Fuel Processing Technology 142 (2016) 370–395

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Numerical investigation of firing concepts for a flexible Greek lignite-fired power plant

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 20 October 2015
Accepted 23 October 2015
Available online 10 November 2015

Keywords:
Lignite
CFD
Partial-load
Flexibility

ABSTRACT

In the present work the behavior of a lignite boiler under both full and partial load conditions is investigated by means of CFD modeling. The simulated furnace is that of the Megalopolis Unit IV, a 300 MW_e power plant operated by Public Power Corporation S.A. (PPC) and located in Peloponnese, Southern Greece. Due to the extremely low quality lignite utilized in the particular power plant, a special system for dried lignite dust separation from vapors — composing of a) an additional vapor ESPs – partial vapor discharge and b) a dry lignite dust recirculation and firing system, is designed and operated in the particular boiler. Hence, pre-dried lignite is continuously used as the additional supporting fuel, through a special feeding, dosing and firing system along with separation and vapor discharge.

Scope of the present work is the evaluation and optimization of different firing modes for the decrease of minimum load operation lower than 40%. The numerical analysis is focused on the induced flue gas flow field characteristics, associated with average exhibited temperature, main gas species concentrations, wall heat flux and particle burnout. The boundary conditions for partial load operation are provided by Mitsubishi Hitachi Power Systems Europe (MHPSE) and the basic design data of the furnace are provided by PPC S.A. In total, eight operating conditions are investigated corresponding to five boiler thermal loads, thus covering a wide range of thermal load operation. Furthermore, the boiler performance under different air and fuel distributions among the burners is also examined, in order to identify useful trends regarding the optimum conditions, under which a stable and safe furnace operation for very low load operation (less than 40%) can be assured. The CFD results are compared against design values provided by MHPSE. Finally, conclusions concerning the furnace membrane wall erosion and accretion rates under various operating configurations are derived, providing useful information about potential operating issues that could be expected, if the examined firing cases were applied. Finally, the case of a thermal load equal to 40% is of interest, for which a stable pulverized lignite flame can be achieved when two mills instead of three are operating.

1. Introduction-literature survey

Nowadays, it is estimated that 30% of the primary energy demands worldwide as well as over 40% of the electricity generation are provided by coal-fired power plants [1]. By applying the best available techniques the net efficiency of newly designed and operated coal power plants can be as high as 46%, compared to the current average efficiency of the existing units, which is a little higher than 37% (EU-27) [2]. Actions towards the efficiency and environmental impact improvement of newly erected and operating power plants are nowadays considered to be essential, since their operation is closely related to climate change and greenhouse gas emissions increase. It is estimated that an efficiency improvement of a conventional pulverized-coal power plant by 1% percent can lead to a 2–3% reduction of the associated CO_2 emissions [3].The resulting fuel reduction in consumption is financially as well as environmentally beneficial.

The increasing capacity of renewable energy sources (RES) in the electrical grid is another reason for improving the efficiency and flexibility of coal-fired power plants. The nature of many RES, in particular solar and wind, is widely stochastic, which means that the corresponding energy production could considerably vary even within a few hours based on the meteorological phenomena. Thus, in order to secure the stability of the electrical grids, flexible and efficient power plants are required, which can easily adjust their load and operation mode according to: a) the current power supply of RES, b) the relevant residual load and c) the grid requirements for primary and secondary energy reserves.

Consequently, the investigation of the coal-fired power plants boiler behavior and stability under partial-load conditions is a vital issue. However, especially for the currently operating PPs, the achievement

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http://dx.doi.org/10.1016/j.fuproc.2015.10.033
0378-3820/

Nomenclature

Abbreviations

CFD	Computational Fluid Dynamics
DPM	Discrete Phase Model
ESP	Electrostatic Precipitator
LHV	Low Heating Value
LUVO	Luftvorwärmer (Air Preheater)
MCR	Maximum Continuous Rating
MHPSE	Mitsubishi Hitachi Power Systems Europe
PCC	Public Power Corporation S.A.
PP	Power Plant
RANS	Reynolds Averaged Navier Stokes
RES	Renewable Energy
SH	Superheater
UDF	User-Defined Functions

Latin letters

A	pre-exponential factor (kg m^{-2} s^{-1} Pa^{-1})
A′	surface area (m^2)
b(w)	function of particle relative velocity
C_1	mass diffusion-limited rate constant, (5×10^{-12})
$C(d_P)$	function of particle diameter
d	diameter (m)
D_o	diffusion rate of char combustion (kg s^{-1} $m^{-2}$$(Nm^{-2})^{-1}$)
E	activation energy (J $kmol^{-1}$)
$\vec{F}$	external body forces (volumetric) (N m^{-3})
f(ω)	function of particle impact angle respective to the wall boundary
g	gravitational acceleration (9.81 m/s^2)
h	heat transfer coefficient W $(m^2 \cdot K)^{-1}$
J_i	species diffusion flux (kg $(m^2\ s)^{-1}$)
k	thermal conductivity W $(m \cdot K)^{-1}$
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
M_w	molecular weight (kg $kmol^{-1}$)
p	pressure (N m^{-2})

Latin letters

$\dot{Q}$	volume flow rate (m^3 s^{-1})
R	universal gas constant, (8314 J (kmol K)$^{-1}$)
$\mathfrak{R}$	kinetic rate of char combustion (kg s^{-1} $m^{-2}$$(Nm^{-2})^{-1}$)
R_i	net rate of species production (volumetric) (kg $(m^3\ s)^{-1}$)
S_i	species sources (volumetric) (kg $(m^3\ s)^{-1}$)
t	time (s)
T	temperature (K)
u	velocity (m s^{-1})
w	particle relative velocity to the flue gas flow velocity
Y	species mass fraction (−)

Subscripts

comb	combustion
devol	devolatilization
f	fluid (continuous phase)
face	cell face
Di	head loss coefficient of damper
ox	oxidant
p	particle
1i, 2i	head loss coefficient for cross-section variation

Greek letters

ζ	pressure loss coefficient (kg$(m^2\ s^2)^{-1}$)
ρ	density (kg m^{-3})
ω	particle impact angle respective to the wall boundary

of a flexible operation is a difficult task, due to the aged power plant fleet, which is on average more than 25 years [2] and the fuel low quality. Furthermore, these plants have been primarily designed for full-load operation, thus high plant efficiency and stable operation is usually not guaranteed under load conditions lower than 40%. For the above-mentioned reasons, the investigation of their operation under cycling and low load conditions, as well as the development of concepts and technologies for efficiency improvement are considered to be highly important.

An answer to the issue of fuel low quality can be its thermal upgrade. This can be achieved by applying a pre-drying step. Based on an extended review regarding the pre-dried technologies [4] one of the most feasible solutions, in terms of total cost, technological maturity and scale of application would be the modification of the existing milling system of a lignite-fired power plant, in order to allow the temporary storage of pre-dried lignite. This pre-dried lignite can then be used as a supporting fuel, during low load operation. However, it should be highlighted that such an approach is mostly applicable for a specific power plant, which has an already installed lignite separation system, as in the case of Megalopolis IV PP, and it cannot be considered as a general solution. As previously explained, the partial pre-drying of lignite before entering the boiler can result in an improvement of the corresponding power plant efficiency, reducing the flue gas boiler losses. This can be industrially applicable in a wide range, especially in Greece, since local lignite has an average low heating value of about 5–6 MJ/kg, which is much lower than the lignite qualities in other European countries, such as 8–11 MJ/kg which is a representative range of the German lignite. Several investigations on pre-drying concepts of Greek lignite have been carried out in the past in the framework of Greek national and European research projects. Several lignite pre-drying technologies have been investigated by means of thermal cycle calculations by Kakaras et al. [5]. Based on these, a considerable efficiency increase is reported through the integration of pre-drying process in a typical thermal cycle of a Greek lignite power plant, which in some cases may exceed 6%. Furthermore, the combustion behavior of pre-dried Greek lignite has been investigated numerically [6] and experimentally [7] by Agraniotis et al. This work was performed at a semi-industrial scale in a 1 MW_{th} facility and included not only 100% dry coal firing but also co-firing concepts. The results of these studies suggest that co-firing of pre-dried with raw Greek lignite can achieve an overall good combustion performance. The simulation results were in a good agreement with the experimental measurements in terms of temperature and O_2 distribution as well as of NO_x emissions, thus proving the usefulness of the numerical approach as a tool for large scale predictions. Moreover, the experimental investigation revealed that co-firing or even 100% pre-dried lignite firing can be implemented in large scale boilers, without major complications concerning the boiler performance. Finally, the technical and financial aspects of using pre-dried lignite in a typical Greek thermoelectric power plant were investigated in [8]. Two scenarios were examined, using 25% and 100% pre-dried lignite in the fuel mixture, respectively. In the first case, a small efficiency increase up to 1.5% can be achieved. Utilizing 100% dried fuel is much more promising, since a considerable efficiency increase up to 5.9% can be achieved along with significant decrease of CO_2 emissions. However, in order to realize this scenario extensive boiler modifications are required.

Considerable work in the development of lignite pre-drying technologies and the investigation of pre-dried lignite firing has also been carried out by Bergins et al. [9–11], while numerous information about all