Development of High Temperature Air and Oxy-Fuel combustion technologies for minimized CO2 and NOx emissions in Industrial Heating

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Abstract:

The ever increasing requirement to enhance productivity in industrial furnaces and the stringent environmental emissions has lead to the development of the state-of-the-art flameless combustion technologies namely High Temperature Air Combustion (HiTAC, using Air) and Flameless Oxy-Fuel Combustion (using commercial oxygen). This paper presents an evaluation of these commercially available technologies for heating applications in the industry. Two types of burners that exhibit flameless combustion were evaluated in this study carried out in a semi-industrial furnace. These were HiTAC burner (with and without oxygen enrichment) and Flameless Oxy-Fuel burner. Additionally a Cold Air burner and conventional Oxy-Fuel burner were also evaluated. The results of improved performance due to oxygen enhancement in regenerative air burner are also presented. The main parameters studied for the different types of burners include the thermal efficiency, inflame temperature distribution, heat flux, gas composition and NO_X emissions for different levels of in-leakage of air. The flameless burners exhibit a high energy utilization efficiency, a large combustion 'flame' with uniform temperature and heat flux profiles. The results also clearly indicate that NO_X emissions can be maintained at low levels and thus meeting the highest environmental norms at industrial-scale operation.

Keywords: High Temperature Air Combustion, Flameless Oxy-Fuel Combustion , Oxy-Fuel Combustion, High Temperature Air Combustion-Oxy Enhanced

1. INTRODUCTION

In order to achieve the reduction in emissions of various global warming gases by 5% of 1990 levels by the year 2012 as per Kyto Protocol, it is indispensable to make every effort in reducing CO_2 and other anthropogenic pollutants like NO_x gases. Fossil fuel, such as gas and oil is well used in the various industrial process and the energy savings on these will result in big effects in reducing of 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 they should be applied as soon as possible in the practical fields.

The most efficient energy saving method in industrial furnaces is either preheating combustion air by recovering flue gas heat or reducing the flue gas volume (removing/reducing the nitrogen ballast by oxygen enrichment) or combining both of them. However, direct use of these methods will lead to high combustion temperature, thus high NOx emission. Internal Flue Gas Recirculation (FGR) has been found to be very effective technique in controlling NOx emissions. Combining FGR and above mentioned methods has led to the development of new combustion technologies. They are High Temperature Air Combustion (HiTAC) and Flameless Oxygen-Fuel Combustion. HiTAC uses air as oxidizer and Flameless Oxygen-Fuel Combustion uses commercial oxygen as oxidant .These technologies carry out combustion under diluted oxygen conditions and are also referred as Flameless combustion. These technologies hold the potential to overcome the limitations of conventional combustion, thus achieving maximized energy savings and minimize pollution.

The High Temperature Air Combustion (HiTAC)[1-4] uses highly efficient heat exchanger in the form of regenerators to extract upto 90 % of the heat from the exhaust gases. The regenerators are in turn used to highly preheat the combustion air up to around 900°C and combustion is done under oxygen diluted condition achieved by good internal recirculation inside the combustion chamber. The new development in the Oxy-Fuel combustion technology that uses internal flue gas recirculation is called Flameless Oxygen-Fuel Combustion. Both these technologies exhibit superior combustion characteristics in terms of high energy efficiency, uniform heat flux distributions and low NOx emissions.

This paper presents an evaluation of the state-of-the-art flameless combustion technologies for heating applications in direct fuel fired industrial furnaces. These technologies are all commercially available. Two types of burners that exhibit flameless combustion using two different combustion technologies are evaluated in a semi-industrial furnace. These were HiTAC burner (using regenerators) and a recently developed Flameless Oxy-Fuel burner. The tests with HiTAC burner was also carried out with oxygen enhancement to evaluate the performance.The experimental conditions were kept the same for all the burners. Additionally a cold air burner (conventional combustion) and conventional Oxy-Fuel burner were also evaluated for bench marking reasons. The parameters studied were Temperature, Total Heat flux, Radiative Heat Flux, Available heat based on exhaust gas losses, Flame volume from the in flame gas composition, NOx at different levels of in-leakage of air.

2. COMBUSTION TECHNOLOGIES

The important difference in the various combustion technologies is the difference of oxygen concentration during combustion. According to the use of oxygen in combustion, they can be classified as the following

- **Oxy-Fuel combustion**: In many industrial processes, heating may be enhanced by replacing some or all of the air with high-purity oxygen. When pure oxygen is used, it is referred as Oxy-Fuel combustion. The characteristics of this combustion are fast chemical reaction ratio, high flame peak temperature and a visible flame. The potential problems of traditional oxy-fuel technologies are refractory damage, non uniform heating, etc. In particular, the influence of air leakages on NOx emission is very large.

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- **Air Combustion (AC)-conventional:** The conventional combustion which uses cold air or preheated air using the recuperative heat exchangers. The available heat is very low.
- **High Temperature Air combustion or Flameless oxidation (FLOX®):** The concept of High Temperature Air Combustion (HiTAC) [3] is based on very efficient preheating of the combustion air by means of regenerators. The regenerators are heated by the exhaust flue gases. The Combustion is carried out using internal Flue gas recirculation coupled with high temperature air under diluted oxidant conditions.
- **Flameless Oxy-Fuel Combustion:** The combustion occurs under diluted oxygen concentration achieved by internal flue gas recirculation. The oxidizer is commercial oxygen. The characteristics of this combustion are flameless combustion, low flame peak temperature, large flame reaction zone.

3. EXPERIMENTAL SET -UP

3.1 Furnace set-up

The test furnace used for the study is a cylindrical furnace of internal volume 7.9 m^3. The burners were fixed in the position as shown in Figure 1. 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).

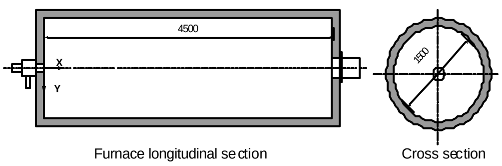

Fig 1: The test Furnace.

The burner center is considered as the origin with coordinates X=0,Y=0,Z=0. The measurements were done only in the center horizontal plane of the furnace. The combustion is assumed to be symmetrical about the furnace axis. There are several openings in the wall of the furnace to facilitate the measurements and visual inspections. The openings were conical and this enabled measurements not only perpendicular to the furnace axis but also at various angle. A traversing system was used to move and angle the probes.

4. TESTED BURNERS

4.1 REBOX®-W
Flameless Oxygen-Fuel Combustion

The advanced Flameless Oxy-Fuel Combustion burner, REBOX®-W (Linde AG), shown in Fig 2 was used in this study. This burner uses pure oxygen as oxidizer and gives a flameless combustion in the furnace. The velocity of oxygen at the exit of the nozzles was higher than local sonic speed causing excellent internal mixing and accounting for the flameless combustion. The salient features of this burner are extremely simple construction, operation and its very small in size.

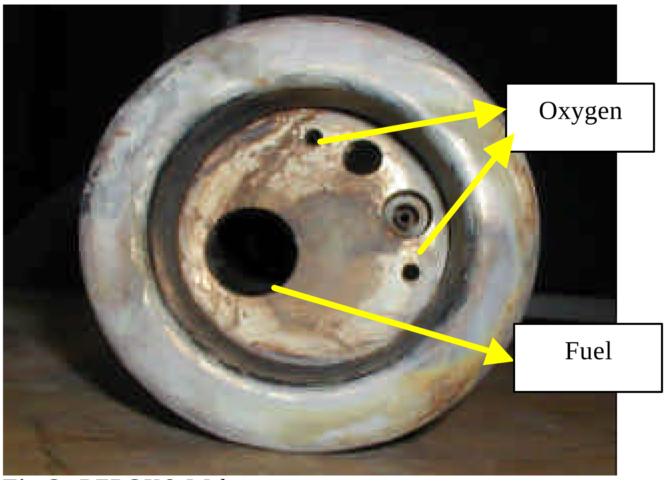

Fig 2: REBOX®-W burner;

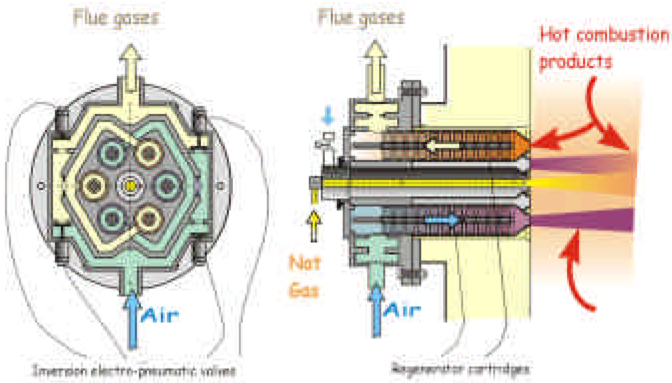

Fig.3: REGEMAT® 350

4.2 REGEMAT®
High Temperature air Combustion

One-flame HiTAC burner used for the study was REGEMAT® burner, shown in Figure 3. It is a Scheme of REGEMAT® 350 FLOX burner regenerative type that heats combustion air to 950°C. For efficient extraction of the heat from the regenerators, there are two sets that get alternatively heated and cooled by passing of flue gases and combustion air respectively. This is done with a cycle time of 10 seconds. During operation, 80% of flue gas is extracted through the regenerator. This burner is characterized by a single flame created by one fuel nozzle surrounded by air inlets and flue gas outlets. This single flame develops along the axis of the fuel-jet nozzle during cooling and heat periods of the regenerators. Fuel is supplied continuously through the same nozzle and in this way a single flame can be formed with a permanent position. This position remains almost unchanged between heating and cooling periods, as the regenerators are located around the nozzle

4.3 REGEMAT ®-OXY ENHANCED
High Temperature Air Combustion- Oxy Enhanced

The effect of oxygen enhancement on a HiTAC burner was studied by adding oxygen to air in the REGEMAT® burner. The mole fraction of oxygen (O) in the oxidizer was O=29.2.

4.4 OXY-FUEL

The conventional Oxy-Fuel combustion was carried out by modifications to the REBOX®-W burner.

4.5 COLD AIR BURNER

A cold air burner was used in the study. The data obtained was used as a reference and all sets of measurement were not performed as it exhibited far inferior performance in Comparison to the above burners

Table 1 Operating Conditions

Burner	Fuel flow Nm^3/hr	Oxidizer	Furnace Temp, °C	O_2 in Chimney
REBOX®-W	7.7	O_2=100%	1200	3%
REGEMAT®-FLOX	7.7	O_2=21% N_2=79%	1200	3%
REGEMAT® -FLOX Oxy-Enhanced	7.7	O_2=29% N_2=71%	1200	3%
Oxy-Fuel	7.7	O_2=100%	1200	3%
Cold air Burner	7.7	O_2=21% N_2=79 %	1100	3%

Table 2 Maximum temperatures measured in difference cases

Burner	Peak Temperature
REBOX-W	1434°C
REGEMAT	1398 °C
REGEMAT –Enhanced	1402°C
Oxy-Fuel	>1600 °C
Cold Air	1404 °C

5. RESULTS AND DISCUSSIONS

5.1 Available heat

The operating conditions for various burners are given in Table 1. Both HiTAC and Flameless Oxy-Fuel technologies can offer very high energy utilization efficiency. Theoretical studies (Fig 4) have proved that both of them are able to offer very high available heat. The 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 Fig 4 it can also be seen, that the available heat for the technology, that uses Oxygen (Commercial) is higher than that for air-fuel technology for the same temperature of exhaust. The difference in available heat increases as the exhaust temperature increases. The available heat for oxygen-enhanced combustion is in the middle of these two technologies. Moreover, the technique of combining of HiTAC and Oxygen Enhancement (HiTAC-OE) can further increase the available heat.

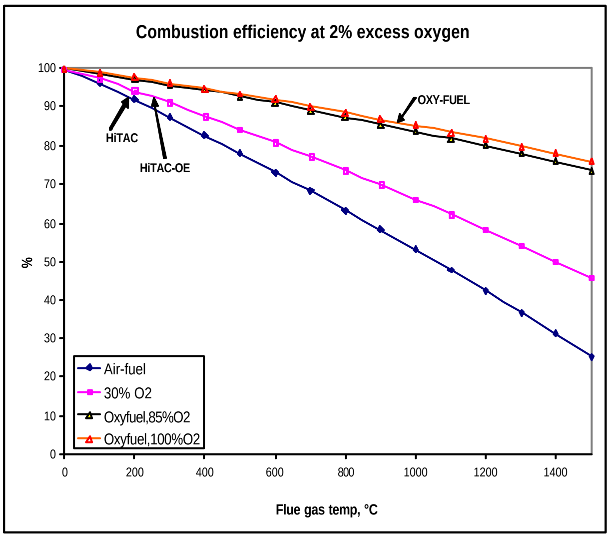

Fig. 4. Available heat vs exhaust gas temperature for Propane combustion at 2% oxygen conc. in exhaust gases

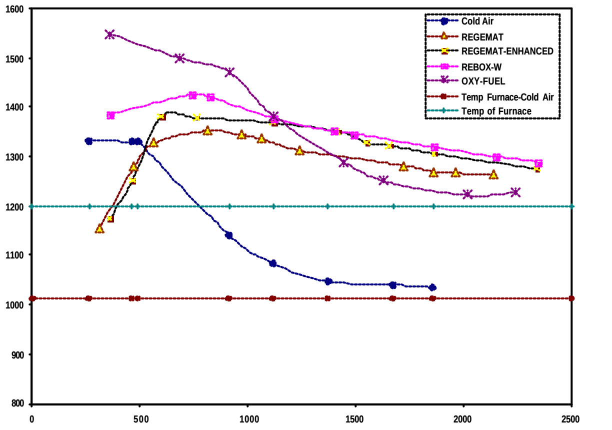

Fig.5 Temperature profiles on the central line of burner (furnace), °C

The available heat for studied REBOX®-W and REGEMAT (HiTAC) burners were around 86 %, and this value for REGEMAT-ENHANCED (HITAC -OE) with oxygen enhanced to 29% (vol) is 91%. It is mentioned here that only 80% of flue gas is extracted through the regenerator for REGEMAT burners. The cold air burner had an available heat of around 50 %. It can be concluded that for these new combustion technologies, high efficiency of fuel utilization is achieved, thus less CO_2 emissions consequently

5.2 Temperatures in flame

The temperature distribution in the centerline of the furnace for the tested burners is shown in the Figure 5. The peak temperatu res recorded are shown in the Table 2

The position of the peak temperature for REBOX ®-W slightly closer to the burner face than that for REGEMAT as shown in Figure 5.The temperatures above 1600° C for the Oxy-Fuel was not measured as the thermocouple use in the suction pyrometer was S type and the max permissible temperature was 1480 °C. For the REGEMAT and the REGEMAT- ENHANCED the peak temperatures measured were lower than REBOX-W. With the COLD AIR burner the temperature of the furnace achieved was only 1012 ^{o}C. To achieve the same Furnace temperatures of 1200^{o}C, the required power was 380 KWs. This shows clearly the low efficiency of the burner. The high nozzles' momentum and well-dynamic design of the REGEMAT® and REBOX®-W burners lead to larger entrainment of products and result in dispersed combustion and flat temperature profiles. The REGEMAT®-ENRICH also shows uniform temperature distribution in the furnace

5.3 Total and Radiative heat flux

The Total Heat Flux measured for distances, from the burner face, X =359mm, and X=1116mm are shown in the Figures 6 and Figure 7 respectively. These measurements were done across the furnace that is for various values of Y. The Total Heat Flux at the same temperatures for REGEMAT®, REGEMAT®-ENHANCED and REBOX®-W show similar characteristics. However, for the REBOX®-W the maximum Total Heat Flux measured was 433kW/m^{2},observed at a distance of (X=)350mm from the its face and Y= 50mm from the Furnace axis as shown in Figure 7.For X>350 mm 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 burner.

The Total heat fluxes were highest for the Oxy-Fuel till a distance of about 500 mm from the burner face and for greater distance it was lower than the REBOX-W and REGEMAT burners. It is mentioned here that the peak heat fluxes for Oxy-Fuel were not measured due reasons of very high temperatures. The total heat fluxes as seen from the Figure 9 (E-H) were uniform through out the central plane of furnace for REGEMAT®, REGEMAT®-ENHANCED and REBOX®-W. The radiative heat fluxes are in same levels for all the burners except for cold air burner as shown in Fig. 8.

5.5 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, C_3H_8, UHC, CO_2, NO_X, O_2). The CO profiles are shown in Fig 9 A-D. The REGEMAT® [5], REGEMAT®-ENHANCED and REBOX®-W show a larger chemical reaction zone. It is mentioned here that that scales for the molar fraction for all the burners are different and are shown in the respective figures

5.4 NOx emissions

The NOx formations are basically a function of temperature, oxygen concentration, and residence time. In a typical industrial furnace, residence time is usually long enough to enable the generation of NO_x. For flameless combustion technology, the basic reason for NOx-reduction is due to lower peak temperature of the flame and due to reduced oxygen concentration.

The NO_x emissions were as low as 2 mg/MJ in case of the REBOX®-W, 54mgs/MJ in the case of REGEMAT, 37 mgs/MJ for REGEMAT ENHANCED and was 14mgs/MJ for Oxy-Fuel as shown in Fig.10. All of them are lower than the limit of emission standards for industrial furnace (100mg/MJ). NOx emissions decrease with the increase in Enhancement (oxygen %) in the case of REGEMAT burner

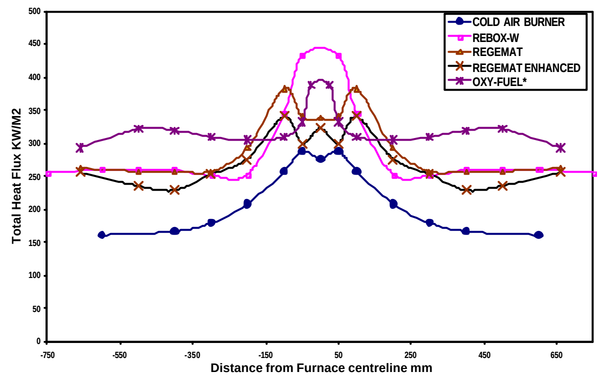

Fig.6: Total Heat Fluxes profiles at X = 359 mm

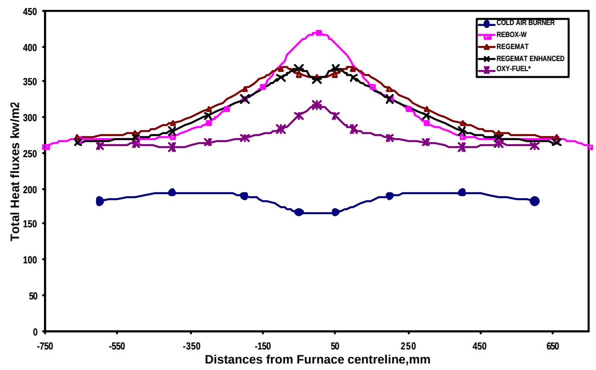

Fig 7: Total Heat Fluxes profiles at X = 1116 mm

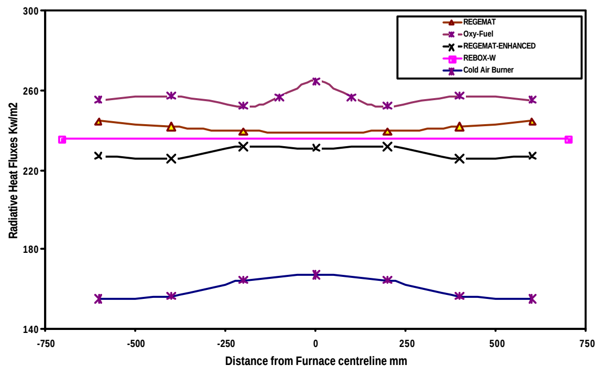

Fig 8 :Radiative Heat Fluxes profiles at X =359 mm

Another interesting effect on NOx emission is air leakage, which always occurs in real industrial furnace. The air leakage is indicated by the amount of Oxygen in the flue gases. The results for the air leakages done beneath the burner at the furnace bottom are shown in Figure 11. It can be seen that sensitivity of air leakage on NOx emissions is the lowest for REBOX®-W burner compared to all the burners. To achieve an emission of 100 mg/MJ of fuel used the oxygen content in chimney for REBOX®-W, REGEMAT® REGEMAT®-OE were approximately 14%, 7 %, 7% respectively.

7. CONCLUSIONS

The conventional combustion, High Temperature Air Combustion (HiTAC) with or without oxygen enhancement, Oxy-Fuel and Flameless Oxy-Fuel were evaluated and compared. The following conclusions can be drawn

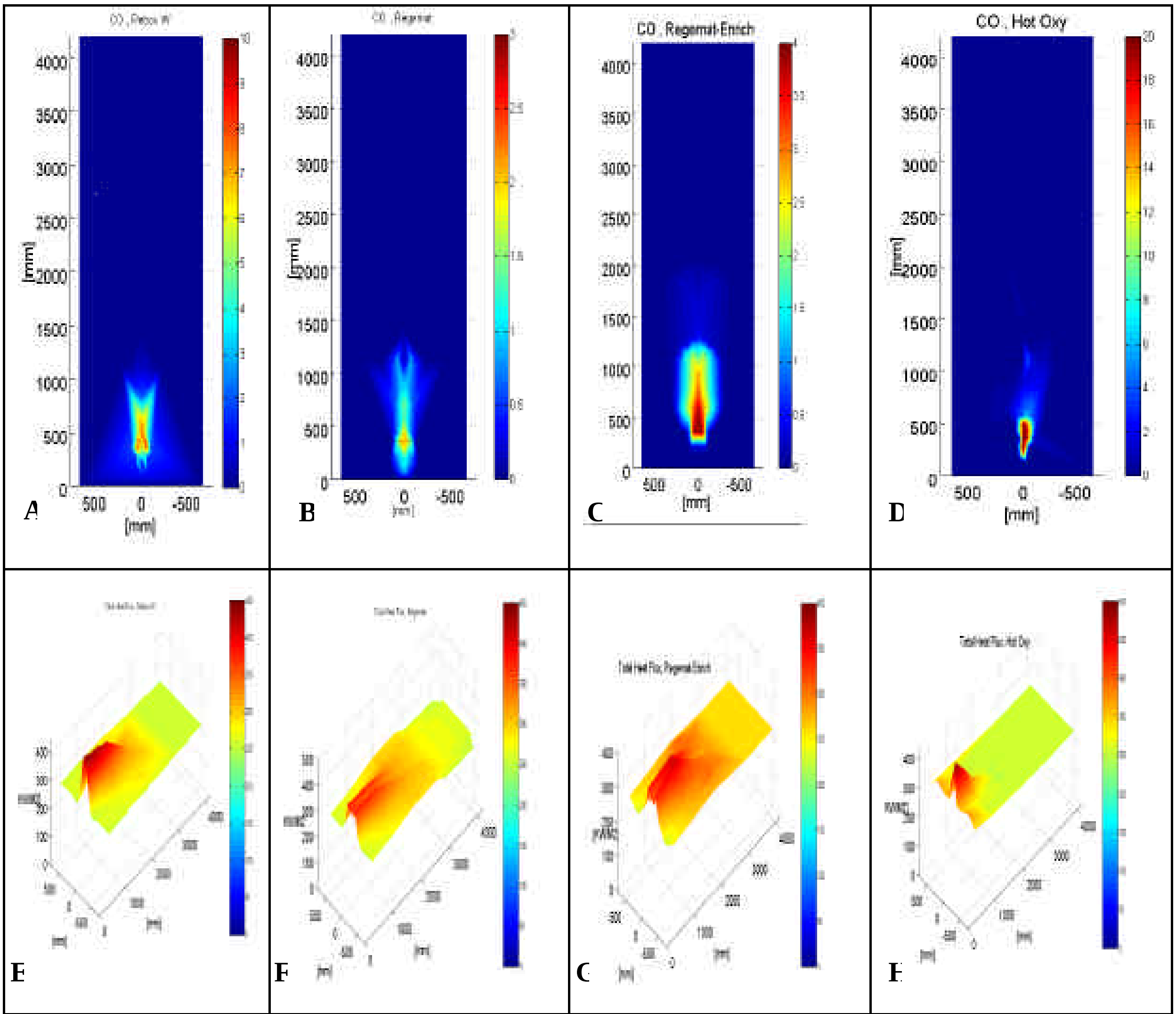

Fig 9:CO profiles (molar fraction %) on the central plane of the burner (furnace) **A**-REBOX-W, **B**-REGEMAT, **C**-REGEMAT-ENHANCED, **D**-OXY-Fuel . THF distribution on the central plane of burner(furnace), kW/m2 **E**-REBOX-W, **F**-REGEMAT, **G**-REGEMAT-ENHANCED, **H**-OXY-FUEL

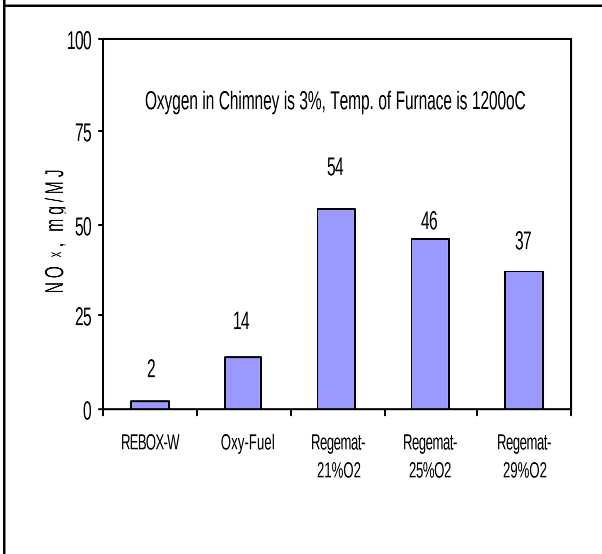

Fig 10 NOx-emission for the three combustion technologies for a firing capacity equal to 200 kW

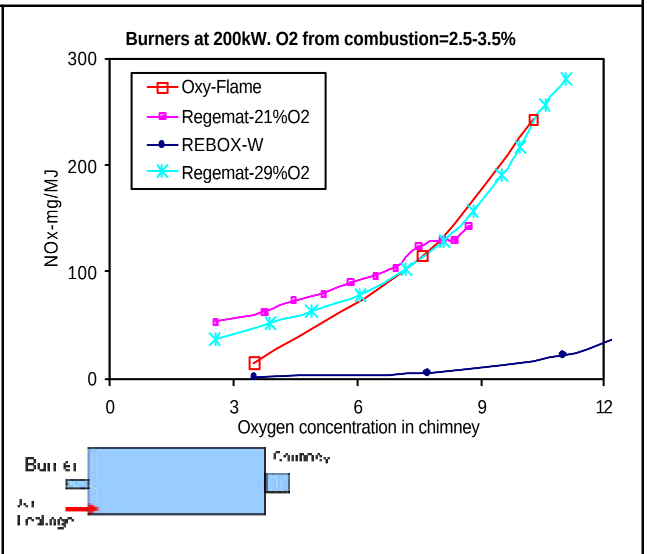

Fig 11 NOx emissions for different air leakages done beneath the burner

- Flameless Oxy-Fuel combustion , High Temperature Air Combustion (HiTAC), HITAC-Oxygen Enhanced can offer very high energy utilization efficiency, thus low CO_2 emissions.
- Flameless Oxy-Fuel Combustion, HITAC and HITAC-OE technologies can offer low peak temperature and uniform temperature distribution in the furnace.
- Flameless OXY-Fuel Combustion, HiTAC, HiTAC-OE can offer high values total heat fluxes and radiative heat fluxes along with their uniform distribution compared to conventional combustion technologies
- A larger chemical reaction zone can be obtained for Flameless Oxy-Fuel Combustion, HiTAC, HiTAC- OE technologies
- NO_X emissions can be maintained at low or even very low levels well meeting restrictions at industrial-scale operation with Flameless Oxy-Fuel Combustion, HiTAC, HiTAC-OE technologies. The NOx emissions were the lowest for Flameless Oxy-Fuel Combustion (REBOX® burner -Linde AG). For HiTAC with oxygen enhancement, NOx decrease with oxygen concentration increases in combustion air for studied various range of oxygen concentration. (21%-29%). The sensitivity of leakage air on NOx emissions is very small

APPLICATION

An example showing the benefits of implementation of the Flameless Oxy –Fuel combustion technology in a customer Furnace is shown in Fig. 12.

The production capacity of 11t/h was the maximum possible with Air Fuel burner. On oxygen enhancement the capacity was increased to 16t/h. The complete conversion to Flameless Oxy-Fuel operation, increased the production to 23t/h..The production was further enhanced to 38t/h using Direct Flame impingement coupled with Flameless Oxy-Fuel combustion.

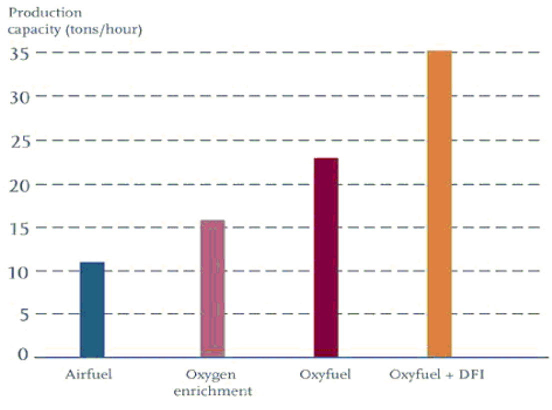

Fig.12: An example of benefits of implementation of Flameless –Oxy Fuel combustion. Source : Linde AG

ACKNOWLEDGMENTS

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