Applied Energy 125 (2014) 308–318

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Oxy-fuel combustion in circulating fluidized bed boilers

Bo Leckner [a,*], Alberto Gómez-Barea [b]

[a] Department of Energy and Environment, Chalmers University of Technology, 41296 Göteborg, Sweden
[b] Department of Chemical and Environmental Engineering, University of Seville, Camino de los Descubrimientos s/n, 41092 Seville, Spain

HIGHLIGHTS

- CO_2 reduction in a circulating fluidized bed (CFB) oxy-boiler is studied.
- Two cases are analyzed: (1) an air CFB boiler adapted to operate with O_2 and (2) a new boiler designed for oxycombustion.
- For (1) the boiler performance adapted to operate in a similar way as in air-fired CFB is studied.
- For (2) the advantages and challenges are identified for future developments.

ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 17 February 2014
Accepted 21 March 2014
Available online 19 April 2014

Keywords:
Oxycombustion
Circulating fluidized bed
Boiler
Coal
Carbon capture

ABSTRACT

The conditions for CO_2 reduction in a circulating fluidized bed (CFB) oxy-boiler are studied, that is, operation with pure oxygen, diluted by recirculated flue gases to moderate the combustion process. Two cases are analyzed: the ready-to-convert case, a normal air-fired CFB boiler, only slightly modified to be operated with oxygen instead of air for CO_2 capture, and a more general option, an entirely new design, employing high oxygen concentration in the input to the oxy-fuel CFB boiler. It is found that at a given fuel load, the relevant parameters for maintaining the CFB performance (bed temperature and fluidization velocity) in the ready-to-convert case cannot be kept entirely equal to those in the air-fired case, and some compromise has to be found. The new-design case results in a smaller boiler than that of the comparable air-fired case, depending on the oxygen concentration and the corresponding flue-gas recirculation. This case is expected to contribute favorably to reduction of the cost of CO_2 removal.

1. Introduction

In oxy-fuel combustion it is proposed to substitute air by oxygen in boilers to avoid dilution of the flue gases with nitrogen in order to facilitate CO_2 handling for deposition. So far, most investigations in this area have been related to pulverized-coal (PC) combustion [1–3], where even pilot plants have been operated [4]. Some work has also been done for circulating fluidized bed (CFB) boilers by the major manufacturers [5–7], and a rather large test facility has been put into operation [8].

To avoid using pure oxygen in the combustion chamber, the oxygen injected is diluted by recirculated flue gas, predominantly consisting of CO_2 and H_2O. There are several options. The first one uses the same amount of recirculated flue gas as would be needed to substitute the nitrogen present in the flue gas during air operation with oxygen in an existing boiler, or a new boiler is built, designed for air-combustion to be operated eventually with oxygen. The two variants of this approach are called the "retrofit" case or the "ready-to-convert" case. The other alternative, so far little studied, is the "new-design" case, where the inlet oxygen concentration is the parameter to be chosen and the boiler is designed accordingly. A major difference between the PC and CFB applications is that the flame temperature in a PC boiler will rise with the oxygen concentration, and boilers of the "new-design" type will encounter situations that differ essentially from the "retrofit" case, whereas in a CFB boiler the bed material serves as a moderator that maintains the combustion temperature and transports the heat to heat transfer surfaces. Another difference is that PC boilers are already developed since some decades, whereas CFB is still under development, implying a gradual rise in capacity to attain the size needed to compete economically with PC as electric utility boilers. Progress is being made in this respect, and a large CFB boiler (460 MW_e) was built in Poland just a few years ago [9] and a 600 MW_e boiler was recently put into operation in China [10]. Already in this size range (300–600 MW_e), now offered by the major manufacturers, CFB is large enough to be a suitable candidate for CO_2 reduction by oxy-combustion.

---

* Corresponding author. Tel.: +46 31 772 1431.
E-mail addresses: ble@chalmers.se (B. Leckner), agomezbarea@us.es (A. Gómez-Barea).

http://dx.doi.org/10.1016/j.apenergy.2014.03.050
0306-2619/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

Symbols

A	cross section (not considering tapering unless explicitly stated), m^2
a	quantity of ashes in the fuel as delivered, kg/kg fuel
b	combustible content in the fuel as delivered, kg/kg fuel
c_p	mean specific heat at constant pressure in the range of ΔT, kJ/kg, K
c	carbon content in the combustible part of fuel, –
F	feed rate of dry and ash-free fuel, kg/s
G	vertical particle flux, kg/m^2, s
g	specific gas quantity, kmol/kg, kg/kg, m^3/kg combustibles
h	height of combustion chamber, m
h	hydrogen content in the combustible part of fuel, –
H	heating value related to dry and ash-free fuel, kJ/kg
H_{H_2O}	heat of evaporation of water, kJ/kg
ℓ	stoichiometric oxygen demand, kg/kg combustible, kmol/kg or m^3/kg
M	molecular mass, kmol/kg
$m_{CO_2,se}$	mass flow rate of CO_2 fed to fluidize the seal and external heat exchangers, kg/s
$m_{CO_2,sorb,max}$	maximum mass flow rate of the CO_2 that could be adsorbed by the sorbent, kg/s
o	oxygen content in the combustible part of the fuel, –
P	pressure, Pa, bar
Q_{gas}	heating of fuel and gas, kW
$Q_{internal}$	total quantity of heat absorbed in the furnace to maintain bed temperature, kW
Q_{ext}	quantity of heat absorbed in the external particle loop, kW
s	sulphur content in the combustible part of the fuel, –
T	temperature, °C
ΔT	temperature difference, degrees
u	fluidization velocity, m/s
V	furnace volume, m^3
w	moisture content in the fuel as delivered, kg/kg fuel
x	specific mass fraction, mass of the gas component, kg/kg flue gas
y	volume concentration, –
ρ	density, kg/m^3
λ	global stoichiometric ratio, –
λ'	internal stoichiometric ratio, –

Indices

air	air-firing, refers to the case of air-firing, not necessarily to air as such
b	bed
c	carbon
cw	condensed water
oxy	oxy-firing, N_2 replaced by CO_2
u	lower (heating value)
ext	external
g	gas
H_2	hydrogen
in	entering
j	stream
k	gas components, species
mass	based on mass
mix	mixture
N_2	nitrogen
o	initial, environmental, stoichiometric, standard
O_2	oxygen
out	leaving the combustion chamber
r	recirculation
s	solids, sulphur
se	loop seal + fluidized bed heat exchanger
sorb	sorbent, lime
total	oxygen + nitrogen
vol	based on volume
ΔT	temperature difference

The conditions for oxy-fuel combustion in PC boilers have been studied for some time. An early work [11] determined the flue gas recirculation required to substitute nitrogen in air combustion. Later several studies have been made with flue-gas recirculation e.g. [12] identifying the O_2 fraction in the entrance of the burners yielding the same adiabatic temperature as in air combustion (the volume fractions obtained were 0.28 for wet and 0.35 for dry flue gas recirculation at 3.3% O_2 in the exit gas). It was mentioned that such identification between air and oxy-firing is an invalid design criterion due to differences in radiative heat transfer in an N_2 and a CO_2 dominated (PC) furnace. The impact of the substitution of air with oxygen in CFB has not been studied so much, but a few work can be mentioned [13–16]. Still, an explicit analysis is needed, focusing on the performance of a CFB boiler. This is the purpose of the present study where two different cases are analyzed to understand the conditions for CO_2 capture: a situation when an air-fired CFB boiler is built prepared for conversion to CO_2 capture, the "ready-to-convert" case, and a "new-design" case where a new boiler is built particularly for CO_2 capture. The study attempts to catch the essential features of an oxy-fuel installation, and obvious simplifications are made to facilitate the understanding of these features rather than engaging in details of secondary importance. It is also assumed that despite the disregard of a detailed description of local processes, such as heat balance on char particles, these do not prevent from treating the global conditions as they are studied here.

2. Model development

2.1. General description

Fig. 1 shows the configuration of a CFB boiler and the related flue-gas recirculation system, similar to that of a PC boiler. Theoretically, the three recirculation options shown in the sketch (dirty, wet, and dry recirculation) are possible, but material and species accumulate as a consequence of recirculation, and the dirty option can be ruled out because of anticipated high particle loading: some type of particle separator will be necessary in all systems. It is more uncertain to decide a priori whether to employ

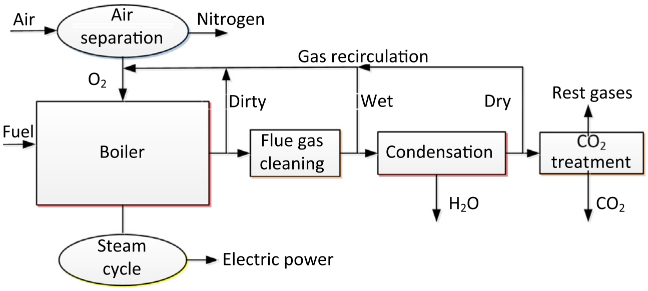

Fig. 1. Boiler with oxygen supply and several options of flue-gas recirculation.