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Configuration effects of natural gas fired multi-pair regenerative burners in a flameless oxidation furnace on efficiency and emissions

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HIGHLIGHTS

- We executed experiments and simulations for flameless oxidation burner.
- Four combinations of burner were examined to derive out reaction characteristics.
- Single digit of NO and CO occurred together for a parallel burner configuration.
- Smooke reaction model shows reasonable explanation of flameless oxidation.
- However, the reaction kinetics is lower than the experimental results.

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ABSTRACT

We report the characteristics of heat transfer and emissions in natural gas fired flameless oxidation conditions created using multiple semi-industrial regenerative burners. Burner positions and firing modes (parallel and staggered) are varied, and their effects on efficiency, emissions (NO, CO) and temperature uniformity are studied. Also the excess air ratio and the cycle time have been varied. The operation uses two burner pairs together to provide 200 kW_{th} giving a volumetric heat release closely resembling real industrial operating conditions (48 MW/m^3). The parallel mode operation shows better results concerning low emission of CO and NO, and uniform temperature distribution in the furnace. On the other hand, the staggered mode operation showed a comparatively low performance due to a developed unsymmetrical flow pattern in the furnace. Single digit NO emission was measured for the parallel mode with low CO concentration due to low and uniform temperature. CO concentration is strongly dependent on the burner cycle time because the switching of burners generates periods of unstable and non-uniform flow pattern and also temperature distribution temporarily. The numerical simulation with skeletal reaction showed typical reaction characteristics of flameless oxidation, which is a slow and uniform reaction progress in the furnace. Meanwhile, the reaction model needs to improve its accuracy because the reaction speed appears to be slower than the experiment, and the simulation of a case showed extinguished reaction. The comparable simulation results also showed an order higher CO emission and an order lower NO emission, which is assumed to be related with low reaction kinetics.

1. Introduction

Energy efficiency and emission reduction are two main issues in combustion. The control of nitrogen oxides (NO_x) is also still a main issue in combustion because it plays a key role in acid rain and photochemical smog formation [1]. Dilution of oxidizer or fuel with flue gas [2] and ultra-lean premixed combustion [3] were applied to lower flame temperature in order to suppress thermal NO_x formation. However, these techniques are faced with flame instability when using a high level of dilution or ultra-lean combustion. Flameless Oxidation (FLOX™) [4], also known as High Temperature Air Combustion (HiTAC) [5], or MILD combustion [6], is a technology capable of accomplishing high efficiency and low emissions without flame instability phenomena. It uses delayed mixing of fuel and oxidizer combined with high level of dilution by flue gas via internal recirculation in the main reaction zone. The high momentum injection of the separate fuel and oxidizer flows drives the entrainment of flue gas, thus decreasing the oxygen concentration in the combustion zone. This leads to a more distributed heat release by chemical reaction, avoiding high peak

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temperatures (hot spots) and reducing the thermal NO_x formation [7]. Combined with high preheat temperature of the combustion air, this combustion technique also achieves a high efficiency. The technology of flameless combustion is currently finding gradually more widespread use, e.g. also in gas turbine application [8].

In the earlier studies, flameless oxidation has been investigated in small furnaces to evaluate the characteristics of the turbulent flame structure using laser measurement techniques, such as Laser Induced Fluorescence [9]. Szegö et al. tested a 20 kW_{th} single MILD combustion burner to evaluate the stability criteria and visualize the flame. They also made a simulation of the furnace using the Perfectly Stirred Reactor (PSR) model [10]. A 200 kW_{th} multi-burner HiTAC furnace has been studied at KTH (Kungliga Tekniska Högskolan), Sweden [11,12]. The furnace was operated using two pairs of NFK-HRS-DF regenerative burners, varying the firing mode (parallel, staggered and counter firing). At TU Delft both experimental [13,14] and computational [15] studies were made of a flameless oxidation furnace operating at 300 kW_{th} using three pairs of regenerative burners. The most original feature of this furnace is that it allows for the use of many different burner arrangements, with different distances between the burners and the cooling tubes. This makes it possible to understand the basics of the interplay between the flow fields and reaction zones induced by different burner configurations. However, the previous flow fields in the furnace were limited to be symmetric and the distances between the burners were close so that the effect of the configuration of burner could not be fully investigated. Furthermore, the previously applied thermal load (300 kW_{th}) was too high so that a furnace temperature lower than 1050 °C could not be achieved. Further research at lower thermal load and the effects of asymmetric flow patterns were needed to understand and to derive appropriate design rules for the flameless oxidation furnace. The previous numerical simulation results [15] showed overall effects of the flow field due to the burner configurations, however, the details of the chemical reaction in the flameless oxidation furnace were not fully described.

In the present study, the operation condition is changed to 200 kW_{th} with two pairs of regenerative burners, which enables simpler burner configurations of the parallel or the staggered type, and can allow operation at lower temperatures in the range of 953–1076 °C by the existing cooling tube heat extraction. An asymmetric flow pattern was also investigated by using a staggered burner configuration. The effect of burner configuration and furnace temperature was experimentally investigated with emphasis on study of CO and NO_x emissions. A sample numerical simulation is described to explain how the chemical reaction is estimated by using the simplified Smooke et al. reaction kinetics model [16,17] and to understand the flameless oxidation phenomena in the furnace. Furthermore, the experimental results of furnace temperature, CO and NO concentration of comparable two cases are compared with the simulation results to discuss the accuracy of the reaction model.

2. Experimental setup

Fig. 1 shows a schematic diagram of the multi-burner furnace, which is in operation with two burner pairs. The thermal power is 100 kW_{th} per burner pair. The test series aims at experimentally studying the influence of burner pair configurations, firing modes (parallel, staggered) and operation temperature on emissions of NO and CO.

During the furnace operation two burners are firing simultaneously, while the other two burners are regenerating heat from the flue gas. During regeneration the sucked flue gas traverses the ceramic honeycomb heat absorbers in the burners, while during firing mode the cold combustion air is heated up by the honeycombs. After a preset time interval, i.e. the cycle time, the burners switch from firing to regenerating mode, or vice versa. The fuel used was Dutch Natural Gas (DNG, LHV 31.67 MJ/m^3) which consists of CH_4 81.3%, N_2 14.35%, C_2H_6 2.85%, CO_2 0.89% and 0.61% of some other small concentrations of higher hydrocarbon and inert species (volume basis).

The furnace has inner dimensions of 1500 × 1500 × 1850 mm (length × width × height). The insulation consists of three layers of ceramic bricks of 100 mm thickness each, together 300 mm thick. During the experiments, the temperature in the furnace was measured at various locations with S-type thermocouples. One of those thermocouples, installed in the middle of one sidewall of the furnace, was used to characterize the furnace temperature. Also, the temperature of the preheated air (regenerator temperature) was measured in two burners (one burner pair). The flow rates of fuel and combustion air were measured using orifice plate differential pressure meters (Kalinsky Sensor Elektronik, DS2). Manual valves were used to control the flow rate of combustion air, allowing variation of the exhaust gas O_2 concentration (excess air ratio).

Around 80% of the flue gas is sucked by a fan via the air nozzles over ceramic honeycombs of the regenerating burners, while the remaining flue gas leaves the furnace directly via the central stack at the roof of the furnace. Because the suction flow rate is practically constant, a change in excess air ratio implies a change in the ratio between both exhausts. A cooling system consisting of eight horizontal single ended concentric tubes, four placed close to the bottom of the furnace and four close to the top is applied to control overall furnace temperature as shown in Fig. 1. Air enters the inner tube, turns at the end and flows back through the annulus.

An NDIR gas analyzer set (Sick, MAIHAK S710) monitors the flue gas composition downstream of the regeneration suction fan to detect NO and CO concentrations. In the same position the O_2 concentration is detected using an on-line analyzer based on the paramagnetic method. Every second all the data are stored.

Total amount of 18 flanges for the burners are divided over two opposite sides of the furnace (nine for each wall) and three levels at each wall side (1st, 2nd and 3rd from the bottom), so, it is possible to investigate different burner configurations in the furnace. Among various configurations, two different burner configurations I (C-I) and II (C-II), show in Fig. 2, have been selected and investigated. Burner were positioned the 1st and 2nd level for C-I or 1st and 3rd level for C-II. Also, each of these configurations is operated with two different firing modes (parallel, staggered). Investigation of these different configurations and firing modes could elucidate the effect of burner distance between firing and regenerating burners on efficiency and emissions.

In Fig. 2, the large circles represent the burner flanges, whereas the small circles represent the location of the cooling tubes. Two burners are firing, while the other two burners are regenerating. The [1]red circles represent the firing burners and the blue circles (meshed) represent the regenerating burners. In the unused burner flanges (blank circles) thermocouples have been installed. Two burners fire from the same side wall in a parallel mode operation, while one burner of a pair fires at one side and the other at the opposing side in a staggered mode. After a certain time interval (cycle time), all burners switch and the firing burners start regenerating and vice versa.

The burners are REGEMAT CD 200 B regenerative flameless oxidation burners manufactured by WS Wärmeprozesstechnik GmbH.

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.