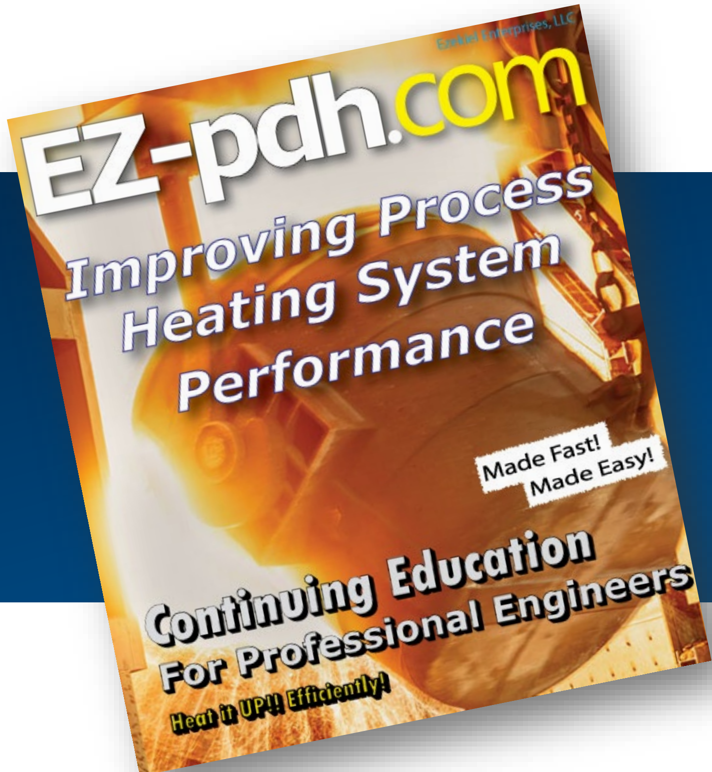

Improving Process Heating System Performance

Four (4) Continuing Education Hours Course #ME1485

Approved Continuing Education for Licensed Professional Engineers

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Course Description:

The Improving Process Heating System Performance course satisfies four (4) hours of professional development.

The course is designed as a distance learning course that provides an overview of process heating systems and outlines opportunities for improving process heating system performance.

Objectives:

The primary objective of this course is to enable the student to understand process heating systems and their components and practical guidelines to enhance performance and increase efficiency.

Grading:

Students must achieve a minimum score of 70% on the online quiz to pass this course. The quiz may be taken as many times as necessary to successful pass and complete the course.

A copy of the quiz questions are attached to last pages of this document.

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Improving Process Heating System Performance

Process Heating System Basics

Overview

Process heating is essential in the manufacture of most consumer and industrial products, including those made out of metal, plastic, rubber, concrete, glass, and ceramics. Process heating systems can be broken into three basic categories:

Fuel-Based Process Heating

With fuel-based systems, heat is generated by the combustion of solid, liquid, or gaseous fuel, and transferred either directly or indirectly to the material. The combustion gases can be either in contact with the material (direct heating), or be confined and thus be separated from the material (indirect heating, e.g., radiant burner tube, retort, muffle). Examples of fuel-based process heating equipment include furnaces, ovens, kilns, lehrs, and melters. Within the United States, fuel-based process heating (excluding electricity and steam generation) consumes 5.2 quads of energy annually,[1] which equals roughly 17% of total industrial energy use. Typically, the energy used for process heating accounts for 2% to 15% of the total production cost.[2]

Electric-Based Process Heating

Electric-based process heating systems (sometimes called electrotechnologies) use electric currents or electromagnetic fields to heat materials. Direct heating methods generate heat within the work piece, by either (1) passing an electrical current through the material, (2) inducing an electrical current (eddy current) into the material, or (3) exciting atoms and/or molecules within the material with electromagnetic radiation (e.g., microwave). Indirect heating methods use one of these three methods to heat an element or susceptor, which transfers the heat to the work piece by either conduction, convection, radiation, or a combination of these.

Steam-Based Process Heating

Steam has several favorable properties for process heating applications. Steam holds a significant amount of energy on a unit mass basis (between 1,000 and 1,250 British thermal units per pound [Btu/lb]). Since most of the heat content of steam is stored as latent heat, large quantities of heat can be transferred efficiently at a constant temperature, which is a useful attribute in many process heating applications. Steam-based process heating has low toxicity, ease of transportability, and high heat capacity.

Hybrid systems use a combination of process heating systems by using different energy sources or different heating methods of the same energy source. Electric infrared, in combination with either an electric convection oven or a gas convection oven is a hybrid system. A paper-drying process that combines a natural gas or electric-based infrared technology with a steam-based drum dryer is also a hybrid system.

Efficiency Opportunities

The performance of a process heating system is determined by its ability to achieve a certain product quality under constraints (for example, high throughput, and low response time). The energy efficiency of a process heating system is determined by the costs attributable to the heating system per unit produced. Efficient systems manufacture a product at the required quality level and at the lowest cost. Energy-efficient systems create a product with less input energy to the process heating systems per unit produced.

Approaches to improve a certain heating operation might be applicable to multiple processes, but may be unknown within and/or outside a given industry segment. To identify synergies and encourage improvements by technology and knowledge transfer, opportunities common to industry segments, applications, and, where possible, equipment type, are identified in this course. References to further reading and other information sources are given where appropriate.

In some cases, a process heating requirement can be eliminated altogether. For example, there is a current trend to use chemicals that do not require heating to be effective in washing systems used to clean metals parts prior to painting operations.

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. One of the goals of the course is to build awareness of the economic benefits resulting from the improvement of the energy efficiency of these systems.

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[1] A quad is a unit of energy equal to 1 quadrillion British thermal units.

[2] *Roadmap for Process Heating Technology: Priority Research & Development Goals and Near-Term Non-Research Goals To Improve Industrial Process Heating*, Industrial Heating Equipment Association, U.S. Department of Energy Industrial Technologies Program, Capital Surini Group International, Inc., Energetics, Inc., March 16, 2001.

Since process heating system performance is fundamental to the quality of a wide range of finished products, efficiency and performance must be considered together. In order to identify system improvement opportunities, it is helpful to understand some common losses and avoidable costs. The reader is also encouraged to seek greater technical detail in other resources, such as those listed in the "Where to Find Help" section. Due to a wide range of operating characteristics and conditions, the guidelines and recommendations given in the course tend to be fairly general. The intent is to help industry identify and prioritize potential improvement opportunities, and implement projects that are technically and economically feasible.

Systems Approach

Depending on the process heating application, system sizes, configurations, and operating practices differ widely throughout industry. For a given system, there are usually a variety of improvement opportunities. Consequently, there are many different ways to improve the system performance. In order to achieve maximum improvement at the lowest cost, a systems approach should be used.

A systems approach analyzes both the supply and demand sides of process heating systems and how they interact, essentially shifting the focus from individual components to total system performance. In engineering, a common approach is to break down a system or process into basic functional units (components, modules, process steps), optimize and/or replace them, and then reassemble the system. Since the basic functional units have a lower complexity, their optimization might be easier. The approach is well suited if the functional units are independent, and do not interact. In contrast, a systems approach evaluates the entire system to determine how the end-use requirements can be most effectively and efficiently served.

Simplistic approaches, which focus solely on the optimization of individual components of a process heating system, fail to recognize that system efficiency, reliability, and operating stability are closely connected and depend on the performance of multiple components. By considering dependencies between components, adverse effects can be avoided and maximum performance and efficiency can be achieved at the lowest cost.

In practice, process heating systems evolve over time; components are added, removed, or replaced by newer or alternate versions. Individual components might age in unpredicted ways, steadily changing the performance of the system. Adding new components to a process heating system may require substantial changes to operating conditions and practices. Regular process design reviews can help to reduce the complexity of process heating systems, and increase their reliability and overall performance.

The benefits of a systems approach can be illustrated through examples. Operators often focus on the immediate demands of a particular process step, but underestimate the effects of a particular setting on the long-term performance of the equipment, or other processes downstream. A systems approach would take those effects into account, and weigh them against each other to achieve optimum overall performance.

Poor insulation might reduce a process heating system's efficiency, thereby increasing the amount of energy needed to perform a given process heating task. In addition to an increased cost for energy, the system is exposed to higher stress, which can accelerate wear and subsequently lead to more frequent breakdowns. Other side effects can be reduced product quality and increased maintenance.

Other examples are short-term fixes, including replacements and routine maintenance, which might require multiple partial upgrades of an aging infrastructure. Short-term fixes can increase the complexity of a system, lower its reliability, and effectively block improvements that have the potential to lead to substantial long-term gains.

Basic Process Heating Operations

Process heating is used in many industries for a wide range of applications, which often comprise multiple heating operations. The manufacture of steel often involves a combination of smelting, metal melting, and various heat treatment steps. The fabrication of polymers typically employs fluid heating to distill a petroleum feedstock and to provide heat for a curing process to create a final polymer product.

Common to all process heating applications is the generation and transfer of heat. In general, they can be grouped into 14 major categories:

- **Agglomeration and Sintering**

Agglomeration and sintering refers to the heating of a mass of fine particles (e.g., lead concentrates) below the melting point to form larger particles or solid parts. Sintering is commonly used in the manufacturing of advanced ceramics and the production of specialty metals.

- **Calcining**

Calcining is the removal of chemically bound water and/or gases, such as carbon dioxide, through direct or indirect heating. Common applications include construction materials, such as cement and wallboard, the recovery of lime in the kraft process of the pulp and paper industry, the production of anodes from petroleum coke for aluminum smelting, and the removal of excess water from raw materials for the manufacture of specialty optical materials and glasses.

- **Curing**

Curing is the controlled heating of a substance to promote or control a chemical reaction; in the manufacture of plastics, curing is the cross-linking reaction of a polymer. Curing is a common process step in the application of coatings to metallic and nonmetallic materials, including ceramics and glass.

- **Drying**

Drying is the removal of free water (water that is not chemically bound) through direct or indirect heating. Drying is common in the stone, clay, and glass industries, where the moisture content of raw materials, such as sand, must be reduced; and in the food processing, textile manufacture, and chemical industry, in general. There are several types of dryers, including conveyor, fluidized bed, rotary, and cabinet dryers.

A rotary dryer for removal of free water.

- **Fluid Heating**

Fluid heating is used to increase the temperature of a liquid or gas, including the complete or partial vaporization of the fluid, and is performed for a wide range of purposes in many industries, including chemicals, food processing, and petroleum refining. In chemical manufacturing, fluids are heated in both batch and continuous processes to induce or moderate a chemical reaction. Food processing applications include cooking, fermentation, and sterilization. In petroleum refining, fluid heating is used to distill crude oil into several component products.

Fluid heating in a petroleum process heater.

- **Forming**

Forming operations, such as extrusion and molding, use process heating to improve or sustain the workability of materials. Examples include the extrusion of rubber and plastics, the hot-shaping of glass, and plastic thermoforming.

- **Heating and Melting: High-Temperature**

High-temperature heating and melting is conducted at temperatures higher than most steam-based systems can support (above 400˚F, although very high-pressure steam systems support higher temperatures and are used in applications like petroleum processing). High-temperature heating is typically performed on metals, but this category does not include metals reheating or heat treating (see below). High-temperature melting is the conversion of solids to a liquid by applying heat, and is common in the metals and glass industries. Melting can be combined with refining processes, which demand the increase of temperature to remove impurities and/or gases from the melt. Metal melting processes comprise both the making of the metals, such as in the conversion of iron into steel, and the production castings. Energy-intensive nonmetal melting applications include container and flat glass production.

- **Heating and Melting: Low-Temperature**

Low-temperature heating and melting is done at temperatures that steam-based systems can support (less than 400˚F), although not all applications are steam-based. Nonmetallic liquids and solids are typically heated or melted.

- **Heat Treating**

Heat treating is the controlled heating and cooling of a material to achieve certain mechanical properties, such as hardness, strength, flexibility, and the reduction of residual stresses. Many heat treating processes require the precise control of temperature over the heating cycle. Heat treating is used extensively in metals production, and in the tempering and annealing of glass and ceramics products.

A quench furnace line for heat treating.

Incineration/Thermal Oxidation

Incineration refers to the process of reducing the weight and volume of solids through heating, whereas thermal oxidation refers to heating waste (particularly organic vapors) in excess oxygen at high temperatures. The main application is the treatment of waste to render it disposable via landfill.

Metals Reheating

Metals are reheated to establish favorable metalworking properties for rolling, extrusion, and forging. Metal reheating is an important step in many metal fabrication tasks.

Separating

Separation involves dividing gaseous or liquid streams into various components. Separation can be accomplished through distillation, membranes, or by other means.

A walking beam furnace for metal reheating.

Smelting

Smelting is the chemical reduction of a metal from its ore, typically by fusion. Smelting separates impurities, thereby allowing their removal from the reduced metal. A common example is the reduction of iron ore in a blast furnace to produce pig iron. Other applications include the extraction of aluminum from bauxite in arc furnaces, and the production of copper.

Other Heating Processes

Many process heating applications do not fall in the preceding categories; however, collectively, they can account for a significant amount of industrial energy use. Common applications that use process heating include controlling a chemical reaction, cooking foods, and establishing favorable physical or mechanical properties, such as in plastics production. In the food products industry, process heating is used in preparation tasks, particularly baking, roasting, and frying. In the textile industry, process heating is used to set floor coverings and to prepare fabrics for various types of subsequent treatments. This category includes fuel, electric, and steam-based applications.

Table 1 on page 7 summarizes the processes and identifies the applications, equipment, and industries where these processes are commonly used.

Common Types of Process Heating Systems and Equipment

In all process heating systems, energy is transferred to the material to be treated. Direct heating methods generate heat within the material (e.g., microwave, induction, or controlled exothermic reaction), whereas indirect methods transfer energy from a heat source to the material by conduction, convection, radiation, or a combination of these functions. In most processes, an enclosure is needed to isolate the heating process and the environment from each other. Functions of the enclosure include, but are not restricted to, 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 thereof.

Common industrial process heating systems fall in one of the following categories:

- Fuel-based process heating systems
- Electric-based process heating systems
- Steam-based process heating systems
- Other process heating systems, including heat recovery, heat exchange systems, and fluid heating systems.

The choice of the energy source depends on the availability, cost, and efficiency; and, in direct heating systems, the compatibility of the exhaust gases with the material to be heated. Hybrid systems use a combination of process heat systems by using different energy sources, or different heating methods with the same energy source.

Table 1. Summary of Process Heating Operations

Process	Application	Equipment	Industry
Agglomeration—Sintering	Metals Production	Various Furnace Types, Kilns, Microwave	Primary Metals
Calcining	Lime Calcining	Various Furnace Types	Cement, Wallboard, Pulp and Paper Manufacturing, Primary Metals
Curing and Forming	Coating, Polymer Production, Enameling	Various Furnace Types, Ovens, Kilns, Lehrs, Infrared, UV, Electron Beam, Induction	Ceramics, Stone, Glass, Primary Metals, Chemicals, Plastics and Rubber
Drying	Water and Organic Compound Removal	Fuel-Based Dryers, Infrared, Resistance, Microwave, Radio-Frequency	Stone, Clay, Petroleum Refining, Agricultural and Food, Pulp and Paper, Textile
Forming	Extrusion, Molding	Various Ovens and Furnaces	Rubber, Plastics, Glass
Fluid Heating	Food Preparation, Chemical Production, Reforming, Distillation, Cracking, Hydrotreating, Visbreaking	Various Furnace Types, Reactors, Resistance Heaters. Microwave, Infrared, Fuel-based Fluid Heaters, Immersion Heaters	Agricultural and Food, Chemical Manufacturing, Petroleum Refining
Heating and Melting—High-Temperature	Casting, Steelmaking, Glass Production	Fuel-Based Furnaces, Kilns, Reactors, Direct Arc, Induction, Plasma, Resistance	Primary Metals, Glass
Heating and Melting—Low-Temperature	Softening, Liquefying, Warming	Ovens, Infrared, Microwave, Resistance	Plastics, Rubber, Food, Chemicals
Heat Treating	Hardening, Annealing, Tempering	Various Fuel-Based Furnace Types, Ovens, Kilns, Lehrs, Laser, Resistance, Induction, Electron Beam	Primary Metals, Fabricated Metal Products, Glass, Ceramics
Incineration/Thermal Oxidation	Waste Handling/Disposal	Incinerators, Thermal Oxidizers, Resistance, Plasma	Fabricated Metals, Food, Plastics and Rubber, Chemicals
Metals Reheating	Forging, Rolling, Extruding, Annealing, Galvanizing, Coating, Joining	Various Furnace Types, Ovens, Kilns, Heaters, Reactors, Induction, Infrared	Primary Metals, Fabricated Metal Products
Separating	Air Separation, Refining, Chemical Cracking	Distillation, Membranes, Filter Presses	Chemicals
Smelting	Steelmaking and Other Metals (e.g., Silver)	Various Furnace Types	Primary Metals
Other Heating Processes	Food Production (including Baking, Roasting, and Frying), Sterilization, Chemical Production	Various Furnace Types, Ovens, Reactors, and Resistance Heaters. Microwave, Steam, Induction, Infrared	Agricultural and Food, Glass, Ceramics, Plastics and Rubber, Chemicals

Although steam is generated by using fuel or electricity in a boiler, it is a major source of energy for many industrial processes, such as fluid heating and drying. In addition to steam, several other secondary energy sources are used by industry. They include hot air, heat transfer by liquids, and water. The secondary sources are generated by a heating system of its own that can fall under the general category of "other process heating systems."

Some energy sources are more expensive than others, and equipment efficiency needs to be considered. Comparatively expensive energy types tend to promote shorter payback periods for projects that improve system efficiency. In contrast, byproduct fuel sources, such as wood chips, bagasse (the residue remaining after a plant has been processed, for instance, after the juice has been removed from sugar cane), and black liquor (a byproduct of the paper production process) tend to be much less costly than conventional fuels, making the payback periods for efficiency improvement projects comparatively longer.

Figure 1 illustrates how fuels are used in several process heating applications. In many industries, "other" fuels account for a large portion of the energy use. A significant portion of other fuels usually refers to opportunity fuels, which are often waste products, such as sawdust, refinery gas, or petroleum coke. In many of these systems especially, justifying energy efficiency projects must emphasize performance and reliability benefits that usually accompany improvements in efficiency.

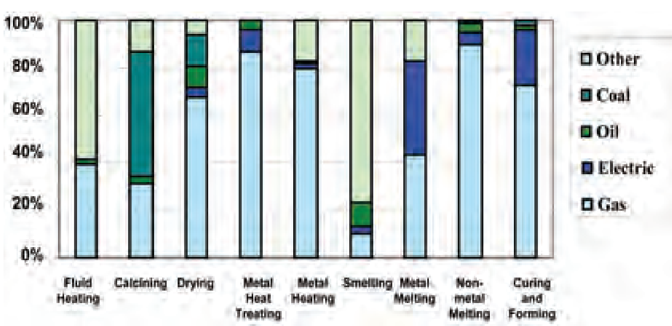


Figure 1. Energy sources for key industrial process heating operations.

Fuel-Based Process Heating

Heat is generated by the combustion of solid, liquid, or gaseous fuels, and transferred either directly or indirectly to the material. Common fuel types are fossil fuels (e.g., oil, natural gas, and coal), and biomass (e.g., vegetable oil, wood chips, cellulose, charcoal, and ethanol). To enhance combustion, gaseous or liquid fuels are mixed with oxidants (e.g., oxygen and air). The combustion gases can be either in contact with the material (direct heating), or be confined and thus be separated from the material (indirect heating, e.g., radiant burner tube, radiant panel, and muffle). Solid fuels are utilized in a wide variety of combustion systems, including fluidized bed, grate, and stokers.

Examples of fuel-based process heating equipment include ovens, heaters, kilns, and melters. Throughout the course, the term "fuel-based furnace" describes this broad range of equipment. In many cases, similar electronic-based equipment is also available. Fuel-based process heating systems are common in nearly every industry segment, and include furnaces like ovens, heaters, kilns, and melters, but also the surface treatment in ambient air. Typical fuel-based furnaces include the following:

Atmosphere generators. Used to prepare and/or condition protective atmospheres. Processes include the manufacture of endothermic gas used primarily to protect steel and iron during processing, and exothermic gas used to protect metals, but also to purge oxygen or volatile gases from confined areas.

Blast furnaces. Furnaces that burn solid fuel with a blast of air, often used to smelt ore.

Crucible furnaces. A furnace in which the heated materials are held in a refractory vessel for processes such as melting or calcining.

Dryer. A device that removes free water, or other volatile components, from materials through direct or indirect heating. Dryers can be grouped into several categories based on factors such as continuous versus batch operation, type of material handling system, or source of heat generation.

Flares. Used to protect the environment by burning combustible waste products in the petrochemical industry.

Indirect process heaters. Used to indirectly heat a variety of materials by remotely heating and circulating a heat transfer fluid.

Kilns. Afurnace used to bake, dry, and fire ceramic ware or wood. Kilns are also used for calcining ores.

Lehrs. An enclosed oven or furnace used for annealing, or other forms of heat treatment, particularly in glass manufacturing. Lehrs may be the open type (in which the flame comes in contact with the ware), or the muffle type.

Muffle furnaces. A furnace in which heat is applied to the outside of a refractory chamber or another enclosure containing the heated material that is enveloped by the hot gases. The heat must reach the charge by flowing through the walls of the container.

Ovens. A furnace-like chamber in which substances are heated for purposes, such as baking, annealing, curing, and drying. Heated systems can use forced convection or infrared.

Radiant-tube heat-treating furnaces. Used for processing iron, steel, and aluminum under a controlled atmosphere. The flame is contained within tubes that radiate heat to the work. Processes include carburizing, hardening, carbonitriding, and austempering. The atmosphere may be inert, reducing, or oxidizing.

Reverberatory furnaces. Furnaces in which open flames heat the upper portion of a chamber (crown). Heat is transferred to the material mainly by radiation (flame, reflection of the flame by the crown) and convection (combustion gases).

Salt bath furnaces. Metal pot furnaces filled with molten salt where heat is applied to the outside of the pot or inside of the pot by radiant tube. Salt bath furnaces are used for processes such as heat treating metals and curing plastics and rubber.

Solid waste incinerators. Used to dispose of solid waste material through burning.

Thermal oxidizers. Used to oxidize volatile organic compounds (VOC) in various industrial waste streams. Processes include paint and polymer curing and/or drying.

Furnaces in any configuration can be considered heating systems that consist of many functional components. Most opportunities to improve process heating efficiency are related to optimizing the combustion process, extracting and/or recovering energy from the exhaust gases, and reducing the amount of energy lost to the environment.

■ Electric-Based Process Heating (Electrotechnologies)

Electric currents or electromagnetic fields are used to heat the material. Direct heating methods generate heat within the work piece by passing an electrical current through the material; by inducing an electrical current into the material; or by exciting atoms or molecules within the material with electromagnetic radiation. Indirect heating methods use one of these three methods to heat an element or susceptor, and transfer the heat either by conduction, convection, radiation, or a combination of these to the work piece.

Examples of electric-based process heating systems include:

Arc furnaces. Electric arc furnaces are process heating systems that heat materials by means of an electric arc. Arc furnaces range in size from foundry applications as small as 1-ton capacity for producing cast iron products, to units of more than 400 tons used for making steel from scrap iron.

Electric infrared processing. An electrical current is passed through a solid resistor, which in turn emits infrared radiation. Electric infrared heating systems are generally used where precise temperature control is required to heat treat surfaces, cure coatings, and dry materials, but infrared can also be used in bulk heating applications such as booster ovens. The work piece to be heated must have a reasonable absorption to infrared. This is determined and measured by the emissivity of the material and is helpful to determine which infrared spectrum is best suited; short-, medium-, or long-wave.

Electron beam processing. In electron beam heating, metals are heated by a directed, focused beam of electrons. In electron beam curing, materials can be chemically transformed by cross linking of molecules from exposure to electrons. Electron beam heating is used extensively in many high-volume applications for welding, especially in the automotive industry. Heat treatment with electron beams is relatively new; the primary application is the local surface hardening of high-wear components for automotive applications.

Induction heating and melting. Induction heating occurs when passing alternating magnetic fields through conductive materials. This is accomplished by placing an alternating current carrying coil around or in close proximity to the materials. The alternating fields generate eddy currents in the materials. These currents interact with the resistance of the material to produce heat. There is a secondary heating process called hysteresis. This disappears at the temperature at which the material loses its magnetic properties.

- *Direct induction***.** Direct induction heating occurs when the material to be heated is in the direct alternating magnetic field. The frequency of the electromagnetic field and the electric properties of the material determine the penetration depth of the field, thus enabling the localized, near-surface heating of the material. Comparably high power densities and high heating rates can be achieved. Direct induction heating is primarily used in the metals industry for melting, heating, and heat treatment (hardening, tempering, and annealing).

- *Indirect induction***.** With indirect induction heating, a strong electromagnetic field generated by a water-cooled coil induces an eddy current into an electrically conducting material (susceptor), which is in contact with the material to be treated. Indirect induction heating is often used to melt optical glasses in platinum crucibles, to sinter ceramic powders in graphite crucibles, and to melt materials in crucibles prior to drawing crystals. Indirect induction is also used to heat susceptors used for joining operations.

Laser processing. A laser beam rapidly heats the surface of a material to create a hardened layer, either by subsequent quenching or self-quenching. The beam shape, beam direction and power output of lasers can be precisely controlled. A common application is the localized hardening of metal parts.

Microwave processing. Microwave heating systems use electromagnetic radiation in the microwave band to excite water molecules in the material, or to generate heat in a susceptor (for example, graphite). Common applications include the drying of textiles and polymers, food processing, and drying and sintering of ceramics. Microwave process applications typically have high efficiency, high energy densities, reasonably good control, and a small footprint for the equipment. However, uniform heating of materials in microwave systems operating on a single frequency is difficult due to standing waves in the cavity, which generate local hot spots. To avoid harm to living organisms and interference with other equipment, proper shielding of the equipment is required.

Plasma processing (arc and nontransferred arc). An electric arc is drawn between two electrodes, thereby heating and partially ionizing a continuous stream of gas; the partly ionized gas is known as plasma. There are two basic configurations, namely, transferred arc and nontransferred arc. In the transferred arc configuration, the arc is transferred from an electrode to the work piece, which is connected to a return electrode; heating of the material occurs through radiation, convection, and direct resistance heating. In nontransferred arc configurations, the arc is drawn between two electrodes not connected to the work piece; heating of the work piece occurs via radiation, and to a certain extent, through convection. In both configurations, either AC (single-phase, three-phase) or DC current can be used.

Radio frequency processing. Radio frequency heating is similar to microwave heating (high-frequency electromagnetic radiation generates heat to dry moisture in nonmetallic materials), but radio frequency waves are longer than microwaves, enabling them to more efficiently heat larger volume objects better than microwave energy.

Resistance heating and melting (direct and indirect).

- *Direct resistance heating.* This refers to systems that generate heat by passing an electric current (AC or DC) through a conductor, causing an increase in temperature; the material to be treated must have a reasonable electrical conductivity. Contact to the work piece is made by fixed connectors, or in the case of melts, by submerged electrodes. The connector and/or electrode material has to be compatible with the material to be heat-treated or melted. In industrial applications, consumable and nonconsumable electrodes are common. Applications of direct resistance heating include the melting of glass and metal.

- *Indirect resistance heating and melting.* This refers to systems in which an electrical current is passed through a resistor, and energy is transmitted to the work piece through convection and/or radiation.

Ultraviolet curing. Ultraviolet (UV) radiation is applied to initiate a photochemical process to transform liquid polymers into a hard, solid film. Applications include decorative and protective coatings, laminations (glass-to-glass, glass-to-polymer, glass-to-metal, polymer-to-polymer), electronics, and printing. Due to the absence of solvents, processes using UV-cured polymers can be faster, and in some cases, less toxic than those using conventional, solvent-based adhesives or coatings.

■ Steam-Based Process Heating

Boilers account for a significant amount of the energy used in industrial process heating. In fact, the fuel used to generate steam accounts for 84% of the total energy used in the pulp and paper industry, 47% of the energy used in the chemical manufacturing industry, and 51% of the energy used in the petroleum refining industry.[3] Hybrid boiler systems combining a fuel-based boiler with an electric-based boiler using off-peak electricity are sometimes used in areas with inexpensive electricity.

Boilers generate steam, generally using heat from fuel combustion, although electric-based boilers have a niche market. Steam has several favorable properties for process heating applications. For example, steam holds a significant amount of energy on a unit mass basis (between 1,000

[3] *Steam System Opportunity Assessment for the Pulp and Paper, Chemical Manufacturing, and Petroleum Refining Industries,* U.S. Department of Energy, October 2002.

and 1,250 Btu/lb). Since most of the heat content of steam is stored as latent heat, large quantities of heat can be transferred efficiently at a constant temperature, which is a useful attribute in many process heating applications. Among the advantages of steam as a source of process heat are low toxicity, ease of transportability, high heat capacity, and low cost. About 30% to 35% of the total energy used in industrial applications is for steam generation.

Steam systems can be relatively complex. As a result, there are many sources of inefficiencies and many opportunities to improve their performance.

■ Other Process Heating Systems

Many industrial facilities have process heating applications that are end-use specific. These applications often use heat exchangers to transfer energy from one process to another. Other examples are chemical reaction vessels that rely on energy released by exothermic reactions to heat another process, and hot-water-based systems.

A common type of heat exchange system is called thermal fluid systems. Thermal fluid systems use an oil- or salt-based heat transfer medium to carry heat from the generation source to the heated product, similar to the way steam is used in process heating applications. Thermal fluid systems have much lower vapor pressure-to-temperature characteristics, which means that thermal fluids can provide high-temperature service (up to 750˚F) without the high pressures that would be required with steam.

This catchall group of process heating applications represents a significant amount of energy, and also includes various types of fuel-, steam-, and electric-based systems. In many cases, the opportunities available to improve these systems depend on many different characteristics, including equipment, type of heating operation (e.g., melting, heating, or calcining) and material handling type. As a result, characterizing efficiency and performance opportunities is difficult; however, taking a systems approach provides the best way of finding the “low-hanging fruit” or the options that usually provide the shortest payback.

Performance Improvement Opportunities—Fuel-Based Systems

Figure 2 shows a schematic of a typical fuel-based process heating system, as well as potential opportunities to improve the performance and the efficiency of the system. Most of the opportunities are not independent, for example, in the case for heat recovery and heat generation. Transferring heat from the exhaust gases to the incoming combustion air reduces the amount of energy lost from the system, but also allows the more efficient combustion of a given amount of fuel, thereby delivering more thermal energy to the material to be heated.

Fuel-Based Process Heating Equipment Classification

Fuel-based process heating equipment is used by industry to heat materials under controlled conditions. The process of recognizing opportunities and implementing improvements is most cost effective when accomplished by combining a systems approach with an awareness of efficiency and performance improvement opportunities that are common to systems with similar operations and equipment.

It is important to recognize that a particular type of process heating equipment can serve different applications and that a particular application can be served by a variety of equipment types. For example, the same type of direct-fired batch furnace can be used to cure coatings on metal parts at a foundry and to heat treat glass products at a glassware facility. Similarly, coatings can be cured either in a batch-type furnace or a continuous-type furnace. Many performance improvement opportunities are applicable to a wide range of process heating systems, applications, and equipment. This section provides an overview of basic characteristics to identify common components and classify process heating systems.

Equipment characteristics affect the opportunities for which system performance and efficiency improvements are likely to be applicable. This section describes several functional characteristics that can be used in classifying equipment. Fuel-based process heating equipment can be classified in many different ways, including:

- Mode of operation (batch versus continuous)
- Type of heating method and heating element
- Material handling system.

Table 2 lists these classification characteristics by equipment/application and industry.

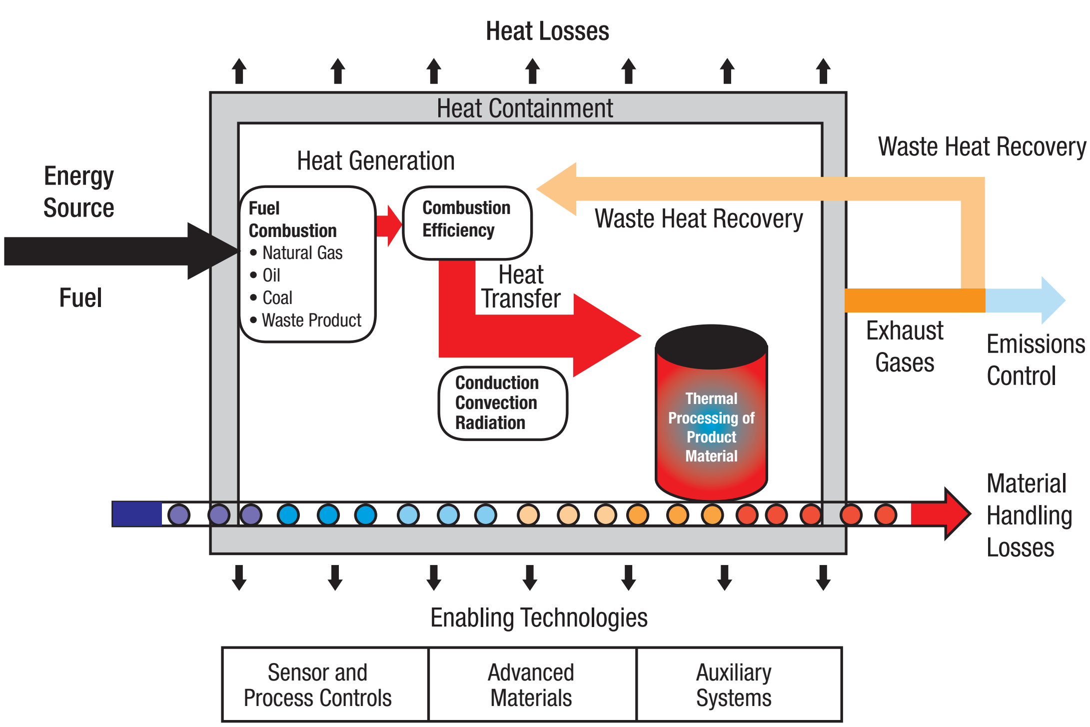


Figure 2. A fuel-based process heating system and opportunities for improvement.

Table 2. Process Heating System Equipment Classification

Furnace Classification Method	Equipment/Application Comments	Primary Industries
Batch versus Continuous		
Batch	Furnaces used in almost all industries for a variety of heating and cooling processes.	Steel, Aluminum, Chemical, Food
Continuous	Furnaces used in almost all industries for a variety of heating and cooling processes.	Most manufacturing sectors
Type of Heating Method		
Direct-fired	Direct-fired furnaces using gas, liquid or solid fuels or electrical heated furnaces.	Most manufacturing sectors
Indirectly heated	Heat treating furnaces, chemical reactors, distillation columns, salt bath furnaces, etc.	Metals, Chemical
Material Handling System		
Fluid heating (flow-through) systems	Gaseous and liquid heating systems including fluid heaters, boilers.	Petroleum Refining, Chemical, Food, Mining
Conveyor, belts, buckets, rollers, etc.	Continuous furnaces used for metal heating, heat treating, drying, curing, etc.	Metals, Chemical, Pulp and Paper, Mining
Rotary kilns or heaters	Rotary kilns used in cement, lime, heat treating, chemical and food industry.	Mining, Metals, Chemical
Vertical shaft furnaces	Blast furnaces, cupolas, vertical shaft calciners, exfoliators, and coal gasifiers	Metals, Minerals Processing, Petroleum Refining
Rotary hearth furnaces	Furnaces used for metal or ceramics heating or heat treating of steel and other metals, iron ore palletizing, etc.	Metals
Walking beam furnaces	Primarily used for large loads, such as reheating of steel slabs, billets, ingots, etc.	Metals (Steel)
Car bottom furnaces	Used for heating, heat treating of material in metals, ceramics, and other industries.	Metals, Chemical, Ceramics
Continuous strip furnaces	Continuous furnaces used for metal heating, heat treating, drying, curing, etc.	Pulp and Paper, Metals, Chemical
Vertical handing systems	Primarily for metal heating and heat treating for long parts and in pit, vertical batch, and salt bath furnaces.	Metals, Chemical, Mining
Other	Pick and place furnaces, etc.	Most manufacturing sectors

Mode of Operation

During heat treatment, a load can be either continuously moved through the process heating equipment (continuous mode), or kept in place, with a single load heated at a time (batch mode). In continuous mode, various process heating steps can be carried out in succession in designated zones or locations, which are held at a specific temperature or kept under specific conditions. A continuous furnace generally has the ability to operate on an uninterrupted basis as long as the load is fed into and removed from the furnace. In batch mode, all process heating steps (i.e., heating, holding, cooling) are carried out with a single load in place by adjusting the conditions over time.

Type of heating method. In principle, one can distinguish between direct and indirect heating methods. Systems using direct heating methods expose the material to be treated directly to the heat source or combustion products. Indirect heating methods separate the heat source from the load, and might use air, gases or fluids as a medium to transfer heat from the heating element to the load (for example, convection furnaces).

Type of heating element. There are many types of basic heating elements that can be used in process heating systems. These include burners, radiant burner tubes, heating panels, bands, and drums.

Material Handling Systems

The selection of the material handling system depends on the properties of the material, the heating method employed, the preferred mode of operation (continuous, batch) and the type of energy used. An important characteristic of process heating equipment is how the load is moved in, handled, and moved out of the system. Important types of material handling systems are described below.

Fluid heating (flow-through) systems. Systems in which a process liquid, vapor, or slurry is pumped through tubes, pipes, or ducts located within the heating system by using pumps or blowers.

Conveyor, belt, bucket, or roller systems. Systems in which a material or its container travels through the heating system during heating and/or cooling. The work piece is moved through the furnace on driven belts or rolls. The work piece can be in direct contact with the transporting mechanism (belt, roller, etc.), or supported by a tray or contained in a bucket that is either in contact with or attached to the transporting mechanism.

Rotary kilns or heaters. Systems in which the material travels through a rotating drum or barrel while being heated or dried by direct-fired burners or by indirect heating from a kiln shell.

Vertical shaft furnace systems. Systems in which the material travels from top to bottom (usually by gravity) while it is heated (or cooled) by direct contact of the hot (or cooling) gases or indirectly from the shell of the fluidizing chamber.

Rotary hearth furnaces. Systems in which the load is placed on a turntable while being heated and cooled.

Walking beam furnaces. The load is “walked” through the furnace by using special beams. The furnaces are usually direct-fired with several top- and bottom-fired zones.

Car bottom furnaces. The material is placed on a movable support that travels through the furnace or is placed in a furnace for heating and cooling of the load.

Continuous strip furnace systems. Systems in which the material in the form of a sheet or strip travels through a furnace in horizontal or vertical direction while being heated and cooled. The material heating could be by direct contact with hot gases or by radiation from the heated “walls” of the furnace.

Vertical material handling systems (often used in pit or vertical batch furnaces). The material is supported by a vertical material handling system and heated while it is “loaded” in an in-ground pit or an overhead furnace.

Other types. Various types of manual or automatic pick and place systems that move loads of material into salt, oil, air, polymers, and other materials for heating and cooling. Other systems also include cyclone, shaker hearth, pusher, and bell top.

Many furnace types, such as pit and rotary, can be designed and configured to operate in batch or continuous mode, depending on how material is fed into the furnace. A pit furnace used for tempering manually fed material with a pick-and-place system is a type of batch furnace. In contrast, a pit furnace used for heat treatment of automatically fed material with a vertical material handling system is a continuous furnace.

Efficiency Opportunities for Fuel-Based Process Heating Systems

The remainder of this section gives an overview of the most common performance improvement opportunities for fuel-based process heating systems. The performance and efficiency of a process heating system can be described with an energy loss diagram, as shown in Figure 3. The main goals of the performance optimization are reduction of energy losses and increase of energy transferred to the load. It is therefore important to know which aspects of the heating process have the highest impact. Some of the principles discussed also apply to electric- or steam-based process heating systems.

Performance and efficiency improvement opportunities can be grouped into five categories (shown in italics in Figure 4):

- Heat generation: discusses the equipment and the fuels used to heat a product
- Heat containment: describes methods and materials that can reduce energy loss to the surroundings
- Heat transfer: discusses methods of improving heat transferred to the load or charge to reduce energy consumption, increase productivity, and improve quality
- Waste heat recovery: identifies sources of energy loss that can be recovered for more useful purposes, and addresses ways to capture additional energy
- Enabling technologies: addresses common opportunities to reduce energy losses by improving material handling practices, effectively sequencing and scheduling heating tasks, seeking more efficient process control, and improving the performance of auxiliary systems. Enabling technologies include:
  - Advanced sensors and controls
  - Advanced materials—identifying performance and efficiency benefits available from using advanced materials
  - Auxiliary systems—addressing opportunities in process heating support systems.

Figure 4 shows several key areas where the performance and efficiency of a system can be improved. It is important to note that many opportunities affect multiple areas.

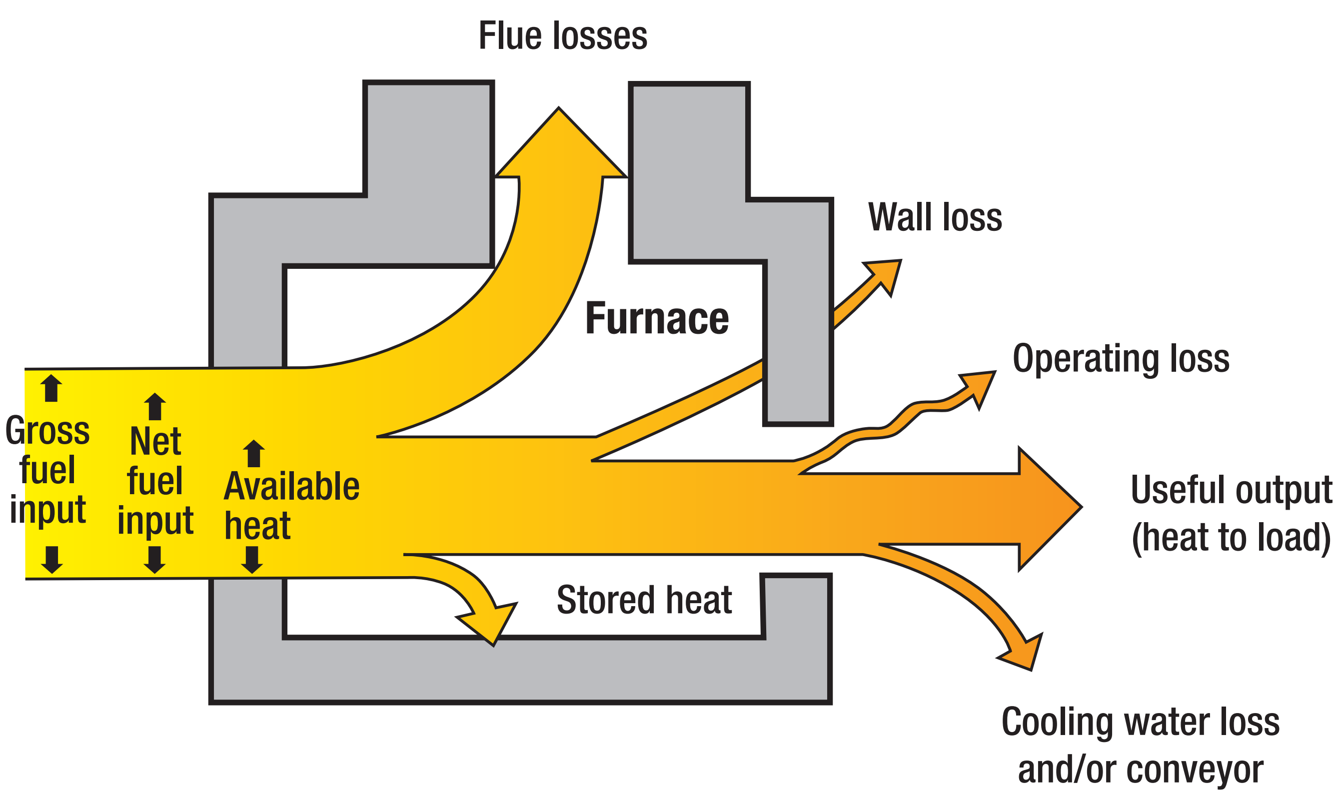


Figure 3. Energy loss diagram in a fuel-based process heating system.

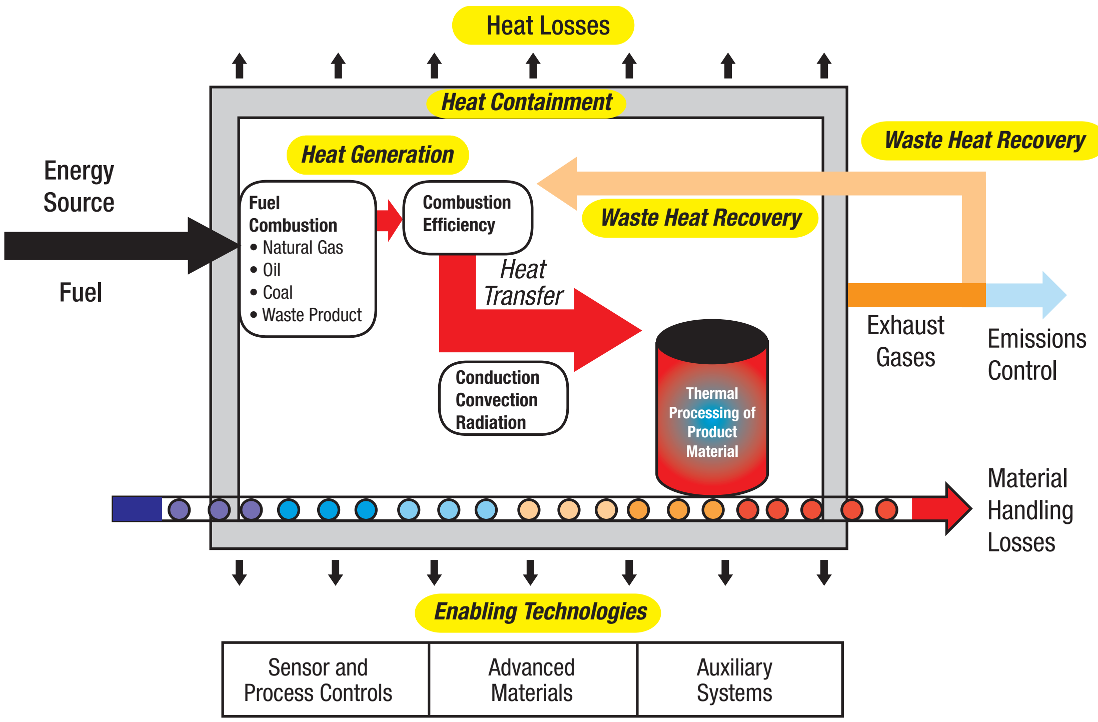


Figure 4. Key opportunities in a fuel-based system.

Transferring heat from the exhaust gases to the incoming combustion air or incoming cold process fluid reduces the amount of energy lost from the system and also allows more thermal energy to be delivered to the heated material from a certain amount of fuel.

Despite overlaps among the five categories, these groupings provide a basis for discussing how process heating systems can be improved and where end users can seek further information for opportunities that seem to be applicable to their system.

Many improvement opportunities are addressed in a series of tip sheets developed by the U.S. Department of Energy's (DOE) Industrial Technologies Program (ITP), which are included in this course. These tip sheets provide low- and no-cost practical suggestions for improving process heating system efficiency. When implemented, these suggestions often lead to immediate energy-saving results.

The following sections discuss the principal components of a process heating system and the associated opportunities, how to identify said opportunities, and where to seek additional information.

■ Heat Generation

In basic terms, heat generation converts chemical or electric energy into thermal energy, and transfers the heat to the materials being treated. The improvement opportunities related to heat generation address the losses that are associated with the combustion of fuel and the transfer of the energy from the fuel to the material. Key improvement areas include:

- Controlling air-to-fuel ratio
- Reducing excess air
- Preheating of combustion air or oxidant
- Enriching oxygen.

Controlling air-to-fuel ratio and reducing excess air. For most process heating applications, combustion burns a hydrocarbon fuel in the presence of air, thereby forming carbon dioxide and water, and releasing heat. One common way to improve combustion efficiency is to ensure that the proper air-to-fuel ratio is used. This generally requires establishing the proper amount of excess air.

When the components are in the theoretical balance described by the combustion reaction, the reaction is called stoichiometric (all of the fuel is consumed and there is no excess air). Stoichiometric combustion is not practical, because a perfect mixing of the fuel with the oxidant (oxygen in air) would be required to achieve complete combustion. Without excess oxidant, unburned hydrocarbons can enter the exhaust gas stream, which can be both dangerous and environmentally harmful. On the other hand, too much excess air is also not desirable because it carries away large amounts of heat.

Caution should be used when reducing excess air. Although this approach is often worth considering, it is important to maintain a certain amount of excess air. Excess air is essential to maintain safe combustion; it is also used to carry heat to the material. As a result, operators should be careful to establish the proper amount of excess air according to the requirements of the burner and the furnace. Important factors for setting the proper excess air include:

- Type of fuel used
- Type of burner used
- Process conditions
- Process temperature.

Preheating combustion air. Another common improvement opportunity is combustion air preheating. Since a common source of heat for this combustion air is the stream of hot exhaust gases, preheating combustion air is also a form of heat recovery. However, the higher combustion air temperature does increase formation of nitrogen oxide (NO_x), a precursor to ground level ozone.

Enriching oxygen. Oxygen enrichment is another opportunity that is available to certain process heating applications, particularly in the primary metals industries. Oxygen enrichment is the process of supplementing combustion air with oxygen. Recall that standard atmospheric air has oxygen content of about 21% (by volume), so oxygen enrichment increases this percentage for combustion. Oxygen-enhanced combustion is a technology that was tried decades ago, but did not become widely used. However, because of technological improvements in several areas, oxygen enrichment is again being viewed as a potential means of increasing productivity.

Heat Generation Opportunities

Performance Improvement	Savings
• Control air-to fuel ratio	**5% to 25%**
• Preheat combustion air	**15% to 30%**
• Use oxygen-enriched combustion air	**5% to 25%**

What to Watch

- Combustion air leaks downstream of control valve.
- Linkage condition can lead to poor control of the fuel/air mixture over the range of operating conditions.
- Excess oxygen in the furnace exhaust (flue) gases indicates too much excess air.
- Flame stability indicates improper fuel/air control.

Find Additional Information

ITP's BestPractices offers these resources to help you implement energy efficiency measures in process heating generation:

- Process Heating tip sheets

■ Heat Transfer

Improved heat transfer within a furnace, oven, or boiler can result in energy savings, productivity gains, and improved product quality. The following guidelines can be used to improve heat transfer:

- Maintain clean heat transfer surfaces by:
  - Using soot blowers, where applicable, in boilers
  - Burning off carbon and other deposits from radiant tubes
  - Cleaning heat exchanger surfaces.
- Achieve higher convection heat transfer through use of proper burners, recirculating fans or jets in the furnaces and ovens.
- Use proper burner equipment for the location within the furnace or ovens.
- Establish proper furnace zone temperature for increased heat transfer. Often, furnace zone temperature can be

increased in the initial part of the heating cycle or in the initial zones of a continuous furnace to increase heat transfer without affecting the product quality.

Heat Transfer Opportunities

Performance Improvement	Savings
• Improve heat transfer with advanced burners and controls	**5% to 10%**
• Improve heat transfer with a furnace	**5% to 10%**

What to Watch

- Higher than necessary operating temperature.
- Exhaust gas temperatures from heat recovery device.

Find Additional Information

ITP's BestPractices offers these resources to help you implement energy efficiency measures in heat transfer:

■ Heat Containment

Heat containment refers to the reduction of energy losses to the surroundings. In most heat generation equipment, convection and radiation losses at the outer surface and through openings are major contributors to heat loss. Insulating materials, such as brick, heat-shields, and fiber mats, as well as the proper sealing of openings, are essential in minimizing heat that can be lost to the surroundings.

Another important cause for heat loss is air infiltration. Often, furnaces are operated at slightly negative pressure because of nonexistent or improper pressure control operation to prevent the loss of furnace gases to the surroundings. The slightly negative pressure can cause air to infiltrate the furnace. Air infiltration can cause significant energy loss as the cool air carries heat away from the product and up the stack. However, fixing leaks around the furnace chamber and properly operating a pressure control system can be a cost-effective way to improve furnace efficiency.

Major loss sources from process heating system containment include:

Walls. The hot surfaces of the furnace, dryer, and heat exchanger lose energy to the ambient spaces through both radiation and convection.

Air infiltration. Many furnaces operate at slightly negative pressure. Under these conditions, air can be drawn into the furnace, especially if integrity of the furnace is not inspected often.

Openings in furnace walls or doors. This is the result of not having proper seals at the doors used for material handling.

Water- or air-cooled parts located within the furnace. These parts should be avoided where possible or insulated to avoid direct exposure to the hot furnace surroundings.

Extended parts from the furnace. Parts such as roller shafts get hot and result in heat losses.

Poor insulation condition. Like furnace walls, surfaces such as piping and ductwork that have poor insulation are also sources of energy loss. In many cases, the loss of energy to work spaces that are HVAC conditioned often creates additional burdens on cooling systems. This added demand on the cooling system should be accounted for when considering the restoration or installation of the insulation.

Heat Containment Opportunities

Performance Improvement	Savings
• Reduce wall heat losses	**2% to 5%**
• Maintain furnace pressure control	**5% to 10%**
• Maintain door and tube seals	**up to 5%**
• Reduce cooling of internal parts	**up to 5%**
• Reduce radiation heat losses	**up to 5%**

What to Watch

- Air leaks into the furnace.
- Localized cold spots.
- Furnace shell and casing conditions such as hot spots, cracks, or insulation detachment.
- Piping insulation sagging and distortion.
- Damper positioning and operation.

Find Additional Information

ITP's BestPractices offers these resources to help you implement energy efficiency measures in process heating containment:

■ Heat Recovery

Heat recovery is the extraction of energy, generally from exhaust gases, and subsequent reintroduction of that heat energy to the process heating system. Heat recovery opportunities depend largely on the design of the system and the requirements of the process. In most cases, thermal energy from the exhaust gases is transferred back to the combustion air. This type of preheating reduces the amount of fuel required to establish and maintain the necessary temperature of the process. In some cases, heat can be "cascaded," a process in which waste heat is used several times on subsequent lower levels. Another example of heat recovery is the transferring exhaust gas energy back to the material being heated, which also reduces fuel use. The heat lost from exhaust gases depends on mass flow and temperature of gases.

In many process heating systems, the exhaust gases contain a significant amount of energy, particularly in high-temperature applications. Products that must be heated to high temperatures are limited in the amount of energy that they can extract from combustion gases by this temperature requirement. For example, a forging that must be heated to 1,200°F will have exhaust gases close to this temperature. Unless there is some form of waste heat recovery, the exhaust gases in this application will leave the system with a significant amount of thermal energy.

Transferring excess energy from exhaust gas back to some other part of the system can be an excellent efficiency improvement. Two common targets for receiving this energy are the combustion air and the product being heated. Combustion air accounts for a significant amount of mass entering a furnace. Increasing the temperature of this mass reduces the fuel needed to heat the combustion gases to the operating temperature. In many systems, particularly in solid-fuel burning applications or when using low heating-value fuels such as blast furnace gas, combustion air preheating is necessary for proper flame stability. However, even in applications that do not require this type of preheating for proper performance, combustion air preheating can be an attractive efficiency improvement.

Where permitted by system configuration, preheating the product charge can also be a feasible efficiency improvement. Much like combustion air preheating, this form of energy transfer to an upstream mass can reduce fuel use.

Preheating air reduces the exhaust gas temperature and mass flow through the heating system. Using waste heat from waste or flue gases from high-temperature processes to supply heat to lower temperature processes can improve the efficiency of the overall process. For example, using flue gases from process heaters to generate steam or to heat feedwater for other boilers can increase the system efficiency significantly.

Heat Recovery Opportunities

Performance Improvement	Savings
• Combustion air preheating	**10% to 30%**
• Fluid or load preheating	**5% to 20%**
• Heat cascading	**5% to 20%**
• Fluid heating or steam generation	**5% to 20%**
• Absorption cooling	**5% to 20%**

What to Watch

- Air leaks into the furnace or hot gas into the furnace.
- Combustion air temperature.
- Exhaust gas temperature from heat recovery device
- Stack temperature.
- Heat losses from the piping.
- Air-to-fuel ratio control over the turndown range.
- Pressure drop across the heat recovery system.

Find Additional Information

ITP's BestPractices offers these resources to help you implement energy efficiency measures in process heating containment:

■ Enabling Technologies

Enabling technologies include a wide range of improvement opportunities, including process control, advanced materials, and auxiliary systems.

Sensors and process controls. Process control refers to opportunities that reduce energy losses by improving control systems that govern aspects such as material handling, heat storage, and turndown. This opportunity addresses energy losses that are generally attributed to system operation during periods of low throughput. Process heating systems have both fixed and variable losses. Variable losses depend on the amount of material being heated, while fixed losses do not. Fixed losses are incurred as long as the unit is being used, regardless of the capacity at which it is operating.

In many cases, fixed losses can be minimized by improving process scheduling, such as reducing the amount of time that systems operate far below rated capacity, and minimizing idle time between batches.

Similarly, energy loss from heat storage can often be minimized with more effective process control. Heat storage refers to the energy required to bring a system up to operating temperature. In many process heating applications, the system has a considerable mass that must be heated until it reaches a sufficient temperature to begin the heating operation. Though a certain amount of heat storage loss is unavoidable, reducing the number of times that a process heating system is cycled from a de-energized to an energized state can reduce the size of heat storage losses.

Increasing the turndown capacity of a process heating system can also reduce some energy losses. Turndown is the ratio of the highest capacity to lowest capacity that a system can operate. Heating equipment often cannot support operation at very low capacities because of combustion instabilities. Generally, when the load on a system drops below its lowest safe operating capacity, the system must be shut down. Frequently shutting down and restarting a system results in heat storage losses, and also causes purge losses that accompany clearing the remaining combustible gases from the burner area. However, increasing a system's turndown ratio allows the unit to remain operating until the load picks back up and can offer opportunities for savings.

In addition, improving production schedules to maintain a system's continuity of operations is often worth consideration.

Advanced materials. The use of advanced materials can improve the performance and efficiency of a process heating system. To avoid thermal damage, many high-temperature processes require the cooling of components. In some cases, advanced materials that can safely withstand higher temperatures may replace conventional materials. This can avoid or reduce energy losses associated with cooling. Use of advanced materials can reduce the mass of fixtures, trays, and other material handling parts, with significant reduction in process heat demand per unit of production. Furnace heat transfer can also be improved by using lighter, high-temperature convection devices such as fans for dense, tightly packed loads.

Auxiliary systems. Most process heating applications have auxiliary systems that support the process heating system. For example, large furnaces require forced draft fans to

Enabling Technology Opportunities

Performance Improvement	Savings
• Install high-turndown combustion systems	**5% to 10%**
• Use programmed heating temperature setting for part-load operation	**5% to 10%**
• Monitor and control exhaust gas oxygen, unburned hydrocarbon, and carbon monoxide emissions	**2% to 15%**
• Maintain furnace pressure control	**5% to 10%**
• Ensure correct sensor locations	**5% to 10%**

What to Watch

- Frequent and avoidable furnace starts and stops.
- Long periods of idle time between batches.
- Extended periods of low-capacity furnace operation.
- Piping insulation sagging and distortion.
- Higher than necessary operating temperature.

supply combustion air to the burners. Inefficient operation of these fans can be costly, especially in large process heating systems with high run times.

- *Material handling.* Another important auxiliary system is the material handling system, which controls the delivery of material to the furnace and removes the material after the process heating task is completed. The type of process heating application has a significant effect on potential losses and the opportunities to reduce these losses. In continuous systems, the material is fed to the furnace without distinctive interruption. Batch systems, in contrast, are characterized by discrete deliveries of material to be treated into and out of the system.

Opportunities to improve the overall process heating system efficiency by modifying the material handling system are generally associated with reducing the amount of time that the furnace is idle or that it operates at low capacity. For example, a slow mechanical action into and out of an oven can result in unnecessary heat loss between batches. Similarly, imprecise mechanical controls can result in uneven heating and the need for rework. A systems approach is particularly effective in evaluating potential improvement opportunities in material handling systems.

- *Motor systems.* Motor systems are found throughout industry, accounting for approximately 59% of manufacturing industrial electricity use.[4] Within process heating systems, motors are used to power fans, and run pumps and material handling systems. Motors, in general, can be very efficient devices when properly selected for an application and properly maintained. In contrast, when motors operate far below their rated capacity or are not properly maintained, their corresponding efficiency and reliability can drop significantly. One common opportunity to improve the efficiency of auxiliary motor systems is to use motors controlled by variable frequency drives instead of controlling motors with dampers or throttle valves.

ITP has several resources that address the opportunities available from improving motor system performance and efficiency. Motor Master+ is one of the software programs that helps end users make informed motor selection decisions. This tool can be downloaded along with many other useful motor-related resources at ITP's BestPractices Web site, www.eere.energy.gov/industry/bestpractices.

- *Fans.* Fans are used to supply combustion air to furnaces and boilers. In many process heating applications, fans are used to move hot gases to heat or dry material, and, frequently, fans are used in material handling applications to move heated materials. The performance, efficiency, and reliability of fans, as with motors, are significantly affected by sizing and selection decisions and the fan maintenance effort.

[4] *United States Industrial Electric Motor Systems Market Opportunities Assessment,* U. S. Department of Energy, 1998.

Performance Improvement Opportunities—Electric-Based Systems

Electric-based process heating systems are manufacturing technologies that use electricity to make or transform a product through heat-related processes. Electric-based process heating systems (sometimes called electro-technologies) perform operations such as heating, drying, curing, melting, and forming.

Electric-based process heating systems are controllable, clean, and efficient. In some cases, electric-based technologies are chosen for unique technical capabilities, while in other cases the relative price of natural gas (or other fuel) and electricity is the deciding factor. Sometimes the application cannot be performed economically without an electric-based system. For some industrial applications, electric-based technologies are the most commonly used; in others these are only used in certain niche applications.

Types of Electric-Based Process Heating Systems

Electric-based process heating systems use electric currents or electromagnetic fields to heat materials. Direct heating methods generate heat within the work piece, by either:

1. Passing an electrical current through the material
2. Inducing an electrical current (eddy current) into the material
3. Exciting atoms and/or molecules within the material with electromagnetic radiation (e.g., microwave) Indirect heating methods use one of these three methods to heat an element or susceptor that transfers the heat either by conduction, convection, radiation, or a combination of these to the work piece.

The remainder of this section covers these process heating electrotechnologies:

- Arc furnaces
- Electric infrared electric processing
- Electron beam processing
- Induction heating and melting
- Laser heating
- Microwave processing
- Plasma processing (arc and nontransferred arc)
- Radio-frequency processing
- Resistance heating and melting (direct and indirect)
- Ultraviolet curing.

Arc Furnaces

History and Status

The first commercial electric arc furnaces were established in the United States in 1907. Initially, arc furnaces were used to produce specialty metals such as spring steel. Today, they are increasingly used for the production of more common carbon and low-alloy steels, and in foundries to melt iron and steel for casting operations.

How the Technology Works

Arc furnaces melt steel or iron scrap by direct contact with an electric arc struck from an electrode to the metal charge. At the beginning of the direct arc melting process, a charge of steel scrap is placed into the furnace. Then, the furnace is sealed and the arc is struck. Direct arc furnaces range 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).

For steelmaking, electric arc furnaces consist of a water-cooled refractory-lined vessel, which is covered by a retractable roof through which graphite or carbon electrodes protrude into the furnace. The distance between the electrode tips and the melt surface can be adjusted, and during operation the electrodes are lowered into the furnace to compensate for wear. The cylindrical electrodes consist of multiple segments with threaded joints; new segments can be added to the cold end of the electrode as the wear progresses. The arc forms between the charged material and the electrodes, and the charge is heated both by current passing through the charge and by the radiant energy from the arc.

The electrodes are raised and lowered by a positioning system. A control system maintains the proper current and power input during charge melting – control is important because the amount of scrap may change under the electrodes while it melts. The arms holding the electrodes carry bus bars, which are usually hollow, water-cooled copper pipes, and convey current (electricity) to the electrode holders. The electrodes move up and down automatically to regulate the arc, and are raised to allow removal of the furnace roof. Heavy water-cooled cables connect the bus tubes with a vault-protected transformer, located adjacent to the furnace. The hearth, the bowl-

Improve the Efficiency of Existing Arc Furnace Systems

- Use bottom stirring/stirring gas injection. An inert gas (e.g., argon) is injected in the bottom of the arc furnace, increasing heat transfer in the melt and the interaction between slag and metal (increasing liquid metal).
- Install ultra-high-power transformers. Transformer losses depend on the sizing and age of the transformer. When replacing a transformer, the furnace operation can be converted to ultra-high-power, increasing productivity and reducing energy losses.
- Preheat scrap. The waste heat of the furnace is used to preheat the scrap charge.
- Insulate furnaces. Insulation using ceramic low-thermal mass materials reduces the heat losses through the walls better than conventional ceramic fiber linings.
- Use oxy-fuel burners in hybrid systems in first part of melt cycle. 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. Burning 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.
- Use variable speed drives on flue gas fans. Monitoring flue gas and controlling flue gas fans with variable speed drives reduces heat loss.

shaped bottom of the furnace, is lined with refractory bricks and granular refractory material. The furnace can tilt (be tapped) so liquid steel can be poured into another vessel for transport.

To produce a ton of steel in an electric arc furnace requires around 400 to 500 kilowatt-hours per short ton. This is about one-third to one-tenth the energy required by basic oxygen furnaces or integrated blast furnaces. Electric arc furnaces used for steelmaking are usually employed where there is a plentiful and inexpensive supply of electric power.

The systems described above are direct arc melting applications. Another type of furnace, using indirect arc melting, is also available. These furnaces have a horizontal barrel-shaped steel shell, lined with refractory. An arc is drawn between two carbon electrodes positioned above the load, and heat is transferred by radiation from the arc to the metal being melted. The shell rotates and reverses to avoid excessive heating of the refractory above the melt level, and to increase the efficiency. Indirect arc furnaces are common in the production of copper alloys. These units are generally much smaller than direct arc furnaces.

Submerged air furnaces are another type of arc furnace. The term “submerged” is used because the electrodes are deep in the furnace and the reaction takes place at the tip of the electrodes. These furnaces are used to produce various metals by smelting minerals, and also used for producing foundry iron from scrap iron. Ore materials are mixed with a reducing agent (usually carbon) outside the furnace, and this charge mix is added periodically to the furnace. The reduction reaction inside the furnace proceeds continuously, and the metal accumulates until the furnace is tapped at intervals.

■ Process, Applications, and Industries

The primary application of large arc furnaces is in processes for melting of metals, primarily iron and steel from scrap steel and iron as raw materials; applications for smaller arc furnaces include the melting of iron and steel, and refractory metals.

Direct arc furnaces used for steelmaking are typically smaller than integrated basic oxygen furnaces. These direct arc furnaces (sometime known as mini-mills) use scrap iron and steel, instead of iron ore, to make steel. Arc furnaces use electricity, while basic oxygen furnaces typically use coal. In terms of capital cost, direct arc furnaces are less expensive (in terms of dollars per ton of steel capacity) than basic oxygen furnaces.

Direct arc furnaces used in foundries are usually for producing iron for casting operations. These units are typically less than 25 tons, and also use scrap steel and scrap iron. These furnaces are often used for the continuous casting for flat products like steel plates.

Submerged arc furnaces are used in smelting processes to produce materials such as silicon alloys, ferromanganese, calcium carbide, and ferronickel.

Induction arc furnaces are used for a variety of metal melting applications and perform the same processes as various types of fuel-based furnaces.

Electric Infrared Processing

Electric infrared processing systems are used by many manufacturing sectors for heating, drying, curing, thermal-bonding, sintering, and sterilizing applications. Electric infrared is most often used on applications in which only the surface of an object needs to be heated. Natural gas infrared systems can also be used on many of these same applications.

■ History and Status

Industrial electric infrared systems were first used in the mid-1930s by Ford Motor Company to cure paint on auto bodies. With the advent of new infrared-tolerant coatings, and improved emitter designs and controls, electric infrared is used in many successful applications throughout the manufacturing sector.

■ Operation

Infrared is the name given to the part of the electromagnetic spectrum between visible light and radio waves. Infrared wavelengths range from 0.8 to 10 microns. Infrared energy, like light energy, can be transmitted, absorbed, and reflected, and is usually used when the object being heated is in line-of-sight of the emitters and/or reflector. Some infrared systems can cure coatings that are not in line of sight. An example is curing a coating on the inside of pipe using infrared focused on the outside of the pipe. While the curing is being accomplished by conductivity, it is using infrared processing.

Electric infrared heating systems typically comprise an emitter, a reflector system, and controls. Most electric infrared applications also have a material handling system and a ventilation system. Because infrared systems can dry or cure a product in as little as seconds, accurate control is critical. Figure 5 shows a schematic of a typical electric infrared system.

The emitter shown in Figure 5 is a long tube-type (shown in profile), but there are many varieties of emitters and systems, including panel heaters, ceramic bodies with embedded coils, metal coils, ribbons, foils, fiber heaters, and other designs. These design variations give manufacturers the flexibility to use electric infrared technology in many applications.

Infrared radiation is emitted by conducting electric current through the emitter or filament, and systems are classified by wavelength: short, medium, and long. Each class of wavelength has its own heat transfer qualities.

Short-wave emitters are clear quartz tubes with tungsten filiments that are sealed at each end, creating a lamp that looks similar to a fluorescent tube. An inert gas, such as argon, is used to prevent oxidation of the filament. Operating temperatures are around 3,500°F and heat-up times are short—less than a few seconds. Shortwave systems are often used for spot heating or booster ovens.

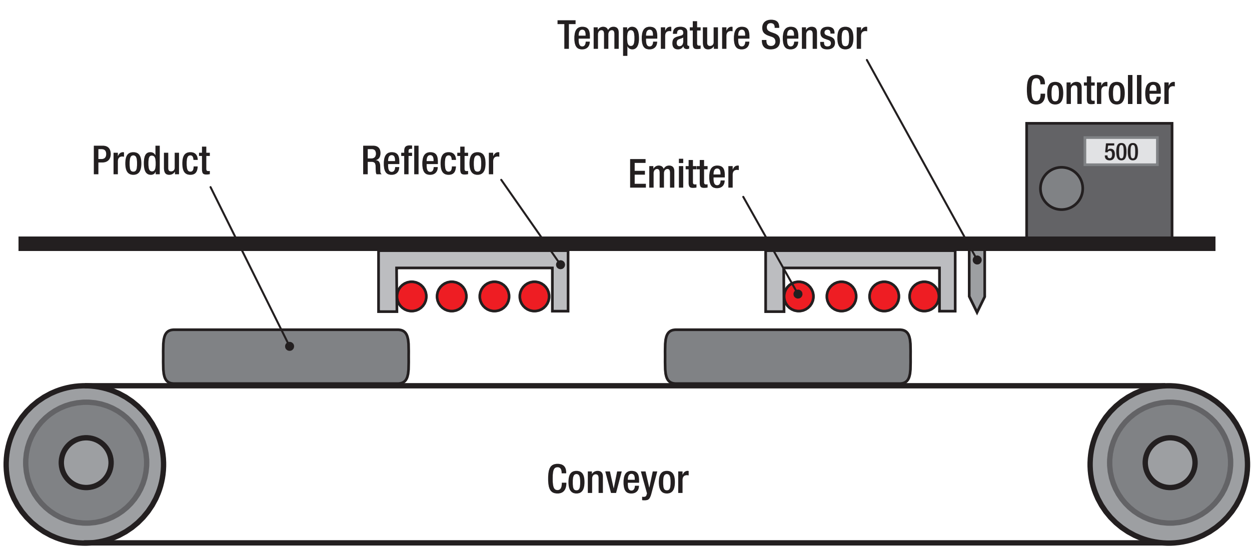


Figure 5. An electric infrared heating system.

Medium-wavelength emitters come in two main varieties. The first type has a helically wound coil encased in a long quartz glass tube that is unsealed. These systems use convection and radiant energy to heat. The second type uses metal radiant tubes that encase a resistance coil surrounded by magnesium oxide. Long-wave emitters normally are wires embedded in ceramic panels. Typical applications for medium-wave and long-wave systems are drying and heating.

■ Processes, Applications, and Industries

Electric infrared is ideal for situations where a fairly flat product is being heated, dried, or cured. Because infrared primarily heats the surface, it is usually not good for products that need to be heated deep beneath the product surface. Products with complex hidden surfaces require a hybrid system with a convection oven or a material handling system that can rotate parts. The work piece must also have a reasonable absorption in the infrared part of the spectrum.

Special paints, adhesives, and other coatings are made specifically for infrared drying.

Common industrial applications of infrared are:

- Adhesive drying
- Annealing and curing of rubber
- Drying of parts (coated with paints or varnishes)
- Drying textiles and paper
- Drying coatings on steel and aluminum coil
- Ink curing
- Molding plastics
- Power coating curing
- Shrink wrapping
- Silk screening.

Electric infrared is used in some of the same applications as direct-fired and fuel-fired process heating systems. Sometimes fuel-based equipment is used in conjunction with electric (or natural gas) infrared in hybrid systems (see below). Ultraviolet (UV) curing, another electric-based process heating system, is used for applications such as curing inks, coatings, adhesives, and liquid and powdered coatings. UV usually uses less energy and has lower volatile organic compound (VOC) emissions than infrared or convection ovens. However, UV can only be used with certain coatings for niche applications.

Hybrid systems. In many applications, electric infrared systems are used in conjunction with conventional direct-fired process heaters. In some cases, 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. A hybrid system can be used and configured to perform fuel switching based on energy signals sent by the energy provider. Such a configuration can result in energy cost savings.

Natural gas-fired infrared. Natural gas-fired emitters can be used in industrial infrared systems. Many factors are considered in the decision to use electric versus gas, including:

- The relative price of electricity and natural gas
- The cost of upgrading the electrical control panel or gas lines
- The required temperature control
- Equipment cost.

Improve the Efficiency of Existing Electric Infrared Systems

- Add baffles or additional reflectors to sides/top/bottom of the oven to re-radiate stray infrared energy back to the product.
- Keep a regular maintenance schedule that includes the cleaning of reflectors, end caps and emitters; and the replacement of any failed emitters. Clean reflectors and emitters will more efficiently radiate the heat to the intended target.
- Perform testing* to ensure the best emitter type is employed for the process.
- Consider zoning that can direct the radiant energy most appropriately to the product. Zoning can be configured horizontally or vertically, and can be specifically profiled for the product, due to the controllability of electric infrared energy. A more sophisticated control system will be required.
- Consider the addition (retrofit) of moveable infrared banks. The electric emitters can be moved closer to smaller products and moved farther out for larger products. Proper emitter positioning with respect to the product can improve efficiency.
- Install a more efficient control system. In addition to providing for zoning, an effective control system can also provide for a variable control system instead of simple on/off control. Some systems employ "closed-loop" control that can precisely deliver the required amount of radiant energy to the product, even if product size, shape, or color, etc. might vary. These systems generally employ non-contact radiometers and a PLC-based control panel.

* The Infrared Equipment Division (IRED) of the Industrial Heating Equipment Association (www.ihea.org) can provide a list of companies with infrared testing facilities. These companies generally provide free testing in their infrared labs.

Incorporating one or more of these recommendations can show significant savings. Efficiencies (lower cost/part) from 10% to 30% in existing ovens have been demonstrated with the employment of these recommendations.

Electron-Beam Processing

History and Status

The principle of electron-beam heating, in which the kinetic energy of an accelerated stream of electrons is converted to heat when impinged on a metal surface, was first developed as early as 1905. Electron-beam heating is used extensively in many high-production applications for welding, particularly in the automotive industry. Using electron-beam technology for heat treating applications is relatively new. The primary application is local surface hardening of high-wear components for the automotive industry. Electron beams can cure multiple layers of web material simultaneously, as well as curing surface coatings.

How the Technology Works

In electron-beam heating, metals are heated to intense temperatures when a directed beam of electrons is focused against the work surface. In electron-beam curing, a liquid is chemically transformed to a solid on the work surface by a stream of directed electrons. Electron-beam processing can be done under vacuum, partial vacuum, and nonvacuum conditions. High-vacuum conditions result in fewer gaseous molecules between the electron gun and the work piece, and this results in less scattering and a tighter beam. Creating vacuum conditions, however, can slow production because of idle time between treating work pieces.

Process, Applications, and Industries

Electron-beam processing is used for welding metals, machining holes and slots, to harden the surface of metals, and for heat treating and melting. This technology can be more than ten times faster than conventional welding systems. Other competitive benefits include minimal thermal distortions, because the power density and energy input can be precisely controlled. In addition, setup and cleaning time are substantially reduced, labor costs are low, and it can achieve complex and precise heating patterns.

Electron-beam curing is generally used to cure thicker, heavily pigmented coatings in cases where UV curing is limited. It is used widely in web lamination, with applications also found in the wood finishing and automotive industries. Electron-beam curing systems can require much less floor space and operating labor, can improve productivity levels, and can reduce curing time from minutes to a second or less. Electron-beam systems provide environmental benefits because they eliminate solvents, use little energy, and produce less indoor heat.

Electron-beam processing of materials in a high vacuum is used in many industries as a melting technique that does not introduce contamination. It has been used to produce materials ranging from refractory metal alloys to metallic coatings on plastic jewelry. Electron-beam processing allows for super-pure materials, and can impart unique properties to existing products.

Improve the Efficiency of Electron-beam Existing Systems

- Operate under vacuum conditions. When electron-beam processing is performed under vacuum conditions, there is less scattering of the beam, resulting in higher energy efficiency because more of the energy is transferred to the product.
- Improve control systems. Better process control systems, including those with feedback loops, allow systems to use less energy per product produced. Good control systems allow precise application of heat at the proper temperature for the correct amount of time.
- Electron-beam systems require highly engineered designs. The output of electron-beam devices does not diminish as a function of time as in some technologies that have “wearable” components. The operation of such systems is either designed output or zero output due to component failure. Any changes in any of the original design parameters requires analysis of the original design to assure an efficient application of the technology.

For welding, other technologies include arc welders or laser welders. For machining operations, other systems include numerically-controlled machine tools. For melting and heat treating operations, electron furnaces can perform the same operations as electron-beam systems. For curing coatings, ultraviolet systems and curing ovens can perform the same function as electron-beam systems.

Electron-beam systems are easily controlled by computer, and they have low inertia, so the systems can quickly and easily move from point to point. In addition, they can be easily pulsed on and off. They also produce energy in a very small area, and can be used for selective surface hardening.

Induction Heating and Melting

■ History and Status

The principles of induction heating have been applied to manufacturing operations since the 1930s, when the first channel-type induction furnaces were introduced for metals melting operations. Soon afterward, coreless induction furnaces were developed for melting, superheating, and holding. In the 1940s, the technology was also used to harden metal engine parts. More recently, an emphasis on improved quality control has led to increased use of induction technology in the ferrous and nonferrous metals industries.

■ How the Technology Works

Heating and heat treating. In a basic induction heating setup, a solid state power supply sends an alternating current (AC) through a copper coil, and the part to be heated is placed inside the coil. When a metal part is placed within the coil and enters the magnetic field, circulating eddy currents are induced within the part. These currents flow against the electrical resistivity of the metal, generating precise and localized heat without any direct contact between the part and the coil.

Melting. An induction furnace induces an electric current in the material to be melted, creating eddy currents which dissipate energy and produce heat. The current is induced by surrounding the material with a wire coil carrying an electric current. When the material begins to melt, electromagnetic forces agitate and mix it. Mixing and melting rates can be controlled by varying the frequency and power of the current in the wire coil. Coreless furnaces have a refractory crucible surrounded by a water-cooled AC current coil. Coreless induction furnaces are used primarily for remelting in foundry operations and for vacuum refining of specialty metals.

Channel furnaces have a primary coil wound on a core. The secondary side of the core is in the furnace interior, surrounded by a molten metal loop. Channel furnaces are usually holding furnaces for nonferrous metals melting, combined with a fuel-fired cupola, arc, or coreless induction furnace, although they are also used for melting as well.

The efficiency of an induction heating system for a specific application depends on several factors: the characteristics of the part itself, the design of the induction coil, the capacity of the power supply, and the degree of temperature change required for the application.

■ Process, Applications, and Industries

Heating and heat treatings. Induction heating works directly with conductive materials only, typically metals. Plastics and other nonconductive materials often can be heated indirectly by first heating a conductive metal susceptor that transfers heat to the nonconductive material.

With conductive materials, about 80% of the heating effect occurs on the surface or “skin” of the part. The heating intensity diminishes as the distance from the surface increases, so small or thin parts generally heat more quickly than large thick parts, especially if the larger parts need to be heated all the way through.

It is easier to heat magnetic materials with induction

Improve the Efficiency of Existing Induction Systems

Melting

- Use high-efficiency solid state power supplies. High-efficiency units have less heat loss in the power supply itself.
- Improve the refractory. Improving refractory provides better insulation and reduces heat loss. Savings up to 20%.
- Apply short bus bars. Shorter bus bars reduce resistive losses.
- For highly conductive metals such as aluminum, copper alloys, and magnesium, increase the load resistance by coupling the electromagnetic field to the crucible instead of the metal itself.
- Shared power supply. Two melters can share the same power supply by taking advantage of an optimized melting schedule.
- Melting without a cover on the crucible can account for approximately a 30% energy loss.

Heating and Heat Treating

- Use high-efficiency solid state power supplies. High-efficiency units have less heat loss in the power supply itself.
- Adopt a dual-frequency design. 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 nonmagnetic.
- Use flux concentrators. These passive devices channel the induction field to provide a contained pathway for the magnetic fields. Stray magnetic fields are reduced and less power is required to complete the tasks.
- For multi-stage coil designs, any existing open inspection or work access gaps needs to be shielded to reduce heat loss. If an inspection port is needed, a quartz window can be installed.
- Vary coil by product. In many cases, the same coil is used to produce a number of different products. Using coils designed specifically for a product will improve efficiency by up to 50%.

technology. In addition to the heat induced by eddy currents, magnetic materials also produce heat through the hysteresis effect. During the induction heating process, magnetics naturally offer resistance to the rapidly alternating electrical fields, and this causes enough friction to provide a secondary source of heat. This effect ceases to occur at temperatures above the “Curie” point, which is the temperature at which a magnetic material loses its magnetic properties. The relative resistance of magnetic materials is rated on a “permeability” scale of 100 to 500: nonmagnetics have a permeability of 1, while magnetic materials can have a permeability as high as 500.

Induction heating can also be used to heat liquids in vessels and pipelines, primarily in the petrochemical industry. Induction heating involves no contact between the material being heating and the heat source, which is important for some operations. This lack of contact facilitates automation of the manufacturing processes. Other examples include heat treating, curing of coatings, and drying.

Induction heating often is used where repetitive operations are performed. Once an induction system is calibrated for a part, work pieces can be loaded and unloaded automatically. Induction systems are often used in applications where only a small selected part of a work piece needs to be heated. Because induction systems are clean and release no emissions, sometimes a part can be hardened on an assembly line without having to go to a remote heat treating operation.

For heat treating metals in selective areas, technologies such as laser processing can perform the same operation as induction heating.

Melting. For melting operations, induction processing is used primarily in the refining and remelting of metals. Other applications include foundry melting and casting of various metals. Metals that are melted include aluminum, copper, brass, bronze, iron, steel, and zinc. Fuel-based cupolas and other fuel-based metals melting furnaces can perform the same process heating applications as induction melting furnaces.

Laser Processing

History and Status

Laser processing systems started with small laboratory lasers developed in the 1960s. Today, thousands of commercial-scale units are in use by industry for surface hardening, material removal, and welding operations.

How the Technology Works

The word “laser” is an acronym for Light Amplification by the Stimulated Emission of Radiation. Lasers are a source of high-intensity light produced by passing electricity through a lasing medium. Lasing mediums can be gases or solid state. All of a laser's light is of the same wavelength and is in phase, creating a high-energy density.

With laser beam processing, a laser beam is focused with high intensity, which causes a surface to be heated rapidly. Laser heat treating transmits energy to a material's surface to create a hardened layer, caused by metallurgical transformation. After being heated, the material is quenched, or heat sinking from the surrounding area provides rapid self-quenching.

Lasers can be precisely controlled dimensionally and directionally, and can be varied in output and by timeframe. They are best used to harden a specific area instead of an entire part. Because of their controllability, laser hardening is generally an energy-efficient technology. These attributes also make laser processing good for precise material removal.

■ Processes, Applications, and Industries

Except for single-phase stainless steels and certain types of cast iron, most common steels, stainless steels, and cast irons can be surface heat treated (hardened) by laser processing. Each kind of steel has special characteristics that need to be considered. A laser is typically used to harden localized areas subject to high stress, such as crankshafts, gears, and high-wear areas in engine components
Laser processing can also be used for a variety of other applications, including trimming electronic components; cutting fabrics, metal, and composites; and material removal.

For cutting and material removal operations, lasers have capabilities beyond conventional numerically controlled machine tools. In the past, laser processing was generally used for prototypes or small production runs, but now it is increasingly used for metal working applications, such as a new way of stamping. Laser processing can rapidly and accurately cut most materials with little heat-induced distortion.

For welding operations, conventional welders can perform the same operations as laser welding. Laser processing is usually used for applications requiring a narrow weld, such as welding turbine blades onto rotor shafts. Laser processing tends to be faster and has less product distortion compared to conventional welding techniques.

For surface hardening applications, laser processing performs the same process as induction heating and fuel-based furnaces. Laser processes are generally used for applications where selective areas within a given work piece need to be hardened.

Improve the Efficiency of Existing Laser-Processing Systems

- Understand the type of laser used in the process. There are many types of lasers used which have different efficiencies and performance parameters. Each type has its own set of steps to improve efficiency.
- Many lasers cannot be turned off/on quickly enough for a process and therefore must dump the beam into a closed shutter. In this position, heat is generated and must be removed by the cooling system. Improving your laser path layout can reduce closed shutter time.
- Chiller operational efficiency. This is the system component that uses the most energy in a laser process. Better laser efficiency uses less chiller process energy. Maintenance on the chiller can mean energy savings of up to 35%.
- Beam delivery optical losses. Maintain beam optics by assuring cleanliness. Dirty optics reduce power at delivery, generating heat and reducing efficiency by up to 10%
- Laser cavity optical losses. Check mirrors for alignment; misalignment can cause thermal distortion and will degrade performance by up to 20%.

Microwave Processing

■ History and Status

Microwave processing technology development was a result of research on radar systems during World War II. The first industrial use of microwave processing was in the food industry. Although considerable research and development was spent in the 1950s and 1960s to develop other industrial applications, few emerged. Interest in microwaves increased in the 1980s as a way to raise productivity and reduce costs. There are currently many successful applications of microwave processing in a variety of industries, including food, rubber, pharmaceutical, polymers, plastics, and textiles.

How the Technology Works

Microwave refers to the radio-frequency portion of the electromagnetic spectrum between 300 and 300,000 megahertz (MHz). To avoid conflict with communications equipment, several frequency bands have been set aside for industrial microwave processing. Microwaves are used to heat materials that are electrically nonconducting (dielectrics) and composed of polar molecules. Polar molecules have an asymmetric structure and align themselves to an imposed electric field. When the direction of the field is rapidly alternated, the molecules move in synchronization, creating friction and producing heat.

Microwaves are produced by magnetron tubes, which are composed of a rod-shaped cathode surrounded by a cylindrical anode. Electrons flow from the cathode to the anode, creating an electric and magnetic field. The field frequency is a function of the dimension of the slots and cavities in the magnetron. Oscillations in the slots and cavities form microwaves.

A microwave processing system usually comprises four components:

1. **Generator.** The power supply and the magnetron. A magnetron is typically water or air-cooled and is a wearable component.
2. **Applicator.** Wave guides direct microwaves to the product being heated.
3. **Materials Handling System.** System that positions the product under the applicator or exposure area.
4. **Control System.** System that monitors heating and regulates exposure time.

Process, Applications, and Industries

The most widespread use of industrial microwave processing is in the food industry for applications such as heating, tempering (bringing from deep-freeze to just below freezing), drying, and precooking. Other applications include the following:

- Vulcanizing rubber
- Polymerizing resins
- Welding plastics
- Dewaxing molds
- Drying products.

Microwave operations can perform many of the functions of convection ovens, but are typically used where speed and unique heating requirements are dictated. Hybrid systems, in which microwave processing is combined with other process heating systems, are common.

Improve the Efficiency in Existing Microwave Systems

- Frequent visual inspection of the overall system process to include cleanliness of the wave guides and the operating condition of all motors and drives associated with process will reduce system down time.
- Re-evaluate the system. Once a system is installed for a designed application, the efficiency of that system will remain the same until the product parameters change. Any change in the material, e.g. a change in width, depth, or weight will require a re-evaluation of the system in order to maintain system efficiency.
- Replace aging generators. Magnetrons have a serviceable life measured in hours. Replacing them per the vendor's recommendations will keep the system operating at designed efficiency.

  The 50 ohm generators are most prevalent in industrial processes.

Microwaves have a higher power density than radio-frequency waves and usually heat material faster. Radio-frequency processing's lower frequency waves are better for thicker material. For a given application, one technology is usually better than the other.

Plasma Processing (Arc and Nontransferred Arc)

History and Status

Industrial plasma processing systems have been in use for more than 30 years. In the early stages, plasma processing was used for welding, cutting, and surface hardening. Metals heating and melting applications were first commercialized about 20 years ago.

How the Technology Works

Plasma is a state of matter formed when a gas is ionized. Plasma is formed when gas is exposed to a high-intensity electric arc, which brings it up to temperatures as high as 20,000˚F, freeing electrons from their atoms. Plasmas are good conductors of both heat and electricity.

Plasmas can be generated by exposing certain gases to a high-intensity arc maintained by two electrodes, or by rapidly changing electromagnetic fields generated by induction, capacitive, or microwave generators. Power is regulated by levels of arc current and arc voltage.

There are two types of plasma processing: transferred arc and nontransferred arc. In transferred arc processing, an arc forms between the plasma torch and the material to be heated. The torch acts as the cathode, the material as the anode, and an inert gas passing through the arc is the plasma. These systems are used for metals heating and melting. In nontransferred arc processing, both the anode and the cathode are in the torch itself and compressed air is used to extend the arc to the process. The torch heats plasma gas composed of gases like argon or hydrogen, creating extremely high temperatures for chemical reactions or other processes.

Process, Applications, and Industries

Applications include bulk melting of scrap and remelting in refining processes. Plasma processing is common in the titanium industry, as well as in melting high-alloy steels, tungsten, and zirconium. Plasma processing can also be used in the reduction process for sponge iron and smelting reduction of iron ore and scrap.

Other heating applications include disposal of toxic ash, asbestos, and sludge; diamond film production; hydrocarbon cracking; boiler ignition; and surface hardening. Plasma processing is also used for metals fabrications processes, welding, cutting, and spray metal and ceramics coatings. It is also used in the semiconductor industry for water production.

Improve the Efficiency of Existing Plasma Processing Systems

- Replace aging torch electrode. As torches age, they become less efficient.
- Improve control systems. Better process control systems, including those with feedback loops, allow systems to use less energy per product produced. Good control systems allow precise application of heat at the proper temperature for the correct amount of time.
- Perform preventative maintenance on the process gas and cooling systems to maximize electrode life.

For melting metal applications, electric arc furnaces and various types of fuel-based furnaces can perform the same function as plasma processing. Unlike the electric arc, the nontransfer arc plasmas can be used to heat nonconductive materials.

Radio-Frequency Processing

History and Status

The concept of using radio waves to heat material was known in the late 19th century, but industrial applications did not arrive until the 1930s, when techniques for generating high-power radio waves were developed.

How the Technology Works

The radio-frequency portion of the electromagnetic spectrum is between 2 and 100 MHz. Radio-frequency waves can be used to heat materials that are electrically nonconducting (dielectrics) and composed of polar molecules. Polar molecules have an asymmetric structure and align themselves to an imposed electric field. When the direction of the field is rapidly alternated, the molecules move in synchronization, producing heat by creating friction.

Radio-frequency waves are produced by radio frequency generators. These generators are either a controlled frequency oscillator 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.

A radio-frequency processing system usually has five components:

1. **Generator.** The oscillator and an amplifier.
2. **Impedance matching network**. Used only in 50-ohm generators.
3. **Applicator.** Electrodes that expose the radio-frequency electric field to the product being heated.
4. **Material handling system.** The part of the system that positions the product under the applicator or exposure area.
5. **Control system**. This monitors heating and regulates exposure time.

Process, Applications, and Industries

The most widespread use of industrial radio-frequency processing is in the production of plasmas for semiconductor processing and in drying products in the food, lumber, and paper industries. Other applications include drying yarn and film, curing glue, heating plastics, baking, drying ceramic products, and sterilizing medical waste.

Convection ovens can perform the same heating processes as radio-frequency ovens. Radio-frequency processing is generally used because of increased production needs, increased energy efficiency, labor savings, or space savings. In some cases, hybrid systems have both radio-frequency processing and a convection oven.

Microwave processing systems have higher power density than radio-frequency waves and usually heat material faster. Radio-frequency processing's lower frequency waves are better for thicker material. For a given application, one technology is usually better than the other.

Improve the Efficiency of Existing Radio-Frequency Systems

- Verify that the correct frequency is being used. The amount of heat generated is a function not only of the output of the power supply, but also the frequency of the field.
- Use programmable logic controller to optimize your process. Good control systems allow for precise application of heat at the proper temperature for the correct amount of time.
- Consider a hybrid radio-frequency/convection heating system. The efficiency of a convection dryer drops significantly as the moisture level in the material decreases. At this point, radio frequency is more efficient at removing the moisture.

Resistance Heating and Melting

History and Status

Resistance heating is the simplest and oldest electric-based method of heating and melting metals and nonmetals. Efficiency can reach close to 100% and temperatures can exceed 3,600ºF. With its controllability, and rapid heat-up qualities, resistance heating is used in many applications from melting metals to heating food products. Resistance heating can be used for both high-temperature and low-temperature applications.

How the Technology Works

There are two basic types of this technology: direct and indirect resistance heating.

Direct resistance. With direct resistance (also known as conduction heating), an electric current flows through a material and heats it directly. This is an example of the Joule Law or effect[5] at work. Typically, metal is clamped to electrodes in the walls of the furnace and charged with electric current. Electric resistance within the load generates heat, which heats or melts the metal. The temperature is controlled by adjusting the current, which can be either alternating current or direct current.

The material to be heated must conduct at least a portion of the electric current for direct resistance to work. Metals with low conductivity, such as steel, create more resistance and more heat, which makes the process more efficient. Direct resistance heating is used primarily for heat treating, forging, extruding, wire making, seam welding, glass heating, and other applications. Direct resistance heating is often used to raise the temperature of steel pieces prior to forging, rolling, or drawing applications.

Indirect resistance. With indirect resistance heating, a heating element transfers heat to the material by radiation, convection, or conduction. The element is made of a high-resistance material such as graphite, silicon carbide, or nickel chrome. Heating is usually done in a furnace, with a lining and interior that varies depending on the target material. Typical furnace linings are ceramic, brick, and fiber batting, while furnace interiors can be air, inert gas, or a vacuum.

Indirect resistance heating can also be done with an encased heater, in which the resistive element is encased in an insulator. The heater is placed in liquid that needs to be heated or close to a solid that requires heating. Numerous other types of resistance heating equipment are used throughout industry, including strip heaters, cartridge heaters, and tubular heaters.

[5] When electricity flows through a substance, the rate of evolution of heat in watts equals the resistance of the substance in ohms times the square of the current in amperes.

Resistance heaters that rely on convection as the primary heat transfer method are primarily used for temperatures below 1,250˚F. Those that employ radiation are used for higher temperatures, sometimes in vacuum furnaces.

Indirect resistance furnaces are made in a variety of materials and configurations. Some are small enough to fit on a counter top, and others are as large as a freight car. This method of heating can be used in a wide range of applications.

Improve the Efficiency of Existing Resistance Heating Systems

- Improve control systems. Better process control systems, including those with feedback loops, use less energy per product produced. Good control systems allow precise application of heat at the proper temperature for the correct amount of time.
- Clean heating elements. Clean resistive heating elements can improve heat transfer and process efficiency.
- Improve insulation. For systems with insulation, improvements in the heat containment system can reduce energy losses to the surroundings.
- Match the heating element more closely to the geometry of the part being heated.

■ Process, Applications, and Industries

Direct resistance heating is used extensively in the glass industry. Resistance furnaces are also used for holding molten iron and aluminum. Direct resistance processing is also used for welding steel tubes and pipes.

Indirect resistance heaters are used for a variety of applications, including heating water, sintering ceramics, heat pressing fabrics, brazing and preheating metal for forging, stress relieving, and sintering. This method is also used to heat liquids, including water, paraffin, acids, and caustic solutions. Applications in the food industry are also common, including keeping oils, fats, and other food products at the proper temperature. Heating is typically done with immersion heaters, circulation heaters, or band heaters. In the glassmaking industry, indirect resistance provides a means of temperature control. Many hybrid applications also exist, including “boosting” in fuel-fired furnaces to increase production capacity.

Resistance heating applications are precisely controlled, easily automated, and have low maintenance. Because resistance heating is used for so many different types of applications, there are a wide variety of fuel-based process heating systems, as well as steam-based systems, that perform the same operations. In many cases, resistance heating is chosen because of its simplicity and efficiency.

Ultraviolet Processing

■ History and Status

Ultraviolet (UV) processing has been used for many years to cure various types of industrial coatings and adhesives, as well as for curing operations in printing and electronic parts applications.

■ How the Technology Works

UV radiation is the part of the electromagnetic spectrum with a wavelength from 4 to 400 nanometers. Applying UV radiation to certain liquid polymeric substances transforms (cures) them into a solid coating. Curing is the process of bonding or fusing a coating to a substrate and developing specified properties in the coating. Curing involves a change in the molecular structure of the coating to form a solid. Curing is different than drying in which coating materials are suspended in a solvent and remain on a surface when the solvent evaporates.

UV radiation is created using a UV lamp, typically a mercury vapor lamp or xenon gas arc. The most common UV system is a medium-pressure mercury lamp. A high-voltage discharge ionizes a mercury gas-filled tube, creating UV radiation. The discharge can be created by an arc between two electrodes by microwave radiation, or by solid state light emitting diode devices. The lamp is housed in an enclosure with a reflector, with air or water cooling to prolong lamp life.

■ Process, Applications, and Industries

The four main applications for UV curing are coatings, printing, adhesives, and electronic parts.

Coatings. Common industrial coatings cured with UV radiation include those applied to wood, metals, paper, plastics, vinyl flooring, and wires. The coating can be a liquid or a powder, with both having similar characteristics.

Printing. Lithographic, silk screen, and flexographic printing operations can use UV curable inks instead of solvent-based, thermally cured inks.

Adhesives. Adhesive materials processed with UV radiation are common in the structural and packaging markets.

Electronic parts. UV processing is used throughout the electronics and communications parts manufacturing industry to cure polymeric materials, especially with printed circuit board lithography.

UV processing is also used in the wastewater industry to treat water and to purify indoor air. Convection and radiant systems can perform the same curing processes as UV-based systems. However, UV-based systems typically have more rapid curing speeds, produce fewer emissions, and can cure heat-sensitive substrates. The cross linking of molecules requires minimal or no solvents as part of the coating. These systems require special UV-curable coatings and generally a custom-made lamp system for a particular application. UV curing takes about 25% of the energy required by a thermal-based system using a fuel-fired oven. They can increase output because of the nearly instantaneous curing time. Although UV coatings are more expensive on a cost-per-gallon basis, they do not require costly thermal oxidizers to destroy VOCs emitted by solvent-based coatings. In addition, there is no reduction in the cured coating thickness versus applied coating thickness.

Improve the Efficiency of Existing UV Systems

- Keep lamps clean. Lamps should be cleaned on a regular schedule. A clean lamp surface not only provides unrestricted output of the UV wavelength but more importantly prevents devitrification, or breakdown of the quartz envelope, which would cause premature lamp failure.
- Keep reflectors clean. Dull and corroded reflectors can reduce UV output by up to 50%. Also check for dented or distorted reflectors which can change the focus point and the performance of the UV emitter.
- Visually inspect all components of the system. The cooling and exhaust systems must be properly maintained to prevent overheating and premature failure of the lamps and other system components. Actions such as cleaning cooling fan filters per manufacturer's recommendations should be performed.
- Monitor the hours of operation. Under normal operating conditions, UV lamps have an expected serviceable life measured in hours. Going beyond the recommended hours will result in a drop-off of UV output.

Best Practices Process Heating Tips

The U.S. Department of Energy's Industrial Technologies Program (ITP) has developed this series of tip sheets through its Best Practices program.

1. Preheated Combustion Air (recovery)
2. Check Burner Air to Fuel Ratios (generation)
3. Oxygen-Enriched Combustion (recovery)
4. Check Heat Transfer Surfaces (transfer)
5. Reduce Air Infiltration in Furnaces (containment)
6. Furnace Pressure Controllers (generation)
7. Reduce Radiation Losses from Heating Equipment (containment)
8. Install Waste Heat Recovery Systems for Fuel-Fired Furnaces (recovery)
9. Load Preheating Using Flue Gases from a Fuel-Fired Heating System (recovery)
10. Using Waste Heat for External Processes (recovery)
11. Use Lower Flammable Limit Monitoring Equipment to Improve Oven Efficiency

Preheated Combustion Air

For fuel-fired industrial heating processes, one of the most potent ways to improve efficiency and productivity is to preheat the combustion air going to the burners. The source of this heat energy is the exhaust gas stream, which leaves the process at elevated temperatures. A heat exchanger, placed in the exhaust stack or ductwork, can extract a large portion of the thermal energy in the flue gases and transfer it to the incoming combustion air. Recycling heat this way will reduce the amount of the purchased fuel needed by the furnace.

Many processes produce dirty or corrosive exhaust gases that will plug or attack heat exchangers. Some exchangers are more resistant to these conditions than others, so if your process is not a clean one, do not give up without investigating all the options. When discussing it with potential vendors, be sure to have a detailed analysis of the troublesome materials in your exhaust gas stream.

Fuel savings for different furnace exhaust gas temperature and preheated combustion air temperature can be found in the table below and can be used to estimate reductions in energy costs.

Percent Fuel Savings Gained from Using Preheated Combustion Air

Furnance Exhaust Temperature, ˚F	Preheated Air Temperature, ˚F					
	600	800	1,000	1,200	1,400	1,600
1,000	13	18	–	–	–	–
1,200	14	19	23	–	–	–
1,400	15	20	24	28	–	–
1,600	17	22	26	30	34	–
1,800	18	24	28	33	37	40
2,000	20	26	31	35	39	43
2,200	23	29	34	39	43	47
2,400	26	32	38	43	47	51

Fuel: Natural gas at 10% excess air Source: IHEA Combustion Technology Manual (see references)

There are two types of air preheaters: recuperators and regenerators. Recuperators are gas-to-gas heat exchangers placed on the furnace stack. Internal tubes or plates transfer heat from the outgoing exhaust gas to the incoming combustion air while keeping the two streams from mixing. Recuperators are available in a wide variety of styles, flow capacities, and temperature ranges. Regenerators include two or more separate heat storage sections, each referred to as a regenerator. Flue gases and combustion air take turns flowing through each regenerator, alternately heating the storage medium and then withdrawing heat from it. For uninterrupted operation, at least two regenerators and their associated burners are required: one regenerator is needed to fire the furnace while the other is recharging.

Payback Guidelines

Process temperature is customarily used as a rough indication of where air preheating will be cost effective. Processes operating above 1,600˚F are generally good candidates, while preheated air is difficult to justify on processes operating below 1,000˚F. Those in the 1,000˚ to 1,600˚F range may still be good candidates but must be evaluated on a case-by-case basis.

These guidelines are not ironclad. Financial justification is based on energy (or Btu) saved, rather than on temperature differential. If a low temperature process has a high enough exhaust gas flow, energy savings may still exist, even though the exhaust gas temperature is lower than 1,000˚F.

References

1. *Combustion Technology Manual.* Published by Industrial Heating Equipment Association (IHEA), Arlington, Virginia.
2. *Maintenance and Adjustment Manual for Natural Gas and No. 2 Fuel Oil Burners.* Technical Information Center, U.S. Department of Energy.
3. *Handbook of Applied Thermal Design,* edited by Eric C. Guyer. Published by McGraw Hill Book Company.

Payback Period = (Cost of combustion air preheating system, obtained from the supplier or contractor) + (Reduction in fuel usage, Million Btu/hr x Number of operating hours per year x Cost of fuel per Million Btu)

Example

A furnace operates at 1,600˚F for 8,000 hours per year at an average of 10 million British thermal units (MMBtu) per hour using ambient temperature combustion air. At $9 per MMBtu, annual energy cost is $720,000. Use of preheated air at 800˚F will result in 22% fuel savings, or $158,400 annually. The preheated air system installation is estimated to cost $200,000 to $250,000, with a simple payback period of 15 to 19 months.

Suggested Actions

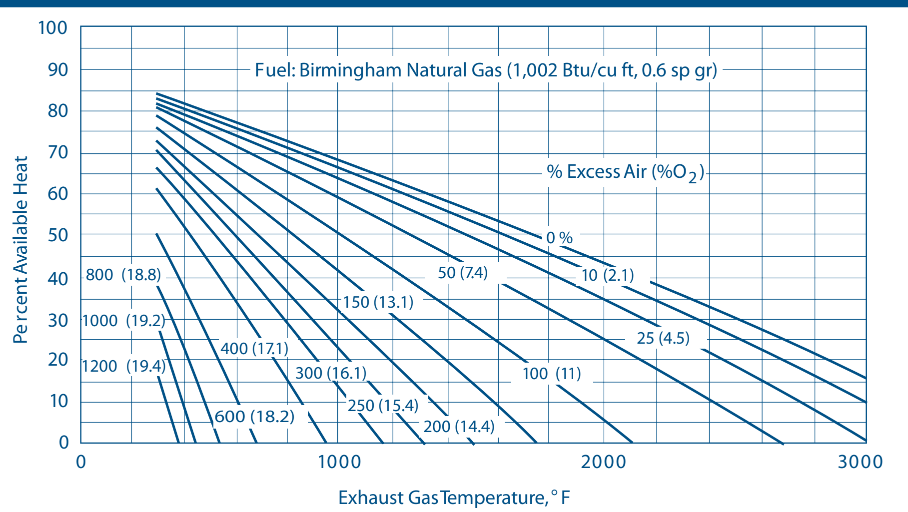
- **Using current or projected energy costs, estimate preheated air savings with this example or the Process Heating Assessment and Survey Tool (PHAST) available from the U.S. Department of Energy's Industrial Technologies Program.**
- **Contact furnace or combustion system suppliers to calculate payback period or ROI.**

Check Burner Air to Fuel Ratios

Periodic checking and resetting of air-fuel ratios for burners is one of the simplest ways to get maximum efficiency out of fuel-fired process heating equipment such as furnaces, ovens, heaters, and boilers. Most high temperature direct-fired furnaces, radiant tubes, and boilers operate with about 10% to 20% excess combustion air at high fire to prevent the formation of dangerous carbon monoxide and soot deposits on heat transfer surfaces and inside radiant tubes. For the fuels most commonly used by U.S. industry, including natural gas, propane, and fuel oils, approximately one cubic foot of air is required to release about 100 British thermal units (Btu) in complete combustion. Exact amount of air required for complete combustion of commonly used fuels can be obtained from the information given in one of the references. Process heating efficiency is reduced considerably if the combustion air supply is significantly higher or lower than the theoretically required air.

Air-gas ratios can be determined by flow metering of air and fuel or flue gas analysis. Sometimes, a combination of the two works best. Use the Available Heat Chart below to estimate the savings obtainable by tuning burner air-gas ratios. The excess air curves are labeled with corresponding oxygen percentages in flue gases.

Available Heat Chart



Source: Calculations by Mr. Richard Bennett, published in *Process Heating* magazine, September 1997.

To figure potential savings, you need to know:

- The temperature of the products of combustion as they leave the furnace
- The percentage of excess air or oxygen in flue gases, at which the furnace now operates
- The percentage of excess air or oxygen in flue gases, at which the furnace could operate.

Factors Affecting Excess Air Level Requirements

Combustion systems operate with different amounts of excess air between high and low fire. Measurement of oxygen and combustibles such as carbon monoxide in flue gases can be used to monitor changes in excess air levels. For most systems, 2% to 3% of oxygen with a small amount of combustibles—only 10 to 50 parts per million—indicate ideal operating conditions.

Processes that evaporate moisture or solvents need large amounts of excess air to dilute flammable solvents to noncombustible levels, to ensure adequate drying rates, and to carry vapors out of the oven. Lowering excess air to minimal levels can slow down the process and create an explosion hazard.

References

Combustion Technology Manual. Published by Industrial Heating Equipment Association (IHEA), Arlington, Virginia 22209.

Maintenance and Adjustment Manual for Natural Gas and No. 2 Fuel Oil Burners. Technical Information Center, Department of Energy.

Handbook of Applied Thermal Design, edited by Eric C. Guyer.Published by McGraw Hill Book Company.

On the chart, determine the available heat under present and desired conditions by reading up from the flue gas temperature to the curve representing the excess air or O_2 level; then, read left to the percentage available heat (AH). Calculate the potential fuel savings:

% Fuel Savings = 100 X ((%AH Desired - %AH Actual) / %AH Desired)

Example

A furnace operates at 2,400°F flue gas temperature. The optimum ratio is 10% excess air (2.1% O_2 in flue gases), but tests show an actual ratio of 25% excess air (4.5% O_2 in flue gases). The chart shows an actual available heat of 22% compared to an ideal of 29%.

Fuel Savings = 100 X ((29 – 22) / 29) = 24%

Note: The graph on the front page is for combustion air at ambient temperature (about 60ºF) using natural gas with specific gas composition. The exact numbers may vary slightly if the natural gas composition is different from the one used for this graph. The available heat will also be different if the combustion air temperature is different. Use the Process Heating Assessment and Survey Tool (PHAST) or other methods to estimate fuel savings if your operating conditions are significantly different from the conditions stated above.

Suggested Actions

To get the most efficient performance out of fuel-fired furnaces, ovens, and boilers:

1. Determine the best level of excess air for operating your equipment.

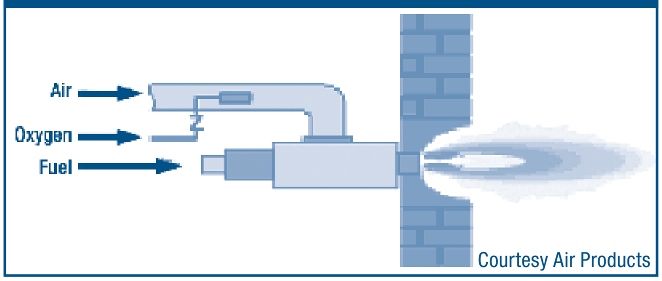
2. Set your combustion ratio controls for that amount of excess air.

3. Check and adjust ratio settings regularly.

Oxygen-Enriched Combustion

When a fuel is burned, oxygen in the combustion air chemically combines with the hydrogen and carbon in the fuel to form water and carbon dioxide, releasing heat in the process. Air is made up of 21% oxygen, 78% nitrogen, and 1% other gases. During air–fuel combustion, the chemically inert nitrogen in the air dilutes the reactive oxygen and carries away some of the energy in the hot combustion exhaust gas. An increase in oxygen in the combustion air can reduce the energy loss in the exhaust gases and increase heating system efficiency.

Figure 1. Oxygen-enriched burner



Most industrial furnaces that use oxygen or oxygen-enriched air use either liquid oxygen to increase the oxygen concentration in the combustion air or vacuum pressure swing adsorption units to remove some of the nitrogen and increase the oxygen content. Some systems use almost 100% oxygen in the main combustion header; others blend in oxygen to increase the oxygen in the incoming combustion air (see Figure 1). Some systems use auxiliary oxy-fuel burners in conjunction with standard burners. Other systems use staged combustion and vary the oxygen concentration during different stages of combustion. Still others "lance" oxygen by strategically injecting it beside, beneath, or through the air–fuel flame.

Benefits

Oxygen-enriched combustion can:

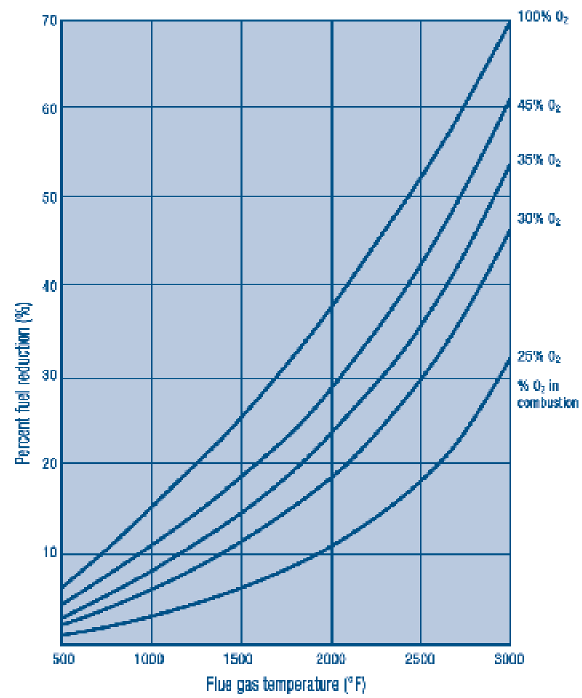
- **Increase efficiency.** The flue gas heat losses are reduced because the flue gas mass decreases as it leaves the furnace. There is less nitrogen to carry heat from the furnace.
- **Lower emissions.** Certain burners and oxy-fuel fired systems can achieve lower levels of nitrogen oxide, carbon monoxide, and hydrocarbons.
- **Improve temperature stability and heat transfer.** Increasing the oxygen content allows more stable combustion and higher combustion temperatures that can lead to better heat transfer.
- **Increase productivity.** When a furnace has been converted to be oxygen enriched, throughput can be increased for the same fuel input because of higher flame temperature, increased heat transfer to the load, and reduced flue gas.

Suggested Actions

- Use current or projected energy costs with PHAST to estimate energy savings from oxygen-enriched combustion.
- Contact furnace or combustion system suppliers to calculate payback or return on investment.
- Include the cost of oxygen or of the vacuum pressure swing adsorption unit in the calculations.

Using oxygen-enriched combustion for specific applications may improve efficiency, depending on the exhaust gas temperature and percentage of oxygen in the combus-tion air. Figure 2 can be used to calculate energy savings for commonly used process heating applications. The Process Heating Assessment and Survey Tool (PHAST) can also be used to estimate the amount of energy that can be saved by switching to oxygen-enriched combustion.

Figure 2. Energy savings from oxygen injection



Conversion to oxygen-enriched combustion is followed by an increase in furnace temperature and a simultaneous decrease in furnace gas flow around the product. Unless there is a sufficient increase in the heat transfer to product, the flue gas temperature will rise above the pre-conversion level and little or no energy will be saved. In radiant heat-governed furnaces, the conversion could increase the radiant heat transfer substantially.

Consequently, the flue gas temperature could drop to or below the pre-conversion level. In convective heat-governed furnaces, the furnace gas velocity may drop because the convective heat transfer coefficient may decrease in a larger proportion than the increase in gas temperature. If this happens, the conversion would do little to increase the overall heat transfer, so reducing flue gas temperature to pre-conversion level may not be possible.

Potential Applications

Oxygen-enhanced combustion is used primarily in the glass-melting industry, but other potential applications can be found in Table 1.

Table 1. Potential Applications for Oxygen- Enhanced Combustion

Industry	Applications
Steel	Reheat, soaking pits, ladles
Aluminum	Melting
Copper	Smelting and melting
Glass	Melting
Pulp and Paper	Lime kilns, black liquor boilers
Petroleum	Process heaters, crackers
Power Production	Coal-fired steam boilers
Chemical	Sulfur

Sample Applications

Theoretical — A potential application is a PHAST analysis of a forging furnace where the flue gas temperature is 2,100°F and 95% of the combustion air is oxygen. This shows a 42% fuel saving over a conventional system.

Actual — The U.S. Department of Energy **(**DOE) sponsored a performance study (www.eere.energy.gov/industry/glass/pdfs/oxy_fuel.pdf) in which a glass melter was converted to 100% oxygen-enriched combustion. The plant was a 70 ton-per-day end-fired melter. Natural gas consumption was lowered by 10% to 20% and nitrogen oxide emissions were reduced by 90%.

Check Heat Transfer Surfaces

Industrial process heating systems use various methods to transfer heat to the load. These include direct heat transfer from the flame or heated gases to the load and indirect heat transfer from radiant tubes, muffles, or heat exchangers. Indirect heating systems that use fuel firing, steam, or hot liquids to supply heat are discussed in this tip sheet. In each case, clean heat transfer surfaces can improve system efficiency. Deposits of soot, scale or oxides, sludge, and slag on the heat transfer surfaces should be avoided.

Contamination from Flue Gas and Heating Medium

Figure 1. Example of a poorly maintained heat exchanger from an aluminum melting furnace

Problem areas from flue gas include soot, scale or oxides, sludge, and slag. Soot is a black substance formed by combustion that adheres to heat transfer surfaces. Scale or oxide is formed when metals are oxidized in the presence of oxygen, water vapor, or other oxidizing gases. Sludge is residue from a liquid–solid mixture after the liquid evaporates. Slag is the residue formed by oxidation at the surface of molten metals, which can also adhere to heat transfer surfaces. These contaminants impede the efficient transfer of heat and reduce the efficiency of industrial heating systems.

Problem areas for indirectly heated systems where heating media such as air, steam, or hot liquids are used include scale, dirt, oxide film, or fouling on the heat transfer surfaces that are in contact with the heating medium.

Contamination of heat transfer surfaces is typically the result of:

- Low air:fuel ratios
- Improper fuel preparation
- Malfunctioning burners
- Oxidation of heat transfer surfaces in high temperature applications
- Corrosive gases or constituents in the heating medium
- Stagnant or low-velocity areas in contact with heat transfer surfaces for hot liquid or gas heating systems
- Special atmospheres (such as in heat treating furnaces) that can produce soot during the heating process.

Suggested Actions—Flue Gases

- Examine your flue-side heat transfer surfaces for deposits.
- Clean heat transfer surfaces periodically.
- Use a soot blower to automatically clean heat transfer surfaces.
- Use a soot burn-out practice for radiant tubes or muffles used in high temperature furnaces.
- Use continuous agitation or other methods to prevent materials from accumulating on the heat transfer surfaces.

Suggested Actions—Water Supplies

- Examine your water-side heat transfer surfaces for scale and remove the deposits.
- If scale is present, consult with your local water treatment specialist and consider modifying your chemical additives.

As shown in Table 1, a 1/32-inch thick layer of soot can reduce heat transfer by about 2.5%.

Table 1. Efficiency Reductions Caused by Soot Deposits*

Soot Layer Thickness		
1/32 inch	**1/16 inch**	**1/8 inch**
2.5%	4.5%	8.5%

*Extracted from the Application Note – Energy Efficiency Operations and Maintenance Strategies for Industrial Gas Boilers, Pacific Gas and Electric Company, May 1997.

Contamination from flue gas can also shorten equipment life and lead to unscheduled maintenance. The extent to which dirty heat transfer surfaces affect efficiency can be estimated from an increase in stack temperature relative to a "clean operation" or baseline condition. Efficiency is reduced by approximately 1% for every 40°F increase in stack temperature.

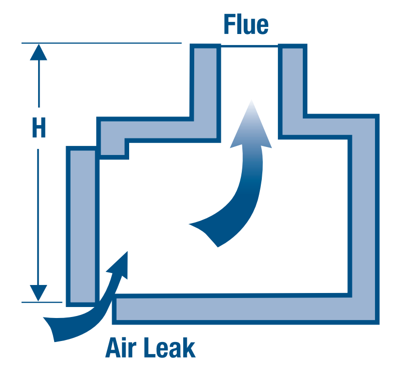
Contamination from Water Supplies

Scale is formed from deposits of calcium, magnesium, or silica from the water supply. Problems occur when these minerals form a continuous layer of material on the water side of heat transfer surfaces; surfaces with scale deposits have much lower thermal conductivity than bare metal. Efficiency losses from scale deposits can range from 1% to 7%. Scale deposits can also lead to decreased heat transfer equipment life, especially because of corrosion. Most scale problems are caused by inadequate water treatment. Scale can be removed mechanically (by manual brushing) or with acid cleaning.

Reduce Air Infiltration in Furnaces

Fuel-fired furnaces discharge combustion products through a stack or a chimney. Hot furnace gases are less dense and more buoyant than ambient air, so they rise, creating a differential pressure between the top and the bottom of the furnace. This differential, known as *thermal head*, is the source of a natural draft or negative pressure in furnaces and boilers.

Figure 1. Air leakage and gas flow in a typical fuel-fired furnace



A well-designed furnace (or boiler) is built to avoid air leakage into the furnace or leakage of flue gases from the furnace to the ambient. However, with time, most furnaces develop cracks or openings around doors, joints, and hearth seals. These openings (leaks) usually appear small compared with the overall dimensions of the furnace, so they are often ignored. The negative pressure created by the natural draft (or use of an induced-draft fan) in a furnace draws cold air through the openings (leaks) and into the furnace. The cold air becomes heated to the furnace exhaust gas temperature and then exits through the flue system, wasting valuable fuel. It might also cause excessive oxidation of metals or other materials in the furnaces.

The heat loss due to cold air leakage resulting from the natural draft can be estimated if you know four major parameters:

- The furnace or flue gas temperature
- The vertical distance H between the opening (leak) and the point where the exhaust gases leave the furnace and its flue system (if the leak is along a vertical surface, H will be an average value)
- The area of the leak, in square inches
- The amount of operating time the furnace spends at negative pressure.

Secondary parameters that affect the amount of air leakage include these:

- The furnace firing rate
- The flue gas velocity through the stack or the stack cross-section area
- The burner operating conditions (e.g., excess air, combustion air temperature, and so on).

Suggested Actions

Taking the following actions can reduce air leakage in a furnace:

1. Repair the air leakage area by replacing or repairing insulation or seals.
2. Close furnace doors properly to maintain a tight seal and avoid opening.
3. Install a pressure control system that maintains balanced, slightly positive (in hundredths of an inch) pressure, at the point of major air leakage.
4. Install a damper in the stack that can be adjusted manually if an automated furnace pressure control cannot be used or justified.
5. Install or use a "draft gage" to monitor furnace pressure at the level of air leakage if it cannot be sealed properly, and adjust the manual damper to maintain balanced, slightly positive (in hundredths of an inch) pressure, at the point of major air leakage.

Note: Actions 3-5 work only in forced and balanced draft furnaces.

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For furnaces or boilers using an induced-draft (ID) fan, the furnace negative pressure depends on the fan performance and frictional losses between the fan inlet and the point of air leakage. In most cases, it would be necessary to measure or estimate negative pressure at the opening.

The amount of air leakage, the heat lost in flue gases, and their effects on increased furnace or boiler fuel consumption can be calculated by using the equations and graphs given in *Industrial Furnaces* (see W. Trinks et al., below). Note that the actual heat input required to compensate for the heat loss in flue gases due to air leakage would be greater than the heat contained in the air leakage because of the effect of available heat in the furnace. For a high-temperature furnace that is not maintained properly, the fuel consumption increase due to air leakage can be as high as 10% of the fuel input.

Example

An industrial forging furnace with an 8-foot (ft) stack operates at 2,300°F for 6,000 hours per year (hr/yr) on natural gas costing $8.00/ MMBtu. The door of the furnace has an unnecessary 36-square-inch (in.^{2}) opening at the bottom that allows air to infiltrate. The table to the right shows the annual cost of the fuel that would be wasted because of the leak.

Cost of Air Infiltration in a Furnace	
Stack height (ft)	8
Stack diameter (ft)	3
Opening size, area (in.^{2})	36
Gross input (MMBtu/hr)	20
Combustion air temperature (°F)	70
Oxygen in flue gases (%)	2
Temperature of flue gases (°F)	2,300
Fuel cost ($/MMBtu)	8
Operating hr/yr	6,000
Air infiltration (ft^3/hr)	15,300
Annual cost of wasted fuel ($)	100,875

Furnace Pressure Controllers

Furnace pressures fluctuate with the burner firing rate and tend to be lowest at the lowest firing rates. To compensate for this constantly changing condition, a furnace pressure control system is used. It consists of a stack damper automatically controlled to maintain a neutral or slightly positive pressure in the combustion chamber. As burner firing rates decrease, the damper throttles the flow out of the stack to hold the pressure constant. Many different types of pressure controllers are available for use with furnaces and boilers. See the tip sheet titled *Furnace Pressure Controllers* for more information.

References

Fan Engineering. Robert Jorgensen, ed. New York: Buffalo Forge Company. 1961.

Gas Engineers Handbook. George C. Segeler, ed. New York: The Industrial Press. 1968.

W. Trinks et al. *Industrial Furnaces, Sixth Edition*. New York: John Wiley & Sons, Inc. 2003.

Furnace Pressure Controllers

Furnace draft, or negative pressure, is created in fuel-fired furnaces when high temperature gases are discharged at a level higher than the furnace openings. This is commonly known as the *chimney effect*. The negative pressure in a furnace that operates at a fixed temperature changes with the heat input rate or mass flow of flue gases moving through the stack. This negative pressure causes ambient air to leak into the furnace.

Figure 1. Air infiltration from furnace draft

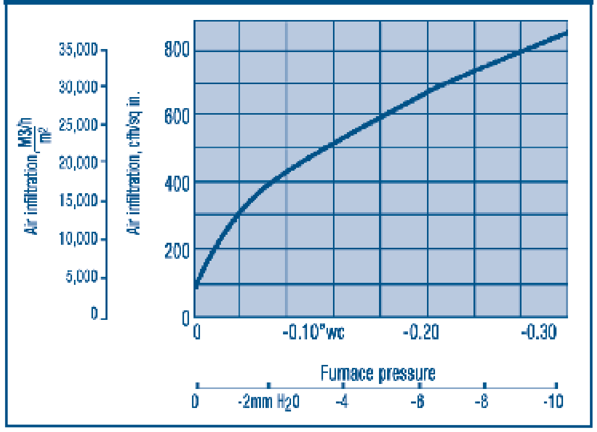
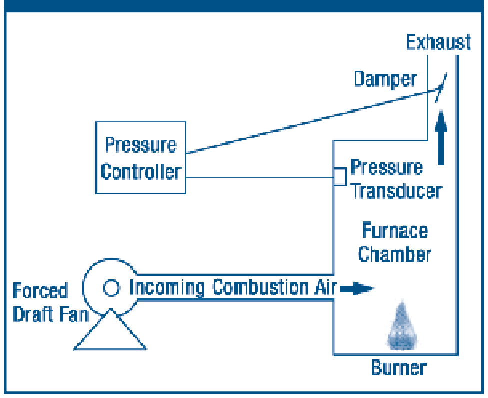


Figure 1 shows rates of air infiltration resulting from furnace draft. This air has to be heated to the flue gas temperature before it leaves the furnace through the stack, which wastes energy and reduces efficiency. The air infiltration can be minimized by reducing or eliminating openings and areas of possible air leaks and by controlling pressure in the furnace. Examples of openings include leakage around burner mountings, seals around heater or radiant tubes, doors that are opened and closed frequently, and observation ports.

Furnace pressure controllers regulate and stabilize the pressure in the working chamber of process heating equipment. Pressure controllers use a pressure gauge in the furnace chamber or duct and regulate the airflow to maintain a slightly positive pressure (a few inches of water gauge) in the furnace chamber (see Figure 2). Airflow can be regulated by varying the speed of draft fans or by changing damper settings for the incoming combustion air or the exiting flue gas.

Figure 2. Furnace pressure controller



Suggested Actions

- Work with process heating specialists to estimate energy savings from using precise furnace pressure control.
- Contact furnace or combustion system suppliers to obtain cost estimates so you can calculate payback or return on investment.

Pressure controllers can be manual or automatic. An equipment operator typically uses a dial on a control panel to set the pressure in a manual system. An automatic system has a feedback loop and continuously monitors and regulates the pressure through an electronic control system. A barometric damper is an inexpensive option for a natural draft furnace or oven.

Four types of draft systems are used in industrial furnaces:

- **Natural.** Uses the chimney effect. Gases inside the stack are less dense and will rise, creating a vacuum that draws air into the furnace.
- **Induced.** A fan draws air from the furnace to the stack.
- **Forced.** A fan pushes air into the furnace.
- **Balanced.** Uses an induced and a forced draft fan.

Furnace pressure controllers can work with any of these systems. Properly sized stack diameters and dampers (or fan speed control) must be used to control furnace pressure for the entire range of furnace operation or firing rates. For safety reasons, controlled atmosphere furnaces require positive pressure and special pressure controllers; furnaces and ovens with volatile vapors (from operations like paint drying) require slightly negative pressure.

Benefits

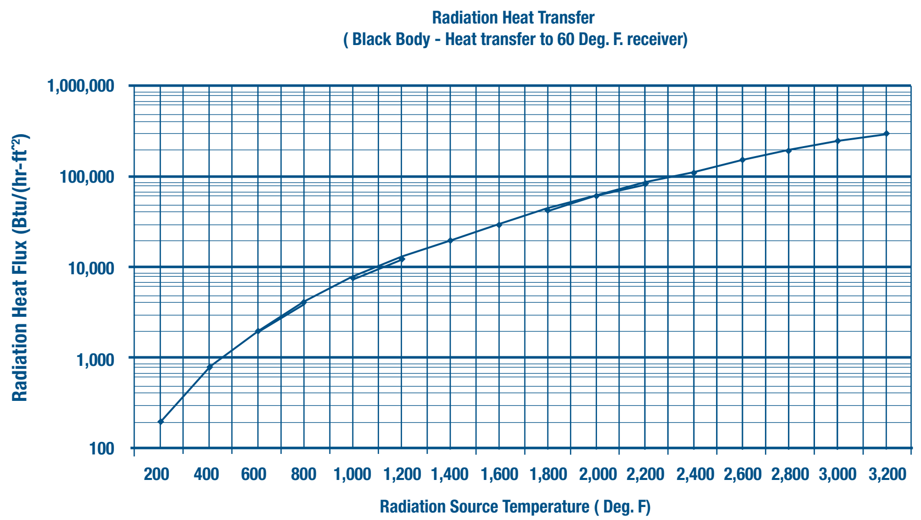
Maintaining slightly positive furnace pressure can have many benefits, including:

- **Energy savings.** Positive pressure eliminates cold air infiltration, which reduces fuel consumption.
- **Improved product quality.** Process heating equipment with regulated pressure control will help maintain a more uniform temperature in the furnaces and avoid cold and hot spots, which can improve product quality. For heat treating applications, positive furnace pressure can reduce oxidation, and for processes like carburizing, create a more stable atmosphere for the diffusion process.
- **Maintenance savings.** Pressure control prevents excessive fluing through cracks and doors in process heating equipment, which can minimize corrosion and crack enlargement.
- **Emissions Reductions.** Improved combustion control can reduce emissions.

Reduce Radiation Losses from Heating Equipment

Heating equipment, such as furnaces and ovens, can experience significant radiation losses when operating at temperatures above 1,000°F. Hot surfaces radiate energy to colder surfaces in their line of sight, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. Figure 1 shows radiation heat flux from a heat source at a given temperature to 60°F ambient.

Figure 1. Radiation heat transfer rates[1]



The biggest radiant energy loss in furnace operations is caused by doors remaining open longer than necessary, or doors left partially open to accommodate a load that is too large for the furnace. Furnace openings not only waste energy through radiation losses, they also allow ambient air to enter the furnace or hot furnace gases to escape if the furnace pressure is not controlled (see the tip sheets titled *Reduce Air Infiltration in Furnaces*; *Furnace Pressure Controllers*).

Radiation losses are a function of three factors:

- The temperature of the internal furnace surfaces facing the opening.
- The effective area of the opening that the radiation passes through. This is the true opening size corrected for both the thickness of the wall surrounding it and for its height/width ratio. The thicker the wall and the higher the opening's aspect ratio (longer dimension divided by shorter dimension), the smaller its effective area. Figure 2 can be used in calculating effective area for openings in a furnace wall. These graphs give results that are within 5% of the results of using detailed view-factor calculations.
- The length of time the opening permits radiation to escape.

Suggested Actions

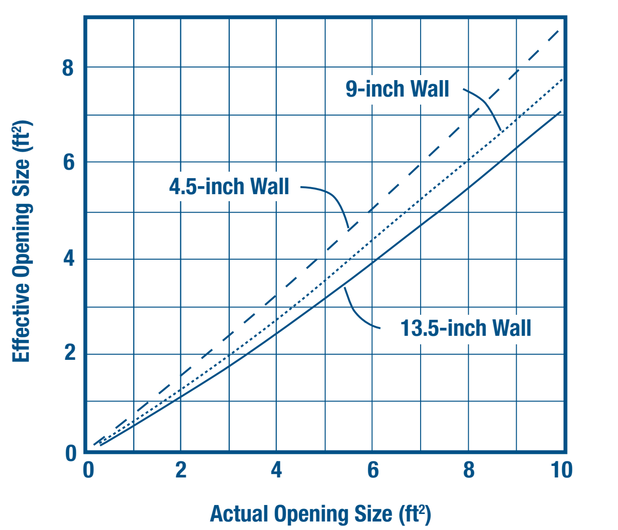
The following actions can prevent or reduce radiations losses:

- Eliminate the furnace opening or keep the furnace door open the shortest possible time.
- For a continuous furnace in which opening size cannot be reduced, you can use flexible materials such as ceramic strips, chains, or ceramic textiles as "curtains." These generally reduce heat loss by half and help reduce infiltration of air into the furnace and leakage of hot furnace gases into the atmosphere. Tunnel-like extensions on the end of the furnace can also reduce the effective opening; shallow inclines in extension tunnels can direct radiation into furnace insulation or incoming cold work. These methods still allow the load to enter the furnace.
- Repair or plug fixed openings. If that is not possible, use a radiation shield such as an alloy sheet or ceramic board. Use proper refractory or insulation to plug holes. For openings such as a sight glass, use a damper or slide valve to block radiation when using the sight glass.

Resources

See also Robert Siegel and John Howell, *Thermal Radiation Heat Transfer*, New York: McGraw-Hill, 1972; and W. Trinks et al., *Industrial Furnaces*, Sixth Edition, New York: John Wiley & Sons, Inc., 2003.

Figure 2. Calculation of effective area for openings in a furnace[2]



Technically, the temperature of the colder (receiving) surface also plays a part. However, this surface is usually the area surrounding the furnace, which can range from 20°F for an outdoor furnace up to 120°F for a hot factory building, and it has little effect on radiation losses.

Estimating Radiation Heat Losses

Radiation losses can be estimated by using a simple formula:

$Q_{radiation}$ (Btu/hr) = (black body radiation at the source temperature – radiation at the ambient temperature) x effective area of the opening x fraction of the time an opening (e.g., the furnace door) is open

In most cases, the furnace temperature can be used as a radiation source temperature for estimating radiation losses. Figure 1 can be used to estimate radiation heat flux based on furnace temperature. As mentioned earlier, ambient temperature has very little effect on the losses and can be ignored. The effective area of the opening can be estimated by using Figure 2 along with the dimensions of the opening and the furnace wall thickness. For a fixed opening, the fraction open time would be 1.0. However, for doors opened for loading or unloading, this should be calculated as the time the door is open divided by the cycle time for loading-unloading. In some cases, the door might not be fully closed, and a small gap is constantly maintained. In this case, the fraction open time would again be 1.0.

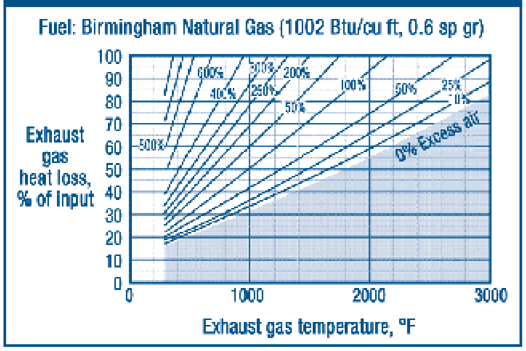
[1] Calculations by Arvind Thekdi, E3M, Inc.

[2] Calculations by Richard Bennett, Janus Technology Group.

Install Waste Heat Recovery Systems for Fuel-Fired Furnaces

For most fuel-fired heating equipment, a large amount of the heat supplied is wasted as exhaust or flue gases. In furnaces, air and fuel are mixed and burned to generate heat, some of which is transferred to the heating device and its load. When the heat transfer reaches its practical limit, the spent combustion gases are removed from the furnace via a flue or stack. At this point, these gases still hold considerable thermal energy. In many systems, this is the greatest single heat loss. The energy efficiency can often be increased by using waste heat gas recovery systems to capture and use some of the energy in the flue gas.

Figure 1. Heat in flue gas

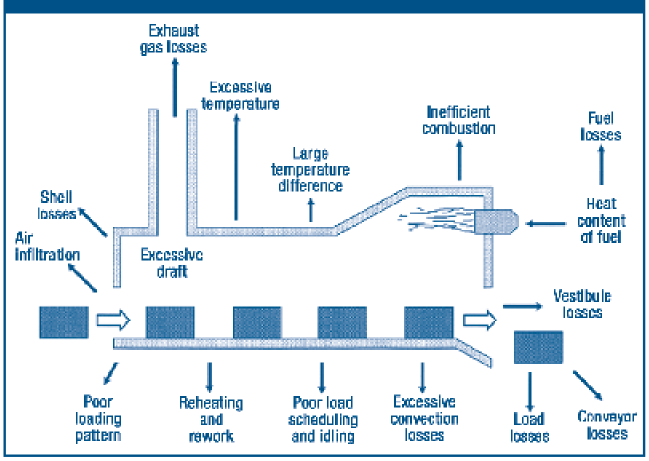


For natural gas-based systems, the amount of heat contained in the flue gases as a percentage of the heat input in a heating system can be estimated by using Figure 1. Exhaust gas loss or waste heat depends on flue gas temperature and its mass flow, or in practical terms, excess air resulting from combustion air supply and air leakage into the furnace. The excess air can be estimated by measuring oxygen percentage in the flue gases.

Waste Heat Recovery

Heat losses must be minimized before waste heat recovery is investigated. Figure 2 highlights opportunities for energy savings.

Figure 2. Heat losses



The most commonly used waste heat recovery methods are preheating combustion air, steam generation and water heating, and load preheating.

Suggested Actions

- Use PHAST with current and projected energy costs to estimate energy savings from waste heat recovery.
- Contact furnace or combustion system suppliers to calculate payback or return on investment.

Preheating Combustion Air. A recuperator is the most widely used heat recovery device. It is a gas-to-gas heat exchanger placed on the stack of the furnace that preheats incoming air with exhaust gas. Designs rely on tubes or plates to transfer heat from the exhaust gas to the combustion air and keep the streams from mixing.

Another way to preheat combustion air is with a regenerator, which is an insulated container filled with metal or ceramic shapes that can absorb and store significant thermal energy. It acts as a rechargeable storage battery for heat. Incoming cold combustion air is passed through the regenerator. At least two regenerators and their associated burners are required for an uninterrupted process: one provides energy to the combustion air while the other recharges.

Steam Generation and Water Heating. These systems are similar to conventional boilers but are larger because the exhaust gas temperature is lower than the flame temperature used in conventional systems. Waste heat boilers can be used on most furnace applications, and special designs and materials are available for systems with corrosive waste gases. Plants that need a source of steam or hot water can use waste heat boilers, which may also work for plants that want to add steam capacity. However, the waste boiler generates steam only when the fuel-fired process is operating.

Load Preheating. If exhaust gases leaving the high temperature portion of the process can be brought into contact with a relatively cool incoming load (the material being heated), energy will be transferred to the load, preheating it and reducing the energy consumption. Load preheating has the highest potential efficiency of any system that uses waste gases. Load preheating systems can be difficult to retrofit and are best suited for continuous rather than batch furnaces.

Benefits

Benefits of waste heat recovery include:

- **Improved heating system efficiency.** Energy consumption can typically be reduced 5% to 30%.
- **Lower flue gas temperature in chimney.** Less heat is wasted.
- **Higher flame temperatures.** Combustion air preheating heats furnaces better and faster.
- **Faster furnace startup.** Combustion air preheating heats furnaces faster.
- **Increased productivity.** Waste heat used for load preheating can increase throughput.

Potential Applications

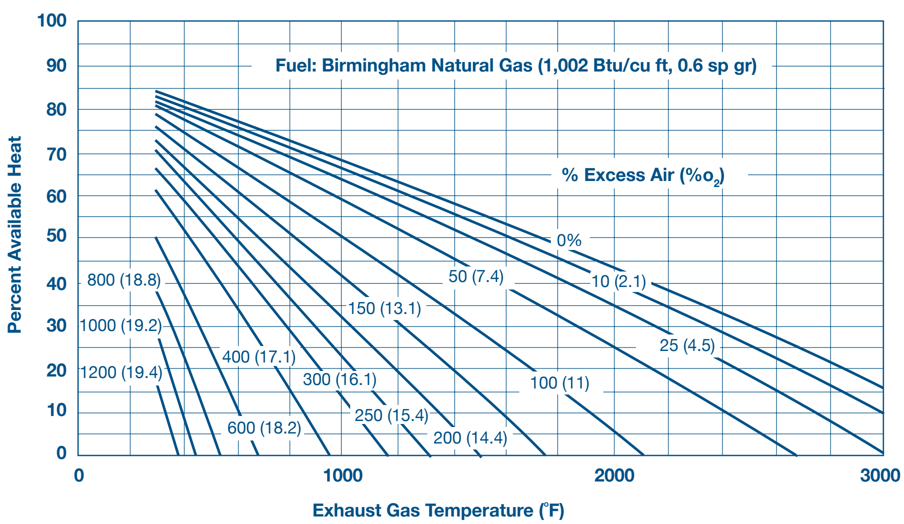
Waste heat recovery should generally be considered if the exhaust temperature is higher than 1,000°F, or if the flue gas mass flow is very large.

Load Preheating Using Flue Gases from a Fuel-Fired Heating System

The thermal efficiency of a heating system can be improved significantly by using heat contained in furnace flue gases to preheat the furnace load (material coming into the furnace). If exhaust gases leaving a fuel-fired furnace can be brought into contact with a relatively cool incoming load, heat will be transferred directly to the load. Since there is no intermediate step, like air or gas preheating, in the heat recovery process, this can be the best approach to capturing waste heat. Load preheating is best suited for continuous processes, but it can sometimes also be used successfully with intermittently operated or batch furnaces. Load preheating can be achieved in a variety of ways, including these:

- Use of an *unfired load preheat section*, in which furnace flue gases are brought in contact with the incoming load in an extended part of the furnace.
- Use of an *external box*, in which high-temperature furnace flue gases are used to dry and/or preheat the charge before loading in a furnace.
- Use of a *counter-current* flow design in a furnace or a kiln, in which the burner gases flow in the opposite direction of the load being heated.

Figure 1. Available Heat Chart



The amount of energy savings obtained by using load preheating is *higher* than the amount of actual heat transferred to the load. The "net" heat delivered to the load has to account for the efficiency of the furnace. Since the furnace efficiency is always less than 100%, the resulting energy savings exceed the energy picked up by the load. Load preheating can result in higher production from the same furnace.

Suggested Actions

Questions to ask if your furnace can be adapted to load preheating (not all can be):

1. Would combustion air preheating or some other savings measure be cost-effective?
2. How large a preheating chamber is needed?
3. Do you have enough space for a preheater that size?
4. You might have to restrict exhaust gas paths so they will come in contact with the load. Will this interfere with exhaust gas flow and cause too much backpressure in the furnace chamber?
5. How will incoming parts move through the preheating chamber? If conveying equipment is needed, can it withstand exhaust gas temperatures?

Questions to ask before adding a separate load preheat section or chamber:

1. How would flue gases move to the heating chamber? Will a fan or blower be needed to overcome pressure drops in ducts?
2. Does heat demand equal heat supply during most of the heating cycle time?
3. How would the hot load be transferred to the main furnace? Would the heat loss be considerable?
4. What type of controls are required to maintain the desired temperature in the preheat chamber? Will an auxiliary heating system be needed?

Example

An aluminum die cast melting furnace has an average production rate of 1,000 lb/hr. As metal is drawn from the furnace at 1,400°F, the molten bath is periodically replenished with ingots at room temperature. The furnace exhaust temperature is 2,200°F. Wall conduction and opening radiation losses average 100,000 Btu/hr. The burners operate at 20% excess air. The graphs and tables in the reference below (and other sources) show that the molten metal requires 470 Btu/lb heat, for a total of 470,000 Btu/hr. Total net input to the furnace equals heat to the load plus wall and radiation losses, or 470,000 + 100,000 Btu/hr = 570,000 Btu/hr.

For 20% excess air and 2,200°F exhaust temperature, the available heat is 31%, based on Figure 1. This means 69% of the heat input is wasted in flue gases. Divide this into the net input: 570,000 Btu/hr ÷ 0.31 = 1, 838,700 Btu/hr total input to the furnace. The exhaust gas loss is 1,838,700 – 570,000 = 1,268,700 Btu/hr.

The furnace is modified to route the exhaust gases to the stack through a slightly inclined, refractory-lined tunnel. Exhaust gases flow counter to the incoming ingots, preheating them. The ingots are heated to an average temperature of 600°F and contain 120 Btu/lb, or 120,000 Btu/hr, for a 1,000 lb/hr production rate. Preheating the cold ingots to 600°F lowers the amount of heat required from the furnace to
(470 – 120) Btu/lb x 1,000 lb/hr = 350,000 Btu/hr.

As an approximation, assume that the flue gas temperature from the melting section of the furnace remains constant at 2,200°F and the available heat remains the same (31%). Total input to the furnace is now (350,000 + 100,000) ÷ 0.31 = 1,451,600 Btu/hr. Savings are (1,838,700 – 1,451,600) / 1,838,700 = 387,100 / 1,838,700 = 0.2105, or 21.1%.

This is a rough estimate. Actual savings will be greater, because lowering the burner firing rate decreases the furnace exhaust gas temperature and volume, resulting in higher available heat with further reductions in fuel input. Because the furnace input could still be 1,838,700 Btu/hr, with net available heat of 470,000 Btu/hr for aluminum, while the heat demand for 1,000 lb/hr aluminum charge is only 350,000 Btu/hr, it is possible to increase production by (470,000 – 350,000)/470,000 = 25.5%. Check the material handling system to see if it is capable of handling the additional load and if the downstream processes can accommodate increased melter production.

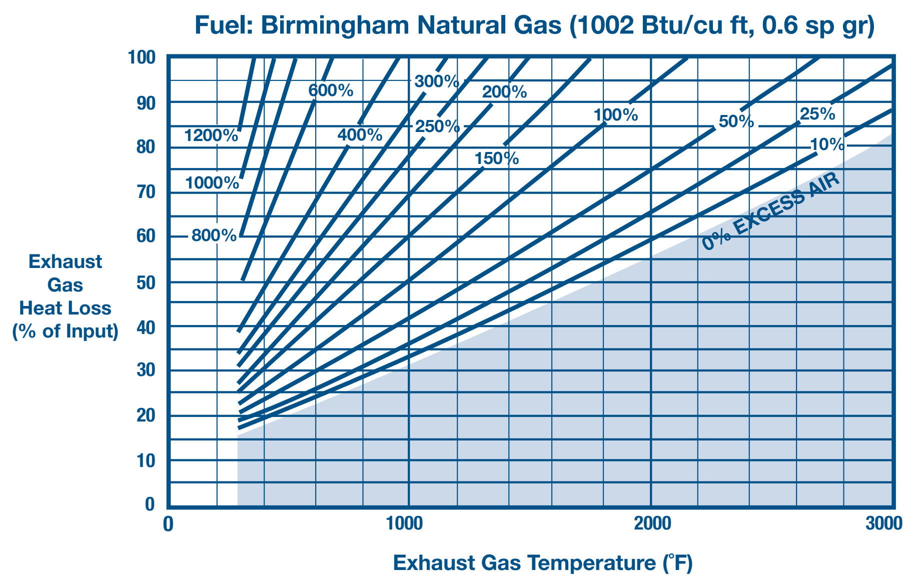
Reference

W. Trinks et al. *Industrial Furnaces, Sixth Edition*. New York: John Wiley & Sons, Inc. 2003.

Using Waste Heat for External Processes

The temperature of exhaust gases from fuel-fired industrial processes depends mainly on the process temperature and the waste heat recovery method. Figure 1 shows the heat lost in exhaust gases at various exhaust gas temperatures and percentages of excess air. Energy from gases exhausted from higher temperature processes (primary processes) can be recovered and used for lower temperature processes (secondary processes). One example is to generate steam using waste heat boilers for the fluid heaters used in petroleum crude processing. In addition, many companies install heat exchangers on the exhaust stacks of furnaces and ovens to produce hot water or to generate hot air for space heating.

Figure 1. Heat loss in exhaust gases at various exhaust gas temperature and excess air percents[1]



Before attempting to use energy from higher temperature flue gases in lower temperature processes, engineers should take the following technical issues into consideration:

- **Nature or quality of the flue gases.** Flue gases from the primary processes should be clean and free of contaminants such as corrosive gases and particulates. Contaminants pose special handling problems for the gases and might affect the quality of work in the secondary process.
- **Temperature of primary process flue gases.** The temperature difference between the primary and secondary process should be high enough (at least 200°F), and there should be a sufficient amount of usable waste heat.

Suggested Actions

Questions to ask when evaluating the use of waste gases for heating secondary processes:

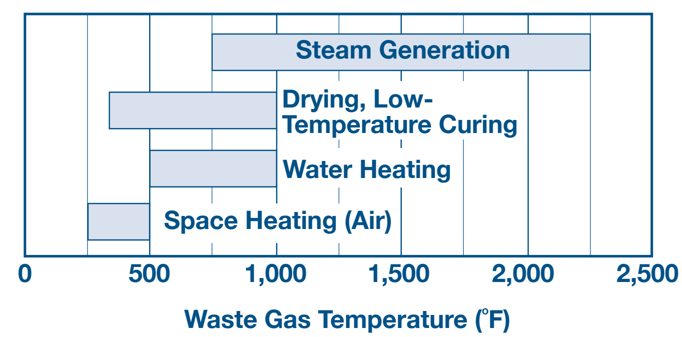
1. Is there a less expensive way to heat the secondary process?
2. Is the temperature of the flue gases high enough to heat the secondary process?
3. Do the flue gases contain enough transferable energy?
4. Are the flue gases compatible with the secondary process (as to cleanliness, corrosiveness, etc.)?
5. Can the primary process deliver energy to the secondary process in time?
6. Are the two processes close enough together to avoid excessive heat losses during waste gas transport?
7. Will the flue gases leave the secondary process at a high enough temperature to avoid problems with moisture condensation?
8. Can the exhaust ductwork and secondary process be designed to avoid excessive pressure resistance to the flue gases, or are additional means like exhaust fans necessary?

Resources

See also the *ASM Handbook*, Volumes 1 (1990) and 2 (1991), Materials Park, OH: ASM International; *Combustion Technology Manual,* Fifth Edition, Cincinnati, OH: Industrial Heating Equipment Association (IHEA), 1994; *Handbook of Applied Thermal Design*, E.C. Guyer and D.L. Brownell, eds., London: Taylor & Francis Group, 1999.

- **Matching the heat demand of the secondary process with the heat supply from the primary process.** The heat supply from the primary process should be sufficiently high to meet a reasonably high percentage of the secondary process heat demand.
- **Matching the timing of the heat supply from the primary process and the heat demand in the secondary process.**

Figure 2. Typical secondary processes and approximate exhaust temperatures [2]



- **Placement of primary and secondary heating equipment.** The closer the primary and secondary process can be situated, the better.

Figure 2 shows some heating processes that commonly use waste heat from a higher temperature process, and the approximate range of waste gas temperatures they require. Sometimes lower temperature gases can be used if the heat recovery device is deliberately oversized.

Example

A plant uses a furnace with a firing rate of 10 MMBtu/hr, which discharges flue gases at 1,400°F (primary process). The plant also has a drying oven that operates at 400°F and requires 2.5 MMBtu/hr of heat (secondary process). The recoverable heat can be estimated using Figure 1. At 1400°F, the heat content of the exhaust gases (at 10% excess air) is about 42% of the heat furnace input. Again using Figure 1, the heat content of exhaust gases at 400°F is approximately 20% (at 10% excess air). The *approximate* amount of heat that can be saved is 42% – 20% = 22% of the heat input to the primary process. The net heat available for the secondary process is approximately 0.22 x 10 MMBtu/hr = 2.2 MMBtu/hr. Actual savings would be greater than this because the available heat at the 400°F exhaust gas temperature is approximately 80% (see Figure 1 in Process Heating Tip Sheet #9, *Load Preheating Using Flue Gases from a Fuel-Fired Heating System*). The actual savings for the oven are thus 2.2/0.8 = 2.75 MMBtu/hr.

In this case, there is more than enough heat to meet the heat demand for the drying oven. It would be necessary to use additional heat in the oven if the exhaust gas heat from the furnace were not sufficient to meet the oven heat demand. At a fuel cost of $8.00 per MMBtu, the company can save $22.00 in fuel costs per hour. Assuming 8,000 hours of operation per year, annual savings are $175,000.

[1] Calculations by Richard Bennett, Janus Technology Group.

[2] Figure by Richard Bennett, Janus Technology Group.

Use Lower Flammable Limit Monitoring Equipment to Improve Process Oven Efficiency

Process heating applications involving flammable solvent removal use large amounts of energy to maintain safe lower flammable limits (LFL) in the exhaust air. National Fire Protection Association (NFPA) guidelines require the removal of significant amounts of exhaust air to maintain a safe, low-vapor solvent concentration. If LFL monitoring equipment is used to ensure proper vapor concentrations, these guidelines allow for less exhaust air removal. LFL monitoring equipment can improve the efficiency of the solvent removal process and significantly lower process energy requirements.

Flammable solvents used in industrial production processes are typically evaporated in industrial ovens. Higher oven temperatures evaporate solvent vapors more quickly, allowing for faster production. Because the vapors are flammable, the exhaust air is discharged (along with the heat) to prevent the accumulation of the vapors in the oven. As the oven temperatures increase, plants have to maintain higher ventilation ratios to reduce the solvent vapor concentration levels and maintain the respective LFL.

For example, the NFPA ventilation safety ratio for batch-loaded ovens operating below 250˚F is 10:1 and xylol has an LFL of 1%. Therefore, exhaust ventilation needs to be added to the vapor until the solvent concentration reaches 0.1%, meaning that the plant has to exhaust 10 times the amount of air required by the process to meet the NFPA requirement. If the process operates above 250˚F, the required safety ratio rises to 14:1, the LFL goes down to 0.07%, and the plant has to exhaust 14 times the amount of air required to keep the process from becoming flammable.

The non-uniform rate of solvent vaporization is one of the reasons why LFLs are so stringent. Solvent vaporization is inherently non-uniform mainly because of wall losses and load characteristics; this causes periodically high solvent concentrations in the oven during the vaporization process. As a result, safe ventilation ratios are calculated using the theoretical peak needs of ventilation based on the highest vapor concentrations that can accumulate during the vaporization process.

LFL Monitoring Equipment

LFL monitoring equipment can reduce energy used in solvent removal by adjusting the ventilation ratio according to the fluctuations in vapor concentration. The equipment continuously tracks the solvent extraction rate in real time and controls the rate of ventilation air based on real needs, thereby maintaining a safe ratio throughout the process. LFL monitoring equipment

Suggested Actions

- Evaluate energy costs, process load and production requirements to determine the economic feasibility of LFL monitoring equipment.
- Examine process energy requirements to confirm the flammable solvent load. If this load has changed over time, ventilation rates may need to be adjusted.
- Using a booster oven can reduce the evaporation requirements in the main oven, thus reducing its exhaust requirements
- Consider a professional outside evaluation to determine the technical and economic feasibility of additional improvements including reducing wall losses, installing heat exchangers and fume incinerators, and recuperating exhaust air to capture the heat value of exhaust air.
- Check all relevant NFPA and other applicable codes, regulations, and standards before adding equipment or making adjustments and consider consulting with an expert.

Resources

Hans L. Melgaard, "Substantial Energy Savings are Often Realized by Monitoring Process Oven Exhausts," *Plant Engineering*, November 1980

can employ several technologies including catalytic systems, infrared sensors, ionization systems and combustion sensors. LFL monitoring equipment has self-check functions and uses a calibrated test gas for periodic self-calibration. Because the vaporization process depends on the intake and exhaust air, linking the LFL controller to an adjustable speed drive on the exhaust system fan can improve process efficiency even further (damper adjustments can also be used).

Example

The NFPA safety ventilation ratios are significantly lower when LFL monitoring equipment is used than when such equipment is absent. This lowers the energy requirements for the process because less air needs to be exhausted to keep the process from becoming flammable. For a continuous strip coating process requiring 46 gallons of xylol with a maximum oven temperature of 800º F and ambient air temperature of 70º F, the safety ventilation ratio is 4:1 without LFL monitoring equipment. This results in an exhaust requirement of 8,330 standard cubic feet per minute and energy consumption of 6.7 million British thermal units (MMBtu) per hour. At a cost of $8/MMBtu assuming a two-shift operation, this process costs approximately $214,000 annually. Installing LFL monitoring equipment would reduce the ratio to 2:1, halving the exhaust and energy requirements. Annual energy savings would total $107,000. With an installed cost of $12,500 for an LFL controller, the simple payback is very attractive at less than 1.5 months.

1. **Since process heating system performance is fundamental to the quality of a wide range of finished products, _____ must be considered together.**
   - cost and efficiency
   - efficiency and performance
   - cost and performance
   - efficiency and cost

2. **Common industrial process heating systems fall in which one of the following categories:**
   - Fuel-based process heating systems
   - Electric-based process heating systems
   - Steam-based process heating systems
   - Other process heating systems, including heat recovery, heat exchange systems, and fluid heating systems.
   - All the above

3. **Most opportunities to improve process heating efficiency are related to?**
   - Optimizing the combustion process
   - Extracting and/or recovering energy from the exhaust gases
   - Reducing the amount of energy lost to the environment
   - All the above

4. **Which of the following fuel-based furnaces are used in "most manufacturing sectors"?**
   - Continuous Direct-fired
   - Continuous Indirectly heated
   - Batch Direct-fired
   - Batch Indirectly heated

5. **True or False. Transferring heat from the exhaust gases to the incoming combustion air or incoming cold process fluid reduces the amount of energy lost from the system and also allows more thermal energy to be delivered to the heated material from a certain amount of fuel.**
   - True
   - False

6. **Which of the following performance improvements could offer the biggest savings in heat generation for fuel-based systems?**
   - Control air-to fuel ratio
   - Preheat combustion air
   - Use oxygen-enriched combustion air
   - None of the above

7. **In regard to heat containment, why is air infiltration a common issue?**
   - Many furnaces operate at slightly positive pressure
   - Inadequate excess air
   - Excessive excess air
   - Many furnaces operate at slightly negative pressure

8. **True or false. One common opportunity to improve the efficiency of auxiliary motor systems is to use motors controlled by variable frequency drives instead of controlling motors with dampers or throttle valves.**
   - True
   - False

9. **Which of the following will improve the efficiency of existing arc furnace systems?**
   - Use bottom stirring/stirring gas injection
   - Install ultra-high-power transformers
   - Preheat scrap
   - All of the above

10. **Adding baffles or additional reflectors to sides/top/bottom of the oven will improve the efficiency of which type of system?**
    - Electron-beam
    - Induction
    - Electric Infrared
    - Laser

11. **In laser processing systems, which of the following improvements will have the highest effect on efficiency?**
    - Beam delivery optical losses
    - Laser cavity optical losses
    - Chiller operational efficiency
    - Improving your laser path layout

12. **_____ is the simplest and oldest electric-based method of heating and melting metals and nonmetals. Efficiency can reach close to 100% and temperatures can exceed 3,600°F.**
    - Radio-Frequency Processing
    - Resistance heating
    - Electric Infrared
    - Ultraviolet Processing

13. **Dull and corroded reflectors on UV systems can reduce UV output by up to?**
    - 25%
    - 100%
    - 50%
    - 10%

14. **For a fuel-fired furnace with an exhaust temperature of 2,000˚F, preheating the combustion air to 1,000˚F will result in a fuel savings of?**
    - 13%
    - 31%
    - 51%
    - 20%

15. **Which is one of the simplest ways to get maximum efficiency out of fuel-fired process heating equipment?**
    - Using oxygen-enriched combustion
    - Reducing air infiltration in furnaces
    - Periodic checking and resetting of air-fuel ratios for burners
    - Installing waste heat recovery systems

16. **Contamination of heat transfer surfaces is typically the result of?**
    - Low air/fuel ratios
    - Oxidation of heat transfer surfaces in high temperature applications
    - Corrosive gases or constituents in the heating medium
    - Stagnant or low-velocity areas in contact with heat transfer surfaces for hot liquid or gas heating systems
    - All of the above

17. **Which of the following is true in regard to pressure controllers?**
    - They regulate the airflow to maintain a slightly positive pressure
    - They can be manual or automatic
    - They can be used on natural, induced, forced, and balanced industrial furnaces
    - All of the above

18. **For a continuous furnace in which opening size cannot be reduced, what can be done to reduce the loss of radiant energy? (Select all correct answers)**
    - ☐ Install flexible materials such as ceramic strips, chains, or ceramic textiles as "curtains
    - ☐ Install tunnel-like extensions on the end of the furnace
    - ☐ Install shallow inclines in extension tunnels
    - ☐ Nothing can be done

19. **Waste heat recovery should generally be considered if the exhaust temperature is higher than _____, or if the flue gas mass flow is very large.**
    - ○ 2,000°F
    - ○ 1,000°F
    - ○ 500°F
    - ○ 10x the intake temperature

20. **True or false. Energy from gases exhausted from higher temperature processes (primary processes) can be recovered and used for lower temperature processes (secondary processes).**
    - ○ True
    - ○ False