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Measurement and theoretical prediction of char temperature oscillation during fluidized bed combustion

Jesús Salinero[a], Alberto Gómez-Barea[a,*], Diego Fuentes-Cano[a], Bo Leckner[b]

[a] Chemical and Environmental Engineering Department, University of Seville, Seville 41092, Spain
[b] Division of Energy Technology, Chalmers University of Technology, Göteborg, S412 96, Sweden

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ABSTRACT

There is experimental evidence of oscillations of the char particle temperature during combustion in a fluidized bed (FB), resulting from the movement of the char throughout the bed. However, in most theoretical FB combustion studies the char particle is assumed to always stay in the emulsion phase, and existing models do not take into account the movement of the char particle explicitly. Moreover, it is difficult to quantify the magnitude and frequency of these temperature oscillations with the common measurement techniques employed in FB (thermocouple and pyrometry with optical probe). In this work, the combustion of single char particles (8 mm) from beech wood and sub-bituminous coal is carried out in a 2-dimensional FB made of quartz, using two O_2 concentrations (11 and 21%$_v$) in N_2. The time-evolution of the temperature and the size of the char in the different phases are estimated by the analysis of images resulting from a new method combining pyrometry with readings from a digital camera. It is found that the combustion temperature oscillates in hundredths of seconds with an amplitude varying from 10 to 100 °C, resulting from the movement of a particle between the emulsion, bubble and splash phases. The amplitude increases with higher O_2 concentration and smaller char-particle size. A combustion model is developed using the experimental characterization of the movement of the char particle through the bed as input. The temperature and burnout time predicted by the model compare well (within 15 %) with measurements obtained from this work and from literature.

1. Introduction

While the growing world energy demand is covered to a great extent by coal combustion [1], the need for reduction of the CO_2 emission involves both the increase in the efficiency of the power plants and CO_2 capture and storage [2]. Oxy-combustion is one of the capture technologies with a reasonable net plant efficiency and avoided CO_2 emissions [3,4]. In this process, coal conversion is carried out in an atmosphere resulting from mixing of O_2 with CO_2 from flue-gas recirculation [4] in order to control the combustion temperature [5–7]. Fluidized bed (FB) fulfills this purpose well and, in addition, the bed moderates excess temperatures by its large thermal capacity. It can be used with inferior fuels having low heating value and high ash content, including not only coals but also biomass or wastes. Operation problems, such as segregation, agglomeration and defluidization, may occur from melting of ashes [8], whose viscosity varies, even with small changes in temperature [9]. To measure and predict the combustion temperature in an accurate and reliable way is essential for further development of this combustion technology [10–12].

In spite of publications showing the presence of the coal/char particle occasionally in the bubble phase and splash zone during fluidization [13–16], most theoretical combustion studies (models) assume that the char particles stay in the emulsion phase during the entire conversion time [17–19]. In this way, it is assumed that the heat and mass transfer from/to the particle is that prevailing in the emulsion phase, without taking explicitly into account the impact of the change in the transport rates in different positions [20–22] on the heat generated by CO oxidation to CO_2 close to a char surface [23], and on the combustion temperature. A few experimental work have been published pointing out the effect of the particle movement on the combustion temperature [13,24–28]. By a thermocouple embedded in a coke particle (8 mm) during its combustion in a sand bed (of 1090 μm particles) fluidized with air, an average oscillation of 75 °C in periods shorter than 50 s has been recorded [13]. By the same technique, an increase of 20 and

Abbreviations: bPh, Bubble Phase; ePh, Emulsion Phase; EMCD, Equi-Molar Counter-Diffusion; FBC 2D, (Two-dimensional fluidized-bed combustor) Experimental set-up used here; sPh, Splash zone.

* Corresponding author.
E-mail address: agomezbarea@us.es (A. Gómez-Barea).

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Nomenclature

A_o	area of multi-orifice distributor per hole, m^2
A_{CO/CO_2}	pre-exponencial factor in Eq. (3),
A_{cb}	pre-exponencial factor for char combustion, m/Ks
Ar	Archimides 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 the fluidiztion gas, J/kg K
C	molar concentration, mol/m^3
C_d	dimensionless isolated sphere drag coefficient,
d_c	diameter of the char particle, m
d_i	average diameter of the bed particles, m
d_b	bubble diameter, m
$d_{i\text{-}j}$	binary diffusivity of *i*th compound through *j*th, m^2/s
$D_{i\text{-}j}$	effective mass diffusivity of *i*th compound through *j*th in the emulsion phase: $(\varepsilon_{mf}/\tau)d_{i\text{-}j}$, m^2/s
E_{CO/CO_2}	activation energy in Eq. (2), J/mol
E_{cb}	activation energy for char combustion, J/mol
h_{bed}	expanded bed height, m
h_{cv}	heat transfer coefficient by convection, W/m^2 K
h_p	penetration depth of a char particle in the bed, m
k_{cb}	external combustion kinetics, m/s
$k_{d,ePh}$	effective thermal conductivity of emulsion phase, W/mK
$k_{d,i}$	thermal conductivity of bed particles, W/mK
$k_{d,g}$	thermal conductivity of the fluidization gas, W/mK
m	number of times the char particle is captured by a bubble during its ascention through the bed in a cycle
m_j	fitting coefficient in Eq. (17) for the particle in the emulsion phase $j = e$, bubble phase $j = b$, or splash zone $j = s$, m^{-1}
n_j	fitting coefficient in Eq. (17) for the particle in the emulsion phase $j = e$, bubble phase $j = b$, or splash zone $j = s$,
N_i	i molar flux around the 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 the 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 char particle – fluidization gas by convection in Fig. 4
$q_{cv,b}$	heat exchange char particle – inert particle of the bed by convection in Fig. 4
$q_{rd,b}$	heat exchange char particle – inert particle of the bed by radiation in Fig. 4
$q_{cv,w}$	heat exchange char particle – wall (black surface) by radiation in Fig. 4
r_c	radius of the char particle, m
$r_{O_2,cb}$	O_2 molar flux consumed by oxidation at the external surface of the char particle, mol/m^2s
R_g	gas constant: 8.315 J/mol,K
Re_{ePh}	Reynold number in the emulsion phase based on char particle size and u_{mf},
Re_{bPh}	Reynold number in the bubble phase based on char particle size and $u_{tf,}$
Re_{sPh}	Reynold 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
$t_{i,T}$	time of the char particle in the emulsion phase (j = ePh), bubble phase (j = bPh), or splash zone (j = sPh) during a cycle of its movement, s
$t_{in,bed}$	time of the char particle inside the bed during a cycle of its movement, s
T	time of a cycle of the movement of the char particle through the bed, s
T_c	combustion temperature of the char particle, K in equations and °C in figures
T_b	bed temperature, K
u_b	average bubble velocity, m/s
u_d	average descence velocity of the char particle through the bed, m/s
u_f	fluidization velocity, m/s
u_g	gas velocity around to the char particle, m/s
u_{mf}	minimum fluidization velocity, m/s
u_r	average rise velocity of the char particle through the bed, m/s
u_{tf}	bubble through-flow velocity, m/s
$x_{i,c}$	molar concentration at the char particle surface in the fluidized phases,
$x_{i,\infty}$	molar concentration in the fluidized phases,
z	dimensionless parameter in Eq. (B.4),

Greek letters

ΔH_{cb}	heat of combustion (exothermic), J/mol
ΔT_{thcal}	predicted oscillation of the char temperature, °C
δ	thickness of the gas-film around the char 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)
θ_j	experimental fraction of the fluidization time the particle is in the emulsion phase j = e, bubble phase j = b, or splash zone j = s,
μ_g	viscosity of the fluidization gas, kg/ms
ξ	CO/CO_2 ratio at the char surface by oxidation,
ρ_b	bed density, kg/m^3
ρ_c	char density, kg/m^3
ρ_g	fluidization gas density
ρ_i	particle bed density, kg/m^3
ρ_{mc}	char molar density, mol/m^3
σ	Stefan–Boltzmann constant, $5.67 \bullet 10^{-8}\ W/m^2K^4$
ω_c	char surface emissivity
τ	tortuosity in Eq. (6)
Ψ_j	dimensionless parameter in Eq. (B.3), j = ePh and j = bPh

50 °C in the combustion temperature of a coke particle (~4 mm) has been quantified after 5 and 20 s in a bed of 460 µm particles fluidized with air [24]. Also, from the temperature recorded by two thermocouples embedded in a lignite coal particle (6 mm) burning in a sand bed (250–350 µm), oscillations were measured of up to 10, 30, and 50 °C in periods shorter than 10 s for 10, 21, and 40 $\%_v$ O_2 in N_2 or CO_2, respectively [25]. Results obtained with thermocouples should be regarded with caution since significant error might be committed with this technique: thermocouples may restrict the free movement of the char particle [16]. By pyrometry using an optical probe inside a bed of sand particles (182 µm and