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Experimental Study on Heat and Mass Transfer of Flexible Filamentous Particles in a Rotary Dryer

Conghui Gu [1], Bin Li [2], Kaili Liu [2], Zhulin Yuan [1+], Wenqi Zhong [1]

[1] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, Southeast University, Nanjing 210096, China

[2] Key Laboratory of Tobacco Processing Technology, Zhengzhou Tobacco Research Institute of China National Tobacco Corporation, Zhengzhou 450001, China

Abstract. The effects of temperature of drum wall, rotational speed, temperature and velocity of gas flow on heat and mass transfer of flexible filamentous particles are experimentally studied. Results showed that temperature of drum wall had an apparent influence on the heat and mass transfer of particles in a rotary dryer, and the temperature of cut stem particles significantly increased with increase in temperature of drum wall, while the moisture content sharply decreased. The rotational speed has little effect on temperature of particles during preheating drying period and constant drying rate period, and moisture content of particles decrease with the increase of rotational speed. Temperature of particles increased, rate of water evaporation increased and the final moisture content decreased with the increasing of temperature of gas flow. Temperature of particles decreased with the increasing of velocity of gas flow during the constant drying rate period, while increased during falling drying rate period. The moisture content significantly decreased with the increasing of velocity of gas flow.

Keywords: Flexible filamentous particles, heat transfer, mass transfer, experimental method.

1. Introduction

Granular particles are loosely piled in gas or fluid phase, which widely exist in the fields of chemical, cement, lime, coal, flour, pharmaceuticals, ceramics, energy, and food industries. Consumption of a large amount of energy makes it one of the most energy intensive operations in the granular particle manufacturing process. Drying is one of the main methods that generally used to store food by removing the moisture from material through thermal treatment [1]. Internal self-heating starts to take place at storage temperature range from 30°C to 50°C. A second order partial differential equation was used to investigate transient temperature distribution within a container [2]. It can be described as an important industrial preservation way where water content and activity of food and agricultural products are decreased to minimize biochemical, chemical, and microbiological deterioration [3]. Furthermore, heat and mass transfer always occur between material and gas flow while drying, and play an extremely important role on the drying process [4], [5]. Drying process is usually effected by the state of material particles, vaporization rate of surface and internal moisture diffusion rate. In addition, much typical drying equipment, for example, fixed bed dryers, fluidized bed dryers, rotary dryers and microwave dryers have been used to deal with particles in many attempts. Several researchers have figured out investigations on heat and mass transfer between material and gas flow, material and rotary drum in a rotary dryer by experimental and numerical methods. Myklestad firstly predicted product moisture content of particles throughout a single pass dryer, which based on temperature of drying gas flow, initial moisture content of particles, and the product feed rate [6]. Moisture content and temperature of wood particles were studied by using heat and mass transfer equations [7]. Arrhenius equation was used to calculate the relationship between temperature of particles and the efficient coefficient of mass transfer [8], [9].

[+]Corresponding author. Tel.: +86 13851999198; fax: +86-25-83689730.
E-mail address: 101004322@seu.edu.cn.

However, flexible filamentous particles in different parts of dryer are heated in different temperatures, which can improve the efficiency of the process and quality of materials. Heat and mass transfer of flexible filamentous particles in the rotary dryer within the real-time were researched. And results of drying under different operating conditions could be forcasted, and temperature and humidity of particles and gas flow in the rotary dryer were analysed [10]. Thermal Particle Dynamics model was put forward, which assumed that flow between particles was stationary and the heat transfer of gas phase could be negligible [11]. Sharples had established a model to research drying process and described the rotary dryer as three periods, preheating, constant rate drying and reduction rate [12]. Experimental results on the drying kinetics of millet showed that the drying rate was found to increase significantly with the increase in temperature and marginally with flow rate of the heating medium, while decrease with increase in solids holdup [13]. An overview of emerging and innovative thermal drying technologies was taken, which were commercialized the potential for industrial exploitation [14]. Although considerable work in a rotary dryer has been done, there is still a lack of scientific and appropriate information on drying behavior of flexible filamentous particles. There are there main processing on heat transfer in a rotary dryer, namely, particle to drum wall, particle to gas flow, particle to particle, and mass transfer between particle and gas flow. Therefore, moisture content and temperature of moving particles in a rotary dryer were experimentally investigated under different conditions, with respect to the operating parameters such as temperature of drum wall, rotational speed, temperature and velocity of gas flow.

2. Materials and Experimental Methods

2.1. Material properties

Drying experiments on flexible filamentous particles were conducted using rotary dryer, the experimental parameters covered in the present research are listed in Table 1. In this paper, cut stem was employed as experimental materials, which are considered as flexible filamentous particles due to the structure, which have larger aspect ratio. Such approach utilize cut stem particles physical properties, and hence offer some advantages and convenience over empirical relations, as shown in Fig.1. The length, width and thickness of cut stem were 14mm, 1mm, and 0.1mm, respectively. Cut stem particles were stored in air tight containers to maintain the uniformity in moisture content for all experiments in this study.

Table 1: Experimental parameters presented in this paper

Properties	Value
Length of dryer, mm	570
Diameter, mm	330
Height of flights, mm	40
Number of flights	4
Plot ratio of particles	18.60%
Initial moisture content of particles, kg/kg	21%
Drying time, s	840

Fig.1: Experimental material.

2.2. Experimental method

The experiment equipment included three parts, temperature control system, gas flow system and drum system. The rotary drum wall was heated by oil bath method. Air flow was compressed from outside, and then been heated to a desired temperature before provided to the rotary drum through air distribution plate. The structure of rotary dryer was shown in Fig. 2. Cut stem particles in a close-loop while drying. Approximately 5g sample of cut stem particles were scooped out of the rotary dryer at regular intervals of time, at the same time, the temperature was tested by infrared radiation thermometers. In addition, particles stored in air tight container that were weighed before drying in a convective air oven for 2h at 100oC ± 2°C.

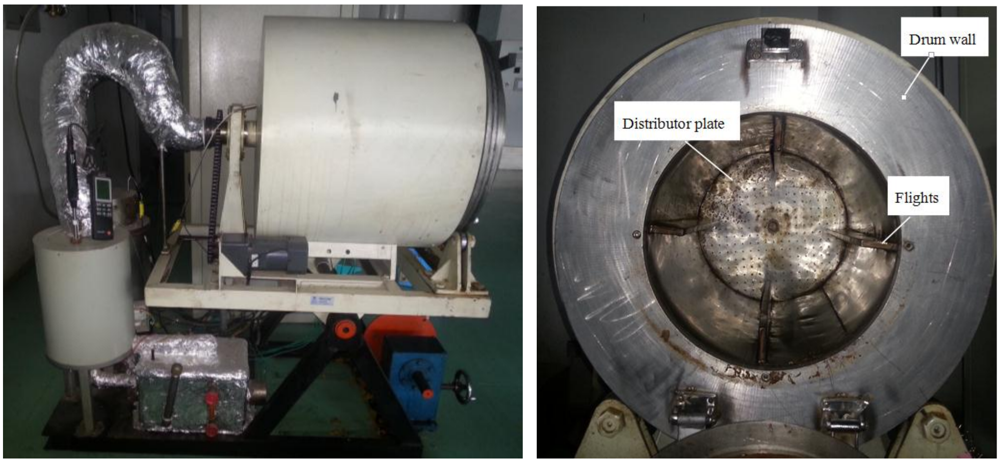


Fig. 2: Structure of the experimental set up

2.3. Experimental operating conditions

Table 2 shows the range of experimental parameters and operating conditions that used in the rotary dryer. The gas flow rate was controlled by a speed regulator.

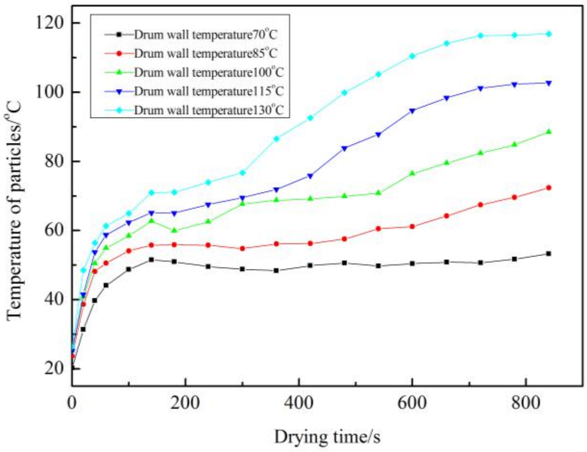
Table 2: Experimental operating conditions in present study

Conditions	Value
Temperature of drum wall, °C	70, 85, 100, 115, 130
Rotational speed, r/min	8, 10, 12
Temperature of gas flow, °C	70, 90, 110
Velocity of gas flow, m/s	0.1, 0.2, 0.3, 0.4

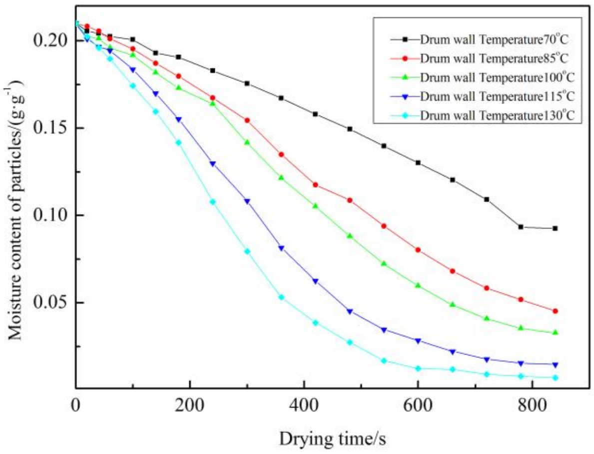
3. Results and Discussion

The figures address the effect of different operating conditions on heat and mass transfer of cut stem particles, such as temperature of drum wall, rotational speed, temperature and velocity of gas flow. The moisture content and temperature of particles during drying process were analyzed as follows.

The working temperature of rotary dryer is usually less than 150 ℃ [15]. The temperature of drum wall plays a significant role on the heat and mass transfer of cut stem particles during drying process, which was tested to vary from 70°C to 130°C in this study. Accordingly, the moisture content and temperature of particles in terms of drying time were shown in Fig. 3(a) and (b). Results indicate that the temperature of particles obviously increase during the early period of drying is attributed to the direct contact between particles and drum wall. It is found that the temperature of cut stem particles significantly increases with increase in temperature of drum wall, while the moisture content enormously decreases. The moisture content of particles just decline 1% at the preheating period under the drum wall temperature condition of 70°C, while dropped 3.5% at 130°C. Heat obtained from thermal conductivity between drum wall and particles was almost used to rise the temperature of particles, and hence the moisture content slightly decreased. Convective heat and mass transfer between particles and gas flow apparently took place at the constant drying rate period due to the increase of contact time. Furthermore, evaporation of surface moisture resulted in the generation of moisture gradient and temperature gradient between internal and external of cut stem particles, as a consequence, transfer of moisture from interior to exterior was accelerated, the temperature remained steady at that period by contrast.



(a)



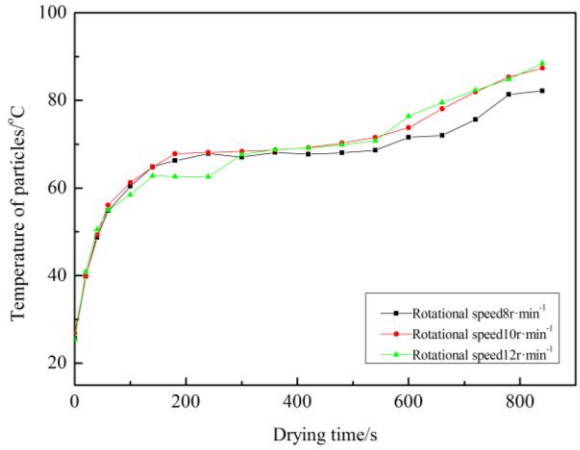
(b)

Fig. 3: Moisture content and temperature of cut stem particles under different temperature of drum wall.

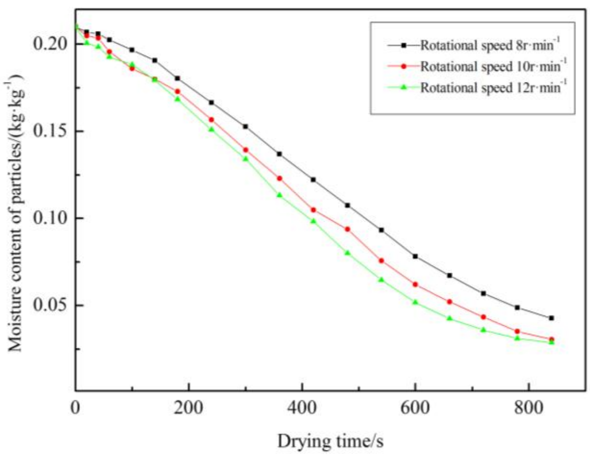
It is clearly presented that the time of constant drying rate period reduces with the increase of temperature of drum wall. Particles stayed in that period for 680s at the condition of 70°C, and the temperature remained at approximately 49°C. However, Fig. 3(a) and (b) revealed that the time of constant drying rate period was about 90s when temperature of drum wall grew to 130°C, and the temperature of particles remained at 71°C. The moisture content was found to considerably decrease with increase in temperature of drum wall, drying rate markedly increase as well. Moisture content slowly decreased during falling drying rate period, at the same time, temperature of particles significantly increased because of the low moisture content. It could be apparently observe the characteristics of each drying rate period under the condition of 115°C and 130°C, and the final moisture content were 1.46% and 0.71%, respectively. Particles might stay in different drying rate period under different conditions at a certain time.

Rotational speed has an influence on movement of particles in a rotary dryer. Uniform circular motion of cut stem particles is effected by flights. Heat and mass transfer on cut stem particles are experimentally studied, and therefore moisture content and temperature curves in a rotary dryer under three kinds of rotational speed, which value are 8r/min, 10r/min and 12r/min, as shown in Fig. 4(a) and (b). It can be found that the rotational speed has little effect on temperature of particles during preheating drying period and constant drying rate period. Furthermore, the distribution and heating surface are more homogeneous with the increase in rotational speed. More surface moisture is vaporized according to larger contact area between particles and gas flow, and hence drying rate fast increase and the time of constant drying rate period short.

Both drying rate and moisture content of particles decrease, and temperature of particles fast increase with the increase of rotational speed during the falling drying rate period.



(a)



(b)

Fig. 4: Moisture content and temperature of cut stem particles under different rotational speed.

Fig. 4(a) and (b) show that particles reach to the falling drying rate period after drying for 660s when rotational speed is 8r/min, while drying for 540s under the condition of 10r/min, and for 400s under the condition of 12r/min. At lag drying rate period, moisture content marginally decreases, convective mass transfer between particles and gas flow, particles and particles are small, heat obtained by convective heat transfer and thermal conductivity is used to raising temperature.

Gas flow has a key role on convective heat and mass transfer of particles. On one hand, gas system can be used to make up for heating area, which increases the drying energy. On the other hand, water vapor can be effectively taken out of the rotary dryer by gas flow. Rate of water evaporation was significantly effected by different temperature of gas flow. Therefore, heat and mass transfer on cut stem particles under different gas flow temperature 70^{o}C, 90^{o}C and 110^{o}C, respectively, as shown in Fig. 5(a) and (b). Temperature curves indicate that temperature of particles increased with the increase in temperature of gas flow. Particles were brought and dropped continuously in a rotary dryer. Convective heat rate between particles and gas flow decreased with decrease of gas flow temperature, which resulted in temperature of particles slowly increasing during preheating drying period. Cut stem particles still stayed in the constant drying rate period after drying for 840s under the condition of 70^{o}C, however, particles of the other two conditions reached to falling drying rate after drying for 700s. Whereas, rate of water evaporation increased and the final moisture content decreased with the increase in temperature of gas flow, the value of final moisture content of particles under these three conditions were 8.88%, 6.86% and 4.88%, respectively.

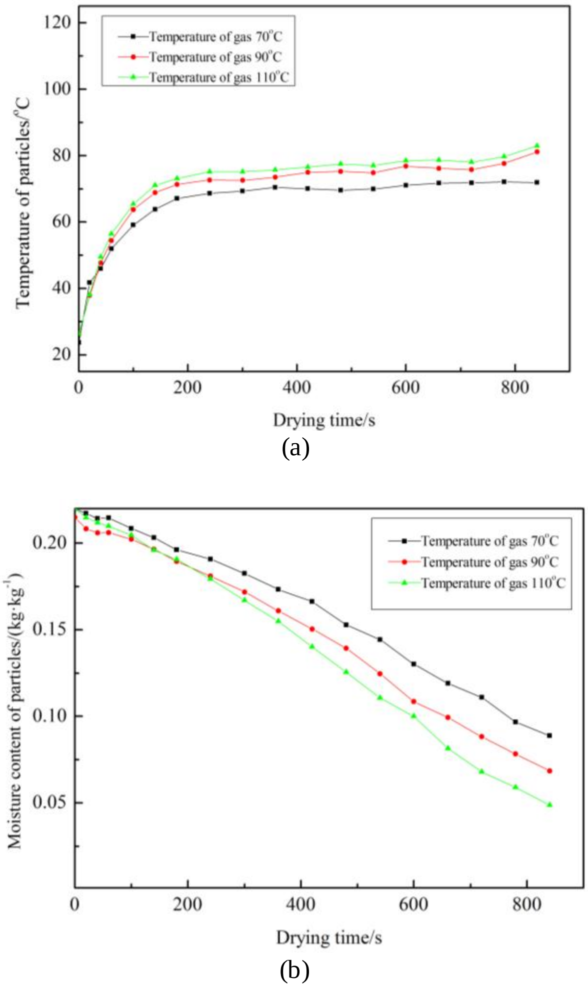


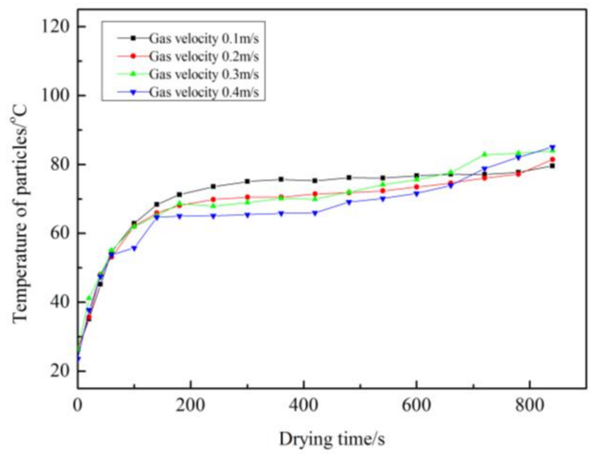
Fig. 5: Moisture content and temperature of cut stem particles under different temperature of gas flow.

Fig. 6(a) and (b) show results on moisture content and temperature of particles under different velocity of gas flow, which value are 0.1m/s, 0.2m/s, 0.3m/s and 0.4m/s, respectively. The velocity of gas flow had slightly influence on the temperature and moisture content of cut stem particles at preheating drying period. Increasing the velocity of gas flow could strengthen convective heat and mass transfer between particles and gas flow during constant drying rate period, rate of water evaporation considerably increased as well. Therefore, heat obtained from heat transfer is used to evaporate, which resulting in temperature of particles marginally increase and drying rate significantly increase. The final moisture content of these four conditions were 10.05%, 7.19%, 5.16% and 4.39%, respectively, and the temperature of particles varied from 78°C to 83°C. Cut stem particles of these four kinds of conditions remained at the constant drying rate period after drying for 840s. Moreover, it can be clearly found that velocity of gas flow has little effect on heat transfer and significantly on mass transfer.

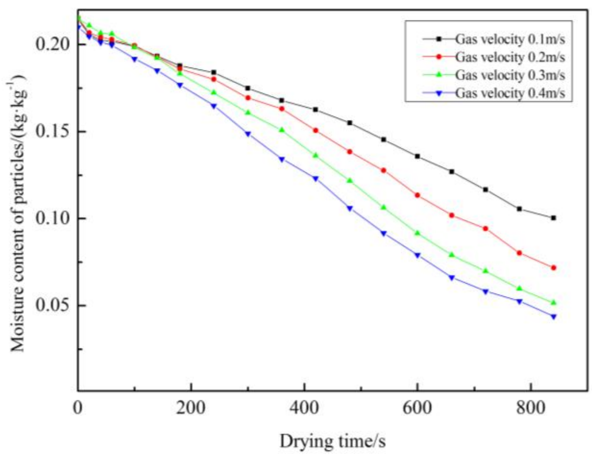
4. Conclusion

In this study, a series of drying experiments was conducted using a rotary dryer in order to research the heat and mass transfer on flexible filamentous particles. The characteristics of moisture content and temperature of cut stem particles were experimentally investigated under different conditions, with respect to the operating parameters such as temperature of drum wall, rotational speed, temperature and velocity of gas flow. The temperature of cut stem particles significantly increases with increase in temperature of drum wall, while the moisture content enormously decreases. The rotational speed has little effect on temperature of particles during preheating drying period and constant drying rate period, and moisture content of particles decrease with the increase of rotational speed. Temperature of particles increased, rate of water evaporation increased and the final moisture content decreased with the increasing of temperature of gas flow.

Temperature of particles decreased with the increasing of velocity of gas flow during the constant drying rate period, while increased during falling drying rate period. The moisture content significantly decreased with the increasing of velocity of gas flow. Results presented in this paper could also suggest to be used in industry. More experimental methods may be further developed to test the temperature and moisture content along with the length of dryer, the effective thermal conductivity and mass transfer coefficient of flexible filamentous particles under different temperature and moisture content are still need to further research.



(a)



(b)

Fig .6: Moisture content and temperature of cut stem particles under different velocity of gas flow.

5. Acknowledgments

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