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Research article

Comparative investigation of a co-firing scheme in a lignite-fired boiler at very low thermal-load operation using either pre-dried lignite or biomass as supporting fuel

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ABSTRACT

This work presents an investigation of an indirect firing scheme using biomass (cardoon) as supporting fuel for a pulverized-lignite boiler during its operation at a thermal load of 35%, lower than the current minimum one. Results are compared with an alternative indirect firing scheme which employs pre-dried lignite (PDL) as supporting fuel. The numerical investigation of the boiler has been conducted using the commercial software ANSYS Fluent® v15.0, supported by in-house built functions for the combustion rate of the fuels and the drag force exerted on biomass particles. The simulation and the comparison of the combustion of two different fuel blends in a co-firing strategy is important in order to evaluate technically the available possibilities and select among them the optimal firing concept (number and position of the operating injection ports) and the ideal fuel blend for the operation of the unit at lower than technical minimum thermal loads, in order to attain reduction of emissions and improvement of the boiler flexibility. Due to the implementation of a two-stage over-fire air (OFA) system and the consideration of sub-stoichiometric conditions exhibited at the nominal load, this work also takes into consideration the modeling of the boiler convective section, following the porous media analysis provided by the available Macro Heat Exchanger Model, ANSYS Fluent®. The validation of the applied models has been performed in previous works of the same group of authors, while the combustion results regarding crucial combustion parameters have been compared against corresponding values derived by a suitably-developed thermodynamic model. The agreement between these two models is good, since the maximum percentage deviation is calculated to be in the range of approximately 10%. Based on the numerical results, it can be concluded, that the utilization of both types of supporting fuel can ensure the stable operation of the boiler at thermal loads, lower than the technical minimum of the unit, promoting its flexibility. Between the two different supporting fuels, it is observed, that biomass ensures higher combustion efficiency compared to pre-dried lignite. However, it is also indicated, that the reduction of NO_x emissions and the intensity of the induced thermal loading on the membrane walls with the utilization of biomass is more dependent on the firing strategy compared to lignite, proving the key role that this parameter plays to the operation of a boiler using this specific fuel blend.

1. Introduction

Coal and lignite are still the most common energy sources for the power sector worldwide, accounting to 40.8% of the global power production in 2014 [1]. Even though the utilization of these solid fossil fuels is still on an increasing trend in countries like China, India and others, the European Union is undergoing a rapid de-carbonization of its power sector in order to reach targets for reduction of greenhouse gas emissions and increased penetration of renewable energy sources in the power system. Thus, hard coal and lignite consumption in the EU-28 in 2016 was reduced at 50 and 60% of the 1990 levels, respectively [2]. The new market conditions imposed by the changes in the legislation have resulted in increased installed capacities of wind and solar plants, which are intermittent energy sources. In order to maintain its

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Abbreviations

BAT	best available technologies
BC	boundary condition
CFD	computational fluid dynamics
EU	European Union
LHV	lower heating value (kJ/kg)
MHEM	Macro Heat Exchanger Model
MHPSE	Mitsubishi Hitachi Power Systems Europe
NTU	number of transfer units
OFA	over-fire air
PDL	pre-dried lignite
PPC	Public Power Corporation
RES	renewable energy sources
RFG	recirculation flue gas

Nomenclature

A	pre-exponential factor (s^{-1})
A′	surface area (m^2)
C_1	diffusion rate constant ($kg\,m^{-1}s^{-1}\,Pa^{-1}\,K^{-0.75}$)
C	heat capacity rate ($J/s\,K^{-1}$)
C_r	heat capacity ratio (−)
d	diameter (m)
D_o	diffusion rate coefficient ($kg\,(m^2\,s\,Pa)^{-1}$)
E	activation energy ($J\,kmol^{-1}$)
k	rate constant ($m^3\,mol^{-1}/s$)
L	length (m)
m	mass (kg)
$M_{w,ox}$	molecular weight of oxide ($kg\,kmol^{-1}$)
N	order of reaction (−)
p_n	pressure (Pa)
P_{o2}	partial pressure of oxygen (Pa)
q	heat transfer rate (W)
R	universal gas constant ($8314\,J\,K^{-1}\,kmol^{-1}$)
R_{jr}	combustion rate ($kg\,(m^2s)^{-1}$)
R_{kin}	kinetic rate of combustion ($kg\,(m^2\,s\,Pa^N)^{-1}$) lignite; ($kg\,(m^2\,s\,Pa)^{-1}$) biomass
T	temperature (K)
t	time (s)
V	volume (m^3)
ε′	heat exchanger effectiveness (−)
ρ	density (kg/m^3)
Y_{ox}	local mass fraction of oxidant in the gas (kg/kg)

Subscripts

comb	combustion
g	flue gas
f	forward reaction
in, aux	inlet auxiliary
in, prim	inlet primary
k	cylinder
min	minimum
p	particle
r	reverse reaction
s	sphere
sph	spherical particle

economic sustainability, the current fleet of coal-fired power plants has to make the transition from base-load units to plants capable of operating flexibly under cycling or peak-load conditions [3], responding almost immediately to the frequent system load changes due to the volatile behavior of RES [4]. This implies that coal power plants will have to operate in “unusual” regimes, often not considered in their initial design.

The reduction of minimum operating load of such units is a key target for their increased flexibility. The minimum operating load is defined as the lowest safe and reliable power plant operation mode without the use of supplementary firing [5]. By operating at low loads, a power plant is expected to exhibit higher emission levels and lower efficiencies compared to the full load; however, the plant may continue running on the grid and avoid expensive start-up and stop procedures. The plant can then quickly increase its load when the grid conditions demand it (e.g. when intermittent renewable energy sources are not available) and provide stability services to the grid.

Conventional plants have typical minimum load values of 20–40% for hard coal and 40–60% for lignite-fired boilers [5]. BAT can result in a minimum load of less than 20–25% for hard coal plants and less than 40% for lignite plants [6]; indirect firing schemes, e.g. through the co-firing of biomass or pre-dried lignite in BAT plants can help to achieve even lower values.

Co-firing of biomass has been extensively studied and is considered as a low-cost and quick to deploy technological option for the reduction of CO_2 emissions of coal power plants. Implementing co-firing schemes, in which biomass replaces 5–20% of the coal thermal input, can result in significant CO_2 and NO_x emissions reduction, especially when these schemes are combined with emission-reducing techniques such as air staging [7]. On the contrary, coal plant operators have to solve several issues related to biomass co-firing, such as issues with biomass milling, fouling and corrosion, due to higher chlorine and alkali content of biomass compared to coal [8]. Moreover, they have to consider the combustion efficiency, since the high moisture content, the fibrous structure and the low calorific value of biomass can affect negatively the thermal efficiency of the unit and deteriorate the combustion flame stability [9], especially for the case of low-load operation, which is nowadays the primary objective for the flexible operation of a coal-fired boiler.

Numerous studies – both numerical and experimental - in the literature focus on the investigation of feasible firing strategies either in industrial/large-scale or laboratory/small-scale pulverized boilers to identify the most promising and technically possible pathways to achieve the co-firing scheme. The basic research objectives of all these publications are the investigation of: a) the influence of the particles' size and shape in the combustion efficiency [10–13], b) the influence of various biomass shares and/or different oxidant agents or operating conditions in combustion parameters and emissions even in CFB units [14–24] c) the comparison of the energy efficiency and the combustion behavior of a boiler before and after the implementation of a co-firing strategy [25] and d) the composition and thickness of the ash fouling deposits depending on the biomass share [26–29].

Despite the fact that a thorough search of the open literature reveals the existence of numerous works which methodically investigate the biomass/coal co-firing concept, the investigation of such approaches in conventional pulverized-fuel boilers at thermal loads lower than the current operating minimum of the units is still insufficient. The present work aims to give valuable insight into the operation of a lignite-fired boiler with a co-combustion firing strategy at very low thermal load using biomass as supporting fuel. Results are compared with an indirect firing scheme that uses pre-dried lignite, another alternative for achieving lower operating loads [30]. Although similar in terms of the firing strategy, the two cases have different implications for the plant operator. Using biomass as a supporting fuel requires external sourcing and the expansion of the operator's activities; it is however a renewable energy source which can lower the CO_2 emissions of the plant by substituting lignite. Using pre-dried lignite does not fundamentally alter the fuel sourcing but requires the installation and operation of suitable