Evaluation of new combustion technologies for CO$_2$ and NO$_x$ reduction in steel industries

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Abstract

The paper presents state-of-the-art combustion technologies for heating applications in the steel industry. Two types of burners that exhibit dilution combustion were evaluated in this study carried out in a semi-industrial furnace. These were regenerative air-fuel burner and oxy-fuel burner. The tests with regenerative air-fuel were carried out applying operation both with and without oxygen-enrichment. The main parameters studied for the different types of burners and operations include heat flux, thermal efficiency, and NO$_x$ at different levels of in-leakage of air. The in-flame parameters were measured including temperature, gas composition, total and radiative heat fluxes. All the studied burners provide a high efficiency of fuel utilization, a large ‘flame’ with uniform temperature and heat flux profiles. The results also clearly indicate that NO$_x$ emissions can be maintained at low or even very low levels well (less than 100 mg/MJ of fuel) meeting the restrictions at industrial-scale operation.

Keywords: heating process, High temperature air combustion, oxy-fuel combustion, fuel savings, NO$_x$ reduction.

1 Introduction

In order to achieve the reduction of global warming gases until 2010 by 6% of that for 1990, it is indispensable to make every effort in reducing CO$_2$ and NO$_x$ gases as it is two of the major global warming gases. Fossil fuel, such as gas and oil is used in the various fields such as steel production, petroleum, electronics and machinery and the energy saving on these industrial processes will result in big effect for reducing global warming gases. For example, 5.7 % primary energy demanded in EU is used in Steel industry. It accounts for 5 to 6% of
anthropogenic emissions in the world. Therefore the energy saving and environment protection technologies should be developed and then applied as soon as possible in the practical fields.

The most efficient saving energy method is either preheating combustion air by recovering flue gas heat or reducing the flue gas volume, or combining both of them. However, directly used of these methods will lead to high combustion temperature, thus high NOx emission. Flue Gas Recirculation (FGR) has been found to be very effective technique in controlling NOx emissions. Application of the FGR as well as preheating of air or use of oxygen led to the development of new combustion technologies. These are High temperature Air Combustion (HiTAC) and Diluted-Oxygen-Fuel (DOF), which hold the potential to overcome the limitations of conventional combustion and achieve energy saving and minimized pollution.

This work presents these combustion technologies and results of their evaluation performed in a semi-industrial test furnace.

2 State-of-the-art

The important issue of combustion phenomena of these new combustion technologies is the difference of oxygen concentration during combustion occurring. According to the use of oxygen in combustion, the technologies can be classified:

- **Oxygen Enhanced Combustion (OEC)**, which enhances heating processes by replacing some or all of the air with high-purity oxygen. When pure oxygen is used, it is referred as oxy-fuel combustion technology. Characteristics of this combustion are: fast chemical reaction ratio, high flame peak temperature and very intensive visible flame.
- **Air Combustion**.
- **Oxygen Deficient Combustion**, when combustion occurs with low oxygen content in oxidizer, for example, when FGR is used. The characteristics of this combustion are; slow chemical reaction ratio, low flame peak temperature, large flame reaction zone and weak or even non-visible flame.

2.1 High Temperature Air Combustion (HiTAC)

The concept of High Temperature Air Combustion (HiTAC) [1] is based on using highly preheated air combining with flue gas recirculation. High temperature air is supplied by means of very efficient heat regenerator. In HiTAC, the temperatures of air and/or fuel are raised well above the auto-ignition temperature of the fuel, which means that the conditions for flame stabilization are very favourable.

When a modern regenerator heat exchanger switching in the high cycle is used, the combustion air can be obtained a temperature of 800-1350°C, and only lower 50°C as exhaust flue gas. The materials of regenerators may be in the form of balls, honeycomb or even a granular refractory. The honeycomb regenerator
has a larger heat exchange surface area per unit volume as well as a larger gas passage opening area per unit cross-sectional area of a regenerator [2-9].

In a heat regenerator, heat is periodically stored and withdrawn from the heat storage solid. Maintaining continuous operation requires at least two regenerators. Continuous operation is achieved by switching periodically from hot to cold gas with a very short switching interval. Shorter switching times lead to an increasingly efficient waste-heat recovery rate and a uniformly high temperature [3-4]. When more than one pair burner is used, difference firing configure can be utilised to obtain better heating performance according to special application [4, 9]. The switch interval used varied from 4-5 seconds to 60 seconds, and correspond to known applications of HiTAC referred to as High-cycle Regenerative combustion System (HRS).

In order to reduce NOx in HiTAC fuel and air are both injected directly into the furnace chamber at high velocity. Because of strong entrainment the flue gas will dilute the combustion air. Combustion air in the near burner zone is thoroughly mixed and partial pressure of oxygen is lowered. As a results a low peak temperature, thus low thermal NO formation is observed. The chemical reaction rate is slower than in normal combustion also because of lower oxygen concentration [1-5]. A typical characteristic of this technology is its capacity to generate larger volumes of flame than conventional combustion, which results in increased transfer of heat. Furthermore, if FGR is large enough, the flame becomes less or even totally invisible.

The two main HiTAC solutions currently used feature either a one or a two-flame burner system. One-flame HiTAC is characterized by the single flame created by a one fuel nozzle surrounded by number of air inlets and flue gas outlets [2, 7], (Figure 1). In two-flame HiTAC, there are two separated high-cycle regenerative burners (Figure 2). The two burners are located in the walls of the furnace and work in pair by means of a set of valves, which change the direction of the air and flue-gases according to the required switching time.

Two examples of commercially available solutions are REGEMAT 350 FLOX®, and HRS®-NFK regenerative air-fuel burner, and the scheme is shown
in Figure 3. REGEMAT 350 FLOX® was used evaluated and studied in this work. It is a regenerative type that heats combustion air to 950°C with a cycle time of 10 seconds. During operation, 80% of flue gas is extracted through the regenerator. In order to study the upper extreme of energy utilization efficiency, the regenerative burner was also operated with oxygen enriched and preheated air. Up to 29% of oxygen enrichment was tested in this work. This case was named as OE-HiTAC, (Oxygen Enrichment - HiTAC).

Figure 3: Examples of HiTAC burners.

2.2 Diluted Oxy-Fuel (DOF)

The potential problems of traditional oxy-fuel technologies are: refractory damage, non-uniform heating, flame disturbance and flashback. In particular, the influence of air leakages on NO emission is very large.

The new approach in the oxy-fuel combustion technology with use of strong internal Flue Gas Recirculation as well as separated fuel and oxygen injection (Figure 4) can be named as Diluted Oxygen Enhanced Combustion. If pure oxygen is used as oxidizer, it can be named as Diluted-Oxy-Fuel.

Figure 4: Oxygen and fuel inlets configuration at the newly developed burner REBOX®-W.

Commercially available REBOX®-W burner (made by Linde Gas, Sweden) overcomes all the above listed problems of the conventional oxy-fuel combustion technology. This burner uses pure oxygen as oxidizer. The velocity of oxygen at the exit of the nozzles was higher than local sonic speed causing excellent internal mixing [10,11]. The results in cold flow model test found [12]
that the entrainment of these high velocity nozzles is 7 times as the mass of initials fuel and oxygen. This means that combustion occurs at the oxygen concentration of around 14% although pure oxygen is used as oxidizer. This combustion also has the characteristics of oxygen deficient combustion.

3 Experimental set-up

The test furnace used for the study is a cylindrical furnace of internal volume 7.9 m³. The burners were fixed in the position as shown in Figure 5. The temperature of the furnace was an average of 16 thermocouples mounted on furnace wall. For all the tests the furnace temperatures were maintained at around 1200°C and oxygen concentration in chimney was at the level of 3% (dry).

![Furnace longitudinal section and cross section](image)

Figure 5: Cross section of the test furnace.

4 Results and discussions

4.1 Available heat

As can be known, both HiTAC and Oxy-fuel technologies can offer very high energy utilization efficiency. Theoretical studies (Figure 6) have proved that both of them are able to offer more 85% available heat, which available heat is defined as the gross heating value of the fuel less the energy carried out of the combustion process by the hot exhaust gases. This value is much higher than that of traditional combustion technologies.

From figure 6 also can be seen, the available heat for oxy-fuel technology is higher than that for air-fuel technology for the same temperature of exhaust. This trend increases with the exhaust temperature increases. The available heat for oxygen-enhancement-combustion is in the middle of these two technologies. Moreover, the technology combining of HiTAC and OEC (OE-HiTAC), will further increase available heat.

The available heat for studied REBOX®-W (DOF) and REGEMAT (HiTAC) burners were around 86 %, and this value for HiTAC with oxygen enhanced to 29% (vol) is 91%. It would be mentioned in here is only 80% of flue gas is extracted through the regenerator for REGEMAT burners. It can be concluded
that for these new combustion technologies, high efficiency of fuel utilization is achieved, thus less CO₂ emissions consequently.

Figure 6: Available heat vs exhaust gas temperature for C₃H₈ combustion at 2% oxygen concentration in exhaust gases.

4.2 Temperatures in flame

The in-flame temperatures were measured by a suction pyrometer. The temperature distribution in the centerline of the furnace for the tested burners is shown in the Figure 7. The peak temperatures recorded were 1398°C for REGEMAT and 1434°C for REBOX®-W. The position of the peak temperature for REBOX®-W is slightly closer to the burner face than that for REGEMAT as shown in Figure 7.

Figure 7: Temperature profiles on the central line of burner (furnace), °C.

The temperature distributions on the center plane for REGEMAT and REBOX®-W are show in Figures 8.
There is uniform temperature distribution and absence of any hot spots in the furnace. The high nozzles’ momentum and well-dynamic design of the burners lead to larger entrainment of products and result in dispersed combustion and flat temperature profiles. REGEMAT burner can offer a little more uniform temperature than that from REBOX burner. The temperature profile becomes more uniform with increase in the oxygen concentration for REGEMAT burner. This is because the velocity of oxidizer for REGEMAT burner with oxygen enhanced decrease for the same fuel capacity, thus the mixing of fuel and oxidizer within the primary combustion zone is worse than that for REGEMAT burner without oxygen enhanced. This leads to a slower combustion rate, and a lower maximum temperature.

Figure 8: Temperature distribution on the central plane of burner (furnace), °C.

4.3 Total and radiative heat flux

The total heat flux probe used for measurements was a conductive plug type. For the REBOX®-W burner a maximum total heat flux was 433kW/m² observed at 50mm from the burner axis and at a distance of 350mm from the its face as seen from Figure 9.

Figure 9: THF distribution on the central plane of burner (furnace), kW/m².
Though higher total heat fluxes (THF) were observed close to burner with REBOX®-W burner, however at distance greater than 350mm the THF values were about 4-5% higher in case of REGEMAT burners. This is due to higher convection and presence of faint flame in case of REGEMAT burners. The total heat fluxes as seen from the Figure 9 were uniform throughout the furnace for both the burners.

An ellipsoidal radiative heat flux probe was used to measure the radiation falling on the tip of the probe inserted in the furnace. The radiative heat flux for REBOX®-W and the REGEMAT burner were found to be uniform throughout the furnace. The average radiative heat fluxes at 1200°C furnace temperature are 250kW/m², 253kW/m² and 255 kW/m² for REBOX®-W, REGEMAT and REGEMAT with 29% oxygen enhanced, respectively. They are almost at the same level. This value for traditional cold air combustion burner is only 200 kW/m².

4.4 In flame flue gases composition

A water-cooled gas-sampling probe was inserted at different points inside the furnace, and gas composition was analysed by a gas chromatograph (including CO, C₃H₈, UHC, CO₂, NOₓ, O₂). The CO profiles are shown in Figure10.

![CO profiles](image)

Figure 10: CO profiles on the central plane of the burner (furnace).

All of them show a larger chemical reaction zone. In particular, the CO concentration in REBOX burner is much higher than that in REGEMAT burner, this is easy understand that N₂ is not included in the flue gas for REBOX burner. The peak concentration of CO increases with the increase in oxygen concentration in combustion air for REGEMAT burner as well as its spatial distribution. This implies a larger combustion volume is needed.

4.5 NOₓ emissions

The NOₓ emissions were as low as 2 mg/MJ in case of the REBOX®-W and were 54mg/MJ in the case of HiTAC technologies (Figure 11). All of them are lower...
than the limit of emission standards for industrial furnace (100mg/MJ). NO$_x$ emission decreases when oxygen concentration increases in the case of HiTAC technologies. This is because the momentum of oxidizer decreases with increase of oxygen content in oxidizer in order to keep the same oxygen concentration in the chimney. At the same time, the momentum of fuel was kept as constant. A lower momentum of oxidizer decreases the mixing of fuel and air within the primary combustion zone. This leads to a lower maximum temperature and larger flame volume as argued as above. Further analysis of fuel/air injection momentum ratio on NO emission is can be found in Reference [9].

![Graph](image1.png)

**Figure 11:** NO-emission from the three combustion technologies at the same firing capacity equal to 200 kW.

![Graph](image2.png)

**Figure 12:** NO$_x$ emissions for different air leakages done beneath the burner.

Another interesting effect on NO$_x$ emission is air leakage, which always occurs in real industrial furnace. The results for the air leakages done beneath the burner at the furnace bottom are shown in Figure 12. It can be seen that sensitivity of air leakage on NO$_x$ emissions is very small up to 8% oxygen content in chimney in the case of REBOX®-W burner for the tested conditions. The NO$_x$ emission for the REGEMAT burner for oxygen content up to 6% in chimney was less than the emission standard.

### 5 Conclusions

- High Temperature Air Combustion (HiTAC) and Oxygen Enhanced Combustion (OEC) can offer very high efficiency of fuel utilization, low CO$_2$ emissions consequently.
- All elevated technologies can offer low peak temperature and uniform temperature
- Heat fluxes are high for all evaluated technologies, and also radiative heat fluxes are very uniform.
- A larger chemical reaction zone can be obtained for all the evaluated technologies.
• NO\textsubscript{x} emissions can be maintained at low or even very low levels well meeting restrictions at industrial-scale operation, and the sensitivity of leakage air on NO\textsubscript{x} emissions is very small.
• For HiTAC with oxygen enhanced, NO\textsubscript{x} decrease with oxygen concentration increases in combustion air for studied various range of oxygen concentration (21%-29%).

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References