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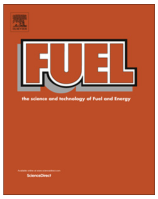

Mass transfer under segregation conditions in fluidized beds

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HIGHLIGHTS

- Mass transfer under segregation conditions in fluidized beds was measured.
- Sh of floating particles was about 35% less than that of a floating particle.
- Sh of floating particles was about 35% less than that of immersed particles.

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ABSTRACT

In the present work, mass transfer under segregation conditions in fluidized beds was measured in two cold-model reactors with different shapes. Silica gel particles, representing biomass char, were used as active particles to absorb water from the fluidizing agent (humidified air), while bronze powder served as the inert bed material. The amount of active particles in the bed was 1–2 wt.%. In both reactors, the measured Sherwood number (*Sh*) for multiple floating particles was approximately 35 % lower than the calculated value for a single floating particle. This is because the floating particles stay close to each other, and then the concentration boundary layer around these particles is affected by the neighbouring active particles. However, with the same fuel concentration in a fluidized bed converting coal, the char particles are entirely immersed in the bed and are well dispersed as single particles. Thus, *Sh* for these immersed active particles is the same as for a single immersed active particle. Moreover, the calculated *Sh* for a single floating particle was approximately similar to for a single immersed particle. The reason for this coincidence is that the two terms in the expression for *Sh* tend in opposite directions and compensate each other. As a consequence, the measured *Sh* for multiple floating particles was also approximately 35% less than the calculated value for multiple immersed particles that can be treated as single particles in the bed. Overall, due to the segregation effect mentioned, the mass transfer coefficient for the biomass char reaction is less than for the coal char reaction, because coal char is usually immersed in a bed.

1. Introduction

Fluidized beds are capable of handling several types of fuel. In recent years biomass has been in the focus of interest, much due to the need for meeting climate goals and for creating a more sustainable society [1]. In practical fluidized bed combustion and gasification systems, due to the rather large size of fuel char particles, the char reaction rate is generally modelled assuming either mass transfer control only, or combined mass transfer and surface kinetic control [2–5]. Therefore, knowledge of the transfer of gas towards the surface of fuel char is needed to efficiently design new equipment and to predict the change in performance while using a new fuel.

An impressive amount of measured mass transfer data has been presented in the literature concerning coal combustion in fluidized bed [6–14], where the coal char particles are immersed and well dispersed in the bed. However, biomass char has lower density and larger size than coal char. This tends to cause segregation between char particles and bed material at relatively low fluidization velocities in biomass gasification and in biomass combustion during part-load operation. This results in a top-to-bottom variation in fuel-particle concentration. The segregation affects the contact among char, bed material, and reaction gas and consequently influences the overall performance of fluidized bed boilers or gasifiers. Fluidized bed combustion or gasification involves a wide size range of particles and two or more species of different density (fuel and bed material), where the segregating tendency mainly depends on the particle size and density [15]. A wide range of particle size can be tolerated in a fluidized bed, which remains homo-

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Nomenclature

A_{bed}	cross-section area of the bed (m^2)
$C_{H_2O,in}$	water concentration in the gas at the inlet (g/m^3)
$C_{H_2O,out}$	water concentration in the gas at the outlet (g/m^3)
C_{H_2O,out_local}	the water concentration in the gas at the top of the active particle layer (g/m^3)
$C_{H_2O,pe}$	water concentration in the gas in the environment of the active particle layer (g/m^3)
$C_{H_2O,ps}$	water concentration in the gas on the outer surface of the silica gel particles (g/m^3)
d_b	diameter of bubble (m)
d_{bed}	diameter of the bed (m)
D_{H_2O}	diffusivity of water in the air (m^2/s)
d_p	diameter of silica gel particle (m)
f	end of absorption (–)
g	standard gravity (9.8 m^2/s)
k_g	mass transfer coefficient (m/s)
L	total height of the bed (m)
N_{hole}	number of holes on the gas distributor (–)
N_{H_2O}	amount of water absorbed by the silica gel particles (g)
Re	Reynolds number of the active particle (–)
Re_{mf}	Reynolds number at minimum fluidization condition (–)
S_{active}	total outer surface area of active particles (m^2)
$S_{active,bottom}$	total outer surface area of active particles immersed in the bed (m^2)
$S_{active,top}$	total outer surface area of active particles floating on the surface of the bed (m^2)
S_p	total outer surface area of the silica gel particles (m^2)
Sc	Schmidt number of the gas (–)
Sh	Sherwood number (–)
Sh_{bottom}	Sherwood number for a single active particle immersed in the bed (–)
Sh_{top}	Sherwood number for a single active particle floating on the surface of the bed (–)
t	absorption time (s)
u	gas velocity (m/s)
u_b	bubble velocity (m/s)
u_{mf}	gas velocity at minimum fluidization condition (m/s)
V_{active}	volume of a single active particle (m^3)
$V_{active,bottom}$	volume of a single active particle immersed in the bed (m^3)
$V_{active,top}$	volume of a single active particle floating on the surface of the bed (m^3)
X	mixing ratio of water to dry air in the humidified air (g/kg)
δ	fraction of bubble phase (–)
$1-\delta$	fraction of emulsion phase (–)
ε	bed voidage (–)
ε_{mf}	bed voidage at minimum fluidization condition (–)
ρ_{active}	density of active particle (g/m^3)
ρ_{em}	bulk density of emulsion phase (g/m^3)

geneous, but quite small density differences may result in segregation; density is a stronger factor than size in determining the degree of segregation [15,16]. The denser bed material behaves like jetsam in the binary system that tends to sink in the bed, while the lighter fuel and fuel char particles behave like flotsam that tends to rise in the bed [17,18]. The combustible material is usually present in small quantities (<5 wt.%) in the fluidized bed, and hence, it corresponds to flotsam in a jetsam-rich system. Moreover, the segregating tendency is most marked at low fluidization velocity (e.g. close to minimum fluidization velocity), especially when there is an appreciable particle density difference [15,19]. Increasing fluidization velocity gives rise to bubbles and improves the mixing. This leads to dragging of flotsam down into the bed, which reduces segregation [15,19,20].

Besides the segregating tendency during char conversion owing to the difference in particle density, segregation may also take place during devolatilization, not only caused by the particle density difference, but also by endogenous bubbles originating from the release of volatiles. The endogenous bubbles yield a lift force on the devolatilizing particles, which tends to drag the particles to the surface of the bed. Work related to segregation arising from emission of gas can be found in the literature [21–24]. For coal particles, segregation may take place during devolatilization [25–27], while for biomass particles, it takes place both during devolatilization and char conversion [28–33]. Other light fuel particles, such as some types of solid wastes, also float on top of the bed for the entire duration of their burning, and they behave like biomass particles [34]. Moreover, in the Chalmers' gasifier [35], it shows that the biomass char particles are pushed aside by the bubbles, gather in groups, and float on the surface of the bed in the regions where no bubbles are seen. Therefore, the conclusion, based on many observations, is that segregation is more severe with biomass than with coal.

The present work focuses on the segregation during biomass char conversion at relatively low fluidization velocities, for instance, in fluidized bed gasification of biomass. This raises a new question on whether the segregation conditions could significantly affect the mass transfer related to the char conversion. In the present work, this question is approached by measuring the mass transfer in the fluidized bed under segregation conditions. The fluidizing agent was humidified air, and silica gel particles were used as active particles to absorb the water in the bed, while the inert material was bronze powder. These materials simulate the biomass char particles and the bed material, respectively. The effect of segregation on mass transfer was evaluated by comparing the measured mass-transfer data in the experiments to the calculated value for single particles, either entirely immersed in a fluidized bed, or floating on the surface of the bed.

2. Experimental

2.1. Materials

In a well-designed downscaled cold model of a fluidized bed gasifier for biomass [36–38], according to the set of scaling relations established by Glicksman et al. [39], aluminum particles and bronze powder are applied to simulate biomass char particles (active particles) and bed material (inert material), respectively. Also in the present work, bronze powder was used as the inert material, while silica gel particles, which have a density similar to aluminum particles, served as active particles to absorb the water in the fluidizing agent. The properties of the selected materials are listed in Table 1. The density ratio of silica gel to bronze is about 0.25, which is between the ratios of wood pellets to silica sand (about 0.44) and wood char pellets to silica sand (about 0.12), as applied in the Chalmers' gasifier [36–38]. Compared with coal, converted in a fluidized bed (density: about 1100–1500 kg/m^3, size: usually <10 mm), biomass chips or pellets usually have lower density and larger size (biomass chips, density: about 300–