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Heat transfer in the external heat exchanger of oxy-fuel fluidized bed boilers

Irene Bolea [a,*], Luis M. Romeo [a], David Pallarès [b]

[a] CIRCE – Center of Research of Energy Resources and Consumptions, Mariano Esquillor Gómez 15, 50018 Zaragoza, Spain
[b] Department of Energy and Environment, Chalmers University of Technology, SE 412 96 Göteborg, Sweden

HIGHLIGHTS

- Heat transfer in oxy-fuel BFB is empirically characterized.
- A correlation is formulated to account for solids circulation in the heat transfer.
- Proposed expressions are used to model a large EHE with recarbonation.
- Heat exchange area in the EHE of a large oxy-fuel CFB unit is estimated.

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ABSTRACT

The external heat exchanger (EHE) plays an essential role in the adequate control of the heat balance in large-scale oxy-fuel circulating fluidized bed (CFB) boilers. However, the EHE of an oxy-fuel CFB presents two particularities compared to the known air-combustion case: the composition of the fluidizing gas and the higher flow of recycled solids. Both these issues are addressed in this paper: Firstly, heat transfer coefficients are measured in a 90 kW bubbling fluidized bed, operated at different temperatures, with air and with a wide range of O_2/CO_2 mixtures. Thereafter, experiments are also carried out in a cold scaled-down EHE in order to assess the influence of an increment in the solids flow across the EHE on heat transfer.

Based on the results of these experiments, an expression for the heat transfer coefficient is proposed which accounts for gas composition and solids flow rate. Finally, a model for the EHE is integrated into a large oxy-fuel CFB model in order to quantify the influence of oxy-fuel operation mode on the heat transfer surfaces required in the EHE.

1. Introduction

Oxy-fuel combustion in fluidized beds has revealed as an attractive and feasible option to reach the concept of *clean-coal* technology. It gathers the environmental advantages of both technologies: SO_2 and NO_x control inherent to fluidized bed combustion and the oxy-fuel capability of generating a flue gas stream suitable for efficient CO_2 capture. In addition, the fuel flexibility characterizing fluidized bed units represents the possibility to implement oxy-fuel boilers for bio-energy with carbon capture and storage for negative CO_2 emissions.

In the last decade, several experimental pilot plants have been focusing on overcoming and understanding the main differences as regards on the combustion and pollutant formation reactions when the fluidizing atmosphere changes to oxy-fuel conditions, as summarized in Table 1. The largest installation already at demonstration scale is the 30 MW CIUDEN oxy-fuel circulating fluidized bed (CFB), running successfully since 2011 [1].

Some authors made use of simulations to predict the implications of oxy-fuel combustion in large scale CFB boilers [6,15–18]. All these works coincided on recognizing the need of external heat exchangers (EHE) to adequately fulfill the energy balance of the plant without compromising the temperature limits in the boiler. When increasing inlet O_2 concentrations, in-furnace heat transfer area decreases due to reduced furnace dimensions. To compensate for this, a higher flow rate of elutriated solids, G_s, is set which enhances the heat transfer coefficient inside the furnace (due to the increased solids hold-up in the freeboard) and the heat extraction potential from the circulating solids in the EHE. In order to avoid impurities in the resulting CO_2 outlet stream, the EHE of an oxy-fuel

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* Corresponding author. Tel.: +34 976 761 863; fax: +34 976 732 078.
E-mail addresses: ibolea@unizar.es, irene.bolea@gmail.com (I. Bolea).

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Nomenclature

A	area, m^2
BFB	Bubbling Fluidized Bed
c_p	specific thermal capacity, J/kg K
CFB	Circulating Fluidized Bed
d	diameter, m
e	error
EHE	External Heat Exchanger
G_s	recycled solids, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
k	conductivity, W/mK
L	length, m
M	empirical parameter
m	mass flow, kg/s
T	temperature, °C
t	time, s
t_R	residence time of particles in the EHE, s
u	velocity, m/s
V	volume m^3

Subscripts

B	bed
b	bubble
bw	bed-to-wall
c	cluster
conv	convective
Cu	copper tubes
e	emulsion
eff	effective
g	gaseous
gc	gaseous convection (bubble phase)
HT	Heat Transfer
in	instantaneous
mf	minimum fluidization
p	particle
Pa	packet
pc	particle convection (emulsion phase)
r	radiation
s	solid
w	water
0	no solids recirculation

Greek symbols

δ	volumetric fraction
ε	void fraction/emissivity
H	dimensionless heat transfer coefficient
ρ	density kg/m^3
σ	Boltzmann constant, m^2 kg/s^2 K
τ	residence time, s
Θ	dimensionless residence time

CFB is fluidized with recycled flue gas (consisting mainly of CO_2) instead of air.

The change in the fluidizing atmosphere and the higher amount of solids circulation will influence heat transfer in the EHE. The former leads to variations in gas properties (density, viscosity, thermal capacity, conductivity) affecting heat transfer and fluid dynamics. The latter will enhance heat transfer coefficients but also have an effect on the solids residence time, yielding non-uniformities among the heat transfer tubes.

In this paper, both issues cited are experimentally examined and results are used to formulate a mathematical model. Firstly, measurements of heat transfer coefficients are presented from air and oxy-fuel experiments in a bubbling fluidized bed (BFB) 203 mm I.D. This work presents unique values for heat transfer coefficients during oxy-firing in BFB and the first published attempt to analyze through modeling and experiments the differences between air and oxy-fuel combustion in BFB units. Secondly, the distribution of heat transfer coefficients among the tubes of a cold scaled-down EHE model operated at different solids flows is measured. From this, an empirical correlation is proposed to be combined with the previous expression for a stagnant bed. Finally, by means of mathematical modeling integrated into an oxy-fuel CFB simulation, an assessment is performed of the heat transfer surface needed in a large scale EHE to achieve the heat balance requirements at different oxy-fuel conditions.

Table 1
Research groups with experimental experiences on oxy-fuel fluidized bed pilot plant.

Group	Experimental facility (Type/I.D./H)	Issues[a]	Refs.
CANMET	CFB/100 mm/5 m	a, b	[2]
VTT	CFB/167 mm/8 m	a, b	[3]
Czestochowa University of Technology	CFB/250 mm/5 m	a, b, c	[4,5]
ALSTOM	CFB/0.66–1 m/18 m	a, b, c, e	[6]
CSIC-ICB	BFB/100 mm/0.6 m	a	[7]
University of Utah	CFB/250 mm/6.4 m	a, b	[8]
METSO	CFB/1 × 1 m^2/13 m	a, b	[9,10]
Wien Technical University	CFB/150 mm/5 m	a, b, c	[11]
CNR	BFB/40 mm/1 m	a,d	[12]
CIRCE	BFB/207 mm/2.7 m	a, b, c, d, e	[13,14]

[a] a: sulfur capture; b: NO_x emissions; c: combustion mechanisms; d: fluid-dynamics; e: heat transfer.

2. Heat transfer in an oxy-fuel bubbling fluidized bed

Heat transfer from a gas-solids fluidized bed to a heat exchange surface is extensively addressed in the literature. The review below of the more common approaches to modeling heat transfer in fluidized beds intends to provide a background from which our choice of model was taken, which better can account for the changes in the fluidizing atmosphere during oxy-fuel.

Earlier common approaches to model heat transfer to surfaces in fluidized beds assumed similarity to gaseous convection and assigned thermal resistance to a boundary layer at the heat transfer surface [19]. Heat transfer enhancement found at gas velocities greater than minimum fluidizing velocity, u_{mf} [20] was attributed to the decrease in effectiveness of the film thickness. Models following this approach attempted to correlate a Nusselt number with the gas Prandtl number, a modified Reynolds number and the Archimedes number, using either the particle diameter or the tube diameter and other non-dimensional parameters. Thus, the influence of the operational conditions, bed geometry or solids and gas properties are to be regarded and heat transfer correlations can be found in several compendia [19,21,22]. Molerus et al. [23] proposed an empirical correlation that could predict the experimental dependence of heat transfer with the Reynolds number. However, most of these approaches fail to provide correct predictions when applied to plant configurations different from those in which they were derived [24].