Technical and operational measures to increase energy efficiency of industrial furnaces

by Dominik Schröder

The measures, which are traditionally taken for energy saving, aim at the selection of the most adequate heating system. Due to the burner manufacturers’ endeavours to further increase the efficiency, recuperators have been improved and regenerators have more thoroughly been designed to the process. No doubt that these measures are correct and important, but they only represent one possibility of energy saving. The efficiency is improved by only a few per cent.

The seven possibilities described herein below reveal a considerably high potential to save energy, if the research work does not only focus on the optimization of the heating system. The following examples and measures mainly refer to reheating furnaces (Fig. 1) and heat treatment furnaces (Fig. 2).

OPTIMIZATION MEASURES IN FURNACE TECHNOLOGY

Optimization of heating systems
An expansion of the heat exchanger surface evidently improves the combustion efficiency of recuperator burners. In case of existing recuperator burners, it is striking that the specific heat exchanger surface decreases with increasing burner capacity. In other words, smaller recuperator burners feature better combustion efficiency. It is generally known that a doubling of the heat exchanger surface only results in a minor improvement of the combustion efficiency. In this case, the combustion efficiency of the smaller recuperator burners should be modelled on the recuperator burners with larger capacity.

The actual situation reveals that the combustion efficiency can be improved by using several smaller recuperator burners instead of few high-capacity recuperator burners. In terms of process technology, the more uniform energy input into the furnace can be advantageous. A small recuperator burner is, however, disadvantageous, if the
impulse from large recuperator burners is indispensable due to its size.

In case of regenerators, the combustion efficiency is only granted, if the regenerator filling is not clogged by dirt, which may happen with honeycomb recuperators and ball fillings. Obviously, the clogging is due to dust-loaded processes. Cases are known of regenerators clogged during high-temperature heat treatment processes – particularly of some kind of stainless steels – which are supposed to be dust-free. In case of molybdenum-containing metals, the molybdenum evaporates, MoO$_2$ oxidizes and sublimates in the regenerator filling. As a consequence of the reduced available heat exchanger surface, the combustion efficiency is substantially impacted.

Therefore, it is essential to always consider measures taken at the heating system in connection with the entire plant and the plant-internal processes.

**Indirect heating**

Many processes require indirect heating which is implemented by either an electrical heating system or a radiant tube heating with gas burners. If a radiant tube heating with gas burners is used, the burners must be designed in consideration of the fact that the radiant tubes must not transmit more energy than the furnace is able to absorb (see Fig. 3). This is based on purely physical conditions of the radiation exchange between two bodies with a defined surface and temperatures.

Regarding the design of the radiant tube heating, it must be considered that oversized burners increase the waste gas temperature. Consequently, the combustion efficiency will be reduced. A considerably oversized burner may lead to damages at the radiant tube, at the flame tubes and at the burner itself.

**Direct heating**

The correct waste gas routing plays an important role in directly heated continuous furnaces. The proper waste gas discharge is illustrated in Fig. 4. Having left the heating-up zones, the waste gas has usually not yet reached the process temperature. If the waste gas from the heating-up zones is led to the waste gas stack via the holding zones, the holding zones need to be heated additionally. In terms of process technology, this means that the heating good will reach the holding temperature only later. The waste gas leaves the furnace at a higher temperature so that the combustion efficiency of the furnace is reduced. It is possible to recuperate the waste gas heat, which, however,
requires far larger heat exchangers.

**Oxygen control in the furnace**

There are two possibilities to reduce the oxygen content in the waste gas of a furnace. It is generally known that a low oxygen concentration indicates a higher efficiency as only a minor amount of excessive air needs to be heated to the waste gas temperature.

The first of these two possibilities comprises the measurement of oxygen concentration in the waste gas and the control of the gas pressure or combustion air pressure of the burners via the combustion air fan speed so that the oxygen concentration will constantly be kept to 1.5% in the waste gas volume flow. This possibility is, however, only feasible for furnaces with a process temperature exceeding the self-ignition temperature.

The oxygen concentration in the waste gas flow can also be kept low by a pressure control as function of the operation characteristics of the combustion air fan. To put it in concrete terms: If all burners of a furnace are fed by a combustion air fan, 10% less pressure will be built up compared with a volume flow of 50%. In this case, the pressure will also be compensated via the speed adjustment of the combustion air fan. In contrast to the first possibility, this alternative is not restricted to furnaces with a process temperature exceeding the self-ignition temperature, but it is also applicable to the heat treatment of aluminium or to radiant tube heating.

**Division of the furnace heating system**

What about burner distribution respectively division of the heating system in the furnace?

This question can easily be answered: As much heat energy as discharged by the heating good at the respective point in the furnace must always be installed, which is illustrated in Fig. 5. In case of continuous furnaces, the heat amount to be discharged results from measurements of the temperature distribution along the furnace length.

A uniform energy supply to the furnace must also be ensured at those points where the heating-up process has been completed and the subsequent holding time has started. These points also require a uniform burner distribution to compensate furnace heat losses.

In case of chamber furnaces, the time-wise temperature development must be recorded at various points of the furnace to find out how much heat energy needs to be installed at the respective points. For sure, the design must also consider the combustion efficiency, furnace heat losses via the walls, floor and ceiling as well as losses via heat bridges, rollers and door opening. Moreover, the heating of the protective or process gas is an essential factor to be taken into consideration.

**Losses due to door opening and radiation**

Fig. 6 shows a preheating furnace for forged steel parts with a door surface of 2 m². Due to thermal deformations, the door can no longer be shut; the consequential energy loss amounts to approx. 2,000 kW. A more serious problem is caused by the penetrating cold air. It does not only cool the furnace floor, but also introduces oxygen into the furnace, which additionally promotes the scaling.

A continuous furnace additionally requires a control reserve so that e.g. the heating-up zone can be heated up within short upon charging of a new heating good. This new cold charge must not cool down again the previous charged and already heated goods. A critical situation will arise, if the previous charge has already reached the holding temperature and is now cooled down by the new charge to a temperature below the holding temperature. The control reserve must be large enough to keep the zone temperature at the nominal temperature, even if the charge is still cold. Consequently, the control reserve capacity may be twice or even three times the calculated required capacity. The capacity of the control reserve should not been integrated via one burner (in that case the controllability in the low-load range would not be sufficient), but via at least two burners so that the entire range of low and full load can be properly controlled.

**Optimization of insulation**

The insulation materials are frequently selected only from the economic point of view by considering preferably the investment costs and not the operation costs. This procedure is understandable, as a furnace plant, in which the best insulation material will be installed, can no longer be offered at a competitive price.

Microporous insulation materials have been available on the market for more than 20 years. They dispose of the
property that the air molecule in the pores can no longer oscillate as function of temperature. Compared with similar fibre ceramics, these microporous materials distinguish themselves with an up to ten times better insulation effect. As they must not be used at a temperature of more than 800 °C, they have to be installed in the middle of the wall structure – in combination with other insulation materials.

The temperature curves for a 250 mm thick wall insulation structure with and without microporous intermediate layer are compared in Fig. 7 and Fig. 8.

The heat loss in furnaces with an operation temperature of 950 °C and a low-cost standard insulation amounts to approx. 1 kW/m². A maximum of 500 kW can be saved in a 70 m long, 3 m high and 5 m wide furnace, if microporous insulation materials are integrated, which is equivalent to a saving of more than € 200,000 per year for a natural gas heating and an operation time of 8,000 h/a. As the additional costs for the microporous insulation materials amount to € 150,000 the return on invest can already be achieved after nine months.

**Losses due to door opening and convection**

In accordance with the specified normal operation, the opening of furnaces for charging purposes cannot be prevented. The charging and discharging of heating goods usually take place via opened doors. The doors of chamber furnaces are less frequently opened compared with the doors of continuous furnaces. It happens that the doors on the charging and discharging side of continuous furnaces are opened every 5 minutes for up to 30 seconds each. Cold air can penetrate into the furnace during 20 % of this period. According to measurements, a maximum of 0.3 m³/s of the atmosphere is exchanged in case of a door opening of 1 m². Fig. 9 shows an unbalanced flow distribution of the incoming and escaping atmosphere, which is due to the different densities. In this case, a capacity of 1,000 kW is lost at an operation temperature of 900 °C. Whereas the lost capacity directly impacts the operation costs, the already heated charges in the furnace floor area are cooled down again by the uncontrolled penetration of cold air into the furnace. This in turn leads to a non-uniform temperature distribution and quality losses.

![Fig. 7: Standard temperature curve](image1)

![Fig. 8: Temperature curve with micro-insulation](image2)

![Fig. 9: Flow ratios at the door of a furnace heated to 900 °C](image3)

![Fig. 10: Hydrogen combustion in a bell-type furnace](image4)
The heat losses due to door opening can be reduced by an air curtain, which is not a new, but nevertheless highly effective idea. Referring to the example above, the heat losses due to door opening can be reduced by one third so that a heating capacity of more than 600 kW can be saved.

**Internal combustion of process gas**

Combustible gases are used for carburization or bright annealing processes. These gases are far too often flared as this is the easiest method. To maintain the furnace atmosphere particularly in indirect heated continuous processes, substantial amounts of combustible (reaction) gases are fed into the furnace at different points and flared afterwards. Alternatively, this gas could be used in a controlled manner for heating the furnace. The use of hydrogen in a bell-type furnace with hydrogen atmosphere is illustrated in Fig. 10. In this example, a heating capacity of 50–500 Kw can be achieved.

As the use depends from the furnace pressure, no stable heating capacity is available. Therefore, the heating capacity can only be used in the heating-up zones where the temperature is not fine-tuned to a specific reaction temperature. Also in this case the investment costs are amortized within a short time due to the saving of natural gas.

**OPERATIONAL OPTIMIZATION MEASURES**

**Coupling processes**

A heat treatment of steel or aluminium usually consists of the following processes: austenitizing/solution annealing, quenching and tempering/ageing.

Recoverator burners are preferably used for the austenitizing process. At this time, the waste gas temperature is still higher than 500 °C. The subsequent tempering is executed at temperatures between 200 and 650 °C. The tempering furnace is usually installed next to the austenitizing furnace so that the heating-up zone of the tempering furnace can easily be fed with the hot waste gas without long and complicated piping being required. Fig. 11 is a scheme for a coupled austenitizing- and tempering furnace. In case of temperature-controlled bypass control, it is possible to use up to 100 % of the remaining waste gas energy of the austenitizing furnace.

The heat treatment of aluminium is carried out in a similar way. Cold air burners are used for the solution annealing so that the waste gas has a temperature of 400–500 °C. Ageing processes are executed at a temperature of max. 230 °C so that up to 100 % of the waste gas of the solution annealing furnace can be used for a temperature-controlled bypass control.

Depending on the furnace size and capacity, it is possible to internally use a capacity of 200–1000 kW. In case of directly heated furnaces, the additional flue gas amount results in an increased atmosphere recirculation in the furnace and consequently in a more uniform heating up of the charge.

**Air in factory hall**

Practice shows that the doors of factory halls are wide opened – particularly in summer – to improve the air in the halls. The resulting draught in the halls is associated with an increased heat transfer coefficient at the furnace plants. As the associated increased surface heat losses only amount to 1–2 % of the total surface heat losses, they can be neglected.

The heat losses due to door opening were already dealt with above. A draught in the factory hall (see Fig. 12) also impacts the furnace with open doors. The heat losses due to door opening increase by max. 20 % up to 200 kW. As it
Heat Treatment

Is absolutely necessary to open the doors of some factory halls in summer because of the very high indoor temperature, it must be considered in the design phase not to install the furnace plants in the factory hall in draught direction.

**Furnace Charging**

As function of the operation temperature, a furnace suffers from waste gas losses, surface heat losses and losses via heat conduction for inspection glasses, measuring points, rollers, fans and burners – no matter whether the furnace is empty, half-loaded or fully loaded. The simple scheme in **Fig. 13** shows that the specific surface heat losses of a half-loaded furnace (losses/throughput) are as twice as high in comparison to a fully-loaded furnace.

If possible, a furnace should always be operated at full load, which also helps to stabilize the temperature distribution in the furnace. If gaps occur in continuous furnaces between the charges, the zone control is hardly in a position to maintain a uniform temperature field without considerable increase of the measuring and control efforts.

A uniform charging is of importance for both, chamber and continuous furnaces. The heating goods should feature identical or similar size and wall thickness. This means that the heating-up time and the process times should be the same for the charges. The process times are based on the holding times required for different alloys. In case of heterogeneous charges, the heating-up time is determined by the thickest heating good, while the holding time is defined by the diffusion and transformation processes.

**Extension of balance scope**

If there is no possibility to internally use the waste gas energy, it must be checked how the waste gas can be used in the surroundings of the furnace plant. The simplest way is to use the waste gas energy for heating pre- or post-treatment baths, for heating water to be used as industrial water or for heating air required in the factory hall heating system. If the waste gas only has a temperature of 100–200 °C, it is most efficient in the above-mentioned application fields. In addition, if hotter waste gas is available, the best efficiency is achieved in heating water or air for the factory hall heating system. In case of higher temperatures, the waste gas energy can also be used for other applications.

It is e.g. possible to use it for the generation of cooling energy or electricity. ORC-processes (Organic Ranking Cycle), steam generation and decompression via turbines are available for the generation of electricity. The conversion into electricity, however, works at a very low efficiency. Depending on the waste gas temperature, efficiencies between 8 and 12 % can be achieved [Source: Specht, FOGI report].

**Process coupling**

I do not refer to new processes; instead I suggest the coupling of processes without suffering from inferior quality. Should the plate cooling prior to the heat treatment prove to be indeed no longer needed due to the thermomechanical rolling process, much energy could be saved. This is very similar to forged parts. In terms of energetics, a heat treatment using the forge heat would be optimal. The potential comprises the process steps of all metal alloys and is thus not limited to steel and aluminium. The implementation would be feasible from the plant-technological point of view. New alloys and process steps will pave the way for the microstructure fulfilling the required outstanding mechanical properties.

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**Fig. 13:** Influence of furnace load on specific surface heat loss
SUMMARY
Consuming about 2500 TW/a (50 % consumption of electricity and gas), the German industry ranks among the major energy consumers. The above-mentioned potential describes the actual state-of-the-art technology and could immediately be implemented or upgraded. According to my cautious assessment, 10 % energy could be saved as a minimum, if the above-mentioned measures were partly implemented. If the entire potential were used, a saving of 20 % energy, i.e. 500 TW/a would even be realistic and Germany would be relieved by 100 million t/a CO₂.

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