APPLICATION NOTE

INTRODUCTION TO INDUSTRIAL ELECTRICAL PROCESS HEATING

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Summary

This application note provides an introduction to a series of papers on industrial electric process heating technologies, hereinafter referred to as *electro-heat* or *electro-heating* technologies.

It briefly describes the basic principles of each of the various electro-heating technologies and explores their common ground. The economic and process related advantages of electro-heat are discussed. In the majority of cases, electro-heat has a better environmental performance than an industrial heating system utilizing natural gas or other fossil fuels. This application note provides some insight into why this is the case.

Finally, this paper provides an overview of the most appropriate applications as well as a short overview of the specific areas of technological development for each of the electro-heat technologies.

Acknowledgement

Koenraad Van Reusel: *Context and Technology Bound Motives for the Use of Electricity in Industrial Thermal Processing* (KUL, October 2010)—a work that was of much use while writing this paper. I would like to thank Koenraad Van Reusel for this valuable study.

INTRODUCTION

SITUATION WITHIN LEONARDO ENERGY

This application note presents a short introduction of electro-heating technologies for the non-specialists.

In addition to this, three electro-heating technologies are discussed in further detail in other publications of the Leonardo Energy Good Practice Guide:

- Cu0122—Dielectric Heating
- Cu0123—Induction Heating
- Cu0126—Infrared Heating

More on electro-heat technologies and the Electro Processing of Materials (EPM) can be also be found on the Leonardo EPM Academy (e-learning platform).

WHY ELECTRO-HEATING?

At first sight, using electricity for heating seems inefficient. It appears to be an unnecessary detour to first upgrade the low quality energy of fossil fuels to the high quality energy of electricity—a process that inevitable entails energy losses—only to produce low quality energy in the form of heat again in the next step. Despite this fact, electro-heat has a high potential for improving both the environmental and economic performance of industrial heating. This is because of following reasons:

1) Electro-heat technologies—with the exception of indirect resistance heating—**generate the heat directly inside the target material** making use of electro-magnetic phenomena that function on a micro-level. This “short-cut” offsets the “detour” discussed above.
2) **Electricity is increasingly generated from renewable energy sources** instead of fossil fuel. Systems such as wind turbines and photovoltaic panels produce electricity directly without intermediate heat production.
3) **Large-scale reduction of emissions** can be achieved much more efficiently in large, centralized power plants than in local fossil fuel heating systems. This gives electricity an additional environmental advantage over direct heating systems with fossil fuels.
4) **Energy efficiency is not the one and only goal** in industrial applications. In many cases, there are (also) other reasons to favour electro-heat technologies that are related to process and economic efficiency.

We will discuss the different reasons to use electro-heat in more detail after we first present a short overview on the most common electro-heat technologies currently in use.

COMMON ELECTRO-HEAT TECHNOLOGIES

- **Resistance heating**
  - **Direct**: An electrical current is driven through the material to be heated. The material heats up due its electrical resistivity. This is called the Joule effect.
  - **Indirect**: An electrical current is driven through a resistance, which heats up through the Joule effect. Through convection and radiation, this hot resistance will heat up a surrounding fluid, gas or even solid material. Often this fluid or gas (e.g. hot air) will be used to heat yet another material.
- **Infrared heating**: A heat source at high temperature emits infrared waves that are subsequently absorbed by a colder object. The heat is transferred by electromagnetic radiation (infrared spectrum of light radiation), without the aid of any intermediary, i.e. it also works in a vacuum. The radiation of the sun is a good example of infrared heat.
- **Induction heating**: A solenoid is used to generate a magnetic field alternating at high frequency. If a conductor is placed inside this field, alternating electric currents are induced in this conductor that opposes the alternating magnetic field. These are called eddy currents. The eddy currents heat up the conductor through the Joule effect.
- **Dielectric heating**: Electrical non-conducting materials (dielectrics) can be dielectrically heated if they have an asymmetrical molecule structure. When a changing electrical field is created, such molecules will continuously flip-flop as they attempt to align with this field. At well-defined frequencies, friction will occur between the vibrating molecules, leading to internal heat development.
  - **Microwave heating**: Dielectric heating with a frequency range between 900 and 3,000 MHz
  - **Radiofrequency heating**: Dielectric heating with a frequency range between 10 and 30 MHz
- **Electric arc heating**: This is typically used to melt metals. The metal is placed between two graphite electrodes. The electrodes are charged and an electric arc is generated between them. The high currents of this arc go right through the metal and heat it through the Joule effect. The arc reaches temperatures between 1,000 and 3,000 °C.
  - **Plasma arc heating**: A special type of electric arc heating, using plasma torches instead of graphite electrodes.
- **Electron-beam heating**: This technique employs a hot cathode for the production of electrons and a high voltage difference beaming those electrons at the target material.

General Advantages

Economic reasons to choose electro-heat

It is obvious that the life-cycle cost is one of the first things to be taken into account when comparing the financial impact of two heating technologies. However, it is not always a simple matter to determine which factors should be included in this cost calculation. The investment cost and the energy costs over the life time of the installation are in most cases fairly easy to calculate. Other cost elements may be much more difficult to determine, since a production line with a built in electro-heat technology will often be conceived completely differently than a production line with a natural gas furnace. As a result, it might be necessary to calculate the life-time cost of the complete line with all its investment, production, and maintenance factors to make a fair comparison. The result of such a calculation will be case specific.

Aside from the life-cycle cost, other economic arguments can be involved as well. For SMEs, **the initial investment cost of the installation** can be a decisive argument. Except for dielectric heating, electro-heat technologies generally score well on this point. In many cases this will be a major reason to prefer electro-heat technologies over heating techniques employing fossil fuel.

Another economic argument in favour of all electro-heat technologies is that electricity prices are less volatile than the prices of natural gas or other fossil fuels. Moreover, electro-heat installations often offer the opportunity to buy low-cost base-load electricity during low load periods of the day. Consequently, they fit well into programs of Demand Side Management (DSM), which is of growing importance and is expected to play an important role in the electricity system of the future.

Finally, electricity is the major option for the future for all but a few energy using systems. Natural gas is a depletable energy source and its price will rise substantially long before the last reserves are cracked. The Energy Return On Energy Investment (EROEI) is a good measure for assessing the economic viability. Today, the EROEIs of both oil and natural gas are in steep decline, showing that the most accessible reserves have already been used[1]. This means that—even without taking climate change and other environmental issues into account—we will be forced to shift to a non-fossil-fuel economy at some point in the upcoming decades.

Logistic advantages

Accessible technologies

Not only do electro-heat technologies often have a low initial investment cost thanks to their high power density, they are also **compact installations** relative to their production capacity. While this argument is especially true for infrared heating, it also holds for other electro-heat technologies. Add to this the fact that there are **no fuel transport and storage issues** involved as with some fossil fuels. These advantages combine to make electro-heat technologies much more accessible and therefore popular among SMEs, for example for metal processing, food processing or for the thermo-hardening of resins.

Suited for automation

Electrical energy is **well suited for use in control and automation**. The output of electro-heat appliances can be adjusted to a high degree of sensitivity and adapted to circumstances and the target material by regulating

[1] Richard Heinberg: *Searching for a miracle / "Net Energy" limits & the fate of industrial society* (the *International Forum on Globalization* and the *Post Carbon Institute*, September 2009)

parameters such as frequency voltage and current. This makes electro-heat installations highly suitable for fully automated production lines. The selection of infrared heating, in particular, is often motivated by this argument. Electro-heat appliances are also highly flexible, thanks to the easy regulation of the output power and the ability to turn the installations on and off at high speed and without significant energy losses.

ENVIRONMENTAL PERFORMANCE

The main environmental impact categories that are relevant for today's electrical energy systems are:

1. Global warming potential (mainly CO_2 emissions)
2. Acidification potential (mainly SO_2 emissions)
3. Eutrophication potential (mainly NO_x emissions)
4. Photochemical ozone creation potential (mainly CO and Volatile Organic Compound (VOC) emissions)

Well-equipped fossil fuel power stations reduce SO_2, NO_X, CO, and VOC emissions to a minimum through controlled combustion and a treatment of the flue gasses. Some of those emissions are difficult to avoid in small, local heating installations. For example, natural gas heaters emit a contributory amount of NO_x and to a lesser degree CO. Oil and coal fired ovens emit significant quantities of SO_2.

Today, global warming potential is generally considered to be the most crucial environmental impact category. Thanks to nuclear power and a growing share of renewable power, **the average CO_2 emissions per mega-watt-hour of electricity has decreased significantly** in recent decades. Even when transmission and distribution losses are taken into account, electro-heat techniques still exhibit significantly better results than local fossil fuel heating systems in terms of CO_2 emissions in the large majority of cases. Since the share of renewable energy in the generation mix is expected to continue its rapid increase in the upcoming decades, CO_2 emissions related to electro-heat technologies will decrease further.

The research laboratory of Laborelec executed a study comparing a natural gas furnace and an induction furnace for melting aluminium. The study compared primary energy use as well as CO_2 emissions. The following table shows the resulting figures for melting one ton of aluminium scrap:

	Natural gas furnace	**Induction furnace**
Natural gas use [GJ]	3	/
Electricity use [GJ]	/	1.8
Losses due to oxidized Al [kg]	18	6
Specific primary energy use [GJ/t]	**3,080**	**4,527**
CO_2 emissions [kg/t, 2002 Belgian electricity generation mix]	175 + 132 = **307**	156 + 43 = **199**

Table 1 – Comparison of a natural gas and an induction furnace for aluminium melting.
The CO_2 emissions in this table are calculated as the sum of two terms: the emissions linked to primary energy use and those linked to the energy lost due to oxidized metal.

The results show that the natural gas furnace is about 1.5 times more efficient in terms of primary energy use. However, in regards to carbon emissions, the proportions are the other way around: the induction furnace has approximately two third of the CO_2 emissions compared to the natural gas furnace. This example was calculated using the Belgian electricity mix as of 2002. With the increasing share of renewable energy in today's and tomorrow's electricity mix, the result will be even more favourable for the induction furnace.

Main application domains and specific advantages

Each electro-heat technology has specific advantages and specific application domains where these advantages can be fully exploited:

Resistance heating

Indirect resistance heating

Indirect resistance heating is the most common type of resistance heating. Energy efficiency is generally not the reason indirect resistance heating is chosen, since its efficiency is often rather poor. However, it can still be cost-effective by making use of special electricity tariffs at periods of low demand (e.g. at night).

Energy efficiency can be improved by optimizing the geometrical position and by heat recuperation. The latter requires an additional investment in the installation.

The following are a few common arguments in favour of resistance heating over direct fossil fuel heating:

- Consistent product quality, essential in the food and drinks industry
- Even energy supply over the volume, essential in metallurgy
- Exact production capacity, essential for some drying processes
- Modularity, essential in many chemical processes
- No flue gasses, essential in many metallurgical processes to avoid surface oxidation
- High heating rate and high temperature processing (up to 3,000 °C). An important development domain is the search for high temperature resistant materials to enable even higher temperatures.

Direct resistance heating

Direct resistance heating is much less common, but is used frequently in the glass industry. Energy efficiency is much better than with indirect resistance heating and this is often a decisive argument. A reduced initial investment cost, compact furnaces, and relatively simple operation are the reasons why the glass industry prefers direct resistance heating over natural gas furnaces.

Infrared heating

Infrared heating is a widely employed heating technique and one that is typically used for **surface treatments** (heating or drying) as well as for pre-heating purposes. Among many other applications, it is frequently used in the **food industry** for baking and in the metallurgy and textile industries for **fixing coatings and drying paint**. It is also frequently used for localized space heating.

Its major advantages are the low investment cost of the installation and its high power density, resulting in very compact installations with a high heating rate. This makes it a largely accessible technology for SMEs.

Other major advantages are:

- Heating rate can be scaled with high precision (by frequency control)
- Low thermal inertia
- Heating of local spots is possible
- Continuous process instead of batch oven
- Comfortable working conditions

All of which makes infrared heating well suited for automated, continuous processing.

Infrared heating likewise has several application-specific advantages over gas burners and hot air heating:

- It avoids surface corrosion of metals
- It can dry paint containing explosive solvents
- It can dry viscous surface layers that would be blown away by hot air heating

An important field of development is the improvement of the energy efficiency by a dynamic adaptation of the emissivity of the emitters as a function of the changing absorptivity of the load. A second field under development is Near Infrared Heating (NIR), which uses emitters at very high temperature producing very short wavelength infrared.

For more about infrared heating, see the Leonardo Energy Application Note Cu0126—*Infrared Heating*.

INDUCTION HEATING

Induction heating is mainly used as a **melting technique for non-ferrous alloys**. The target material should be electrically conductive.

Induction heating is intrinsically more efficient than a gas oven, since it generates the heat directly inside the material. It is also intrinsically more efficient than infrared for heating metal strips, since there is no reflection loss involved. In reality, this high efficiency is only achieved if certain measures are taken: a reduction of the stray fields, sufficient cooling, a good coupling between the inductor and the work-piece, and operation at optimal frequency.

Some major advantages—other than the energy efficiency—are:

- High power density: it can reach high temperatures at high speed, homogeneously distributed over the work-piece. This not only raises production capacity and speed, but can also improve certain characteristics of the material. In addition, it results in a compact installation.
- Easy automation, including a very precise control of heat localization
- Control of the penetration depth (by frequency control)

Overall, those characteristics lead to a flexible installation with scalable output.

Induction heating also has a few application-specific advantages:

- Paint curing on metal tubes: curing starts from the inner side, driving the solvent out rather than trapping it
- Melting alloys: stirring effect gives a better homogeneity of the product
- Brazing and welding: better working conditions than with gas brazing

Find out more about induction heating in the Leonardo Energy Application Note Cu0123—*Induction Heating*.

DIELECTRIC HEATING

Dielectric heating is used for materials with proper dielectric characteristics, namely good electrical insulators.

Despite its relatively low energy efficiency, it will often be **the most energy efficient option for materials with low thermal conductivity, such as rubber and certain plastics**.

Contrast to the previously discussed electro-heat techniques, dielectric heating systems require a high initial investment. Moreover, it is a complex technology that is restricted to a smaller power range.

Despite those barriers, it is a common technology in a wide variety of industries. This is primarily due to a few very specific advantages.

The technology is particularly **common in the food and drink industry**. The vacuum environment guarantees a clean workspace. The volumetric heating avoids agglomeration and the overheating of the contact surface. The highly controlled heating is ideal for tempering, thawing, and viscosity control. For the pasteurization and sterilization of food, dielectric heating can ensure that all the volume has passed through the imposed temperature-time curve.

Apart from the food industry, dielectric heating is also common in wood, textile and printing industries. Its main advantages in these sectors are its high power density, its suitability for continuous processing, and the fact that the power is exclusively dissipated where it is needed.

Some other application specific advantages are:

- The transparent recipients enable a safe heating of chemically highly reactive products
- Precise moisture control and the avoidance of a hot contact area make it suitable for heating inflammable products

For drying applications, dielectric heating is often combined with hot air or infrared heating. The main part of the water is damped out with hot air or infrared, while the final moisture content is removed with the more precisely controlled dielectric heating.

Microwave assisted organic synthesis is a good example in which the concept 'electromagnetic processing of materials' is shown in its full advantage. This technology is not only an efficient way to heat the target material, it also brings along non-thermal catalyst effects.

Some areas of technology development are:

- Microwave irradiation for polymerization
- Microwave heating for soil vapour extraction in the context of soil remediation.
- Improving the insight into the effects of microwave interaction on material of all kind
- Ensuring that the system can follow varying load impedances more closely
- Avoiding flashing by better arc detection systems

Find out more about dielectric heating in the Leonardo Energy Application Note Cu0122—*Dielectric Heating*.

Electric arc heating

Electric arc and plasma heating are ideal for creating very high temperatures.

Electric arc furnaces are common for **melting steel**. Approximately one third of all melting furnaces for crude steel in Europe use the electric arc technology. The technology is also common for melting cast steel and for welding, thanks to its low melting times. Electric arc furnaces are also used in stone wool manufacturing, the production of inorganic chemicals, the reduction and pre-reduction of non-ferrous metals, and the production of high-carbon ferro-alloys, among other application domains.

Plasma heating is an established technique for reaching very high temperatures in waste incineration plants.

Electron beam heating

Electron beam heating is the least well-known of the electro-heat technologies. Nevertheless, it is a common technique for **melting refractory metals with a high melting point**. It is also used in the textile industry for starting polymerization reactions, having the advantage that solvent free formulations can be used.

Conclusions

Electro-heating is an umbrella term for all industrial process heating systems that use electricity as an energy source, as opposed to process heating systems that use fossil or bio fuel.

The inherent power of most electro-heat technologies lies in the fact that **they generate heat within the target material**, leading to advantages in terms of process control and end-use energy efficiency.

As a result, **the environmental performance of electro-heating systems will be superior** to that of natural gas heating systems in the majority of the cases.

This was demonstrated by a case comparing a natural gas furnace to an induction furnace for melting aluminium. Although the natural gas furnace had a lower primary energy use (3,080 GJ/t compared to 4,527 GJ/t) the induction oven had significantly lower CO_2 emissions (199 kg/t compared to 307 kg/t). This difference will only grow larger in the future.

Other common advantages of electro-heat technologies, apart from the lower environmental impact, are:

- A **low investment cost** in most cases
- A **compact installation** relative to the production capacity in most cases
- **No fuel transport and storage** is required

Each electro-heat technology has particular application domains in which it is used to its full advantage:

- **Direct resistance heating**: used frequently in the glass industry
- **Induction heating**: mainly used as a melting technique for non-ferrous alloys
- **Dielectric heating**: the most energy efficient option for materials with low thermal conductivity such as rubber and certain plastics; also common in the food and drink industry because of its vacuum environment, among other advantages
- **Electric arc heating**: commonly used for melting steel
- **Electron-beam heating**: a common technique for melting refractory metals with a high melting point

The application domains for the electro-heat technologies are certainly not restricted to these examples. Electro-heat technologies are often used in particular niche domains for very specific advantages, and **new application domains for electro-heating continue to be explored**. **Industry is not yet exploiting the full potential of this technology.**