Fuel 92 (2012) 308–317

Contents lists available at SciVerse ScienceDirect

Fuel

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

Study of ash deposition during coal combustion under oxyfuel conditions

L. Fryda [a,*], C. Sobrino [b,1], M. Glazer [b], C. Bertrand [a], M. Cieplik [a]

[a] Energy Research Centre of the Netherlands (ECN), Westerduinweg 3, 1755 LE Petten, The Netherlands
[b] Process and Energy Department, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 4 May 2011
Received in revised form 29 July 2011
Accepted 2 August 2011
Available online 18 August 2011

Keywords:
Oxyfuel
Combustion
Pulverized fuel
Ash deposition

ABSTRACT

This paper presents a comparative study on ash deposition of two selected coals, Russian coal and lignite, under oxyfuel (O_2/CO_2) and air combustion conditions. The comparison is based on experimental results and subsequent evaluation of the data and observed trends. Deposited as well as remaining filter ash (fine ash) samples were subjected to XRD and ICP analyses in order to study the chemical composition and mineral transformations undergone in the ash under the combustion conditions. The experimental results show higher deposition propensities under oxyfuel conditions; the possible reasons for this are investigated by analyzing the parameters affecting the ash deposition phenomena. Particle size seems to be larger for the Russian coal oxy-fired ash, leading to increased impaction on the deposition surfaces. The chemical and mineralogical compositions do not seem to differ significantly between air and oxyfuel conditions.

The differences in the physical properties of the flue gas between air combustion and oxyfuel combustion, e.g. density, viscosity, molar heat capacity, lead to changes in the flow field (velocities, particle trajectory and temperature) that together with the ash particle size shift seem to play a role in the observed ash deposition phenomena.

1. Introduction and scope of work

Combustion in O_2/CO_2 mixture (oxyfuel) has been recognized as a promising technology for CO_2 capture as it produces flue gas with a high CO_2 concentration, which can be sequestered and stored [1–8]. The technology consists of combusting the fuel with a blend of oxygen, produced in an Air Separation Unit (ASU), and recirculated flue gas. In theory, it is possible to retrofit existing air-blown pulverized fuel (PF) units in order to enable oxyfuel combustion. However, key issues such as equivalent heat transfer between air and oxyfuel operation, ash formation and deposition, flue gas cleaning prior to recycling or storage and burner adjustments still need to be further investigated prior to the commercialization of the technology. In this frame, targeted lab-scale tests and advanced modeling are cost-effective and relatively fast tools to gain insight and knowledge on specific operation parameters. This approach allows testing a wide variety of fuels in a consistent range of combustion conditions, while at the pilot scale level technical issues relative to the whole plant operation are confronted.

The objective of this work is the comparative study of ash formation and deposition of two coals fired under oxyfuel and air conditions in a lab-scale pulverized fuel combustor.

An overview of research activities and technology developments on oxyfuel combustion including char combustion temperatures, fuel burnout, gas composition, heat transfer, coal reactivity and flame ignition has been published by Wall et al. [9]. The gas environment experienced by pulverized coal particles under oxyfuel combustion is different from the conditions experienced under standard air combustion, which may impact the combustion processes including ignition [10,11], combustion characteristics [5,10,12], char reactivity under high CO_2 concentrations [9,13,14], and pollutant formation [5,12,15–18]. The consequence of these may become important when the pulverized fuel boilers are planned to be retrofitted to oxyfuel. The higher thermal capacity of CO_2 compared to N_2, the lower mass diffusivity of O_2 in CO_2 than in N_2, and the endothermic reaction between char and CO_2 lowers the char combustion temperature in O_2/CO_2 mixtures compared to O_2/N_2 mixtures with a same oxygen concentration [19].

Ash formation and ash-related behavior depends on the combustion conditions as well as on coal composition and mineralogy. Understanding of the impact of oxyfuel combustion on the ash behavior has not yet been fully established. Experiments on more coals are required to allow generalization of the results and conclusions to a wide range of applications. Few studies have been published on ash formation and deposition under oxyfuel combustion [15,19–23]. Sheng et al. [15] and Suriyawong et al. [21] showed that, in comparison with air, the combustion in a $20\%O_2/80\%CO_2$ mixture, shifted the particle size distribution of the submicron

---

[*] Corresponding author. Tel.: +31 224 56 4641.
E-mail address: fryda@ecn.nl (L. Fryda).
[1] Present address: Departamento de Ingeniería Térmica y de Fluidos, Universidad Carlos III de Madrid, Spain.

0016-2361/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2011.08.013

Nomenclature

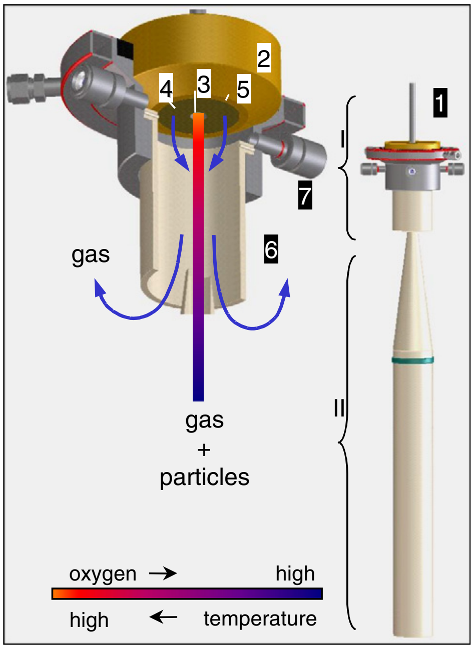
DP	deposition propensity
d_c	deposition probe diameter (m)
d_p	particle diameter (m)
EF	enrichment factor
F_i	fouling index
ICP	Inductively Coupled Plasma
LCS	Lab-Scale Combustion Simulator
HF	heat flux (W/m^2)
HHV	Fuel Higher Heating Value (K J/kg)
m_{dep}	ash mass deposited (g)
m_{ash}	ash mass fed by the fuel (g)
XRD	X-ray diffraction
$X_{sample\ ash,i}$	mass fraction of the element i (expressed as oxide) in the ash sample
$X_{fuel\ ash,i}$	mass fraction of the element i (expressed as oxide) in the fuel ash
$R_{B/A}$	ratio of acidic to basic oxides
R_f	fouling factor (K m^2/W)
St	Stokes number
t	time (s)
T_g	flue gas temperature (K)
T_c	coolant medium temperature (K)
U	heat transfer coefficient (W/K m^2)
U_p	particle velocity (m/s)
μ_g	gas viscosity (kg/s m)
ρ_p	particle density (kg/m^3)

ash to a smaller size and decreased the yield of submicron particles. The elemental composition of submicron particles showed also variations. This was attributed to a decrease in the char particle combustion temperature. However, the increasing O_2 concentration in the oxyfuel case diminished these differences.

The varying bulk gas composition changes the CO/CO_2 ratio within the char particle, fact that could affect the vaporization of refractory oxides and consequently affect the formation of fine ash particles. Krishnamoorthy et al. [24] showed that an increased amount of CO_2 in the bulk gas reduces the rate of formation of submicron-sized ash. It is demonstrated in various publications that the submicron ash generated during coal combustion is mainly the result of mechanisms like vaporization and homogeneous condensation of refractory oxides such as SiO_2, CaO, MgO and Fe_2O_3 [25,26].

Furthermore, also the phase transformations of coal mineral matter during combustion are influenced by the coal char combustion temperatures. XRD measurements can thus give insights into the peak intensities of main crystalline species from the ashes formed in O_2/CO_2 and O_2/N_2 combustion. It is known that the presence of iron in the coal ash promotes the mechanisms of slagging in pulverized coal-fired furnaces when combined with sulfur in the form of pyrite. The transformations of iron-bearing minerals during air-fired pulverized coal combustion include pyrite decomposing to pyrrhotite, an intermediate phase that further oxidizes to a molten FeO–FeS phase and then to the stable magnetite and hematite. The intermediate products, including pyrrhotite with the melting point of 1100 °C and FeO–FeS with the eutectic temperature of 940 °C, are prone to coalesce with inherent silicates and form glass silicates. Char combustion under O_2/CO_2 may lead to higher CO concentrations than under O_2/N_2 combustion, which slows the transformation of pyrite to oxides, thus possibly increasing the slagging propensity of the ash [20,27].

Finally, deposit sampling tests performed by Mönckert et al. [28] indicate that besides sulfation, carbonization of deposit surfaces occur. The implication of this observation is not clear.



Legend:
I Devolatilisation zone,
II Combustion zone,
1 Solid fuel feed,
2 Multi-stage flat flame gas burner,
3 Inner burner,
4 Outer burner,
5 Shield gas ring,
6 Reactor tube,
7 Optical access

Fig. 1. Schematic of the ECN's Lab-Scale Combustion Simulator (LCS).