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Effect of the particle shape and swirling intensity on the breakage of lump coal particle in pneumatic conveying

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ABSTRACT

This work studied the influence of the particle shape and flow regime on the lump coal breakage in pneumatic conveying using CFD-DEM simulation. A variety of agglomerates with different sphericities were modelled by the parallel bond method to analyse the breakage characteristics of lump coal. The numerical parameters, simulation conditions and CFD-DEM simulation results were separately validated by experimentation. To demonstrate the lump coal breakage process, the mechanism energy variation in the coal agglomerate was analysed. The fragmentation degree of the coal agglomerate was positively correlated with the energy difference in collision. The integrality ratio of the coal agglomerate increased with the particle sphericity and swirling number in pneumatic conveying. A quasi-periodical downgrade in the coal agglomerate integrality ratio was shown in the swirling flow. A remarkable improvement in the coal agglomerate integrality ratio from approximately 0.85 to 0.975 was observed in swirling flow pneumatic conveying. The regression relationship of the particle sphericity and swirling number fit the Exp3p2 exponential function well.

Nomenclature

A_b	parallel bond cross sectional area	m^2	S_s	surface area of sphere	m^2
D	pipe diameter	m	S_p	surface area of given particle	m^2
E	Young's modulus	GPa	u_1	axial velocity of gas	m/s
E_c	contact Young's modulus	GPa	u_3	tangential velocity of gas	m/s
E_s	shear modulus	GPa	g	gravitational acceleration	m/s^2
F_n	normal direction force	N	$\boldsymbol{G}_p$	particle gravity	N
F_s	shear direction force	N	$\boldsymbol{F}_C$	contact force	N
I	inertia moment of parallel bond cross-section	m^4	$\boldsymbol{F}_D$	drag force	N
I_p	Inertia moment of particle	m^4	$\boldsymbol{F}_L$	lift force	N
J	polar moment of inertia of parallel bond cross-section	m^4	$\boldsymbol{F}_M$	the Magnus force	N
k_n	normal stiffness per unit area	N/m^3	$\boldsymbol{T}_p$	rotating torque on the particle surface	N m
k_s	shear stiffness per unit area	N/m^3	$\boldsymbol{u}$	gas velocity	m/s
L_b	boned disk length	m	$\boldsymbol{u}_p$	particle velocity	m/s
L_{in}	length of inlet section	m	φ	sphericity	–
L_{out}	length of outlet section	m	λ	radius multiplier	–
m_p	particle mass	kg	ρ	density of the gas	kg/m^3
M_b^n	normal direction moment	N m	ρ_c	macro-particle density;	kg/m^3
M_b^s	shear direction moment	N m	ρ_p	micro-particle density	kg/m^3
r	radial distance	m	ξ	gas volume fraction	–

(*continued*)

R	pipe radius	m	$\boldsymbol{\tau}$	stress tensor	N/m^2
R_b	boned disk radius	m	$\overline{\tau}$	shear stress	MPa
R_{bend}	rend radius	m	$\overline{\tau}_c$	bond critical shear stress	MPa
R_i	radius of particle i	m	σ_c	critical normal stress	MPa
R_j	radius of particle j	m	$\overline{\sigma}$	normal stress	MPa
R_p	micro-particle radius	m	$\overline{\sigma}_c$	bond critical normal stress	MPa
S	swirl number	–	$\boldsymbol{\omega}$	particle rotational velocity	rad/s

1. Introduction

Green coal logistics, a key constituent component of the green coal industry, bridges coal production and consumption. Coal pipeline transportation is an appropriate approach for green coal logistics that considers the environmental, public health, and safety assessments [1]. Pneumatic conveying, the most mature technique in pipeline transportation, is eco-friendly, operationally simple, flexible, and secure, but it has problems with power consumption, pipe erosion, and particle degradation. Therefore, this approach is widely applied to fly ash conveying in pulverized coal fired thermal power plants [2–3], but it is restricted in other industry applications, such as coking, coal gasification, ceramics and so on, in which the lump coal with specific a size is required to ensure the combustion efficiency. The breakage of lump coal due to

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pneumatic conveying may significantly change the size distribution of lump coal so that it no longer meets the application requirement.

To meet the application and economic requirements, the lump coal particle size commonly ranges from 6 to 50 mm. Based on the prior usages and studies on pneumatic conveying, lump coal particles that are no more than approximately 5 mm are generally transported. The mechanism of lump coal particle pneumatic conveying should be different from the conventional dilute phase, dense phase or slug flow conveying. Previous studies [4–8] have indicated that the gas flow and particle properties, such as the size, shape, and density, are the most import parameters of the conveying system and they determine the system performance, such as the conveying capacity, power consumption, pressure drop, pickup velocity and more. However, few studies have evaluated the pneumatic conveying system for particles that are tens of millimeters in size. Other studies [8–10] have shown that the conveying velocity is likely positively correlated with the particles size and density. A relatively higher conveying velocity is necessary to prevent erratic operability. However, this requirement would increase the possibility of particle breakage and pipe erosion, especially at the bend where the most particle-wall and particle-particle collisions occur [11–12]. Obviously, the breakage of lump coal particles at bends is a crucial issue in lump coal particle pneumatic conveying.

A few studies have conducted numerical simulations and experiment measurements on particle motion and breakage in pneumatic conveying pipeline bends. Kruggel-Emden [11] numerically investigated the rope formation and dispersion of non-spherical particles at the pipe bend as well as provided transient descriptions of particle and fluid interactions based on a computational fluid dynamics and discrete element method (CFD-DEM) framework. The authors modelled the system as a series of regular, unbroken polyhedron particles; however, this is impractical for lump coal particles. Rinoshika [12] studied the effect of soft fins on the pneumatic conveying of granular particles in various curved 90° bends using high-speed PIV. The study focused on the changes in pressure drop, gas velocity, and power consumption and an additional pressure drop rather than the particle breakage. Salman [13] experimentally analysed the characteristics of single fertilizer particle fragmentation at various particle velocities, impact angles and particle sizes in a horizontal pipe with a fixed bend. The study evaluated fertilizer particles that were 3.2 mm, 5.15 mm, and 7.1 mm. The author reported a series conclusion about fertilizer breakage. Because of the weak material properties and nearly spherical shape, the breakage rules for fertilizer do not apply for the lump coal. Halstensen [14] used acoustic chemometric monitoring of the fish feed pellet velocity to analyse the particle damage for pellets that were 10 mm in length and 9 mm in diameter, which is close to the lump coal size. However, the study primarily emphasized the particle velocity real-time prediction. Other studies have investigated the breakage of brittle material, such as coal, in geotechnical engineering. Liu [15] experimentally studied the impact crushing probability of coal particles based on the fractal statistical strength theory and found a relationship between the impact crushing probability and maximum contact pressure stress base on the Hertz contact hypothesis. Zheng [16] studied the impact breakage behaviour of non-spherical coal agglomerates by DEM simulation and found that debris and fragments created after the agglomerates fracture have independent shapes and impact modes. Additionally, Shi [17–19] presented breakage testing, modelling, and applications for coal breakage.

The particle-wall interaction and particle breakage in pneumatic conveying have been extensively studied [4–14]; the lump coal impact breakage has also been studied in detail [15–19]. However, few studies have examined the pneumatic conveying of lump coal particles. The mechanisms of lump coal particle motion and breakage characteristics in pneumatic conveying have yet to be explored. Nonetheless, according to the prior studies [4–19], the particle size, particle morphology and flow systems should influence the lump coal breakage during pipeline transportation.

In addition, a few studies examined other flow systems for pneumatic conveying, such as swirling flow [20–21], spiral pipe [22], and built-in soft fins [12 and 23]. These studies indicated that an optimized flow regime could optimize the conveying velocity and pressure drop. Additionally, the swirling flow is one of the more well-recognized techniques in pneumatic conveying due to the low pressure drop and low power requirements. Furthermore, swirling flow conveying can mitigate the particle size degradation, deposition and blockage in pipes.

Meanwhile, the numerical approach is widely employed in both pneumatic conveying [5,11,24–25] and coal particle breakage [16, 19] because the numerical simulations can provide convenient methods to study the breakage mechanism of lump coal particles in pneumatic conveying and to model high numbers of transient parameters [16,24–25].

In this study, the commercial CFD code FLUENT and commercial DEM code EDEM are used for modelling. A two-way coupling Eulerian-Lagranian approach was employed to describe the pneumatic conveying system. The gas phase is modelled as a continuum, while the particle is discretely tracked. This study involved a series of simulations to analyse the effects of the particle shape and swirling intensity on lump coal particles breakage in pneumatic conveying; the breakage process of single lump coal with consideration for the energy variation is also analysed.

2. Materials and methods

2.1. Numerical coal particle definition

In a pneumatic conveying system, the particle shape is associated with the motion and gas flow field structure, such as the particle pickup velocity, particle incipient motion, and pressure distribution. Several studies have examined these variables for real particles [26–27]. In analytical and numerical simulations, these particles are simplified to fine or near spherical geometries [26–28]. Recently, regular polyhedron particle models [8, 11, 16, and 29] have been employed to study the effects of morphology. In view of this, common non-spherical objects are investigated to quantitatively analyse the effect of the particle shape on breakage in this study. Six different agglomerate polyhedrons, including tetrahedron, hexahedron, octahedron, dodecahedron, icosahedron and sphere, and two common lump coal particles are examined with numerical reconstitution, as shown in Table 1. In this study, non-spherical polyhedrons and common lump coal are modelled as clusters of agglomerated microscopic particles using a DEM framework. The representation of a numerical coal particle model is shown in Fig. 1. A coal particle was placed on a rotating platform and scanned by a scanner to produce a geometrical template using stereolithography (STL). The regular polyhedrons were built with a computer using the stereolithography (STL) form. A particle cluster with an appropriate distribution was defined using the generated STL file. Then, positions and radii for all particles in geometrical space were recorded.

As one of the primary parameters used to describe the morphology of a non-spherical particle, sphericity has become the degree to which a particle's shape approaches the shape of a sphere [30]. The sphericity, φ, is defined as the ratio of the surface area of a sphere with the same volume as the given particle to the surface area of the particle [31].

$$\varphi = S_s/S_p \tag{1}$$

Where the S_s is the surface area of the sphere, and the S_p is the surface area of the given particle.

The parallel bond model, which is a well-known model for particle contact and has been widely adopted to model the breakage of brittle rocks such as coal, granite, sandstone, concrete etc., was used to analyse the breakage of lump coal particles [16,32–35]. This model employed a