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Fuel particle shape effects in the packed bed combustion of wood

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ABSTRACT

Experiments on the overfeed packed bed combustion and gasification of seven different shapes of parallelepipedal wood particles are presented. Attention is focussed on the part of the bed in which char conversion occurs; results for the pyrolysis zone at the top of the bed are not included. It is shown that fuel particle shape can affect conversion through the sphericity of the particle, through the orientation of the wood grain in the particle, and through the overlap of particles in the bed. These effects were incorporated into an existing numerical model of packed bed combustion and gasification. Particle sphericities for input to the model were determined directly from particle geometry, and particle overlap factors were estimated photographically. Comparison of predicted gas analyses and temperatures in the bed with experimental values then allowed the effect of the orientation of the original wood grain on char conversion to be estimated, with the conclusion that the rate of carbon conversion by the CO_2 reduction reaction is faster by a factor of about 5 on surfaces normal to the wood fibres compared to the rate on surfaces parallel to the fibres. The carbon oxidation reaction at the bottom of the bed, on the other hand, is controlled by external gas phase diffusion and is not affected by the fibre orientation.

1. Introduction

Packed bed combustion is the burning of fairly large particles of fuel heaped up on a grate, with primary air supply occurring from below. In most cases the bed is thick enough that a part of the process is actually gasification, with gaseous products being burned above the bed. Most industrial applications of this process, such as biomass combustion and gasification, waste incineration, and wood waste combustion, use fuels with a wide range of particle sizes and shapes, and fuel particle shape can therefore be expected to affect the process by influencing the surface area available for reaction, the packing of particles and the fluid flow in the bed. Although many previous studies on packed bed combustion and gasification have used non-spherical fuel particles (see for example the works cited in [1]), few have dealt explicitly with fuel particle shape, and little information is available on shape effects on conversion. The purpose of this work is therefore to investigate the effects of particle shape by conducting packed bed combustion experiments using wood particles with several different controlled geometries. The results are compared with a numerical model which incorporates several different possible fuel particle shape effects. The focus is on the char conversion part of the bed: the pyrolysis zone at the top of the bed in this paper is primarily regarded as a means of supplying char particles of controlled geometry to the char oxidation and gasification reactions. For this reason a simplified one-equation model of pyrolysis is used, and no measurements are presented for the pyrolysis zone. Only beds of monosized particles with identical shapes are considered here: mixtures of different particle sizes and/or shapes are excluded. This work concentrates on fixed beds; although industrial applications of this process often use moving beds (e.g., travelling grates), the processes occurring are the same if transverse mixing of fuel particles can be neglected.

2. Review of particle shape effects

At least four different possible effects of particle shape on packed bed processes have been identified in the literature, as detailed below.

2.1. Particle geometry

The most obvious effect of particle shape is in the surface area, usually expressed in terms of the sphericity Φ [2,3]:

$$\Phi = \frac{\pi d_p^2}{particle\ surface\ \ area} = \frac{\pi^{1/3}(6V)^{2/3}}{particle\ surface\ area} \tag{1}$$

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Nomenclature

a_B	specific surface area of bed (m^2/m^3 bed volume)
a_I	particle internal specific surface per unit solid volume (m^2/m^3)
A	total particle external surface area (m^2)
A_{bc}	area of the *b-c* face of the particle (m^2)
A_{CO_2}	pre-exponential factor for CO_2 reduction reaction (kg char/m^2 internal surface kPa s)
A_P	pre-exponential for pyrolysis reaction (s^{-1})
d_P	volume-equivalent spherical diameter (m)
D	diffusivity (m^2/s)
D_{EFF}	effective diffusivity in particle pores (m^2/s)
E_{CO_2}	activation energy for CO_2 reduction reaction (kJ/gmol)
E_P	activation energy for pyrolysis reaction (kJ/gmol)
G	solid surface reaction rate, kg/m^2 s
m	particle mass (g)
M_C	molecular mass of carbon (kg/kmol)
p	partial pressure (kPa)
r_P	rate of pyrolysis reaction (kg/(m^3 of solid s)
R	universal gas constant
T	temperature (K)
T_G	gas temperature (K)
T_S	solid temperature (K)
V	particle volume (m^3)
Y_W	mass fraction of unpyrolyzed wood in fuel particle
β	particle reaction effectiveness
ε	void fraction in bed
ε_P	particle porosity
ζ	proportion of particle surface area that is end grain
η	particle surface availability (= 1 – fraction of particle surface covered by overlap)
η_P	particle pore effectiveness
θ	angle of particle surface (see Fig. 1)
ξ_V	volatiles yield (kg volatiles/kg dry fuel)
ρ_{FO}	initial fuel density (kg/m^3)
τ	tortuosity of particle pore
ϕ	Thiele modulus (Eq. (10))
Φ	particle sphericity
χ	ratio of end grain to side grain solid surface reaction rates

Subscripts

CO_2	referring to CO_2
P	referring to pyrolysis reaction

where the particle diameter d_P is defined as that of the volume-equivalent sphere:

$$d_P = (6V/\pi)^{1/3} \tag{2}$$

(Symbols are defined in the nomenclature.) This is the most widely accepted definition of sphericity, and the only one used in this paper, although the older literature sometimes contains alternatives. Any non-spherical particle has a greater surface area than the volume-equivalent sphere, and hence $\Phi \leq 1$. The specific surface area per unit bed volume is then

$$a_B = 6(1-\varepsilon)/(\Phi d_P) \tag{3}$$

The sphericity is not a unique descriptor for particle shape. It can easily be shown that such radically different shapes as thin flat chips and long thin sticks can have the same sphericity.

A few works in the literature deal explicitly with sphericity effects in combustion. Horttanainen et al. [4] presented experiments on transient combustion in packed beds of wood chips, characterizing the chips by means of equivalent diameter and sphericity. They found some degree of correlation between sphericity, bed void fraction and ignition rate. Porteiro et al. [5,6] conducted transient burns in beds of a variety of different biofuels. Again, there appeared to be some correlation between sphericity and void, but little effect of these on ignition rates. Hallett and co-workers [7–9] included sphericity in their numerical model of packed bed conversion, but did not further investigate its effects. Instead of sphericity, the bed specific surface area may be used to characterize particles, as shown by Eq. (3). This was done by Mandl et al. [10] for the gasification of cylindrical wood pellets, and by Johansson et al. [11]. The latter also reduced the effective specific surface by a factor of 60% to compensate for particle contact and overlap. Huff et al. [12] showed that burning times for individual suspended particles increased with sphericity because the specific surface area decreased, while Lu et al. [13] studied the effects of particle shape on pyrolysis for single particles and for particles in an entrained flow reactor. Although these last two are not packed bed studies, they are among the few combustion or gasification papers to deal explicitly with particle shape.

As an alternative treatment of particle shape, several researchers have advocated the assumption of a cylindrical rather than a spherical particle as a model for biomass particles in packed beds [10,14–16], whose dimensions may be determined from measurements of particle aspect ratio and specific surface [17].

2.2. Packing in the bed

The particle shape also determines how particles pack together in the bed, which is reflected in the bed void fraction ε. This affects combustion through the related processes of heat and mass transfer, which depend on the hydrodynamics of flow in the bed. The underlying theory for flow and pressure loss in a bed is based on the hydraulic diameter of the bed channels, which is directly related to the specific surface area a_B, and Eq. (3) shows that this yields ($\Phi\ d_P$) as an effective particle diameter [18–22]. Heat and mass transfer between solid and gas become analogous to pressure loss at low Reynolds numbers, and therefore some of the published heat and mass transfer correlations are similarly based on hydraulic diameter (or equivalently on specific surface area) [23–25]. Some others, however, do not specify a definition for particle diameter despite being based on measurements with non-spherical particles [26–28].

No theories are available for predicting the relationship between particle shape and bed void fraction; ε must be measured experimentally for each bed.

2.3. Particle overlap

Particles having flat or concave surfaces may overlap in the bed and hence reduce the surface area available for heat and mass transfer and chemical reaction. (Particle overlap does not occur if all of the particle surfaces are convex, e.g., spheres, crushed rock). The effects of this for pressure loss have been addressed by Comiti and Renaud [20] and Trudel and Hallett [22]. The overlap may be characterized by defining a particle surface availability η as

$$\eta = \frac{\textit{particle surface area in contact with flow}}{\textit{total particle surface area}} \tag{4}$$

Some of the correlations for heat and mass transfer also include this effect by means of a "shape factor" which reflects the accessibility of surface to the flow [23,26,29]. This is not identical to η, since in some cases it accounts for internal surfaces in ring packings, nor is it related to sphericity despite being given the same