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Full Length Article

Experimental investigation on fragmentation initiation of mm-sized coal particles in a drop-tube furnace

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ABSTRACT

The investigation of mm-sized coal particle fragmentation initiation is of practical interest because of its great importance in the analysis of coal utilization processes such as combustion or gasification in fluidized-bed reactors. Fragmentation experiments were conducted within a drop-tube furnace with eleven kinds of coals of different sizes, and the influences of different factors were discussed. The fragmentation index increased monotonically as the temperature and particle size increase, and the heating rate at different conditions was estimated. No significant correlation was revealed between the fragmentation and the volatile matter, and the thermal stress was deemed to be the main cause of fragmentation. The influences of porosity and tensile strength on fragmentation were more pronounced. Generally, the fragmentation tended to be less extensive as the porosity and tensile strength increased. Accordingly, a parameter consisting of porosity and tensile strength was proposed and defined as the fragmentation resistance number (FRN). The results showed that the larger the FRN is, the more difficult the particles are to fragment; furthermore, the FRN was found to apply well for predicting the fragmentation initiation temperature (FIT) and evaluating fragmentation.

1. Introduction

The fragmentation of mm-sized coal particles is a common phenomenon during coal combustion or gasification in fluidized-bed reactors [1–4]. The fragmentation influences the coal utilization processes in many different ways, such as accelerating the reaction rates, increasing the carbon loss, influencing the heat transfer between the particles and surrounding environment, etc. [5–11]. Depending on heating conditions such as the gas atmosphere and residence time, the particles may experience the following size reduction processes in sequence or parallel after being introduced into the reactors [1,12–16]:

(1). Primary fragmentation, caused by the pressure and stress built up inside the particles during rapid heating processes, associated with devolatilization and thermal shock.
(2). Secondary fragmentation, as a consequence of the burn-off or breaking up of solid bridges connecting different parts of the devolatilized particle.
(3). Fragmentation by percolation, indicating pore enlargement and internal-reaction-induced connectivity loss inside the char particles.
(4). Particle attrition, in which case many fine particles are produced because of the abrasion between the particles, or between the particles and the furnace wall.

Regarding the primary fragmentation, this has been extensively investigated previously. Stanmore et al., Zhang et al. etc. investigated fragmentation during combustion in fluidized-bed reactors [1–3,17], Dacombe et al., Friedemann et al. etc. conducted fragmentation experiments with drop-tube reactors [13,18], and Senneca et al. developed a pressurized version of a heated-strip reactor to investigate the fragmentation of coal particles under severe heating conditions, i.e. a high heating temperature, high heating rate and high pressure [15,19,20]. Different fragmentation models have also been developed [2,4,7,16,18,21–23] to explain and predict the fragmentation behavior. For example, Dacombe et al. have suggested that the thermal stress in the form of tensile stress at the particle center make the particle fragment into relatively larger sub-fragments, and the compressive stress at particle surface make the outer part fragment into more and smaller particles [18]. Senneca et al. have also explained the generation of relatively large fragments from the particle center and fine particles from the particle surface with models of the volatile matter release, combustion and thermal stress, and pointed out that the fragmentation pattern depends on boundary conditions and coal properties [7,16].

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Nomenclature

C_p	Heat capacity of coal particle, kJ kg^{-1} °C^{-1}
d_a	Average diameter of parental particles
di	Average diameter of coal particles at size interval i after fragmentation
E	Young's modulus of coal, GPa
F_d	Particle size changing ratio
h	Convective heat transfer coefficient W m^{-2} °C^{-1}
i	Number, 1,2…N
I_f	Fragmentation index
n	Total number
N_f	Number of fragmented parental particles
N_{in}	Number of parental coal particles
N_{out}	Number of particles after fragmentation
P_b	Cumulative breakage probability
P_f	Fragmentation probability
P_v	Volume fraction porosity
r	Arbitrary internal radius of coal particle, mm
R^2	Coefficient of determination
R_f	Fragmentation ratio
S_e	Standard error
T	Temperature, °C
t	Time, s
t_{crit}(DF)	Value of Student's t-distribution with specific confidence level and degree of freedom
T_f	Furnace temperature, surrounding gas temperature, °C
T_s	Temperature of particle surface, °C
V_d	Volatile matter content, dry basis, wt%
x_i	Mass fraction of particles at size interval i
α	Thermal expansion coefficient of coal, °C^{-1}
β	Shape parameter in Weibull distribution
δ	Stefan-Boltzmann constant, $5.67*10^{-8}$ W m^{-2} k^{-4}
ε	Coal particle emissivity
λ	Thermal conductivity of coal particle, W m^{-1} °C^{-1}
ν	Poisson's ratio of coal particle
ξ	Thermal diffusivity of coal ($\lambda/\rho C_p$), m^2 s^{-1}
ρ	Density of coal, kg m^{-3}
ρ_{app}	Apparent density of coal, kg m^{-3}
ρ_{true}	True density of coal, kg m^{-3}
σ_t	Tensile strength, MPa
σ_{tm}	Median tensile strength, MPa
$\sigma_{t\theta}$	Characteristic tensile strength, MPa

Abbreviations

FIT	Fragmentation initiation temperature
FRN	Fragmentation resistance number
PRN	Pore resistance number
RSD	Relative standard deviation

In terms of the influences of different factors on the fragmentation, there is no disagreement on the effects of temperature, heating rate, particle size and porosity: there is agreement that a higher temperature, higher heating rate, larger particle size and lower porosity benefit fragmentation. However, different opinions have appeared on the role of volatile matter. Some investigators have claimed that fragmentation is caused by the volatile matter evaporating, meaning that the extent of fragmentation should increase with an increase in volatile matter content or the pore resistance number (PRN) [17,24]. However, in some other investigations the volatile matter content or the PRN have been found to be irrelevant to fragmentation [2,18]. By contrast, in the reports presented by Stanmore et al. and Adesanya et al. [2,25], it was mentioned that escaping gaseous matter decreases the rate of convective heat transfer at the particle surface, hence lowering the temperature gradient and consequently decreasing the thermal stress inside the coal particles.

In the present work, a series of experiments were conducted within a laboratory-scale drop-tube furnace to investigate the initiation of coal particle fragmentation, something which occurs immediately after the coal particles are introduced into a hot reactor and which directly influences the following reactions. The aim is to achieve a better understanding of particle fragmentation.

2. Experimental

2.1. Materials

Eleven kinds of coals of different ranks were selected for fragmentation experiments. The coal samples were crushed and separated by sieving them into different size groups, i.e. 0.8–1.0, 1.0–2.0 and 2.0–3.15 mm, and then stored in sealed glass flasks ready for use. The proximate and ultimate analysis results of the samples are given in Table 1.

As the porosity has a major influence on the fragmentation, the volume fraction porosity and the density of the samples were also determined. A mercury porosimeter, the Micromeritics AutoPore IV 9500, was employed to determine the apparent density and a helium pycnometer was used to determine the true density of the samples. The porosity and specific pore volume were then calculated according to the obtained values of the apparent and true density, as presented in Table 2.

2.2. Apparatus and procedure

The fragmentation experiments were carried out under inert

Table 1
Proximate and ultimate analysis of coal samples.

Coal	Proximate analysis (wt%)				Ultimate analysis (wt%, dry ash free basis)				
	M_{ad}	A_d	V_d	$C_{fix\text{-}d}$	C	H	N	S	O
Schleenhain	15.5	11.6	52.4	36	70.60	5.10	0.60	4.30	19.40
Schoeningen	12.57	11.55	51.82	36.62	70.80	5.54	0.40	7.52	15.75
Mongolia	12.72	12.69	38.99	48.32	76.30	5.31	1.55	0.48	16.36
Rudoltowy	1.73	5.7	33.1	61.2	86.88	5.36	1.55	0.56	5.65
Murki	5.8	12.22	31.85	55.93	81.83	4.55	1.31	0.68	11.63
Sapropel	2.55	34.41	30.14	35.45	80.85	5.67	1.91	0.69	10.89
Mongolia MGB	0.73	9.67	28.4	61.93	88.35	5.47	2.06	0.79	3.33
Lazy	1.32	23.48	24.96	51.56	87.35	4.94	1.42	0.42	5.87
Sasol	6.04	25.33	23.29	51.38	79.58	4.06	2.06	0.29	14.00
Uong Bi	0.95	1.1	7.55	91.35	93.83	3.66	1.37	0.08	1.06
Ibbenbueren	2.89	10.66	6.54	82.8	94.13	3.16	1.21	0.85	0.65