STUDY ON HEAT AND MASS TRANSFER CHARACTERISTICS IN DRYING PROCESS OF DRUM DRYER BASED ON THE DEM-CFD COUPLED METHOD

Jiawen HOU* [1] *, Dongdong WANG* [1]*, Fan LI* [1]*, Hongxia ZHAO* [1]*, Jiangtao ZHANG* [2]*, Lijie JIN* [2*]*,

***Chu-an ZHANG* [3]*, Dening XIANG* [3*]*, Ya-nan CHEN* [4]*, Xuehong WU* [4*]**

[1] Henan Zhongyan Zhumadian cigarette factory，Zhumadian, 463002，Henan, China

[2] Baoding Cigarette factory, China Tobacco Hebei Industrial Co., Ltd., Baoding 071000, China;

[3] Wuhan Cigarette factory, China Tobacco Hubei Industrial Co., Ltd., Wuhan 430051, China;

[4] School of Energy and Power Engineering, Zhengzhou University of Light Industry, Zhengzhou, Henan, China, 450000

* Corresponding author: E-mail: 410356782@qq.com, xiangdn@wh.hbtobacco.cn,wuxh1212@163.com

In order to analyze the heat and mass transfer characteristics of cut tobacco in a horizontal drum dryer, the discrete element method (DEM) was used to calculate the particle collision model and DEM-CFD coupled heat transfer model. With the increase of the rotating speed, the mixing degree gradually increases, and when the rotating speed is 16 rpm, the mixing degree is higher. When the heat flux of EDEM-CFD coupling is 0.2 W-1W, the particle temperature will gradually increase and tend to a fixed value. The residence time of the material has a great influence on the drying quality of the material particles. If the residence time is too short, the heat of the material will be uneven, and if the residence time of the material is too long, the damage of the material particles will increase, increased crushing rate.

Key words: *DEM-CFD coupling; heat and mass transfer; cut tobacco, drum dryer*

1. Preface

Drum dryers are widely used in material drying and processing in industries such as chemical, pharmaceutical, and food. Due to its significant improvement in drying efficiency and quality of materials, it has been widely favored[1-4].No matter what kind of drum is used, it is directly related to the drum rotation speeds, and the appropriate drum speed is the basis for particle mixing or further processing[5, 6].

The drum dryer can stir and bake the tobacco, so the effective stirring and baking can promote the heat exchange between the tobacco particles and the uniformity of the mix. At a certain wall temperature the heat conduction between the drum wall and the tobacco mainly depends on the stirring speed, which also affects the uniformity of the particles[7]. The movement of the tobacco in the dryer is that the tobacco is picked up and dropped continuously by the inner plate, and the tobacco is transported forward periodically. At the same time, the airflow interacts with the falling tobacco, which is easy to transport and does not have the phenomenon of the tobacco stuck in the dead corner, etc. , the drying is more even[8]. The movement of tobacco particles in the drum dryer is very complex, the mechanism of particle movement depends on a series of state factors and the characteristics of tobacco itself.

With the development of computer technology, numerical simulation has become an effective method to investigate particle movement. At present, Euler multiphase flow model and discrete element model (DEM) are the main research methods[9].The DEM discretizes the solution space into a discrete element array, and connects adjacent elements with reasonable connecting elements based on actual problems; Calculate the resultant force and moment of force between a unit and other units in various directions, as well as the external forces caused by other physical fields acting on the unit. According to Newton's second law of motion, the acceleration of the unit can be obtained and integrate it in time to obtain the velocity and displacement of the element, and to obtain physical quantities such as velocity, acceleration, angular velocity, linear displacement, and rotation angle of all units at any time.When calculating the heat transfer of tobacco particles, hot air is passed into the drum, and the parameters of the gas are set by FLUENT. The operation is relatively simple, and the solid phase, that is, the particle phase, is set by EDEM software. The two software achieve coupling calculation through the DDPM model in FLUENT software[10-14]. Scherer et al.[15] investigated convective drying of wood chips in a baffled laboratory rotary dryer used coupled DEM-CFD simulations. Wu et al. [16]used the DEM-CFD coupled heat transfer model to study the three-dimensional simulation of gas-solid flow in a flexible zonal particle fluidized bed. The dynamic behavior of flexible ribbon particles is studied vividly. Darius Markauskas et al.[17] used the DEM-CFD method to analyze the transportation process of flexible fibrous particles.

The drying of cut tobacco has an important effect on the quality of cut tobacco, but the drying process is a complex physical process, which involves three heat transfer processes, the heat and mass transfer process of cut tobacco in drum dryer is the key to control the drying process of cut tobacco. The tobacco particles are relatively fine and have a certain degree of flexibility, and single computational method cannot effectively obtain the particle motion and heat and mass transfer process.Therefore, this paper based on DEM-CFD method to analyze the heat and mass transfer characteristics of tobacco drying process, the research results provide theoretical guidance for cut cuttobacco drying.

2. Numerical model

2.1. Particle collision model

The aim in this paper is the tobacco particles of the horizontal right-angle sheet roller drying machine. The CFD-DEM coupled method is applied in the present, the particles are modelled by means of the DEM theory and treated as real discrete particles. The particle interaction force needs to be added on the spheres as part of Newton's second law when coupled DEM-CFD simulations are performed. Because the tobacco particles are similar to the soft ball model, the soft ball model is usually the Hertz-Mindlin non-slip contact model, which analyzes the collision between the particles through the damping vibration of the simplified spring oscillator. The normal and tangential forces of the model are determined by formula (1) and (2) respectively[18]:

$$F_n = -K_n \delta_n + C_n v_n \tag{1}$$

$$F_t = min\{\mu_s F_n, \quad -K_t \delta_t + C_t v_t\} \tag{2}$$

Where: K_n, K_t- normal and tangential elastic coefficients of particles; δ_n, δ_t- the amount of overlap between normal and tangential; C_n, C_t - normal and tangential damping coefficients; v_n, v_t- relative normal and tangential velocities between particles.

The motion of particles is described using Newton's second law of motion equations such as (3) and (4) [9, 11]:

$$m_i \frac{dv_i}{dt} = \sum_{j=1,j\neq i}^{N} \left(F_{nij} + F_{tij}\right) + m_i g \tag{3}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1,j\neq i}^{N} \left(\frac{d_i}{2} F_{tij} + T_{rij}\right) \tag{4}$$

The mass of m_i - i particles in the formula; Velocity of v_i - i particles; Angular velocity of ω_i - i particles;

I_i - the moment of inertia of the i particle; d_i - diameter of particle i; N - the number of colliding particles; F_{nij}, F_{tij}, T_{rij} - normal force, tangential force and rolling friction moment between particles i and j.

The central difference method is used to numerically integrate the equations of velocity and displacement for (3) and (4), iteratively obtain the new displacement value of the particle, and then substitute the new displacement value into the force-displacement relationship to obtain the new force, so the calculation is repeated to track the movement of the particle at any time.

In addition, there is rolling friction, which can be solved by the moment of the contact surface:

$$T_i = -\mu_r F_n R_i \omega_i \tag{5}$$

Where: μ_r is rolling friction factor; $R_i$is the distance between the center of mass and the contact point; ω_i is the unit angular velocity vector of the object at the contact point.

2.2. DEM-CFD coupled heat transfer model

The Hertz-Mindlin contact model with heat conduction was chosen because of the heat exchange between the tobacco particles and the drum dryer. The heat transfer process in the cylinder mainly includes the heat transfer between hot air and particles on the inner wall of the heat exchanger cylinder and material particles. The EDEM software can only calculate the heat transfer between the inner wall of the cylinder and the material particles, while the convective heat transfer between air and particles requires the coupling of EDEM and FLEUNT, and the heat flow data is imported into the EDEM to heat the particles in parallel.

2.2.1 Convection heat transfer model

Convective heat transfer mainly occurs between the gas phase and the particle phase. Due to the temperature difference between the gas phase and the particle phase, the two phases carry out heat transfer, and its expression is shown in equation (6)[19].

$$Q_{pf} = h_{pf} A_p \Delta T_{pf} \tag{6}$$

Where, p is the particle phase; f is the liquid phase; Q_{pf} is the heat transfer flux; h_{pf} is the heat transfer coefficient of the two phases. A_p is the surface area of the particle phase; ΔT_{pf} is the temperature difference between the two phases.

The heat transfer coefficient is calculated by equation (7).

$$h_{pf} = \frac{k_q Nu_p}{d_p} \tag{7}$$

Where, k_q is the thermal conductivity of the gas phase; d_p is the surface particle diameter; Nu_p is Nussel number.

2.2.2 Radiation heat transfer model

For the radiative heat transfer model, the emissivity of the particle surface needs to be set, and temperature-update needs to be set in EDEM to ensure that the particle Temperature is updated. According to the Stefan-Boltzmann law, the heat transfer between particles and the surrounding environment can be described by equation (8) [19].

$$Q_{rad} = \sigma \varepsilon_p A_P (T_P^4 - T_{local}^4) \quad (8)$$

Where σ is the blackbody radiation constant; ε_p is the emissivity of a spherical particle; T_{local}^4 is the average temperature of the particles in a closed grid cell.

2.2.3 Hertz Mindlin heat conduction model

For the heat conduction model, EDEM simulation of particle flow heat exchange in rotary equipment provides a method of inter-particle heat exchange, and its expression is shown in equation (9) and (10)[20].

$$Q_{p1p2} = h_c \Delta T_{p1p2} \quad (9)$$

$$h_c = \frac{4k_{p1}k_{p2}}{k_{p1}+k_{p2}} \sqrt[3]{\frac{3F_N r^*}{4E^*}} \quad (10)$$

Where, k_p is the thermal conductivity of particles; F_N is the normal component of the contact force. r^* is the effective radius of the contact part; E^* is the effective elastic modulus of the particle.

2.2.4 Transverse heat transfer between geometry and particles

The transfer process between the cylinder wall surface and the particles is described by equation (11)[21] :

$$Q_{ij} = H_{c,ij}(T_j - T_i) \quad (11)$$

Where Q_{ij} is the heat transferred by the geometry to the particle; T is the temperature of the geometry or particle; $H_{c,ij}$ is the thermal conductivity between the geometry and the particles.

2.3. Computational model

Data interactions between CFD and DEM are implemented by calculating forces. The modelling of the cut tobacco by DEM is at the individual particle level, while the heat transfer by CFD is at the computational mesh level. Firstly, Fluent is used to calculate the flow field information at a time step, and then EDEM is initiated for the same time iteration. The coupling interface is used to transfer the position, motion, volume, temperature and other information of particles to Fluent, and the interaction between particles and fluid is calculated. The effect of fluid on particles will be transmitted to EDEM through the interface as a particle volume force affecting particle motion, while the effect on fluid will act on the fluid through momentum source phase. In CFD-DEM model, cut tobacco are seemed as discrete phase, and Newton's second law is used to establish the equations of motion of each particle.

The cut tobacco is assumed to consist of seven 5 mm diameter particles with a straight line length of approximately 23 mm, as shown in Figure 1. The geometric model used in this paper is a horizontal drum dryer. The diameter of the drum is 1960mm, the length is 9000mm, the wall thickness of the drum is about 50mm, and the angle between the drum and the horizontal plane is 2°. As shown in Figure 2, the drum dryer is mainly composed of a front chamber, a cylinder and a back chamber. At the entrance of the front chamber, a particle factory is set up to fill the cylinder with cut tobacco particles at an initial speed of 2 m/s. the set particles can generate 10000 particles in the form of the number of particles, and the particle formation speed is 5000 particles/s. The rotating speed of the cylinder is set to 6 rpm during the formation of particles, and after the formation of particles, the rotating speed of the cylinder is set to 9rpm, 11rpm, 13rpm, 15rpm, 16rpm respectively. In fact, the particle filling amount is 50%, but because of the larger drum size, the calculation amount is too large to carry out stable calculation. Therefore, in this paper, the filling amount of particles is set to 2%, which improves the calculation efficiency, and the influence of drum speed on the motion state and temperature of particles can be obtained. The parameters used in the simulation are shown in Table 1.

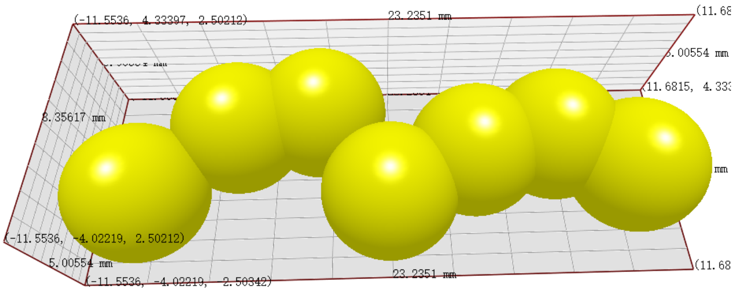


Fig. 1 Particle model size

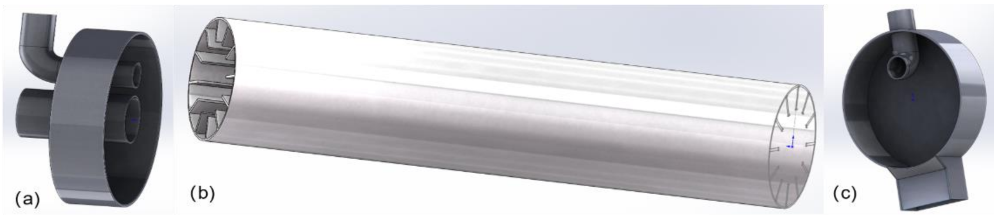


Fig. 2 Geometric model of drum drying machine (a) the front chamber (b) cylinder body (c) rear chamber of the drum respectively.

Table 1 Simulation parameters

Parameter Property	argument	Numerical value
Particle properties	Particle density $kg\cdot m^{-3}$(packing density)	125
	Shear modulus /Pa	1e+07
	Poisson's ratio	0.25
Cylinder property	Density $kg\cdot m^{-3}$	7800
	Shear modulus /Pa	7e+10
	Poisson's ratio	0.3
Interaction	Coefficient of static friction between particle and cylinder	0.5
	Dynamic friction coefficient between particle and cylinder	0.01
	Dynamic recovery coefficient of particle and cylinder	0.2
	Particle to particle static friction coefficient	0.408
	Particle to particle dynamic friction coefficient	0.355
	Particle to particle collision recovery coefficient	0.27
Other parameters	Acceleration of gravity $g/(m/s^2)$	9.81
	Roll Angle	2°
	Time step /s	1.8e-05

3. Results and analysis

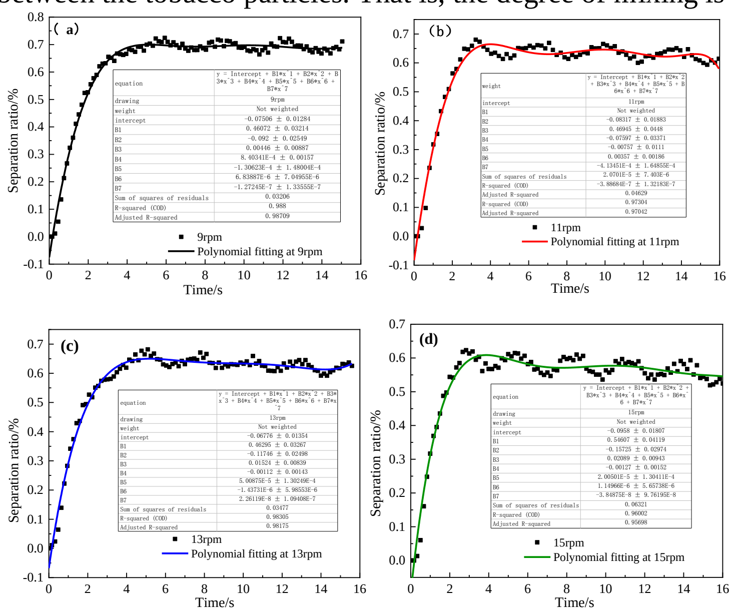
3.1. Mixing degree of particles

The tobacco particles in the drum dryer are continuously stir-fried in the process of moving along the drum axis. The mixing process has a great influence on the heat and mass transfer and the uniformity of the drying process, therefore, it is necessary to study the mixing process. Through EDEM post-processing, the mixing of tobacco particles can be observed directly, and the contact number between tobacco particles and tobacco particles at different time can be recorded. A Bin Group is established in the EDEM post-processing to record the number of contact between the tobacco particles and the drum wall and plate. According to the method proposed by Gupta to describe particle mixing degree by particle contact number[22], the ratio of the number of contact between tobacco particles and tobacco particles to the total number of contact between tobacco particles was used to characterize the dispersion of tobacco particles at the cylinder wall and plate, the value is calculated by the separation ratio Q between the cut tobacco particles and the drum wall and plate:

$$q = \frac{C_s}{C_{total}} \quad (12)$$

In the formula, C_s is the contact number between tobacco particles and tobacco particles; C_{total} is the total number of contacts (the total number of contacts between tobacco particles and the drum wall and the drum guide vane, and the total number of contacts between tobacco particles).

The dispersion degree of the tobacco particles can be analyzed by comparing the size of the separation ratio q between the tobacco particles and the drum wall and the guide vane plate. The larger the value is, the closer the tobacco particles are and the smaller the contact area with the drum and the guide vane plate is, which is not conducive to the uniformity of the baking wire. By statistical analysis of the contact number of tobacco particles in the process of hot air drum drying, the curve of the separation ratio q between tobacco particles, drum wall and guide vane plate as shown in Figure 3 changes with time can be obtained. Figure 3f shows the separation ratio of the drum drying machine at different speeds within 16s. It can be seen that the separation ratio gradually decreases with the increase of the rotating speed. When the rotating speed is 16 rpm, the separation ratio is close to 0.5, and the contact number between the tobacco particles and the drum wall and the guide vane of the drum is similar to that between the tobacco particles. That is, the degree of mixing is high.



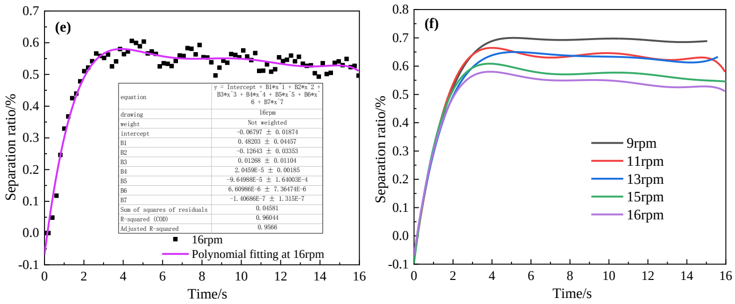
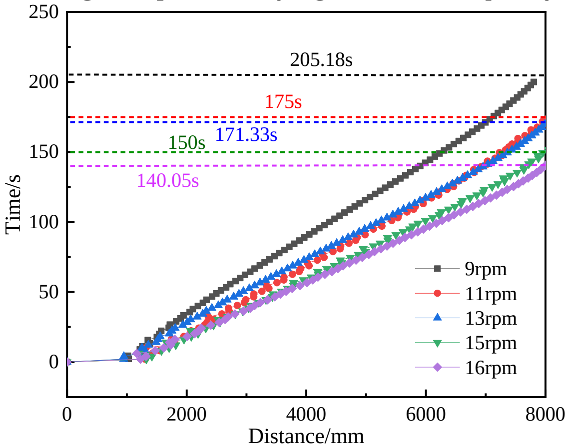


Fig. 3 Curve of tobacco separation ratio with roller speed

3.2. Velocity, time and distance of tobacco particles

Given that all particles have an equal coefficient of static and dynamic friction, the time taken for the particle to move along the axis within the same displacement and the change in the velocity of the particle to move along the Axis were investigated in the case of particles with only gravity and friction. According to the analysis of the drying process of the drum dryer, when the angle of the drum is 2°, the relationship between the drum speed and the drying time is shown in Figure 4. It can be concluded from the diagram that the drying time of cut tobacco particles in the drum decreases linearly with the increase of the drum speed, the drying time was 205.18 s, 175 s, 171.33 s, 150 s and 140.05 s respectively when the drum speed was 9 rpm, 11 rpm, 13 rpm, 15 rpm and 16 rpm. The dynamic change curve of the axial velocity of the particle motion is shown in Figure 5, and the dynamic change cloud picture of the radial velocity of the particle motion is shown in Figure 6, when the material is raised by the plate, the particle velocity will increase when the material falls off the plate, so the velocity has a certain periodicity, and the average velocity curve has no obvious upward or downward trend, therefore, it also shows that the movement of materials has reached a relatively stable state. At 16 rpm, the average axial velocity of particles is about 1.75 m/s. The drum speed affects the retention time of cut tobacco in the drum, the increase of drum speed will lead to the reduction of cut tobacco retention time in the drum, on the contrary, low drum speed tobacco retention time, therefore, the drum speed will directly affect the drying time of cut tobacco, thus affecting the drying effect. By increasing the drum speed to achieve the goal of increasing the efficiency of drying cut tobacco, or by controlling the speed of drying cut tobacco quality.



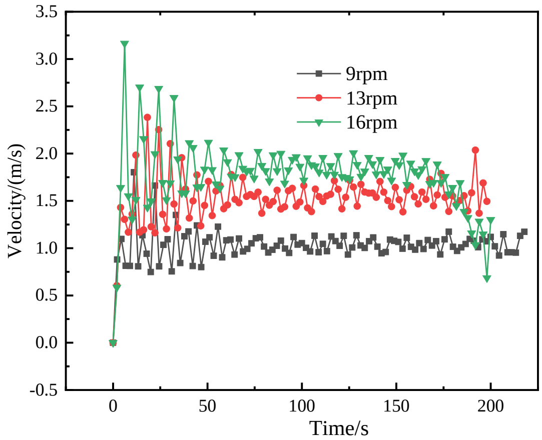


Fig. 4 Drying time at different rotational speeds **Fig.5 Axial velocities at different rotational speeds**

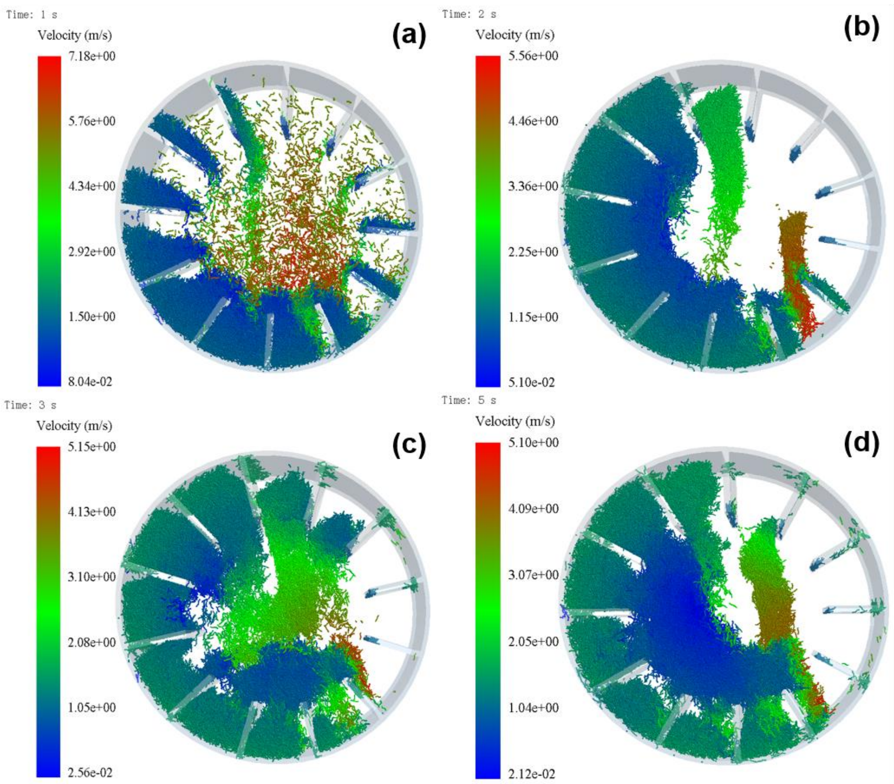
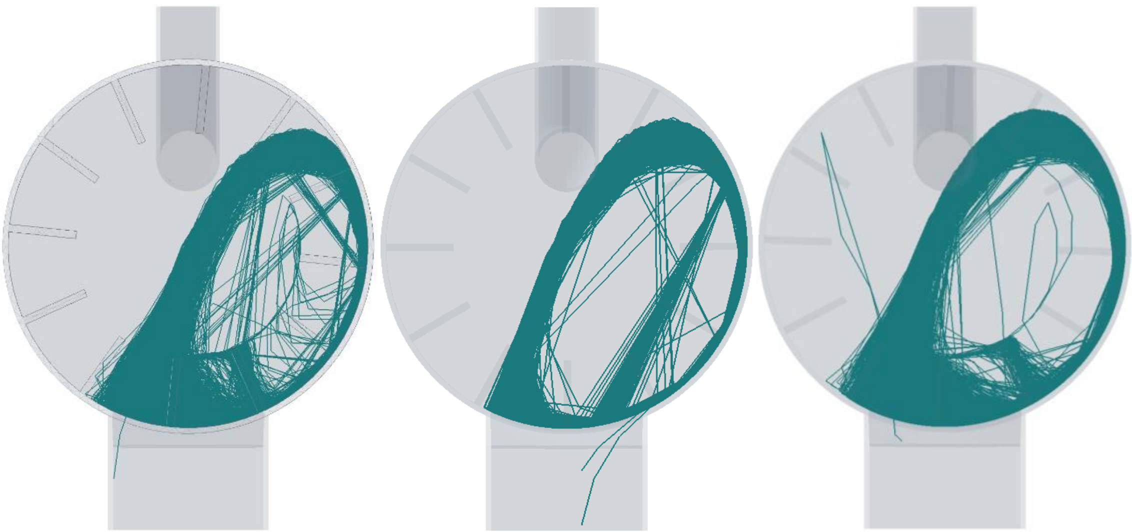


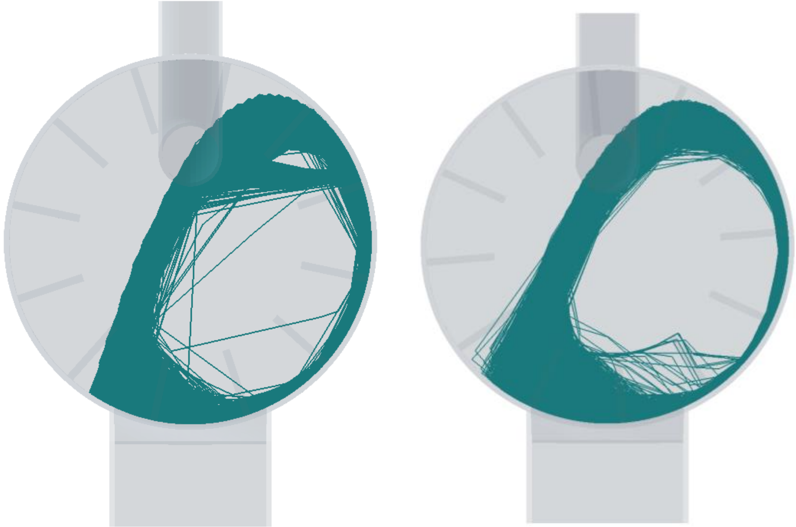
Fig. 6 Velocity distribution of particles in the radial direction of the drum

3.3. Curtain range of tobacco particles

Manual Selection was added in the Setup Selection post-processing of EDEM, 500 particles were numbered, and the trajectory diagram of particle movement along the axis was calculated. The X-axis view of the drum drying machine is shown in Figure 7. The roller rotates in the counterclockwise direction, and the material curtain formed by the particles at different speeds can be visually seen through the superposition diagram of particle tracks. Due to the low rotation speed of the cylinder, the ratio of the contact area between the material and the cylinder wall and the entire area of the cylinder is between 6:12 and 7:12.



（a）9rpm （b）11rpm （c）13rpm



（d）15rpm （e）16rpm

Fig.7 Range of material curtain formed by particles at different rotational speeds

3.4. Temperature change of tobacco particles

The DEM-CFD coupled heat transfer model is built by using DDPM coupling interface, and the rotating speed of the cylinder is set to 16rpm. The Euler model of particle-fluid coupling was selected in FLUENT, and hot air of 113℃ was introduced into the material inlet. Hertz-Mindlin heat transfer model and Temperature Update are selected in EDEM. The heat transfer model of the EDEM itself is compared with the DEM-CFD coupling, and its heat flow and temperature are shown in figures 8 and 9. In Figure 8, EDEM -0 is the heat flow of EDEM when EDEM is calculated separately, the heat flow of EDEM when EDEM-CFD-0 is coupled, and the heat flow of CFD when EDEM-CFD-1 is coupled. Figure 10 shows the temperature change of particles when EDEM-CFD coupling and EDEM alone are calculated. Since the heat flux generated by EDEM alone is negligible as shown in Figure 8(a) , the particle temperature hardly changes. As shown in Figure 9(b) , the heat flux generated by EDEM-CFD coupling is between 0.2 W and 1 W, so the particle temperature will gradually increase, but the rate of temperature change will gradually decrease, and the particle temperature will tend to be constant. A cloud image of the temperature changes of the particles over 80 s is shown in Figure 10.

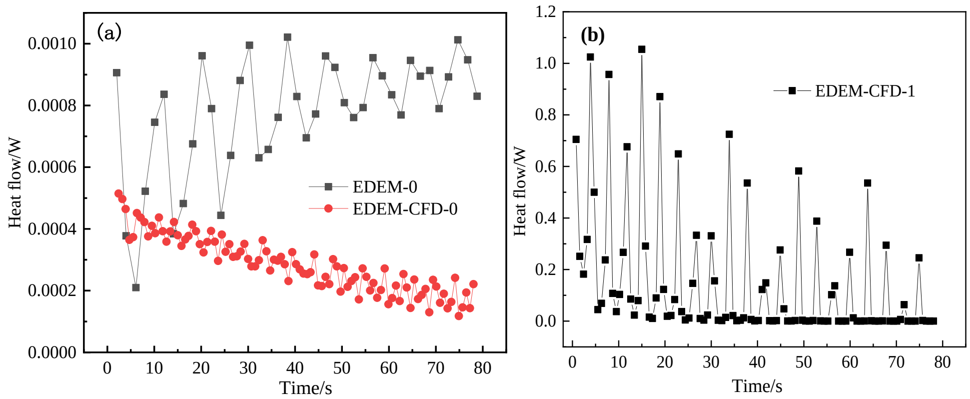


Fig. 8 Heat flow (a) generated by EDEM and heat flow (b) generated by fluent at 16rpm.

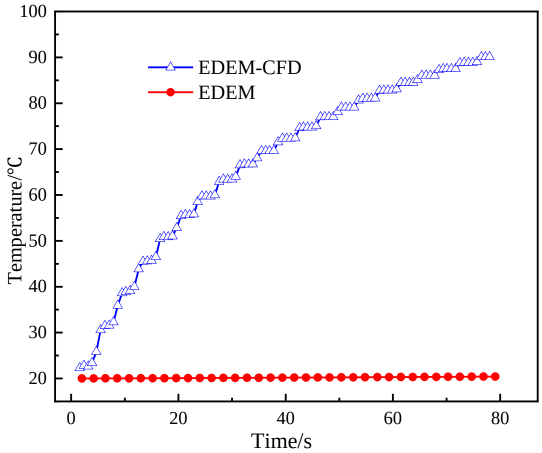


Fig.9 Change of tobacco particle temperature with time

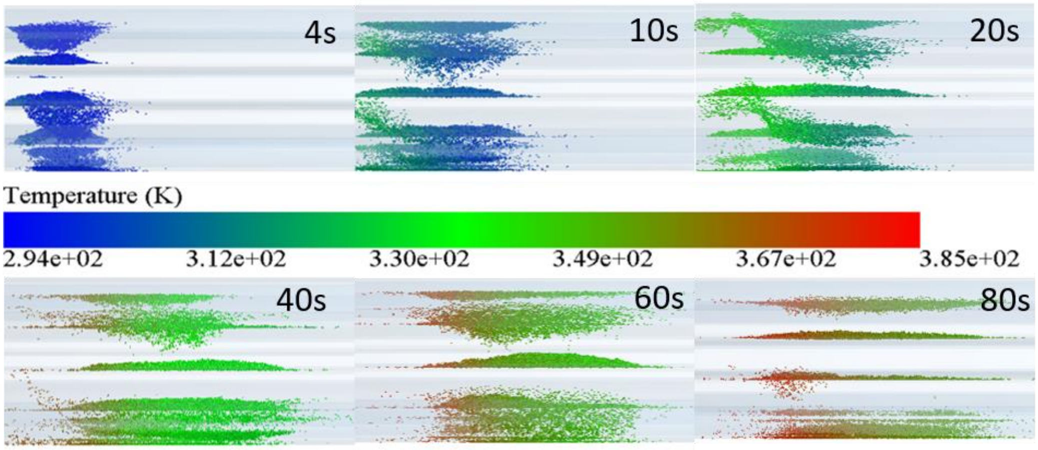


Fig. 10 Cloud picture of temperature change of tobacco particles

3.5. Distribution of particle residence time

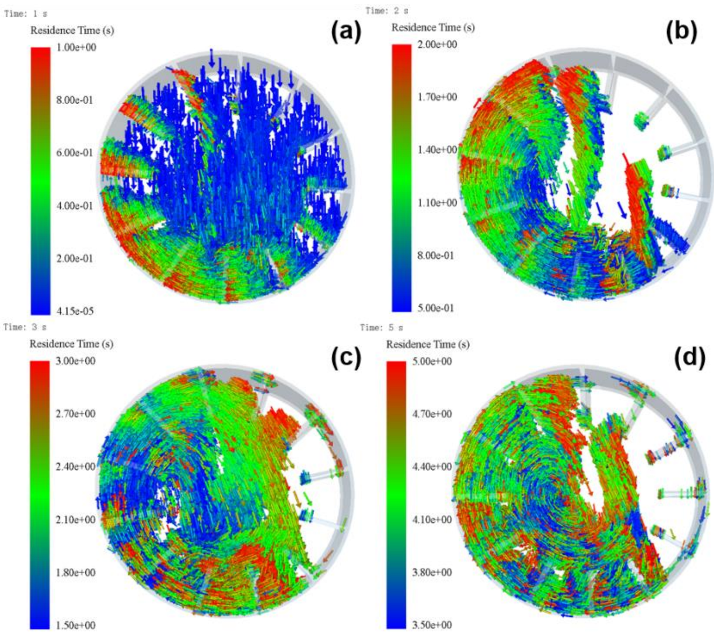


Fig.11 Residence time of particles

As shown in Figure 11, the residence time (RTD) distribution at 16 rpm has a great influence on the drying quality of the particles. If the residence time is too short, it will lead to uneven heating of the materials, if the residence time of material is too long, it will lead to the increase of the damage degree of material particles, and the corresponding output will be reduced. Figure 11 shows the distribution of particle residence time in the first 5 seconds, the longer distribution time mainly concentrated near the wall, which is more consistent with the reality of tobacco drying.

4. Conclusions

In this paper, the EDEM-FLUENT coupling method was used to calculate the heat and mass transfer characteristics of tobacco drying process in a drum dryer, the heat and mass transfer characteristics of cut tobacco at different rotating speeds were studied. The results show that: (1) with the increase of the rotary speed of the drum dryer, the degree of mixing increases gradually. When the rotary speed is 16rpm, the contact number between the tobacco particles and the drum wall and the drum sheet is equal to the contact number between the tobacco particles, that is, a higher degree of mixing. The drying time of tobacco particles in the drum decreases linearly with the increase of the rotating speed of the drum. When the rotating speed is 16rpm, the average axial velocity of the particles is about 1.75 m/s, the drying efficiency can be improved by increasing the rotating speed of the drum. (2) When the heat flux of EDEM-CFD coupling is between 0.2 W and 1W, the temperature of tobacco grain will increase gradually, but the rate of temperature change will decrease gradually, and the temperature of tobacco grain will tend to be constant. (3) the residence time of material has a great influence on the drying quality of material particles. If the retention time of cut tobacco is too short, it will lead to uneven heating of cut tobacco, if the retention time of cut tobacco is too long, it will lead to the increase of the dryness of cut tobacco.

Acknowledgments

The authors would like to acknowledge the project of Zhongyuan science and technology innovation talents (234200510011) and Collaborative Innovation Program of Zhengzhou (Major and Key Program of ZZULI) (2021ZDPY0107)，Key Science and Technology project of China Tobacco Hebei Co., LTD.(HBZY2023A056) and Key Science and Technology project of China Tobacco Henan Co., LTD.(AN202130).

Reference

[1] Rezaei, H.,S. Sokhansanj, A review on determining the residence time of solid particles in rotary drum dryers, *Drying Technology, 39*. (2021), 11, pp. 1762-1772
[2] Balakrishnan, M., *et al.*, Design, development, and evaluation of rotary drum dryer for turmeric rhizomes (Curcuma longa L.), *Journal of Food Process Engineering*, *45*. (2022), 6, pp. 1-16
[3] Mikulionok, I.O., Classification of Convective Drum Dryers (Survey of Patents), *Chemical and Petroleum Engineering*, *56*. (2020), 7, pp. 588-596
[4] Zhu, W.K., *et al.*, Effect of two-stage dehydration on retention of characteristic flavor components of flue-cured tobacco in rotary dryer, *Drying Technology*, *34*. (2016), 13, pp. 1621-1629

[5] Lee, J., *et al.*, Effect of Fabric Characteristics and Drum Rotation Speeds on the Movements and Drying Performances of Clothes in a Tumble Dryer, *Fibers and Polymers*, *23*. (2022), 6, pp. 1741-1752

[6] Namwong, K., *et al.*, Thermal analysis of hot air drying of chicken manure pellets in a modified portable horizontal rotary dryer, *Heat and Mass Transfer*, *58*. (2022), 11, pp. 1997-2007

[7] Gui, N.,J. Fan, Numerical study of heat conduction of granular particles in rotating wavy drums, *International Journal of Heat and Mass Transfer*, *84*. (2015), pp. 740-751

[8] Yang, G., *et al.*, Numerical study on the uniform distribution of flow field of airflow dryer, *Heliyon*, *10*. (2024), 8, p. e29439

[9] Nascimento, S.M., *et al.*, Comparison between the Eulerian (CFD) and the Lagrangian (DEM) approaches in the simulation of a flighted rotary drum, *Computational Particle Mechanics*, *9*. (2022), 2, pp. 251-263

[10] Zhong, W., *et al.*, DEM/CFD-DEM Modelling of Non-spherical Particulate Systems: Theoretical Developments and Applications, *Powder Technology*, *302*. (2016), pp. 108-152

[11] Ma, H., *et al.*, A review of recent development for the CFD-DEM investigations of non-spherical particles, *Powder Technology*, *412*. (2022), p. 117972

[12] Quan, X., *et al.* (2024) *CFD-DEM Modeling of Cryogenic Hydrogen Flow and Heat Transfer in Packed Bed*. Sustainability 16

[13] Chen, H.,Z. Zheng, Binary Packing of Spherical Particles with Moderate Size Ratios in Viscous Fluid: A CFD-DEM Study, *Brazilian Journal of Physics*, *54*. (2024), 4, p. 110

[14] Zhang, X.,P. Newell, Simulation of Microcapsule Transport in Fractured Media Using Coupled CFD-DEM, *Water Resources Research*, *60*. (2024), 6, p. e2023WR035728

[15] Scherer, V., *et al.*, Coupled DEM–CFD simulation of drying wood chips in a rotary drum – Baffle design and model reduction, *Fuel*, *184*. (2016), pp. 896-904

[16] Wu, K., *et al.*, Three-dimensional simulation of gas-solid flow in a fluidised bed with flexible ribbon particles, *International Journal of Multiphase Flow*, *124*. (2020), p. 103181

[17] Markauskas, D., *et al.*, Comparative numerical study of pneumatic conveying of flexible elongated particles through a pipe bend by DEM-CFD, *Powder Technology*, *399*. (2022), p. 117170

[18] Chen, L., *et al.*, Study on collision between single coarse particle and wall in viscous media using CFD–DEM, *European Journal of Mechanics - B/Fluids*, *97*. (2023), pp. 199-207

[19] Tao, W., *heat transfer(Fifth Edition)*. Higher Education Press Beijing, 2019.

[20] Hou, Z.J., Study on heat transfer characteristics of electrothermal alumina rotary kiln, Shandong University,2021.

[21] Chaudhuri, B., *et al.*, Modeling of heat transfer in granular flow in rotating vessels, *Chemical Engineering Science*, *61*. (2006), 19, pp. 6348-6360

[22] Gupta, A., *et al. Discrete Element Study Mixing in an Industrial Sized Mixer， Word Congress of Particle Technologies 2010*, '*Proceedings*' (I.N.M. GmbH),2010, pp. 1-4

Submitted 19.4.2024.
Revised 25.6.2024
Accepted 27.6.2024.