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The influence of CO_2 gas concentration on the char temperature and conversion during oxy-fuel combustion in a fluidized bed

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HIGHLIGHTS

- Pyrometry with digital camera allows accurate measurement of char temperature in FB.
- Carbon gasification is significant even at a relatively low char temperature (850 °C).
- The char time out of the emulsion explains the different rate in O_2/CO_2 and O_2/N_2.
- The model takes into account explicitly the char particle's movement between phases.
- The model predicts and explains our own measurements and other from literature.

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ABSTRACT

In spite of the extensive theoretical and experimental work carried out on coal/char oxy-combustion in a fluidized bed (FB), the effect of changing the atmosphere from O_2/N_2 to O_2/CO_2 for a high O_2 concentrations is not entirely understood. In this work, experiments with single char particles are conducted in a bi-dimensional FB at 800 and 850 °C, varying the O_2 concentration from 11 to 50%$_{v/v}$ in N_2 or CO_2. The FB reactor has a quartz window for visual observation, allowing the measurement of temperature and tracking the char conversion process by pyrometry with a digital camera. The method is shown to overcome the inherent limitations of other methods used in FB, such as thermocouples or pyrometry with an optical probe. Results indicate that the transfer of O_2 from the bulk gas of the bed to the surface of a char particle controls the overall rate of char conversion in O_2/N_2 and in O_2/CO_2. In the latter gas mixture, the carbon consumption by gasification is significant even at a relatively low char temperature (850 °C). This additional carbon consumption makes the apparent char consumption rate in both atmospheres roughly equal (at the same O_2 concentration) for char temperatures below 925 °C, and higher in O_2/CO_2 than in O_2/N_2 for char temperatures above 925 °C. Moreover, during the time in which the char stays in the emulsion phase, its temperature is roughly the same in both atmospheres, but when the char is in the bubble or splash zone its temperature is much higher than that in the emulsion phase. As a result, the difference in char conversion rate, observed in both atmospheres, is mainly controlled by the time in which the char particle is out of the emulsion phase. These results underline the importance of paying attention to the movement of a char particle through the different phases of the bed in order to improve the understanding of the oxy-fuel behavior in FB.

1. Introduction

More than 25% of the global electric energy demand is currently covered by coal combustion and an increase of coal utilization is expected, since it is the main energy source in some developing countries [1]. As a result, the need of reduction of CO_2 emission will need both increasing efficiency of power plants and the development of methods of CO_2 capture and storage [2]. Oxy-combustion is one of the proposed technologies for this purpose with reasonable net efficiency and avoided CO_2 emissions [3,4]. In this process, coal conversion is carried out in an O_2 atmosphere diluted with CO_2 from recirculation of the flue gases [4] in order to control the conversion temperature and to reach a CO_2 concentration at the exit of the boiler ready for capture (> 90%) [5]. Furthermore, the NO_x and SO_2 emissions are reduced [6].

The first generation of oxy-boilers involves a retrofit of power plants where flue-gas recirculation maintains similar conditions inside the

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Nomenclature

$A_{co/co2}$	pre-exponential factor for CO/CO_2 ration, –
A_{cb}	pre-exponential factor for char combustion, m/Ks
A_{gf}	pre-exponential factor for char gasification, m/Ks
Ar	Archimedes number based on average inert particle diameter, –
c_p	specific heat of char particle, J/kg K
$c_{p,i}$	specific heat of inert particles of the bed, J/kg K
$c_{p,g}$	specific heat of fluidization gas, J/kg K
C	total molar concentration, mol/m^3
C_d	dimensionless drag force of a isolated sphere, –
d_c	diameter of a char particle, m
d_i	average diameter of bed particles, m
d_{ij}	binary diffusivity of compound i through j, m^2/s
D_{ij}	effective mass diffusivity of compound i through j in the emulsion phase: $(\varepsilon_{mf}/\tau)d_{ij}$, m^2/s
$E_{co/co2}$	activation energy for CO/CO_2 ratio, J/mol
E_{cb}	activation energy for char combustion, J/mol
E_{gf}	activation energy for char combustion, J/mol
h_{bed}	expanded bed height, m
h_p	penetration depth of a char particle in the bed, m
k_{cb}	external combustion kinetics, m/s
k_{gf}	external gasification kinetics, m/s
$k_{d,ePh}$	effective thermal conductivity of emulsion phase, W/m K
$k_{d,i}$	thermal conductivity of bed particles, W/m K
$k_{d,g}$	thermal conductivity of the fluidization gas, W/m K
N_i	i-th molar flux around a char particle (>0 from the fluidized phases to the char surface), mol/m^2s
$N_{i,c}$	i molar flux at the external surface of a char particle (>0 from the fluidized phases to the char surface), mol/m^2s
Nu	Nusselt number based on char particle diameter, –
Pr	Prandtl number: $c_{p,g}\,\mu_g/k_{d,g}$, –
$q_{cv,g}$	heat exchange between the char particles and the fluidization gas by convection in Fig. 1
$q_{cv,b}$	heat exchange between the char particles and the inert particles of the bed by convection in Fig. 1
$q_{rd,b}$	heat exchange between the char particles and the inert particles of the bed by radiation in Fig. 1
$q_{cv,w}$	heat exchange between char particles and the wall of the FB reactor by radiation in Fig. 1
r_c	radius of a char particle, m
$r_{O2,cb}$	O_2 molar flux consumed by oxidation at the external surface of a char particle, mol/m^2s
$r_{O2,gf}$	CO_2 molar flux consumed by gasification at the external surface of a char particle, mol/m^2s
R_g	gas constant: 8.315 J/mol K
Re_{ePh}	Reynolds number in the emulsion phase based on char particle size and u_{mf}, –
Re_{bPh}	Reynolds number in the bubble phase based on char particle size and u_{tf}, –
Re_{sPh}	Reynolds number in the splash zone based on char particle size and u_f, –
Sc	Schmidt number, $\mu_g/d_{ij}\rho_g$, –
Sh_{EMCD}	Sherwood number when there is equimolar counter-diffusion and the gas-film around the particle is not static: there is a convective flow
Sh_o	Sherwood number when there is equimolar counter-diffusion and the gas-film around the particle is static
SUPM	Shrinking Unreactive Particle Model
t*	characteristic time in which the char particle changes the temperature
T	time of a cycle of the movement of a char particle through the bed, s
$T_{j,T}$	time of a char particle in the emulsion phase (j = ePh), bubble phase (j = bPh), or splash zone (sPh) during a cycle of its movement, s
T_c	combustion temperature of a char particle, K in equations and °C in figures
T_{bed}	bed temperature, K
u_b	average bubble velocity, m/s
u_d	average descent velocity of a char particle through the bed, m/s
u_f	fluidization velocity, m/s
u_{mf}	minimum fluidization velocity, m/s
u_r	average rise velocity of a char particle through the bed, m/s
u_{tf}	bubble through-flow velocity, m/s
$x_{c,fx}$	content of carbon in the char particles in Eq. (29)
$x_{i,c}$	molar concentration at the surface of a char particle, –
$x_{i,bed}$	molar concentration in the fluidized phases, –
z	dimensionless parameter in AI:4, –

Greek letters

Γ_c	apparent carbon consumption in Eq. (29), $g/m^2\,s$
ΔH_{cb}	heat of combustion (exothermic), J/mol
ΔH_{gf}	heat of gasification (endothermic), J/mol
δ	thickness of the gas-film around achar particle that absorbs the mass transfer, m
ε_{mf}	bed porosity at minimum fluidization velocity, –
θ	correction factor when there is no equimolar counter-diffusion, Eq. (7)
μ_g	viscosity of the fluidization gas, kg/ms
ξ	CO/CO_2 ratio at the char surface by oxidation, -
ρ_b	density of the bed, kg/m^3
ρ_c	density of a char particle, kg/m^3
ρ_g	density of the fluidization gas, kg/m^3
ρ_i	density of a inert particle of the bed, kg/m^3
ρ_{mc}	molar density of a char particle, mol/m^3
σ	Stefan-Boltzmann constant, $5.67\cdot10^{-8}$ $W/m^2\,K^4$
ω_c	surface emissivity of a char particle
τ	tortuosity in Eq. (6)
Ψ_j	dimensionless parameter in AI:3, j = ePh and j = bPh

Abbreviations

bPh	bubble phase of the bed
ePh	emulsion phase of the bed
EMCD	equi-molar counter-diffusion
FB	fluidized bed
FBC 2D	(Two-dimensional fluidized-bed combustor) Experimental set-up used here
sPh	splash zone of the bed

furnace as the ones in air-combustion: an inlet O_2 concentration between 25 and 35%$_{v/v}$ is required [2]. Although this first generation reduces the CO_2 emissions, the technology can use higher inlet O_2 concentration in new designs. Despite extensive research [7–10], there is still a number of challenges related to design and building of a second-generation oxy-boiler. Among those are the clarification of the effect on combustion from changing from an O_2/N_2 atmosphere (air-firing conditions) to O_2/CO_2 (oxy-firing conditions) and the control of the conversion temperature in a smaller reactor with less volume available for heat-exchanger surfaces at high oxygen concentration (> 35%$_{v/v}$) [11,12]. Pulverized-coal boiler is the main type of boiler in existing power plants, and publications have been focused mainly on