Characteristics of Multi-Burner Positioning and Operating Mode in a FLOX^{TM} Furnace

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ABSTRACT

The characteristics of multi-burner positioning and operating modes are studied in order to find an optimal configuration of three regenerative burner pairs to maximize the energy efficiency and minimize the pollutant emissions. In this study, a semi-industrial 300kW$_{th}$ regenerative FLOX^{TM} furnace has been investigated. Five different burner configurations (C1-C5) and two different operating modes (parallel and staggered) have been compared based on furnace efficiency, emissions (NO, CO) and temperature uniformity. Additionally, the excess air ratio (λ) has been varied. Increasing the excess air ratio leads to higher NO and lower CO emissions and a decreasing efficiency. Parallel mode shows lower emissions and higher efficiency than staggered mode. Also, parallel mode shows better temperature uniformity in the furnace. It shows that in parallel mode temperature distribution is more uniform and better mixing is established in the furnace. This leads to a reduction in the NO and CO emissions simultaneously. The best configuration is chosen considering the efficiency and emissions.

Keywords: Flameless oxidation, Burner configuration, Temperature uniformity, Emissions, Firing mode

1. *Introduction*

Energy efficiency and clean combustion are two main issues in recent 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 ozone depletion and the generation of photochemical smog [1]. Flameless Oxidation (FLOX^{TM} [2], also known as High Temperature Air Combustion, HiTAC [3] or Moderate and Intensive Low oxygen Dilution, MILD combustion [4]) is a promising combustion technology among various techniques [5, 6] capable of accomplishing high efficiency and low emissions. It is based on delayed mixing of fuel and oxidizer and high flue gas recirculation in the flame zone. High momentum injection of the fuel and air 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 a high peak temperature (hot spot) that can reduce the thermal formation of NO$_x$ [7]. Combined with high preheat temperature of the combustion air, this combustion technique achieves a high efficiency. In this work, the impact of burner positioning and operating modes are studied in a multi-burner FLOX furnace in order to find an optimal configuration of three regenerative burner pairs to maximize the energy efficiency and minimize the pollutants emissions.

2. *Experimental Set-up*

Figure 1 shows a schematic diagram of the multi-burner FLOX^{TM} combustion furnace. It consists of three pairs of regenerative FLOX^{TM} burners, each with a rated thermal power of 100 kW$_{th}$, 300 kW$_{th}$ in total. The furnace has inner dimensions of 1500 x 1500 x 1850 mm (length x width x height). The insulation consists of three layers of ceramic bricks, together 300 mm thick. In total 18 flanges for the burners are divided over two opposite sides of the furnace (nine each). In this way, it is possible to investigate different burner configurations in the furnace.

Thermal load is simulated by a cooling system which consists of eight single ended con-

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centric tubes, four placed at the bottom of the furnace and four at the top. Air enters the inner tube, turns at the end and flows back through the outer tube. This design was made to minimize the temperature gradients along the length of the outer tube, thus, creating an as uniform as possible heat extraction distribution.

Temperatures, flow rates and pressures are measured at various locations. An NDIR gas analyzer monitors the flue gas after the regeneration suction fan for NO and CO concentration in the flue gas. In the same position the O$_2$ concentration was determined paramagnetically. All the data are stored by a data acquisition system every second.

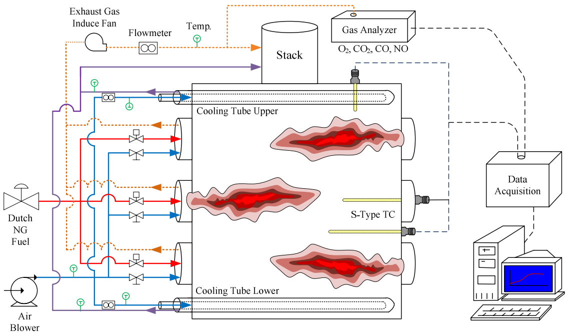

Figure 1. Schematic diagram of the multi-burner excess enthalpy combustion (MEEC) furnace.

In this paper 10 different cases are discussed. They consist of five different burner installation configurations (C1-C5) and each of them two different operating modes (parallel and staggered). Figure 2 shows the map of various burner installations.

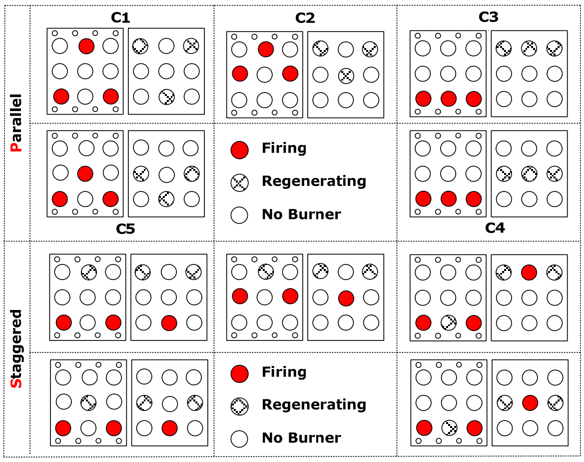

Figure 2. Multi-burner installation map for the definition of configurations and operating modes.

The large circles represent the 18 burner flanges (nine flanges in two opposing walls), whereas the small circle represent the location of the cooling tubes. Three burners are firing, while the other three burners are regenerating. The marked circles represent the flanges occupied by the burners. In the unused burner flanges (blank circles) thermocouples are installed. Filled circles represent firing burners and meshed circles represent regenerating burners.

During the regeneration the sucked flue gas is traverses ceramic honeycomb heat exchangers situated inside the burner. The inlet temperature is around 950^{o}C and the outlet temperature is approximately 150 ^{o}C, under the steady state conditions. In parallel mode three burners fire at the same side and in staggered mode two burners fire at one side and one burner at the other side. After a certain frequency time interval, the burners switch and the firing burner start regenerating and vice versa. The burner configuration can also be divided two spatial patterns: triangular (C1, C2, C5) and horizontal (C3, C4).

The three pairs of regenerative FLOX^{TM} burners were manufactured by WS Wärmeprozesstechnik GmbH. The type of model is REGEMAT CD 200 B. Each burner has four combustion air/flue gas nozzles (ϕ=20 mm) around a central fuel nozzle (ϕ=12 mm). They can operate in two different modes and each pair has a capacity of 90/100 kW$_{th}$ for flame and FLOX operation, respectively.

Figure 3 shows a schematic diagram of the burner firing in flame and FLOX mode.

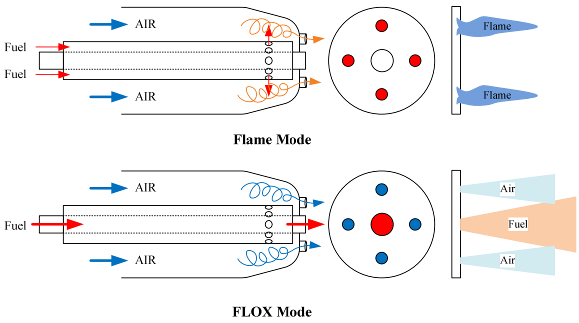

Figure 3. Schematic diagram of burner firing mode for flame and FLOX mode.

In flame mode the air and fuel are mixed in advance and the mixture is injected through the air nozzles only. In FLOX mode the combustion air is injected through the air nozzles and the fuel is injected separately through the fuel nozzle. During the heating up of the furnace the burners fire in flame mode. Once the furnace temperature exceeds 850 ^{o}C (this temperature is above the auto-ignition temperature of the fuel/air mixture) the burners switch to FLOX firing mode automatically. Flame mode fires with a partially premixed flame and in FLOX mode direct fuel injection is applied.

The burners have ceramic honeycomb heat exchangers incorporated. Eighty percent of the flue gas is sucked by a induce fan via the air nozzles over these honeycombs for regeneration of the heat, while the remaining twenty percent leaves the furnace via the central stack at the roof.

3. Mass and Heat balance

The mass and heat balances were calculated over the furnace. Figure 4 shows the control volume of the MEEC furnace. For the different experiments, the heat and mass balances are calculated under steady state conditions. Steady state condition is assumed to be reached when the variation of the furnace temperature is almost zero with respect to time. The steady state temperature of the furnace is between 1080 and 1100 °C, depending on the operation parameters.

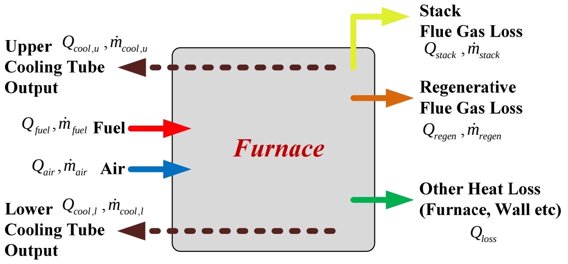

Figure 4. Control volume and mass and heat fluxes of the MEEC furnace.

The mass balance is shown in equation (1).

$$\dot{m}_{fuel} + \dot{m}_{air} = \dot{m}_{regen} + \dot{m}_{stack} \tag{1}$$

The flowrates of fuel ($\dot{m}_{fuel}$) and combustion air ($\dot{m}_{air}$) to the burners are monitored by orifice plates. The ratio of flue gas that is sucked over the regenerators ($\dot{m}_{regen}$) and that leaves the furnace via the central stack ($\dot{m}_{stack}$) can be controlled by a manual valve which is installed before the suction fan. With a vortex flow meter the volume flow of flue gas sucked over the regenerating burners is measured and subsequently normalized with a local pressure and temperature. The unknown mass flowrate of the flue gas through the stack ($\dot{m}_{stack}$) is calculated by conservation of mass. Generally, the regenerated flue gas ($\dot{m}_{regen}$) flow is about 80 %-wt of the total flue gas flow.

For the mass balance, the cooling air flowrate ($\dot{m}_{cool}$) can be taken apart since there is no mass exchange between the furnace and the heat sink. The mass flow of the cooling air is measured for the upper and lower cooling tubes separately with two thermal flow meters.

For the calculation of the heat balance equation (2) is used.

$$Q_{fuel} + Q_{air} = Q_{cool} + Q_{regen} + Q_{stack} + Q_{loss} \tag{2}$$

Inputs are the fuel heating value (Q_{fuel}) and the air sensible heat (Q_{air}). The used fuel is Dutch natural gas, with a LHV (Lower Heating Value) of 31.67 MJ/m^3 [8]. The efficiency is defined as the upper and lower cooling tube heat gain which is calculated by measuring air flowrates supplied to the cooling tubes and inlet, outlet temperatures. The outlet temperatures and flowrates of the cooling air to the upper and lower cooling tubes are measured separately.

Losses are divided into three types; the first is the regenerative flue gas loss (Q_{regen}, low temperature flue gas exit, around 150 °C), the second is the stack flue gas loss (Q_{stack}, high temperature flue gas exit, around 1100 °C) and the last type is formed by unknown other losses (Q_{loss}, furnace insulation heat storage, wall loss, etc.). These losses are calculated by heat balance. The outside wall temperature varies at different operating conditions. The values are between 60 °C and 80 °C under steady state conditions.

4. Results and discussion

4.1 Flame to FLOX transition

Figure 5 show the characteristics of the burners changing from flame to FLOX mode in the C3 parallel case.

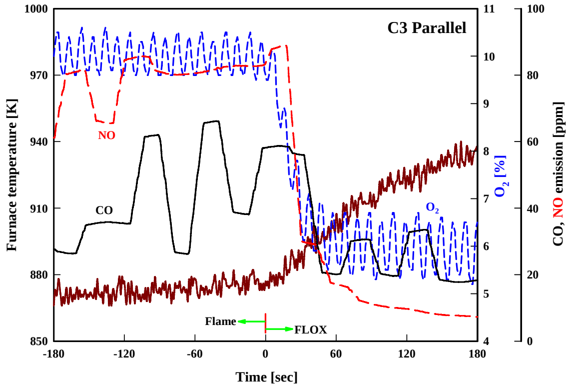

Figure 5. Evaluation of furnace temperature and emissions during flame to FLOX transition.

During the transition period the furnace temperature slope increases because in FLOX mode the fuel flowrates are increased and the excess air ratio is decreased. Also, FLOX combustion may enhance the heat transfer based on the high momentum direct injection method because the flame spreads all around the furnace. The NO emission sharply drops in FLOX mode which shows that the FLOX is a promising method to achieve low NO_x combustion. Also, CO emissions are decreases in FLOX mode.

4.2 Cooling tube efficiency

The efficiency of the furnace is slightly different for the configurations and operating modes. Figure 6 shows the cooling tube efficiencies for the various cases. Cooling tube efficiency decreases with an increase in the excess air ratio. This decrease in efficiency is assumed to be due to the increase of the combustion air flowrates which leads to an increased flue gas mass flowrate. Thus, the flue gas energy losses are higher and the furnace efficiency is lower. Also, the furnace temperature decreases with the excess air ratio increasing.

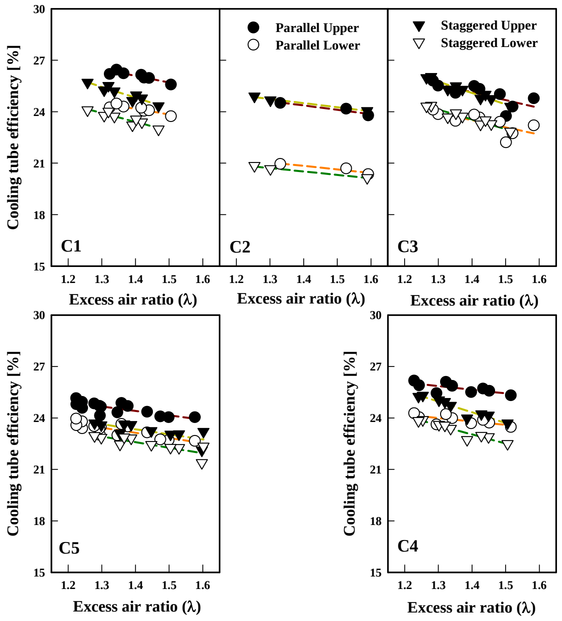

Figure 6. Cooling tube efficiency of each configuration and operating mode.

In every configuration the upper cooling tube efficiency is higher than the lower cooling tube. The difference is 1~2 %. However, in case C2 a larger difference between upper and lower cooling tube is observed. In this case, the lower three burners are installed in the middle level, instead of in the lower level, as in the other cases, see also Figure 2. It is assumed that in case C2 the temperature in the lower zone of the furnace is somewhat lower than the overall furnace temperature, since the hot flue gases flow upwards due to buoyancy effects. The total efficiency of case C2 is also lower than in the other cases. Comparing between parallel and staggered mode, the parallel mode in all cases shows slightly higher efficiencies except for the C2 cases. It shows that parallel mode has better heat transfer characteristics than staggered mode.

Figure 7 shows the comparison of the total cooling tube efficiency of each configuration in the high efficiency parallel mode. Both the upper and lower cooling tube efficiency is around 25% and the total is 50%. Cases C1, C3 and C4 show the highest efficiencies. This is an important criterion for choosing the optimal burner configuration.

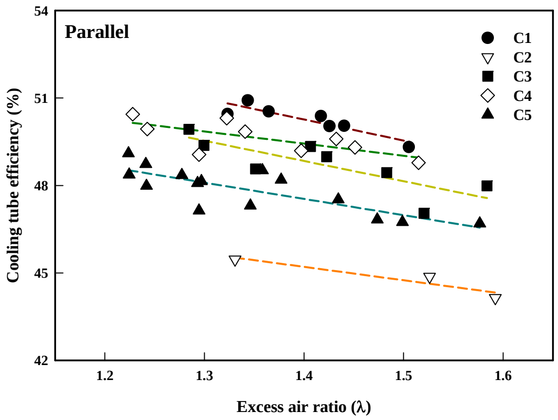

Figure 7. Comparison of cooling tube efficiency for each configuration in parallel mode.

Figure 8 shows the pie charts of the heat balance for all cases.

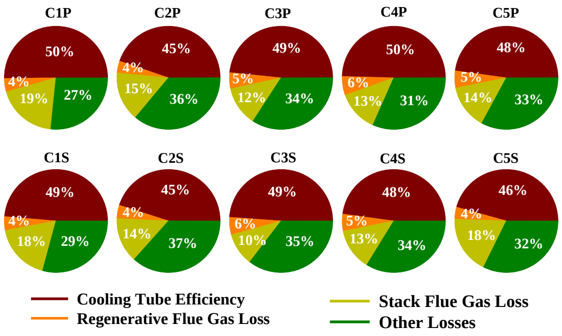

Figure 8. Heat balance of each configuration (C) in parallel (P) and staggered (S) mode.

The percentages for each case are similar and the cooling tube efficiency is around 50%, except for case C2 (45%). Regenerative flue gas loss is around 5% in all cases, stack flue gas loss is 10~19% and other losses are 27~37%.

4.3 Temperature uniformity

The spatial uniformity of the temperature in the furnace can be characterized by one number. This is the normalized root mean square value computed from all temperature measurement locations (hence perfect uniformity is corresponding to the value zero). It is defined in equation (3) [9].

$$\sqrt{\sum\left(\frac{\left(T_i-\bar{T}\right)}{\bar{T}}\right)^2} \tag{3}$$

where, T_i is the measured temperature at a certain location and $\bar{T}$ is the averaged value of all measured locations in the furnace.

In the furnace, temperatures are measured in 18 points in the furnace. The thermocouple is protruding installed around 100 mm distance from the inside wall.

Figure 9 shows the temperature uniformity ratios for each configuration case. Parallel mode shows more homogeneous temperature uniformity ratios than staggered mode. Among the parallel mode, Configurations C4 and C3 show a lower temperature uniformity than the other configurations. Case C2, with a low efficiency, shows a quite high value of the temperature uniformity in staggered mode. Thus, temperature uniformity may be related to the furnace efficiency.

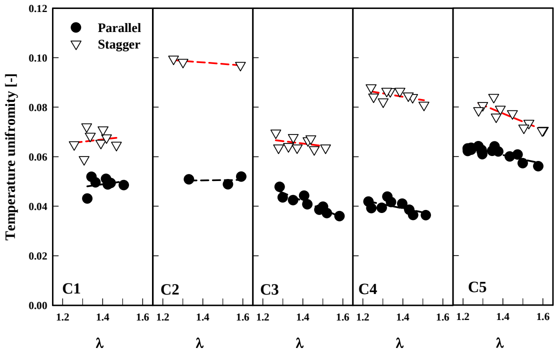

Figure 9. Comparison of the spatial temperature uniformity ratio for each configuration.

4.4 Emissions

Emissions of NO and CO are measured in the various operating conditions under steady state conditions. Figure 10 shows the NO and CO emissions for each burner configuration and operating mode. Case C2 is not included because of low efficiency shown in Figure 7.

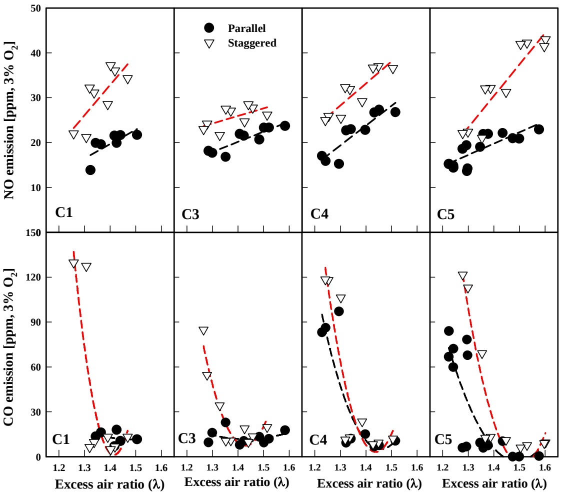

Figure 10. NO and CO emissions for each configuration and operating mode.

Each configuration shows somewhat different slope but similar trends. NO emissions increase with the excess air ratio, because O_2 availability increases in the combustion zone which enhances thermal NO_x formation. Parallel mode shows lower NO emission than staggered mode in all configurations. CO decreases with the excess air ratio increasing which is an inverse trend compare to NO. Under high excess air ratio conditions, CO is produced in small amounts but at lower excess air ratios CO increases exponentially. The parallel mode generally shows somewhat lower CO production than staggered mode.

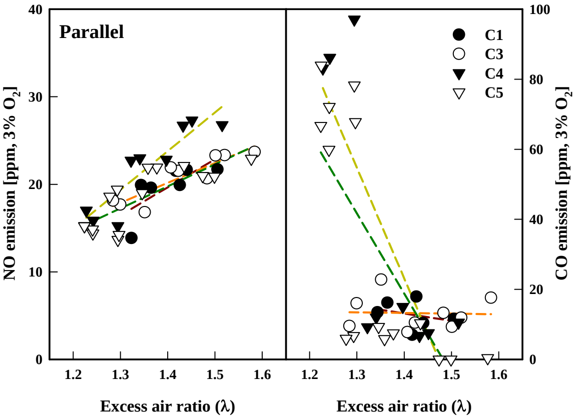

Figure 11. Comparison of NO and CO emissions for each configuration in parallel mode.

In all cases, the parallel mode is better than the staggered mode. This means that in the parallel mode the temperature distribution is more uniform and better mixing is established which reduces the unburned hydrocarbons in the flames.

Figure 11 shows the comparison of NO and CO emissions for each configuration in parallel mode. Cases C1, C3 and C5 are similar, but C4 shows higher NO emissions than the other. Regarding the CO emissions, cases C4 and C5 show high CO under low excess air ratio conditions but cases C1 and C3 show lower CO emission under these conditions.

5. Conclusions

The characteristics of a multi-burner excess enthalpy combustion furnace have been studied in detail for five different burner configurations and each two different firing modes. The optimal configuration is chosen regarding the efficiency and emissions of NO and CO. First of all, parallel mode is better than staggered mode because it shows higher efficiency, better temperature uniformity and lower CO, NO emission for all configurations. In the parallel mode, cases C1, C4 and C3 cases show high efficiency and C3 and C4 show a good temperature uniformity ratio. Regarding the emissions, C1 and C3 show low CO emissions and NO emissions show similar values except case C4 which shows higher NO emissions. Considering all cases, the C3 case shows the best performance.

In the future, the transient effect of the periodic operation and the regenerating ratio variation will be investigated. Furthermore, the in-furnace conditions will be measured using laser diagnostics, such as CARS and LDA for temperature and velocity, respectively.

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