rotary dryers during the drying process.

RESULTS AND DISCUSSION

Rationale and reliability of numerical mathematical models have been proved by numerous previous studies. Therefore, the approach on heat and mass transfer of particles under different drum wall temperatures and rotational speeds in a rotary dryer is employed.

Specifications for the numerical mathematical model used in this research are listed in Table 2.

Table 2. Simulation conditions

Parameters	Value
Length of rotary dryer	8000
Diameter, mm	1700
Height of flights, mm	410
Number of flights	12
Mass flow of particles, kg/h	4500
Velocity of gas flow, m/s	0.2
Temperature of gas flow, °C	95
Inlet moisture content of particles, kg/kg	0.2
Inlet temperature of particles, °C	28
Temperature of drum wall, °C	130, 135, 140, 145
Rotational speed, r/min	9, 10, 11, 12
Drum slope, °	3

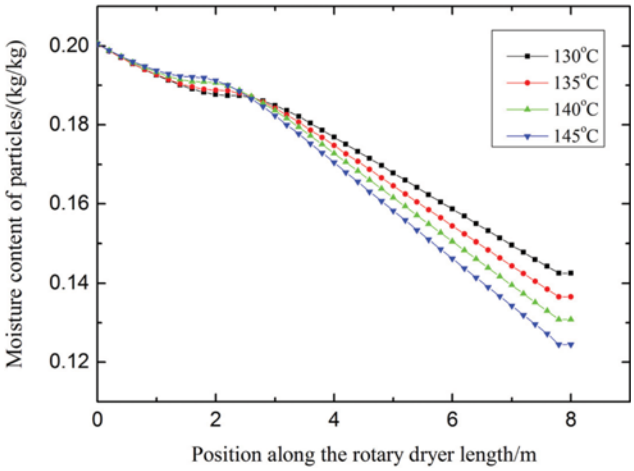

Fig. 5. Moisture content of particles along the drum dryer with different temperature of drum wall.

The temperature and moisture content of the particles along the drum dryer length were determined at a rotational speed of 11 r/min under various drum wall temperatures, including 130, 135, 140 and 145 °C, respectively. The changes of temperature and moisture content of the particles inside the rotary dryer are shown in Fig. 5 and Fig. 6. The results revealed that the moisture content of particles slightly reduced during the preheating period. The temperature of the drum wall had greatly impacted the particles by increasing the particle temperature and drying rate. Furthermore, they showed that the temperature of the particles marginally climbed with the increase of drum wall temperature. During the constant speed drying period, moisture flowed from inside to the surface due to the moisture difference of the particles. The outlet temperature of the particles was between 63 °C to 67 °C when the drum wall temperature rose from 130 to 145 °C. The moisture content was between 14.25% to 12.45% under those conditions. In addition, the outlet moisture content of the particles experienced a significant drop with the increase of the drum temperature. Nevertheless, the temperature and moisture conductivity had little effect on the particles due to the negligible temperature difference between the inside and the surface. Thus the temperature of the particles was only changed slightly in that period.

The temperature and moisture content of the particles that were ascertained along the drum dryer length at a drum temperature of 145 °C at different rotational speeds (9, 10, 11 and 12 r/min respectively) are shown in Fig. 7 and Fig. 8. These results illustrate that the temperature of the particles decreased from 67 °C to 65 °C when the rotational speed increased from 9 r/min to 12 r/min. The moisture content of particles varied from 12.49% to 14.26% under the same conditions above. Furthermore, the residence time of the particles in a rotary dryer was reduced with the increase of rotational speed. Accordingly, the outlet moisture content of the particles was higher at the faster rotational speed, whereas the outlet temperature was lower. During the preheating period, the rotational speed exerted a little influence on the moisture content of particles. However, with the increase of rotational speed, the particles moved vigorously inside the rotary dryer. It resulted in the

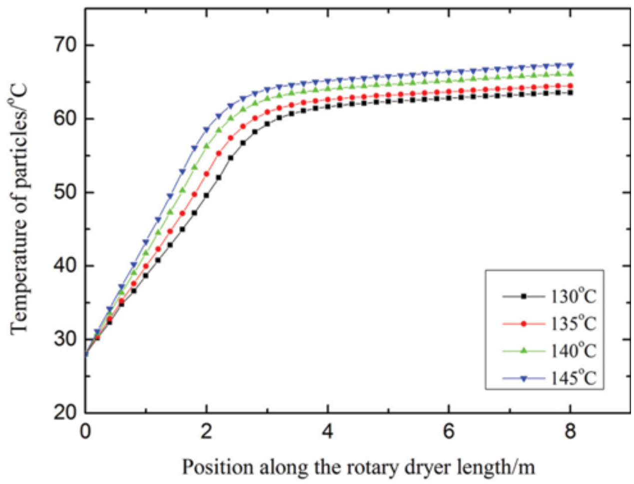

Fig. 6. Temperature of particles along the drum dryer with different temperature of drum wall.

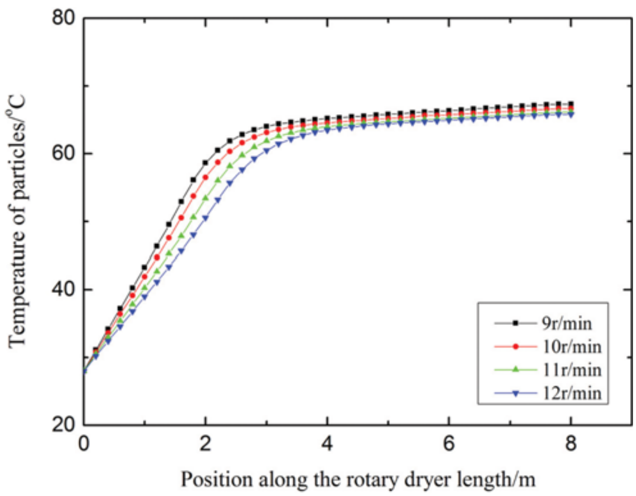

Fig. 7. Moisture content of particles along the drum dryer with different rotational speed.

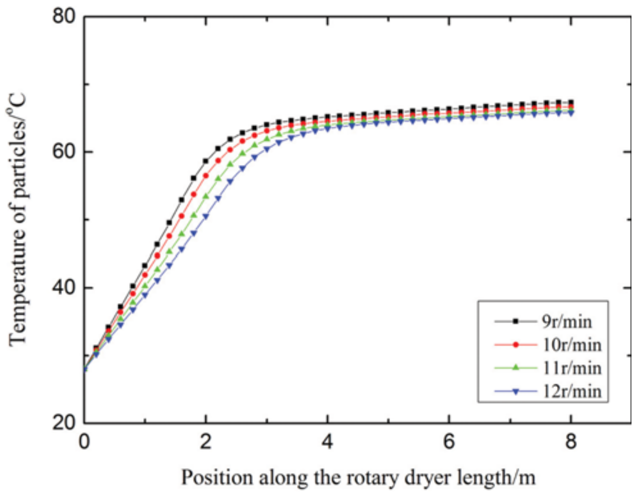

Fig. 8. Temperature of particles along the drum dryer with different rotational speed.

temperature of particles slowly increasing. In comparison, the moisture content of particles decreased much faster at a lower rotational speed during the constant speed drying period and the temperature was changed marginally.

CONCLUSION

The heat and mass transfer in flexible filamentous particles within rotary dryers was experimentally and numerically studied. A mathematical model was established to estimate the temperature and moisture content of particles within the rotary dryers. Additionally, the results demonstrated that the theoretical calculation on temperature and moisture content corresponds to the experimental data. The maximum error in the moisture content is 0.8% and that of the temperature is less than 10%. The results of simulations reflect that the moisture content of the particles slightly changes in the preheating period. However, the temperature increases significantly during that period because of the heat from the drum wall. Then, the change of temperature is insignificant during the drying period at a constant rotational speed. However, the drying rate of the particles increases significantly because the steam partial pressure on the surface is higher than that on the gas flow. The numerical simulations indicate that the moisture content of particles declines and the outlet temperature climbs following the increase of the drum wall temperature. Moreover, the outlet moisture content rises and the temperature reduces with the increase of the rotational speed. Thereby, the results presented in this paper can be applied to the chemical and energy industry. Future research on drying behavior in rotary dryers may also call for more experimental tests to ascertain more performance data in realistic conditions.

NOMENCLATURE

Q_{1i} : thermal heat transfer from drum to cut-tobacco particles [W]
Q_{2i} : connective heat between drum and hot gas flow [W]
Q_{3i} : connective heat between gas flow and particles [W]
Q_{ph} : heat for cut-tobacco particles [W]
Q_{hv} : heat for vaporization of water [W]
Q_v : latent heat of vaporization [W]
H_p : enthalpy of particles [W]
H_g : enthalpy of gas flow [W]
α_1 : heat transfer coefficient between drum and cut-tobacco particles [$W/m^2 \cdot K$]
α_2 : convective heat transfer coefficient between drum and hot gas [$W/m^2 \cdot K$]
α_3 : convective heat transfer coefficient between particles and hot gas [$W/m^2 \cdot K$]
F_1 : contact area between particles and drum in each elementary control volume [m^2]
F_2 : contact area between drum and hot gas in each elementary control volume [m^2]
F_3 : contact area between gas flow and particles in each elementary control volume [m^2]
T_w : temperature of drum wall [K]
T_{gi} : temperature of gas flow [K]
T_{pi} : temperature of particle [K]
T_{ref} : reference temperature [K]
W_{dp} : mass flow of dry cut-tobacco particles [kg/s]
W_{dg} : mass flow of dry air [kg/s]
X_i : moisture of particles in elementary control volume i [kg/kg]
Y_i : humidity of gas flow in elementary control volume i [kg/kg]
r : latent heat of vaporization [kJ/kg]
C_v : specific heat of vapor [kJ/kg·K]
C_{dp} : specific heat of dry cut-tobacco particles [kJ/kg·K]
C_{dg} : specific heat of dry gas [kJ/kg·K]
C_{H_2O} : specific heat of water [kJ/kg·K]
c_{gi} : substrate concentration of gas flow [$kmol/m^3$]
c_{pi} : substrate concentration of particles [$kmol/m^3$]
k_m : mass transfer coefficient [$kg/m^2 \cdot s$]
τ : residence time of granular particles [s]
L : length of rotary dryer [m]
S : slope of rotary dryer [°]
N : rotational speed [rev/s]
G : gas flow rate per cross section area [$kg/m^2 \cdot s$]
D : diameter of dryer [m]
S_s : solid rate per cross section area [$kg/m^2 \cdot s$]
d_p : diameter of particle [m]

Subscripts

w : wall
p : particle
g : gas
ref : reference
s : solid
m : mass

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