Combustion and Flame 158 (2011) 1542–1552

Contents lists available at ScienceDirect

Combustion and Flame

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

A combustion concept for oxyfuel processes with low recirculation rate – Experimental validation

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ARTICLE INFO

Article history:
Received 14 June 2010
Received in revised form 12 August 2010
Accepted 27 December 2010
Available online 27 January 2011

Keywords:
Oxyfuel
Recirculation rate
CSNB
Experiments
Natural gas

ABSTRACT

Oxyfuel combustion is a technology for Carbon Capture & Storage from coal fired power plants. One drawback is the large necessary amount of recirculation of cold flue gases into the combustion chamber to avoid inadmissible high flame temperatures. The new concept of Controlled Staging with Non-stoichiometric Burners (CSNB) makes a reduction of the recirculation rate possible without inadmissible high flame temperatures. This reduction promises more compact boiler designs. We present in this paper experiments with the new combustion concept in a 3×70 kW natural gas combustion test rig with dry flue gas recirculation of 50% of the cold flue gases. The new concept was compared to a reference air combustion case and a reference oxyfuel combustion case with recirculation of 70% of the cold flue gases. FTIR emission spectroscopy measurements allowed the estimation of spectral radiative heat fluxes in the 2–5.5 μm range. The mixing of the gases in the furnace was good as the burnout and the emissions were comparable to the reference cases. The flame temperatures of the CSNB case could be controlled by the burner operation stoichiometry and were also similar to the reference cases. The heat flux in the furnace through radiation to the wall was higher compared to the oxyfuel reference case. This is an effect of the lowered recirculation rate as the mass flow out of the furnace and therefore the sensible heat leaving the furnace decreases. The higher oxygen consumption with lower recirculation rate could be compensated by a lower furnace stoichiometry. This was possible due to better burnout with increased oxygen concentrations in the burner. The results prove that a reduction of the flue gas recirculation rate in oxyfuel natural gas combustion from 70% down to 50% is possible while avoiding inadmissible high flame temperatures with the concept of Controlled Staging with Non-stoichiometric Burners.

1. Introduction

The man made climate change has its main reason in the burning of fossil fuels for production of power and heat and the resulting release of carbon dioxide into the atmosphere. Coal is the most carbon intense fossil fuel. But it will be necessary for future power generation due to its widely distributed resources and its large proven reserves. One way of mitigating the release of carbon dioxide is the separation of the carbon dioxide with the oxyfuel combustion process and the following storage of the captured gases into underground reservoirs.

The high reaction temperatures are the main problem in oxyfuel combustion as the fuel is burned with pure oxygen without the presence of the temperature moderating nitrogen in the combustion air. Several options exist to lower these temperatures:

1. External flue gas recirculation (commonly used option).
2. Internal flue gas recirculation.
3. Burner operation under non-stoichiometric conditions.

Almost all proposed oxyfuel combustion concepts rely only on the first option for controlling the flame temperature. A number of review articles are available on the topic [1–7].

The concept of Controlled Staging with Non-stoichiometric Burners (CSNB) uses additionally to the first option the third option to control the flame temperature (Fig. 1). The concept aims to reduce the necessary external flue gas recirculation rate ϵ from the common value of 60–80% [1, p. 589] down to 50%. This relates to a reduction of the recirculated flue gas mass flow of 20–60%. The flue gas recirculation rate is defined as

$$\epsilon = \frac{\dot{m}_{recirculation}}{\dot{m}_{furnace\ end}} \quad (1)$$

where $\dot{m}_{recirculation}$ is the mass flow of cold recirculated flue gas and $\dot{m}_{furnace\ end}$ is the total mass flow at the end of the furnace including the recirculated mass flow.

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doi:10.1016/j.combustflame.2010.12.029

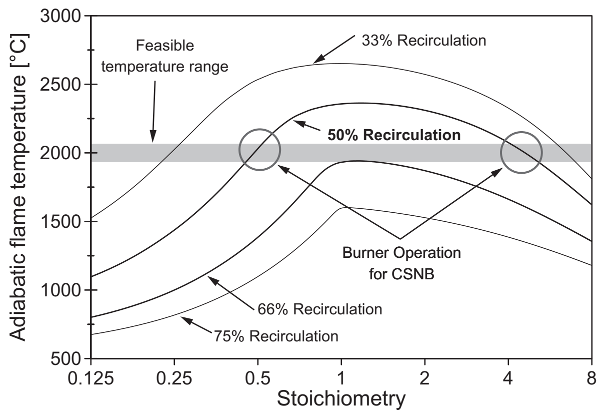

Fig. 1. Theoretical adiabatic flame temperature vs. stoichiometry; calculated from factsage database [8]; $T_{recirculation}$ = 300 °C, wet recycle, T_{oxygen} = 300 °C, fuel = hard coal, overall combustion stoichiometry = 1.05 [9].

An arrangement of over- and substoichiometric burners has to be used in the furnace to ensure complete combustion with a minimal oxygen excess at the end of the furnace (Fig. 2). Non-stoichiometric burner operation in this sense means that the fuel and oxidant streams to the each burner result in an equivalence ratio for the combustion reaction of substantially less or more than one. The oxidant stream is a mixture of oxygen and recirculated flue gas. The heat of reaction is transferred to the furnace wall before more reaction energy is released in the next burner. The temperature in the furnace never exceeds critical values.

A shift in the heat transfer distribution in the whole steam boiler is a direct effect of the lowered mass flow in the furnace. The furnace exit temperature has to be kept constant due to the fuel ash melting behavior. Therefore more heat has to be transferred to the steam cycle in the furnace through radiation if the recirculation rate is lowered (Fig. 3). A recirculation rate ϵ of 67% in oxyfuel combustion results in a similar heat transfer distribution between the radiative and convective part as in air combustion. This theoretical value calculated based on the sensible heat of the flue gas at the exit of the furnace is in the range of recirculation rates experimentally found [1, p. 593] and is very dependent on coal composition, type of recirculation (wet or dry) and design flue gas exit temperature. If these two base cases are compared with the CSNB case with around 50% recirculation, 49% more heat has to be transferred in the furnace to the water-cooled wall. The tendency in the shift in heat transfer is independent of fuel type and only a function of the reduced mass flow through the steam generator.

The main questions for the experimental validation of the concept presented in this article are:

1. Can the flame temperature and the heat flux be controlled by the stoichiometry?
2. What is the difference in wall heat fluxes and radiation for the Controlled Staging concept in comparison to combustion with air and to oxyfuel combustion with high recirculation?
3. Is the mixing of the gases in the combustion chamber sufficient to ensure complete combustion at the furnace exit?
4. What other implications have to be considered for a reduction of the recirculation rate?

2. Methods

The concept was studied experimentally in a 210 kW natural gas test rig. Natural gas was chosen as fuel as the additional costs and complexities of operation of a coal test rig could be avoided.

2.1. Air cooled combustion chamber

The cylindrical combustion chamber had a height of 4 m and an inner diameter of 700 mm (Fig. 4). It was divided into four parts which were each split up in two sections. Each section had its own independently controlled wall air cooling and four access ports, which were each 90° apart. The inner wall of the combustion chamber was a 1.5 mm thick oxidized austenitic high temperature steel (1.4876/X10NiCrAlTi32-21/heat resistant ⩽1100 °C).

The air cooling for the walls consisted of two cold air supply lines and two hot air exhaust lines for each section. The air flowed along a 90° section of the wall. Mass flow controllers in the cold air supply line controlled and measured the amount of cooling air. The temperatures of the cold supply air and of the hot exiting air were recorded and allowed over an energy balance the calculation of the

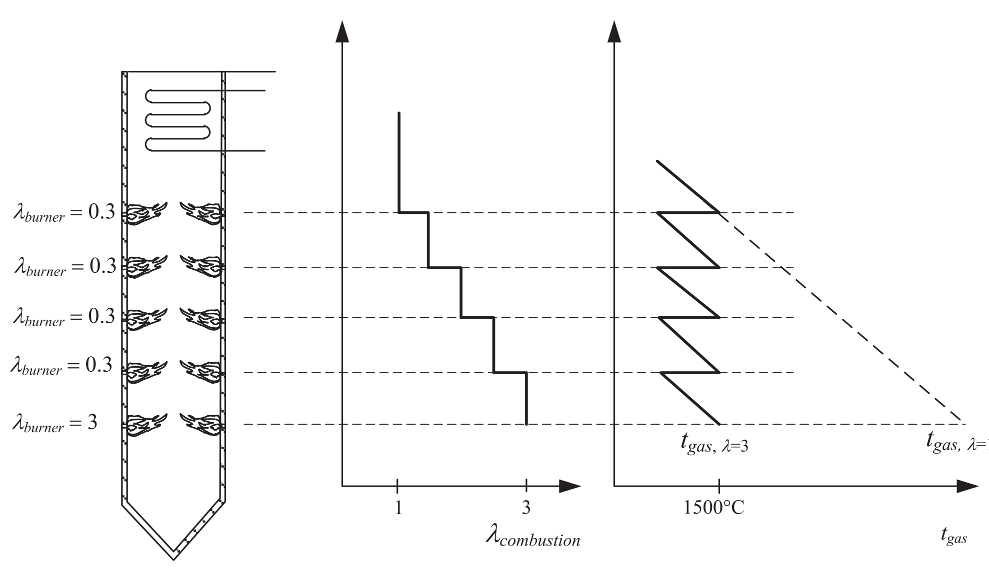

Fig. 2. Arrangement of burners in furnace for concept of Controlled Staging with Non-stoichiometric Burners (CSNB) to reach complete combustion ($\lambda_{combustion} \approx 1$) at the exit of the furnace. λ_{burner} is the stoichiometry of the fuel and oxidant streams to the burner, $\lambda_{combustion}$ is the combustion stoichiometry in the furnace and t_{gas} is the gas temperature inside the furnace.