10

Industrial Heating Processes

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The industrial sector uses about one-third of the total final energy consumed annually in the United States [1] and 28% in the EU [2]; for the latter, the two most energy-intensive users are the iron and steel industry, consuming 20% of industrial energy use, and the chemical industry, with a share of 16.3%. If we are talking about the total electricity consumption in the EU, industry takes 41%.

Process heating is essential in most industrial sectors, including those dealing with products made from metal, plastic, rubber, concrete, glass and ceramics; the energy sources involved in this process are quite varied, as shown in Figure 10.1 [3]. In the figure, 'other' fuels usually refers to opportunity fuels (frequently, waste products such as sawdust, refinery gas, petroleum coke, etc.) and to by-product fuel sources, such as wood chips, biogases or black liquor. In many industries, they account for a large portion of the energy use.

According to Figure 10.1, there are many options for industrial processes involving heating, melting, annealing, drying, distilling, separating, coating, drying, etc. The old existing solutions use direct fuel burning (oil, gas, by-products or waste products), hot air, steam, water, etc. On the other hand, the last several decades have witnessed the rapid expansion of different electric-based process heating systems (usually called *electrotechnologies* or *electroheating technologies*) that assure the necessary heat by transforming the electrical energy into thermal energy. The practical implementation of these systems is based on direct, indirect or hybrid heating methods.

Direct heating methods generate heat directly within the work piece, based on one of the following techniques: passing an electrical current through the material; inducing an electrical current (eddy current) into the material; or exciting atoms and/or molecules within the material with electromagnetic radiation (e.g., microwaves). *Indirect heating methods* use one of these three methods to heat a special element; the latter transfers the heat to the work piece by either conduction, convection, radiation, or a combination of these, depending on the work temperature and the type of heating equipment. *Hybrid systems* use a combination of process

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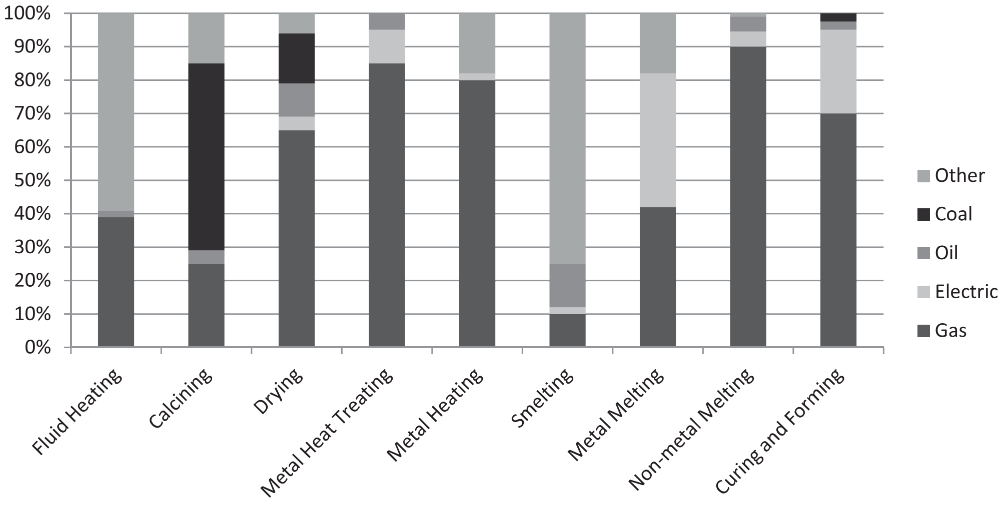

Figure 10.1 Energy sources for key industrial process heating operations (based on [3])

heating systems based on different energy sources or different heating methods based on the same energy source.

The rapid development of electrotechnologies in the last decades is based on the following aspects [2, 3, and 4]:

- *Huge progress in power electronics*. The widespread industrial implementation of power electronics was based on their high performances and reduced prices, largely contributing to the successful application of electricity in heating processes. The main contribution was the possibility of changing the frequency of industrial distribution networks; indeed, the enhancement of heating process efficiency requires that power can be supplied to the application at an appropriate (depending on the heating method) controlled frequency;
- *Accurate modelling*. New, very powerful and accurate modelling programs have been developed. Based on the increasing calculation power of modern computers, they allow Maxwell's equations to be solved point by point in space and are so accurate that the impasse is more in obtaining the correct knowledge of the material parameters (and their variation during the heating process);
- *Manufacturing of advanced materials*. New advanced materials for heat sources or enclosures, for instance, allowed the improvement of the working parameters (temperature, pressure, type of atmosphere, etc.) and the system's efficiency, or even introducing new technologies (laser processing, microwave processing, plasma processing, ultraviolet processing, etc.);
- *Finiteness of energy resources*. In the 1970s there was a growing awareness of public opinion of the finiteness of available energy resources. Coinciding with the abrupt increase in fossil fuel price, this encouraged the implementation of new technologies based on alternative (renewable) energy sources;

- *Acid rains*. Generation of electricity from coal and the use of heating technologies based on direct fuel burning have generated important emissions of sulphur dioxide and nitrogen oxides. The resultant acid deposition produced important environment pollution problems;
- *Climate change*. The principal reason for the environmental problems is inappropriate human activities, i.e. the burning of ever-larger quantities of oil, gas, and coal, the cutting down of forests, certain farming methods, etc. Since many countries have agreed to implement the Kyoto Protocol for reducing greenhouse gas emissions, the way in which energy is looked upon in industry has thoroughly changed. The Kyoto Protocol links energy efficiency with costs, so that the industrial world has started to realize that in the near future CO_2 emission costs will have to be added to the traditional energy bill. Any electrotechnology will now be accepted only if it proves its merits in energy efficiency, thus reducing greenhouse gas emissions;
- *Economic challenges*. Globalization, the migration of manufacturing to countries with much lower remuneration and increasing energy prices are forcing manufacturing industries in different developed countries to become more efficient, produce superior quality products, and remain competitive in order to survive. A possible solution consists in replacing the old heating technologies by electric-based process heating systems;
- *Economic policies*. At the moment, many companies focus on productivity-related issues. While productivity and output are clearly important, significant energy cost savings are also achievable in industrial utility systems, including process heating systems, and these opportunities are often overlooked. Taking into account these aspects, but also the international policy regarding sustainable development, a plant manager's responsibilities include minimizing the amount of energy used in the plant, maximizing product quality, maintaining the highest possible rate of production and reducing, as much as possible, the environmental impact of the operation.

Many techniques are nowadays used for transferring the supplied electrical energy into thermal energy to heat up the material: resistance heating (direct, indirect), infrared radiation, induction, dielectric heating, etc.; all of these methods have both advantages and drawbacks, so the choice often has to be made on a case-by-case basis. In some cases, electric-based technologies are chosen for their unique technical capabilities, as the application cannot be used economically without an electric-based system; in other cases, the relative price of natural gas (or other fossil fuels) and electricity is the deciding factor.

Often, the electroheating technologies compete with concurrent technologies using fossil fuels, reducing on industry's investment and operating costs, energy costs and primary energy requirements. For some industrial applications, electric-based technologies are the most commonly used; in others, these are only used in certain niche applications. It is important to mention that in all cases, efficiency and performance must be considered together, always based on a life cycle cost analysis.

Regarding the whole industrial process, the implementation of electroheating fulfils the following expectations [4, 5]:

- *It reduces the energy required to produce goods (a better energy efficiency).*
  Heating a manufactured component by producing heat inside the material (as many electrotechnologies do), rather than by heating it from the outside in (typical of classical heating technologies), requires less energy. Moreover, in many cases, the existing heating equipment

must be kept fired continuously during the whole production process, increasing the fuel consumption.

- *It reduces greenhouse gases.*
  By reducing the total energy consumption, electroheating processes also assure a decrease in greenhouse gas emissions. The implementation of some special technologies, heating in controlled atmosphere enclosures (for instance, induction and radio-frequency techniques) further reduces the environmental impact.
- *It improves product quality.*
  The quality of numerous finished products fundamentally depends on the performances of the heating process. In many applications, electrotechnologies have the best ability to achieve a certain product quality under constraints (for example, high throughput and low response time); more importantly, they can be applied to simultaneously improve product quality and value while saving energy.
- *It increases the speed of production.*
  Classical heating technologies are very time-consuming processes; indeed, a product normally requires a quite long time to reach the imposed temperature due to material thickness, its thermal conductivity, and surface properties. On the other hand, the temperature limits and temperature gradient should be accurately imposed in order to avoid product damage or undesirable changes. Some electric technologies (direct resistance heating, induction or dielectric heating) can speed up the rate of material heating without exceeding surface temperature limits; the efficiency of these processes is normally much higher than that of conventional ovens, heating tunnels and radiant heaters. An improved rate of heat transfer and higher efficiency translates into a faster production rate and lower energy costs.
- *Electric-based process heating systems are controllable.*
  In most equipment, a quite simple control system used during the heating procedure maintains the proper values for power input and other electrical or technological parameters.
- *It improves the work environment for employees.*
  Since electrotechnologies do not use fossil fuels, the work environment is usually improved by lowering temperatures and eliminating combustion products from the shop floor.

10.1 General Aspects Regarding Electroheating in Industry

Electroheating technologies comprise high-power heating processes that are powered through electrical energy and cover a large percentage of industrial electricity consumption, ranging from 20 to 40% within the EU. Figure 10.2 [6] represents the percentages of different electroheating processes in industry (in this chart, ‘Others’ include techniques as ultraviolet, plasma, air knife, electric arc, etc.).

As was previously indicated, the industrial applications of electroheating technologies lead to energy savings and product quality improvements versus other processes. They have the following main characteristics [7, 8]:

- Electroheating technologies use electric currents or electromagnetic fields to heat a large variety of materials (metals, ceramics, natural fibres, polymers, foodstuffs, etc.).
- Currently they are associated with many industrial processes involving heating, melting, annealing, drying, distilling, separating, coating, drying, etc.

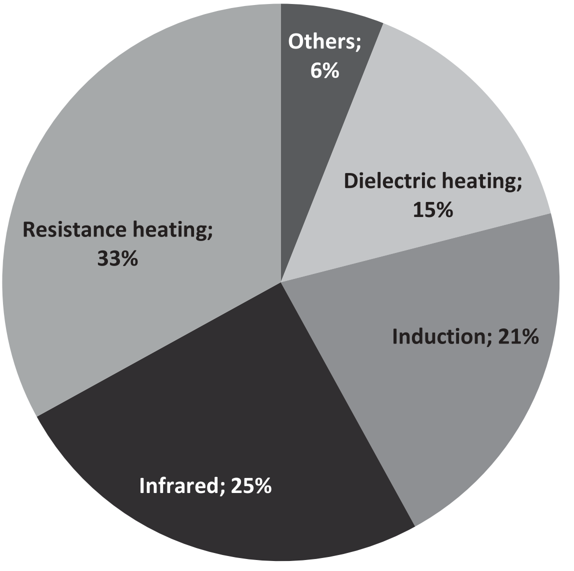

Figure 10.2 The percentages of different electroheating processes (based on [6])

- Most of the electroheating installations can be very accurately controlled and/or process materials in controlled atmosphere enclosures. These attributes guarantee a better quality product, less material and energy wasted, and reduced operation time, that is energy savings, reduced costs, and reduced CO_2 emissions.
- Sometimes, the electroheating technologies are the unique solution for some particular technological processes (for instance, high-temperature heating and melting or localized hardening of metal parts) and in the production of new materials. They also support the development of new technologies such as nanoelectronics and optoelectronics.
- In high-temperature applications, the electroheating installations are generally more energy efficient than their alternatives (furnaces based on direct fuel burning). The optimal efficiency of an electric furnace can reach up to 95% process efficiency, whilst the equivalent for a gas furnace is only 40–80%.
- Normally, the electric-based heating systems do not emit, at the location of use, gases (NOx, SOx, CO_2 or other gaseous products of heating processes), dust or hazardous salts and metals, so improving the working environment.
- They are the only solution for technological processes involving very high temperatures.

Figure 10.3 shows a basic classification of electroheating technologies currently used in industry [7, 9]. An overview of application potential in industry is presented in Table 10.1 [5]. The table shows the electrotechnologies that may be applicable to specific industry groups depending on the actual technological processes in the plant; the intersections are labelled with a qualitative potential for application (High, Medium or Low).

The industrial practice clearly confirmed that, apart from technological benefits, electroheating processes can be very advantageous from the point of view of energy consumption and CO_2-emissions. Figure 10.4 [7] presents a global comparison of different drying technologies

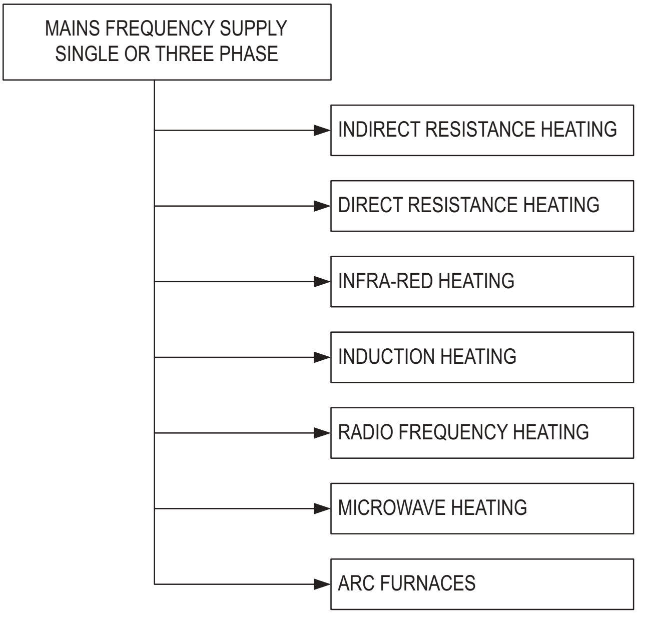

Figure 10.3 Classification of the principal industrial electroheating processes

and highlights that in this area the dielectric heating (microwave in this case) represents the best choice compared with old technologies (oil heated and gas fired) but also compared with another electrical solution (resistance heating).

Figure 10.5 illustrates an additional significant example; here, the energy consumption and CO_2-emissions for melting aluminium are compared for two technologies: a large gas-fired furnace and a large electric channel induction furnace (CIF).

In Figure 10.5, the analysed quantities refer to the following aspects:

- *Primary energy*: represents the energy required to heat the furnace (for the gas-fired furnace) and the energy required for generating the necessary amount of electric energy at a power plant (for the CIF), respectively;
- *Final energy*: the energy required by the melting process;
- *CO_2 emission:* the figures presented relate to the primary energy used.

For each bar, the upper section represents the energy equivalent for the melt losses, while the lower section is the energy used in the melting process. After a comparative analysis of the data presented, the following conclusions can be made:

- If the energy equivalent for the substitution of the melt losses is taken into account, the electric furnace consumes less primary energy than the gas-fired furnace for melting an equal amount of aluminium.
- The final energy is also lower for CIF.
- The channel induction furnace emits less CO_2.
- The relative difference between primary and final energy is the largest for the CIF (this ratio is typical for generation of electric power).

Table 10.1 Application potential of electrotechnologies in industry (based on [5])

Electrotechnology	Food	Textile product	Clothing	Leather allied	Wood products	Paper	Printing & related	Petroleum & coal products	Chemical manufacturing	Plastic & rubber	Non-metallic mineral products	Primary metal manufacturing	Fabricated metal products	Machinery manufacturing	Computer & electronic product manufacturing	Electric equipment, appliances & components	Transportation equipment manufacturing	Furniture and related product manufacturing
Infrared	M	H	M	M	M	H	H	M	M	H	H	M	H	H	H	H	H	M
Induction	L	M	L	L	L	L	L	L	M	M	M	H	H	H	M	H	H	M
Radio-frequency	M	H	L	L	M	M	L	L	L	H	L	L	H	H	L	H	L	M
Microwave	H	L	L	L	L	L	L	L	M	M	M	M	L	L	L	H	L	L
Direct Resistance	M	L	L	L	L	L	L	L	L	L	M	H	H	M	M	M	M	M
Indirect Resistance	H	M	M	M	M	M	M	M	M	M	M	M	H	M	M	M	M	M

Legend: Application potential – **H** = High; **M** = Medium; **L** = Low

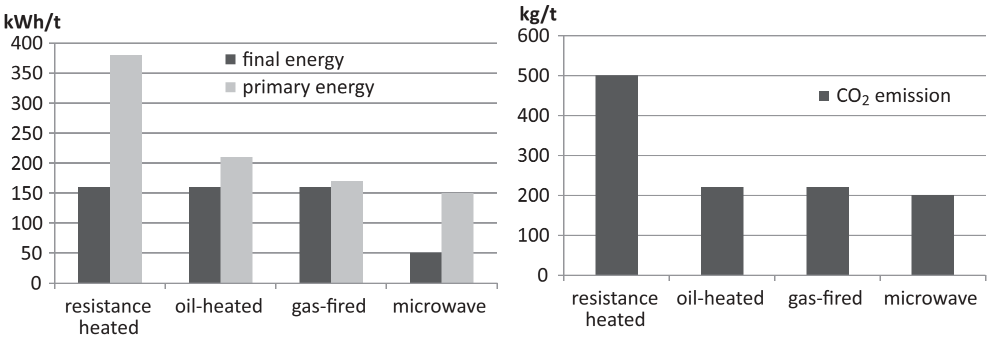

Figure 10.4 Final and primary energy and CO_2-emission in different drying technologies (based on [7])

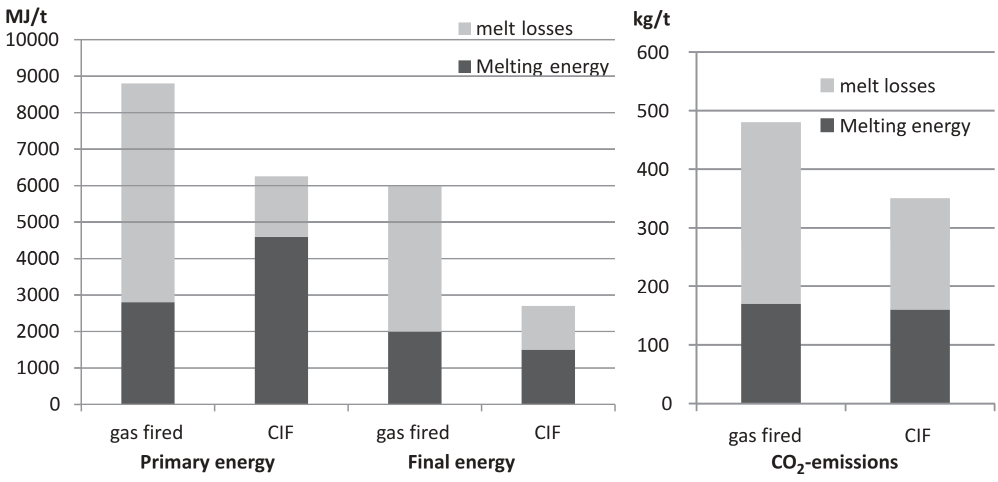

Figure 10.5 Energy requirements and CO_2-emission for melting of aluminium (based on [7])

10.2 Main Electroheating Technologies

Different electric-based process heating systems assure the necessary heat by transforming the electrical energy into thermal energy transmitted to the material to be treated. In the case of direct heating methods (e.g., direct resistance, dielectric heating, induction), the heat is generated within the material; for indirect methods (e.g., indirect resistance, indirect induction, infrared, electric arc, laser, etc.) energy is transferred from a heat source to the material by conduction, convection, radiation, or a combination of these techniques.

In most processes, an enclosure is needed to isolate the heating process and the environment from each other. The enclosure reduces thermal losses and assures the containment of radiation (e.g., microwave or infrared), the confinement of combustion gases and volatiles, the containment of the material itself, the control of the atmosphere surrounding the material, and combinations of these.

The most important electroheating technologies further presented are resistance heating (direct or indirect), infrared radiation, induction, dielectric heating and arc furnaces. Depending on the process heating application, system sizes, configurations, and operating practices differ widely throughout industry.

10.2.1 Resistance Heating

Resistance heating is the simplest (but also the oldest) electric-based method of heating and melting metals and non-metals. The efficiency of this technique can rise up to close to 100%, while working temperatures can exceed 2000°C, so it can be used for both high-temperature and low-temperature applications. With its controllability and rapid heat-up qualities, resistance heating is used in many applications from melting metals to heating food products. There are two basic types of this technology: indirect and direct resistance heating.

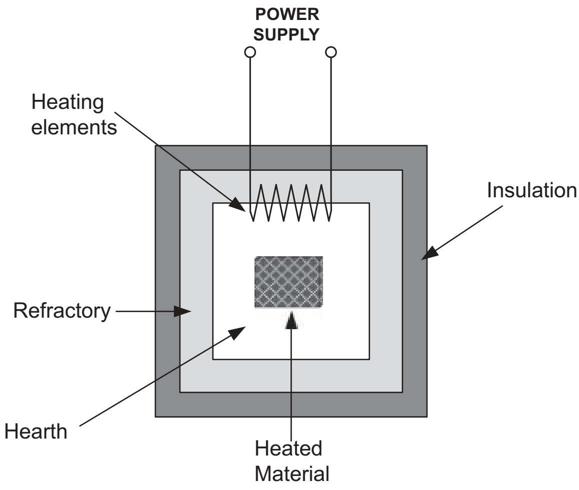

Figure 10.6 Outline of indirect resistance heating ([7])

10.2.1.1 Indirect Resistance Heating

1. Principle

Indirect resistance heating involves passing line-frequency current through a set of heating elements made of a high resistance material such as graphite, silicon carbide, or nickel chrome. When current flows throughout this element, heat is generated by the Joule effect and then transferred to the work piece via conduction, convection, and/or radiation. Heating is usually done in a furnace, with a lining and interior that varies depending on the target material; the outline of a system of indirect resistance heating is shown in Figure 10.6.

The process material temperatures can range from ambient to 1700°C or more (with an inert atmosphere), depending on the application and type of heating elements. Resistance heating systems that rely on convection as the primary heat transfer method are mainly used for temperatures below 650°C, while those that employ radiation are used for higher temperatures, sometimes in vacuum furnaces.

Usually, this type of heating is typically performed in a well-insulated enclosure; characteristic furnace linings are ceramic, brick and fibre batting, whilst furnace interiors can be air, inert gas, or a vacuum (at high temperatures an inert atmosphere is required around the work piece in order to prevent corrosion of the surface of the material). This solution minimizes thermal losses and provides a high heating efficiency, typically in the 80% range.

2. Types of Systems and Applications

Indirect resistance heating can be implemented in several ways [4, 5, 8]:

- custom heating solutions, using a wide variety of encased heaters, in which the resistive element is enclosed in an insulator (the coat is needed to isolate the heating element and the working environment from each other). Usually, this solution is adopted for low-power applications;

- direct contact with the material to be heated (in this case the heater is placed in the liquid that needs to be heated or close to a solid that requires heating, e.g. immersion-element water heater);
- by heating an intermediate substance (typically water or air);
- as the heat source in a thermally insulated enclosure (as a rule, in high-power industrial applications – resistance furnaces).

For furnace applications, various types of heating elements and enclosures may be used, depending on the temperatures needed, the product to be heated and the process used. There are four general categories of resistance furnace:

- normal or controlled atmosphere furnaces;
- batch process or continuous-process furnaces;
- batch feeding furnaces (manual, by motor, etc.);
- continuous feeding (e.g. conveyor belt, etc.) furnaces.

Indirect resistance heating is used in a wide variety of applications, including:

- high-temperature heating and melting in metal and glass industries, including metal preheating or reheating for forging and sintering (melting can be combined with refining processes, which demand the increase of temperature to remove impurities and/or gases from the melt);
- low-temperature heating and melting (for non-metallic liquids and solids);
- heat treatments, extensively used in metals production, and in the tempering and annealing of glass and ceramics products;
- calcining (familiar applications include construction materials, such as cement and wallboard, the recovery of lime in the craft process of the pulp and paper industry, the production of anodes from petroleum coke for aluminium smelting, and the removal of excess water from raw materials for the manufacture of specialty optical materials and glasses, powders, grains, etc.);
- agglomeration and sintering (commonly used in the manufacturing of advanced ceramics and the production of specialty metals);
- cooking, baking and roasting of food products;
- drying and curing processes (application of coatings to metallic and non-metallic materials, including ceramics and glass; in stone, clay, and glass industries, where the moisture content of raw materials, such as sand, must be reduced; in the food processing, textile manufacture, and chemical industry, in general);
- liquids (water, paraffin, acids, caustic solutions, etc.), air and gas heating;
- steam generation.

Most of the above-mentioned applications can be also performed by a wide variety of fuel-based process heating systems or steam-based systems. In many cases, resistance heating is chosen because of its simplicity and efficiency; on the other hand, there are also many hybrid applications, including ‘boosting’ in fuel-fired furnaces to increase production capacity.

3. Advantages and Limitations

Indirect resistance heating has several advantages justifying its extended use. Some of them are as follows:

- Although an old technique, it is simple and has a high flexibility of application, assuring an easily replacement of fuel oil or gas burners.
- It can be conveniently controlled and automated.
- The maintenance costs are low.
- Heating installations do not generate smoke, dust or combustion gases, improving the working conditions and reducing the environment pollution.
- The equipment is compact and may be adopted for a wide variety of heating technological processes (including those requiring special atmospheres or vacuum), generally improving the quality of the product and reducing energy consumption.

On the other hand, indirect resistance heating has some limitations and problems to be solved:

- The working temperature is limited by the melting point of the refractory material (for instance, fire clay and silica: 1700°C; chrome iron: 2000°C; zirconium: 2400–2500°C; graphite: 3000°C, etc.) and the maximum operating temperature for the electrical heating elements used (nickel: 1000°C; graphite: 1800°C, molybdenum: 2500°C; wolfram: 2800°C, etc.; it must be underlined that their service life can be severely reduced if the working temperature goes beyond the maximum allowable limit). Several types of heating elements are described in Table 10.2;
- Efficiency is strongly influenced by the heat transfer rate between the heating elements and load and also by the quality of the insulation; sometimes the operating cost may be high.

4. Typical Performance

Typical performances of indirect heating technologies are as follows:

- Conversion of electrical energy: higher than 95%.
- Power density: about 15–25 kW/m^2 of surface of furnace wall for installations equipped with metallic resistances and up to 70 kW/m^2 of surface for furnaces equipped with non-metallic resistances.

5. Application Considerations

For selecting the suitable heating technique and accurate design of the equipment, the subsequent elements have to be considered:

- the desired heating application (heating and melting, preheating, heat treating, baking, etc.) and load characteristics: nature (metal or non-metal, solid or fluid, etc.), geometrical dimensions, and working temperature (it decisively influences the heat transfer method: for instance, over 500°C the radiation is predominant);

Table 10.2 Heating element types ([5])

Heating element family	Material	Maximum temperature of element [°C]	Application–Remarks
Iron-Nickel-Chrome Alloys	Fe-20Ni-25Cr	900	Widely used because of their availability and low cost. Wide range of temperatures. Used in oxidizing atmospheres.
	Fe-45Ni-23Cr	1050	
	Fe-65Ni-15Cr	1100	
	80Ni-2-Cr	1150–1200	
Iron-Chrome-Aluminium Alloys	Fe-22Cr-14, 5Al	1280	Higher temperatures than Ni-Cr at about same cost. Embrittlement on first heating. Used in oxidizing atmospheres
	Kantal AF	1400	
Non-metallic Alloys	SiC (silicon carbide)	1600	Bars are brittle – susceptible to thermal and mechanical shocks. Used in oxidizing or reducing atmospheres
	$Cr_2O_3La_2O_3$ (lanthanum chromite)	1800–1900	
	Graphite	2500	Low cost of bars. Used in neutral or reducing atmospheres, or under vacuum.
Noble metals	Molybdenum	2300	Wire or plates. Very high cost. Only in neutral or reducing atmospheres, or under vacuum.
	Tungsten	2500	
	Tantalum	2500	

- family (according to desired temperature) and shape (related to furnace contour and size) of heating elements;
- furnace operation method (continuous/discontinuous) and maximum allowable thermal losses through walls and openings.

10.2.1.2 Direct Resistance Heating

1. Principle

Direct resistance heating involves passing an electric current directly through the product to be heated, causing an increase in temperature; based on this, direct resistance heating is often referred to as ‘conduction heating’. Direct resistance heating is an example of the Joule law or effect at work: the resistance of the work piece to the current passing through generates

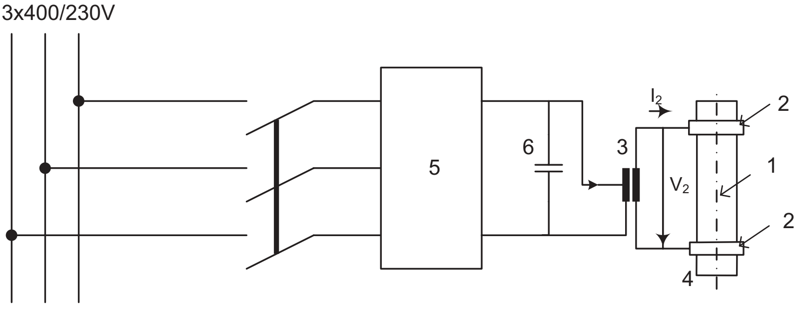

Figure 10.7 Outline of a direct resistance heating installation: 1 – heated part; 2 – contacts; 3 –power transformer; 4 – flexible jumper leads; 5 – symmetrizing system; 6 – power factor correction capacitor

heat. The material to be treated must have a reasonable electrical conductivity, but metals with higher resistivity, such as steel, create more resistance and more heat, which makes the process more efficient.

As shown in Figure 10.7, a direct resistance heating installation basically consists of a single-phase power transformer fed at constant voltage, of fixed bus bars and flexible jumper leads and of the contact assemblies whereby the current is carried into and out of the bar to be heated. Consumable or non-consumable electrodes are used to physically make contact with the product being heated; different solutions are nowadays implemented: fixed (clamp types) or mobile connectors (roll type) for metal heating applications and submerged electrodes for metal melting or liquid heating. The connector and/or electrode material has to be compatible with the processed material.

The temperature is controlled by adjusting the current, which can be either alternating or direct. Low-frequency current (DC or 50 Hz) heats the part throughout; high frequency current tends to heat only the surface of the work piece.

The equivalent circuit of the installation can be represented by the simplified series circuit shown in Figure 10.8 [10, 11].

In this circuit, the external reactance X_e takes into account the series reactance of the supply transformer (referred to the secondary terminals) and the external reactance of the high-current circuit; R_e represents the resistance of the same elements, while R_c is the contacts' resistance.

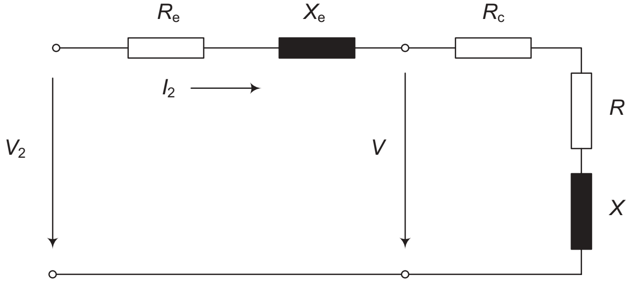

Figure 10.8 Simplified equivalent circuit of a direct resistance heating installation (V_2 – transformer secondary voltage; I_2 – heating current)

X and R correspond to the internal reactance and the AC resistance of the bar to be heated, respectively; both of them undergo strong variations during the heating transient.

Detailed data for the evaluation of the equivalent circuit parameters are given in [10] and [12]. For a proper design of a heating installation, the appropriate estimation of the X_e value is very important as it has a strong influence on the VA rating of the supply transformer, also on the maximum value of the current I flowing in the bar (from which in turn depends the life of contacts), the skin effect (which define the power density distribution in the bar cross-section) and the circuit power factor.

The reactance X_e is mainly made up of the 'external' reactance of the transformer high-current secondary circuit and therefore depends on its construction and geometry. The above-mentioned references present a series of theoretical procedures for the calculation of X_e; they consider various cross-sections and geometrical layouts of conductors. The consequence of proximity and skin effects may be taken into account or neglected (the current density in the heated bar is considered to be uniform).

Appropriate procedures also exist for the internal impedance (resistance and reactance) of the heated element; in this case, the following elements are considered: the nature of the material, its geometrical form and dimensions and the frequency of the heating current (DC or AC). It is important to mention that the dynamic values of these parameters are current- and temperature-dependent. However, modern computing software allows a detailed numerical analysis of the heating process, providing an in-depth knowledge of all these dependencies at each instant of the heating transient; for this purpose, the variations of the electrical and thermal material's physical characteristics with temperature and the local magnetic field intensity (for magnetic permeability) are taken into account.

2. Types of Systems and Applications

Nowadays, direct resistance heating is quite extensively used in industry [5]:

- metal heaters (billet heating for further forming operations, such as extrusion, heat treating, etc.) and resistance welders (spot welders, seam welders, etc.);
- non-metal heaters (heating and/or melting glass, silicon carbide, salt baths, etc.);
- food cookers and sterilizers;
- steam generators (e.g. high voltage electrode boilers, humidity generators in building HVAC systems).

These types of system clearly indicate the following areas of application:

- heat treatment and melting of metals and glass;
- heating of ferrous metals before shaping or forming;
- metal joining: spot, seam and flash welding;
- water heating and steam generation;
- production of graphite electrode and silicon carbide.

3. Advantages and Limitations

Direct resistance heating has the following advantages:

- It has high efficiency, due to two important elements: (i) only the work piece is heated, and (ii) the radiation and convection losses from the piece surface are very small.

- There is a reduced heating time (rapid rate of heating) due to the high-power density (up to 105 kW/m^2) existing in the working material, whilst the final temperature, as well as temperature differences in the cross-section of the heated product can be very precisely controlled.
- The technology allows heating of only parts of a complex piece.
- The process can start very quickly (seconds) and does not generate combustion products.
- There is a lower equipment space requirement and moderate capital investment.

At the same time, the following limitations must be considered:

- The contact surfaces must be clean and scale free for good electrical connection, whilst the number of contacts and the contact pressure must be suitably selected in order to avoid local melting.
- The piece configuration must provide realistic high resistance to current flow but uniform cross-section is required for uniform heating.
- The work piece must be long and slender (i.e. length-to-diameter at least 6:1), direct heating being better suited to smaller cross-sections (i.e. < 3 cm diameter).
- Large systems (e.g. glass melting) may be limited to moderate production rates by power supply ratings.
- The power factor can be quite low (0.3–0.95).

4. Typical Performance
- electrical energy conversion: above 95%;
- overall process efficiency: typically 75– 95%;
- energy consumption: 200–350 kWh/t.

5. Application Considerations
For correct design of the equipment, the following elements have to be taken into consideration:

- the shape, size and homogeneity of material and its electrical resistivity;
- connection resistances (local overheating);
- thermal losses through the surfaces (radiation, convection) and connections (conduction);
- voltage and power supply (DC, AC, capacity required);
- skin effect (dissipated power varies according to operating frequency and depth of penetration of the current).

10.2.2 Infrared Heating

10.2.2.1 Principle

Infrared radiation heating is practically a variant of indirect resistive heating; it uses radiation emitted by electrical resistors, usually made of nickel-chromium or tungsten, heated to relatively high temperatures – Figure 10.9 [4, 10]).

The used infrared region (wavelength λ: 0.78–10 μm) is commonly divided into three ranges: near-infrared or short-infrared ($\lambda = 0.78$–2 μm), intermediate-infrared or medium-infrared ($\lambda = 2$–4 μm) and far-infrared or long-infrared ($\lambda > 4$ μm). Although the electric infrared

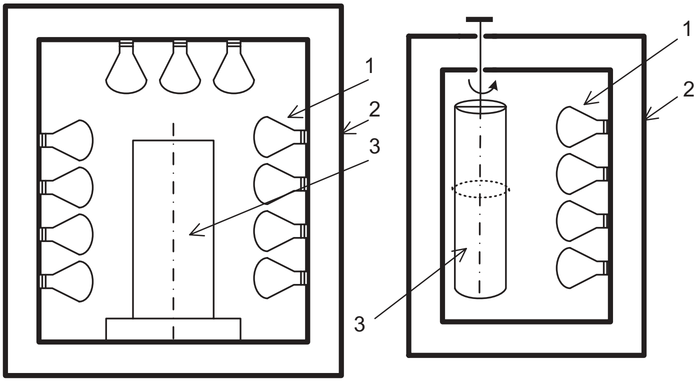

Figure 10.9 Outline of infrared heating: 1 – IR emitters (including the reflector system); 2 – furnace wall; 3 – heated part

is most often used in applications in which only the surface of an object needs to be heated by infrared, it can also be used in bulk heating applications.

As Figure 10.9 shows, electric infrared heating systems typically consist of an emitter, a reflector system, and controls (because operation time can be as little as seconds and an exact temperature of the work piece to be heated is usually required, accurate control is critical). Most electric infrared applications also have a material handling system and a ventilation system.

10.2.2.2 Types of Systems and Applications

Infrared energy is usually used when the object being heated is in line-of-sight of the emitters and/or reflector; however, some infrared systems can cure coatings that are not in line-of-sight (for example, curing a coating on the inside of a pipe using infrared focused on the outside of the pipe: while the curing is being accomplished by conductivity, it is using infrared processing).

Emitters used in infrared heating systems are solid resistors emitting energy in the infrared regions mentioned above; emitter technologies and performances correspond to each of the three infrared radiation spectrum bands, as presented in Table 10.3 [5, 8, 13, 14].

Because of the shape of the curve giving the spectral distribution of the radiated energy versus temperature and wavelength, the following rules must be respected in order to place the radiated energy within the desired band of wavelengths:

- for short and medium infrared radiation, the emitter temperature must be much higher than that defining the upper limit of the band;
- for long infrared radiation, this temperature must be close to the limit of the lower emission band, or even in the upper part of the medium infrared band.

Electric infrared processing systems are used by many manufacturing sectors for heating, drying, curing, thermal-bonding, sintering and sterilizing applications. They are often combined

Table 10.3 Infrared sources

	Near infrared		Intermediate infrared		Far infrared
Emitter	Tungsten filaments under vacuum		Nickel-chromium wire in quartz or silica	Steel-clad elements	Elements embedded in Pyrex or ceramic
	Glass or quartz lamp	Quartz tube with reflector			
Power	150 W	12–14 cm: 500W	30–250 cm: 6000 W	600–6000 W	150–1000 W
	250 W	27–28 cm: 1000 W			
	375 W	64–70 cm: 5000 W			
Operating temperature	2000°C	2200°C	Quartz tubes: 1050°C	750°C	Pyrex panels: 350°C
			Silica panels: 650°C		Ceramic elements: 300–700°C
Maximum product temperature	300°C	600°C	Quartz tubes: 500°C	400°C	Pyrex panels: 250°C
			Silica panels: 450°C		Ceramic elements: 500°C

with hot air to remove vapours and to help prevent premature surface hardening. Examples of applications include:

1. Drying and polymerization of coatings on various supports
   - drying of paint, varnish, adhesives, inks or vitreous enamels on metal, wood, glass, paper and textiles;
   - coatings on leather or hides and on paper;
   - polymerization of resins on textiles and of different plastifying agents.
2. Dehydration and partial drying
   - papers, cardboards, textiles (including water paints and inks);
   - drying of plastic granules and washed sheets;
   - preheating of plastic pipes before bending and curing of powder coatings.
3. Miscellaneous heating
   - drying of washed metallic parts, preheating of metals before shot blasting or welding and heat treatment (annealing, hardening, etc.);
   - baking dehydration of breads, biscuits and cookies;
   - reheating of food products, roasting of meat;
   - pasteurization and sterilization of milk and fruit juice;
   - drying of wood panels and tobacco;
   - heat shrinking of plastic wrapping.

10.2.2.3 Advantages and Limitations

In the above mentioned applications, infrared radiation may represent a highly efficient and attractive means of heating. Its main advantages are:

- a high energy efficiency (energy is transferred from the emitter to the surface of the work piece without contact and without any significant direct absorption by the environment, according to the laws of optics);
- a low thermal inertia of the heating system and high temperature rise due to the possibility of high-power densities (up to 30 W/cm^2);
- short start-up periods and reduced heating time (rapid processing);
- the energy radiated can be concentrated, focused, directed or reflected, allowing a convenient control of heating process;
- compact equipment (it is several times smaller in size than a hot air oven due to quite low processing temperatures).

The limitation of this electrotechnology results from its operation principle:

- It is best suited to products in layers or sheets (for bulk heating, the heat takes time to travel from the surface through the material).
- It is difficult to treat complex shaped pieces or reflective coatings.
- The maintenance of IR emitters is higher in dirty environments.

10.2.2.4 Typical Performance

- The power densities that can be exchanged are much higher than with convection.
- There is low to moderate capital cost depending on application.

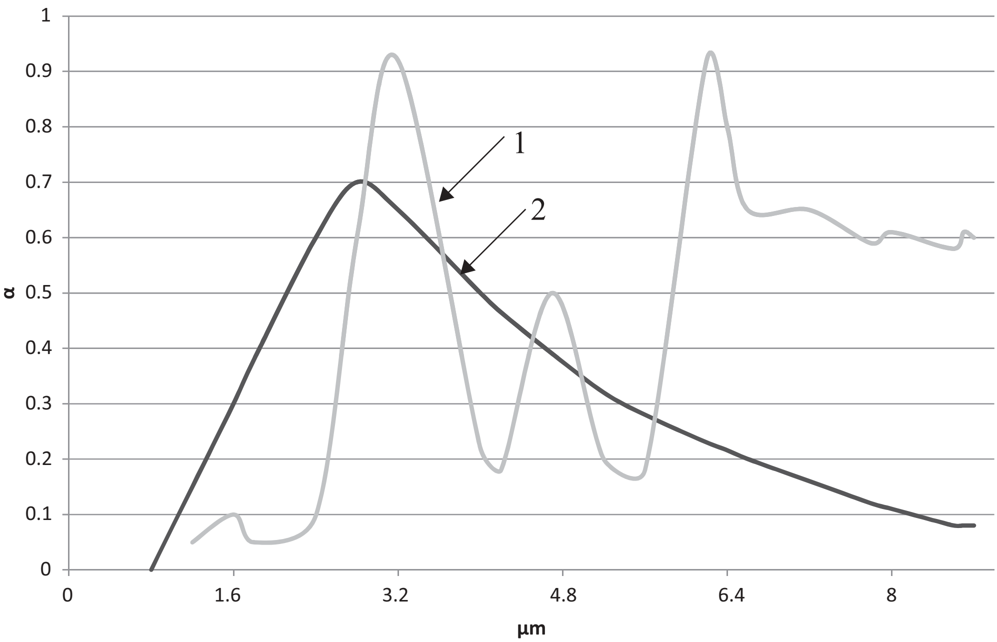

Figure 10.10 Optimum use of the absorption spectrum of the product to be heated (1) and of the emission spectrum of source (2)

- There is low maintenance, primarily emitter cleaning and replacement.
- There is high overall efficiency compared to alternative heating processes.

10.2.2.5 Application Considerations

As previous stated, in infrared radiation the heating energy is transferred from the emitter to the surface of an object according to the laws of optics. Absorption of the radiation by the piece to be heated is gradual and takes place at a certain depth from the surface; it is also a selective phenomenon that depends greatly on the incident wavelength and on material thickness. On the other hand, reflection depends mostly on the surface condition and the wavelength of the incident radiation.

It results that, for a high efficiency, the work piece to be heated must have a reasonable absorption to infrared and a reduced reflection. For this, it is desirable that the wavelengths emitted by heating sources be located within the product's maximum absorption range, Figure 10.10 [4, 10].

When analysing the possibility of selecting the infrared heating, the following factors must be taken into account:

- the heating operation to be performed (drying, heating, curing, etc.) and the required emission wavelength, based on the absorption factor of the product to be treated – the latter depends

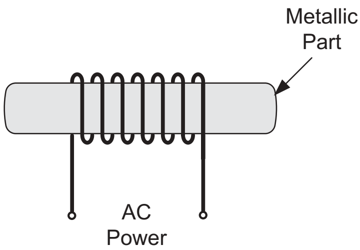

Figure 10.11 Induction heating

on type of material or the formulation (e.g. solvent-based vs. powder coating), thickness, surface conditions, etc.;
- the product shape (for complex shaped parts, the energy received by each elementary surface of the body varies with the distance from the source and angle of incidence of the radiation);
- the processing method (continuous/batch treatment) and oven characteristics (e.g. risks of shock between product and emitters);
- the type of emitter (temperature of active element, power density, etc.), distance between emitters and product to be heated, and ventilation conditions.

10.2.3 Induction Heating

1. Principle

Induction heating consists of applying an alternating magnetic field created by an inductance coil (inductor) to an electrically conducting object, Figure 10.11. The variable (oscillating) magnetic field produces an electric current (called an induced current) that flows through this body and heats it by the Joule effect. In addition to the heat induced by eddy currents, magnetic materials also produce heat through the hysteresis effect: magnetics naturally offer resistance to the rapidly alternating electrical fields, and this causes enough friction to provide a secondary source of heat (however, this secondary heating process has a reduced weight and disappears at the temperature at which the material loses its magnetic properties, the Curie point).

Induction heating uses the same principle as a power transformer [15]. The primary circuit (the inductor) creates a variable magnetic field, while the heated metal piece, through which the short circuit current flows, represents the secondary circuit. As alternating currents are concentrated on the outside of a conductor (the *skin effect*), the currents induced in the material to be heated are the largest on the outside and diminish towards the centre. The skin effect is characterized by its so-called *penetration depth*, δ, defined as the thickness of the layer, measured from the outside, in which 87% of the power is developed (Figure 10.12 [16]). The penetration depth, δ, results from Maxwell's equations:

$$\delta = 503 \cdot \sqrt{\frac{\rho}{\mu_r \cdot f}}\ [\mathrm{m}] \tag{10.1}$$

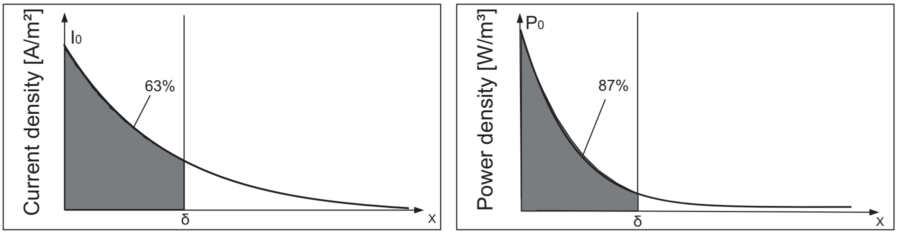

Figure 10.12 Penetration depth ([16])

where ρ is the material resistivity (Ω m); μ_r is the magnetic permeability of the material to be heated; and f is the supply frequency (Hz).

Both the frequency of magnetic field and the characteristics of the material to be heated (ρ, μ_r) influence the penetration depth. The frequency dependence offers a convenient possibility to control the penetration depth and, in this way, other parameters of the heating system: energy efficiency, power factor, mixing and melting rates, etc. Table 10.4 [13] gives several values of interest with regard to the influence of the material and magnetic field frequency on the depth of penetration.

The heating intensity diminishes as the distance from the surface increases, so small or thin pieces generally heat up more quickly than large thick parts, especially if the larger parts need to be heated all the way through.

2. Types of Systems and Applications

Induction heating is accomplished by placing an alternating current-carrying coil around or in close proximity to the material. When talking about the heating of processed material, there are two variants of this electrotechnology:

1. *Direct induction:* this occurs when the material is heated directly by the alternating magnetic field (eddy currents induced within the piece flow against the electrical resistivity of the metal, generating precise and localized heat without any direct contact between the piece

Table 10.4 Penetration depth ([13])

Material		Steel 20°C	Steel 20°C	Copper 20°C	Copper 900°C	Graphite 20°C
ρ [$\mu\Omega$ m]		0.16	0.16	0.017	0.086	10
μ_r		40	100	1	1	1
δ [mm]	50 [Hz]	4.50	2.85	9.31	20.87	225.08
	100 [Hz]	3.18	2.01	6.58	14.76	159.15
	1 [kHz]	1.01	0.64	2.08	4.67	50.33
	10 [kHz]	0.32	0.20	0.66	1.48	15.92
	100 [kHz]	0.10	0.06	0.21	0.47	5.03
	1 [MHz]	0.03	0.03	0.07	0.15	1.59

and the coil). Direct induction heating is primarily used in the metal industry for melting, heating and heat treatment (hardening, tempering, and annealing).

2. *Indirect induction:* in this case, the electromagnetic field generated by a coil induces eddy currents into an electrically conducting material (also referred to as susceptor), which is in direct contact with the material to be treated. Indirect induction heating is used to heat plastics and other nonconductive materials by first heating a conductive metal susceptor that afterwards transfers heat to the work-material.

The inductor and the heated part behave as an inductive load and are compensated with capacitors, while a frequency converter feeds the coil with a single-phase current at the desired frequency. Other components of an induction installation are: the cooling system (for frequency converter and inductor), a transport system (if required by the heating process) and the necessary control system. From the power supply point of view, the following variants can exist:

- 50 Hz installations: the compensated load is directly connected to the industrial distribution network;
- frequency converters with thyristors (rated power up to 10 MW), working in the frequency range 0.1–10 kHz with an efficiency of 90–97%;
- frequency converters with transistors (rated power up to 500 kW), with frequency range up to 500 kHz and efficiency 75–90%;
- frequency converters with vacuum tubes (rated power up to 1.2 MW): frequency range up to 3 MHz and efficiency 55–70%.

The applications of induction are usually associated with the melting of metals, heating of metals for forging, brazing and welding, and all sorts of surface treatments; the heating of non-metallic materials are also possible (however, the induction systems involved in this kind of applications require high-frequency magnetic fields).

Direct Heating of Metals (Metallurgical Applications)

- Smelting and melting of steel, cast iron, aluminium, copper, zinc, lead, magnesium, precious metals and alloys;
- heating prior to forming/forging (slabs, sheets, tubes, bars, etc.) and selective heating of parts and bonding of metals and non-metallic bodies;
- heat treatments (hardening of gears and annealing of tubes, welds, wire, sheets, etc.) or heating prior to surface treatments of metal elements (cleaning, stripping, drying, galvanizing, tinning, enamelling, organic coatings, etc.);
- welding and brazing.

Indirect Heating of Materials in Metal Containers

- Heating of dies and press platens in the plastics industry or of chemical reactors in the manufacture of resins, paints and inks;
- heating of vats in the food industry;
- melting and crystallization of glass, refractory oxides and nuclear waste.

3. Advantages and Limitations

Owing to its operation principle, induction heating has a number of essential advantages, such as:

- It has a very quick response (practically instant) and a high efficiency (the overall efficiency is 70–75% on average, and as much as 90%; in addition, there is no energy loss during idling time), for faster production rate and very high temperatures.
- It allows heating very locally (no risk in heating undesired components) and controlled depth of penetration, at extremely high heating speeds (due to the high-power density: 50–50 000 kW/m^2).
- Remarkable purity is possible in the absence of any physical contact between the energy source and the object to be heated and/or by working under vacuum or inert atmospheres.
- There is a reduction of oxidation losses and an absence of decarburization.
- There is a substantial improvement in working conditions (less heat and noise released to the local area) and environmental conditions (elimination of combustion products).
- The power input to the piece can be accurately controlled by the shape of the coils, the intensity of the field and the time applied.
- It uses bath stirring in the melting processes (this favours the homogeneity of alloys and rapid melting).
- Good repeatability (often used where repetitive operations are performed: once an induction system is calibrated for a part, work-pieces can be loaded and unloaded automatically).

The next limitations must be considered:

- A large investment is needed that must be considered and compared with alternative heating techniques.
- It is not well suited to irregularly-shaped parts during forging.
- It is necessary to change the inductor and sometimes compensate for pieces that are non-repetitive in shape.
- The power factor of the inductor and the load usually lies around 0.05–0.6.

4. Typical Performance

- The efficiency depends on the operating parameters: geometry of the inductors, distance between inductor and material, nature of materials to be treated and the properties of the inductor's conductors, etc.;
- It has a specific power output up to several MW.

5. Application Considerations

- According to the material properties, the direct (metallic bodies) or indirect (non-metallic materials) heating is selected but the latter has only specific areas of application.
- The size and shape of the piece must be analysed and, sometimes (for long and slender work-pieces), the direct resistance heating can be more efficient.
- The configuration of the inductors must be as close as possible to that of the materials (in order to reduce the air gap between the inductor and the load, so improving the power factor and efficiency).

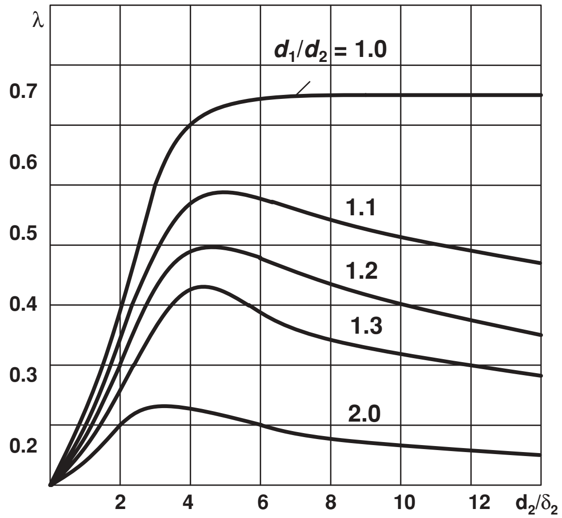

Figure 10.13 Variation in power factor λ for an induction heating system: d_1 – interior diameter of the inductor; d_2 – exterior diameter of the part; δ_2 – penetration depth in the part

- Great attention must be paid to the parameters of the material to be heated (magnetic permeability, electric resistivity and thermal conductivity), and to their changes with temperature.
- The choice of the frequency of the variable magnetic field is important because it decisively influences the energy efficiency and the power factor, Figure 10.13 [4, 10].

10.2.4 Dielectric Heating

Dielectric heating is used for heating materials that are poor electrical conductors (but also poor conductors of heat) and corresponds to a term covering two similar approaches: *radio-frequency heating* (RF heating) and *microwave heating* (MW heating). In both techniques, the material to be heated is exposed to an electromagnetic field that is continuously reversing direction (alternating) at a very high frequency.

When a non-electrically-conducting material is placed in a high frequency electric field, the electron and proton charges within the molecules of the material try to align themselves with the applied field. This results in a rapid agitation of the molecules, which is converted into heat within the material as a result of molecular interaction (e.g. friction); this is known as heating by dielectric hysteresis or, in short, dielectric heating. The heat produced depends mainly on the dielectric properties of the material to be treated. In RF heating the frequency is between 1 and 300 MHz; for MW heating, the frequency lies between 300 and 30 000 MHz, typical 2.45 GHz. To avoid conflict with communications equipment, several frequency bands have been set aside for industrial dielectric processing.

The essential advantage of dielectric heating resides in the generation of heat directly within the material to be heated. In comparison with other more conventional heating techniques (hot air, infrared) in which the material is heated via the outer surface, dielectric heating is much more rapid (as materials are poor conductors of heat, the transfer of the heat by conduction

Table 10.5 Dielectric properties

Material	Temperature [°C]	30 [MHz]		2500 [MHz]	
		ε'	ε''	ε'	ε''
Water	−12	3.8	0.7	3.2	0.003
	+25	78	0.4	77	13
	+85	58	0.3	56	3
Salt solution 0.1	+25	76	480	76	20
0.5 molar	+25	75	2400	68	54
Alumina ceramic	+25	8.9	0.0013	8.9	0.009
Quartz glass	+25	3.78	<0.001	3.78	<0.001
Nylon66	+25	3.2	0.072	3.02	0.041
Polyethylene	+25	2.25	<0.0004	2.25	0.0007
Teflon	+25			2.05	<0.0005
PVC	+20	2.86	0.029	2.85	0.016

from the outer surface takes time) and more efficient (savings from 15 to 40% in primary energy can be obtained). However, a forced-air system can be added to a dielectric heating system; the moving air removes moisture from the heating chamber and the drying processes are accelerated.

Different materials react differently to alternating electromagnetic fields; therefore, not all materials are equally suitable for dielectric heating. For instance, water heats up very fast as it absorb microwaves very easily; rubber is another good absorber. The ease with which a dielectric material can be heated is represented by what is known as the *loss factor*, reflecting the two phenomena playing a role in the dielectric heating of a material (the polarization and the molecular friction), and expressed by:

$$\varepsilon'' = \varepsilon' \tan \delta, \tag{10.2}$$

where ε' is the *relative permittivity* or *dielectric constant* of the material and δ is the *loss angle*.

The higher the loss factor, the more energy can be absorbed in the material. For a given material, the loss factor is variable, depending on temperature, moisture content (adding salt or carbon to a material increases its loss factor) and frequency. Other elements, such as the orientation of the electrical field, can also have an effect. When objects consist of materials with different loss factors, interesting applications are possible (e.g. pasteurizing pharmaceuticals and foodstuffs within their packages without burning the packaging material). Table 10.5 gives an overview of the dielectric properties of some common materials [17].

10.2.4.1 Radio-frequency Heating

1. Principle

In an RF system the field is generated between two conducting plates (electrodes), to which an alternating voltage is applied; the material to be heated is placed between these plates (see Figure 10.14 [5]).

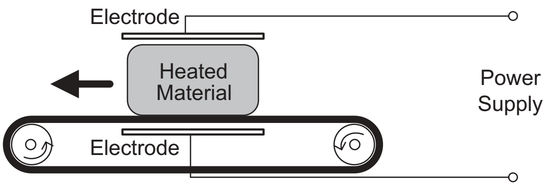

Figure 10.14 Radio-frequency heating ([5])

2. Types of Systems and Application

Generally, as shown in Figure 10.14, an RF heating system includes the power supply, the applicator (or operating space) containing the product that is to be heated and a material handling system (sometimes a ventilation system may also be added). The following types of systems, based on different criteria, are used in industrial applications [5]:

- fixed or variable frequency operation;
- batch or continuous heating (i.e. conveyor) systems;
- conveyor systems (characterized by the electrode configuration) – flat plate types for thick objects, stray field types for thin webs, and staggered electrode types for thick sheets;
- tubular heating systems (for liquids).

The RF generators are either controlled frequency oscillators with a power amplifier (also called '50-ohm' or 'fixed impedance'), or a power oscillator in which the load to be heated is part of the resonant circuit (also known as 'free-running' oscillators); the 50-ohm generators are used most prevalently in industrial processes. As stated above, only authorized frequencies may be used for open systems; for furnaces that are closed and suitably shielded, the frequencies used may range from 1 to 300 MHz.

Applicators can be constructed in different ways, depending on the specific characteristics of the product or the process; from an electrical point of view, every configuration is a capacitor with the material to be heated acting as its dielectric (for this reason, the radio-frequency heating is also referred to as capacitive heating). In radio frequency installations several configurations are possible, depending on the application, Figure 10.15 [17].

1. *'Stray field' electrodes*: the electrodes, produced as tubes or rods, are located on one side of the product to be heated, successive electrodes having a reversed polarity. This configuration is used for products or layers very thin (up to 10 mm), flat and having a large surface area.
2. *'Staggered-through' electrodes (garland arrangement):* in this configuration, the product to be treated is located between two rows of electrodes. The solution usually offers a more homogeneous field, while the field strength can be regulated easily by varying the electrode distance.
3. *Plate electrodes*: the electrodes are parallel plates located on either side of the treated product (forming a flat capacitor); this arrangement is mostly used when the product is thick or complex in shape.

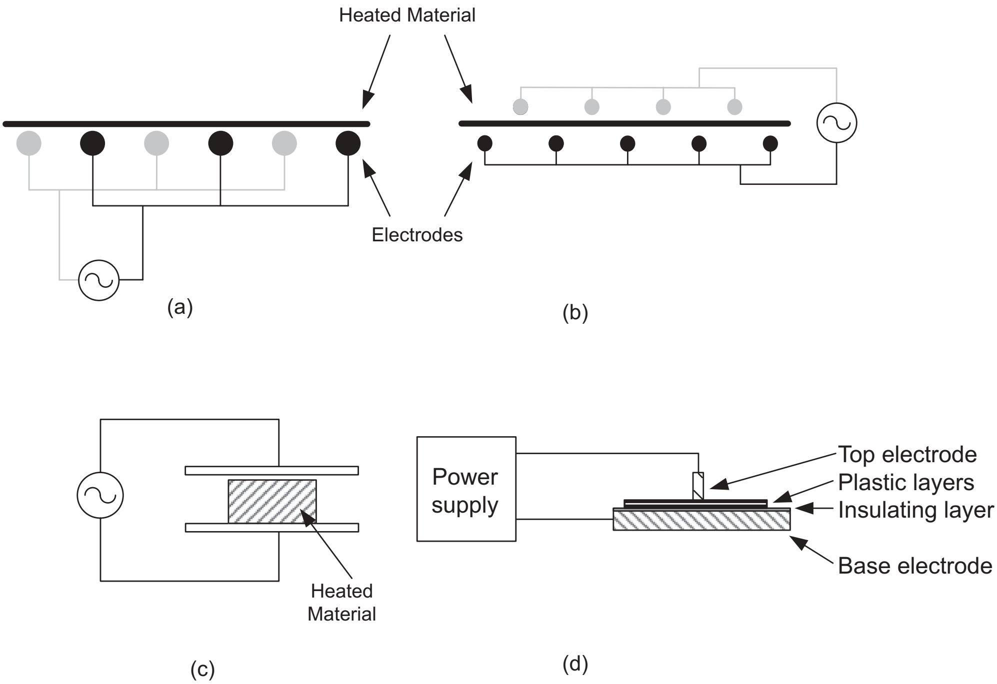

Figure 10.15 Main types of applicators for radio-frequency heating: (a) 'stray field'; (b) staggered through'; (c) flat plate; (d) welding electrodes (based on [17])

4. *Welding electrodes*: the configuration is used in such applications as thermoplastic welding and consists of a plate-like electrode and an electrode that is especially designed for the application (required pressure is exerted on the top electrode).

The main applications of capacitive heating are:

- the heating of any dielectric material, so long as it has a convenient loss factor (glues, plastics, resins, etc.);
- evaporation of water in dielectric and fairly regular in shape materials (paper, cardboard, board, textiles, wood, etc.), or drying of water-based coatings, inks and adhesives in paper manufacturing and converting;
- the welding and sealing of plastics;
- post-baking drying and moisture control of biscuits, crackers, cereals and other food products;
- heat treating, de-infestation and pasteurizing of bagged materials.

3. Advantages and Limitations

Based on the general advantages of the dielectric heating (the material is heated directly and instantly, there is the possibility of applying high-power densities throughout the process, significantly reduced treatment time and floor space, increased productivity, instant start and stop, etc.) the following specific positive attributes for RF heating applications can be derived:

- high efficiency, mainly in applications requiring a good water-elimination gradient (overall process efficiency in the range 50–70%), due to the selective water heating – moisture-levelling within the material treated and no overheating of the product (resulting in less energy used and better quality);
- power consumption with humid materials alone (advantageous for separate or spaced parts), with possible power density up to 200 kW_{RF}/m^2;
- heat transfer more or less independent of temperature and volume of ventilating air.

The main limitations in the industrial implementation of capacitive heating are:

- the high capital cost, but applications are more cost-effective for products with high added value or when combined use with less expensive processes (e.g. infrared, hot air);
- only authorized frequencies can be used, requiring expensive protection against electromagnetic radiation.

4. Typical Performance
- Efficiency of supply converter (rated output up to 900 kW): typically 55–70%, but up to 80% with newer solid-state, high frequency amplifier technology;
- floating-frequency systems offer a higher overall efficiency, but a higher level of RF-shielding is required;
- tube service life: 5000–10 000 hours.

5. Application Considerations
When selecting this technology or designing the equipment, the following aspects have to be considered:

- The materials to be treated must be dielectric and the chosen frequency (floating or fixed, according to the material reaction) has to correspond to a high loss factor (otherwise the electric field is totally reflected at the piece surface and does not penetrate).
- The treatment (heating, drying, gluing, etc.) may be performed in batches or continuously.
- The parts to be treated should preferably be regular or flat in shape, their characteristics imposing the electrode and conveyer types, power density and total power to be installed.
- The possibility of combining the high-frequency technique with another one, such as infrared or hot air should seriously be considered in order to reduce capital costs.

10.2.4.2 Microwave Heating

1. Principle
In microwave ovens, material is heated by means of microwaves, packages of energy travelling through space; the higher the frequency of this wave, the higher its energy. The frequency typically used in industry is 2.45 GHz. Microwaves have a higher power density than radio-frequency waves and usually heat material faster.

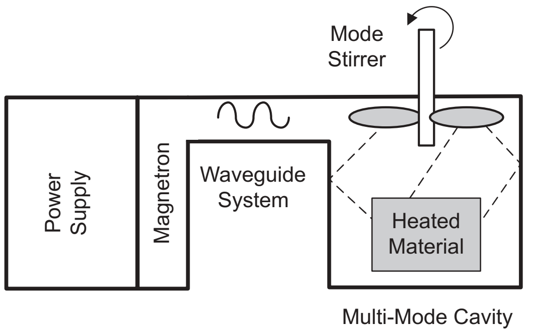

Figure 10.16 Microwave heating (based on [5])

The electromagnetic waves are generated in a wave generator (magnetron), which is situated outside of the heating chamber, Figure 10.16 [5]. As microwaves have a wavelength that is comparable to the dimensions of the installation, the energy cannot be transported via standard conductors and discrete networks. In this case, the waves are sent to the heating chamber through a tube, called the waveguide, produced as metal (copper or aluminium) pipe, mostly with a rectangular cross-section; the dimensions are dependent on the frequency. Waveguides can be both straight and curved, but the inside surface must be smooth and clean. The waves are then absorbed by the material placed inside the heating chamber.

2. Types of Systems and Applications

The MW heating can be implemented either as Batch Systems or Continuous Systems, with the following alternatives:

- single-mode (the product runs though a folded rectangular wave guide), Figure 10.17(a) [17];
- multi-mode (the product to be heated is placed in a large heating cavity or oven), Figures 10.16 and 10.17(b);

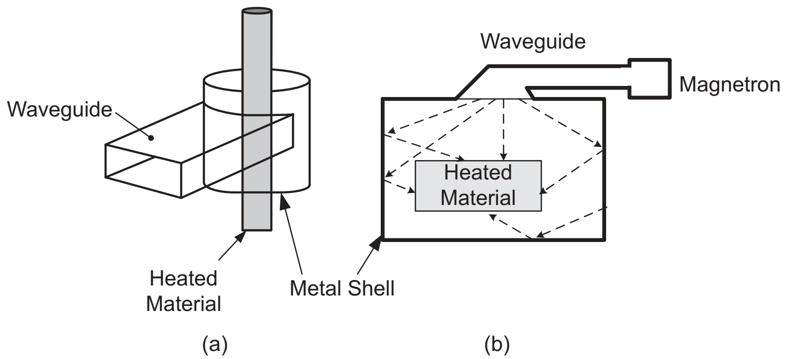

Figure 10.17 Microwaves installations: (a) monomode applicator; (b) multimode applicator (based on [17])

- tubular types (for liquids), implemented as standing wave and serpentine or coiled tube;
- radiating slotted waveguide and horn;
- rotary tube systems (for granular and powder materials);
- slotted waveguide (for webs).

Nowadays, microwave heating has been established in some key industries; the available applications practically cover the same areas as capacitive heating, but also some specific uses may be encountered:

- heating and evaporating water in any dielectric material requiring drying (even of complicated shapes);
- preheating and vulcanizing rubber products;
- heating and tempering frozen meat and other food products;
- drying and hardening coatings on carpets, textiles, paper, plastics, and electronics;
- sintering ceramics;
- production of plasma in chemical processes.

3. Advantages and Limitations

MW heating has the same advantages as radio-frequency technology. The limitations are also quite similar, but we can add the following:

- Only low power units are available and that may require multiple power sources or may restrict the quantity of heated material.
- Undesirable heating effects can appear in some applications, depending on the processed material (runaway temperature rise, burning).
- It may be difficult to treat large areas uniformly.

4. Typical Performance

Nowadays, the typical performances of MW heating equipment are:

- overall process efficiency ranges from 50% to 70% for power densities up to 500 kW/m^2;
- generator unit power: up to 30 kW per tube at 2.45 GHz, and 100 kW per tube at 915 MHz;
- power tube life: typically 5000–8000 hours of operation.

5. Application Considerations

The application considerations are similar to those presented for radio-frequency heating. However, for a given application, one technology is usually better than the other.

10.2.4.3 Comparisons Between Radio-Frequency Heating and Microwave Heating

Radio frequency and microwave techniques are both based on the principles described above. The operating frequency is, however, different and the two electrotechnologies differ notably in the behaviour of the various materials treated and the nature of the components used [5]:

- Power outputs available from RF sources (tubes or solid-state amplifiers) are higher than for microwave sources, thus allowing a scale reduction in costs (RF: up to 900 kW_{RF}; MW: up to 75 to 100 kW_{MW}). Overall, the capital cost for RF equipment is about half as much as for MW equipment.
- There is no RF power dissipation when there is no load (unlike MW).
- RF is better suited to large (thick), flat materials (uniform power and applicator type) while irregularly shaped products are more easily treated in MW multimode cavities.
- There is a wider choice of RF frequencies to adapt to different situations.
- MW heating is more suited to materials with low dielectric-loss factor and lends itself better to the application of high-power densities without creating a breakdown (e.g. arcing).

10.2.5 Arc Furnaces

1. Principle

Electric arc furnaces are process heating systems that heat materials by means of an electric arc created when a current (AC or DC) passes through an ionized gas between two electrodes. Such arcs are quite powerful and allow temperatures of up to 4000°C to be reached; these temperatures are high enough to melt steel, iron scrap or other materials. The electric arcs are used in furnaces as radiant heat sources or as submerged arcs, and the charge is usually heated both by current passing through the charge and by the radiant energy from the arc.

2. Types of Systems and Applications [3]

There are three types of electric arc heating systems, namely direct arc (contact) furnaces, indirect arc furnaces and submerged arc furnaces. In the first case, the furnace consists of a water-cooled refractory-lined vessel, covered by a retractable roof through which graphite or carbon electrodes (typically there are three electrodes) protrude into the furnace. As the electric arc strikes from an electrode to the metal charge, the distance between the electrode and the melt surface must be adjusted, in order to assure a constant arc length (the electrode wear is compensated by a positioning system that lower the electrodes into the furnace during operation).

The indirect arc furnaces have a horizontal barrel-shaped steel shell, lined with refractory, the arc being drawn between two carbon electrodes positioned above the load. Because the heat is transferred by radiation from the arc to the metal being melted, excessive heating of the refractory above the melt level may occur.

In the case of submerged arc furnaces the electrodes are deep in the furnace and the reaction takes place at the tip of the electrodes.

The main application of direct arc furnaces is in processes for melting of metals, largely iron and steel from scrap steel and iron as raw materials; applications for smaller arc furnaces include the melting of iron, steel and refractory metals. Direct arc furnaces used in foundries are usually for producing iron for casting operations, including the continuous casting for flat products such as steel plates.

Indirect arc furnaces are common in the production of copper alloys (these units are generally much smaller than direct arc furnaces), while submerged arc furnaces are used in smelting processes to produce materials such as silicon alloys, ferromanganese, calcium carbide, and ferronickel.

3. Advantages and Limitations

The most important advantages of arc furnaces are:

- They have large production capabilities (more than 400 tons in industrial-scale processes that make steel from scrap steel), allowing very high operation temperatures (up to 4000°C).
- Direct arc furnaces are less expensive (in terms of money per ton of steel capacity) than basic oxygen furnaces.
- They have higher efficiency than basic oxygen furnaces or integrated blast furnaces.
- The final product has a very good quality even when starting from scrap steel and scrap iron.

The limitations refer mainly to the excessive wear of the refractory and the negative impact on power quality in the point of common coupling (mainly flicker, voltage variation and harmonic pollution).

4. Typical Performance

- Energy consumption ranges between 400 and 500 kWh per short ton, depending on furnace production capacity (about 1/3–1/10 from the energy required by basic oxygen furnaces or integrated blast furnaces).
- Production capacities are from less than 10 tons (in foundries that melt iron and steel for castings) to more than 400 tons (in industrial-scale processes that make steel from scrap steel).

5. Application Considerations

Electric arc furnaces used for steelmaking are usually employed where there is a plentiful and inexpensive supply of electric power.

10.3 Specific Aspects Regarding the Increase of Energy Efficiency in Industrial Heating Processes

In practice, the increase of energy efficiency in industrial heating processes may be obtained in the following ways:

- the replacement of traditional technologies (direct fuel burning hot air, steam, water, etc.) by existing electrotechnologies, selecting the most appropriate technology for the required application;
- increasing the efficiency of the existing electroheating equipment;
- ensuring suitable operation and maintenance of the industrial electroheating equipment.

10.3.1 Replacement of Traditional Heating Technologies

The main advantages (from different points of view) of existing electrotechnologies and practical examples referring to the substitution of old technologies are further presented [5, 7].

10.3.1.1 Resistance and Infrared Heating

Resistance heating is the simplest and oldest electrotechnology, used for both high-temperature and low-temperature industrial applications. With its excellent efficiency, good controllability, and rapid heat-up qualities (especially for direct heating), resistance heating can substitute the fuel-based process heating equipment in many applications, from melting metals to heating food products.

1. Energy Efficiency/Energy Savings

Modern indirect resistance heating equipment uses well-insulated enclosures, based on new advanced materials, consequently minimizing the thermal losses; as a result, this technology is more energy-efficient than the existing alternatives, especially at higher temperatures (for instance, the optimal efficiency of an electric oven can reach up to 95%, while those of a gas furnace can amount to 40–80%; in fact, the real heating efficiency of a gas furnace averages 15–20%).

Direct resistance heating and infrared heating also have good energy efficiency characteristics. With the advent of new power sources, materials and controls, both technologies are used in numerous manufacturing sectors. In many applications, electric infrared systems are used in conjunction with conventional direct-fired process heaters; frequently, the infrared system pre-dries the product, and then the process is finished in a conventional oven. For example, auto body production lines use infrared to rapidly set the paint on the body, and then the car goes into a convection oven to complete the curing process (the rapid setting of the coating on the body eliminates dust damage). An additional benefit of a hybrid system is the potential to increase throughput by increasing line speed.

2. Other Benefits

Environmental

- There is no output of harmful combustion products (NOx, SOx, COx), hazardous salts or metals.
- As the heating process is very precisely controlled, there is less heat transferred to the environment.

Technical

- Resistance equipment can be operated in a flexible way and less space is required (especially for direct and infrared heating).
- Precise temperature control and operation in controlled atmosphere are also possible, with benefits regarding the quality of final products.
- Melting in a resistance furnace can decrease dross or material loss.

Financial

- Investments depend on the size and type of the installation and are usually comparable to those required by fossil-fired systems.
- Return on investment is about 2 years (for high temperature indirect furnaces and direct heating equipment) or less (for infrared heating systems).
- There are reduced operation costs as little maintenance is required.

10.3.1.2 Dielectric Heating

The concept of using radio waves to heat material was known in the late 19th century, but industrial applications depended on the techniques for generating high-power at high frequency. Radio frequency generators were developed in the 1930s, while the microwave processing technology development was a result of research on radar systems during World War II; however, interest in microwaves considerably increased only in the 1980s as a way to raise productivity and reduce costs.

There are currently many successful applications of radio-frequency and microwave processing in a variety of industries, including food, rubber, pharmaceutical, polymers, plastics and textiles.

1. Energy Efficiency/Energy Savings

The conventional way of heating dielectric materials is to apply heat to the surface, which is further transferred to the interior by means of thermal conduction (a very slow process because these materials are also poor conductors of heat). As electromagnetic fields penetrate the material, dielectric heating occurs inside the piece and the thermal conduction is of minor importance during the heating process (this results in very fast heating).

As a result, heating processes can be shortened from hours to minutes and, partly due to this gain in time, dielectric heating offers large energy savings. Another reason for the low energy consumption is that only the work pieces are heated (no energy is lost in heating the walls or other parts of the oven or the air inside); supplementary, in drying or polymerization processes, energy is absorbed in a selective way, i.e. only the moisture and adhesives inside the work piece absorb supplied energy.

In general, dielectric heating can reach an efficiency of 65–75% (however, in the majority of applications the efficiency lies between 50 and 70%); for comparison, the efficiency of conventional heating methods is about 35–50%. Therefore energy savings of 15–40% compared with conventional methods are common; other sources indicate savings of between 25 and 50%. The high energy efficiency of dielectric heating systems is the main reason why manufacturers install them as replacements for conventional systems (e.g. hot air, steam).

2. Other Benefits

Environmental

- Dielectric heating is environment-friendly (no medium is required to transfer heat to the product and no fuels are burned at the production site).
- The electromagnetic waves are kept inside the heating chamber, so the technology does not put workers' health at risk and does not create other problems in adjacent areas.

Technical

- Dielectric heating assures high production rates (due to reduced processing time and because the heating process can be started up and shut down quickly, enabling just-in-time production).
- The course of the temperature during heating can be controlled very accurately, improving the quality of final products.
- Sometimes dielectric heating can represent a unique method of manufacturing different products.
- The heating chamber of a dielectric system is small and simple, compared with other systems, resulting in easier and faster maintenance.

Financial

- Because the quality of the products is very high, very few products are rejected.
- Dielectric heating systems are smaller than comparable conventional systems (space savings of 50–90% are possible).

10.3.2 Selection of the Most Suitable Electrotechnology

As stated above, nowadays many electric-based technologies can be used for various industrial heating processes. However, each of these technologies has its one characteristic and performance; that is why, in order to benefit fully from all the existing advantages, a suitable electrotechnology must be selected for an existing industrial heating process.

The first example was presented in Figure 10.4; the data offered there highlight that for drying processes, dielectric heating (in this particular example, microwave heating) is more suitable than resistance heating from both energy consumption and CO_2 emissions points of view.

Another example is direct resistance welding. In this case, an electric current is sent through the point where the metallic pieces touch and the resistance to the current flow generates heat that melts the metal; when the current is interrupted, the metal cools down and the two objects are fused. In a factory, the conventional machine, using an alternating current, was replaced by a new device; equipped with modern power electronics, the latter enables the system to produce a controlled direct current. This action assured significant energy savings (64% in annual energy consumption) and better product quality, Table 10.6 presents several comparative results (for a production of 1 320 000 drums per year). The cost of replacing an old unit is paid back in less than 2 years; a new, additional unit is paid back in less than 1 year.

Table 10.6 Energy consumption of welding systems ([7])

Parameter	Old system	New system	Difference
Power demand [kW]	250	90	160
Annual energy consumption [kWh]	390 323	140 620	249 700
Energy cost [€]	45 503	16 393	29 110

10.3.3 Increasing the Efficiency of the Existing Electroheating Equipment

A continuous maintenance process is required in order to maintain the good efficiency properties of any electric-based process heating system; on the other hand, the industrial implementation of new power electronic devices, advanced materials and new control techniques allows an improvement in the initial characteristics of existing electroheating equipment. However, it is important to mention that in general electroheating equipment requires less maintenance activities (and costs) than conventional heating technologies.

Several actions, adapted from [2, 4, 8] are further presented.

10.3.3.1 Resistance Heating

For the resistance-based process heating systems, the following actions are of interest:

- taking a continuous survey of the furnace envelope in order to notice as soon as possible any supplementary heat losses source (for instance, wall cracks);
- maintenance actions must include the cleaning of heating elements (clean resistive heating elements can improve heat transfer and process efficiency);
- for high-power direct resistance heating systems, the implementation of solutions aiming to reduce the unbalance (for instance, Steinmetz circuitry) can assure the required levels of electromagnetic disturbances in the point of common coupling;
- a permanent improvement of the control system can have both technological and energy saving benefits; good control systems allow precise application of heat at the proper temperature for the correct amount of time.

10.3.3.2 Infrared Heating

In this case, the subsequent measures can be valuable:

- The existing system must be used only for suitable materials (the absorption spectrum of the product to be heated must match the emission spectrum of the IR source).
- Maintenance actions have to include the cleaning of heating elements, but also of reflectors and end caps and additional reflectors can be installed in the oven in order to reduce energy losses and to re-radiate stray infrared energy back to the product.
- The oven shape must be reconsidered for every piece to be heated as the IR banks or panels are straightforwardly moveable (proper emitter positioning with respect to the product clearly improves energy efficiency).
- Zoning the IR system is also very energy efficient as it assures the consumption of the electricity only in a constrained area. This action is necessary especially when pieces having diverse dimensions are heated in the same oven; zoning can be configured horizontally or vertically, and can be specifically profiled for the product, due to the controllability of electric infrared energy (unfortunately, a more sophisticated control system will be required).

- A high-quality control system is also important: in addition to providing for zoning, an effective control system can also provide for a variable control system instead of simple on/off control, precisely delivering the required amount of radiant energy to the product, even if product size, shape, or colour, etc. might vary.

According to [3], better efficiencies (lower cost/part) – from 10% to 30% in existing ovens – have been demonstrated with the employment of these recommendations.

10.3.3.3 Induction Heating

Taking into account the flexibility of induction heating systems, possible actions differ according to the operation areas:

Melting

- When medium or high frequency is required, solid state power supplies are more efficient then rotative generators (they also allow operation with a variable frequency and require less maintenance).
- Continuous surveying of the furnace refractory is important (this reduces heat losses and also avoid an inductor breakdown).
- Bus bars system must be as short as possible and conductors must be selected according to the operation frequency.
- For highly conductive metals such as aluminium, copper alloys and magnesium, channel furnaces are more efficient than crucible furnaces.
- If the production line and schedule allow, two furnaces can share the same power supply by taking advantage of an optimized melting program.
- Melting without a cover on the crucible can account for approximately a 30% energy loss.
- For high-power mains frequency furnaces, the implementation of solutions aiming to reduce the unbalance (for instance, Steinmetz circuitry) is compulsory.

Heating and Heat Treating

- Usually, the heating and heat treating systems require high frequency; as previously mentioned, the use of solid state power supplies is strongly suggested.
- A dual-frequency design also has positive effects; in this case, a low-frequency design is used during the initial stage of the heating when the bar retains its magnetic properties, and a higher frequency is used in the next stage, when the bar becomes non-magnetic. However, this solution can be avoided by using a self-adaptive frequency converter (the supply works near the resonance frequency of the circuit represented by the heating system and the capacitor bank for power factor correction and follows the parameter modification during the heating process).
- For coreless systems, the use of flux concentrators is recommended. As these passive devices provide a contained pathway for the magnetic fields, stray magnetic losses are reduced.

- For good efficiency, the configuration of the inductor must be as close as possible to that of the heated materials (in many industrial applications, the same coil is used to produce a number of different products; actually, using coils designed specifically for a product will improve efficiency by up to 50%).
- Any existing gap (for inspection or work access) needs to be shielded to reduce heat loss.

10.3.3.4 Dielectric Heating

Dielectric heating is also widespread in modern industry. The following action must be considered:

Microwave Heating
- Systems involving water evaporation require a frequent visual inspection to avoid a dangerous water deposition on the heating chamber.
- The maintenance actions must include cleanliness of the wave guides and the operating condition of all motors and drives associated with the process.
- The shielding against electromagnetic radiation must be also periodically established.
- Whenever the characteristics of the material to be heated change (e.g. a change in width, depth or weight), the system must be re-evaluated in order to maintain its efficiency and all necessary modifications must be implemented.
- Power tube life is limited (as indicated before) so that the ageing generators must be replaced according to the vendor's recommendations (this action will assure the rated energy efficiency and will reduce system down time).

Radio-Frequency Heating
- The same maintenance actions previously mentioned for microwave heating are necessary (here, water deposition on the applicator system must be avoided).
- A good control system allows for better product quality and energy efficiency.
- The implementation of a hybrid radio-frequency/convection heating system must almost always be studied: the efficiency of a convection dryer drops significantly as the moisture level in the material decreases. At this point, radio frequency is more efficient for removing the moisture.

10.3.3.5 Arc Furnaces

The number of arc furnaces is lower than that of other electric-based process heating systems. However, due to the rated power of the existing units and their influence on the power supply, the experts pay special attention to the accurate operation of these systems. Some such actions are as follows:

- The injection of an inert gas (e.g., argon) in the bottom of the arc furnace can increase the heat transfer in the melt and the interaction between slag and metal (increasing liquid metal).
- By using ultra-high-power transformers, the furnace operation can be converted to ultra-high-power, increasing productivity and reducing energy losses.

- By introducing heat recovery systems, the waste heat of the furnace is used to preheat the scrap charge, so that the required energy for the technological process decreases.
- New advanced materials can be used for furnace insulation (for instance, ceramic low thermal mass materials instead of conventional ceramic fibre).
- The implementation of a hybrid heating system can ensure some advantages: for example, using a fuel-based system in the first part of the heat cycle saves energy by increasing heat transfer and reducing heat losses.
- Post-combustion of flue gases optimizes the benefits of oxygen and fuel injection: the carbon monoxide in the flue gas is oxidized to carbon dioxide, while the combustion heat of the gases helps heat the steel in the arc furnace ladle.
- Advances in power electronics allow the use of variable speed drives on flue gas fans (this reduces heat loss as well as the electricity consumption of the driving system itself).
- The maintenance must pay a special attention to the electrodes' positioning system as the accuracy of the electrodes' positions during the melting process decisively influences the energy efficiency and the operation costs (electrodes wearing).
- The negative impact on power quality at the point of common coupling (mainly flicker, voltage variation and harmonic pollution) must be compensated by appropriate means (harmonic filtering, active power factor compensation, etc.).

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