Heating Industrial Furnaces Clean and Efficient

J. G. Wünning

Refractories and heating systems play an essential role for the efficiency of industrial furnaces. Heating the furnaces in a clean, efficient and cost effective way can be obtained by various measures. This article will compare different heating concepts and strategies to reduce waste gas losses and pollutant emissions.

1 Introduction

Various products are heated or heat-treated in industrial furnaces. This requires energy but often conserves energy and resources because heat-treating could modify material properties in a way that makes products lighter or suitable for special applications. An example are press-hardened parts for car bodies. Stronger material properties save material (thereby also the energy required to make the material) and reduce fuel consumption of the lighter car. The required energy for heating industrial furnaces is usually provided in the form of fuel gas, generally natural gas, or in the form of electrical energy. Liquid and solid fuels are rarely used.

2 Comparing fuel and electic heating

A comparison of different heating systems is shown in Tab. 1, assuming that a certain amount of energy is provided to the furnace. The exhaust gas temperature prior to a heat exchanger is 1000 °C for the fuel fired systems. In case of a fuel-fired system without heat recovery, the waste gas losses are about 50 % of the fuel input. That relates to a normalized fuel input of 2 (twice the heat input) and also normalized CO_2 emissions of 2 (twice the CO_2 emissions of lossless natural gas heating). If the hot exhaust gases are used to preheat the combustion air, the waste gas losses can be reduced. Typical figures for state of the art waste heat recovery systems are air preheat temperatures of around 500 °C what relates to exhaust gas temperatures of 600 °C behind the heat exchanger and corresponding waste gas losses of 30 %.

Tab. 1 Comparison of different heating concepts

Heating system	Natural gas without air preheat	Natural gas with air preheat	Natural gas with opt. air preheat	Natural gas with O_2***	Electric
Waste gas losses in the furnace*	50 %	30 %	15 %	15 %	–
Losses in the power plant	–	–	–	7 %	58 %
Primary energy** (normalized)	2	1,4	1,2	1,3	2,4
CO_2 emissions (normalized)**	2	1,4	1,2	1,4	2,6

*) 1000 °C ; **) energie mix power plants Germany (Source: BMWi); ***) O_2-generation 0,5 kWh_{el}/m^3

The normalized fuel input and the normalized CO_2 emissions for these conditions have a value of 1,4. With optimized heat exchangers, the waste gas losses could be cut in half again by preheating the combustion air to 850 °C and waste gas temperatures of only 300 °C. Such values can only be reached by regenerative or special recuperative systems. Often, the replacement of air by oxygen is proposed as an energy efficiency measure.

Actually, the waste gas losses can be reduced using oxygen but the electricity, which is required to produce the oxygen, has to be considered. Taking into account that todays systems require about 0,5 kWh_{el}/m^3 oxygen, the efficiency gains are almost compensated. If future technologies allow for producing oxygen much more efficient, the situation has to be reconsidered. By far the highest values regarding primary fuel input, CO_2 emissions and cost result in the use of electricity for heating industrial furnaces, even when assuming lossless operation.

The reasons are the high losses and CO_2 emissions at the power plants. A comparison of gas heating with electricity, which is produced in nuclear power plants is problematic since environmental risks from nuclear contamination have to be weighed up against problems resulting from burning fossil fuels. In the coming decades, a considerable part of electricity will be generated from burning fossil fuels. As long as this is the case, natural gas heating will be the best method to preserve natural resources when heating industrial furnaces.

3 Energy efficiency related to flue gas losses

Efficiency is usually defined as:

$$efficiency = \frac{benefit}{expenditure}$$

Regarding firing systems for industrial furnaces, efficiency or available heat is defined as:

$$efficiency = \frac{fuel\ input - waste\ gas\ losses}{fuel\ input}$$

or

$$efficiency = 1 - \frac{waste\ gas\ losses}{fuel\ input}$$

Fig. 1 shows the efficiency as a function of exhaust gas, or process temperature. For a system without air preheat, it becomes obvious that the efficiency is vanishing with rising exhaust gas temperature. At 1000 °C process temperature, at least 50 % of the fuel input will be lost as hot exhaust gas heat. To deter-

Joachim G. Wünning
WS Wärmetechnik GmbH
71272 Renningen
Germany

E-mail: j.g.wuenning@FLOX.com

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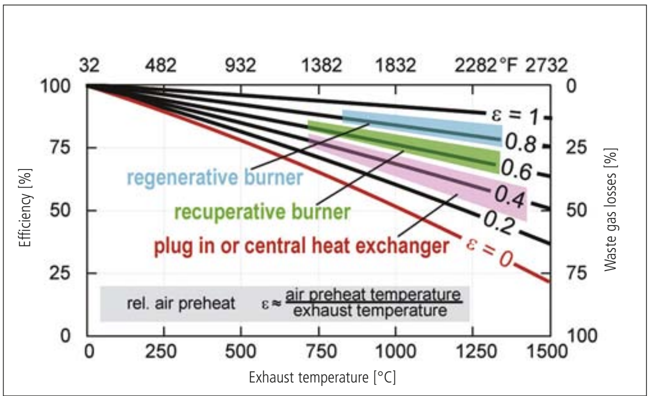

Fig. 1 Efficiency of fuel heated systems

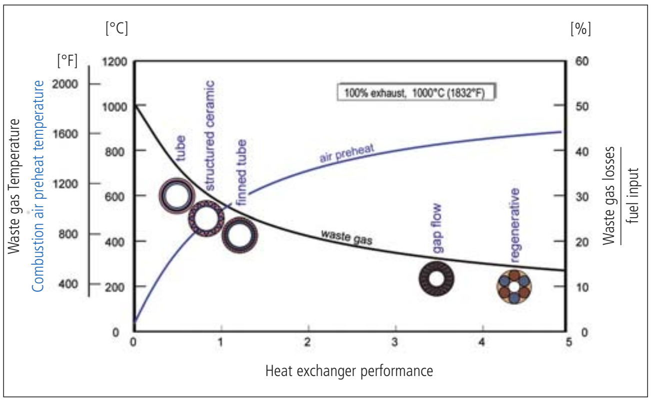

Fig. 2 Heat exchanger performance

mine the usefulness of air preheat, the relative air preheat ε can be defined as:

$$\varepsilon = \frac{\vartheta_{preheat} - \vartheta_{air}}{\vartheta_{preheat} - \vartheta_{air}} \approx \frac{\vartheta_{preheat}}{\vartheta_{preheat}}$$

with:

$\vartheta_{preheat}$ air preheat temperature [°C]
$\vartheta_{exhaust}$ hot exhaust temperature [°C]
ϑ_{air} air inlet temperature [°C]

The air preheat temperature is the temperature which is supplied to the burner. Energy losses between a central heat exchanger and the burner have to be considered. The hot exhaust temperature is the temperature of the exhaust gases leaving the furnace. In most cases this temperature is close to the process temperature. In radiant tube heated furnaces this temperature can be substantially higher than the furnace temperature. The air inlet temperature is usually ambient air and therefore the relative air preheat can be expressed as the ratio of preheat temperature to hot exhaust temperature. The relative air preheat is a good figure to characterize a heat exchanger for air preheating [1]. A heat exchanger performance is also evaluated by the NTU – number of transfer unit. The NTU are proportional to the heat exchanger area, the heat transfer and inversely proportional to the heat capacity flow through the heat exchanger.

$$NTU = \frac{k \cdot A}{m \cdot c_p}$$

with:

A - heat exchanger surface area
k – heat transfer coefficient
m – mass flow
c_p – specific heat

Fig. 2 shows the air preheat and waste gas temperatures versus NTU for counter-flow heat exchangers and a waste gas temperature of 1000 °C. What can be seen in the diagrammes is, that it is relatively easy to achieve air preheat temperatures of 400 – 500 °C with simple heat exchangers. But to gain more air preheat, requires effective counter-flow heat exchangers with large heat exchanger surface areas. To get to high air preheat temperatures (relative air preheat of 0,8 – 0,9), requires heat exchanger surface areas which are 5 to 10 times as large. The savings can be calculated as:

$$savings = 1 - \frac{low\,efficiency}{high\,efficiency}$$

That translates to savings of 20 % if a system with 68 % efficiency is upgraded to 85 % efficiency.

4 Exhaust gas losses

Finned tube recuperative burners or plug-in recuperators are state of the art for heat-treating furnaces. They have been widely used since the energy crisis in the 1970s and early 1980s. In the 1990s, due to stagnant or actually falling energy prices (inflation-adjusted), little was done to further improve the efficiency of recuperators. In some cases, making heat exchangers simpler and cheaper even lead to a loss in efficiency. Examples are, plain tubes instead of a finned tube recuperator or increasing burner capacity without increasing the heat exchanger surface area. The market was rather asking for increased power and higher operating temperature, which was enabled by the use of ceramic heat exchangers and other ceramic burner components. In some areas it was common to install cold air burners without any heat recovery even for high temperature processes. Due to higher energy prices and climate change discussions, it is widely acknowledged that more effort is needed to preserve energy. Using a heat exchanger for combustion air preheating is the measure for high temperature processes, which offers the largest energy cost savings with the lowest expenditures. Today, this potential for energy savings is not at all fully utilized in heat-treating furnaces.

5 NO_x emissions

The issue of NO_x emissions is closely related to air preheating. For natural gas combustion, only thermal NO formation is technically relevant. Thermal NO formation, as the name indicates, is depending on combustion temperatures. Since peak flame temperatures rise with increasing air preheat temperatures, this leads to not acceptable high NO_x emissions if no appropriate countermeasures are applied. While in the 1990s only little was done to increase efficiency, a lot of progress was made to reduce NO_x emissions [2]. As an example, the German clean air standard TA-Luft 86 set a NO_x limit of 250 ppm for many heat-treating furnaces which represented a problem for many burner models [3]. Therefore, an allowance for higher emissions was granted for a transition period for systems using preheated combustion air. It was possible to comply using high-velocity burners in combination with pulse-fired systems. The development of air-staged burners and other low NO_x measures lead to further reduction of emissions [2]. The invention of flameless oxidation (FLOX® – registered trade mark of *WS Wärmeprozesstechnik GmbH*, Renningen/DE) enabled to suppress NO formation even with extremely high-preheated combustion air. NO_x emissions of less than 100 ppm and under certain conditions even below 50 ppm could be guaranteed for direct and indirect fired applications. Flameless oxidation is based on the internal recirculation of hot combustion products [1]. Recuperative burners, which utilize the principle of flameless oxidation, were first installed in large numbers in a

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horizontal strip processing line for silicon steel in 1994 [4]. Both burner types, which will be described below, are utilizing the principle of flameless oxidation and achieve very low NO_x-emissions despite very high air preheat temperatures.

6 Regenerative burners

The principle of regenerative air preheat is long known and was already used in Siemens-Martin furnaces in the 19th century. Still today, the majority of glass-melting tanks are built in a similar design. During the 1980s, projects for applying the regenerative air preheaters, also for burners with less capacity, were carried out in the laboratories of *British Gas* [5]. A problem was the NO_x emissions, which easily exceeded 1000 ppm due to high air preheat temperatures. Further developments were carried out mainly in Japan, USA and Germany for burners in the megawatt range for usage in large steel reheat and aluminium melting furnaces. In 1996, a continuous annealing line for stainless steel strip was equipped with a new type of regenerative burners. These

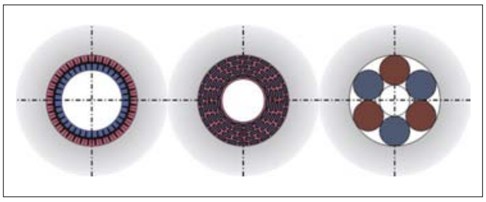

Fig. 5 Cross sections of heat exchangers

Fig. 6 Gap flow burner

Fig. 7 Gap flow burner in operation

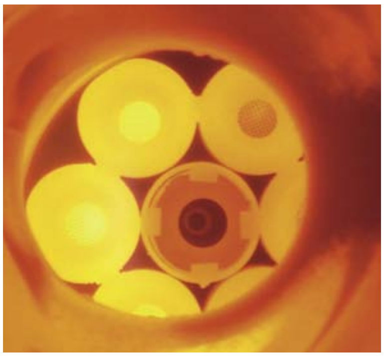

Fig. 4 Regenerative burner in operation

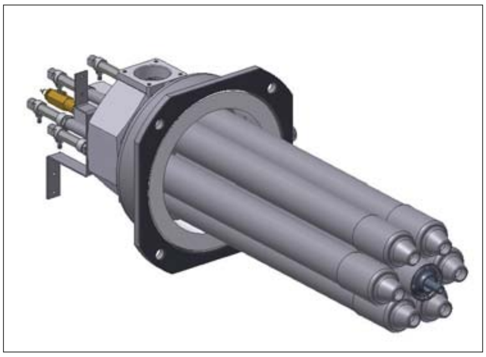

Fig. 3 Regenerative burner

200-kW burners were not designed as pairs but as single regenerative burners, working with the principle of flameless oxidation. Even for air preheat temperatures of more the 900 °C, the NO_x emissions could be kept < 50 ppm [6, 7]. To apply such a regenerative burner in a radiant tube, all components had to be designed even more compact. This was possible by using optimized regenerators, fluid flow optimization and a switching cycle of only ten seconds. Installed in double-P tubes, combustion efficiency of more than 80 % was achieved. The exhaust gas temperature averages at 300 °C for exhaust gas inlet temperatures of 1000 °C. This corresponds to waste gas losses of only 15 % and savings of 15 – 20 % compared to finned recuperative burners and > 40 % compared to cold air burners. With todays energy prices, the additional investment for regenerative burners versus recuperative burners is compensated after less than 10 000 operating hours, what relates to about one and a half years in continuously operated plants. Fig. 3 shows a regenerative burner, Fig. 4 shows this burner in operation.

7 Gap flow recuperative burner

Regenerative burners offer the highest potential for heat recovery. If burner capacities of less than 100 kW are required, they are not always economical with today's energy prices. The goal of a new development was a burner system, which achieves almost the efficiency of a regenerative design with a recuperative design. This goal was met by a larger heat-exchanger surface area and a better heat transfer. Therefore, the combustion air is distributed to a large number a small recuperators. The flow in small gaps provides high heat transfer coefficients. As shown in Fig. 5 the flow arrangement has a three-dimensional character, compared to the two-dimensional arrangement of tube-in-tube heat exchangers. The regenerative heat exchanger is also realized as a three-dimensional structure. The gap flow recuperative burner can be realized in identical dimensions as finned tube recuperative burners with similar pressure drops for air and exhaust. Compared to a regenerative burner, no exhaust suction fan is required. The gap flow recuperative burner is utilizing the principle of flameless oxidation and can provide very low NO_x emissions. Fig. 6 shows a gap flow recuperative burner, Fig. 7 shows this burner in operation. The exhaust gas temperature is about 350 °C for 1000 °C exhaust gas inlet temperature. This corresponds to waste gas losses of less than 20 % and energy saving of 10 – 15 % compared to finned tube recuperative burners. Several burners of this design are operating in a heat-treating plant for bolts since the spring of 2009.

8 Conclusions

Combustion air preheat represents are large potential for increasing the energy efficiency of heat-treating processes. Modern burner design allows reliable, low emission operation.

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