



Co-combustion of coal and waste in pulverized coal boiler



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ARTICLE INFO

Article history:

Received 1 September 2015

Received in revised form

5 November 2015

Accepted 9 November 2015

Available online 18 December 2015

Keywords:

Pulverized coal boiler

Co-combustion

RDF

Waste

SO₂ emission

Model

ABSTRACT

A novel reactor reproducing PCB (pulverized coal boiler) environment was used to evaluate the potential of sorbent co-firing and waste co-combustion as cheap retrofitting techniques to reduce SO₂ emissions of existing boiler. Several co-feeding tests of coal and CaCO₃ and coal and Ca(OH)₂ have been performed for a gas residence time around 0.5 s (4 times shorter than PCB). Results show sulfur emission reduction up to 18% with Ca(OH)₂ injection, and up to 20% with limestone for a Ca/S ratio of 2. Co-firing of a 20% thermal share of a waste derived fuel called ReEFTM, led to SO₂ emissions reduction of around 20%. Co-firing of this ReEFTM led also to HCl emissions of more than 20 ppm due to the PVC content of the ReEFTM.

In order to describe the gas and particles evolution along the reactor height, a model combining almost 30 kinetic reactions from the literature and without any fitting parameters was developed. The model shows that the ReEFTM particles had higher residence time in the furnace than coal and sorbent particles. For the temperature and air injection pattern tested, the model accurately predicted the emissions measured at the exit of the reactor for all the feed compositions.

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1. Introduction

The use of coal, which currently provides 40% of the world's electricity needs, has never stopped increasing and the forecasts indicate that, unless a dramatic policy action occurs, this trend is expected to continue in the future [1]. In the United States, for example, more than 30% of the electricity is produced from coal power plants. The great majority of those power plants use PCB (pulverized coal boilers), which were mostly built in the 1980's [2]. Due to the coal's intrinsic sulfur content, coal combustion is a major source of SO₂ emissions, which are greatly damageable for the environment as they can cause acid rain and fine particles emissions.

Up to date, different desulfurization technologies are commercially available, varying in complexity, effectiveness and cost. The most commonly used is wet scrubbing with a SO₂ removal efficiency above 95%, but it presents serious problems of waste material disposal and high investment and operating cost [3,4]. Co-firing of coal and sorbent could be an affordable alternative [5]; its efficiency is up to 40%, or higher, while the investments are much lower: sorbent blending costs, compared with wet scrubbers,

are only of about 15% for the entire installation [3]. Due to its large availability and its low cost, the sorbent generally considered for co-firing is limestone (CaCO₃), which reacts with SO₂ to produce CaSO₄. At high temperature, CaCO₃ decomposes into calcium oxide and carbon dioxide through a process called calcination [6]:



Calcination produces highly porous particles of CaO: the molar volume of CaCO₃ is around 36.9 cm³/mol and that of CaO is around 16.9 cm³/mol [7] and since the particle size is not affected by calcination, this can only mean increased pore sizes [8]. The calcium oxide formed can then interact with SO₂ to form calcium sulfate [6]:



Since the molar volume of CaSO₄ is around 46 cm³/mol [7], the sorbent particles experience loss of porosity and pore blockage as the sulfuration reaction proceeds [9].

Ordinary limestone used at a Ca/S ratio of 2–3 yields SO₂ reduction efficiencies of 70–90% in fluidized-bed combustors with furnace temperature of 800–1000 °C; but they give a lower SO₂ reduction efficiency of 25–50% in PCB at 1000–1600 °C [10]. The higher contact time between gas and sorbent and the lower temperature associated with a lesser extent of sintering in fluidized bed boilers allows higher SO₂ reduction. Furthermore, the sulfuration

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Nomenclature	
a_i	stoichiometric coefficient (mol _i /g _{coal,daf})
A	pre-exponential constant (variable)
A_c, A_s	total external surface area of char and soot particles per reactor m ³ (m ² /m ³)
$\alpha_{i,j}$	stoichiometric coefficient of species i in reaction j (–)
$\beta_{i,j}$	stoichiometric coefficient of i produced by devolatilization of coal j (mol _i /g _{coal,daf})
c_{pi}	thermal capacity (J/kg K)
C_i	concentration (mol/m ³)
$C_{i,wt}$	mass concentration (g/m ³)
C_{di}	drag coefficient (–)
C_{tot}	total concentration of the gas phase (mol/m ³)
d_{p_i}	particle diameter (m)
D_i	diffusion coefficient (m ² /s)
Δh_{dec_m}	heat of decomposition (J/g)
Δh_{melt_m}	heat of melting (J/g)
ΔQ_m	heat flux (W/m ²)
E	activation energy (J/mol)
ϵ_i	emissivity (–)
F_i	molar flow rate (mol/s)
η	effectiveness factor of sulfurization (–)
g	acceleration of gravity (9.81 m/s ²)
γ	empirical coefficient (g/mol)
h_i	heat transfer coefficient (W/m ² K)
k_i	thermal conductivity (W/m K)
K	kinetic coefficient (variable)
M_i	molar mass (g/mol)
μ_i	viscosity (Pa s)
N_p	flow rate of particles (s ^{–1})
p	pressure (Pa)
p_i	partial pressure (Pa)
$p_1 \text{ à } 5$	polynomial coefficients (variable)
φ	mechanism factor (–)
Φ	step function (–)
r_j	reaction rate (mol/m ³ s or g/m ³ s)
R	ideal gas constant (8.31 J/mol K)
ρ_i	density (kg/m ³)
S_f	reactor transversal surface area (m ²)
S_{ac}, S_{as}	total external surface area per unit mass of char or soot particles (m ² /g)
σ	Stefan–Boltzmann constant (5.67 × 10 ^{–8} W/m ² K ⁴)
T_g	gas temperature (K)
T_{p_i}	particle temperature (K)
U_i	superficial velocity (m/s)
V_j	product yield (g/g _f)
V_j^*	ultimate product yield (g/g _f)
$W_{i,0}$	initial mass flow rate (g/s)
ω_{coal_j}	reference coal composition in terms of C, H and O (–)
$x_{i,j}$	mass fraction of i in j (–)
y_i	mole fraction of i in the gas phase (–)
z	reactor height (m)
Sub-/superscripts	
0	initial
c	coal
d	diffusion layer
f	fiber
g	gas
h	hard plastic
m	plastic (either h or s)
p	particle
s	soft plastic
wt	mass

product CaSO₄ scarcely decomposes below 1050 °C and only gives decomposition percentage of 13 wt% at 1150 °C. However, it increases to 57 wt% at 1200 °C and reaches 96 wt% at 1300 °C [5]. CaSO₄ may therefore decompose significantly in the high temperature regions of pulverized coal boilers.

They are ways to improve sulfur capture efficiency of sorbent co-firing while minimizing the amount of sorbent injected in the boiler. One of them is to tailor the sorbent injection so that it is injected at lower temperature [11]. Another is to use hydrated lime which is perceived to be more reactive towards SO₂ due to the increased surface area and porosity of its calcinations product [12].

Sorbent injection has been studied for many years. However a large majority of the studies were performed in absence of coal, with a gas flow simulating typical combustion atmosphere [13–19] and/or at uniform temperature [13–21]. These conditions are satisfactory for the study of the sulfation kinetics, but they are not representative of real PCB environments; where the SO₂ capture can vary with the concentration and temperature gradients as well as with potential interactions between sorbent particles and coal ashes.

Similarly to coal blending, another solution to reduce SO₂ emissions is to partially substitute coal with waste-derived fuel, as non-recyclable MSW (municipal solid wastes) are readily available. Since MSW generally contain a biogenic fraction, waste derived fuel are considered partially renewable and their combustion partially CO₂ neutral [22]. Furthermore, their very low sulfur content ensures, when co-fired with fossil fuels in existing boiler, lower SO₂ emissions [23]. Co-firing of waste derived fuel in existing power plant is also sound from the point of view of waste utilization

efficiency, as the electricity efficiency of existing coal power plant is more than 40% [2], while that of MSW incinerator is limited to 13–24% by incombustible and water [24]. Depending on the waste source and the production scheme, several types of waste derived fuel are defined: RDF (refuse derived fuel), SRF (solid recovered fuel) and EF (engineered fuel).

In the literature, few co-combustion studies of coal and WDF in a PCB environment have been reported. The co-combustion ratios tested generally vary between 2%th and 25%th [25–29]. A small decrease to no effect at all on NO_x and SO₂ are reported and only one study reports an increase in HCl emissions, while all of them see no difference in the carbon content of the ashes. Furthermore, only one study modeling the global combustion behavior of SRF and coal in a PCB was found, but their model was not verified with experimental data [30].

In this study, SO₂ emissions obtained by co-combustion of an Engineered Fuel developed by the company Accordant Energy is compared to SO₂ emissions obtained by CaCO₃ and Ca(OH)₂ co-feeding in a novel reactor reproducing the combustion environment of a PCB. SO₂ emissions variations with injection temperature and air feeding pattern, more precisely air staging or OFA (over fire air), a widely used method to reduce NO_x emissions in PCB, are evaluated. The flame temperature and the air feeding pattern are both characteristics that change from one boiler to another and need to be studied to ensure robustness of the SO₂ emissions reduction methods proposed. Finally, in order to describe the combustion behavior of the different species in the combustion chamber, a model is developed. This model is build from kinetic

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