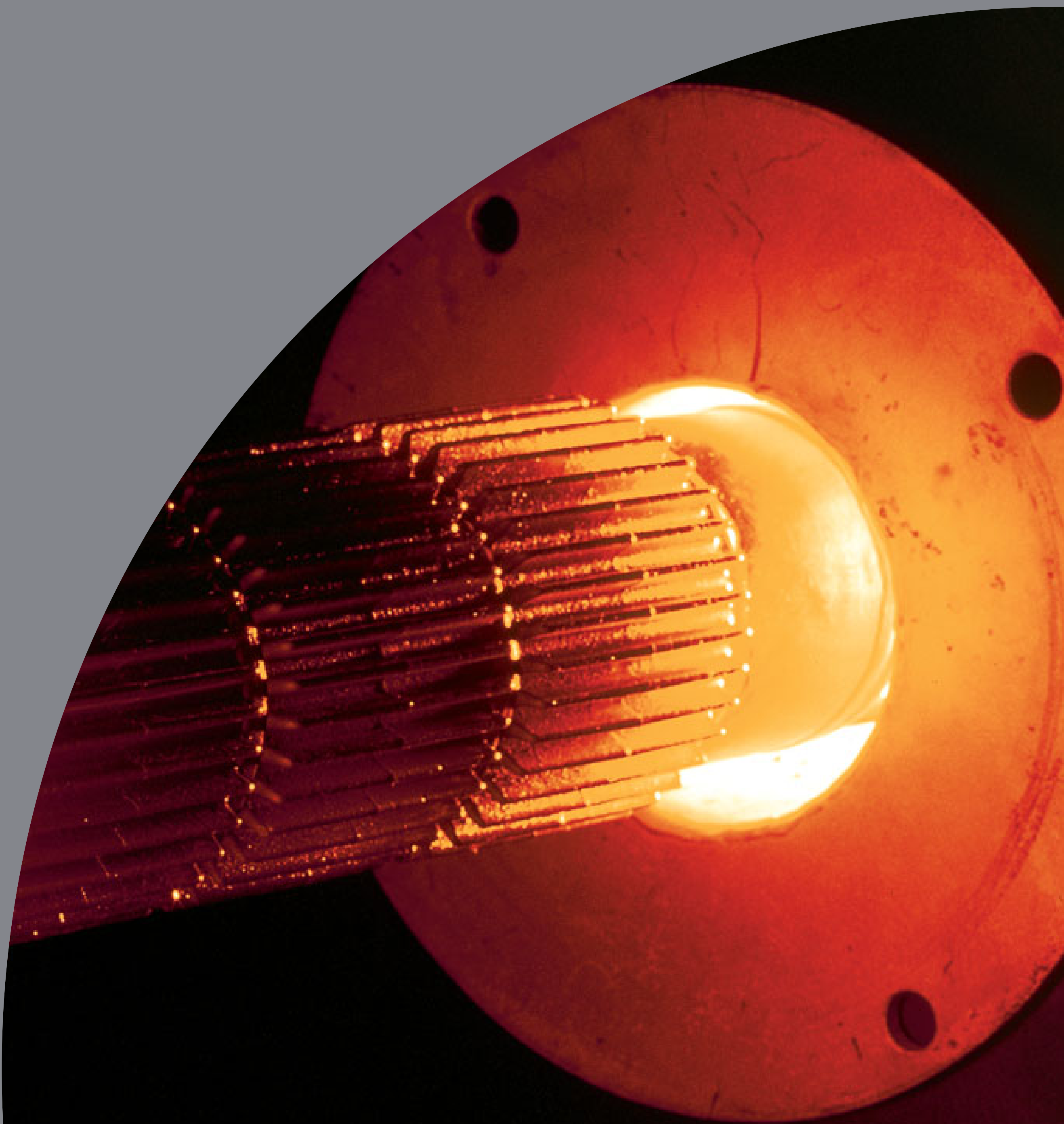
Thermo Process Technology

Energy Efficiency Manual for Thermo Processing Plants



Contact

VDMA
Thermo Process Technology
Dr. Franz Beneke

Lyoner Straße 18
D-60528 Frankfurt am Main
Phone +49 69 6603-1854
Fax +49 69 6603-2854
E-Mail franz.beneke@vdma.org
Internet www.vdma.org/thermoprocessing

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Foreword

Foreword

This manual has been drawn up by a working party consisting of members of the Thermo Process Technology specialist association of VDMA and FOGI – the Industrial Furnace Research Association.

The manual is intended to indicate the potential for energy efficiency improvement and to provide the designers and operators of thermo processing plants with suggestions in this context.

We wish to thank everyone who has taken part in the production of this manual.

1 Energy efficiency of thermo processing plants

In the 27 member states of the European Union, industry accounts for about 25 percent of final energy demand. Process heating has an overwhelming share in industrial energy demand. The operators of thermo processing plants, i.e. industrial furnaces, are therefore among the largest energy users in Europe.

The high energy demand of thermo processes results in considerable costs. Every year, plant operators in Europe face energy bills totalling more than a hundred billion euros.

In addition to energy and environmental policy aspects, the reduction in the specific energy consumption of thermo processing plants is therefore of considerable importance in lowering production costs.

Improved energy efficiency is a key target for 2020 in Europe and will also be a major factor in the achievement of long-term energy and climate protection objectives. Higher energy efficiency is the most economical way of lowering emissions and making European industry more competitive.

Despite the advanced stage of development of thermo processing technologies and processes now in use, there is still considerable potential

Changes in greenhouse gas emissions in Europe (EU27)

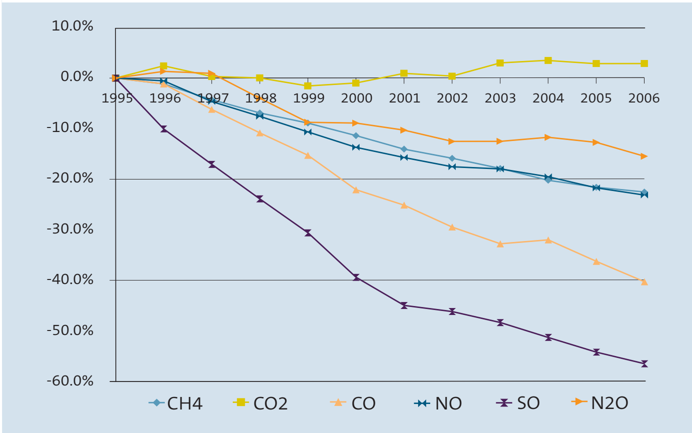


Fig. 1.2 Source: Eurostat

for energy saving. Especially in view of economic aspects, this potential will need to be exploited systematically in the future.

Development of energy consumption in Europe

Fig. 1 indicates that total energy demand in Europe has risen by about 10% since 1990, while industrial energy demand has fallen by about the same percentage over the same period.

A consideration of greenhouse gas emissions (Fig. 1.2) shows that especially emissions of nitrogen and sulphur oxides have fallen. These effects are the result of industrial restructuring over the past 15 years and the continued development of combustion systems.

However, the carbon dioxide situation is unsatisfactory, with a renewed increase in emissions since 2002. CO_2 mitigation means reducing the use of fossil fuels or the more effective utilization of energy, in other words energy saving and efficiency enhancement.

Each cubic metre of natural gas saved reduces CO_2 emissions by 1.07 m³. Each kilogram of fuel oil saved reduces CO_2 emissions by 1.60 m³.

Development of End-Use Energy by Sectors use in Europe

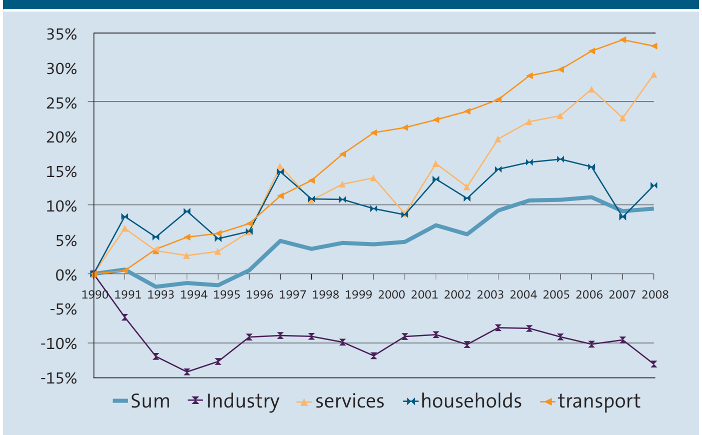


Fig. 1.1 Source: Eurostat

Change in electricity prices in selected European countries

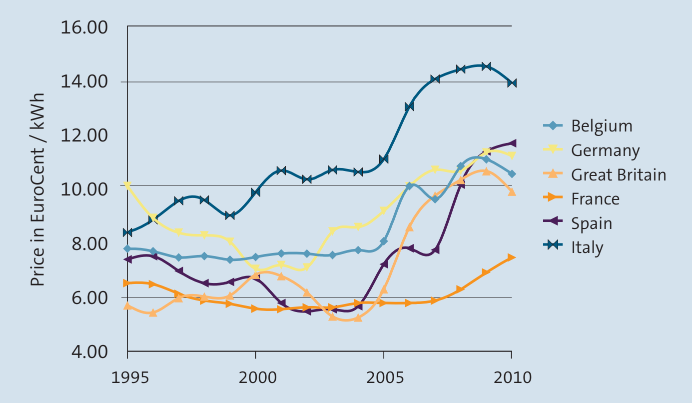


Fig. 1.3 Source: Eurostat

Reduced electric power consumption also improves the CO2 balance as power generation also causes significant CO2 depending on the specific energy mix.

Energy saving and energy efficiency

Energy saving and energy efficiency are terms which are well-known in the household sector as sales arguments and decisive factors when purchasing air conditioning and heating systems. These aspects are also becoming increasingly important in the engineering industry, especially in thermo processing, and in the component supply industry.

Thermo processing plants, or industrial furnaces, have been at the centre of public debate over the past few years because they are among the largest industrial energy users as a result of the processes employed. Efforts led by the European Union are therefore in progress to limit the energy demand of thermo processing plants.

- In the Ecodesign Directive, the European Union lays down requirements for the environmentally compatible design and development of products. In this context, industrial furnaces are in the spotlight. Studies are in progress on future adaptation of energy limits and/or specific energy consumption restrictions.
- The EU member states have undertaken to reduce their greenhouse gas emissions by 20 percent by 2020. This figure is to be raised to 30 percent if an appropriate international agreement can be conclude
- The agreements reached under the Kyoto Protocol expire in 2012. Industrial furnaces are normally not yet affected by CO2 emission trading. However, the possibility that the European Union may change its assessment criteria in the future cannot be excluded. Depending on the industrial sector, inefficient plants would then face additional levies.

Energy costs are rising

Energy costs in Europe are rising now and will continue to rise in the future. In many countries in Europe, electric power prices for industry have surged dramatically by up to 60 percent since 2000. In some countries, gas prices have even risen by more than 300 percent since 1999.

Development of electricity and gas prices in Europe

- Belgium
- Germany
- Great Britain
- France
- Spain
- Italy

Change in gas prices in selected European countries

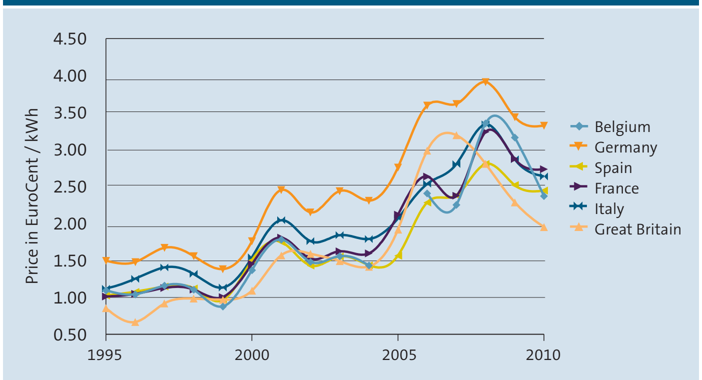


Fig. 1.4 Source: Eurostat

General areas of efficiency improvement

In addition to energy saving potentials in certain sectors (such as thermo processing), there are certain areas where efficiency improvements would be possible in all sectors of industry.

These include:

- Pumps and pumping systems
- Fans and fan systems
- Drive systems e.g. electric motors)
- Steam generation and refrigeration
- Compressed air systems
- Industrial lighting
- Industrial space heating and air conditioning
- Cogeneration (combined generation of heat, power and cold)
- Water cooling systems

Comparison of the energy demand of a simple and an advanced thermo processing plant for a specific application

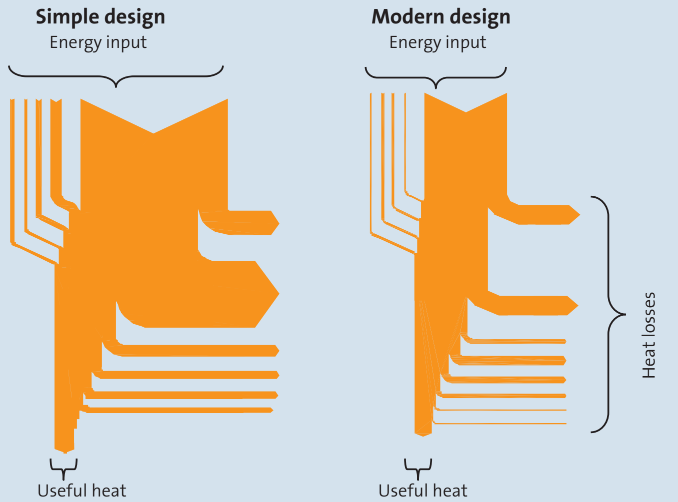


Fig. 1.5

Industrial furnaces: energy saving at all levels

Many plant operators are not aware that energy efficiency is by no means a new topic for industrial furnace producers. A comparison of the energy demand of thermo processing plants built a few decades ago (or even earlier) with more modern plants indicates that energy losses have steadily fallen.

The savings potential depends on the age of a thermo processing plant. Some modern plants use a third less energy than older plants. Even in the case of new plants, energy savings of up to 15 percent can be achieved by optimizing the plant design, integrating the plant into the production process in heat energy terms or utilizing waste heat from the plant.

The energy flows determined on the basis of an initial analysis of thermo processing plants can be presented in the form of a Sankey diagram (Fig. 1.5).

The diagram compares the energy demand of old and new, or simple and advanced industrial furnaces. The schematic diagram indicates energy flows and possible savings potentials.

Application in practice

Normally, thermo processing plants are complex and are produced to order in line with customers' specifications. The customer provides details of the thermo process and the material to be treated while the plant producer contributes knowledge of alternative processes and plant types in discussions with the customer.

The furnace producer then designs an overall plant; parameters such as fuel, air water, power and utility requirements are determined by the specifications.

The plant consists of a large number of individual modules (furnace frame, casing, heating system, atmosphere gas supply system, conveyor systems, etc.) which the furnace producer assembles on the basis of its experience and the requirements of the operator.

Only certain base data (such as furnace type and heating system) are agreed with the customer and the individual components are designed by the producer.

The furnace producer therefore plays a key role in determining the design and energy consumption of the plant.

Selection of plant type and heating system

The type of plant selected plays a key role in determining energy consumption. If the plant operator does not require a specific plant type and the plant type is not limited by the space available, the following variants may be considered for a furnace plant comprising a preheating furnace, a soaking furnace and a cooling section for example:

Variant 1: Separate preheating and soaking furnaces and cooling chamber (three-chamber pusher-type furnace plant)

Variant 2: Three-zone furnace with preheating, soaking and cooling zone (single-chamber pusher-type furnace

Variant 3: Separate preheating furnace, rotary hearth furnace and cooling chamber (flexible three-chamber furnace)

Variant 4: Rotary hearth furnace with three zones

The second major factor which determines the energy demand of a plant is the heating system selected. The capital cost and operating expenses must be considered. If a specific type of heating system is not required for process reasons, the following options may be available:

- Gas-fired, oil-fired or electric heating
- Direct or indirect heating
- Inductive or non-inductive heating
- Various types of electric heating

The resource efficiency (e.g. burn-off and metal losses) and environmental impact must also be taken into consideration. Factors which must be included in the analysis include the need for a flue gas system (including space requirements), additional electrical equipment and units and control systems, etc.

General rule

The most effective way to reduce energy consumption is to analyse the overall process and to consider the possibility of waste heat utilization. Energy recovered and used within the thermo processing plant or in other parts of the facility reduces energy costs.

What possibilities are available?

Example 1: The waste heat contained in the flue gas of a burner system may be used for air preheating.

Example 2: The waste heat from a reheating furnace in the steel or ceramics industry, with temperatures above 1000°C, may be used for heating a preheating furnace, with temperatures of about 300° C.

For further details, see Section 4, "Process optimization".

Depending on the process and the plant type, there may be further potential for energy saving in other areas, such as:

- The design of the furnace wall (see Section 2)
- Heating system, burner design (See Section 3)
- Air and fuel preheating (See Section 3)
- Reducing the energy consumption of ancillary systems (see Section 4)
- Reducing waste heat losses in connection with utilities and conveyor systems (see Section 5)
- Intelligent control systems
- Management of peak power loads
- Selection of charge materials by type and size (for melting)
- Type and design of electrical switchgear and transformers
- Type and design of heating system conductors, induction coils and inductors

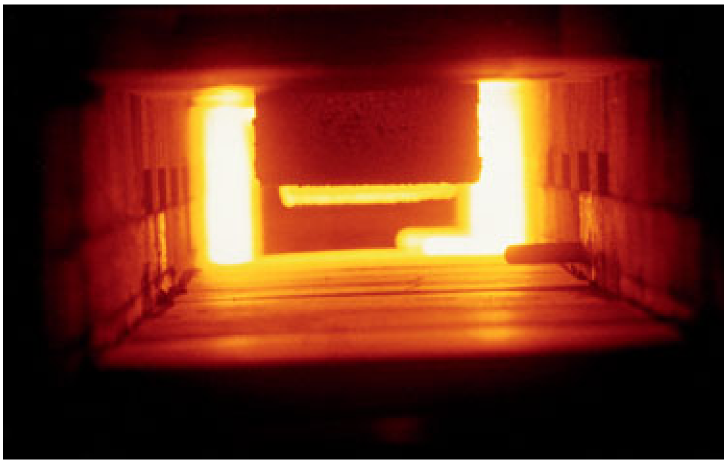
Basic principles:

- The energy actually required as a result of the process can only be reduced within very narrow limits.
- Furnace doors should be as small as possible (manipulators or robots may be used for charging).
- Furnace doors should be opened for as short a time as possible.
- Charge trays must be heated and cooled with the charge (the heat capacity of the material must be taken into consideration).
- The charge trays must be adapted to the charge (the ratio of charge mass to tray mass must be optimized).
- Openings should be tightly sealed.
- Intelligent plant designs combined with new heating/burner systems, waste heat recovery systems, process simulation, advanced control systems and new materials for new and upgraded plants really reduce energy losses.
- Enhanced energy efficiency often brings benefits in terms of process security and product quality.
- Charging losses should be minimized, for example using vestibules.
- Waste heat can be utilized for charge preheating (should be integrated in furnace).
- Counter-current heat exchangers are more efficient than co-current units.
- Apart from temperature control, intelligent furnace control systems also include furnace pressure control functions as well as the automation of the charging and/or discharging sequence.
- In the case of new plant projects, plant purchasers and operators must be prepared to carry out a holistic analysis of energy use and to provide the means for optimization.
- etc.

When should you pay attention to the energy efficiency of your industrial furnace?

There are various signs which may indicate that the energy consumption of an industrial furnace is excessive:

- For example, if the outer wall of the furnace is too hot. In the case of coated metal surfaces, the temperature should be well below the admissible limit of 85°C. If the temperature is higher, the thermo insulation of the furnace is not effective.
- If the flue gas temperature downstream from the burner is too high. This temperature should be significantly lower than the furnace temperature.
- If the coolant does not flow through a heat exchanger. This is the most environmentally compatible way of producing hot water for your company.
- If the burner uses combustion air that has not been preheated. Air preheating represents the greatest savings potential.
- If the energy contained in the burner flue gases is not utilized. It can be used for preheating the combustion air or the charge material of the furnace. Waste heat recovery represents significant savings potential.
- If the burner receives more air than is actually needed for the combustion process. The ideal excess air ratio is 10%.
- In the case of water-cooled plants, if the water return temperature is too high even though the cooling water flow rate is adequate.
- If the furnace has leaks. The doors and inspection ports must be effectively sealed.
- If the furnace cools rapidly in soaking operation (e.g. as a result of missing sealing devices such as covers, valves and flaps, etc. or as a result of a lack of furnace pressure control functions).
- If there are severe fluctuations in the soaking temperature (e.g. as a result of missing or inadequate temperature control).
- If the furnace is operated with complex processes without using a process control model and the control systems are outdated.
- If thermographs indicate weak points.
- If all the electric motors are not equipped with frequency converters.
- If maintenance has been neglected.



Outlook

Industrial furnace manufacturers are the first port of call when considering improvements to the energy efficiency of thermo processing plants. On the basis of many years of development work and their experience with the construction of new plants as well as the refurbishment and modification of old plants and the integration of thermo processing plants in the manufacturing process, manufacturers are well-positioned to provide competent advice.

It not only makes business sense to reduce the energy consumption of an industrial plant; it is also an economic necessity.

Public discussions underline the fact that companies cannot avoid their responsibility for the environment.

The members of the specialist Thermo Processing Plant Association of Verband Deutscher Maschinen- und Anlagenbau (VDMA) have prepared this manual to provide suggestions on measures to improve energy efficiency.

If you have specific questions concerning efficiency enhancement, you are recommended to contact the manufacturer of your thermo processing plant.

Operators, manufacturers and the public can only achieve their common objective of saving energy and reducing CO2 emissions through comprehensive knowledge of the relevant technical conditions and possibilities.

The specialist Thermo Processing Plant Association offers training for operators of thermo processing plants.

Efficiencies

Thermo processing plants can be assessed and compared from the technical and economic point of view on the basis of their efficiency figures.

"Efficiency" is normally defined as the ratio between input and useful output.

When analysing the efficiency of a plant, the first step is to define the limits of the system analysed.

All the heat and material inputs and outputs at the system limits must then be determined or defined.

Note:

In the following formulae, the terms power P, thermo flux $\dot{Q}$ and enthalpy flow $\dot{H}$ are used.

The relationship between these three terms is as follows:

a) Energy flows which are coupled to material flows or quantities are referred to as enthalpy flows $\dot{H}$
b) Energy flows which are transferred from one body (e.g. the furnace wall or charge surface) to another body are referred to as thermo flux $\dot{Q}$.
c) Power P is energy per unit time; it is proportional to the thermo flux $\dot{Q}$

Three efficiency values can be calculated.

Energy flows in a furnace

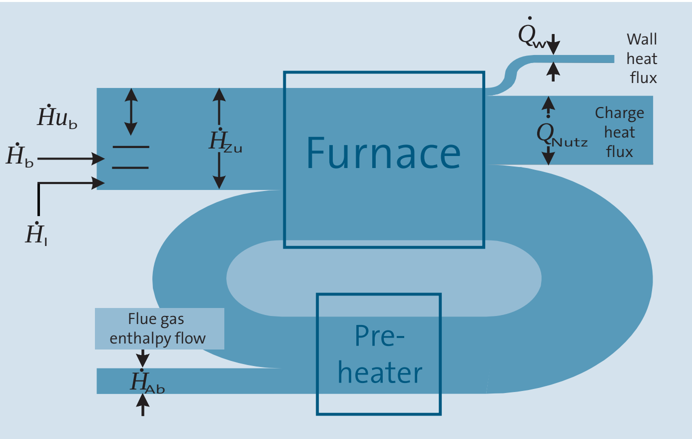


Fig. 1.6

Combustion efficiency η_f

The combustion efficiency η_f can be used for assessing the efficiency of firing systems:

$$\eta_f = \frac{\dot{H}_{Zu} - \dot{H}_{Ab}}{\dot{H}_{Zu}}$$

$\dot{H}_{Zu}$ Enthalpy flow into the system, including he caloric enthalpy of the fuel and air and the chemical enthalpy of the fuel

$\dot{H}_{Ab}$ Enthalpy flow of flue gas

When assessing the efficiency of firing systems, the "output" is the useful heat output of the system – in the case of furnaces, this is the heat flux to the furnace . The input to the firing system is the energy content of the fuel supplied. The heating system rating must not be taken as the input because the preheating of the fuel or combustion air using flue gas waste heat is not an "input" as it does not add new energy to the system (see Fig. 3.1 in "Heating system" section).

Furnace efficiency η_{Of}

The furnace efficiency η_{Of} indicates the efficiency of the furnace itself

$$\eta_{Of} = \frac{\dot{Q}_{Nutz}}{\dot{H}_{Zu} - \dot{H}_{Ab}}$$

$\dot{Q}_{Nutz}$ useful thermo flux.

In an efficiency assessment of a thermo processing plant, the input is the useful thermo flux transferred to the charge. The input in this case is the heat flux to the furnace .(see Fig. 3.1 in "Heating system" section)

Overall efficiency η_{ges}

The overall efficiency η_{ges} of the furnace plant is calculated by multiplying the two efficiency values:

$$\eta_{ges} = \eta_f \, \eta_{Of} = \frac{\dot{Q}_{Nutz}}{\dot{H}_{Zu}}$$

2 Wall design and energy losses

Depending on the temperature inside the furnace, the walls of a thermo processing plant may consist of one or more layers of refractory or insulating materials and atmosphere isolation layers.

Refractory materials are selected on the basis of material properties and economic criteria.

The selection criteria include:

- The furnace temperature range
- The geometric shape of the furnace (height, width, length)
- The furnace type (car bottom, pusher-type, roller hearth, ...)
- Mode of operation (continuous or discontinuous/periodic)
- Furnace atmosphere (reducing, oxidizing)
- Furnace atmosphere dew point
- Hazardous substances in furnace (alkalis, heavy metals, hydrochloric acid, ...)
- Direct (gas- or oil-fired) or indirect heating (electric heating, radiant tubes)
- Mechanical stress on refractory materials (vibration, collisions with charge, exposure to dust, vapours, slag or molten metal, -...)
- Flow of gases through furnace (flow rate, dust concentration, ...)

Properties of refractory and insulating materials:

- Type
  - Shaped products (e.g. bricks)
  - Non-shaped products (e.g. castables, construction and repair materials, jointing materials)
  - Functional products (e.g. metal or ceramic structural elements)
  - Thermo insulation products (both shaped and non-shaped, e.g. porous lightweight bricks, blanket, modules and shapes from high-temperature insulation wools)
- Base materials
  - Chemical compounds and elements: SiO2, Al2O3, MgO, CaO, ZrO2, C, SiC, etc.
  - Ceramic composite products and mineral phases containing the above compounds
- Chemical properties
  - Acid, basic, neutral
  - Resistant to certain materials in furnace atmosphere

Table 2.1 gives an overview of refractory materials and high-temperature insulating materials.

Type	Designation	Continuous service temperature [°C]	Thermo conductivity [W/mK]	Specific heat* [kJ/m³ K]	Density [kg/m³]	Material cost
Concrete	Lightweight concretes	1300	0.5	1500	1400	↓↓
Concrete	High-alumina concretes	1450	2.4	2700	2400	↓
Fireclay	Fireclay bricks	1350	2.1	2500	2400	↓
High-alumina bricks	Andalusite bricks	1500	2.0	2900	2600	↑
Lightweight bricks	Alumina silica bricks	1250	0.4	640	800	↓↓
Lightweight bricks	Corundum bricks	1600	0.5	1200	1100	↑
High-temperature insulation wool	Alumin silica wool	1300	0.2	140	130	↓↓
High-temperature insulation wool	Polycrystalline wool	1600	0.25	90	80	↑↑↑

Table 2.1: Overview of refractory materials and high-temperature insulation wool materials

* Average value for 200°C to 1200 °C

Wall losses

The heat transferred from the furnace to the inside wall is referred to as internal wall loss. This heat is transferred through the wall by conduction and is released from the outer surface of the wall to the surroundings as external wall loss.

As the furnace wall is being heated, the temperature inside the wall rises and part of the heat remains stored in the wall. At this stage, conditions are unstable. When heating-up has been completed, stable conditions are reached and the only wall losses are external.

In addition to wall losses, heat is also lost through openings and passages.

The temperature on the undisturbed outer wall of a furnace gives a first indication of wall losses. Factors influencing the temperature are:

- Conditions inside furnace
  - Temperature in furnace
  - Flow conditions in furnace
  - Radiation conditions in furnace
- Wall design
  - Number and thickness of wall layers
  - Material properties of wall materials (see table 2.1)
- Conditions outside furnace
  - Flow conditions on the outer wall of the furnace
  - Height and shape of outer wall
  - Ambient temperature
  - Geometric position of outer wall (horizontal, top or bottom, vertical)

The following parameters of the furnace wall can be changed:

- Number of layers
- Thickness of layers
- Wall materials

Health and safety aspects/maximum allowable surface temperature

The maximum allowable surface temperature for protection against burns is laid down in ISO 13732-1 as a function of the surface material and the duration of contact with the surface.

For painted metal surfaces, the maximum allowable temperature is ~ 85°C (contact time 0.5 s) or < 55°C (contact time ~ 10 s).

Steady-state conditions

Fig. 2.1 shows steady-state heat transfer for a furnace wall with brick lining (Fig. 2.1 a), a wall of the same thickness with HTIW-modules lining (Fig.2.1 b) and a wall with HTIW-modules lining of normal thickness (Fig.2.1 c).

With the same furnace wall thickness, the outside wall temperature is approx. 20 K lower with HTIW lining. Heat losses are reduced by 45 %.

In practice, instead of retaining the furnace wall thickness with HTIW lining, it is possible to reduce the wall thickness for HTIW lining significantly (Fig. 2.1b), to dispense with the additional mineral wool insulation (Fig. 2.1 c) and to obtain outside wall temperatures and wall losses that are similarly low.

The steady-state analysis is the decisive factor in the design of continuous furnaces. As the temperature profile in the furnace wall does not change, storage losses are not relevant in a long-term analysis of losses.

Heat transfer under steady-state conditions

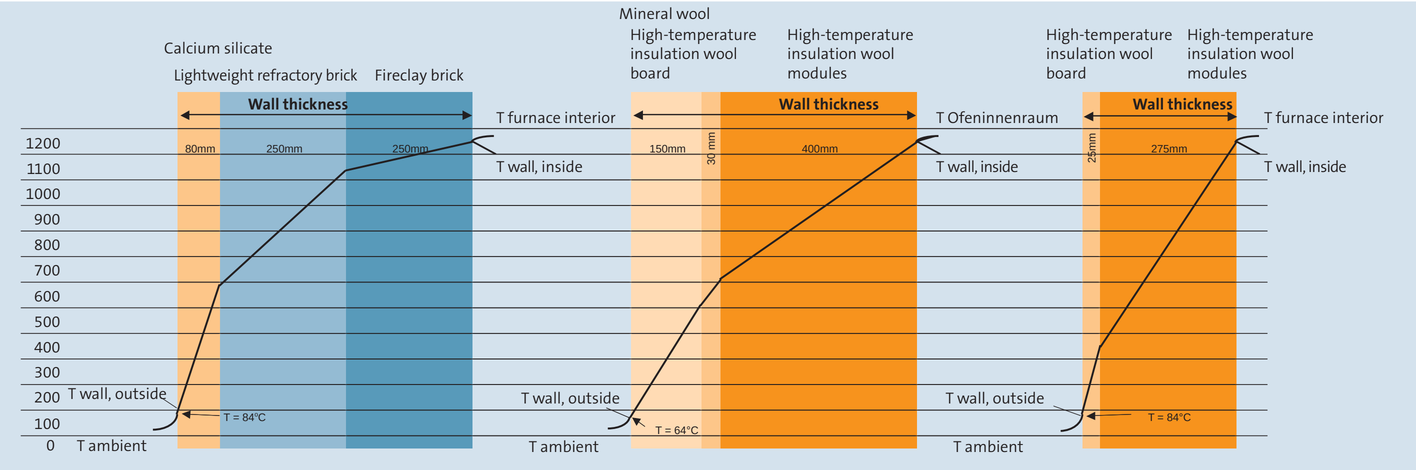


Fig. 2.1 a Fig. 2.1 b Fig. 2.1 c

Heat transfer under transient conditions

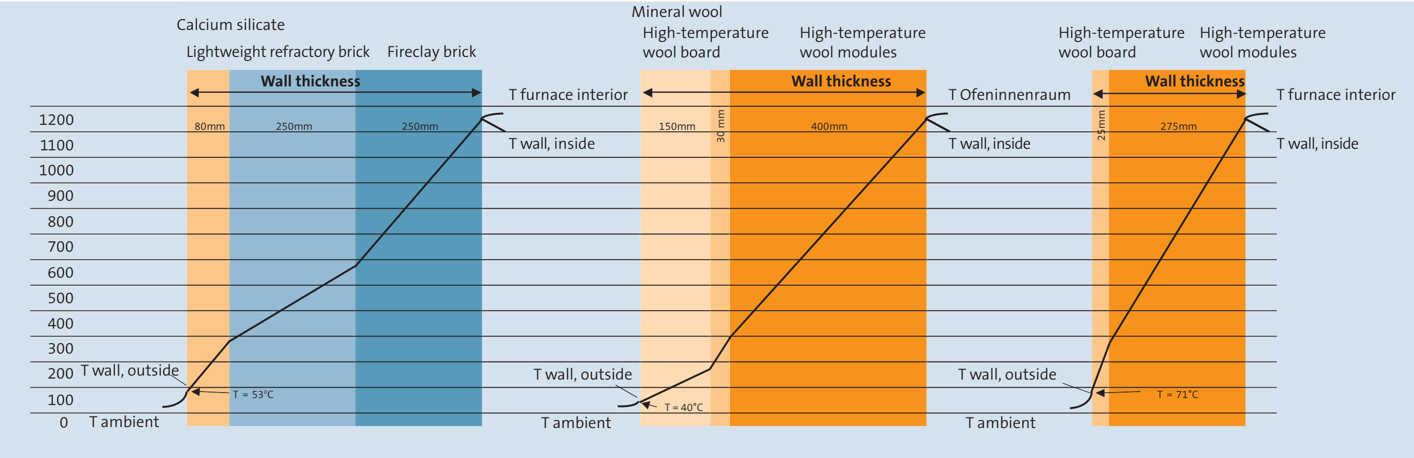


Fig. 2.2 a

Fig. 2.2 b

Fig. 2.2 c

Transient conditions

Fig. 2.2 shows examples of heat transfer under transient conditions through a furnace wall with brick lining (Fig. 2.2 a) and a furnace wall of the same thickness with HTIW-modules lining (Fig. 2.2 b). The diagrams indicate the temperature profile after ten heating and cooling cycles with charging between cycles and a cold-cold cycle time of 45 hours.

In transient furnace operation (i.e. with batch furnaces), heat losses include wall and storage losses. In the case of a brick lining with the design selected (Fig. 2.2 a), heat losses are of the order of 250 MJ/m2, as against about 40 mJ/m² for a very thick HTIW-modules lining (Fig. 2.2 b) and 45 MJ/m2 for a HTIW-modules lining of normal thickness (Fig. 2.2 c). This is the result of the significant differences between the specific heats of the various materials (see table 2.1).

In practice, instead of retaining the furnace wall thickness with HTIW-modules lining, it is possible to reduce the wall thickness for HTIW-modules lining significantly (Fig. 2.2b), to dispense with the additional mineral wool insulation (Fig. 2.2 c) and to obtain outside wall temperatures and wall losses that are similarly low.

What is the cost of the different wall design variants?

When comparing the cost of brick and HTIW-modules lining, not only the cost of the lining materials but also the cost of mountings (such as anchors) and installation must be taken into consideration.

Table 2.2 gives an overview of the share of material and installation costs and the relationship between the costs of the three alternatives (basis: brick lining = 100 %) shown in Fig. 2.1 and 2.2.

Interpretation of table 2.2

Both steady-state and transient conditions can be simulated with simple computer programs. These calculation programs use the material properties of the furnace wall materials as a function of temperature.

		Total cost (normalized)	Cost of Material	Installation	Wall losses (steady-state)	Wall losses (transient)
Brick lining	250 fireclay 250 lightweight brick 80 calcium silicate	100	51	40	100	100
HTIW-modules lining extra thick	250 HTIW modules 30 HTIW board 150 mineral wool	75	70	30	55	15
HTIW-modules lining normal thickness	275 HTIW modules 25 HTIW board	58	71	29	100	18

Table 2.2: Cost overview for different furnace wall designs

Basic rules

- In the case of furnaces operated at steady-state conditions, heat losses at the outer wall of the furnace and not the heat storage capacity are the main criterion for selection.
- In the case of furnaces operated at transient conditions (with frequent heating-up and cooling), the heat storage capacity of the furnace wall must be kept to a minimum.
- For furnaces with a reactive atmosphere, the main selection criterion is the prevention of chemical reactions between the inner layer of the furnace wall and the furnace atmosphere (this also applies to liquid phases in the furnace, e.g. to melting furnaces).
- With multi-layer walls, there is a shift in the dew point in the furnace wall and water can therefore condense in the furnace wall. In this case, appropriate precautions (e.g. installation of moisture barriers) must be taken.
- The furnace structure must be designed to support the weight of the furnace lining. If the furnace lining is modified (e.g. replacement of bricks by HTIW-modules, changes in the thickness of the various layers), it may be necessary to change or redesign the furnace structure.
- If outside insulation is applied retroactively, it is essential to prevent any overheating of internal layers or the steel structure.
- HTIW materials and modules must be attached to the furnace structure by appropriate systems (e.g. adhesives or metal anchors).
- Anchors protruding into the furnace interior may also react with the furnace atmosphere (e.g. they may be carburized or oxidized).
- The maximum allowable temperature on the outer surface of the furnace wall is defined by ISO 13732-1 with reference to health and safety criteria. If these limits are exceeded, appropriate action is required to prevent contact between personnel and the surface (e.g. installation of gratings or guards).
- As a general rule: the higher the service temperature of a refractory or insulation material, the higher the cost.
- Heat storage capacity is important for operation at transient conditions. The specific heat of a refractory material is proportional to its bulk density.
- There are simple programs for calculating wall losses.

Manufacturers of thermo processing plants therefore define the design of furnace walls with respect to process engineering, heating and economic criteria.

3 Heating Systems

Thermo processing plants are mainly heated by firing systems using gas, oil or solid fuels, or by electric heating systems. The type of heating system used may be determined by the process involved, the availability of fuel or in some cases by the furnace type. In such cases, the total capital cost and energy expenses for operation and ancillary facilities (e.g. the cost of electric power) must be taken into account.

There are many different types of electric heating systems for thermo processing plants (resistance heating with elements positioned directly in the furnace, indirect conductive heating, infrared, arc, plasma and induction heating, etc.). It is not possible to make general statements on energy saving that apply to all types of electric heating system, which is why electric heating systems are not considered in greater detail in this section. The energy consumption can be expressed in kW per tonne of material treated, allowing a comparison between different heating systems.

Energy flows in furnace

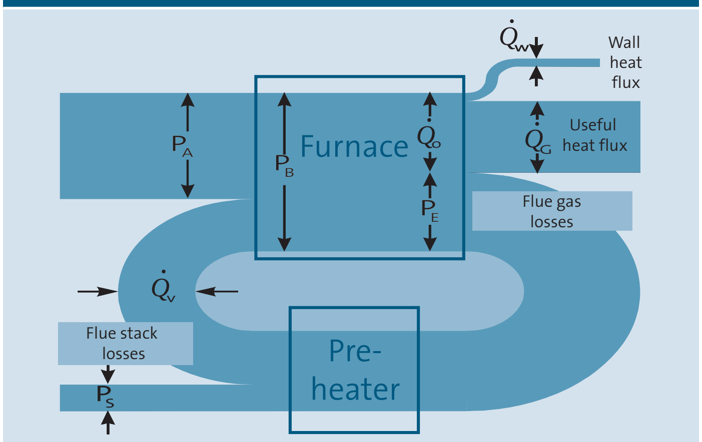


Fig. 3.1

Non-electric heating systems

The combustion efficiency is a measure of the energy efficiency of the firing system. The following basic statements apply to plants heated using fossil fuels:

The higher the combustion efficiency η_f, the lower the energy losses of the firing system and the thermo processing plant as a whole.

$$\eta_f = (P_B - P_E) / P_A$$

where:

P_B	=	Heating system output
P_E	=	Flue gas losses
P_A	=	Fuel energy input

and

$\dot{Q}_W$	=	Wall heat flux
Q_g	=	Useful heat flux
$\dot{Q}_v$	=	Preheating heat flux
$\dot{Q}_O$	=	Furnace heat flux
P_S	=	Flue stack losses

Fig 3.1 shows the factors influencing η_f. The diagram also indicates that η_f can be significantly improved by preheating the combustion air using flue gas losses. Preheating of the fuel is also possible or normal practice with oil and solid fuels, and in some cases with low-CV gas.

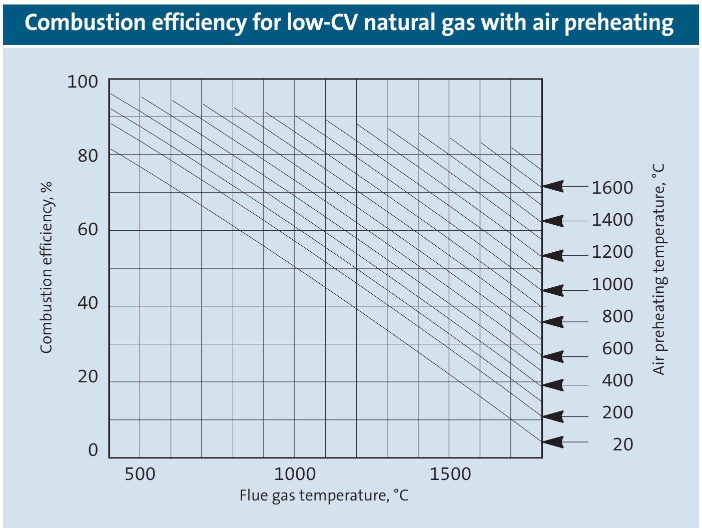


Fig.3.2

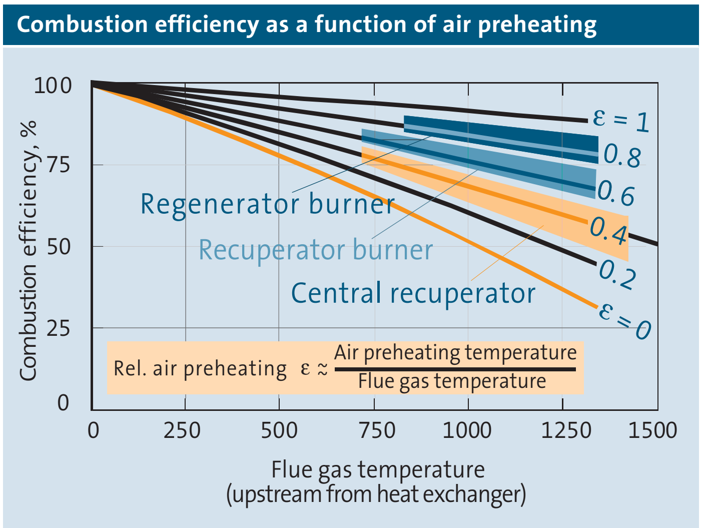


Fig. 3.3

Quantitative parameters for the improvement of η_f are shown in Fig. 3.2.

For air preheating, energy in the form of heat is recovered from the flue gas of the burner(s) by a heat exchanger. Air may be preheated either centrally by a central recuperator or regenerator or in a decentralized configuration using a regenerative or recuperative system or the burner itself.

The potential for energy saving by heat recovery systems and the limits for the application of such systems are indicated by Fig. 3.3.

Basic rules

- Use of the heat contained in the flue gases in the furnace is always preferable to other internal uses.
- The higher the furnace temperature and the flue gas temperature upstream from the heat exchanger, the greater the energy saving potential through air preheating.
- When assessing the energy savings possible with a central recuperator/regenerator, it is necessary to take the heat losses in piping between the burners and the system into account. The economic viability of these systems depends to a large extent on the cost of the piping and valves.
- NOx formation grows exponentially with rising temperature. In the case of air preheating, it may be necessary to take action to reduce NOx formation.
- The burners should be set to keep the excess air factor as low as possible in view of process conditions.
- Waste heat recovered from flue gas should always be used in the plant itself. Use of the waste heat in other units calls for additional links and creates interdependencies between processes.

Burner control systems offer further potential for enhancing energy efficiency.

Possible burner control systems:

- Pull, push, push-pull systems
- Proportional, high-low, on-off control
- Zone control, process firing system control

If radiant tubes are used, the tube design also has an impact on energy efficiency.

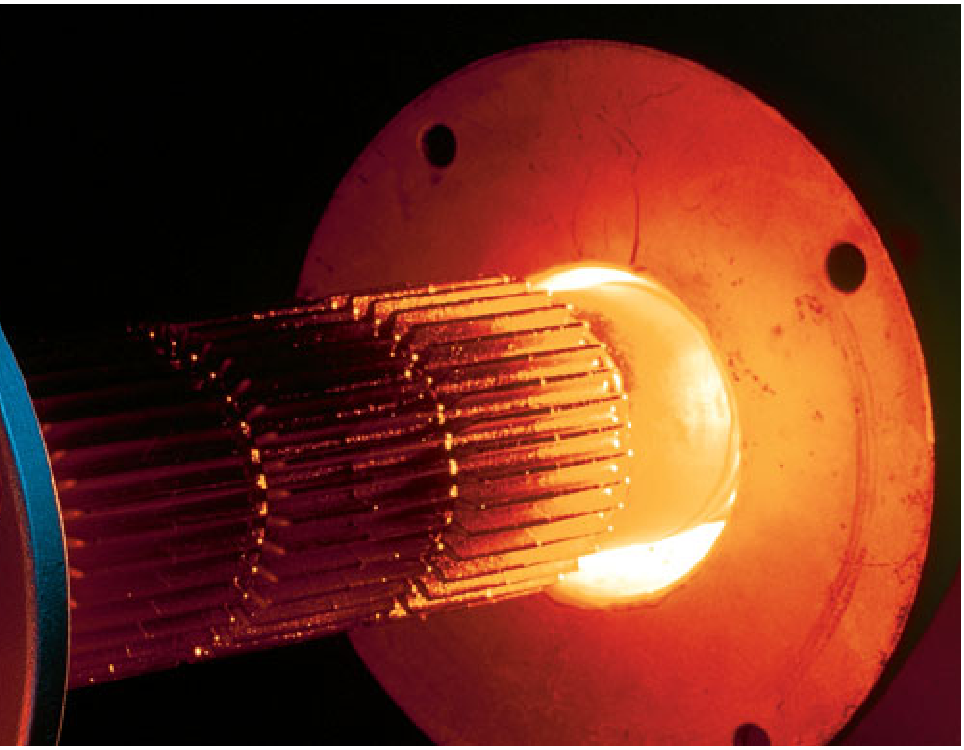
- Heat-resistant steel or ceramic tube
- Outer tube, P-tube, double-P-tube, U-tube, W-tube

Summary

The combustion efficiency is a measure of the energy efficiency of the firing system. Preheating of combustion air is normal practice in high-temperature processes. The selection of the heating, heat recovery and control systems depends on the heating process and the furnace type. In many cases, retrofitting is possible, but not always economically viable.

Apart from technical and economic criteria, environmental protection aspects must also be taken into consideration.

Thermo processing plant manufacturers define heating system parameters on the basis of process engineering and economic aspects. If you insist on high efficiency, this will have an effect on the plant design.



Electric heating systems

There are a variety of different electric heating systems for thermo processing plants. Depending on the configuration of the system, a distinction is drawn between direct and indirect heating systems (see Table 3.1). In the case of indirect heating systems, which include indirect electric resistance heating, the heat is transferred to the furnace or the charge material by radiation, convention and conduction. In the case of direct heating processes, which include direct conductive resistance heating as well as induction and dielectric heating, energy is transmitted by the AC electromagnetic field and converted into heat inside the charge material, which allows very high energy input densities and rapid heating. The following paragraphs concentrate on the processes indicated in Table 3.1

Process	Heating type		Energy transfer to charge	Application examples
	direct	indirect		
Resistance heating	+		Direct passage of electric current	Heating of ingots
		+	Radiation, convection, conduction	Radiant furnace, convection furnace
Induction heating	+		AC electromagnetic field	Heating of wire, shaping, heat treatment, melting, joining, brazing, agitation of molten metal
		+	Through electromagnetically coupled materials such as graphite, platinum or tungsten	Heat treatment, melting in conductive crucible
Dielectric heating	+		High-frequency electromagnetic field	Drying

Table 3.1: Examples of electric heating processes

Electric heating processes for thermo processing plants must be selected on the basis of technical criteria such as temperature levels and heat input required as well as economic factors such as capital cost and operating expenses, and energy aspects such as specific energy requirements, i.e. kilowatt-hours per unit produced. All these factors must be considered with reference to the specific application. The main criteria are outlined below for indirect resistance heating including infrared heating as well as induction and dielectric heating.

Resistance heating

In the case of indirect resistance heating, the furnace is heated by heating elements consisting of electric conductors designed to release a maximum of heat as current passes through them. The metal or ceramic heating elements used must be selected on the basis of maximum heating temperatures and the furnace atmosphere. For effective heat transfer, the furnace must be designed to allow heat to be transferred from the heating elements freely to the furnace or the charge by radiation. Faulty elements must be replaced in order to ensure rapid, energy-efficient heating of the furnace.

Resistance heating systems are also available in the form of heating cartridges and strips, which are used especially in the process industry for heating vessels, pipes and presses. These trace heating systems, which are often widely distributed over the area of a plant, must always be operated in line with actual heat input and temperature requirements.

When constructing a new energy-efficient electric resistance furnace, it is essential to use appropriate wall materials with low specific heat, low density and low thermo conductivity in order to minimize heat losses caused by storage and conduction.

Infrared heating is a special type of indirect resistance heating. In this case, energy is transferred from the electric heating elements to the charge material by electromagnetic radiation. For high efficiency, the radiation properties of the heating elements must be adapted to the absorption properties of the charge material In addition to the spectral range, the temperature level and the heating and cooling behaviour of the heating element must be adapted to the process.

In many cases, energy saving potentials can be tapped by adapting furnace and heating system operating procedures to the heating and melting process concerned. Idle times should be avoided to the greatest extent possible. By using modern control systems, it is possible to achieve temperature control ideally adapted to the process. Especially in the case of older electric resistance furnace plants, further improvements in energy efficiency can often be achieved by retrofitting an automatic furnace control system.

Induction heating

In the case of induction heating and melting, eddy currents are induced in an electrically conductive charge using an induction coil carrying alternative current and directly heat the charge. In order to ensure high electrical efficiency (i.e. a high ratio of the electric power actually heating the charge to the total power required (useful power plus power losses in the induction coil)), the shape of the coil and the frequency of the coil current must be adapted to the dimensions (diameter and thickness) and the electrical material properties of the charge material.

In many cases, energy savings potentials can be tapped by adapting the induction coil geometry (diameter, length and number of windings) and the operating frequency in the event of a change in the shape of the charge material or the throughput.

Factors with a key impact on efficiency include the effective current-carrying cross section of the conductor generating the electromagnetic field and the effective low-loss return of the closed magnetic field lines.

Significant energy savings can often also be realized without any cost impact by avoiding soaking operation, i.e. by optimum adaptation of the induction heating or melting process to downstream process stages.

Dielectric heating

Dielectric heating, including high-frequency (HF) and microwave heating, is based on the physical principle that electric power is converted into heat in non-conductive or only slightly conductive materials exposed to a high-frequency electric field. In high-frequency heating (normal frequency: 13.56 MHz or 27.12 MHz), the charge is heated in the field of a capacitor. For this purpose, the material to be heated should have a sufficiently high dielectric loss value (as is the case with materials containing water) to allow efficient heating. The geometry of the electrodes must be adapted to the shape of the charge to obtain the heating profile required.

With microwave heating (frequency normally 2.45 GHz), electromagnetic waves penetrate the charge material, creating molecular vibrations which cause heating in polarizable materials. In the design of microwave heating systems it is essential to ensure that the microwave chamber is effectively adapted to the charge material and that the positioning of the magnetrons and energy supply points is appropriate in view of the shape and properties of the charge material in order to ensure that the heating process is as efficient and homogeneous as possible and free from hot spots.

Power supply for electrically heated thermo processing plants

In many cases, electric power is supplied via inverters (frequency converters) at the voltage, current, frequency and power level required for the process. The historic development of inverters, culminating in semi-conductor inverters, has been coupled with improvements in efficiency. The units currently used normally have efficiency values in excess of 95%, measured as the ratio of power output to power input.

Especially in the case of older plants which are only operated in the part-load range, it may be beneficial to measure power input and output as a basis for assessing possible efficiency improvements or modernization projects.

Summary

Many different processes are available for the electric heating of thermo processing plants. The heating process used, which may also be a hybrid process based on different technologies, must be selected on the basis of processing engineering, economic and resource conservation aspects. Especially in view of the service life of the plant, which will normally be many years, it is essential to select the heating process carefully.

In order to improve the energy efficiency of electrically heated heating and melting furnaces, it is essential to ensure that the electrical and thermo parameters are appropriate for the charge material.

When reviewing the energy efficiency of an electrically heated thermo processing plant, it is important to include the power supply systems (generators, cables, transformers.).

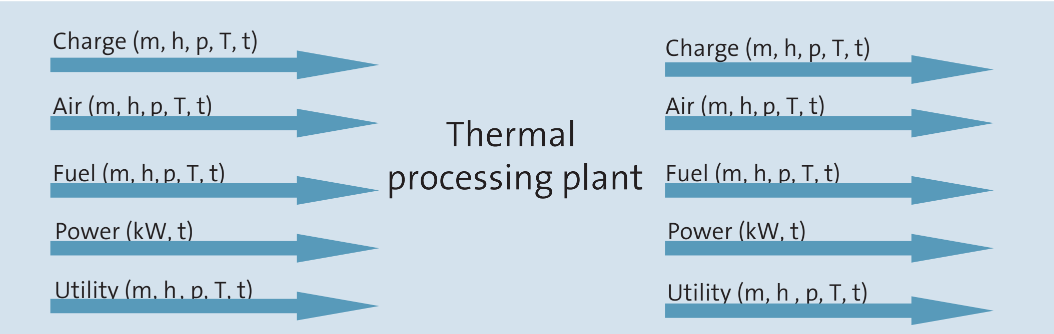
In many cases, the efficiency of a plant can be optimized using automated control systems: The retrofitting of modern control systems may be especially beneficial in terms of energy efficiency in the case of older plants.

In the case of batch processes, the possibility of heat energy storage using a suitable system should be considered so that waste heat which is produced discontinuously may be converted into a continuous source of lower-grade heat.

Waste heat utilization should be considered for all thermo processing plants (e.g. cooling water, spent air, etc.) Often, there is considerable potential for energy savings, even with plants with a rating of over 100 kW.

4 Process optimization

Schematic diagram of a thermo processing plant with input and output parameters



m = mass flow, h = enthalpy flow, T = temperature, p = pressure, t = time/interval

Fig. 4.1:

Thermo processing plants are normally complex plants which are produced to customers' specifications. The customer determines the process and further data of the charge material together with the furnace producer. The furnace producer then designs an overall plant; parameters such as fuel, air water, power and utility requirements are determined by the specifications. The input data are determined by the specified process data.

The plant consists of a large number of individual modules (furnace frame, casing, heating system, atmosphere gas supply system, conveyor systems, etc.) which the furnace producer assembles on the basis of its experience and the requirements of the operator.

Only certain base data (such as furnace type and heating system) are agreed with the customer and the individual components are designed by the producer.

As a result of this procedure, the overall plant defined by input and output parameters in Fig. 4.1 is converted into a large number of individual modules (see Fig. 4.2). Some of these modules will be installed in series, some in parallel.

The individual components of the plant are:

- washing machine for degreasing, de-phosphating, washing and drying
- furnace for austenitizing at 870° C
- oil quench tank
- washing machine for degreasing, washing and drying
- furnace for tempering at C
- emulsion quench tank

Division of an overall plant into individual modules

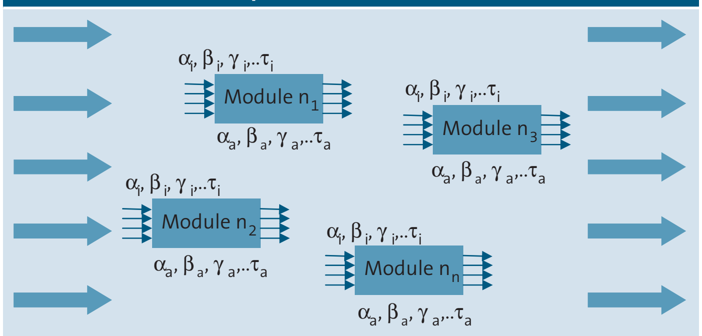


Fig. 4.2

Example of a hardening plant

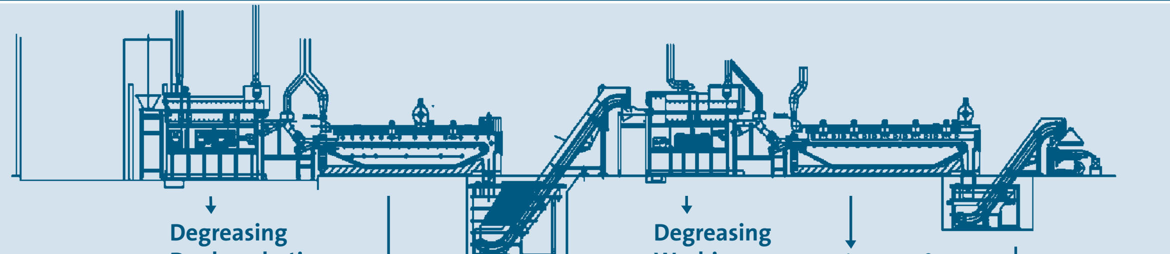


Fig. 4.3 shows a hardening plant as an example

If this plant is subdivided into individual modules, the results are as follows:

Module 1 Washing machine
Module 1.1 Process stage: degreasing
Module 1.2 Process stage: de-phosphating
Module 1.3 Process stage: washing
Module 1.4 Process stage: drying
Module 1.5 Process stage: transfer

Module 2 Industrial furnace
Module 2.1 Process stage: heating
Module 2.2 Process stage: atmosphere gas generation
Module 2.3 Process stage: transfer by chain conveyor

Module 3 Quench tank
Module 3.1 Process stage: oil cooling
Module 3.2 Process stage: transfer by chain conveyor
Module 3.3 Process stage: oil supply and treatment

Module 4 Washing machine with sub-modules
Module 5 Industrial furnace with sub-modules
Module 6 Quench tank with sub-modules

The crucial components are these which directly transfer the charge or are in connect with the charge.

All these components either need energy for heating or drying or emit energy, such as the quench baths.
The next stage in the designer's work is to define the various utility and energy flows required for heating (melting, reheating, heat treatment or drying) or cooling.

Energy analysis

The energy required for the entire plant is the sum of the energy demand of the individual components. In order to reduce the overall energy consumption of the plant. the first step is to consider whether it is possible (in line with the analysis outlined above) to link the energy output of one process stage with the energy input for another stage. A classical example is the use of the hot flue gas to preheat the combustion air (using a recuperator or regenerator).

Parameter variation

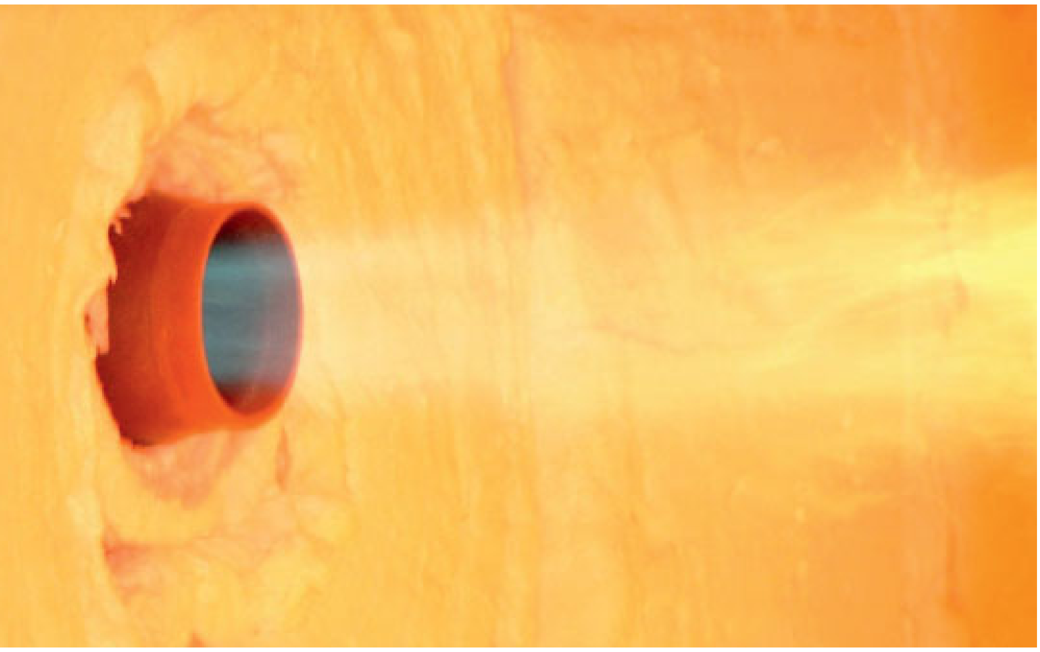
Another step towards energy saving, which is often ignored, is the variation of process parameters.

What is parameter variation?

The input and output data for fuels, air, utilities, electric power and consumables are defined, but it may be possible to change energy levels and flows by modifying the process configuration.

What does this mean in practice?

One module of the hardening plant described above is the washing machine; the washing emulsion normally needs to be heated to a temperature of about 70°C. The plant is also equipped with an oil quench tank. Energy enters the tank during the quenching of hot charge material and the quench fluid needs to be cooled to a temperature of 60°C. It is therefore not possible to use the energy extracted from the quench tank by the heat exchanger at another point in the process. However, by selecting another washing emulsion, it might be possible to reduce the temperature required to 50°C; similarly, by using another quench oil, the maximum quench tank temperature could be increased to 80°C. This would reverse the temperature relationship between quench oil and washing emulsion and allow the use of energy recovered from the oil tank to preheat the washing machine.



Other examples:

- In the case of heating furnaces in the steel and ceramics industries, where temperatures may be in excess of 1000°C, energy can be saved by using waste heat to preheat a furnace or dryer with temperatures of about 300°C.
- In the aluminium and copper industry, the combustion efficiency of an ingot reheating furnace can be increased to 80% by adding a counter-current heating zone and combustion air preheating.
- Major energy savings can be achieved if the material is charged into the furnace at a temperature significantly higher than the ambient temperature. In steel production, this effect can be achieved by charging hot slabs into the walking beam or pusher-type reheating furnace upstream from the hot rolling mill.
- In the ceramics industry, similar effects can be obtained by combining debinding and sintering in the same unit without cooling between the two process stages.
- These are only a few of the possibilities available.

5 Waste heat utilization

Considering a thermo processing plant as a system with defined limits, it must be noted that only part of the energy fed to the system is actually transferred to the charge material. A significant proportion of the energy input leaves the system in the form of waste heat. Waste heat losses can be measured by the overall efficiency of the system ηges (see Section 1)

Energy losses include both energy carried out of the system by substances and energy transferred direct to the surroundings or other materials from the surfaces of the furnace and the charge.

Energy (or enthalpy) may be carried by the following substances and materials:

- Waste gases (burner flue gases, furnace atmosphere, etc.)
- Cooling media (water, steam, air, etc.)
- Quenching media (oil, water, etc.)
- Conveyor systems (charging racks, trays, baskets, etc.)

This section only deals with waste heat as energy carried into the system with the media listed above is dealt with under the heading of process optimization (see Section 3).

Waste heat storage

Waste heat is mainly produced intermittently in the case of discontinuous processes and continuously in the case of continuous processes. The utilization of waste heat produced intermittently normally calls for heat storage possibilities.

Heat can be stored using salts, oils, steam and water.

It is only economically viable to use water as a storage medium with certain restrictions. However, the possibility of including existing water storage facilities (fire water tanks, sprinkler systems, main water tanks, industrial water tanks and space heating systems) should be considered.

If steam is used for cooling thermo processing plants, the possibility of integrating this steam system into the overall steam system of the plant should be considered (example: large roller hearth furnaces in the steel industry). Where large quantities of steam are produced, the option of power generation should be investigated.

Cooling water

Water is the most widely used cooling medium for thermo process plants. Cooling water temperatures range from 45 to 80°C. If a waste heat recovery system is not installed, the cooling water is diluted to obtain the maximum admissible temperature and then discharged into the sewage system in the case of small plants. For large plants, a water/air heat exchanger or cooling towers may be used.

One of the most frequent applications for waste heat is the heating of water used for showers (a hot water storage tank is needed).

Waste heat is also often used for space heating, in underfloor heating systems, as well as for heating garages and factory halls. However, heat is not required for these purposes in the summer, when the plant has to use dilution, heat exchangers or cooling towers, as described above.

Waste heat from thermo processing plants may also be used for heating swimming pools in the vicinity.

The possibility of waste heat utilization at local agricultural or horticultural facilities or for other production plants in the area should also be considered.

More "exotic" examples are also worth investigating. At one plant, waste heat is used for heating fishponds for carp. The pond is integrated in a cooling tower.

Holistic design work required

The utilization of waste heat and energy from hot charges is not normally considered by the manufacturer of a thermo processing plant.

The designers and operators of the entire production plant, as well as building and energy supply technicians are called upon to consider waste heat utilization. Only holistic design work and liaison between all the energy users involved in production and utility systems can produce satisfactory results.

The system analysis presented in Section 4 (process optimization) can be used as a tool for analysing waste heat utilization.

In the same way as a thermo processing plant consists of a large number of individual modules, a production facility with administration building, ancillary units and neighbouring facilities can also be seen as a system comprising individual modules (such as a thermo processing plant).

The energy links indicated by this system analysis must be subjected to a precise economic analysis. Solutions which may appear beneficial from the energy efficiency point of view need not be economically viable at current energy price levels.

Note

Possible approaches to a holistic solution include heat pumps and systems for the combined generation of heat and electric power, or heat, electric power and cold.

In the future, there may also be solutions allowing waste heat from burner flue gases (downstream from combustion air preheating) and/or from cooling water to be converted directly into electric power.

6 Subsystems and ancillaries

In many cases, only the energy required for heating and cooling the charge and plant modules such as washing machines is taken into account in the design of thermo processing plants.

The energy efficiency potential of subsystems and ancillaries is often neglected even though considerable energy savings can be realized in these systems, which do not form part of the main plant. Many ancillary systems are equipped with electric motors, fans, pumps, compressors and similar units; these have a considerable share in a company's power consumption.

Motors and drive systems account for almost two-thirds of industrial power demand. Especially in the case of applications with fluctuating power demand (load profiles) considerable quantities of electric power can be saved by fitting modern drive and control systems.

Energy efficiency of electric motors

CEMEP, the European Committee of Manufacturers of Electrical Machines and Power Electronics, has agreed with the EU Directorate General for Energy on a classification of electric motors. Three-phase motors with ratings between 1.1 and 90 kW (two-pole and four-pole motors) are grouped together in three efficiency classes. Classification is carried out on the basis of three limit curves (Fig. 6.1).

Manufacturers make a declaration certifying compliance with the limits required. The energy efficiency class is indicated on the nameplate of the motor. Energy efficiency class 3 (EFF 3) includes motors with the efficiency values normally available on the market, or "standard motors". Efficiency class 2 (EFF 2) motors feature higher efficiency values and efficiency class 1 (EFF 1) motors have the highest efficiency values available.

Limits of energy efficiency classes for electric motors

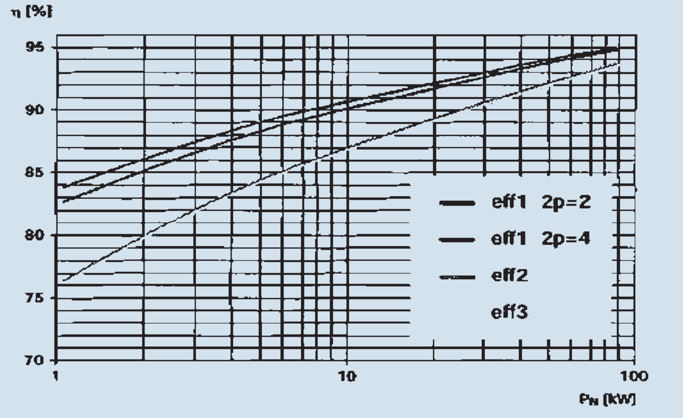


Fig. 6.1

Other classification systems (e.g. EPACT) are in use in North America. However, efficiency values under US standards are not directly comparable with European classifications.

When does it pay to use energy-saving motors with efficiency classes 1 and 2?

Considering the life cycle costs of electric motors, which include purchase price, installation, maintenance and energy costs, the share of energy costs increases significantly as the service life of the motor is extended. In the case of a motor with a service life of 12 years, for example, energy expenses account for 95 % of total expenses.

New motors

If not only the purchase price but also energy expenses are taken into account when purchasing a new motor, it can be assumed that the additional cost of an EFF 1 motor will be recouped after 2,000 to 3,000 operating hours. In the case of actuators or motors with shorter service hours, EFF 2 motors can normally be recommended. Some electric motor manufacturers offer software tools which can be used to calculate the payback time for an EFF 1 electric motor.

Repair of electric motors

In the case of repairs to an EFF 3 motor, it may be more economical to install a new energy-saving motor (EFF 1 or EFF 2). It is also important to remember that some repairs, such as rewinding, reduce the efficiency of a motor.

Replacement of an EFF 3 motor by an EFF 1 moto

It will not normally be economically viable to replace a properly functioning EFF 3 motor by an EFF 1 motor. However, it may be beneficial to carry out a replacement of this type in individual cases where comprehensive plant refurbishments are planned.

Motors – conclusion

Motors are classified in energy efficiency classes EFF 3, EFF 2 and EFF 1 on the basis of their efficiency values. As motors with efficiency classes EFF 2 and EFF 1 are more costly than EFF 3 motors, it may be necessary to carry out a viability analysis in order to convince customers that it would be beneficial to purchase high-efficiency motors. Some motor manufacturers offer software tools for viability analyses of this type.

In view of the low energy consumption, the higher cost of EFF 1 motors may already be recouped after 2,000 to 3,000 operating hours.

In some countries outside Europe, the use of energy-saving motors is mandatory.

Energy efficiency and frequency converters

Conventional control systems are often used for electric motors, fans, pumps and compressors. In the case of electric motors driving equipment items, the motor speed is stepped down by a gear unit to the speed required by the equipment. Fans, pumps and compressors are designed for operation at rated speed. Often, mechanical throttle valves or by-pass systems are used to adapt unit output to actual requirements.

With a gear unit or a throttle control system, the electric motor is operated at rated speed although only part of its rated output is required. This results in excessive power consumption.

With the drive and control systems now available, it is possible to control flows in line with demand without significant deterioration in the efficiency of the machines driven by electric motors. For example, a frequency converter can control motor speed in line with requirements and also ensure smooth start-ups and shut-downs, reducing stress on the entire drive system.

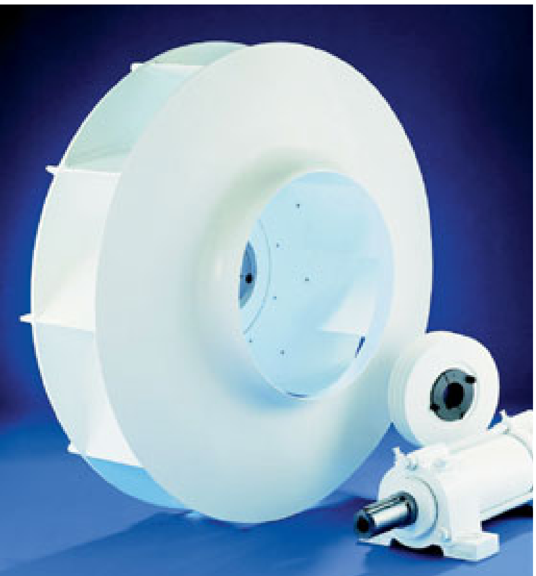
Further development of this technology allows power to be fed back to the grid: i.e. braking energy is used to generate electric power. This approach is especially effective in the case of processes involving frequent acceleration and deceleration.

Energy efficiency and pumps

In the design of industrial furnaces, little attention is often paid to pump systems, comprising electric motor, pump, piping and control system, although these systems may offer energy saving potential of up to 50 %.

Pumps are designed to deliver the maximum flow rate required. A design allowance is often included to ensure that the pump can reliably reach the performance (discharge flow rate or discharge head) required. For this reason, many units are not operated at design conditions and therefore also not at optimum efficiency. In the case of constant flow rates, maximum efficiency can be ensured by selecting the optimum pump. Where flow rates are changed repeatedly, it is not possible to achieve an energy-efficient solution without advanced drive and control systems.

High-efficiency pumps are already available for many applications. These pumps feature advanced control systems for adaptation to the flow rates actually required. As a result of the higher production and material cost, these pumps are of course more expensive than conventional pumps with the same flow rating. The lower power requirements of these pumps mean that the higher capital cost is normally recouped within two to three years.



Energy efficiency and fans

The comments made about speed with reference to pumps also apply to fans.

The key factors in fan selection are the data stated by the manufacturer and especially the characteristic curves. These curves are recorded on standard test rigs and therefore deviate from the characteristic curves actually achieved by units after installation. These deviations are the result of a number of flow disturbances in the system installed, which may include:

- Intake and outlet gratings
- Baffle plate at fan outlet
- Low spacing between wall and fan intake
- Turbulent flow from fan intakes
- Manifold at fan outlet

Fans may be driven by electric motors via belts, couplings, gear units or directly. Direct drive is the best approach in terms of energy efficiency. In the case of belt drives, flat belts are considerably more energy-efficient than vee-belts. If a vee-belt is used to transfer torque to the motor shaft, the total power requirement can be reduced by up to 10 % by selecting the appropriate belt, depending on the overall rating of the system. The selection of a drive system may be restricted by a number of parameters (e.g. torque values and temperatures), which need to be taken into consideration.

Fans operate most efficiently within a specified output range. This is why design precisely based on later operating conditions is so important. Frequency converters have proved to be an efficient drive solution.

The design of a fan system calls for comprehensive knowledge of thermodynamics and flow mechanics in order to obtain a significant reduction in energy demand.

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Lyoner Straße 18
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Contact
Dr. Franz Beneke
Phone +49 69 6603-1854
Fax +49 69 6603-2854
E-Mail franz.beneke@vdma.org
Internet www.vdma.org/thermoprocessing

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