



Simulation of dynamic transport of flexible ribbon particles in a rotary dryer



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ABSTRACT

Flexible ribbon particles are a special type of particles, and there is relatively little research on their processing in a rotary dryer. In the present study, dynamic transport of flexible ribbon particles in a laboratory rotary drum was investigated. First, a box-chain model in three dimensions was established for flexible ribbon particles. Each particle was represented as a long and thin piece, divided into several rigid segments and connected by joint constraints. Periodic boundaries were considered along with constraints, torque, gravity, friction, collision force and air drag force during the drum rotation. Then, dynamic behavior of certain particles was investigated through numerical simulation, which vividly represents particle flexibility, multi-particle entanglement and multiple particle collisions. Based on this model, residence time of particles and mean residence time of particles in the drum were discussed in terms of key variables, including rotational velocity, drum slopes and initial velocity of air flow. The results clearly show the variation trend and the effects of variables on the residence time and dynamic behavior of particles in the drum. Lastly, selected results were compared with our previous experimental results and other relevant findings, and reasonable agreements between these results validate the numerical approach. The presented method and results could provide guides for the further study of flexible ribbon particles as well as other flexible particles.

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1. Introduction

Rotary dryers play a significant role in many industrial applications, such as chemistry, metallurgy and materials science, and mineral industries, and food processing [1,2]. In the food industry, a rotary dryer is frequently used to process special materials, including unusual particles. For examples, herbage is chopped into small pieces and usually dried by a rotary dryer; rotary drums are used for drying and wetting cut tobacco particles; and rotary dryers have been integrated into the seaweed processing industry, where the seaweed is always cut into small strips for drying [3]. These materials are long and flexible particles, which are a special type of non-spherical particles, called flexible ribbon particles. These particles tend to translate, rotate and bend during their processing, undergoing more complicated dynamic motions than normal particles [4]. As a result, it is difficult to characterize the motion of these particles [5]. Their features, including orientation, interactions, and spatial distributions, will directly influence the final quality of particles during the drying process. Therefore, research on flexible ribbon particles in a rotary dryer is indeed necessary.

Understanding particle motion in the rotary dryer is important for many processes. In the rotary drum, particles undergo multiple processes, including mixing, drying, heating, chemical reactions, and transport through the drum [6,7]. Meanwhile, particle transport is essential and occurs in two directions: transverse and axial. Particle transport in the transverse direction is relatively uniform [8–10], while particle transport in the axial direction may vary with different residence times. The residence time of particles through the rotary drums is key for processing, since the time particles spend in the dryer can influence heat and mass transfer between air and particle phases, determine chemical reaction degree [11,12], and finally affect product quality. To improve dryer efficiency, residence time is regarded as one of the key parameters for process control and engineering design, and is usually represented by residence time distribution (RTD) and mean residence time (MRT) [13,14].

Much research has been performed on particle transport in the rotary drum, and RTD or MRT is frequently investigated as well as the influencing factors [11,13]. Different studies on particle transport in rotary drums may have different aims, since particle transport in the rotary drum is complex. Residence time of particles in the rotary drum depends on particle transport, which may take many different routes. These routes are in turn affected by many influencing factors, including nonuniformity of particles, device configuration, rotational velocity, and

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filling degree [6,8]. When considering the nonuniformity of particles, flexible ribbon particles are particularly important, but there is relevantly little research about this type of particles. It is imperative to investigate dynamic transport of flexible ribbon particles when studying their application in rotary dryers. However, experiments on flexible ribbon particles and the rotary drum are very limited due to the multi-scale complexity of the particle system and the limitations of measurement techniques [10,15]. Therefore, a modeling and numerical approach to flexible ribbon particles in the rotary drum is necessary.

In the present study, dynamic transport of flexible ribbon particles was numerically investigated within a rotary dryer. First, a 3D simulation of the box-chain model was developed for particle dynamics. Each particle was treated as a long and thin piece with rectangular cross section, divided into several rigid segments and connected by joint constraints. During simulation, periodic boundaries were applied with consideration of constraints, torque, gravity, friction, collision force, and air drag force. Second, residence time distribution and mean residence time of particles in the drum were analyzed in detail based on the presented methodology. Some key variables were considered, including rotational velocity, drum slopes, and initial velocity of air flow. In the end, the computed results were compared with our experimental results in the laboratory rotary drum as well as other relative experimental findings, and reasonable agreements were found.

2. Computational models

2.1. Physical model

The physical model of the rotary dryer mainly consists of a sloping rotating drum, as shown in Fig. 1(a). The internal shell of the drum is fitted with six vertical lifters, which are used to carry inner particles as

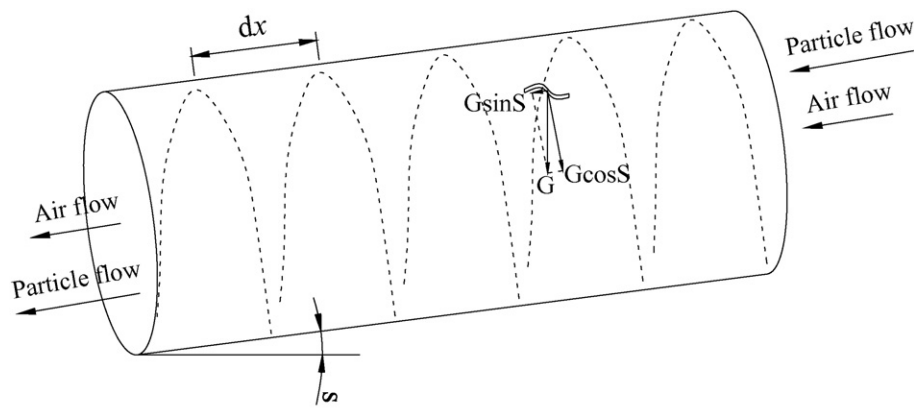
the drum rotates. The cross-section of the rotary drum is shown in Fig. 1(b). Flexible ribbon particles are fed into the drum at the upper end, and transported to the lower end by the cocurrent air flow. Particle transport is relevant to heat and mass transfer between particles and the conveying air flow.

2.2. Mathematical method

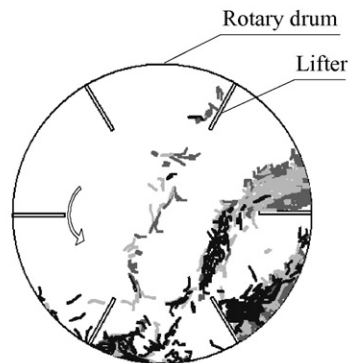
In the rotary drum, particle transport with the cocurrent air flow belongs to gas-solid two-phase flow. To study particle transport in the rotary drum, a mathematical method was established. In the present study, the flowing air was defined as the continuous phase and individual particles were treated as discrete phase.

Air flow was considered as the continuous phase with constant density. Meanwhile, air velocity was defined as constant and did not change with time. Moreover, the air flow was assumed to be a simple shear flow without turbulence. In detail, the air flow was set to decay within a given ratio in the axial direction. In the transverse direction of the drum, the air flow was assumed to be uniform except that the air velocity was zero near the wall. According to the simplified air flow field, the lift force is not considered at present.

Particle dynamic was modeled by the chain model. The relative method has been successfully used in the dense particle system, including the rotary dryer and the fluidized bed. However, the reported chain model was performed in two dimensions in our previous studies [4,5,10,16]. In the present study, a 3D chain model was presented for flexible ribbon particles to further understand the particles. The type of particles is anisotropic with complex forces along with irregular orientation distribution. Meanwhile, interaction between particles and air flow is also complicated due to multiple variables of nonspherical particles [4,6,17,18]. Therefore, a one-way coupling between particles and air flow was



(a) Particle transport in the axial direction of the drum



(b) Particle transport in the transverse direction of the drum

Fig. 1. Schematic diagram of particle transport in the drum.

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