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Experimental characterization of pulverized coal MILD flameless combustion from detailed measurements in a pilot-scale facility

Max Weidmann[a,*], David Honoré[b,**], Vincent Verbaere[c], Guillaume Boutin[b], Simon Grathwohl[a], Gilles Godard[b], Carole Gobin[b], Reinhold Kneer[c], Günter Scheffknecht[a]

[a] *Institute of Combustion and Powerplant Technology, University of Stuttgart, Pfaffenwaldring 23, 70569 Stuttgart, Germany*
[b] *CORIA – CNRS UMR 6614, Normandie Université, INSA de Rouen, Université de Rouen, Avenue de l'Université, 76801 Saint-Etienne-du-Rouvray, France*
[c] *Institute of Heat and Mass Transfer, RWTH Aachen University, Eilfschornsteinstrasse 18, 52062 Aachen, Germany*

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ABSTRACT

This paper presents a series of measurements on pulverized coal MILD flameless combustion in a pilot-scale facility for nitrogen oxides (NO_x) emissions reduction. Local measurements of gaseous species concentrations, gas temperature and velocity associated to reaction zone imaging by OH^* chemiluminescence highlight specific features of this MILD flameless combustion regime. The flameless burner used during the investigation could abate significantly NO_x emission levels.

Specific aerodynamics of the flow in the furnace induced by the burner geometry are discussed. High momentum turbulent air jets favor a large recirculation of hot flue gas in the combustion chamber. Such a recirculation induces a large diluted combustion regime from the entrainment in the air jets of devolatilized species from the pulverized coal jet and of recirculating hot inert combustion products. The main reaction zone is lifted from the burner exit as it starts in the mixing layers of separated pulverized coal and air jets. As is typical of a flameless combustion regime, such a large dilution of reactants induces low local heat release and temperature increase in the reaction zone. Nitrogen oxides are generated from the fuel NO route at quite a limited rate due to the low temperature environment.

The effect of the carrier gas of the pulverized coal jet is also analyzed. The change from carbon dioxide to air as carrier gas generates a first reaction zone attached to the burner exit. This reduces the dilution and increases the heat release in the main lifted reaction zone, leading to higher NO_x emissions.

1. Introduction

Measures aimed at reducing NO_x emissions from combustion processes have been developed and implemented for several decades. Primary measures, such as low NO_x burners or air staging are widely used. In order to comply with environmental directives, secondary – post-combustion – measures are, however, necessary. For reason of costs and ever-increasing environment restrictions, research on primary abatement measures remains a topical issue. Since the 1990s, combustion of gaseous fuels with high recirculation ratio of burnt gases without visible flame, referred to as *flameless oxidation* or *FLOX®*, has demonstrated its potential, especially for high air preheating, in reducing NO_x emissions resulting from thermal N conversion [1]. For pulverized coal (PC) combustion, the IFRF has initiated experiments on flameless combustion by preheating combustion air to about 1300 °C, on one hand, and separately injecting combustion air and coal into the furnace, on the other hand. A remarkable NO_x abatement could be achieved if sufficient separation between coal and air jets is provided and if the oxygen availability is controlled in the primary combustion zone [2,3]. Cavaliere and de Joannon [4] defined as *moderate* or *intensive low-oxygen dilution* (MILD) combustion a diluted regime characterized by air and fuel preheating over self-ignition temperature, as well as a low adiabatic temperature. In this context, the high exergy of exhaust gases presents a significant advantage. From the pollutant point of view, flameless combustion is able to abate the NO_x formation usually found in highly preheated air combustion. However, a high level of preheat remains difficult to implement in solid-fuel fired utility boilers. But, flameless combustion can be operated with moderate preheating temperatures (those encountered in utility boilers) as explained by Wünning [5] and even without any preheat [6–10]. In fact, MILD flameless combustion remains independent of the extent of

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[*] Corresponding author. Fax: +49 711 685 69403.
[**] Corresponding author. Fax: +33 232 95 97 80.

E-mail addresses: max.weidmann@ifk.uni-stuttgart.de (M. Weidmann), david.honore@coria.fr (D. Honoré).

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preheat: the mixing alone of fuel and combustion air with recirculated exhaust gas gives rise to a diluted MILD combustion regime. Wünning stated that air preheating along with a complete separation between incoming fuel and air are by no means always necessary [4]. A common way to generate a strong mixture within the furnace is to provide the incoming combustion air with high velocity. This ensures a reduction of thermal NO due to the achievement of a rather homogeneous temperature field. Furthermore, it reduces the conversion of volatile nitrogen, which here represents a large share (up to 50% [11]) of the total nitrogen contained in coal. According to Chen and Niksa [12], this can be explained by the shift of the devolatilization into regions heavily diluted by exhaust gas; this delays the mixing between coal and oxidizer. Pershing and Wendt [11] already obtained in 1979 a reduction of NO_x emission by 40% by using a low mixing fuel injector.

In their pioneering work, Weber et al. [3] showed the potential of MILD flameless combustion applied to PC by comparison with gaseous and liquid fuels with uniform heat transfers and low pollutant emissions for all operating conditions. An upscaling of PC MILD flameless combustion in a 12 MW industrial-scale test facility has been also reported by Zhang et al. [13]. Other experiments performed at semi-industrial scale (500 kW) by Smart and Riley [14] demonstrated the feasibility of MILD flameless combustion of a high-volatile pulverized coal under oxy-fuel conditions. In this context, their burner was provided with a large separation between coal and the oxidants. They recommended improvements on their burner and operation conditions to ensure stable and safe combustion features.

More recently, an experimental study of several PC MILD flameless burner configurations has been done in a 300 kW pilot facility [15]. By reference to a conventional swirl jet burner, all burner configurations provided with separated injections achieved a MILD flameless regime. The result of this was good heat homogeneity, low NO_x and CO emissions, but a low char burnout. It has to be noted that volatile combustion seems to be invisible as it is for MILD flameless combustion of gaseous fuels, whereas visible sparks of burning particles are still present. Other experiments have also been performed in a 15 kW lab-scale facility with different kinds of coal and carrier gas [16]: incomplete combustion of low-volatile anthracite has been observed as the result of an insufficient residence time. Reynolds-Averaged Navier–Stokes (RANS) CFD simulations have been also carried out. These showed that an increase of air jet momentum facilitates the combustion of volatiles, leading to better MILD flameless performance in terms of homogeneity and pollutant emissions. A similar simulation was presented by Mei et al. [17]. Their post-processing approach unveiled NO_x formation: the fuel NO path has been found to prevail over both thermal NO and prompt NO. They showed the existence of NO reburning, as it has been previously envisaged in MILD flameless of gaseous fuels [18,19]. This study also confirmed the predominant role of the aerodynamics of jets to achieve local diluted conditions.

The potential of NO_x emission reduction with pulverized coal combustion has also been investigated during a previous European research project in a 20 kW_{th} and a 100 kW_{th} furnace, both electrically heated [20,21]. Within this framework, the burner included a central coal nozzle and three combustion air nozzles evenly allocated on a circle centered on the coal nozzle. The results can be summarized as followed: (i) the potential of NO_x reduction depends strongly on the stoichiometric air ratio at the burner and to a lesser extent on the coal type; (ii) beyond 100 m/s the combustion air velocity has little effect on NO_x emissions; (iii) flameless combustion ensures a strong cut in thermal NO, but slightly increases fuel NO, resulting primarily from enhanced char N conversion, with regard to 'standard' flame combustion. In view of these results, the burner geometry has been adapted for the present project and scaled up to a thermal load of 300 kW_{th} [22]. During these experiments presented here, detailed in-flame profile measurements have been performed: temperature and gas concentrations by probe sampling, local velocity by Laser Doppler Velocimetry and reaction zone visualization by OH* chemiluminescence imaging. The present paper gives a complete overview of the results and provides an analysis to point out the specific combustion features of MILD flameless regime applied to pulverized coal.

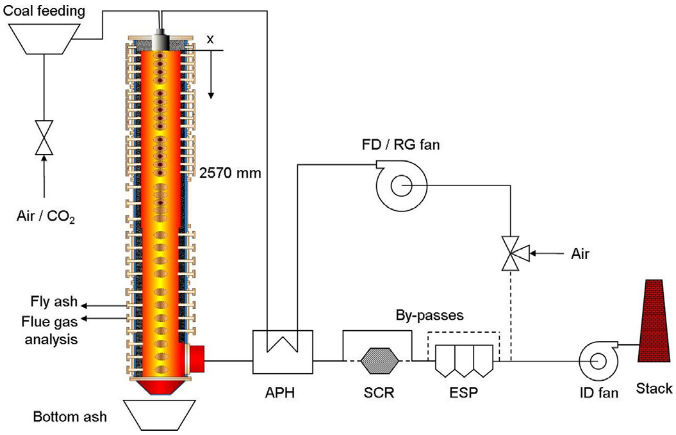

Fig. 1. Schematic diagram of the furnace and flue gas treatment.

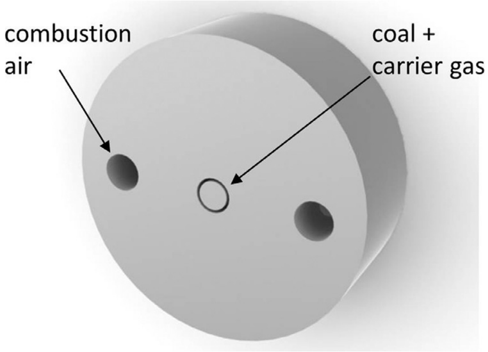

Fig. 2. Configuration geometry of the FLOX burner.

2. Experimental setup

2.1. Pilot-scale test rig and burner

The 500 kW_{th} pilot-scale test facility is based on a conventional down-fired pulverized fuel combustion reactor. The furnace is cylindrical in shape and its axis is vertical to minimize asymmetry due to natural convection and ash deposition. The furnace is made up of six water-cooled segments with a total length of 7000 mm and an inner diameter of 750 mm. Each of the three upper segments is equipped with five series of four measurement ports distributed every 90° along the segment periphery. They enable measurement of gas composition, gas temperature and ash sampling in vertical and horizontal directions by means of specially designed probes. The upper segments of the furnace, as well as, the burner plate are protected from heat by a refractory. Cooling water flowing in upwind direction provides additional protection. An overall sketch of the furnace is shown in Fig. 1.

The design of the FLOX burner (see Fig. 2) used in this work derives from that of previous studies conducted at bench-scale [23]. Coal along with the carrier gas is injected through a central annular nozzle. Two combustion air nozzles are disposed eccentrically

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