HiTAC - one combustion technology – a wide range of industrial applications

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Abstract

A continuous competition among industrial burner manufacturers, the newest and future, very low legislation limits for pollutant emissions (for example: NO_X, CO_2, CO) and an increase in fuel prices result in development of new technologies. One of the technologies which has been recently invented and already successfully proven in hundreds of different industrial applications is the High Temperature Air Combustion (HiTAC).
Using this combustion technology, it is possible to achieve the low emission of NO_X and CO, uniform temperature profiles and heat flux in the combustion chambers for high LHV gas fuel like natural gas and propane as well as for very low LHV gas fuels like blast furnace gases or off-gases

Combination of the unique features of a heat regenerative bed, called “the honeycomb”, and the HiTAC is realized by the High-cycle Regenerative Systems (HRS). In many industrial furnaces the combustion system based on the HRS ensures high thermal efficiency of the heating processes, high quality of the products and at the same time low emission of pollutants like NO_x, CO and CO_2. This paper will present the advantages of the HRS heating system based on the walking beam reheating furnace with nominal capacity of 20 t/h using only the HRS burners.

Combination of the typical central recuperative system, which is still widely used in many industrial furnaces, with the HiTAC combustion technology is realized by the High Temperature Burners (HTB). The combustion systems based on the HTB burners shows all the advantages of the HiTAC combustion technology, especially good temperature distribution as well as low NOx emission. This paper will present the advantages of the HTB combustion systems based on the walking beam reheating furnace with design capacity of 300 t/h using almost only the HTB burners.

The unique features of the HiTAC combustion technology have been also successfully applied in special HTB-WG burners for the copper blast furnace waste gas utilization system. The HiTAC combustion technology, besides the typical advantages like low NOx and CO emission and good temperature distribution, gives one more very important feature. It is insensitivity to very low and fluctuating LHV as well as the flow rate of fuel gases. The paper will present the advantages of the HiTAC combustion technology in the case of the industrial waste gases utilization system with nominal capacity of 65,000.0 Nm^3/h of waste gases with a range of LHV from 1.5 MJ/Nm^3 to 2.4 MJ/Nm^3.

Key words

High Temperature Air Combustion (HiTAC), High-cycle Regenerative System (HRS), High Temperature Burners (HTB), Low NO_x Combustion Technology, Waste Gas Utilization System, Copper Industry, Shaft Furnace Off Gases.

Introduction

Since the beginning of the 90s or even late 80s of the last century a lot of publications regarding the idea of HiTAC have been already presented all over the world. For this reason, it could be assumed that the idea of the HiTAC combustion technology is well-known. Such advantages of HiTAC as low NO_x emission or flat temperature and heat flux distributions inside furnaces have been reported in many publications [1, 2, 3, 4, 5, 6, 7, 8]. Other advantages of HiTAC like low noise [9] or the possibility of burning fuel with very low heating value can be found in many papers too [10, 11, 12].

The unique features of the HiTAC combustion technology have been successfully applied in the HRS and HTB burners. The possibility of burning fuel with very low LHV (Low Heating Value) and other features of this combustion technology are used in the special HTB-DL-WG burners.

This paper presents the advantages of application of the HiTAC combustion technology in three areas of HiTAC applications.

The first area is the combination of the HiTAC technology and the HRS burners. The example of the successful application of the HRS system based on a small size, 20 t/h, walking beam steel reheating furnace is presented.

The second area is the combination of the HiTAC technology and the HTB burners which cooperate with the central recuperative heat recovery system. The description of the HTB system is based on the walking beam reheating furnace with design capacity of 300 t/h using almost only the HTB burners.

The third area is the combination of the HiTAC technology and the HTB-DL-WG burners specialized in the combustion of very low heating value gas fuels (waste fuels). This paper presents the advantages of application of the HiTAC technology in the copper blast furnace waste gas utilization system with utilization capacity up to 65,000.0 Nm^3/h of waste gases with a range of LHV from 1.5 MJ/Nm^3 to 2.4 MJ/Nm^3.

Apart from the typical HiTAC, which is well-known application in the HRS systems, the HiTAC technology has been already successfully applied in the HTB and HTB-DL-WG burners as a result of cooperation between ICS and NFK company.

Advantages of HITAC, HRS, HTB, HTB-DL-WG Technology

The HiTAC combustion technology has been incorporated in hundreds of industrial applications mainly in Japan over the last decades usually with the HRS burners. It has been introduced into the market by the Japanese company called NFK (Nippon Furnace Kogyo) since the beginning of the 90s of the last century.

The first industrial application of the HiTAC combustion technology applied in the HRS burners took place in 1992. Since that time the HiTAC combustion technology has been applied in hundreds of industrial applications, including HRS, HTB as well as HTB-DL-WG systems [13, 14].

The general principle of the HiTAC combustion technology is to carry out a combustion process at high temperature in the whole chamber with a significantly lowered oxygen level in the area where the combustion process takes place. It is conducted by means of intense internal flue gas recirculation and separate injection of air (mixture of air and combustion products from the first step) and fuel into the combustion chamber. Therefore, the HiTAC is referred to as “volumetric combustion” or sometimes as “flameless combustion” due to diluted flame in the combustion process [13, 15, 16].

The combination of the HiTAC combustion technology and the HRS/HTB burners provides many advantages [4, 5, 8, 9, 10, 11, 12, 13, 14, 17] in the applied industrial systems, in comparison with the conventional technology, such as:

1. Flat heat flux distribution,
2. Flat temperature distribution,
3. Low NOx emission,
4. Reducing fuel consumption,
5. Lowering average zone temperature,
6. Increasing zone capacity,
7. Extending refractory lining lifetime,
8. Reducing noise emission,
9. Burning low quality fuels.

The above mentioned advantages of the HRS/HTB burners resulting from the HiTAC technology and other burner features can be grouped in five areas, which are very important from users' point of view:

1. Improvement in final product quality,
2. Reduction in pollutants,
3. Increase in equipment lifetime,
4. Reduction in fuel consumption.
5. Possibility of burning low quality fuels.

Obviously, all these features are available together with reliability and safety [15].

The key issue in all companies is to keep the product quality at the highest level and, at the same time, production costs need to be under control. In metallurgy, the steel as well as non-steel industry in many processes the heating process is of the highest importance. It means that quality of final products depends on the heating system quality. In many of these processes the open fire heating system is used. Therefore, it is very important which combustion technology is applied.

In reference to above, first product quality aspects of the HiTAC combustion technology features will be discussed in detail.

Product quality, pollution reduction and an increase in equipment lifetime as a result of application of the HiTAC combustion technology

In the HiTAC combustion technology several techniques are applied in order to achieve the highest level of the heating technology, which, obviously, the HiTAC as an open-fire combustion technology belongs to. The techniques are as follows [15]:

- very high injection velocity of the fuel gas,
- very high injection velocity of the preheated air,
- air and fuel are injected directly into the combustion chamber through separate nozzles at combustion chamber temperature over the fuel auto-ignition point,
- proper distance between nozzles and its location,
- special way of the burner control in the system.

A separate injection of fuel and preheated air (Fig. 1) into the combustion chamber results in the fact that the fuel and the air are mixed with flue gases before the combustion process takes place (internal flue gas recirculation). This results in lowering of the peak temperature for two main reasons. Firstly, the oxygen level in the oxidizer is lowered. Secondly, fuel is burned partly before the main combustion process takes place, since the flue gas usually includes some amount of oxygen.

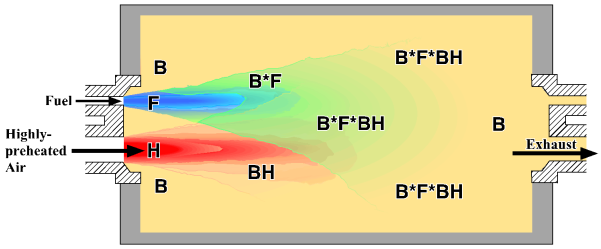


Fig. 1. HiTAC combustion technology concept [17]

The power of the internal flue gas recirculation is controlled by the injection velocity of the preheated air and fuel (design parameters) as well as the location of the nozzles [15]. Higher injection velocity results in faster internal flue gas recirculation and swirls the gas volume. It is similar to the location or distance between the nozzles of fuel and air. Higher distance between them results in faster and more intensive internal flue gas recirculation [18].

High internal flue gases recirculation, high injection velocity and the way of controlling the burner result not only in proper temperature distribution but also in heat flux and flue gas composition. In some cases almost the whole combustion chamber is filled up with the combustion process. The difference between peak temperature and furnace temperature in the HiTAC Combustion Technology is about 5 – 7 times smaller [19] compared to the conventional technology. A similar situation occurs with heat flux – a decrease in the temperature peak results in a decrease in the heat flux peak as well.

The HiTAC Combustion System ensures particularly low emissions in comparison with the conventional technology regarding nitrogen oxides (NO_x) [20]. The typical NO_x emissions from the HiTAC Combustion System and the Conventional Combustion System in the reheating furnaces are presented in Figure 2.

Proper control of the temperature distribution and the composition of flue gas cause that there are no temperature peaks with a high fraction of radicals (OH, CH,…). Both temperature and the amount of radicals play an important role in all NO_x creation mechanisms. Therefore, by applying the HiTAC, that is by avoiding the peak temperature and high concentration of radicals, which appears in the conventional combustion technology, NO_x creation is very low [15].

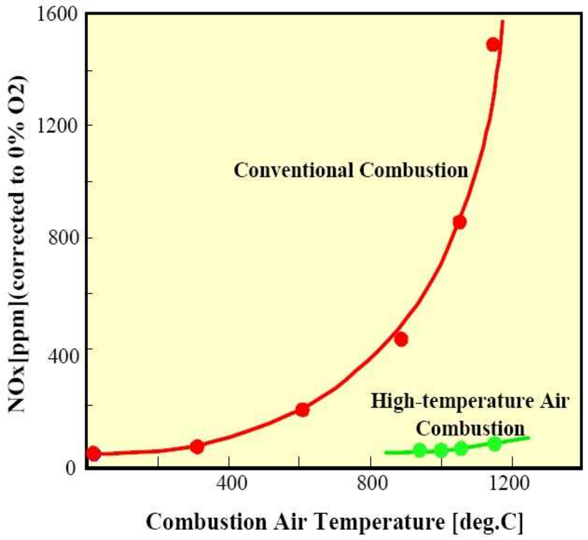


Fig. 2. NOx profiles for the conventional and HiTAC combustion [21]

The proper temperature and heat flux distribution, which means the temperature and heat flux distribution without temperature peaks (hot spots), is one of key issues for the proper quality of the heating system in industrial furnaces. The second very important aspect for the quality of the combustion heating system is the proper distribution of combustion product components. The more equal the distribution is, the better the heating system. In other words, the distribution of combustion products should avoid the area where the heated material can be exposed to a reducing atmosphere or an oxidizing atmosphere.

It needs to be pointed out that proper temperature, heat flux and combustion product distribution without hot spots is important for equipment lifetime as well. The local overheating of the furnace wall and/or furnace skid systems have negative influence on the lifetime of this equipment. The reducing atmosphere or/and oxidizing atmosphere have the same negative influence on the furnace walls or the furnace skid systems. It means that more even temperature distribution, heat flux and combustion product components distribution increase the lifetime of the equipment.

All the above mentioned issues, starting from the temperature distribution, heat flux distribution as well as the combustion product distribution have essential influence on the product quality, low NOx emission and life time of the equipment.

The good example of the industrial confirmation of some of the above described conclusions from the theoretical analysis is the HTB combustion system installed in the reheating furnace in SSAB Tunnplåt AB, Borlänge, Sweden, which is a part of SSAB Group, a global producer of high strength steel [22]. The HTB combustion system is based on the HTB burners, which utilise the HiTAC combustion technology.

The revamped furnace is a part of a steel sheet production plant where steel slabs are rolled. The sketch of the furnace is presented in Figure 3.

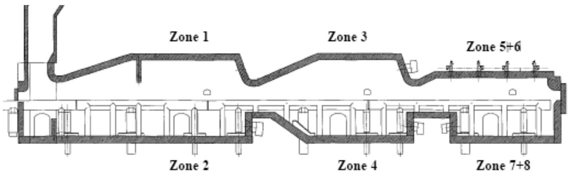


Fig. 3. Layout of the reheating furnace, SSAB

The system works on propane or LPG fuel with the combustion air preheated up to 600℃ by a central recuperative system. The control temperature of the zones is between 1,100℃–1,320℃ during normal operation. The furnace where the burners are installed is a walking beam type furnace with design capacity of 300 t/h. The photo of a part of the HTB burners installed in SSAB is presented in Figure 4.

The combustion system was revamped two times. In 2006 two zones were rebuilt, Zone 1: 8 HTB-DL3.5 burners, each with firing power rate capacity of 3.5 MW and Zone 2: 9 HTB-DL3.8 each with firing power rate capacity of 3.8MW. The total firing power rate of both zones was 62.7 MW. The investor's expectation was to reduce the NO_X emission originating from Zone 1 and Zone 2 down to 65 ppm (normalized to 5% of O_2).

In 2008 four remaining zones were revamped: Zone 3 (8 HTB-DL2.8 – 2.8 MW), Zone 4 (9 HTB-DL2.7 – 2.7 MW), and Zone 7/8 (in total 9 HTB-DL1.2 – 1.2 MW).

The investor's expectation was to reduce the NO_X emission down to 62 ppm (excluding Zone 5/6) to meet the current authorities' demands. The total firing power rate of the rebuilt zones in 2008 was 56.8 MW.

Fig. 4. Photo of the HTB burners, zone 3, SSAB

After both installations the total firing power rate of the units designed by ICS is 119 MW, that is, 92.8 % of the total heating power of the combustion system installed at the furnace. The remaining 7.21% (9.28 MW) of the total heating power comes from the roof burners from Zone 5 and Zone 6 where due to the location it is not possible to install the HTB burners. It has to be emphasized that in both cases the installation was revamped without lowering the overall firing capacity of the furnace and production capacities.

The objective for the revamp of Zone 1 and Zone 2 in 2006 was to reduce the NO_X emission down to 65 ppm from these particular two zones. The goal was fully achieved. Moreover, the performed installation resulted in the total furnace NO_X emission reduction from about 134 ppm down to less than 93 ppm. This reduces the initial NO_X release by about 31%.

The guarantee level for the second revamp in 2008 was to achieve NO_X emission reduction down to 62 ppm for the whole furnace excluding NO_X emission from Zone 5 and 6. The guarantee test was fully performed as well. Moreover, the NO_X emission was reduced from 93 ppm to around 62 ppm for the whole furnace including Zone 5 and 6, which is 33% less compared to the initial levels.

After both revamps the complete obtained emission reduction amounted to over 50% compared to the emission before installation of any HTB burners. All the obtained outcomes are corrected to 5% of oxygen in flue gases. The overall firing capacity of the furnace and production capacities remained unchanged. The graphical presentation of averaged NO_X levels before and after the performed revamps is shown in Figure 5.

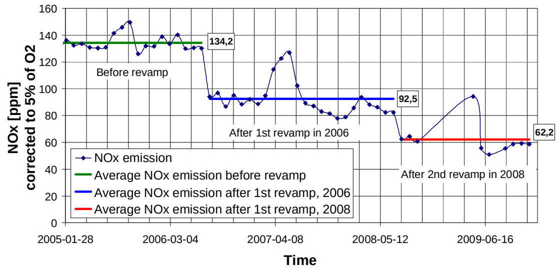


Fig. 5. NO_X emissions before and after HTB burners assembly

Another data analysis coming from the time before and after the erection in 2008 shows the influence of the HTB burners on the temperature distribution of the slabs released from the furnace and rolled at the mill. These data are presented in a graphical form in Figure 6.

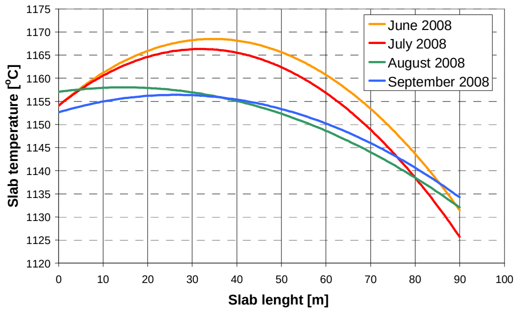


Fig. 6. Slab temperature distribution after the rolling mill before and after the revamp in 2008

The data come from June and July 2008 before the revamp of Zone 3, 4, 7 and 8 and from August and September the same year after the new installation was built. As it can be observed, before new burners were installed (the red and orange line) the temperature distribution in the slab is much more inhomogeneous compared to the slab temperature distribution after the assembly of the HTB burners (the blue and green line). For slabs after the revamp in 2008 there are no significant temperature differences along the elements compared to the slab temperature differences before the revamp. Much better temperature homogeneity over the slab length proves better temperature homogeneity inside the furnace. This is an effect of "volumetric combustion" [16] which takes place in the whole volume of the combustion chamber due to diluted flame. The conventional burners do not posses this advantage. Thus, in the case of the conventional burners the temperature close to the furnace walls can have much lower temperature compared to the temperature in the middle of the furnace (Fig. 6).

Heating with a more uniform temperature profile can give an important economical advantage. Due to the even temperature in the furnace any point or region of the discharging slab have sufficient temperature for rolling and none of the points are overheated. With less energy used, the lower average temperature of the extracted slab is obtained. In fact, the lower average temperature of the slab could need more power for slab thickness reduction, due to higher average resistance. On the other hand, a more uniform and reliable temperature profile gives a lot better situation to deal with quality related problems, such as thickness and with the control and material properties of steel. This in turn makes possible correct performance of steel slabs processing for the first time, which saves both time and energy.

Improvement of slab heating can be observed in Figure 7. The slabs according to rolling treatment at the mill can be divided into three parts: the head, the body and the tail, of which temperatures are measured by the UV temperature meter at different spots of the transfer bar. The division of the slab is the following: the head is approx the first 10%, the body is next 80% in the middle and the tail is the last 10%.

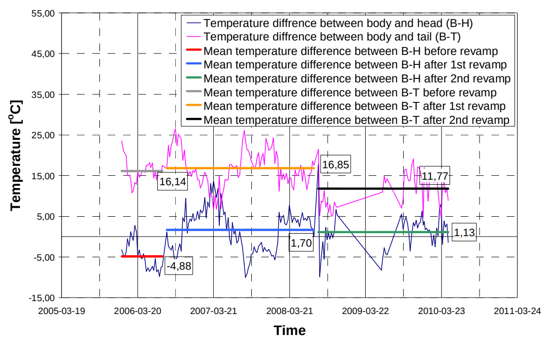


Fig. 7. Presentation of temperature uniformity assessment factors

There are two important factors that are taken into consideration regarding slab temperature homogeneity assessment. First, it is important that a temperature difference between the body and the head ("body − head") as well as the body and the tail ("body − tail") is consistent in time. It has to be noticed that in the case of the consistent slab heating process the pre-settings of the mill are reliable and accurate. Second, the differences between certain slab parts should not be as small as possible, but close to zero for "body − head" and approx "+10" for "body – tail". Then the slab is considered to be evenly heated in the furnace. During the rolling, the tail becomes cooler compared to the body due to longer time before reaching the rolling mill.

One can observe significant improvement of this factor: the temperature difference is very close to "0" after the second revamp, especially in comparison to the value before any revamp was done. One can also observe significant improvement of this factor, which as an assumption for the good temperature homogeneity is close to "+10". The very good result for the second revamp is caused by the fact that it concerns the revamp of both heating and soaking zones, which have much bigger influence on the slab temperature uniformity than preheating zones (Zone 1 and 2).

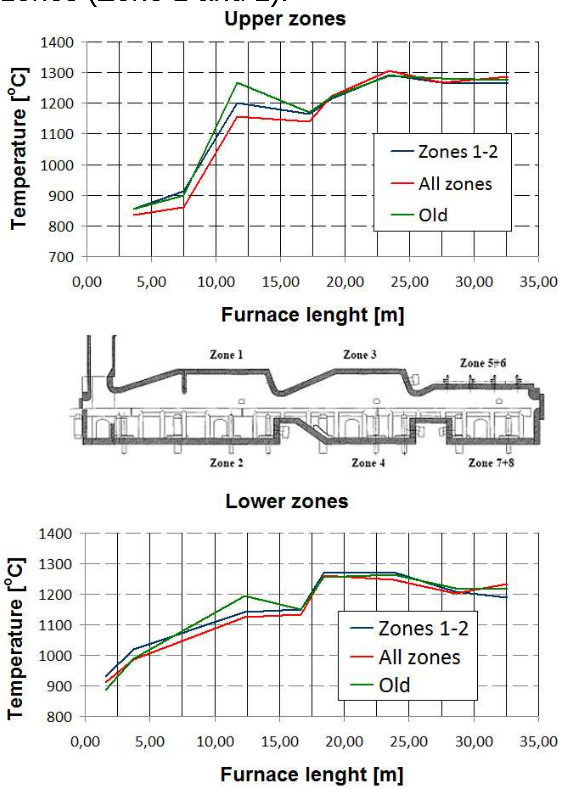


Fig. 8. Zone temperatures before and after the revamp in 2006

The comparison of temperature profiles along the furnace measured by thermocouples on furnace walls are presented in Figure 8. The data come from the time before the revamp (the green line), after the revamp of Zone 1 and Zone 2 (the blue line) and after the revamp of all zones (the red line). For zones 3 – 8 the lines are generally overlapping, since no modifications have been made at the installation in 2006. However, one can observe a trend of lowering the temperature close to the burner area in Zone 1 and Zone 2. This is a positive trend resulting in longer lifetime of the refractory lining around the burners, which is not exposed locally to very high temperatures. On the other hand, the temperature in the area further from the burner wall is higher in Zone 2. This means better uniformity of the temperature in these two zones compared to the situation when conventional burners were installed.
Referring to refractory lining lifetime, the graph presenting the steam production in the walking beam cooling system before and after the revamp of the burners in the furnace is shown in Figure 9.

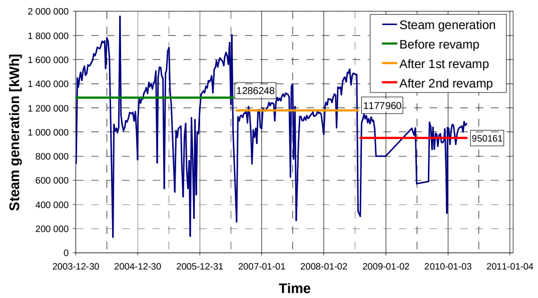


Fig. 9. Graph presenting the steam production in the walking beam cooling system

One can observe that the average steam production before HTB burners installation (the green line) is at the level of 1,286,248 kWh. After the first revamp in 2006 when the burners in Zones 1 and 2 were changed, this value was lowered down to 1,177,960 kWh. The lowest steam generation is recorded after the second revamp in 2008 when burners in four zones were replaced. The value of steam generation dropped down to 950,161 kWh. One can observe that the slopes of the curve for the time before the revamp are big while for the time after the first revamp get smaller to be almost flat for the time after the second revamp. These data prove that the refractory lining covering the beams was in a worse condition, in comparison to the situation after the revamps, and dropped over time resulting in higher steam production. It must be emphasized that working conditions, for example production capacity or furnace temperature, are comparable for the cases. These data prove that when the HiTAC combustion technology is used, the refractory has longer lifetime.

Fuel consumption reduction

Since the energy costs usually play an important role in the total company production costs, then the second item explained below in detail will be the possibility of reduction fuel consumption by means of application of the HiTAC combustion technology in connection with HRS/HTB burners.

The reduction in the fuel consumption comes from two areas:

1. First area is the high efficiency of the regenerative heat exchanger as a part of the HRS burner (High-cycle Regenerative System),
2. Second area are the features of the HiTAC combustion technology, for example: lower average furnace temperature, longer lifetime of the equipment, high turndown ratio,

The first area of fuel reduction is based on the high efficiency of the regenerative heat exchanger installed in the HRS burner. Therefore the HRS burner concept need some elaboration in this paper.

According above mentioned, the HRS burner concept depends on the High Temperature Air Combustion with high performance regenerative heat exchangers. The HRS burners are installed in furnaces where energy flux is exchanged directly between flue gas and heating charge (the open-fire heating system). The idea behind the system is that two burners work alternatively (Fig. 10). When burner A works as a burner (the firing mode), burner B sucks the exhaust gas from the combustion chamber (the regenerative mode). The burners change their functions after the switching time. Burner maximum thermal efficiency for such regenerators is achieved during 30-second switching time [5, 8].

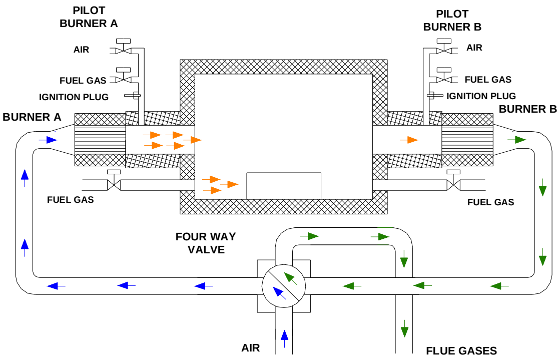


Fig. 10. Scheme of the HRS burners pair operation [23]

The burners enclose a regenerative bed called “the honeycomb”, made of ceramics resistant to high temperature of flue gas. The high performance heat exchanger allows combustion air of ambient temperature to preheat up to the temperature close to the sucked flue gas temperature during the regenerative mode of the burner [15].

A typical honeycomb (Fig. 11) used as a regenerative medium has 100 cells per square inch. This great number of cells per square inch ensures the following features of the regenerative heat exchanger (Fig. 12) [24]:

- high specific surface area equal to 1307 m^2/m^3, about 7 times bigger than in the case of the ball type (a ball diameter – 20 mm)
- high equivalent heat transfer rate per volume equal to 165 $kW/m^3 \cdot K$, about 5 times bigger than in the case of the ball type,
- low unit weight - about 3 times less that in the case of the ball type,
- low unit volume - about 5 times less that in the case of the ball type. This factor causes that burners are compact and easy to install, especially during furnace revamping.
- short optimum switching time equal to 30 s - the time when the highest regenerative efficiency is obtained. It is about 2 to 4 times lower compared to the ball type regenerator. Short switching time results in small fluctuation of the preheated air temperature.
- low pressure drop, about 3 to 4 times lower than in the case of the ball type,
- no problems with plugging due to the construction of the honeycombs (lack of the flow dead zone)

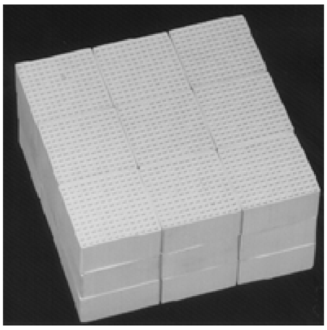


Fig. 11. Square type of ceramic “honeycomb” regenerative heat exchangers [25]

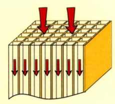
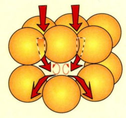
Regenerator	Honeycomb (100 cell/in2)	Ball (20mm dia.)
		
1. Heat transfer surface area per vol.	$1307 m^2/m^3$ (7 times)	$186 m^2/m^3$
2. Heat transfer coefficent@1.5Nm/s	$126 W/m^2.K$ (0.7 times)	$174 W/m^2.K$
3. Equivalent heat transfer rate per vol.	$165 kW/m^3.K$ (5 times)	$32 kW/m^3.K$
4. Temperature efficiency	90~96%	70~85%
5. Pressure loss@1.5Nm/s, 300mmL	$88 mmH_2O$ (0.3 times)	$289 mmH_2O$
6. Weight	$500 kg/m^3$ (0.35 times)	$1430 kg/m^3$

Fig. 12. Comparison of ceramic honeycomb and ball [26]

The high efficiency of the regenerative heat exchanger (the bed of honeycombs) installed in the HRS burners results in fuel saving after the revamp of furnaces. The savings can reach even over 50% (Fig. 13). The highest level of the fuel saving takes place when the furnace before revamping is equipped with a poor recovery system or even does not have one [5, 8, 15].

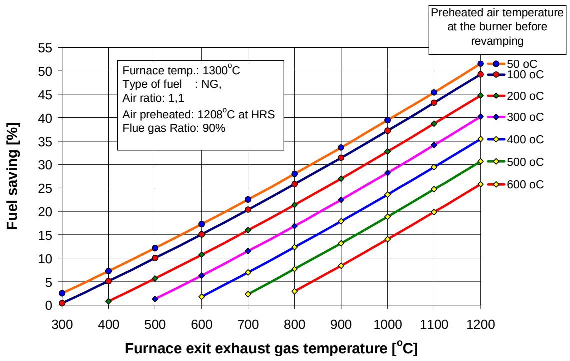


Fig. 13. Fuel saving as a function of furnace exhaust gas temperature [5, 13]

Since in a typical reheating furnace flue gases temperature at the exit of the furnace is at the level between 900°C and 1100°C, the temperature of the preheated air before the burner varies from 300°C to 450°C (the temperature efficiency of the recuperative system is below 50%). In such a case the installation of the HRS burners can result in fuel saving between 20% and 35%.

The good example of the industrial confirmation of the considerable fuel reduction by means of using the HRS burners is the application of the HRS burners in a walking beam steel reheating furnace installed in Rolling Mill Plant Ferrostal Sp.z o.o. in Gliwice in Poland (Fig. 14).

The furnace length is 11.15 m, however the working length from the charging side to the discharge window centre is 10.00 mm. The width of the furnace is 7.54 m and the height is 1.50 m.

The heated material are bars made of carbon steel with of a length of 6.0 m and typically of 0.14 x 0.14 m shape,

The HRS combustion system consists of five pairs of the HRS regenerative burners (Figs. 15, 16). Two pairs of the HRS DL5 burners (2,300.0 kW per burner pair) are installed in the furnace heating zone and 3 pairs of the HRS DL4S burners (1,550.0 kW per burner pair) are installed in the furnace soaking zone.

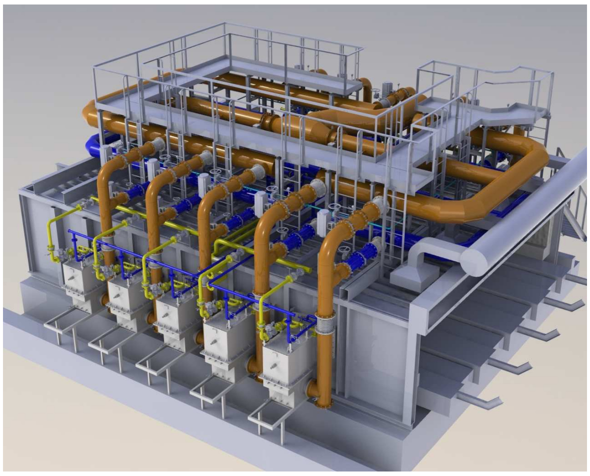


Fig. 14. Installation – design stage

Fig. 15. Furnace sidewall installation - HRS burners

During the furnace operation, heating zone temperature is usually about 1200˚C and soaking zone temperature is about 1250˚C.

The main aims of the project were:

- to increase furnace capacity from 15 t/h to 20 t/h by keeping the furnace shell,
- to reduce unit fuel consumption,
- to improve product quality.

Fig. 16. Furnace and combustion system after revamping

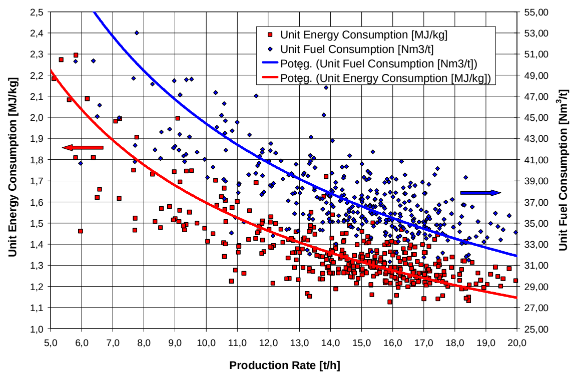


Fig. 17. Relationships between unit energy consumption, unit fuel consumption and a production rate

On the basis of the recorded data from almost six months of furnace operation (the guarantee period), the typical furnace fuel consumption curve is made, where the unit energy consumption falls down along with an increase in the production rate (Fig.17). For the nominal furnace capacity, which after revamping is 20.0 t/h, the energy consumption is about 1.2 MJ/kg (33.0 Nm^3/t). The unit energy consumption for the average production rate, which was 13.39 t/h, amounts to 1.38 MJ/kg (38.37 Nm^3/t). The presented results were calculated based on the average shift (8 hours) fuel consumption and production rates. The average values include furnace operation period (maximum 7.5 hours per shift) and also the furnace hot stand-by period (when the production line after the furnace is adjusted, minimum

0.5 hours). If the furnace works continuously, the achieved results will be better.

The obtained results are compared to the unit fuel consumptions 52.56 Nm^3/t achieved when the old furnace worked with a small production rate (average 12.15 t/h). If the old furnace worked with a higher production rate, its unit fuel consumption would be significantly higher.

However, by simple comparison, the average energy fuel consumption was reduced by about 27%, which is in the typical range of possible fuel savings.

The second area of the fuel reduction is based on the HiTAC combustion technology phenomenon. Since the HiTAC combustion technology phenomenon has been already explained in this paper, only some additional words below need to be added showing clearly the connection between the HiTAC combustion technology and the energy reduction.

The even temperature distribution, as one of the main features of the HiTAC combustion technology, in the combustion chamber without hotspots has the same positive influence on the heating quality, NOx reduction as well as on the lifetime of the equipment - in this case on the refractory furnace walls. Of course, the even distribution of the combustion product components and the even distribution of the heat flux as the consequence of the even distribution of the temperature and combustion products have the important positive influence as well.

The stable and good quality of the refractory lining in the long term, especially between planned maintenance stops, is one of the key issues for keeping energy or maintenance costs at the correct level. The damage of the refractory lining is immediately shown by heat losses like in the case of increasing the steam production in the walking beam cooling system or by an energy increase in the case of the refractory wall damage, which especially can happen in reference to the roof.

The above described energy savings due to the HiTAC technology have been clearly noticed through the comparison of the steam production before and after the revamp of the HTB system shown in Figure 9.

The obtained steam reduction, which can be treated almost as heat losses, is about 26%. Of course, the overall reduction is expressed in this case as single percentages.

It is important to point out that the longer and stable lifetime of refractory lining eliminates to the minimum the unpredicted furnace stops due to the refractory damage, which have a direct connection with the energy consumption and the production level. Even if the maintenance stoppage connected with the refractory lining damage is short, there are always high costs to be paid connected with cooling, heating and drying procedures.

Due to the HiTAC features, the average temperature of the furnace can be reduced or the capacity of the furnace can be increased. In both cases the unit energy cost is lowered. In the first case, the average flue gas and wall temperature are lower. In the second case production rate can be higher by lifting up the average furnace temperature and at the same time by decreasing the maximum temperatures and eliminating hot spots, which are finally observed as the unit fuel consumption reduction.

Possibility of burning low quality fuel

The possibility of burning low quality fuels is one of the HiTAC combustion features, based deeply on the general HiTAC combustion technology concept. Since the HiTAC combustion technology phenomenon has been already explained in this paper, only some additional words will be added below showing clearly the natural capability of HiTAC of burning the low quality fuels, especially low heating value gas fuels.

It is well known that in order to burn the fuels, especially low quality fuels the following combustion process parameters play an important role (so-called 3xT):

- temperature (process temperature),
- time (residence time)
- turbulences (micro and large scale turbulence, including internal recirculation)

The oxygen availability at the required amount and at the correct place and time in the combustion chamber is, of course, an important issue as well.

Keeping in mind the above requirements related to the combustion technology for the combustion of low quality fuels and looking at the HiTAC combustion technology features, it is quite clear that HiTAC has a natural capability of burning low quality fuels.

The HiTAC is the combustion technology that it is designed to work at relatively high process temperature. The high combustion process temperature is a result of preheated air, and the internal flue gas recirculation and the semi-adiabatic combustion chamber, especially in the case of the combustion process of low heating value fuels. The process temperature is kept above the auto-ignition point of fuels (according the safety European standards over 750^{o}C) but at the same time below the temperature level, which are conducive to the NOx production (below the 1,500.0^{o}C).

One of the main features of the HiTAC concept is to apply the intensive internal flue gas recirculation, primarily to reduce the maximum available temperature in the case of the high quality fuel combustion. Since the intensive internal flue gas recirculation is applied in HiTAC, the relative high residence time is already applied in the HiTAC, which in the case of low quality fuels is an important factor.

The internal flue gas recirculation, which provides the required level of the residence time, is made by high velocity of the combustion air and fuel directly injected into the combustion chamber additionally by the separated nozzles. The high velocity of the combustion air and fuel forces the internal flue gas recirculation as well as the required level of the turbulence (the mixing process).

Besides the above, very important combustion process parameters, it is also important to point out that HTB-DL-WG burners are only equipped with simple injectors. Since the HTB-DL-WG burners use the HiTAC technology, there are not equipped with any type of typical mechanical turbulizers. The lack of the mechanical turbulizers, like for example the swirler, is additionally an important advantage in the case of the fuel contaminated by dust or by dust and moisture.

The last important HiTAC combustion technology feature is related to the way of flame stabilization, an especially important issue in the case of low heating value fuels. In the HiTAC combustion technology there is no stabilization in the sense of the typical combustion technology. The combustion process takes place in the whole combustion chamber on the required temperature level over the auto-ignition point. The mixing process is forced by high velocity injection of the combustion air and fuel.

All the above pointed out HiTAC features make the HiTAC combustion technology very suitable for the combustion of low quality fuels and insensitive to a wide range of the waste gas parameters like composition, pressure, temperature and flow rates.

The good example of the industrial confirmation of the theoretical possibility of burning low quality gas fuels by using the HiTAC combustion technology is the copper blast furnace waste gas utilization system [14] based on the HTB-DL-WG burners which was installed in Energetyka Sp. z o.o., in Głogów in Poland (KGHM Group).

The project covered replacing the old steam boiler and the old waste gas utilization system based on waste gas/coal co-firing with a new steam boiler equipped with waste gas/natural gas co-fired burners. The aims of the project were:

- to increase waste gas utilization capacity,
- to increase steam production efficiency,
- to improve combustion process quality,

Due to low LHV (Low Heating Value) of 1.5-2.4 MJ/Nm^3, high moisture content and substantial solid particle contamination, the utilization of copper shaft furnace (blast furnace) waste gas (Tab.1) is led through natural gas co-firing. In this system natural gas is used as a support fuel.

Tab. 1. Waste gas composition and LHV

No	Component	Symbol	Unit	Min	Max
1	Methane	CH_4	%	0	0.97
2	Ethane	C_2H_6	%	0	0.08
3	Propane and higher hydrocarbons	C_3H_8	%	0	0.02
4	Hydrogen	H_2	%	1.13	6.44
5	Carbon monoxide	CO	%	9.22	13.66
6	Carbon dioxide	CO_2	%	6.44	11.28
7	Water vapour	H_2O	%	19.44	19.44
8	Oxygen	O_2	%	0.4	3.22
9	Nitrogen	N_2	%	50.0	62.54
10	Sulphur (VI) oxide (SO_2, CS_2, H_2S)	SO_2	g/Nm^3		33.25
11	Dust	-	g/Nm^3		0.1
12	Low Heating Value	LHV	MJ/Nm^3	1.5	2.4

The installation consists of the three HTB-DL-WG15 burners (Figs. 18, 20), with the nominal power rate of 13.7 MW each, semi-adiabatic combustion chamber as well as the steam boiler (the waste-heat recovery boiler).

The nominal waste gas utilization system capacity is 65,000.0 Nm^3/h, in the nominal conditions natural gas consumption is 600.0 Nm^3/h

The combustion process takes place in the semi-adiabatic combustion chamber (Fig. 19). In order to achieve good quality of the combustion process, the nominal temperature of the combustion process is kept between 950˚C and 1250˚C.

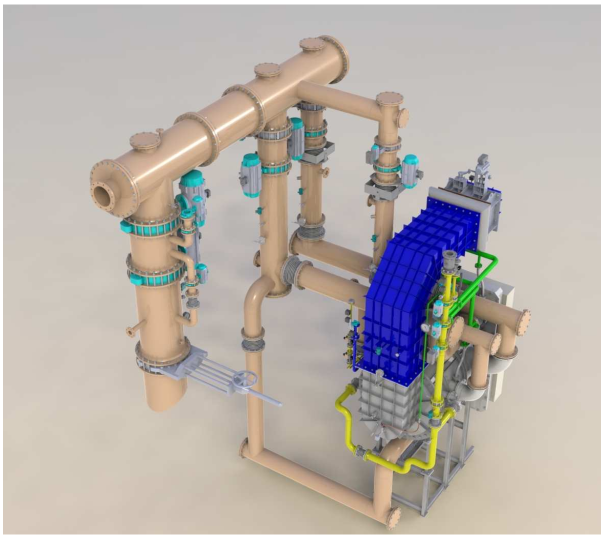


Fig. 18. HTB-DL-WG15 burner with fittings and piping

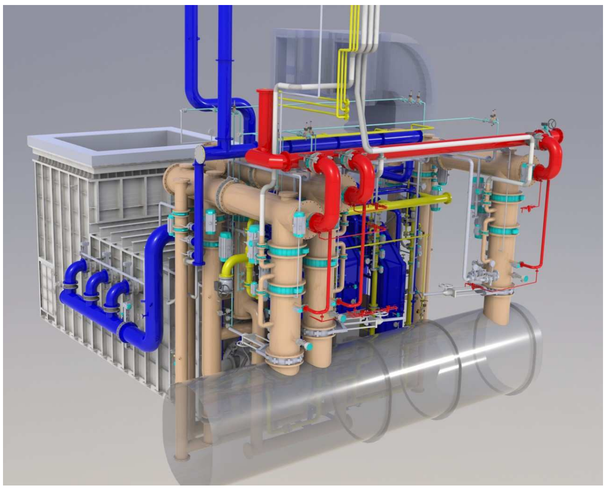


Fig. 19. Combustion chamber with burners and piping

Exhaust gas energy produced in the combustion chamber by waste gas and natural gas co-firing is used for steam production in the heat recovery steam boiler.

Fig. 20. Part of the final installation – the main burner operating platform

During the steam boiler and HTB utilization system operation, measurements of the emission of CO and NO_x were done. The measurements were carried out in stable and possibly comparable conditions, in relation to combustion chamber temperature (950 - 970˚C), combustion air temperature (250 - 320˚C) and oxygen concentration in exhaust gases (usually 1.7 – 2.1%, for small capacities 3.7% - 6.3%).

In the whole range of system operation, CO emission is almost at the same level (Fig. 21). System insensitivity to changes of the waste gas amount shows that the combustion process is of high quality and is very stable.

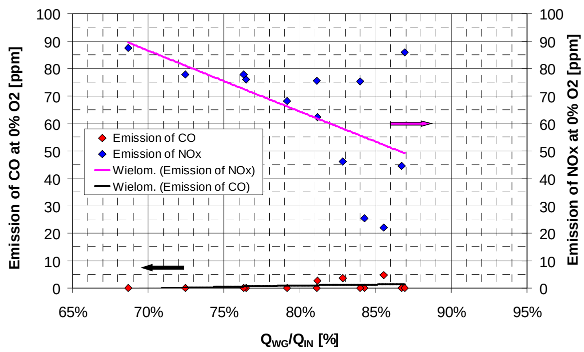


Fig. 21. Relationships between CO, NO_x emissions and the ratio of waste gas input energy (Q_{WG}) to the total energy supplied (Q_{IN})

A different situation occurs with NO_x emission. The NO_x emission slightly falls down along with an increase in the ratio of waste gas input energy to the total energy supplied. This ratio is high when the system work close to the nominal capacity. Then due to influence of the HiTAC combustion, NO_x emission is extremely low. During the system operation with the nominal capacity about

50% of the total waste gas amount is burned in the pure HiTAC mode (the F2 mode).

Additionally, it needs to be pointed out that CO and NO_x emissions in the presented system are at extremely low levels, especially when emission levels are correlated with waste gas composition and parameters (Tab. 1).

In the range of high participation of the waste gas energy in the total input energy (from 81% to 87%), differences between NO_x emissions for analogous measurements (the same participation of waste gas) carried out during an increase and a decrease in waste gas capacity can be observed. This discrepancy can be explained by the fact that the analogous measurements were done at long intervals (about 4 hours) and at that time changes of waste gas parameters probably occurred, which had influence on diversity of NO_x emission levels for the same ratio of Q_{WG}/Q_{IN}.

Relationships between boiler efficiency, exhaust gas temperature and boiler capacity are presented in Figure 22. For the nominal boiler capacity (38.0 t/h), boiler efficiency is almost 82%. Changes of boiler capacity from 20.0 t/h to 38.0 t/h have minor influence on boiler efficiency, which is in the range of 83,5% - 81,5%. It shows that the combustion process is very stable and of high quality, irrespective of natural gas and waste gas participation in the combustion process.

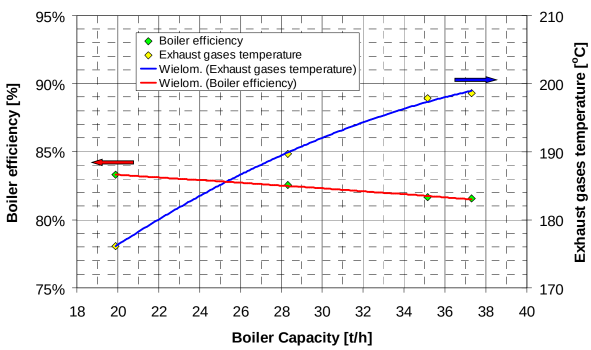


Fig. 22. Relationships between boiler efficiency, exhaust gases temperature and boiler capacity

It can be observed (Fig. 23) that if boiler capacity rises, the ratio of natural gas input energy to the total energy supplied (Q_{NG}/Q_{IN}) decreases from 26% (for 20.0 t/h) to below 15% for the nominal steam boiler capacity (38.0 t/h).

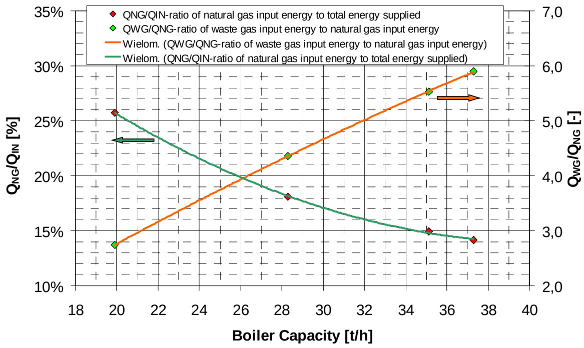


Fig. 23. Relationships between the ratio Q_{NG}/Q_{IN}, the ratio Q_{WG}/Q_{NG} and boiler capacity

In the case of operation of the utilization system with design conditions, the natural gas input energy consumption is 11.6% of the total input energy.

Conclusion

On the basis of the result from HiTAC Combustion Technology and HRS/HTB burner industrial applications the following main advantages can be drawn:

- Revamping of the typical industrial furnaces using the HRS burners with high performance heat regenerators allows to achieve about 30% fuel reduction,
- Revamping of burner system of the industrial furnaces using HRS/HTB burners allows to reduce NO_x emission at least by 50%,
- Application of the HiTAC combustion technology is a simple way to improve the product quality and increase the life time of the equipments,
- The HiTAC combustion technology has been successfully proven as the combustion technology of burning extremely low heating gas fuels.

Almost 20 years of the industrial experience and thousands of sold burners as well as good relationships with the final users of the HRS/HTB burner system results in the optimum construction of the HRS/HTB burners for different type of the applications.

The applying of the HRS/HTB burner systems, which provide the environmentally friendly combustion technology, in the European Industry is one of the way to reduce the CO_2/NOx emission.

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