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Parametric optimization study of a multi-burner flameless combustion furnace

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ABSTRACT

A parametric study on a 300 kW_{th} furnace equipped with three pairs of regenerative flameless combustion burners has been performed. Each burner pair has a rated thermal power of 100 kW_{th} firing Dutch natural gas. The objective of the study was to optimize the furnace performance, i.e., to maximize the cooling tube efficiency and minimize the CO and NO emissions. In the study the following parameters were varied: the positions of the burners in the furnace (burner configuration), the firing mode (parallel and staggered), the excess air ratio (λ) and the cycle time (t_{cycle}). Also, the influence on the furnace performance of the jet momentum of the combustion air and the temperature uniformity in the furnace were studied.

It was concluded that staggered firing mode is disadvantageous, since it results in significantly higher NO emissions than parallel firing mode. Also, out of the five investigated burner configurations one has been exempted, since its cooling tube efficiency was significantly lower compared to the other configurations. Furthermore, a horizontal setup of the firing burners improves the cooling tube efficiency at a fixed temperature uniformity. Also, for the burner configurations with the firing burners positioned closer to the regenerating burners and further from the stack, the temperatures in the regenerators are higher, leading to higher combustion air preheat temperatures. The temperature in the regenerators was also influenced by the cycle time; higher cycle times leading to higher (peak) temperatures in the regenerators. Finally, this temperature in the regenerators was shown to be more decisive for the final amount of CO emitted than the excess air ratio or the jet momentum. In all experiments, due to differences in path length of the mean flow, higher CO emissions were measured in the flue gas from the regenerators compared to in the flue gas from the stack. These two trends in the CO emissions were not observed for the NO emissions.

1. Introduction

Energy efficiency and clean combustion are two main issues in fossil fuel utilization. Control of nitrogen oxides (NO_x) has been a major issue in designing combustion systems, since NO_x plays a key role in acid rain formation and the generation of photochemical smog. Flameless combustion, also known as Flameless Oxidation (FLOX®) [1], High Temperature Air Combustion (HiTAC) [2] or Moderate or intense low-oxygen dilution (Mild) combustion [3], is a promising combustion technology capable of accomplishing the combination of high efficiency and low emissions. It is based on delayed mixing of fuel and oxidizer and high flue gas recirculation. High momentum injection of the separated fuel and air flows entrain the flue gas through internal recirculation, thus diluting the oxygen concentration in the combustion zone. This leads to a more distributed heat release rate of the chemical energy, avoiding high peak temperatures and reducing the thermal formation of NO [4].

Since the introduction of flameless combustion in the early nineties of the last century, many universities and research departments of industry have made efforts in experimentally investigating this new technology. These studies have been performed on many different scales, from small jet-in-hot-coflow setups up to full industrial size furnaces. However, before wide industrial application of this technology can be established, more in-depth knowledge of its behaviour in industrial scale environments needs to become available, especially in (regenerative) multi-burner systems. The most important previous experimental studies that include multi-burner regenerative systems are discussed below.

At the fall of the second millennium, a 200 kW_{th} HiTAC furnace has been commissioned at the Kungl Tekniska Högskolan, Stockholm,

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Sweden [5]. In the furnace two pairs of NFK-HRS-DF regenerative burners firing natural gas and LPG were installed [6]. The two pairs of regenerative burners could be operated in three different firing configurations and the performance of the furnace has been compared extensively for these firing configurations [7–9].

In 2002 an extensive research program was performed at the IFRF research station in IJmuiden, The Netherlands [10]. The heating source in the furnace was one pair of NFK-HRS-DL4 regenerative burners, with a maximal thermal input of 1000 kW_{th}. Several types of fuel were investigated (natural gas, coke oven gas), while the objectives of the experiments were to generate extensive experimental datasets for the development and validation of CFD simulations.

A third large research project on regenerative flameless combustion was performed on a 200 kW_{th} furnace at the Faculté Polytechnique de Mons, Belgium [11]. One autoregenerative REGEMAT burner firing natural gas was used as the heating source. A comparison of the experimental data with CFD simulations was the main objective. In particular the heat transfer, temperatures and NO_x concentrations were compared.

Furthermore, at the NKK steel corporation in Japan, a slab reheating furnace with four pairs of regenerative burners was successfully fired with the by-product gas of the steel making factory [12,13]. The total thermal power input was 2919 kW_{th} and the heat sink was a moving slab in the bottom of the furnace. Also here, the obtained results served as validation data for CFD simulations of the furnace.

As can be concluded, although the above mentioned experimental studies are performed on furnaces equipped with either single autoregenerative burners or multiple regenerative burner pairs, none of them investigated the influence of the positions of the burners. The positioning of the burners can have a large influence on the furnace performance, especially in a regenerative (transient) environment. Therefore, investigation of the influence of burner positioning, such as burner–burner or burner–stack interactions, is required.

In this paper results are presented of an experimental campaign on a furnace equipped with three pairs of regenerative flameless combustion burners. An important degree of freedom in the experiments was the positioning of the three burner pairs. The objective is to investigate and, where possible, optimize the multi-burner furnace performance for the variation of four parameters. These parameters are the burner configuration, the firing mode, the excess air ratio and the cycle time. The optimization of the furnace performance is defined as the maximization of the cooling tube efficiency and minimization of the CO and NO emissions.

2. Experimental setup

A furnace equipped with three pairs of regenerative flameless combustion burners has been designed, built and commissioned at Delft University of Technology. In Fig. 1 a sketch of the furnace is presented. Each pair of regenerative flameless combustion burners has a rated thermal power of 100 kW_{th}, thus 300 kW_{th} in total. The fuel fired is Dutch natural gas, which has a net (lower) calorific value of 31.669 MJ/m^3 and consists of around 81%-vol CH_4, 3%-vol C_2H_6, 1%-vol other higher hydrocarbons, 14%-vol N_2 and 1%-vol other inert gases [14]. The burners were manufactured by WS Wärmeprozesstechnik GmbH and are of the REGEMAT CD 200 B type. Each burner has four combustion air/flue gas nozzles ($d = 20$ mm) around a central fuel nozzle ($d = 12$ mm).

The burners can operate in two different modes, i.e., flame and flameless mode. In flame mode the air and fuel are mixed in the burner before injection and the mixture is injected through the air nozzles only. An electric spark igniter is used in flame mode for ignition. In flameless mode the combustion air is injected through the air nozzles and the fuel is injected separately through the fuel nozzle. In this mode no igniter is necessary because the temperature in the furnace is above the self-ignition temperature of the fuel/air mixture. During the heating up of the furnace the burners fire in flame mode. Once the temperature in the furnace exceeds 850 °C (which is above the self-ignition temperature of the fuel/air mixture) the burners switch to flameless firing mode automatically. In this paper only results from the burners firing in flameless mode are presented.

The furnace has inner dimensions of 1500 × 1500 × 1850 mm (length × width × height). The insulation consists of three layers of ceramic bricks, together 300 mm thick. During the experiments the wall temperature of the furnace was measured at various locations with slightly protruding thermocouples type S. Additionally, the temperature of the regenerated flue gases and the cooling air was measured with thermocouples type K. The measurement error of these thermocouples is around 2–5 K. One of these measurements, a double fitted thermocouple in the side wall close to the reaction zones, was determined to characterize the temperature in the furnace. Also, the temperature of the preheated air was measured in two burners (one burner pair). The fuel and combustion air flow rates are measured by custom-made orifice plate differential pressure meters. The combustion air flow rate is controlled by manual valves, allowing the variation of the excess air ratio.

Heat recirculation of the hot flue gases is achieved by regeneration. Eighty percent of the flue gases is sucked by a fan via the air nozzles of the regenerating burners over a ceramic honeycomb, while the remaining twenty percent leaves the furnace directly via the central stack at the roof. During regeneration the sucked flue gas traverses ceramic honeycomb heat exchangers situated inside the burners. The regenerated flue gas volume flow is measured using a vortex flow meter. The inlet temperature is between 800 and 900 °C and the outlet temperature is between 110 and 140 °C, under steady state conditions.

The thermal load is simulated by a cooling system which consists of eight single-ended cooling tubes, four placed at the bottom of the furnace and four at the top. Every cooling tube consists of two concentric tubes; the cooling air enters the inner tube, turns at the end and flows back through the annulus between the two tubes. This design was made to minimize the temperature

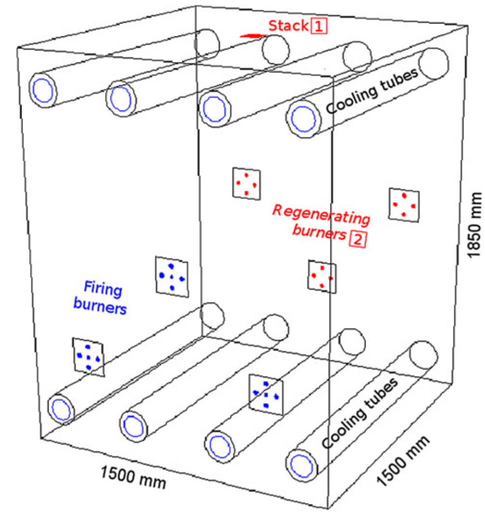

Fig. 1. Furnace sketch. The boxed numbers 1 and 2 indicate the two sample positions for the flue gas. Sampling point 2 is after the regenerators. All dimensions are in mm. The sketch represents burner configuration C5 firing in parallel mode (see also Table 1).