U.S. DEPARTMENT OF
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Renewable Energy

ADVANCED MANUFACTURING OFFICE

Improving Process Heating System Performance

A Sourcebook for Industry

Third Edition

U.S. Department of Energy
Energy Efficiency
and Renewable Energy
Bringing you a prosperous future where energy
is clean, abundant, reliable, and affordable

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FOREWORD

The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office works with industry, small business, universities, and other stakeholders to identify and invest in energy efficient technologies. Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness.

The industrial sector is responsible for about one-third of all U.S. primary energy use, and the associated greenhouse gas (GHG) emissions. The U.S. industrial base is diverse, with about two-thirds of the end-use energy consumed by the energy intensive industries including chemicals, forest products, petroleum refining, iron and steel, glass, aluminum, metal-casting foundries and cement. Beyond the large energy consumers, there are a wide range of energy dependent industries whose products and operations are significantly impacted by energy.

Of all manufacturing operations, process heating consumes more energy in the U.S. than any other manufacturing system – more than 7,000 Trillion Btu (TBtu), or approximately 61% of manufacturing onsite energy use annually. Opportunities to reduce the energy demand for process heat include more efficient heat generation, system design to reduce losses prior to heat use, and alternative manufacturing processes that require less heat to produce the same material.

This Sourcebook outlines opportunities for energy and performance improvements in process heating systems, and is intended to help the reader identify improvement opportunities in their own facilities. This Sourcebook is not a substitute for a rigorous engineering-based assessment and evaluation of the technical and economic potential of any process heating improvement. This Guidebook is also intended to serve as a companion to other resources and sources of information, such as:

- The DOE 2015 Quadrennial Technology Review (QTR) Technology Assessments on Process Heating and Waste Heat Recovery, as well as other Technology Assessments that can provide insights into state-of-the-art and emerging opportunities to improve process heat utilization and production efficiencies.

- AMO's Steam System Modeling Tool (SSMT), available at http://energy.gov/eere/amo/software-tools. This tool help users survey and assess their steam system equipment, perform heat balances, quantify heat losses, and identify potential energy efficiency upgrades.

- Fact sheets, technical analyses, roadmaps and other resources that can be found by searching on the AMO "Information Resources" webpage.

These and other resources that can help the reader find more information can be found in Section 7 of this Sourcebook – "Where to Find Help."

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QUICK START GUIDE

This sourcebook describes basic process heating applications and equipment, and outlines opportunities for energy and performance improvements. It also discusses the merits of using a systems approach in identifying and implementing these improvement opportunities. It is not intended to be a comprehensive technical text on improving process heating systems, but serves to raise awareness of potential performance improvement opportunities, provides practical guidelines, and offers suggestions on where to find additional help. The sourcebook contains information in the following sections:

Section 1: Process Heating Basics

For users unfamiliar with the basics of process heating systems, or for users seeking a refresher, a brief discussion of the equipment, processes, and applications is provided.

Section 2: Performance Improvement Opportunities—Fuel-Based Systems

This section discusses key factors for improving the performance of fuel-based process heating systems. This section is categorized by opportunity type: 1) heat generation; 2) heat containment; 3) heat transfer; 4) waste heat recovery; and 5) enabling technologies.

Section 3: Performance Improvement Opportunities—Electric-Based Systems

This section discusses key factors for improving the performance of electric-based process heating systems. Electric-based solutions and opportunities are described by technology type.

Section 4: Waste Heat Management – Reduction, Recycling and Recovery

This section describes different methods for managing and utilizing the various forms of waste heat that can be generated by process heating systems.

Section 5: Process Heating System Economics

To support the improvement opportunities presented in Sections 2 through 4, this section provides recommendations to financially justify process heating improvement projects.

Section 6: Sustainability of Process Heating Systems

This section addresses the growing concern of sustainability, how it is related to industrial energy consumption, and why improving the sustainability of process heating systems will be beneficial

Section 7: Where to Find Help

In addition to a comprehensive listing of resources and tools, this section contains a directory of associations and other organizations engaged in enhancing process heating system efficiency.

Appendices

Appendix A is a glossary defining terms used in process heating systems. Appendix B contains a series of process heating system tip sheets. Developed by DOE, these tip sheets discuss additional opportunities for improving the efficiency and performance of process heating systems. Appendix C contains technical briefs developed by DOE. These technical briefs discuss specific performance improvement topics in more detail than the tip sheets. Appendix D is a compendium of references used in the development of this sourcebook.

SECTION 1: 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, carbon fiber, 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 (often called electrotechnologies) use electric currents or electromagnetic waves to heat materials. Direct heating methods generate heat within the work piece itself, 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 fields (e.g., Radio frequency (RF), Microwave (MW).

Indirect heating methods use one of these three methods to apply heat to the work piece surface or to a susceptor material which transfers the heat to the work piece by either conduction, convection, radiation, or a combination of these.

Steam-Based Process Heating

Steam systems, covered in a separate sourcebook, account for about 30% of the total energy used in industrial applications for product output. These systems can be indispensable in delivering the energy needed for process heating, pressure control, mechanical drives, separation of components, and production of hot water for process reactions. 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. For more information on steam process heating systems, see the DOE sourcebook *Improving Steam System Performance: A Sourcebook for Industry*.

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

Efficiency and Energy Intensity Opportunities

Energy efficiency refers to the activity or product that can be produced with a given amount of energy; for example, the number of tons of steel that can be melted with a megawatt hour of electricity. Energy

[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, Capital Surini Group International, Inc., Energetics, Inc., 2001.

Intensity is measured by the quantity of energy required per unit output or activity, so that using less energy to produce a product reduces the intensity. In this example, energy intensity is the number of megawatt hours used to melt one ton of steel. The difference between efficiency and energy intensity is insignificant, as one is simply the inverse of the other. Having a goal to improve efficiency or reduce energy intensity puts you on the correct path for process improvements.

Approaches to improve a certain heating operation might be applicable to multiple processes 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 sourcebook. 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 process heating systems, and these opportunities are often overlooked. One of the goals of the sourcebook is to build awareness of the economic benefits resulting from the improvement of the energy efficiency of these systems.

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. Performance improvement opportunities are described in Sections 2 through 4, in the tip sheets in Appendix B, and in the technical briefs in Appendix C. 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 sourcebook 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. In order to achieve maximum improvement at the lowest cost both, a systems approach and individual component analyses should be used.

A systems approach provides a tops-down review of the entire process and how the individual components perform and interact with each other. An important part of this approach is to create process flow diagrams which show the movement of materials and energy throughout the system. This not only gives a birds-eye view of the entire process but also allows the ranking of components according to their importance for efficiency opportunities, and how changing one component may affect the others. Most importantly, the exercise highlights the confidence in the data and therefore what additional measurements are needed.

Next, the individual components, determined to be the most important from the system's approach, are carefully analyzed to determine their detailed performance and ways to improve their efficiency.

Finally, an iterative step is taken in which the component's new performance is fed back to the system's approach analysis to determine the true improvements when interactions among all the components are evaluated.

The benefits of a systems approach can be illustrated through the following example. 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. The operator might notice a product problem related to temperature and might make an adjustment as a quick fix instead of finding the root cause in the system, such as poor insulation.

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 industrial dryers, including conveyor, fluidized bed, rotary, and cabinet dryers.

A rotary dryer for the 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.

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 using electrolytic reduction, Hall-Heroult or Bayer process, referred to as aluminum smelting.

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 8 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
- Electric-based
- Steam-based
- Other, such as 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.

Steam is most commonly generated by using fuel or electricity in a boiler. Focused Solar generation of steam is a reality with several installations being built throughout the world. No matter how the steam is generated, it is a major source of energy for many industrial processes, from fluid heating to drying. In addition to steam, several other secondary energy sources are used by industry. They include hot air, heat transfer by liquids, and water. These secondary sources are generated by a heating system of its own that can fall under the general category of "other process heating systems."

The cost of energy can vary greatly depending on the area of the country your operation resides. You will need to consult your Utility provider to get an accurate assessment of your current energy cost and an evaluation as to price changes that may result from your adding or reducing energy consumption. Some 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) may be much less costly than conventional fuels, possibly making their paybacks comparatively longer.

Table 1. Examples 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, 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, Textiles
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, Transportation Equipment, 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, Transportation Equipment
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, Resistance Heaters, Microwave, Steam, Induction, Infrared	Agricultural and Food, Glass, Ceramics, Plastics, Rubber, Chemicals

Most process heating applications are fueled by gas or electricity, with some fueled by coal or fuel oil. In many industries, other waste product fuels account for a large portion of the energy use. These fuels include sawdust, wood waste, black liquor, refinery gas, blast furnace gas, and petroleum coke. In many of these systems especially, justifying energy efficiency projects must emphasize performance and reliability benefits that usually accompany improvements in efficiency.

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, coal, and biomass such as vegetable oil, wood chips, cellulose, charcoal, and ethanol). For 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.

Fuel-based process heating systems are common in nearly every industry segment. They include enclosed heating, like furnaces, ovens, heaters, kilns, and melters, as well as surface treatment applications 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. A furnace 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, carbo-nitriding, 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. Thermal oxidizing processes include paint and polymer curing and/or drying.

Furnaces in any configuration can be considered heating systems that consist of many components. Examples of improving process heating efficiency include optimizing the combustion process, recovering energy from the exhaust gases, reducing the amount of energy lost to the environment, recycling rejected product, using recycled materials in place of virgin feedstocks, and improving furnace scheduling.

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 from the electrode(s) to the conductive material. The furnace can be either an AC or DC depending on the application. 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 heats up to a desired source temperature to emit infrared radiant energy. 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. It is also used in processing scrap titanium and superalloys.

Gas infrared heating. A flame is contained within a porous surface or impinges onto a surface which then emits radiation with a broad range of wavelengths at high power density. The work piece absorbs energy at high rates due to total summation over the broad spectral range. Gas infrared heating systems are used for food processing, annealing, forming, melting snow, setting (gel) powder coatings before their curing cycle, and for other high power and quick heat time 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; heating that is only produced within magnetic materials as a result of the rapidly changing magnetic fields by the inductor generating internal friction. This secondary heating 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.

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 some cases, the work piece is the electrode and its plasma or glow discharge provides surface treatment.
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 are used to fuel switch based on pricing incentives, off-peak pricing, offered by your utility provider.

Steam holds a significant amount of energy on a unit mass basis (between 1,000 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. Among the advantages of steam as a source of process heat are low

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

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. An excellent resource and companion sourcebook titled *Improving Steam System Performance, A Sourcebook for Industry*, presents efficiency opportunities for boilers and steam systems, so they are not described in detail in this sourcebook. This resource is available from the Steam Systems section of the AMO website at www.energy.gov/eere/amo/steam-systems

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 period.

SECTION 2: PERFORMANCE IMPROVEMENT OPPORTUNITIES – FUEL-BASED SYSTEMS

Figure 1 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, as reducing the energy use of one component may reduce the impact of a second reduction. For example, tuning the burners will reduce energy use, but will also make the gains from flue gas heat recovery less than before the burners were tuned.

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.

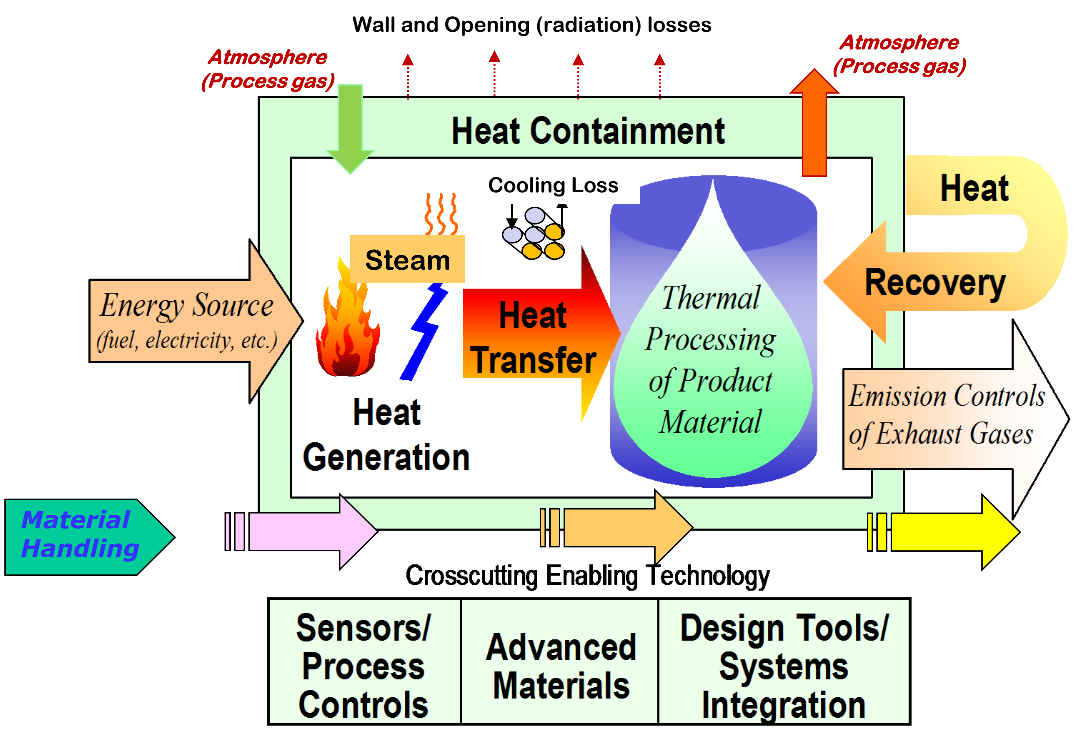


Figure 1. A fuel-based process heating system and opportunities for improvement

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 device
- Material handling system.

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

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, Chemicals, 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 furnaces	Most manufacturing sectors
Indirectly heated	Heat treating furnaces, chemical reactors, distillation columns, salt bath furnaces, etc.	Metals, Chemicals
Material Handling System		
Fluid heating (flow-through) systems	Gaseous and liquid heating systems including fluid heaters, boilers	Petroleum Refining, Chemicals, Food, Mining
Conveyor, belts, buckets, rollers, etc.	Continuous furnaces used for metal heating, heat treating, drying, curing, etc.	Metals, Chemicals, Pulp and Paper, Mining
Rotary kilns or heaters	Cement and lime kilns, heat treating, applications in the chemical and food industries	Mining, Metals, Chemicals, Food
Vertical shaft furnaces	Blast furnaces, cupolas, vertical shaft calciners, exfoliators, 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, Chemicals, Ceramics
Continuous strip furnaces	Continuous furnaces used for metal heating, heat treating, drying, curing, etc.	Pulp and Paper, Metals, Chemicals
Vertical handling systems	Primarily for metal heating and heat treating for long parts and in pit, vertical batch, and salt bath furnaces	Metals, Chemicals, 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 device to the load (for example, convection furnaces).

Type of heating device. There are many types of basic heating devices that can be used in process heating systems. These include burners, radiant burner tubes, gas infrared emitters, 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, also known as a Sanke Diagram, as shown in Figure 2. 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.

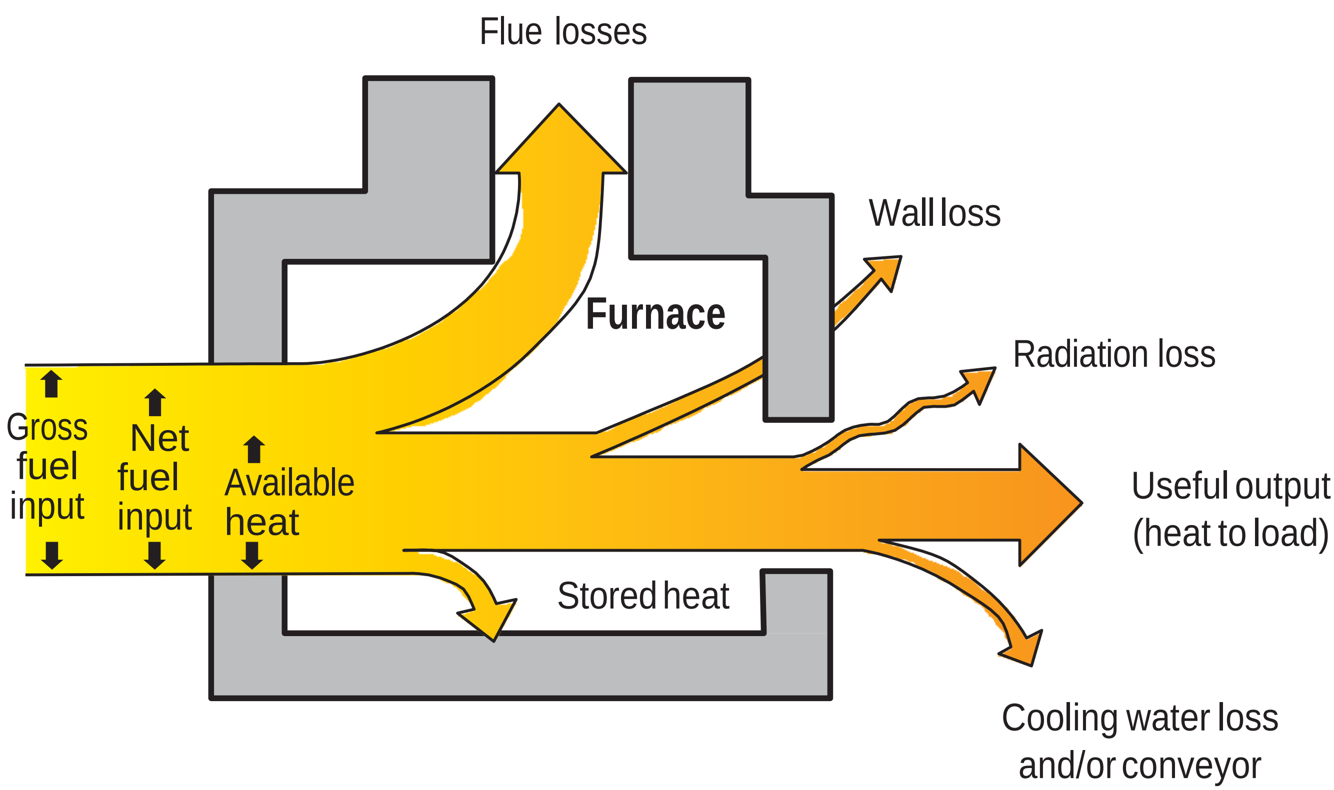


Figure 2. Energy loss diagram in a fuel-based process heating system.

Performance and efficiency improvement opportunities can be grouped into five categories:

- 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 3 shows several key areas where the performance and efficiency of a system can be improved. Some opportunities may affect multiple areas. For instance, reducing radiation losses by sealing the furnace will also reduce flue losses since less fuel will need to be consumed.

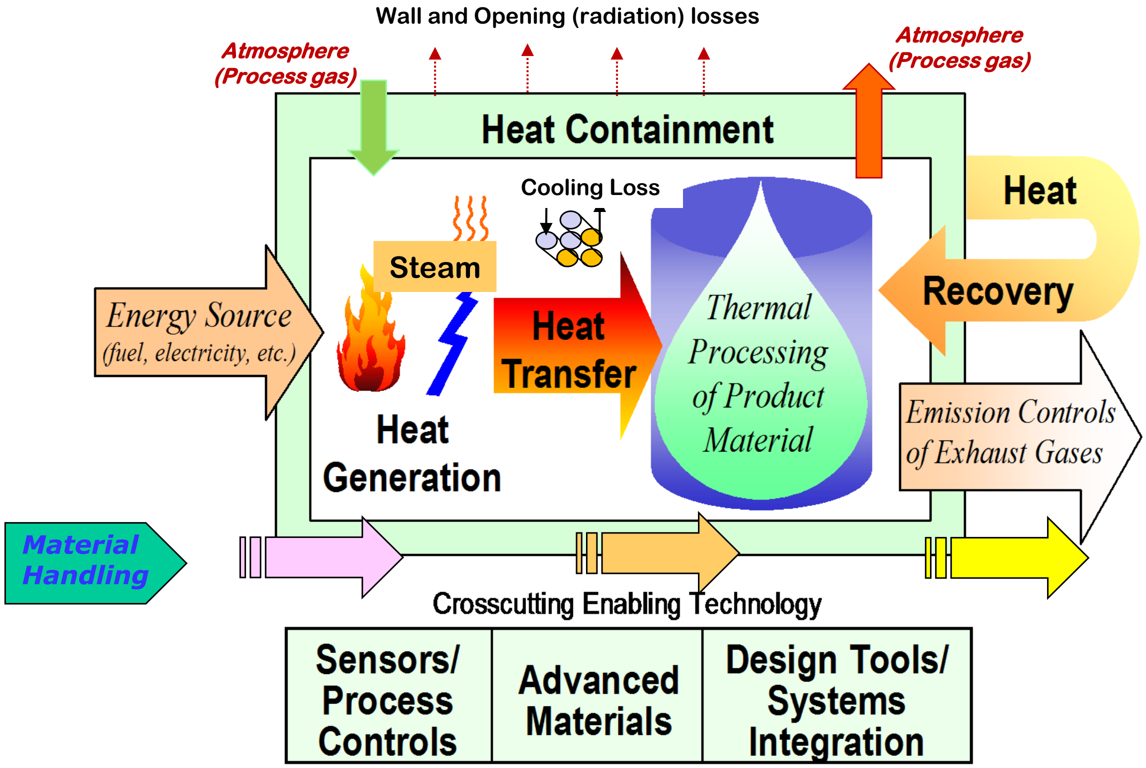


Figure 3. Key opportunities in a fuel-based system

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) Advanced Manufacturing Office (AMO), which are included in Appendix B. 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.

In addition to tip sheets, the AMO has developed technical briefs that cover key issues in greater detail. The first technical brief, *Materials Selection Considerations for Thermal Process Equipment*, discusses how material selection can provide performance and efficiency improvements. The second technical brief, *Waste Heat Reduction and Recovery*, discusses the advantages of reducing energy losses to the environment and heat recovery. These technical briefs are included in Appendix C.

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 and reducing excess air
- Preheating of combustion air or feedstock
- Using oxygen enriched air
- Improving mixing

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, typically around 3%.

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 in nozzle-mix burners, 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. With pre-mix burners, it is easier to approach the stoichiometric ratio since the air and fuel are combined before the nozzle and continue mixing for the length of the mixture piping. Pre-mix equipment can be supplied with automatic adjustment that compensates for variations in air density and fuel content.

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.

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%
• Fuel conditioning	5% to 10%

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

The AMO offers these resources to help you implement energy efficiency measures in process heating generation:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Technical Brief: *Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emission Performance* (see Appendix C)

Also visit the AMO Web site to download these and other process heating related resources: ***www.energy.gov/eere/amo.***

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. 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. However, the higher combustion air may increase formation of nitrogen oxide (NOx), a precursor to ground level ozone, if flue gas recirculation or other burner mitigating strategies aren't used. Also, higher flame temperatures resulting from the higher combustion air temperature may reduce refractory life.

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.

Improving mixing. The mixing of the fuel and oxidant for combustion can be modified to produce the desired heat generating characteristics that are best for the process and type of equipment. A burner's flame can have various shapes and distribution of temperature across its shape by varying the mixing and changing the burner nozzle. New technology has been introduced that changes the mixing and flame temperature of existing burner systems by installing a fuel conditioner in close proximity to the burner.

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. Consider increasing or changing to radiant heat transfer.
- On radiant tube systems, add devices to increase turbulence and radiation in the exhaust leg.
- 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 Containment and Recovery

In addition to improving heat generation and heat transfer, waste heat from process heating systems can be contained, recovered, and utilized. These practices are covered in Section 4, *Waste Heat Management*.

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%
Radiant tube inserts	5% to 20%

What to Watch

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

Find Additional Information

The Advanced Manufacturing Office offers these resources to help you implement energy efficiency measures in heat transfer:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Visit the AMO web site to download these and other process heating related resources: ***www.energy.gov/eere/amo***

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. In addition, emerging technologies can now be used to measure feedstock and melts in real-time, along with feedback controls, can result in substantial energy reductions and productivity increases. Advanced Process controls techniques do also allow for the system to be predictive instead of reactive, with the result of improving process efficiencies.

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.

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. Also, high temperature ceramics and silicon carbides are being used in heat recovery and preheating systems for improved efficiency. Also, complex shapes of these materials are formed through 3D printing which allows higher surface area density and improved effectiveness.

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

The AMO 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 through the Motor Systems section of AMO's web site, www.energy.gov/eere/amo/motor-systems.

- 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. Common fan problems and opportunities to improve fan performance are discussed in a companion sourcebook, *Improving Fan System Performance: A Sourcebook for Industry*. This resource is also available from the Fan Systems section of the AMO web site at www.energy.gov/eere/amo/fan-systems.
- Pumps. Some process heating applications require cooling to prevent thermal damage to certain system parts, such as conveyor systems. Pumps are particularly essential in thermal fluid applications to move hot oil to the end use. In general, pumps do not account for a significant amount of energy used by the system; however, pump performance can be critical to keeping the system up and running. Further information on pumps and pumping systems is available in a companion sourcebook, *Improving Pumping System Performance, A Sourcebook for Industry*. This resource is available from the Pump Systems section of the AMO website, www.energy.gov/eere/amo/pump-systems.

Another key enabling technology is numerical simulation. The development of modeling techniques and ever-increasing computing power has made numerical modeling a useful tool for improving system performance. Computational Fluid Dynamics (CFD) of fuel based systems gives insight in fields like velocities, temperatures, pressures and stresses at any point of the system. These can generate new ideas on how to improve system efficiencies and help further decision making. These tools also have the ability to run virtual experiments – i.e. various design or operating parameters can be investigated on computer without actually building lab set-ups. Also, it may be too risky and costly to run experiments on live equipment such as furnaces.

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.

Find Additional Information

The Advanced Manufacturing Office offers these resources to help you learn more about enabling technology opportunities for process heating:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Technical Brief: *Material Selection Considerations for Thermal Process Equipment* (see Appendix C)

Also visit the AMO Web site to download these and other process heating related resources: ***www.energy.gov/eere/amo***

With techniques such as CFD, the geometry of furnaces, along with the load and all individual burners, can be analyzed in detail. Similarly, Finite Element Analysis (FEA) can give insights to the structural integrity of the system by calculating stresses and displacements. Over the last decade, these numerical tools have become widely used across all industries, as they provide fundamental technical understanding, reduce cost, and increase speed to execution and commercialization. Such tools can also be applied to the electric based systems described in the next section.

SECTION 3: PERFORMANCE IMPROVEMENT OPPORTUNITIES – ELECTRIC-BASED SYSTEMS

The term *electrotechnologies* describes a wide range of electric-based industrial operations. An important class of electrotechnologies incorporates thermal processes like heating, drying, curing, melting, and forming to manufacture or transform products. These technologies utilize equipment and systems that convert incoming electricity at line voltage to a form of applied energy that can efficiently achieve the necessary thermal effect. Some examples of industrial electrotechnology applications include infrared curing of coatings; induction melting and heat treating of metals; radio frequency drying of textiles; laser sintering, microwave curing of rubber, resistive heating by electric boosting of glass furnaces, and electric arc furnaces.

Also included in this section are some non-thermal based technologies such as ultraviolet (UV) and electron beam (EB). Their inclusion is warranted because they compete with other thermal-based technologies. For UV, the process is a photo-initiated reaction chemical conversion process. EB can direct drive cross-linking reactions that achieve curing without the need for high temperatures used in conventional curing processes. Both of these technologies are alternatives to thermal-based curing technologies such as infrared and induction curing.

Types of Electric-Based Process Heating Systems – Direct and Indirect

Electric-based process heating technologies can heat materials in two ways:

1. Direct Heating, heat generated within the material by:
    - Passing an electrical current through the material, making the material a resistive heater
    - Inducing an electrical current called an eddy current into the material
    - Exciting atoms and/or molecules within the material with electromagnetic energy (e.g., microwave and radio frequency)
2. Indirect heating is where the heat is generated external to the material and transferred to the material to be heated by Convection, Conduction, Radiation, or any combination of the three.

Hybrid Systems

Hybrid systems are becoming more common as a best practice to optimize energy use and increase overall process thermal efficiency. Hybrid process heating systems utilize a combination of process heating technologies based on different energy sources and/or different heating methods of the same energy source. Hybrid process heating systems that combine multiple forms of heat transfer through radiant, conductive, and/or convective methods can reduce heating time, increase energy efficiency, and improve product quality. As you read and learn about the different electric heating technologies in this section, do not overlook hybrid systems. Examples include electric infrared in combination with either an electric convection oven or a gas convection oven; and a paper-drying process that combines a natural gas or electric-based infrared technology with a steam-based drum dryer.

The remainder of this section covers these process heating electrotechnologies:

- Arc furnaces
- Electric Infrared processing
- Electron beam processing
- Induction heating and melting
- Laser heating
- Microwave processing
- Plasma processing (arc and non-transferred arc)
- Radio-frequency processing
- Resistance heating and melting (direct and indirect)
- Ultraviolet curing (while this is a chemical conversion process, it competes with thermal processes)

Arc Furnaces

History and Status

The first electric arc furnace was installed at the Sanderson Brothers Steel Company in Syracuse New York in 1907. Initially, arc furnaces were used to produce specialty metals such as spring steel. Today, they are 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 and/or iron scrap by direct contact with an electric arc struck from an electrode to the metal charge. There is also melting occurring from the radiant energy generated by the arc. To begin the direct arc melting process, a charge of scrap metal, often with Direct Reduced Iron (DRI) pellets, is fed into the furnace. The furnace top is sealed and the arc is struck.

There are two ways to power the electrode(s) used in the arc furnace; using Direct Current (DC) or Alternating Current (AC). Generally, the DC arc furnace is identified by the use of one or two electrodes while the AC furnace will have 3 electrodes. Which is used depends on the application.

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- 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.

Producing a ton of steel in an electric arc furnace requires around 400 to 500 kilowatt-hours. This is about one-third to one-tenth the energy required by basic oxygen furnaces or integrated blast furnaces

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 arc 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 are also used to produce 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. Refractory metals are

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.

generally categorized as metals having a high melting point such as Tungsten.

Direct arc furnaces used for steelmaking are typically smaller than integrated basic oxygen furnaces. These direct arc furnaces (sometimes 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.

Electric Infrared Processing

Infrared processing systems are used for heating, drying, curing, thermal-bonding, sintering, and sterilizing applications. Infrared applications, when designed and sized correctly, can rapidly heat an object quicker than hot air ovens. This is successfully accomplished if the absorption characteristics of the material are correctly matched to the wavelength emitted from the infrared system. Infrared systems do most of their heating using radiant energy. However, convection and conductivity can have a role in delivering and moving heat throughout the material being heated.

When discussing infrared applications, wavelength of the applied energy is one of many terms used to describe the heating process. Infrared emitters generate wavelengths generally classified as short, medium, and long, and are based on the temperature of the infrared emitter called the source temperature. Other infrared terms such as emissivity, energy density, and source temperature are important terms to know. These terms and more information on both electric and gas infrared technologies can be referenced in IHEA *Infrared Process Heating Handbook for Industrial 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-absorbing coatings, and improved emitter designs and controls, infrared is replacing many of the traditional hot air heating systems used to cure coatings. Improved quality, faster cycle time, and a smaller footprint are just a few of the advantages.

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. The absorbed energy is what heats the material. Objects being heated generally need to be in line-of-sight of the emitters (and/or reflectors which are used to direct the infrared energy to the part). However, heating and thus curing can still occur in areas not directly seen by the infrared by the heat transfer method of conductivity.

Electric infrared heating systems are typically comprised of an emitter (temperature source), a reflector system that directs the radiant energy toward the part, and a control system designed for the application. There is a wide selection of infrared emitters, reflector designs, and control systems to choose from. Therefore, the best approach for evaluating infrared is to test the application, and work with the many infrared distributors and manufacturers of infrared equipment to determine which option fits best for your application.

Some infrared emitters are designed with a ceramic board as both a reflector and absorber of infrared. The advantage of this design is to re- radiate energy from the board at a different wavelength, because of a different source temperature of the board, in combination with the primary wavelength from the source emitter. For some applications, an exhaust system may not be required. An infrared system designed to rapidly heat a material not releasing VOCs may not require ventilation; an example is water dry-off after a product wash. Because infrared systems can heat a product in as little as seconds, accurate control is critical. Using infrared without giving thought to the controls can lead to quality issues. Figure 1 shows a schematic of a typical electric infrared system with a simple feedback control system where temperature is the control point. More information about control systems can be referenced in the IHEA Infrared Process Heating Handbook for Industrial Applications.

Infrared heaters can be designed and built in a variety of shapes, sizes, and configurations. Ovens can take the form of flat lines, clam shell, tunnel u-shape, square, and round. Emitters can be selected to operate in any xyz axis orientation. There are many emitter designs, including: ceramic body types with embedded coils, exposed metal coils, ribbons, and foils mounted on ceramic boards, carbon fiber heaters, and quartz lamp and tube. These design variations give the end user the flexibility to use electric infrared technology replicate existing process applications as well as to explore new applications. Working with a knowledgeable infrared designer and applications expert, to include product testing, will ensure that the process is efficient and meets the performance required.

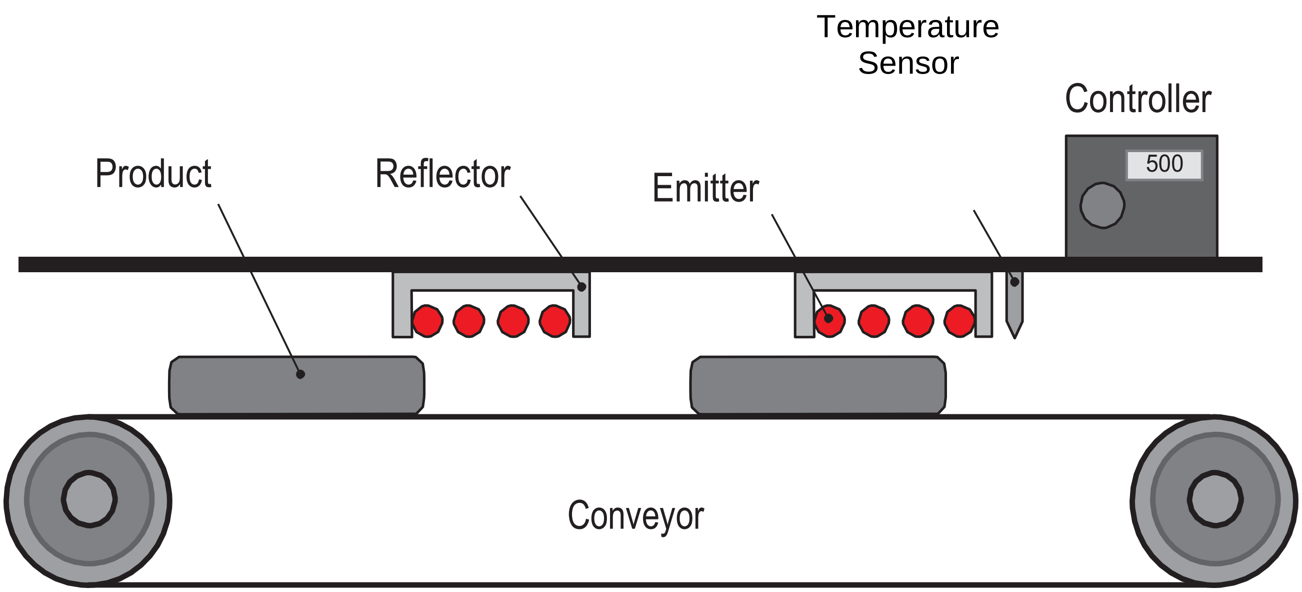


Figure 4. Simple schematic of an electric infrared heating system

Processes, Applications, and Industries

Electric infrared is ideal for situations where a fairly flat product is being heated, dried, or cured. In heating applications where infrared is used to heat heavier objects, the time to temperature is often much faster than hot air systems. However, an uneven heating situation may occur if the system is not properly designed and controlled. An example is an excavator arm that has been painted and is rapidly heated to temperature in the first zone of an infrared oven, then enters the second zone with less radiant energy applied to let temperature differences equilibrate, and finally enters a hold zone to meet curing specifications for the coating being used.

For products with complex hidden surfaces, there are solutions that can work around the line-of-sight issues. It could require a hybrid system with a convection oven where the infrared emitter panels are located in the vestibule or in the hot zone of the oven. Another solution is to use a material handling system to rotate the part to expose as much of the surface to direct infrared energy as possible. This will also assist with a more even heating of the part.

Common industrial applications for infrared are heating, curing, and drying in areas such as:

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

Types of Electric-based Infrared Emitters

Electric infrared heating systems typically comprise an emitter, a reflector system, and controls. The emitter,(heat source), is a key part of the system – the energy emission characteristics must be well matched to the absorption characteristics, called emissivity, of the materials being heated to ensure efficient operation. There are many varieties of emitters that can be incorporated into IR systems, including panel heaters, ceramic bodies with embedded coils, metal coils, ribbons, foils, fiber heaters, and other designs. Manufacturers typically classify emitters based on the wavelength of emitted energy. These classifications are described in Table 3.

Table 3. Infrared emitters by wavelength category

Infrared wavelength category	Source temperature* range (typical)	Peak wavelength/ radiant output	General category of IR emitters (typical)
Short (near)	Up to 4,000 ° F	1.15 µm / 90%	Quartz lamps having an inert gas to sustain the high source temperature. Often called T-3 for its 3/8 inch diameter lamp envelope. Considered very fast response
Medium (middle)	Up to 1,800 ° F	2.3 µm / 60%	Embedded coils in ceramic, surface mounted coils/ribbons, carbon fiber, coils in quartz tubes. Depending on emitter; medium to fast response
Long (far)	Up to 1,000 ° F	3 – 5 µm/ 50%	Embedded coils in ceramics and metal sheath Typically slow heat up time to temp; often because the heating element is of a heavier gauge metal

*Source temperature is the actual operating temperature of the infrared emitter. This is a determining factor as to the primary wavelength and radiant efficiency of the emitter. With controls, this source temperature can changed, within limits of the material, thereby changing both the radiant efficiency and wavelength.

Improve the Efficiency of Existing Electric Infrared Systems

Incorporating one or more of these recommendations can result in significant energy savings. Efficiency improvements from 10% to 30% in existing ovens have been demonstrated with the employment of these recommendations:

- 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 replacement of all failed emitters. Clean reflectors and emitters will more efficiently radiate the heat to the intended target.
- Perform periodic testing* to ensure performance. Data pack the product to review temperature profile is correct. A different emitter type or wavelength change through controls maybe necessary if a coating or process change has been made. 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.

Electron Beam Processing

History and Status

The principle of electron beam (EB) 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. Today, EB systems have become a widely used method of manufacture. They are recognized for their ease of handling, operation, and focus on safety. EB 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 are also used for curing and can cure multiple layers of web material simultaneously, as well as curing surface coatings.

Electron beams can also be used for low temperature processing of some materials. Similar to ultraviolet energy, electron beams are an ionizing form of radiation that can induce chemical reactions such as polymerization for curing of coatings and composites. Sometimes referred to as "cold curing," the process can accelerate curing times and utilize low-temperature tooling. Other non-thermal applications of electron beam processing are food irradiation and sterilization.

How the Technology Works

The basic components needed to produce a typical electron beam are an electron gun and a magnetic optic for controlling the beam to the target. The electron gun is comprised of a cathode, grid, and anode. When energized, the cathode, which directs a stream of electrons in a vacuum, and an anode, which collects the electrons, are accelerated and shaped into a controlled beam, either focused or defocused, onto the work piece. In EB heating, metals are heated to intense temperatures when a directed beam of electrons is focused against the work surface. In EB curing, a liquid is chemically transformed to a solid on the work surface by a stream of directed electrons. EB 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, which 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

EB processing is used in many thermal process applications; welding metals, machining holes and slots, surface hardening of metals, and melting. In addition to thermal heating, EB competes with conventional drying methods to cure coatings, inks, and adhesives.

High Energy EB Applications

Electron beam processing of materials in a high-energy vacuum is used in many industries as a melting technique that does not introduce contamination. High energy EB systems are easily controlled by computer and operate with precise line of sight control of the beam producing energy in a very defined area. They are used to produce materials ranging from refractory metal alloys to metallic coatings on plastic components. EB processing allows for super-pure materials and can impart unique properties to existing products. Another competitive benefit is 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.

Low-energy EB applications

Many of the traditional applications of EB technology are based on the use of low energy EB equipment, which is defined as operating with an accelerating voltage of less than 300 kV. The main processes enabled by low energy electron beam can be classified as: (A) curing, (B) crosslinking, (C) scission, and (D) grafting.

EB Curing

EB curing occurs when an electron beam creates radicals that initiate the polymerization of monomers and oligomers. Acrylate functional materials are most commonly used because of their high reactivity. In most cases, multifunctional monomers and oligomers are used to produce a cross-linked polymer network in the cured state. A well-established application for EB curing is the "drying" of inks on web-offset printed cartons, labels, and flexible packaging. There are also many other well established and emerging applications for EB curing which include applications in wood and metal coil coating and in the converting of release materials used for tape, label, electronics, and casting applications. The usage of EB curing in additive manufacturing is another emerging application area. Electron beam curing provides the ability to cure highly filled and opaque substrates at room temperature where ultraviolet (UV) curing struggles in performance in these areas.

Compared with conventional hot air drying methods, EB curing requires a much smaller footprint and lower operating labor. EB curing also drastically reduces the full cure time for coatings, inks and adhesives to less than a second. EB systems provide environmental benefits because they eliminate most volatile organic compounds, use little energy, and operate at near room temperature. Contrary to free-radical UV curing which requires a photoinitiator (or at least some photo-reactive moiety incorporated into the oligomer), free-radical EB curing occurs without adding a photoinitiator. The accelerated electrons produced by EB systems have sufficient energy to break chemical bonds within the materials themselves.

EB Crosslinking

Electron beam crosslinking occurs when free radicals recombine with each other. Crosslinking usually starts with a linear polymer material and results in the joining of adjacent polymer chains to form a three dimensional network. A relatively small number of crosslinks can often have a large impact on the thermal and mechanical properties of a polymer. Most polymers undergo both crosslinking and scissioning and the process that predominates depends on chemical structure and morphology of the polymer. Other well-established applications for EB crosslinking include high performance pressure sensitive adhesives and the nylon cord layer in automotive tires where electron beam irradiation maintains dimensional stability during the vulcanization process.

EB Scission

Electron beam scission occurs when polymer chains are broken and fail to recombine. The net result of polymer scission is a reduction in molecular weight. Industrial processes for EB scission are less common than curing or crosslinking. An example of scission is the processing of polytetrafluoroethylene (PTFE) to make low molecular weight fragments for use in waxes and lubricants. Electron beam scission can also be applied to biopolymers and cellulose. The irradiation of pulp where the modification of cellulose is needed (such as with cellulose acetate) is another emerging area of electron beam technology that could provide cost saving advantages and reduction in environmental pollutants.

EB Grafting

Electron beam induced graft copolymerization (EIGC) occurs when radicals formed in and on a polymer substrate become a site for initiation of monomer polymerization. The net result is that two dissimilar polymers are covalently joined to form a new copolymer material. Electron beam grafting is less well known than curing or crosslinking but is an important process for creation of new functional materials. It can be used to modify the properties of polymer films, gels, fibers, beads, or membranes. Applications for EB grafting include the production of polymer membranes tailored for specific separation or purification processes.

Improve the Efficiency of Existing Electron-beam 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 consumable part replacement and a consistent maintenance program for “wearable” components such as filaments and foils.
- Any changes in any of the original design parameters will require analysis of the original design to assure an efficient application of the technology.

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

In a basic induction heating setup, a solid-state power supply sends an alternating current (AC) through a copper coil creating an electromagnetic field. The material to be heated is placed inside the magnetic field where circulating eddy currents are induced within the part. These currents flow against the electrical resistivity of the metal generating heat.

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. Induction heating only works with electrically conductive materials, and metals are the usual application. However, carbon fiber is a conductive material and some carbon fiber composites can also be heated using induction. It is possible to introduce heat indirectly into non-conductive materials such as plastics by first heating a conductive metal called a susceptor, which is designed to transfer heat into the nonconductive material.

Heating and Heat Treating. For rapid heating and heat treating processes, the heating depth is easily controlled by the frequency of the electric current applied to the coil. No direct contact between the part and the coil is required, but the coil must be in close proximity to the work piece. Because there is no contract, this technology is ideal for automating industrial processes. Induction heating is often used where repetitive, high volume operations are performed. Once an induction system is calibrated for a part, work pieces can be loaded and unloaded automatically.

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 the liquid. Mixing and melting rates can be controlled by varying the frequency and power of the current in the coil. For melting operations, induction processing is used primarily in the refining and remelting of metals. Metals that are melted include aluminum, copper, brass, bronze, iron, steel, and zinc.

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 consist of a primary coil wound around 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 metal melting, combined with a fuel-fired cupola, arc, or coreless induction furnace.

Process, Applications, and Industries

Common applications for induction heating include the rapid heating of metal based parts, metal joining, welding, soldering and brazing, and selective heating and heat treating processes on metal components. Induction heat treating systems used for hardening, tempering and annealing are common, particularly in the transportation industry. Induction heat treating is used on a range of metal parts, including bar and tubing, bearings, axel shafts, camshafts, gears and sprockets.

Induction heating can produce high power densities resulting in very fast heating times to reach a target temperature. For common hardening processes, induction heating is used for localized surface hardening of an area that needs wear-resistance, while retaining the toughness for the rest of the part. These processes are easily accomplished with induction heating, and they are repeatable from part to part with a precision unmatched by most competing technologies. The depth of induction hardened patterns can be controlled by changing the induction-frequency, power-density and dwell time. With precise control of the heating zone pattern, minimal thermal distortion is seen in the part.

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 easiest to heat magnetic materials with induction 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.

Induction systems are often used in applications where only a small targeted area of a work piece needs to be heated. Hand tools are an example. 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. Other applications for induction heating include the curing of protective coatings on cast and welded pipes

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.
- Tailor the coil design to the product to increase the efficiency of heating. 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%.

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 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 useful 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 use 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, ceramic, 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). Industrial sources of microwaves are generally limited to FCC-allocated frequencies of 915 MHz, 2,450 MHz and 5,800 MHz.[4] Microwaves are used to heat materials that are electrically non-conducting (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.

Industrial 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 is usually comprised of four components:

1. **Generator** - The power supply and the magnetron. A magnetron is typically water or air-cooled and is a replacement component.

2. **Applicator** - Waveguides, usually constructed of aluminum in duct form, 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. Microwaves have a higher power density than radio frequency (RF) energy and usually heat materials faster, although RF's longer wavelengths can penetrate thicker material. For a given application, one technology is usually better than the other, and testing is recommended to determine suitability.

[4] Note – these frequencies and those used in radio frequency (RF) applications are designated as ISM bands (Industrial, Scientific and Medical)

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 will remain the same until product parameters change. Any change in the material (e.g. width, depth, or weight) will require a re-evaluation of the system in order to maintain the 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.

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 created 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 for plasma processing 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. It can also be used in the reduction process for sponge iron and smelting reduction of iron ore and scrap.

Other plasma 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. 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.

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.

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 (RF) portion of the electromagnetic spectrum is between 2 and 100 MHz. RF 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.

RF waves are produced by generators that use 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, and typical frequencies for industrial applications are 13.56 MHz and 27.12 MHz.

RF processing systems 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 RF processing is in the production of plasmas for semiconductor manufacture and in drying products in the food, lumber, and paper industries. Other applications include drying textiles and films, curing adhesives, heating plastics, baking, drying ceramic products, and sterilizing medical waste.

Convection ovens can perform the same heating processes as RF ovens. RF processing is generally used because of increased production needs, increased energy efficiency, labor savings, or space savings. In some cases, hybrid systems utilize both RF energy and a convection heating/drying.

For new applications that involve the heating/drying of dielectric materials, RF and MW should both be considered; testing can provide a good indication of the relative strengths/weaknesses of each technology for a given application.

Improve the Efficiency of Existing Radio Frequency (RF) 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, and RF energy couples directly with the water. At this point, RF energy is more efficient at removing the moisture. This technology is particularly useful for drying of heat sensitive materials, since efficient drying can occur without exceeding the boiling point of water.

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 actually flows through a material and heats it directly. This is an example of the Joule Law or effect5 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 (AC) or direct current (DC).

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. Direct resistance heating is also commonly used for heating and melting applications in the glass industry.

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. Called metal sheath heaters this type of heater can be placed directly in liquid 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.

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. 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.

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.

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.

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 curing systems are based upon either acrylate chemistry or cationically cured coatings
- Acrylate chemistry is much more common and cures free radical polymerization
- A major benefit of the acrylate method is that one can create a cured film with diverse properties because there are a wide variety of oligomers to choose from

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.

A relatively new UV LED (Light Emitting Diode) technology is encroaching on the applications that were previously served by conventional medium pressure mercury lamps. In many UV curing applications, UV LED offers reduced energy and operations costs compared to the incumbent technology. LED UV emitters are becoming more common and they are likely to eclipse the older mercury vapor lamp and xenon gas arc technologies in the coming years.

Process, Applications, and Industries

With the UV light generated, the process of curing can begin. Photoinitiators in the coating or adhesive are excited and activates the polymerization process. Photoinitiators typically absorbs light in two wavelength regions, either 260nm or 365nm. UV curing occurs via a photochemical reaction. UV coatings contain monomers, oligomers, and pigments as well as the photoinitiators. The coatings polymerize almost instantaneously into a hard plastic-like substance.

Wavelength of intense absorption tends to favor coating surface cure while wavelength of lower absorption tends to favor coating through cure, which is why some coatings require a mixture of multiple photoinitiators. There are four ranges of UV wavelengths:

UV Type	Range (nm)	Uses
UVA	315-400	For curing of thick layers i.e. floor coverings w/wear layers
UVB	280-315	In-depth drying for heavier inks coats i.e. silk screen
UVC	200-280	Maintain reaction for through curing i.e. general ink surface hardening
UVV	100-200	For surface cure/touch care; activates photoinitiators; germicidal UV

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.

Summary of Electrotechnologies for Process Heating

Table 4 summarizes the electrotechnologies that were covered in this section, with their applications, the primary industries that utilize them, and competing technologies.

Table 4. Summary of electrotechnologies for process heating

Electrotechnology	Applications	Primary Industries	Competing Technologies
Arc Furnaces	Steel production, melting steel, iron and refractory metals, smelting	Primary metal production, especially steelmaking	Oxygen furnaces (coal), plasma processing
Electric Infrared Processing	Heating, drying, curing, thermal-bonding, sintering, sterilizing	Fabricated metal products, transportation equipment, plastics and rubber	Electron beam processing, ultraviolet curing, resistance heating, induction heating
Electron Beam Processing	Melting, drying, welding, machining, curing, crosslinking, grafting	Fabricated metal products, machinery, transportation equipment, plastics	Infrared processing, laser processing, ultraviolet curing, induction melting, arc welding
Induction Heating and Melting	Heating, heat treating, melting	Fabricated metal products, primary metals, transportation equipment, machinery	Resistance heating, infrared processing, electron beam processing, gas furnaces
Laser Processing	Heat treating, hardening, trimming and cutting, welding	Transportation equipment, fabricated metal products, electronics	Electron beam processing, plasma processing, induction heating, arc welding
Microwave and RF Processing	Heating, tempering, drying, cooking, plasma production	Food/beverage, plastics and rubber, wood products, chemicals	Resistance heating, induction heating, ovens
Plasma Processing	Melting scrap, remelting for refining, reduction, surface hardening, welding, cutting	Primary metals (titanium, high-alloy steels, tungsten)	Arc furnaces, oxygen furnaces, electron beam processing, laser processing
Resistance heating and melting	Heating, brazing, sintering, melting	Glass production, metal products, plastics, chemicals, food	Induction heating and melting, infrared processing, microwave/RF processing, gas furnaces
Ultraviolet Curing	Curing, coatings, printing, adhesives, purifying	Computers, electronics, printing, fabricated metal products, transportation equipment, machinery	Electron beam processing, infrared processing

SECTION 4: WASTE HEAT MANAGEMENT – REDUCTION, RECYCLING AND RECOVERY

The Department of Energy's Advanced Manufacturing Office (AMO) has previously conducted several studies to identify heat losses from industrial energy systems. This section explores major sources and characteristics of industrial waste heat and its generation for industrial sectors, focusing on fuel-based process heating technologies. For tip sheets on specific waste heat management strategies for process heating systems, see Appendix B. A technical brief for waste heat reduction and recovery is also provided in Appendix C.

Waste heat is generated from a number of industrial systems distributed throughout a manufacturing plant. The largest sources of waste heat for most industries are exhaust or flue gases and heated air from heating systems from heat treating furnaces, dryers, and heaters; and heat from heat exchangers, cooling liquids, and gases. While waste heat in the form of exhaust gases is readily recognized, waste heat can also be found in liquids and solids. Liquids containing waste heat include cooling water, heated wash water, and blow-down water. Solids containing waste heat can be hot products that are discharged after processing or after reactions are complete, or they can be hot by-products from processes or combustion of solid materials. Other waste heat sources that are not as apparent include hot surfaces, steam leaks, and boiler blow-down water etc. Table 5 shows major sources of industrial waste heat along with the temperature range and characteristics of the source

Table 5. Temperature range and characteristics for industrial waste heat sources[5]

Waste Heat Source	Temperature Range °F	Cleanliness
Furnace or heating system exhaust gases	600 – 2,000	Varies
Gas (combustion) turbine exhaust gases	900 – 1,100	Clean
Reciprocating engines		
Jacket cooling water	190 – 200	Clean
Exhaust gases (for gas fuels)	900 – 1,100	Mostly clean
Hot surfaces	150 – 600	Clean
Compressor after-inter cooler water	100 – 180	Clean
Hot products	200 – 2,500	Mostly clean
Steam vents or leaks	250 – 600	Mostly clean
Condensate	150 – 500	Clean
Emission control devices – thermal oxidizers, etc.	150 – 1,500	Mostly clean

Typical Waste Heat Streams in Plant Operations

The waste streams from almost all industries vary in temperature, composition, and content, which may include particulates, vapors, or condensable materials. Following are the types of waste heat streams:

[5] Oak Ridge National Laboratory (ORNL), *Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities*, Arvind Thekdi (E3M Inc.) and Sachin Nimbalkar (ORNL), ORNL/TM-2014/622, January 2014.

Exhaust Gases or Vapors

The exhaust gases or vapors can be classified in the following categories:

- High-temperature combustion products or hot flue gases that are relatively clean and can be recovered using commercially viable heat recovery equipment to produce high-temperature air, steam, or water for use in processing equipment or other uses such as direct discharge for building heating. Examples include a large number of directly fired and indirectly fired heating processes that are widely used by all major industries.
- High-temperature flue gases or combustion products with contaminants such as particulates and condensable vapors. In many cases, these contaminants would present problems due to condensation of vapors in liquids or on solids, which can foul the surfaces of the heat transfer equipment. Examples include exhaust gases from melting furnaces, dryers, kilns, and coal-fired boilers.
- Heated air or flue gases containing high (>14%) O_2 without a large amount of moisture and particulates. This stream does not have as many restrictions on condensation temperature as the combustion products due to the low concentration or absence of acid-forming gases (e.g., CO_2) and can be cooled to a lower temperature without having major detrimental effect of corrosion. Examples include indirectly used cooling air from processes, gas turbine exhaust gases, some product cooling systems, and air coolers used in refrigeration or chiller systems.
- Process gases or by-product gases and vapors that contain combustibles in gaseous or vapor form requiring further treatment before their release into the atmosphere. Examples are exhaust from coating ovens and process reactors.
- Process or make-up air mixed with combustion products, large amounts of water vapor, or moisture mixed with small amounts of particulates but no condensable organic vapors. Examples include exhaust air from paper machines, ceramic dryers, and food dryers.
- Steam discharged as vented steam or steam leaks.
- Other gaseous streams.

Heated Water or Liquid

Heated water or liquid can be classified in the following categories:

- Clean heated water discharged from indirect cooling systems such as process or product cooling or steam condensers. This stream does not contain any solids or gaseous contaminants.
- Hot water that contains large amounts of contaminants, such as solids from the process or other sources, but does not contain organic liquids or vapors. The solids can be filtered out without further treatment of water. Examples include quenching or cooling water used to cool hot parts in the metals industry, paper industry, or cement industry.
- Hot water or liquids containing dissolved solids, dissolved gases (e.g., CO_2, SO_2), or liquids. These liquids (water) require further treatment before their use or discharge in the streams. Examples include scrubber water; wash water from chemical processes or from the food, paper, or textile industries.

Heated Products or By-Products

Heated products or by-products can be classified in the following categories:

- Hot solids or products that are cooled after heating and are in an uncontrolled manner. Examples are hot slabs, mineral products, paper or textile web, and food cereals. These products are usually cooled by natural or forced cooling using air, but the heat is not recovered. Hot solids that are cooled after processing using water or an air-water mixture. Examples include hot coke, ash, slag, and heat-treated parts.
- Hot liquids and vapors that are cooled after thermal processing. Examples include fluids heated in petroleum refining, chemical, food, mining, and paper industries.
- By-products or wastes that are discharged from thermal processes. These materials contain sensible, latent, and chemical heat that is not recovered prior to its disposal. Examples include ash from coal- or solid-waste-fired boilers, slag from steel melting operations, dross from

aluminum melters, and bottom waste from reactors or sludge.

High-Temperature Surfaces

High-temperature surfaces can be classified in the following categories:

- Furnace or heater walls where a large amount of heat is lost due to convection and radiation.
- Extended surfaces or parts used in furnaces or heaters.

Waste Heat Management

Waste heat management includes waste heat reduction, recycling, and recovery.

1) Waste heat reduction (heat containment):

Waste heat reduction refers to the reduction of energy losses to the surroundings. Most process heating equipment including boilers loose heat in many different ways. Major areas of heat loss, which can be reduced through use of good system design, operating practices and maintenance of heating systems, are discussed below.

A large amount of literature and a number of tools such as the Process Heating Assessment Tool (PHAST) are available that can be used to reduce heat losses. Major areas of heat loss from process heating systems include:

- Exhaust or flue gas. All fuel fired equipment and some electrically heated equipment require discharge of large amount of hot gases at temperature that is dependent on the process temperature and other factors such as use of heat recovery systems. These gases may contain combustion products such as CO_2, H_2O, O_2, N_2 and, in some cases gaseous. Or solid contaminants
- 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.
- Radiation heat loss from 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 or surfaces 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

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

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.

2) Waste heat recycling:

Waste heat recycling is the use of waste heat from a process heating system for its use within the same system (see Figure 5). Important characteristic of waste heat recycling is complete synchronization of heat supply and heat demand or use for a given heating system. Heat recycling opportunities depend largely on the design of the system and the requirements of the process.

A commonly used method of waste heat recycling is use of exhaust gas heat from a fuel fired system to preheat the burner combustion air or make up air in ovens or dryers. In this case heat from the exhaust gases or combustion products is transferred to combustion air for the burners using a recuperator, regenerator, heat pipes etc. This type of preheating reduces the amount of fuel required to establish and maintain the necessary temperature of the process.

Another example of heat recycling is the transferring exhaust gas heat back to the material being heated or processed, which also reduces energy use in the heating system since the product does not have to be heated from ambient or lower temperature. Use of an economizer used to heat feed water is another example of waste heat recycling. Recycling of waste heat can reduce energy use or energy intensity by as much as 25%.

The heat lost from exhaust gases depends on mass flow and temperature of gases. The exact amount of energy reduction, commonly expressed in terms of energy intensity or energy used per unit of production depends on various factors such as exhaust gas temperature, method of heat recycling, percentage heat recycled, heat recycling equipment design etc. Depending on the factors mentioned earlier, it is possible to reduce energy intensity by 5% to 25% for heating systems.

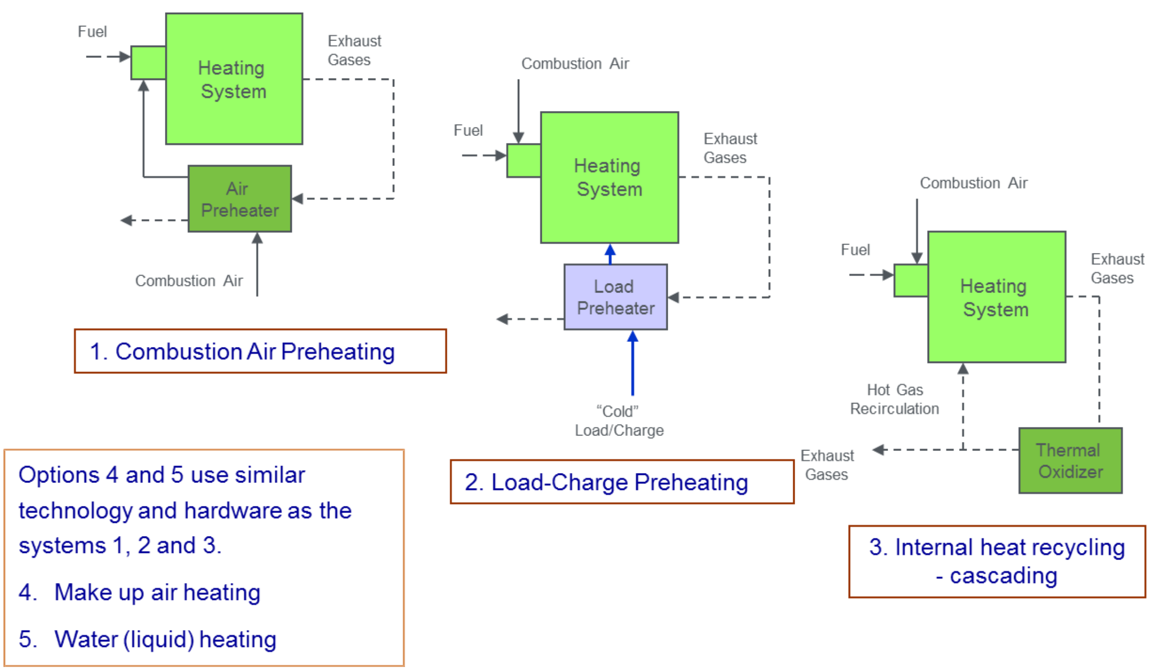


Figure 5. Waste heat recycling options (Courtesy – Arvind Thekdi, E3M Inc.)

Waste heat recycling should be the first consideration before other method of waste heat recovery is considered.

Transferring excess energy from exhaust gas back into the same 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 products to the exhaust 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 combustion and efficiency.

However, even in applications that do not require this type of preheating for proper performance, combustion air preheating can be an attractive method of 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.

Advantages of waste heat recycling are:

- Compatible with process demand and variations in operating conditions
- Can be used as retrofit for existing equipment
- Relatively easy and inexpensive to implement
- Heat recovery – 30% to 90% of the waste heat
- Typical payback periods – one year to three years
- Application temperature range – Typically it ranges from 225°C and higher. Depends on specific process conditions.

3) Waste heat recovery:

Waste heat recovery is the extraction of waste heat from one process heating system and using it in another 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, electrical power or to heat feed water for other boilers can increase the system efficiency significantly. The most important consideration while selecting waste heat recovery system is matching of heat supply to the heat demand for the selected utility within a plant or a neighboring plant.

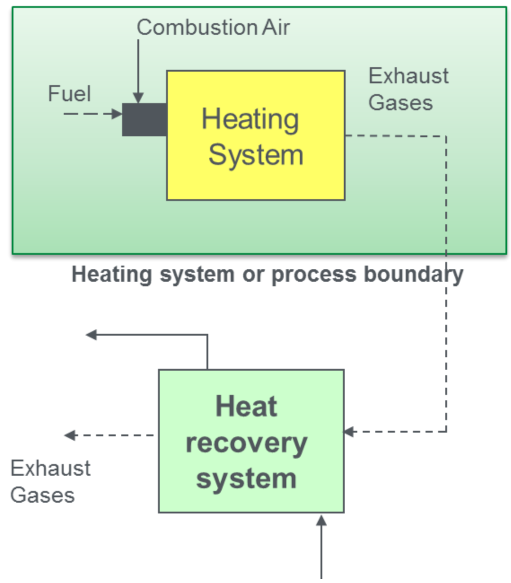


Figure 6. Waste heat recovery concept (Courtesy – Arvind Thekdi, E3M Inc.)

At 2 page tip sheet on waste heat recovery was developed by DOE in 2011[6]. Commonly used waste heat recovery options and equipment are:

- Water (i.e. process, boiler feed water) or other fluid (i.e. heat transfer liquids) heating - use water to gas heat exchangers
- Air heating for process or HVAC application – use gas to gas heat exchanger or regenerative systems
- Steam generation – use waste heat recovery boilers
- Heat cascading (using hot flue gases for lower temperature processes) – use direct injection of gases or heat exchangers.
- Other methods (i.e. absorption chillers) – use specialized equipment such as absorption chillers
- Electrical power generation – use steam based system or other low temperature systems discussed later.

Advantages of waste heat recovery are:

- Use of waste heat to supplement the plant utility or auxiliary systems reduces the plant energy use.
- Can be used as retrofit for existing equipment or for new processes
- Heat recovery – 10% to 75% of the waste heat
- Typical payback periods – one-half year to five years. Installed cost varies with the type of system selected.
- Application temperature range – as low as 225°C exhaust gas temperature. Higher temperature limit is usually 900°C exhaust gas temperature.

Commonly Used Waste Heat Management Systems

Industry uses a wide variety of waste heat management equipment offered by a number of suppliers in United States and from other countries. Much of this equipment is designed for specific crosscutting industrial applications. There is no standard method for classifying this equipment; in many cases the manufacturers offer application-specific designs. A summary of conventional or commonly used waste heat management technologies for various temperature ranges is found in Table 6.

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

The AMO offers these resources to help you implement energy efficiency measures in process heating containment:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Also visit the Advanced Manufacturing Office web site to download these and other process heating related resources: ***www.energy.gov/eere/amo***

Table 6. Commonly used waste heat management systems, by temperature range

[6] Unlock Energy Savings with Waste Heat Recovery, US Department of Energy, DOE/EE-0577, July 2011

Ultra-High Temperature (>1600°F)	High Temperature (1200°F to 1600°F)	Medium Temperature (600°F to 1200°F)	Low Temperature (250°F to 600°F)	Ultra-Low Temperature (< 250°F)
• Refractory (ceramic) regenerators • Heat recovery boilers • Regenerative burners • Radiation recuperator • Waste heat boilers including steam turbine-generator based power generation • Load or charge preheating	• Convection recuperator (metallic) – mostly tubular • Radiation recuperator • Regenerative burners • Heat recovery boilers • Waste heat boilers including steam turbine-generator based power generation • Load or charge preheating • Metallic heat wheels (regenerative system)	• Convection recuperator (metallic) of many different designs • Finned tube heat exchanger (economizers) • Shell and tube heat exchangers for water and liquid heating • Self-recuperative burners • Waste heat boilers for steam or hot water condensate • Load-charge (convection section) preheating • Metallic heat wheel • Heat pipe exchanger	• Convection recuperator (metallic) of many different designs • Finned tube heat exchanger (economizers) • Shell and tube heat exchangers for water and liquid heating • Heat pumps • Direct contact water heaters • Condensing water heaters or heat exchangers • Metallic heat wheel • Heat pipe exchanger	• Shell and tube type heat exchangers • Plate type heat exchangers • Air heaters for waste heat from liquids • Heat pumps • HVAC applications (i.e., recirculation water heating or glycol-water recirculation) • Direct contact water heaters • Non-metallic heat exchangers

Table 7 lists emerging technologies that may be used in a few cases, or are in some stage of development and demonstration

Table 7. Emerging or developing waste heat management technologies, by temperature range

Ultra-High Temperature (>1600°F)	High Temperature (1200°F to 1600°F)	Medium Temperature (600°F to 1200°F)	Low Temperature (250°F to 600°F)	Ultra-Low Temperature (< 250°F)
• Regenerative burners • Systems with phase change material • Advanced regenerative systems • Advanced load or charge preheating systems	• Recuperators with innovative heat transfer surface geometries • Thermo-chemical reaction recuperators • Advanced design of metallic heat wheel type regenerators • Advanced load or charge preheating systems • Systems with phase change material • Self-recuperative burners	• Recuperators with innovative heat transfer surface geometries • Advanced design of metallic heat wheel type regenerators • Self-recuperative burners • Systems with phase change material • Advanced heat pipe exchanger • Advanced design of metallic heat wheel • Thermoelectric electricity generation systems	• Convection recuperator (metallic) of many different designs • Advanced heat pipe exchanger • Advanced heat pumps • Membrane type systems for latent heat recovery from water vapor • Low temperature power generation (i.e., ORC, Kalina cycle, etc.) • Thermally activated absorption systems for cooling and refrigeration • Systems with phase change material • Thermoelectric electricity generation systems • Condensing water heaters or heat exchangers	• Non-metallic (polymer or plastic) corrosion resistant heat exchangers of many different designs • Systems with phase change material • Desiccant systems for latent heat recovery from moisture laden gases • Membrane type systems for latent heat recovery from water vapor • Condensing water heaters or heat exchangers • Thermally activated absorption systems for cooling and refrigeration

Waste Heat to Power Technologies

Waste heat to power (WHP) is the process of capturing heat discarded by an existing process and using that heat to generate electricity. WHP technologies fall under the waste heat recovery category. In general, the least expensive option for utilizing waste heat is to re-use this energy in an on-site thermal process. If it is not feasible to recover energy from a waste heat stream for another thermal process, then a WHP system may be an economically attractive option.

Commonly used WHP technologies are:

- Rankine Cycle (RC) - The most common example of the Rankine cycle is the steam turbine, or steam Rankine cycle (SRC). In a SRC system, the working fluid is water, and steam is created to drive a turbine.
- Organic Rankine Cycle (ORC) - Organic Rankine cycle (ORC) systems are similar to SRC systems, but instead of water the working fluid is a hydrocarbon, hydrofluorocarbon, or ammonia.
- Kalina Cycle (KC) - The Kalina cycle is a variation of the Rankine cycle, using a binary fluid pair as the working fluid (typically water and ammonia).
- Supercritical CO2 Cycle - Another variation of the Rankine Cycle is the supercritical CO2 (sCO2) cycle, which utilizes carbon dioxide in place of water/steam for a heat-driven power cycle.

Waste Heat to Power Considerations

While conducting the feasibility analysis of WHP technologies for specific industrial applications, the following factors should be taken into consideration:

- Need relatively clean and contamination free source of waste heat (gas or liquid source). Avoid heavy particulate loading and/or presence of condensable vapors in waste heat stream.
- Continuous or predictable flow for the waste heat source
- Relatively moderate waste heat stream temperature (at least 150°C, but >325°C is preferred) at constant or predictable value
- Cannot find or justify use of heat within the process or heating equipment itself
- Cannot find or justify alternate heat recovery methods (steam, hot water, cascading etc.) that can be used in the plant
- Try to avoid or reduce use of supplementary fuel for power generation. It can have a negative effect on overall economics unless the power cost can justify it.

An extensive market assessment for WHP applications was published by Oak Ridge National Laboratory in March 2015.[7] This report should be consulted for detailed analyses and recommendations for WHP applications and technologies.

Barriers to Waste Heat Management

Commonly observed barriers to waste heat management are listed below. A few of these barriers may be interrelated. Some of the technical barriers lead to cost barriers.

Temperature of waste streams:

- High – costly high temperature resistant materials needed for the heat recycling or recovery equipment
- Low – Condensation of water vapor or other condensable may result in corrosion of metals used in heat recycling or recovery equipment. It is also necessary to use large surface areas. Few viable uses for recovered heat at lower temperature.
- Temperature variations in streams

Chemical composition of waste streams:

- Deposition reduces heat transfer
- Risk of contamination between streams – product/process risk
- Environmental concerns
- Material constraints
- Operational and maintenance concern

Mass flow rate of waste streams:

- Fluctuations in flow rates
- Intermittent nature of waste heat opportunity
- Waste streams mixed with process or product generated solids, liquids, and gases

Cost effectiveness:

- Long payback period for heat recovery equipment and auxiliary systems
- Material costs
- Operation and maintenance costs
- Economics of scale

Implementation constraints:

- Process specific recovery and design
- Heat recovery complicates process
- Limited space
- Transportability
- Inaccessibility

General Guidelines and Considerations for Waste Heat Management

The first step is to identify waste heat sources and reduce generation of waste heat. Use all possible methods given in resources available in the form of tip sheets and training programs developed by the US DOE – AMO and other organizations. This is the most cost effective and quickest way to reduce energy use and improve overall thermal efficiency of a heating system.

The next step is to select an appropriate method of heat recycling where the waste heat is used within the heating system itself. This would eliminate issues

[7] *Waste Heat to Power Market Assessment*, Prepared by ICF International, Prepared for Oak Ridge National Laboratory, U.S. Department of Energy, March 2015.

related to matching of supply and demand of heat. The most commonly used method of waste heat recycling for fuel fired systems is preheating combustion air where the flue gas temperature is relatively high – usually higher than 1000 deg. F. However, preheating of makeup air or dilution air should be considered at all temperatures for processes using high volumes of air as in case of drying ovens.

The possibility of load or charge preheating should be considered for new equipment and in cases where available space and system configuration allows its use. A few examples of charge preheating include feed water heating for boilers, drying and preheating of materials in metals and non-metal industries.

If heat recycling is not possible, or there is a considerable amount of waste heat remaining after recycling avenues have been explored, then consider using recovered waste heat within the plant. Commonly used examples are:

- Use of hot gases in lower temperature processes, to preheat water or cleaning liquids used in the plant
- Use of heat for space heating in plants located in colder climate
- Steam generation where waste heat streams contain large (>10 MMBtu/hr) amounts of recoverable heat.

Consider use of electric power generation using steam turbine-generator system or other systems such as organic Rankin Cycle (ORC) systems when it is not possible to use heat within the plant or when there is a strong case based on economics to use on site power generation.

It is necessary to evaluate waste heat characteristics such as temperature, flow rates, waste gas, and presence of contaminations (solids or liquid vapors and other condensable materials). These factors, along with variations in temperature and flow rates will affect the overall economics of the waste heat recycling or recovery system.

Finally, consider the use of professional help to investigate and analyze waste heat reduction, recycling and recovery projects so all aspects of the project are considered and a proper economic analysis is carried out before moving forward with a plan.

SECTION 5: PROCESS HEATING SYSTEM ECONOMICS

Usually, industrial facility managers must convince upper management that an investment in efficiency is worthwhile. Communicating this message to decision-makers can be more difficult than the actual engineering behind the concept. The corporate audience will respond more readily to a dollars-and-cents impact than to a discussion of energy use and efficiency ratios. By adopting a financial approach, the facility manager relates efficiency to corporate goals.

Collaboration with financial staff can yield the kind of proposal that is needed to win over corporate officers who have the final say over capital investments such as system upgrades.

Before presenting some recommendations for how to justify improvement projects, it is useful to understand the world as the corporate office usually sees it.

Understanding Corporate Priorities

Corporate officers are held accountable to a chief executive, a board of directors, and an owner (or shareholders). It is the responsibility of these officers to create and grow the capital value of the firm. The corporation's industrial facilities do so by generating revenue that exceeds the cost of owning and operating the facility itself. Plant equipment— including system components—is considered an asset that must generate an economic return. The annual earnings attributable to the sale of goods produced by these assets, divided by the value of the plant assets themselves, describe the rate of return on assets. This is a key measure by which corporate decision-makers are held accountable.

Financial officers seek investments that are most certain to demonstrate a favorable return on assets. When faced with multiple investment opportunities, the officers will favor those options that lead to both the highest return on capital employed and the fastest payback.

This corporate attitude may impose the following (sometimes unpleasant) priorities on the facility manager: ensuring reliability in production, avoiding unwanted surprises by sticking with familiar technology and practices, and helping control costs by cutting a few corners in maintenance and upkeep. This mindset may cause industrial decision-makers to conclude that efficiency is a luxury that cannot be afforded.

However, industrial efficiency can save money and contribute to corporate goals while effectively reducing energy consumption and cutting noxious combustion emissions.

Measuring the Dollar Impact of Efficiency

Process heating efficiency improvements can move to the top of the list of corporate priorities if the proposals respond to distinct corporate needs. Corporate challenges are many and varied, which opens up opportunities to sell efficiency as a solution. Process heating systems offer many opportunities for improvement; the particulars are shared elsewhere in this sourcebook. Once the selections are made, the task is one of communicating the proposals in corporate (i.e., "dollars-and-cents") language.

The first step is to identify and enumerate the total dollar impact of an efficiency measure. One framework for this is known as life-cycle cost analysis. This analysis captures the sum total of expenses and benefits associated with an investment. The result—a net gain or loss on balance—can be compared to other investment options or to the anticipated outcome if no investment is made. As a comprehensive accounting of an investment option, the life- cycle-cost analysis for an efficiency measure would include projections of:

- Search and selection costs for seeking an engineering implementation firm
- Initial capital costs, including asset purchase, installation, and costs of borrowing
- Maintenance costs
- Supply and consumable costs
- Energy costs over the economic life of the implementation
- Depreciation and tax impacts
- Scrap value or cost of disposal at the end of the equipment's economic life
- Impacts on production, such as product quality and equipment efficiency.

One revelation that typically emerges from this exercise, is that in some cases fuel costs may represent as much as 90% or more of life-cycle costs, while the initial capital outlay is only 3%, and maintenance a mere 1%. Clearly, any measure that reduces fuel consumption (while not reducing reliability and productivity) will certainly yield positive financial results for the company.

Presenting the Financial Benefits of Efficiency

As with any corporate investment, there are many ways to measure the financial impact of efficiency investments. Some methods are more complex, and proposals may use several analytical methods side-by-side. The choice of analyses used will depend on the sophistication of the presenter and the audience.

A simple (and widely used) measure of project economics is the payback period. This is defined as the period of time required for a project to break even. It is the time needed for the net benefits of an investment to accrue to the point where they equal the cost of the initial outlay.

For a project that returns benefits in consistent, annual increments, the simple payback equals the initial investment divided by the annual benefit. Simple payback does not take into account the time value of money. In other words, it makes no distinction between a dollar earned today versus a dollar of future (and therefore uncertain) earnings. Still, the measure is easy to use and understand and many companies use simple payback for a quick go/no-go decision on a project. There are several important factors to remember when calculating a simple payback:

- Payback is an approximation, not an exact economic analysis.
- All benefits are measured without considering their timing.
- All economic consequences beyond the payback are ignored.
- Payback calculations will not always indicate the best solution for choosing among several project options (because of the two reasons cited immediately above).
- Payback does not consider the time value of money or tax consequences.

More sophisticated analyses take into account factors such as discount rates, tax impacts, the cost of capital, etc. One approach involves calculating the net present value of a project, which is defined in the equation below:

Net Present Value (NPV) = Present worth of benefits – Present worth of costs

Another commonly used calculation for determining economic feasibility of a project is internal rate of return (IRR), which is defined as the discount rate that equates future net benefits (cash) to an initial investment outlay. This discount rate can be compared to the interest rate at which a corporation borrows capital.

Many companies set a threshold (or hurdle) rate for projects, which is the minimum required IRR for a project to be considered viable. Future benefits are discounted at the threshold rate, and the net present worth of the project must be positive in order for the project to move ahead.

Relating Efficiency to Corporate Priorities

Operational cost savings alone should be a strong incentive for improving process heating system efficiency. Still, that may not be enough for some corporate observers. The facility manager's case can be strengthened by relating a positive life-cycle cost outcome to specific corporate needs. Some suggestions for interpreting the benefits of fuel cost savings include the following. (Finance staff can suggest which of these approaches are best for the current corporate climate.)

New Source of Permanent Capital

Reduced fuel expenditures—the direct benefit of efficiency—can be thought of as a new source of capital to the corporation. The investment that makes this efficiency possible will yield annual savings each year over the economic life of the improved system. Regardless of how the efficiency investment is financed, whether borrowing, retained earnings, or third party financing, the annual savings will be a permanent source of funds as long as efficiency savings are maintained on a continuous basis.

Added Shareholder Value

Publicly held corporations usually embrace opportunities to enhance shareholder value. Process heating efficiency can be an effective way to capture new value. Shareholder value is the product of two variables: annual earnings and the price-to-earnings (or P/E) ratio. The P/E ratio describes the corporation's stock value as the current stock price divided by the most recent annual earnings per share. To take advantage of this measure, the efficiency proposal should first identify annual savings (or rather, addition to earnings) that the proposal will generate. Multiplying that earnings increment by the P/E ratio yields the total new shareholder value attributable to the efficiency implementation.

Reduced Cost of Environmental Compliance

Facility managers can proactively seek to limit the corporation's exposure to penalties related to environmental emissions compliance. Efficiency, as total-system discipline, leads to better monitoring and control of fuel use. Combustion emissions are directly related to fuel consumption. They rise and fall in tandem.

By improving efficiency, the corporation enjoys two benefits: decreased fuel expenditures per unit of production, and fewer incidences of emission-related penalties.

Worker Comfort and Safety

Process heating system optimization requires ongoing monitoring and maintenance that yields safety and comfort benefits, in addition to fuel savings. The routine involved in system monitoring will usually identify operational abnormalities before they present a danger to plant personnel. Containing these dangers precludes threats to life, health, and property.

Reliability and Capacity Use

Another benefit to be derived from efficiency is more productive use of assets. The efforts required to achieve and maintain energy efficiency will largely contribute to operating efficiency. By ensuring the integrity of system assets, the facility manager can promise more reliable plant operations. The flip side, from the corporate perspective, is a greater rate of return on assets employed in the plant.

Call to Action

A proposal for implementing an efficiency improvement can be made attractive to corporate decision-makers if the facility manager takes the following steps:

- Identifies opportunities for improving efficiency
- Determines the life-cycle cost of attaining each option
- Identifies the option(s) with the greatest net benefits
- Collaborates with financial staff to identify current corporate priorities (for example, added shareholder value, reduction of environmental compliance costs, and improved capacity utilization)
- Generates a proposal that demonstrates how project benefits will directly respond to current corporate needs.

SECTION 6: PROCESS HEATING AND SUSTAINABLE MANUFACTURING

Sustainable Manufacturing

Sustainable manufacturing is the ability to continuously utilize resources to manufacture products and maintain the environment and our lifestyles indefinitely. Sustainability requires that our resources remain at their current levels or improve for future generations. Thus, aspects of sustainability include recycling, waste heat management, use of renewable energies, reduction in pollution to levels that our planet can absorb, and reduction in greenhouse gases to reverse the trends of global warming.

Sustainability is growing in importance as a driver and key characteristic for consideration during the evaluation of energy related decisions. Manufacturers can no longer ignore the potential negative brand impacts of business decisions that are viewed as "unsustainable" by activist groups, governments and regulators, key customers, the media and the public at large, particularly in the emerging age of social media.

Sustainability in the context of this discussion refers to choices about the capital acquisition, upgrade, operation and maintenance practices that can have significant implications for a manufacturers future environment, health and safety footprint, profitability and overall standing in the public view with regard to social responsibility. There are obvious and tangible impacts such as solid and hazardous waste streams, regulatory non-compliance events, water usage and pollution reporting requirements. However, less obvious but equally important are issues like air emissions, related Scope I and II pollutants, and carbon footprint reporting that are dominated by a facilities energy consumption.

A manufacturer's sustainability is no longer just a matter of the preference of internal governance. Factors such as a firm's consumer brand awareness, participation in sustainability sensitive supply chains, foreign ownership, global market participation, government contracts, etc. have greatly expanded the list of stakeholders that must be satisfied with a firm's sustainability performance.

Process heating system design and investment criteria must account not only for the direct first and internal operating costs but also indirect and external full life cycle costs associated with each of the process options. Long run sustainable manufacturing must consider the energy sources and uses associated not only with material conversion or treatment processes but also all of the required ancillary equipment and services (e.g., combustion air blowers, compressed air, tower, chilled and city water, HVAC impacts, process fluid handling, treatment and disposal, material handling). Ultimately, the resource intensity of finished goods must become the standard of measurement toward continuous improvement objectives that lead to a sustainable manufacturing future, including:

- Volume/weight of solid waste per lb. of finished goods shipped.
- kWh or DTh energy input per unit of production
- Tons of carbon emissions per/ lb. of finished goods shipped
- Gallons of waste water/ lb. of finished goods shipped

Decisions regarding energy sources and uses options for process heating applications must also contemplate potential human health and safety risks and impacts for the workforce and the immediately surrounding community.

Recycling is a necessary part of sustainability as it reuses discarded products which reduce energy use and emissions. The use of renewable energy such as solar, biomass, and wind is also an important part of sustainability as it conserves our finite fossil fuels and reduces greenhouse gases. Finally, reducing greenhouse gases is imperative for a sustainable world since global warming is likely to produce harmful and irreversible damage to humanity.

Potential Benefits of Sustainable Manufacturing

Sustainability has become a significant non-energy benefit that manufacturers must consider when weighing options for process heating technologies. For example, environmental factors could create market drivers for electrotechnologies that reduce the need for on-site handling or disposal of hazardous materials. Similarly, electrotechnologies like induction heating or resistance heating may be preferentially employed in place of fuel-fired furnaces in locations with strict air quality requirements. The increased use of electrotechnologies in these scenarios can result in increased sustainability in the manufacturing sector.

Similarly, direct fired combustion with a natural gas steam boiler or a radiant tube recuperated gas fired furnace may represent the lowest net carbon footprint and most cost effective option for certain processes. Biofuels, biomass and other renewable options may be attractive in certain markets, particularly when combined heat and power (CHP) can be utilized.

In the municipal water sector, ozonation and UV systems can reduce the use of chemical disinfectants, which require special handling, create undesirable chemical byproducts, and leave excessive residual chemicals in the water. Moreover, increasing concerns about cryptosporidium and giardia in water supply systems are forcing system operators to investigate these electrotechnology alternatives, since the chemical treatments will not eliminate the pathogens.

Sustainability will play an increasingly important role in the decisions made by industrial facilities, including process heating systems. Process heating equipment, fuels, utilization patterns and practices will need to adapt to growing sustainability concerns. Along with improvements in waste heat utilization, incorporating highly efficient electrotechnologies with electricity produced largely by renewable or sustainable fuels will be the most likely result of this trend.

SECTION 7: WHERE TO FIND HELP

This portion of the sourcebook lists resources that can help end users increase the cost-effective performance of process heating systems. Various programs involved in the process heating marketplace are described, including the DOE's Advanced Manufacturing Office (AMO) and the Industrial Heating Equipment Association (IHEA). The Directory of Contacts provides contact information and descriptions of the IHEA and other associations and organizations involved in the process heating system marketplace.

Under Resources and Tools, information on books, reports, technical newsletters, government and commercial statistics and market forecasts, software, training courses, and other sources of information that can help end users make informed process heating system equipment purchase and system design decisions is also provided.

The information provided is current as of the publication of this sourcebook. Please check the AMO web site at www.energy.gov/eere/amo for the latest versions of DOE publications, tools, case studies, tip sheets, software, and other materials referenced throughout this section.

Advanced Manufacturing Office

U. S. Department of Energy
Office of Energy Efficiency and Renewable Energy
www.energy.gov/eere/amo

Overview

The Department of Energy's Advanced Manufacturing Office (http://energy.gov/eere/amo/advanced-manufacturing-office) partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States. Built upon a foundation of strong public-private partnerships, AMO's support of advanced manufacturing process and materials R&D projects and shared technical facilities helps transition scientific innovations into new manufacturing capabilities for the security and well-being of our country and the world. By making direct investments in advanced manufacturing enterprise creation, manufacturing's deep supply chains enable innovation spillovers across more firms and industries than investments in other economic sectors. These spillover benefits extend the reach of the government's assistance far past our initial investments and become reinvestments in the great ideas and promising capabilities that will drive the next generation of manufactured goods for the U.S. economy.

AMO Technical Assistance Activities

In addition to R&D, AMO also delivers solutions for industry that result in significant energy and cost savings, waste reduction, pollution prevention, and enhanced environmental performance. AMO's technical assistance comes through a number of different programs, including Better Plants, Superior Energy Performance, Industrial Assessment Centers, and Combined Heat and Power Deployment. AMO also supports energy system related software tools, training, technical publications and case studies. Information on all of the AMO's Technical Assistance Activities and resources can be found at http://energy.gov/eere/amo/ta.

Better Plants. The DOE's Better Buildings, Better Plants Program is an important partnership where companies sign a voluntary pledge to reduce their energy intensity by up to 25 percent over a ten-year period. In turn, DOE provides public recognition of energy savings excellence as well as technical support in data collection and energy systems to support the goals of our partners. For more information visit www.energy.gov/betterplants.

Superior Energy Performance. DOE is providing resources to facilities that seek to go beyond the ISO 50001 standard and become certified to Superior Energy Performance (SEP). SEP plants are leaders in energy management and productivity improvement have been shown to improve their energy performance up to 25% over three years or up to 40% over 10 years. For more information visit www.energy.gov/isosep.

Industrial Assessment Centers. Small- and medium-sized manufacturers may be eligible to receive a no-cost assessment provided by DOE's Industrial Assessment Centers (IACs). The IAC teams, located at 24 engineering universities around the country, conduct the energy audits to identify opportunities to improve productivity, reduce waste, and save energy. Over 16,000 IAC assessments have been conducted, with case studies available. For more information visit www.energy.gov/iac.

Combined Heat and Power Deployment. Combined heat and power (CHP) provides a cost-effective, near-term technology opportunity to reduce greenhouse gas emissions by efficiently generating on-site electric power and useful thermal energy from a single fuel source. The CHP Deployment Program provides stakeholders with the resources necessary to identify CHP market opportunities and support the implementation of CHP systems. www.energy.gov/chp.

Energy Resource Center

The AMO's Energy Resource Center provides system related software decision support tools, training, technical publications and case studies, as well as information on industrial assistance, state and utility engagement. Related publications available from the AMO's Energy Resource Center are further discussed in the Resources and Tools section of this sourcebook.

Software Tools. AMO's Steam System Modeling Tool (SSMT), located at http://energy.gov/eere/amo/software-tools, is designed to help users survey and assess their steam system.

Properties and equipment calculators within SSMT will allow the user to input the metrics of their system, generate a list of detailed steam specific steam properties, and test a variety of adjustments on individual equipment. The modeler allows the user to create a 3-pressure-header basic model of the current steam system.

Awareness Modules for the SSMT is also available at http://energy.gov/eere/amo/software-tools to orient users on how to utilize this tool.

Other software tools for industrial manufacturing are also available from AMO, including MotorMaster+, AirMaster+, the Pump System Assessment Tool (PSAT), and the Fan System Assessment Tool (FSAT). Descriptions and links to all of the downloadable software and awareness modules can be found at http://energy.gov/eere/amo/software-tools.

Technical Publications. Sourcebooks, handbooks, tip sheets, technical fact sheets, market assessments, case studies, and presentations are available through the AMO website. These publications cover a variety of industrial systems and topics, including process heating equipment. Technical publications by system type are available at http://energy.gov/eere/amo/technical-publications-system. Case studies are covered separately, at http://energy.gov/eere/amo/case-studies-system.

Directory of Contacts

Advanced Manufacturing Office
U. S. Department of Energy
Office of Energy Efficiency and Renewable Energy
www.energy.gov/eere/amo

Industrial Heating Equipment Association (IHEA)
5040 Old Taylor Mill Rd., PMB 13
Taylor Mill, KY 41015
Phone: 859-356-1575
ihea@ihea.org
www.ihea.org

IHEA's mission is to provide services that assist member companies to serve end users in the process heating industry. To achieve this mission, IHEA has determined the following objectives:

- Promote the interest of the industrial heat processing industry to the federal government, plus the many standard-setting groups relevant to this industry
- Educate member companies with regard to government regulations, industry standards, codes, and other matters that impact the heat processing industry
- Enhance the end user's image of member companies by stressing quality as viewed from the end user's perspective
- Raise the level of professionalism within the industrial heat processing industry and member companies

- Provide a forum for optimizing end-user operation of heat processing equipment through technical seminars and training sessions
- Develop and maintain relationships with related trade associations (domestic and foreign) in order to assimilate global information about our industry
- Engage in activities that will promote the common good of member companies such as gathering and disseminating non-competitive employment and statistical information, and providing educational programs for member company employee improvement.

Electric Power Research Institute

3420 Hillview Avenue
Palo Alto, CA 94304
Phone: 650-855-2000
www.epri.com

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California, and Charlotte, North Carolina, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States.

Emerging Technology Applications Center

3835 Green Pond Road Bethlehem, PA 18020-7599
Phone: 610-861-5081
Fax: 610-861-4101
http://www.northampton.edu/center-for-business-and-industry/technical-trades-and-computer-training/emerging-technology-applications-center.htm

The Emerging Technology Applications Center (ETAC) provides confidential assistance to industrial manufacturers to help them increase productivity, improve energy efficiency, and achieve and maintain environmental compliance. This is accomplished through ETAC's Coatings and Ink Research, Energy Management, Process Heating, and Sustainable Manufacturing Institutes. ETAC helps businesses gain a competitive advantage by applying technologies such as high efficiency natural gas systems, infrared, ultraviolet, induction, radio frequency, microwave, resistance, and electron beam to improve their heating, drying, coating and curing processes.

ETAC engineers also use their extensive experience and knowledge of industrial processes and equipment to help manufacturers manage their energy usage and costs. Distance learning and classroom training for industry professionals is also developed and conducted by ETAC staff.

Gas Technology Institute (GTI)
1700 S. Mount Prospect Road
Des Plaines, IL 60018
Phone: 847-768-0500
www.gastechnology.org

GTI is the leading research, development, and training organization serving the natural gas industry and energy markets. GTI is dedicated to meeting the nation's energy and environmental challenges by developing technology- based solutions for consumers, industry, and government.

GTI provides products, services, and information that help customers solve problems or capitalize on opportunities related to finding, producing, delivering, and using natural gas. More specifically, GTI:

- Performs contract research, development and demonstration projects (field and laboratory)
- Provides technical services in areas related to energy and the environment
- Commercializes new energy-related technology, directly and through subsidiaries
- Plans and manages technology development programs for the gas industry and other clients
- Aggregates funding for collaborative R&D programs of interest to individual companies, consortia, and government agencies
- Provides education and training on technical and business topics related to energy and natural gas.

National Insulation Association
12100 Sunset Hills Road
Suite 330
Reston, VA 20190
Phone: 703-464-6422
www.insulation.org

The National Insulation Association is a service organization that promotes the general welfare of the commercial and industrial insulation and asbestos abatement industries, and works to improve the service to the general public performed by the commercial and industrial insulation and asbestos abatement industries.

North American Insulation Manufacturers Association
11 Canal Center Plaza, Suite 103
Alexandria, VA 22314
Phone: 703-684-0084
www.naima.org

North American Insulation Manufacturers Association (NAIMA) is a trade association of North American manufacturers of fiberglass, rock wool, and slag wool insulation products. NAIMA concentrates its efforts on promoting energy efficiency and environmental preservation through the use of fiberglass, rock wool, and slag wool insulation products, while encouraging safe production and use of these products.

Resources and Tools

Several other resources are available that describe current tools, technologies, and practices that can help improve steam system operating efficiency and performance. Many of these resources are intended to increase awareness of the benefits of energy improvement projects and to identify where the industry professional can go for more help.

Note: The descriptions accompanying the following sources have generally been taken directly from the publisher, author, or developer. Inclusion of these sources does not imply endorsement by the U.S. Department of Energy.

Books

American Society for Metals
9639 Kinsman Road
Materials Park, OH 44073-0002
Phone: 440-338-5151
www.asminternational.org

Applications of Induction Heat Treatment
Author: Haimbaugh, Richard E.
Description: Since its introduction in the 1930s, induction heat treatment has been applied to a large variety of mass-produced commercial products. The initial applications involved hardening of the surfaces of round steel parts such as shafts. Subsequent surface-hardening techniques were developed for other parts whose shapes are not so simple. Most recently, induction hardening and tempering techniques have been developed for purposes of heat treating to large case depths and heat treating entire cross sections.

Elements of Induction Heating: Design Control and Applications
Author: S. Zinn, S. L. Semiatin
Description: Provides an overview of a wide range of induction heating applications and includes information on different coil shapes and designs, tips, and data for different heating situations.

CRC Press
2000 NW Corporate Boulevard
Boca Raton, FL 33431
Phone: 800-272-7737
www.crcpress.com

Handbook of Induction Heating
Author: Valery I. Rudnev
Description: Offering ready-to-use tables, diagrams, graphs, and simplified formulas for at-a-glance guidance in induction heating system design, this book contains numerous photographs, magnetic field plots, temperature profiles, case studies, hands-on guidelines, and practical recommendations to navigate through various system designs and avoid surprises in installation, operation, and maintenance. It covers basic principles, modern design concepts, and advanced techniques engineers use to model and evaluate the different types of manufacturing processes based on heating by induction. The handbook explains the

electromagnetic and heat transfer phenomena that take place during induction heating.

Heat Transfer in Industrial Combustion
Author: Charles E. Baukal
Description: This book covers the heat transfer, thermodynamics, and fluid mechanics involved in industrial combustion practices, including a section on flame impingements. It reviews the basics and general concepts, as well as advanced applications and computer modeling.

Radio-Frequency Heating in Food Processing: Principles and Applications
Author: George B. Awuah, Hosahalli S. Ramaswamy, Juming Tang
Description: Radio-Frequency Heating in Food Processing: Principles and Applications covers the fundamentals of radio-frequency (RF) heating and the use of RF-heating technologies in modern food processing, preservation, and related industries. Focusing on industrial and lab-scale applications where RF heating has been employed successfully or reported to have potential benefits over conventional heating options.

Optimization of Industrial Unit Processes: Boilers, Chillers, Clean Rooms, Compressors, Cooling Towers, CSTR AND BSTR Reactors, Dryers, Evaporators, Fans, Heat Exchangers, HVAC Systems, Pumps
Author: Bela G. Liptak
Description: This book describes ways to maximize the productivity, efficiency and safety of industrial equipment while minimizing the cost, taking into consideration issues such as leaks, plugged sensors, corrosion and cavitation.

John Wiley & Sons
111 River Street
Hoboken, NJ 07030-5774
201-748-6000
www.wiley.com

Finite Element Method in Heat Transfer Analysis
Authors: R. W. Lewis, H. Randolph Thomas, K. N. Seetharamu, Ken Morgan
Description: One of the first books specifically devoted to the application of the finite element method to heat transfer analysis. The authors present computation methods used in the course of their research, which demonstrate how the method works in practice.

Krieger Publishing Company
1725 Krieger Drive
Malabar, Florida 32950
321-724-9542
www.krieger-publishing.com

Handbook of Thermal Insulation Design Economics for Pipes and Equipment
Authors: William C. Turner, John F. Malloy
Description: This handbook discusses topics such as: heat transfer, insulation materials properties/selection/application/installation, and energy savings.

McGraw-Hill
1221 Avenue of the Americas
New York, NY 10020
800-352-3566
www.mhprofessional.com

A Working Guide to Process Equipment
Authors: Norman P. Lieberman, Elizabeth T. Lieberman
Description: This book explains the basic technical issues that need to be known to troubleshoot process equipment problems. It provides diagnostic tips, calculations, practical examples, and illustrations.

Marks Standard Handbook of Mechanical Engineers
Authors: Eugene Avallone and Theodore Baumeister, III (Editors)
Description: This handbook provides descriptions of different heat distribution systems using many diagrams, drawings, graphs, and charts.

National Academy Press
500 Fifth Street. N.W.
Washington, D.C. 20001
888-624-8373
www.nap.edu

Microwave Processing of Materials
Author: National Research Council
Description: Introduces the reader to the use of microwaves for processing materials. Identifies gaps, limitations, or weaknesses in the understanding of the use of microwaves in materials processing, and provides an assessment of the state of the art of microwave processing as an industrial technology.

Prentice Hall
One Lake Street
Upper Saddle River, NJ 07458 800-382-3419
www.prenhall.com

Energy Analysis of 108 Industrial Processes
Authors: Harry Brown, Bernard Hamel, and Bruce Hedman
Description: A reference for identifying the quantity and quality of industrial waste energy, which can be economically practical to recover. Presents detailed heat and material balances developed from the process flow diagrams for 108 industrial processes. This book is no longer in publication, but may be available from online book sellers.

Springer Science & Business Media
233 Spring Street
New York, NY 10013-1578
212-460-1501
www.springer.com

Laser Material Processing
Authors: William M. Steen and Kenneth Watkins
Description: Lasers now play a major part in the processing of the disparate materials used in engineering and manufacturing. The range of procedures in which they are involved is ever increasing. With this growing prominence comes a need for clear and instructive textbooks to teach the next generation of laser users. The informal style of Laser Material Processing (3rd Edition) will guide you smoothly from the basics of laser physics to the detailed treatment of all the major materials processing techniques for which lasers are now essential.

Other Publications (Guides, Manuals, and Standards)

IHEA: Industrial Heating Equipment Association
5040 Old Taylor Mill Rd., PMB 13
Taylor Mill, KY 41015
859-356-1575
www.ihea.org

Combustion Technology Manual (fifth edition)
Description: A reference source of combustion engineering principles and practices prepared by many leading authorities involved in combustion processes. It includes in- depth studies of fluid flow, air sources, gas-air ratio control, premixing, burners, fuel oil systems, measuring of gases, flame safety and sequence controls, sizing mixers, and flow-meters for atmosphere generators.

IHEA Heat Processing Manual (first edition)
Description: Provides a ready reference source for basic engineering principles and practices related to process heating. Chapters include: Thermal Energy Sources, Basic Heat Transfer, Safety Technology, Special Thermal Applications, Infrared Technology for Industrial Applications, Incineration and Heat Recovery Methods and Environmental Regulations—Impact on Process Heating Equipment.

Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94303
650-855-2000
www.epri.com

Technology Guide for Electric Infrared Process Heating
Description: This guidebook describes electric infrared process heating as it is used for curing coating and other materials fabrication applications. It is intended to help potential users understand and apply electric infrared technology. This guidebook was published in conjunction with Center for Materials Fabrication and Infrared Equipment Association.

Vulcan-Verlag GmbH
Huyssenallee 52-56 D-45128 Essen
Federal Republic of Germany
+49 (0)201 8 20 02-0

Handbook of Thermoprocessing Technologies
Editors: Axel von Starck, Alfred Mühlbauer, Carl Kramer
Description: This comprehensive book covers both fundamentals and cutting edge design principles of industrial thermoprocessing of materials in achieving the required properties, specific shapes and forms desired.

Software

The Process Heating Assessment and Survey Tool (PHAST)
Description: The Process Heating Assessment and Survey Tool (PHAST) provides an introduction to process heating methods and tools to improve thermal

efficiency of heating equipment. The tool has been used to survey process heating equipment that uses fuel, steam, or electricity, and identify the most energy-intensive equipment. Users have also performed energy (heat) balances on selected equipment such as furnaces to identify and reduce non-productive energy use. Performance of the furnace under various operating conditions can be compared.

Originally developed by the Department of Energy and the Industrial Heating Equipment Association, PHAST is widely used by industry professionals for process heating system analysis.

Advanced Manufacturing Office
U. S. Department of Energy
Office of Energy Efficiency and Renewable Energy
http://energy.gov/eere/amo

Steam System Modeling Tool
Developer: DOE Advanced Manufacturing Office
Description: AMO's Steam System Modeling Tool (SSMT) is designed to help users survey and assess their steam system equipment. Awareness Modules for SSMT is available to orient users on how to utilize the tool.

The tool and the awareness module can be found at http://energy.gov/eere/amo/software-tools.

National Insulation Association
12100 Sunset Hills Rd
Suite 330
Reston, VA 20190
703-464-6422
www.insulation.org

3E Plus Mechanical Insulation Energy Appraisal Program
Developer: National Insulation Association
Description: Demonstrates to plant owners, engineers, specifiers, and contractors the enormous energy savings in dollars through the use of insulation on hot and cold piping, ducts, vessels, and equipment in a facility. Savings are also quantified in CO2, NOx, and CE emission levels. Note that 3E Plus is intended for low-temperature applications and does not include data for high temperature refractories and insulation.

TechniCAL
3445 North Causeway Blvd
Suite 1001
Metairie, LA 70002
504-733-0300
www.tcal.com/calsoft-software

CALSoft32 Thermal Processing Software
Developer: TechniCAL
Description: Conducts heat penetration and temperature distribution testing, evaluates the collected data, and calculates a thermal process or vent schedule/come-up time.

ThermoAnalytics
23440 Airpark Boulevard
P.O. Box 66 Calumet, MI 49913 906-482-9560
www.thermoanalytics.com

WinTherm Software
Developer: ThermoAnalytics
Description: WinTherm is designed for component-level modeling and simulation and provides the user with a complete solution to thermal analysis for models up to 20,000 thermal nodes (typically 10,000 mesh elements). WinTherm runs under Windows 95/98/NT and UNIX and allows users from any engineering background (thermal or other) to analyze their components quickly and accurately. Examples of WinTherm applications are electronics enclosures, fluid tanks, or oven systems. Analysis of heat management techniques such as insulated heat shields, cooling with fans, heat sinks, or surface treatments can be explored.

RadTherm Software
Developer: ThermoAnalytics
Description: RadTherm is full-featured, cross-platform, thermal analysis software for system-level CAE applications. RadTherm utilizes a state-of-the-art Radiation Module and an extremely user-friendly Graphical User Interface to set up boundary conditions for multi-mode heat transfer: multibounce radiation, conduction and convection with one-dimensional fluid flow. Examples of RadTherm applications are complete vehicular systems, aerospace systems, electronic instrument panels, architectural solar analysis, and complex process heating schemes.

Periodicals

Chemical Engineering
Access Intelligence
New York, NY
www.chemengonline.com

Chemical Processing
Putman Media
Itasca, IL
www.chemicalprocessing.com

Energy Engineering
Association of Energy Engineers
Lilburn, GA
www.aeecenter.com

Industrial Heating: The International Journal of Thermal Technology
BNP Media
Troy, MI
www.industrialheating.com

Industrial Maintenance & Plant Operation
Advantage Business Media
Madison, WI
www.impomag.com

Process Heating
BNP Media
Troy, MI
www.process-heating.com

Reports and Technical Papers

Advanced Manufacturing Office
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
http://energy.gov/eere/amo

Roadmap for Process Heating Technology: Priority Research and Development Goals and Near-Term Non-Research Goals to Improve Industrial Process Heating
Description: This roadmap summarizes the future technology priorities for increasing the energy efficiency of industrial process heating systems. It is the outcome of a collaborative effort led by the Industrial Heating Equipment Association and DOE to develop a comprehensive plan for meeting industrial process heating needs. The roadmap includes performance targets for the year 2020, barriers to improvement, priority R&D goals, non-research goals, and next steps for implementation.

Oak Ridge National Laboratory
U.S. Department of Energy
www.ornl.gov

Technologies and Materials for Recovering Waste Heat in Harsh Environments
Description: This 2014 report discusses technologies and materials that are capable of recovering waste heat from exhaust gases in high-temperature environments. The benefits and drawbacks of using steels, superalloys, refractory metals, ceramics, and other materials are covered. Technologies and materials that are currently used to recover waste heat from blast furnaces, arc furnaces, melting furnaces and kilns are reviewed, and potential opportunities for new technologies are highlighted.

Training Courses and Technical Services

Association of Energy Engineers
4025 Pleasantdale Road, Suite 420
Atlanta, GA 30340
770-447-5083
www.aeecenter.org

Area(s) covered: Seminars offered for various topics of interest, including air distribution systems, energy management, conservation, and economics.

Center for Professional Advancement
Box 7077
44 West Ferris Street
East Brunswick, NJ 08816-7077
732-238-1600
www.cfpa.com

Area(s) covered: The CFPA offers courses in piping design, analysis, and fabrication; pressure vessel design and analysis; project management for plant retrofits; and shutdowns.

IHEA: Industrial Heating Equipment Association
5040 Old Taylor Mill Rd., PMB 13
Taylor Mill, KY 41015
859-356-1575
www.ihea.org

Area(s) covered: Annual Combustion Technology and Annual Safety Standards Seminars.

PGS Energy Training
43 Fawnvue Drive
Suite 700
McKees Rocks, PA 15136 412-521-4737
www.pgsenergy.com

Area(s) covered: Managing industrial energy procurement.

TMS: The Minerals, Metals, & Materials Society
184 Thorn Hill Road
Warrendale, PA 15086-7514
724-776-9000
www.tms.org

Area(s) covered: Process Heating Systems Optimization Workshop (TMS Annual meeting)

Appendices

The following appendices have been included in the sourcebook:

Appendix A: Glossary of Terms

This appendix contains a glossary of terms used in process heating systems.

Appendix B: Process Heating Tip Sheets

This appendix contains a series of process heating system tip sheets developed by the U.S. Department of Energy's Advanced Manufacturing Office. These tip sheets discuss common opportunities that industrial facilities can use to improve performance and reduce fuel use.

Appendix C: Technical Briefs

This appendix contains a series of process heating technical briefs developed by ITP. These discuss key process heating issues in detail.

Appendix D: References

This appendix is a list of all the references used throughout the sourcebook.

Appendix A: Glossary of Terms

Adjustable speed drive (ASD)—An electric drive designed to provide easily operable means for speed adjustment of the motor, within a specified speed range.

Air/fuel ratio (a/f ratio)—The ratio of the air supply flow rate to the fuel supply flow rate when measured under the same conditions. For gaseous fuels, usually the ratio of volumes in the same units. For liquid and solid fuels, it may be expressed as a ratio of weights in the same units, but it is often given in mixed units such as cubic feet of air per pound of fuel.

Agglomeration—The combining of smaller particles to form larger ones for separation purposes. Sintering, for example.

Alternating Current (AC)—The characteristic of electricity in which the current flow in a circuit changes direction (180 degrees). Each change is called a cycle. The number of cycles during a given time period is called frequency. The standard frequency in the United States is 60 cycles per second.

Ambient—Immediate surroundings or vicinity.

Amps—A unit of electric current flow equivalent to the motion of one coulomb of charge or 6.24 X 1018 electrons past any cross section in one second.

Ash—Noncombustible mineral matter in residual fuel oils. Ash consists mainly of inorganic oxides and chlorides. ASTM specifications limit ash weight in #4 and #5 oils to 0.1% (no limit in #6 oil). Ash can cause difficulties with heat transfer surfaces, refractories, and burner ports.

Atmosphere (atm)—A mixture of gases (usually within a furnace). Also a unit of pressure equal to 14.7 lb/square inches or 760 millimeters (mm) of mercury.

Atmospheric pressure—The pressure exerted upon the earth's surface by the weight of the air and water vapor above it. Equal to 14.7 lb/square inch or 760 mm of mercury at sea level and 45° latitude.

Available heat—The gross quantity of heat released within a combustion chamber minus both the dry flue gas loss and the moisture loss. It represents the quantity of heat remaining for useful purposes (and to balance losses to walls, openings, and conveyors).

Basic refractories—Refractories consisting essentially of magnesia, lime, chrome ore, or forsterite, or mixtures of these (by contrast, acid refractories contain a substantial proportion of free silica).

Batch-type furnace—A furnace shut down periodically to remove one load and add a new charge, as opposed to a continuous-type furnace. Also referred to as an in-and-out furnace or a periodic kiln.

Blast furnace gas—A gas of low Btu content recovered from a blast furnace as a by-product and used as a fuel.

British thermal unit (Btu)—The quantity of energy required to heat one pound of water from 59°F to 60°F at standard barometric pressure (0.252 kilocalories or 0.000293 kilowatt-hours).

Bunker oil—A heavy fuel oil formed by stabilization of the residual oil remaining after the cracking of crude petroleum.

Calcining—The removal of chemically bound water and/or gases through heating.

Coke—The solid product, principally carbon, resulting from the destructive distillation of coal or other carbonaceous materials in an oven or closed chamber. In gas and oil combustion, the carbonaceous material formed due to abnormal circumstances.

Coke oven gas—A gas composed primarily of hydrogen and methane, saved for use as a fuel when coke is made from coal in byproduct ovens.

Combustion air—Main air. All of the air supplied through a burner other than that used for atomization.

Combustion products—Matter resulting from combustion such as flue gases, water vapor, and ash. See products of combustion.

Compressor—A device that increases the pressure of a gas through mechanical action. Compressors are used to provide compressed air to facilities and in mechanical vapor compression systems to provide cooling and refrigeration.

Conduction—The transfer of heat through a material by passing it from molecule to molecule.

Conductance—See thermal conductance.

Conductivity—See thermal conductivity.

Convection—Transfer of heat by moving masses of matter. Convection currents are set up in a fluid by mechanical agitation (forced convection) or because of differences in density at different temperatures (natural convection).

Curing—The controlled heating of a substance to promote or control a chemical reaction.

Demand—The load integrated over a specific interval of time.

Demand charge—That portion of the charge for electric service based upon a customer's demand.

Diesel fuel—A distillate fuel oil similar to #2 fuel oil.

Direct current (DC)—A unidirectional current in which the changes in value are either zero or so small that they may be neglected. (As ordinarily used, the term designates a practically non-pulsing current)

Drying—The removal of free water (water that is not chemically bound) through heating. The process of removing chemically bound water from a material is called calcining.

Effective area of furnace openings—The area of an opening in an infinitely thin furnace wall that would permit a radiation loss equal to that occurring through an actual opening in a wall of finite thickness. The effective area is always less than the actual area because some radiation always strikes the sides of the opening and is reflected back into the furnace.

Efficiency—The percentage of gross Btu input that is realized as useful Btu output of a furnace.

Emissivity—A measure of the ability of a material to radiate energy. The ratio (expressed as a decimal fraction) of the radiating ability of a given material to that of a black body (a black body always emits radiation at the maximum possible rate and has an emissivity of 1.0). See emittance.

Emittance—The ability of a surface to emit or radiate energy, as compared with that of a black body, whose emittance is 1.0. Geometry and surface conditions are considered when calculating a surface's emittance, while emissivity denotes a property of the bulk material and is independent of geometry or surface conditions. See emissivity.

Emittance factor, Fe—The combined effect of the emittances of two surfaces, their areas, and relative positions.

Equivalent thickness—For refractory walls, this term refers to the thickness of firebrick wall that has the same insulating capability as a wall of another refractory material.

Excess air—The air remaining after a fuel has been completely burned, or that air supplied in addition to the quantity required for complete stoichiometric combustion. A lean fuel/air ratio contains excess air.

f/a ratio or fuel/air ratio—The reciprocal of the a/f (air/fuel) ratio. See a/f ratio.

Fireclay brick—A refractory brick manufactured substantially or entirely from fireclay.

Flue gas—All gases, combustion gas, products of combustion that leave a furnace, recuperator or regenerator, by way of the flue, including gaseous products of combustion, water vapor, excess oxygen, and nitrogen. See products of combustion.

Fluid heating—Fluids are heated in batch or continuous processes to induce or moderate a chemical reaction in the product material.

Forced convection—Convection heat transfer by artificial fluid agitation.

Fuel oil—A petroleum product used as a fuel. Common fuel oils are classified as:

#1 – distillate oil for vaporizing type burners.
#2 – distillate oil for general purpose use, and for burners not requiring #1.
#4 – blended oil intended for use without preheating.
#5 – blended residual oil for use with preheating facilities. Usual preheat temperatures are 120°F to 220°F.
#6 – residual oil, for use in burners with preheaters permitting a high viscosity fuel. Common preheat temperatures are 180°F to 260°F.

Furnace—An enclosed space in which heat is intentionally released by combustion, electrical devices, or nuclear reaction.

Furnace pressure—The gauge pressure that exists within a furnace combustion chamber. The furnace pressure is said to be positive if greater than atmospheric pressure, negative if less than atmospheric pressure, and neutral if equal to atmospheric pressure.

Gross heating value—See higher heating value.

Heat content—The sum total of latent and sensible heat stored in a substance minus that contained at an arbitrary set of conditions chosen as the base or zero point. It is usually designated h, in Btu per pound, but may also be expressed in such units as Btu per gallon and Btu per cubic foot if the pressure and temperature are specified.

Heat transfer—Flow of heat by conduction, convection, or radiation.

Heat treating—The controlled heating and cooling of a material to achieve favorable mechanical properties such as hardness, strength, and flexibility.

Higher heating value (HHV)—Gross heating value—equal to the total heat obtained from combustion of a specified amount of fuel and its stoichiometrically correct amount of air, both being at 60°F when combustion starts, and after the combustion products are cooled. See net or lower heating value.

Insulation—A material that is a relatively poor transmitter of heat. It is usually used to reduce heat loss from a given space.

Kilowatt —A measure of power equal to 1.34 horsepower.

Latent heat—Heat absorbed or given off by a substance without changing its temperature, as when melting, solidifying, evaporating, condensing, or changing crystalline structure.

Lower heating value (LHV)—Net heating value. The gross heating value minus the latent heat of vaporization of the water vapor formed by the combustion of hydrogen in the fuel. For a fuel with no hydrogen, net and gross heating values are the same.

Mineral—A natural, inorganic substance sometimes of variable chemical composition and physical characteristics. Most minerals have definite crystalline structure; a few are amorphous.

Natural convection—Free convection. Transfer of heat due to currents created by the differences in gas density caused by temperature gradients.

Net heating value—See lower heating value.

Nine-inch equivalent—A brick volume equal to that of a standard 9 x 4.5 x 2.5 inch straight brick; the unit of measurement of brick quantities in the refractories industry.

Percent air—The actual amount of air supplied to a combustion process, expressed as a percentage of the amount theoretically required for complete combustion.

Percent excess air—The percentage of air supplied in excess of that required for complete combustion. For example, 120% air equals 20% excess air.

Perfect combustion—The combining of the chemically correct proportions of fuel and air in combustion so that both the fuel and the oxygen are totally consumed. See stoichiometric ratio.

Plastic refractory—A blend of ground refractory materials in plastic form, suitable for ramming into place to form monolithic linings.

Power—The rate of energy transfer, usually measured in watts or Btu/hr.

Preheated air—Air heated prior to combustion, generally transferring energy from the hot flue gases with a recuperator or regenerator.

Products of combustion—Products of combustion gases in a combustion chamber or on their way through a flue, heat recovery device, pollution reduction equipment, or stack. Usually consists of carbon dioxide, water, and nitrogen, but may also include oxygen, carbon monoxide, and H2, complex hydrocarbons, sulfur and nitrogen compounds, and particulates. May be termed flue gas, stack gas, or exit gas.

Radiation—Emission and propagation of wave form energy. A mode of heat transfer in which the energy travels very rapidly in straight lines without leaving the intervening space. Heat can be radiated through a vacuum, through many gases, and through some liquids and solids.

Recuperator—Equipment that uses hot flue gases to preheat air for combustion. The flue gases and airflow are in adjacent passageways so that heat is transferred from the hot gases, through the separating wall, to the cold air.

Refractories—Highly heat-resistant materials used to line furnaces, kilns, incinerators, and boilers.

Regenerator—A cyclic heat interchanger, which alternately receives heat from gaseous combustion products and transfers heat to air before combustion.

Saturated air—Air containing all the water vapor it can normally hold under existing conditions.

Saturated steam—Steam at the boiling point for water at the existing pressure.

Sensible heat—Heat, for which the addition to or removal of will result in a temperature change, as opposed to latent heat.

Smelting—The chemical reduction of a metal from its ore, usually by fusion. Smelting separates impurities, allowing for their removal from the metal.

Specific heat—The amount of heat required to raise a unit weight of a substance under a specified temperature and pressure.

Standard air—Air at standard temperature and pressure, namely 60°F (15.56°C) and 29.2 inches of mercury (14.7 pounds per square inch [psi], 760 mm specific gravity [Hg]).

Standard pressure—Standard atmosphere, equal to a pressure of 29.92 inches of mercury (14.7 psi, 760 mm Hg)

Standard temperature—60°F (15.56°C) in this book and for most engineering purposes. In the fan industry, it is 70°F (21.1°C) and in scientific work it is 32°F (0°C) or 39.2°F (4°C).

Stoichiometric ratio—The chemically correct ratio of fuel to air, i.e., a mixture capable of perfect combustion, with no unused fuel or air.

Sustainable Manufacturing — The ability to continuously utilize resources to manufacture products and maintain the environment and our lifestyles indefinitely.

Thermal conductance, C—The amount of heat transmitted by a material divided by the difference in temperature of the material's surfaces. Also known as conductance.

Thermal conductivity, k—The ability of a material to conduct heat, measured as the heat flow through a square foot of cross sectional area and a one foot (or inch) thickness with 1°F of temperature difference across the thickness. The refractory and insulation industries use the "inch thickness," while most other industries use "foot thickness" to measure this material property.

Three-phase—Commonplace AC electrical service involving three conductors offset in phase from each other. The concept eliminates torque pulsation and accommodates creation of rotating magnetic fields, within motors, to facilitate starting and running torque.

Wall loss—The heat loss from a furnace or tank through its walls.

Warm-up time—The time required to bring a process heating system up to operating temperature.

Watt—The unit of power in the International System of Units (SI). The watt is the power required to do work at the rate of 1 joule per second.

Appendix B: Process Heating Tip Sheets

The U.S. Department of Energy's Advanced Manufacturing Office (AMO) has developed has developed a large portfolio of two-page tip sheets to give advice to make improvements to many industrial process systems. Tip sheets are available for: pump, steam, motor, compressed air, process heating, and plant wide systems. Learn how to determine air-fuel ratios for burners, evaluate adjustable speed drive efficiency, inspect and repair steam traps, benchmark fuel costs, and handle other system efficiency issues.

The tip sheets listed below are presented in full in this Appendix B. They are all related to Process Heating Systems.

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

The tip sheets can also be downloaded from the AMO Tip Sheet site at http://energy.gov/eere/amo/tip-sheets-system.

Tip Sheet 1: 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

Furnace 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, *hours* 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 Steam System Modeling Tools available from the U.S. Department of Energy's Advanced Manufacturing Office.
- Contact furnace or combustion system suppliers to calculate payback period or ROI.

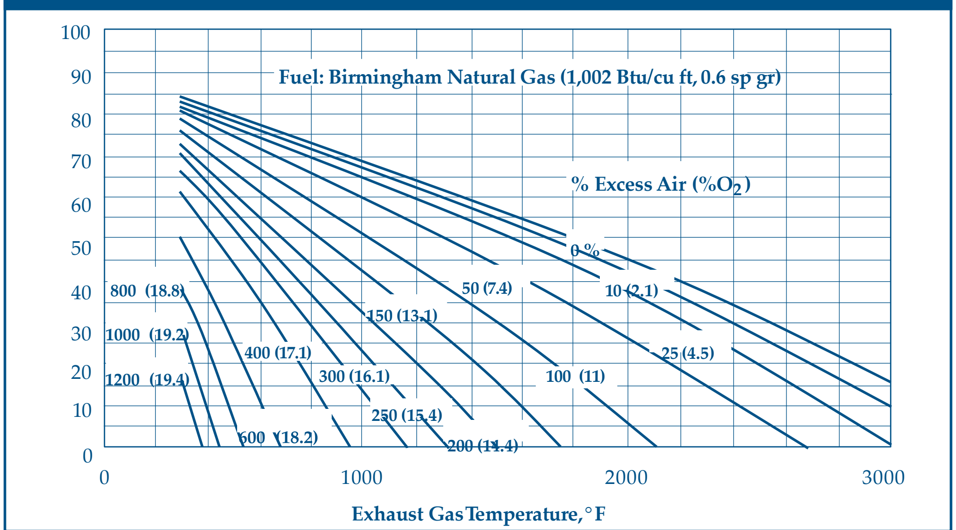
DOE/GO-102007-2482 • October 2007• Process Heating Tip Sheet #1

Tip Sheet 2: 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

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.

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 O2 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% O2 in flue gases), but tests show an actual ratio of 25% excess air (4.5% O2 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 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:

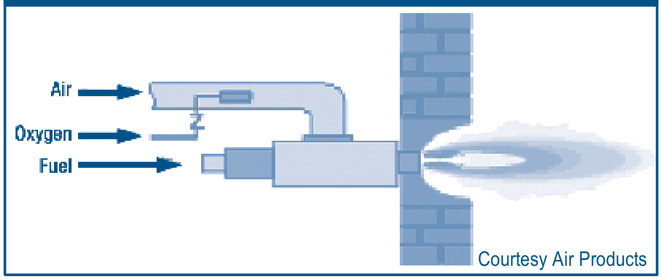
1. Determine the best level of excess air for operating your equipment.
2. Set your combustion ratio controls for that amount of excess air.
3. Check and adjust ratio settings regularly.

DOE/GO-102007-2483 • November 2007 • Process Heating Tip Sheet #2

Tip Sheet 3: 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.

Using oxygen-enriched combustion for specific applications may improve efficiency, depending on the exhaust gas temperature and percentage of oxygen in the combustion 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

Suggested Actions

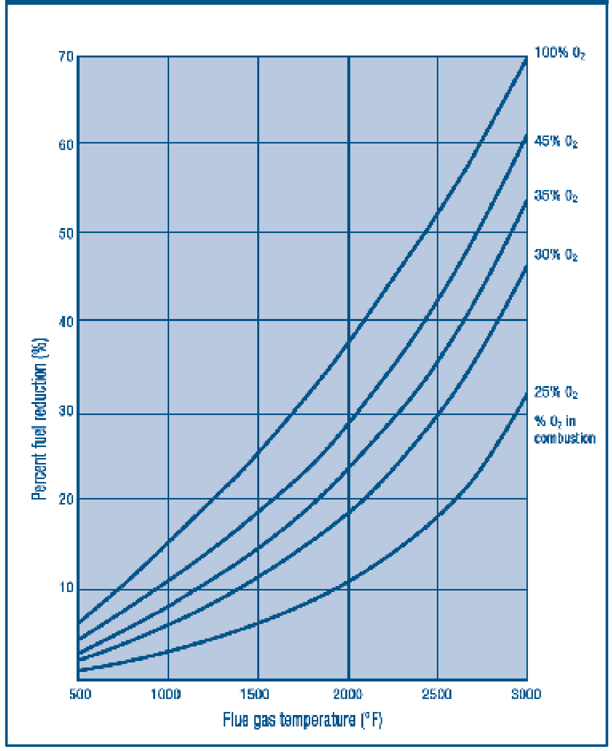
- Use current or projected energy costs with PHAST to estimate energy savings from oxygen-enriched combustion.
- Contact furnace or combustion system suppliers to calculate payback or return on investment.
- Include the cost of oxygen or of the vacuum pressure swing adsorption unit in the calculations.

oxygen-enriched combustion.

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.

Figure 2. Energy savings from oxygen injection



Potential Applications

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

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%.

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

DOE/GO-102005-2178 • September 2005• Process Heating Tip Sheet #3

Tip Sheet 4: 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.

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

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.

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

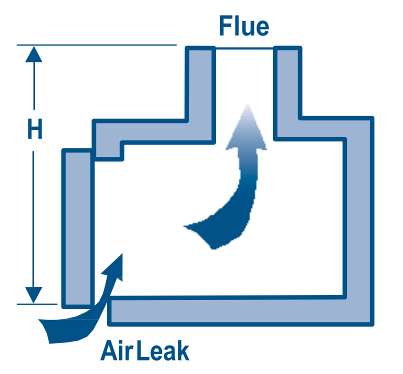
Scale is formed from deposits of calcium, magnesium, or silica from the water supply. Problems occur when these minerals form a continuous layer of material on the water side of heat transfer surfaces; surfaces with scale deposits have much lower thermal conductivity than bare metal. Efficiency losses 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.

DOE/GO-102005-2179 • September 2005 • Process Heating Tip Sheet #4

Tip Sheet 5: 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).

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.

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.

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.

DOE/GO-102006-2222 • January 2006 • Process Heating Tip Sheet #5

Tip Sheet 6: 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

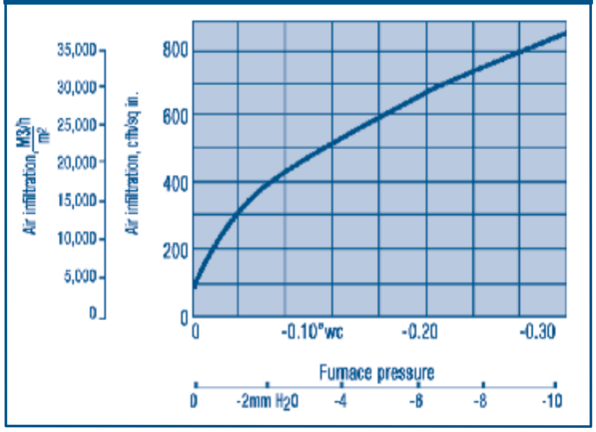
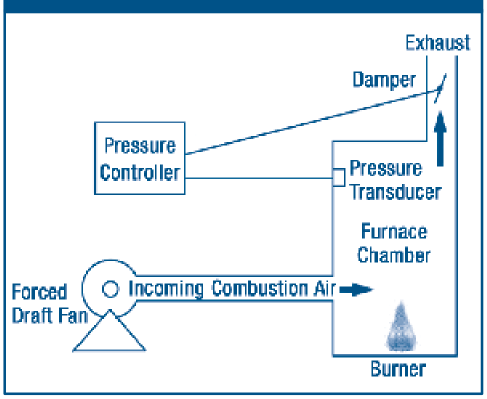


Figure 1 shows rates of air infiltration resulting from furnace draft. This air has to be heated to the flue gas temperature before it leaves the furnace through the stack, which wastes energy and reduces efficiency. The air infiltration can be minimized by reducing or eliminating openings and areas 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



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.

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.

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.

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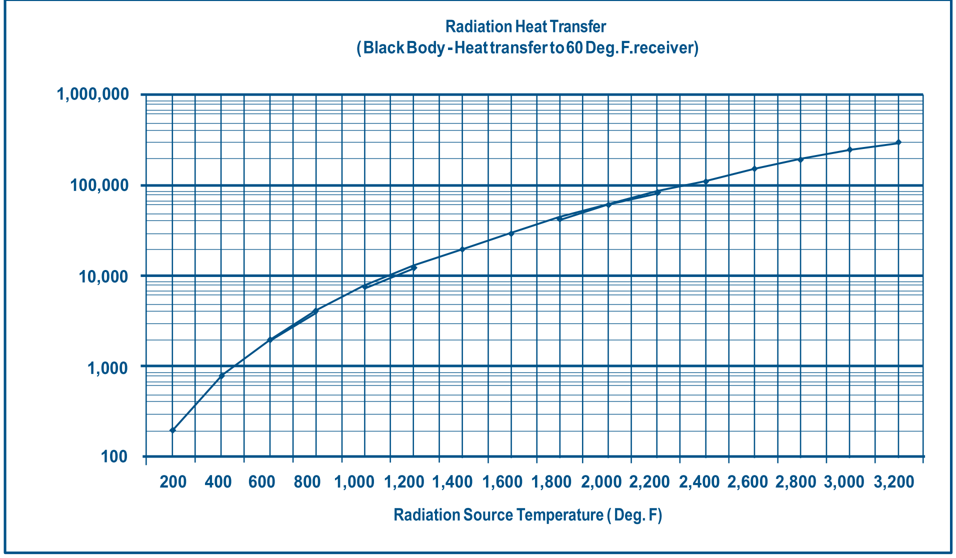
Tip Sheet 7: Reduce Radiation Losses from Heating Equipment

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.

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).

Figure 1. Radiation heat transfer rates[1]



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:

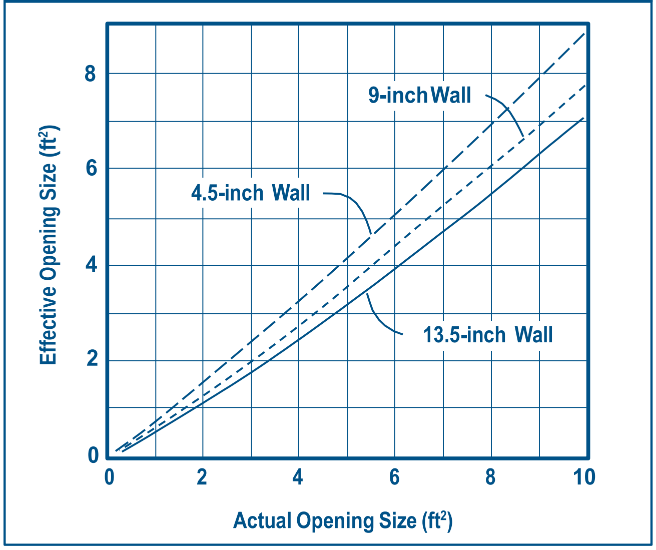
- Eliminate the furnace opening or keep the furnace door open the shortest possible time.
- For a continuous furnace in which opening size cannot be reduced, you can use flexible materials such as ceramic strips, chains, or ceramic textiles as "curtains." These generally reduce heat loss by half and 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

Robert Siegel and John Howell, *Thermal Radiation Heat Transfer*, New York: McGraw-Hill, 1972

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.

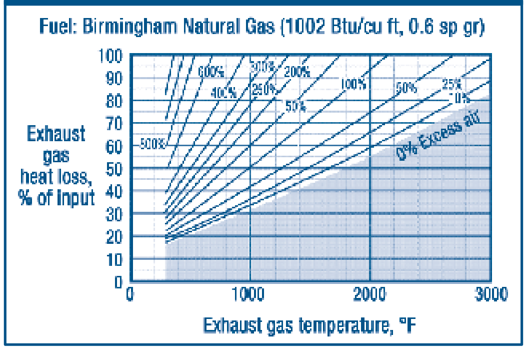
[1] Calculations by Arvind Thekdi, E3M, Inc.
[2] Calculations by Richard Bennett, Janus Technology Group.

DOE/GO-102006-2223 • January 2006 • Process Heating Tip Sheet #7

Tip Sheet 8: 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



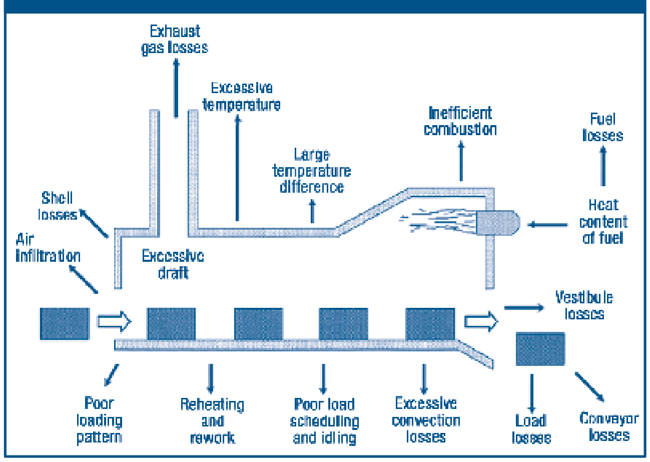
For natural gas-based systems, the amount of heat contained in the flue gases as a percentage of the heat input in a heating system can be estimated by using Figure 1. Exhaust gas loss or waste heat depends on flue gas temperature and its mass flow, or in practical terms, excess air resulting from combustion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

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

Figure 2. Heat losses



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.

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.

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.

DOE/GO-102005-2181 • September 2005 • Process Heating Tip Sheet #8

References

Improving Process Heating System Performance: A Sourcebook for Industry. U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA).

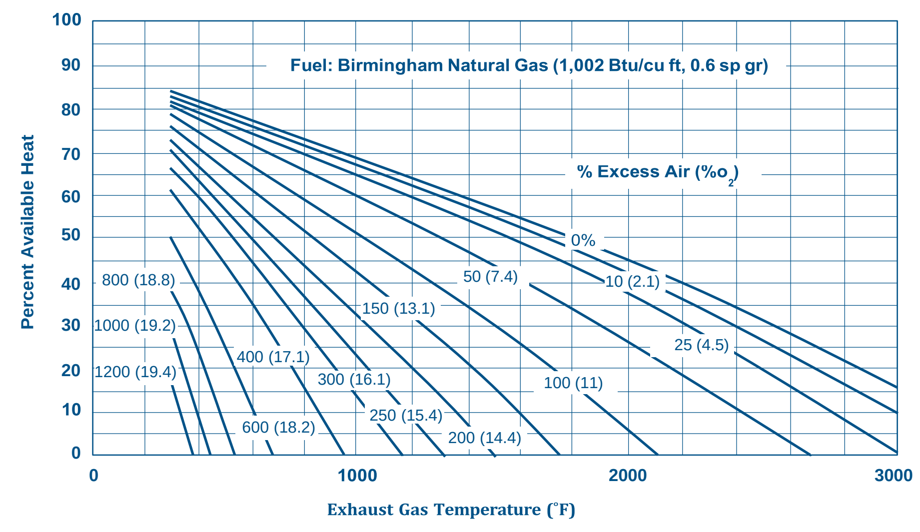
Waste Heat Reduction and Recovery for Improving Furnace Efficiency. DOE and IHEA.

Tip Sheet 9: 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.

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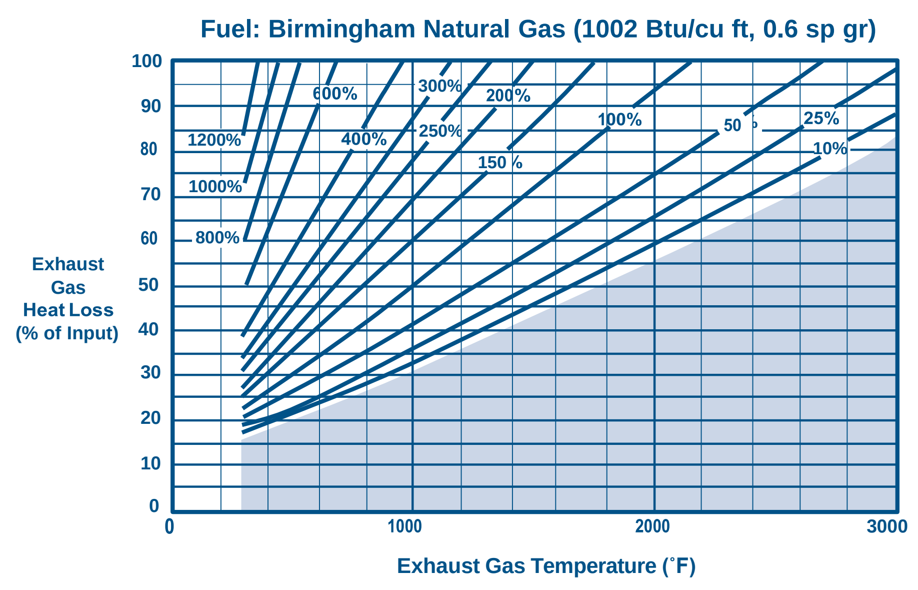
Tip Sheet 10: Using Waste Heat for External Processes

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.
- **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.

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

ASM Handbook, Volumes 1 (1990) and 2 (1991), Materials Park, OH: ASM International

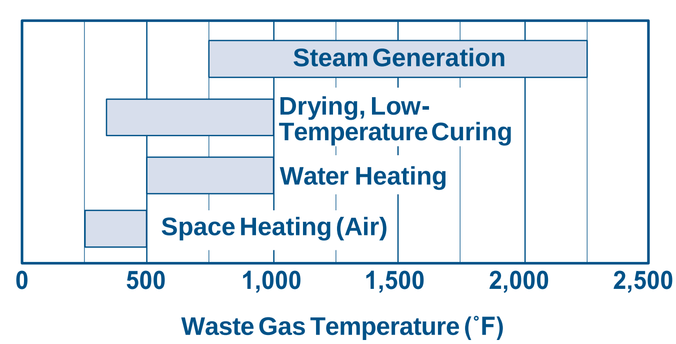
Combustion Technology Manual, Fifth Edition, Cincinnati, OH: Industrial Heating Equipment Association (IHEA), 1994

Handbook of Applied Thermal Design, E.C. Guyer and D.L. Brownell, eds., London: Taylor & Francis Group, 1999.

- **Matching the timing of the heat supply from the primary process and the heat demand in the secondary process.**
- **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.

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



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.

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Tip Sheet 11: 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 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).

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

Improving Process Heating System Performance: A Sourcebook for Industry. U.S. Department of Energy and Industrial Heating Equipment Association.

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.

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Appendix C: Technical Briefs

The technical briefs in Appendix C include:

1. Materials Selection Considerations for Thermal Process Equipment
2. Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emissions Performance

These technical briefs can also be downloaded from the Process Heating section of the AMO website at www.energy.gov/eere/amo/process-heating-systems.

Materials Selection Considerations for Thermal Process Equipment

Introduction

High-temperature metallic materials or alloys used in process heating equipment (furnaces, heaters, ovens, kilns, etc.) have significant effect on thermal efficiency, productivity and operating cost of the equipment. These materials are used in burners, electrical heating elements, material handling, load support, and heater tubes, etc.

A number of factors must be considered to select appropriate materials to improve energy efficiency of the equipment while extending their life at the minimum cost.

These factors include mechanical properties, oxidation or hot corrosion resistance, use of cast or fabricated components, and material availability.

Technical data describing the properties of heat-resistant alloys are necessary guides for selection. However, the behavior of alloys during long exposure to various high-temperature environments is complex. This behavior is not always completely predicted by laboratory tests alone. Service experience with high-temperature equipment is needed to judge the relative significance of the many variables involved.

Selection Criteria

Operating Temperature

Temperature is often the first—and sometimes the only— data point given upon which one is supposed to base alloy selection. However, one cannot successfully choose an alloy based on temperature alone. Nevertheless, one simple guide to alloy selection is an estimate of the maximum temperature at which a given alloy might have useful long- term engineering properties. Considering oxidation in air as the limiting factor, several common alloys, in plate form, rate as shown in Table 1. Thin sheets will have a lower limiting temperature because of proportionally greater losses from oxidation.

Thermal Stability

After long exposure to temperatures in the range of 1,100˚ to 1,600˚F (590˚-870˚C), many of the higher chromium alloys precipitate a brittle intermetallic compound known as sigma phase. Molybdenum contributes to this phase. Sigma reduces room-temperature impact strength and ductility. The quantity and morphology of the sigma phase determines severity of embrittlement.

Glossary of Terms

UNS	Unified Numbering System
EN	European Normal
W.Nr.	Werkstoff Nummer
Al	Aluminum
Cb	Columbium (Niobium)
Ce	Cerium
Co	Cobalt
Cr	Chromium
La	Lanthanum
Mo	Molybdenum
Si	Silicon
Ti	Titanium
Y2O3	Yttria (Yttrium Oxide)
W	Tungsten
Zr	Ziconium

Usually the metal is brittle only near room temperature, and it retains reasonable ductility at operating temperatures between 600˚ and 1000˚F (315˚-540˚C). Higher nickel grades, such as N08811, N08330, N06600 or N06601, are not susceptible to embrittlement by sigma. Because of higher carbon content, which causes carbide precipitation, cast heat-resistant alloys lose ductility in service.

Strength

Creep-rupture properties at temperature are usually available from the various producers, and many alloys are covered by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

Oxidation

Chromium is the one element present in all heat-resistant alloys, and its protective chromia scale is the basis for high-temperature environmental resistance. Nickel is next in importance, then silicon, aluminum, and rare earths.

Oxidation rates in service depend upon thermal cycling and creep, which increase scale spalling. In addition, contaminants, such as alkali metal salts, can damage the chromia scale grain size, which affects chromium diffusion rates, and the particular atmosphere involved also increases oxidation rate. Significant water vapor content usually increases oxidation rates.

Table 1. High Temperature Alloys (in order of increasing performance)	
Alloy	**Comments**
Carbon steel, such as ASTM A 387 Grade 22 (2 1/4Cr, 1Mo)	This may be used to 1,200˚F (649˚C); above 950˚F (510˚C) 304H is stronger, and of course, more resistant to oxidation.
409, and 410S stainless (UNS S40900, S41008) 1,200˚F (650˚C)	Limited by oxidation. Both are subject to embrittlement after several years of service above 600˚F (315˚C).
430 stainless (S43000), with useful oxidation resistance to about 1,600˚F (870˚C)	Subject to embrittlement when exposed to the 600˚-1,100˚F (315˚-600˚C) range.
304/304H & 316L stainless (S30400/ S30409, & S31600), cast HF	This is limited by oxidation to 1,500˚F (816˚C). If product contamination by scale particles is a concern, consider 1,200˚F (650˚C) as limitation.
321 (S32100) stainless	This has an advantage of about 100˚F (55˚C) over 304, and is used to 1,600˚F (1202˚C).
309S (S30908), cast HH-2 (J93633)	Useful up to the 1,850-1,900˚F (1010-1038˚C) range. Above 1,900˚F, oxidation performance becomes unsatisfactory.
Alloy 800HT® [1] (UNS N08811)	Much stronger, and somewhat more oxidation resistant. A practical upper use limit is about 2,000˚F (1,093˚C).
RA 253 MA® [2] alloy (UNS S30815)	Has superior oxidation resistance up to 2,000˚F (1,100˚C). Above this temperature, the oxidation resistance may be adequate, but not exceptional. In vacuum, the maximum temperature can be extended to 2,100° F, as it still exhibits creep resistance.
310 (S31008), and cast HK (J94204)	Very good oxidation resistance to 2,000˚F (1,093˚C), but drops off considerably by 2,100˚F (1,150˚C). The 310's strength is quite low at these temperatures.
RA330® [3] alloy (N08330, EN 1.4886)	Combines useful oxidation resistance and a fairly high melting point; it will tolerate rather extreme temperatures through 2,200˚F (1,200˚C). This grade is available in more product forms than almost any other high-temperature alloy. Applications include muffles, retorts, radiant heating tubes, bar frame baskets in heat treat, tube sheets, and tube hangers for petrochemical and boiler applications.
RA 353 MA® [4] alloy (S35315, EN 1.4854)	Has a melting point (solidus 2,480˚F/1,360˚C) similar to that of RA330, with better oxidation resistance. Experience with muffles, calciners, vortex finders, and cement kiln burner pipes show it to tolerate extreme temperature better than does RA330. Currently not available, except in pipe.
Alloy HR-120® [5]	One of the strongest available wrought alloys up to about 1,900˚F (1040˚C), and is used through 2,100˚F (1,150˚C).
RA333® [6] alloy (N06333)	In open-air use has a practical limit of about 2,200˚F (1,204˚C). Applications include retorts, rotary calciners, muffles for brazing, molybdenum, and tungsten oxide reduction.
625 (N06625)	Has high strength, but is limited by oxidation resistance to 1,800˚F (980˚C).
600 alloy (N06600)	A nickel-chromium alloy. Good oxidation resistance through 2,200˚F, good carburization resistance and ductility.
601 (N06601)	Is very oxidation resistant to 2000˚F (1,204˚C). Applications include muffles, retorts and radiant heating tubes
RA 602 CA® [7] (N06025)	Extremely oxidation-resistant grade; one of strongest available at extreme temperature. Used through 2250˚F. Applications include CVD retorts, vacuum furnace fixturing, rotary calciners and radiant tubes.
Alloy X (N06002)	Is designed for gas turbine combustors, in which hot gases continually sweep over the metal surface. Because of its 9% molybdenum content, this grade may be subject to catastrophic oxidation under stagnant conditions, or in open air above 2,150˚F (1,177˚C).
Alloy 617	Very strong. Typical uses include land-based gas turbine combustors and nitric acid catalyst support grids.
Alloy 230® [8]	Also a strong alloy, with excellent oxidation resistance and good retention of ductility after intermediate temperature exposure. Gas turbine combustors, nitric acid grids, and CVD retorts are some applications of this alloy.
Supertherm® [9], cast 26Cr 35Ni 5W 15Co	Under various trade names, is suited for extreme temperature conditions. The cobalt content is sufficient to minimize high-temperature galling wear when in contact with NiCrFe alloys.

1 Registered trade name of Special Metals, Inc.
2 Registered trade name of Outokumpu
3 Registered trade name of Outokumpu
4 Registered trade name of AvestaPolarit
5 Registered trade name of Haynes International
6 Registered trade name of Rolled Alloys
7 Registered trade name of ThyssenKrupp VDM
8 Registered trade name of Haynes International
9 Registered trade name of Duraloy Technologies, Inc.
10 Registered trade name of AK Steel Corporation

Carburization
Chromium, nickel, and silicon are three major elements that confer resistance to carbon absorption. Nickel and silicon lower the maximum solubility of carbon and nitrogen. Carburization is usually of concern, because highly carburized alloys become brittle. Above about 1% carbon content, most wrought heat-resistant alloys have no measurable ductility at room temperature. Metal dusting, also known as catastrophic carburization or carbon rot, is metal waste, not embrittlement. In the right environment, it appears that any alloy can eventually metal dust.

Disagreement exists regarding appropriate alloy selection. In the steel heat-treating industry, experience has shown that RA333 and Supertherm are two of the best choices, while 602 CA performs well in some petrochemical applications. However, 310 stainless has been used in petrochemical metal dusting environments. Alloys such as N08330 and N08811 do not perform well in metal dusting environments. Recent studies show both 625 and RA 602 to be acceptable substitutions for RA333.

Sulfidation
Low or moderate nickel with high chromium content minimizes sulfidation attack at high temperatures. With the exception of alloy HR-160, less than 20% nickel content is preferred.

Fabricability
Typically, fabricability is not a significant issue for conventionally melted wrought alloys. Grades that are strengthened by oxide dispersion, such as MA956®, offer unmatched strength and oxidation resistance at extreme temperatures, but are difficult to fabricate by conventional means.

Design
Allowable stresses are often based on ASME design codes. For most thermal processing equipment, design stress is either one-half of the 10,000-hour rupture strength, or one-half of the stress to cause a minimum creep rate of 1% in 10,000 hours. Above about 1,000˚F (540˚C), creep or rupture is the basis for setting design stresses. At this temperature, materials are no longer elastic, but deform slowly with time.

Thermal Expansion
A major cause of distortion and cracking in high-temperature equipment is failure to adequately address the issue of thermal expansion, and differential thermal expansion. Temperature gradients of only 200˚F (110˚C) are sufficient to strain metals beyond the yield point.

Molten Metals
In industrial applications, low-melting metals such as copper and silver braze alloys, zinc, and aluminum cause problems. As a rule of thumb, low-melting metals attack the higher nickel alloys more readily than low-nickel or ferritic grades.

Galling
Austenitic nickel alloys tend to gall when they slide against each other. At elevated temperatures, cobalt oxide tends to be somewhat lubricious. Cobalt or alloys with high cobalt content, such as cast Super-therm, are resistant to galling at red heat. For heat treat furnace applications up through 1650˚F, Nitronic® 6010 (S21800) has resisted galling well.

Cast Versus Wrought Heat Resistant Alloys
The alloys are offered in two forms: cast form and wrought form. Each has advantages and disadvantages for use in process heating, as shown in Table 2.

Composition of Alloys
Table 3 provides composition of commonly used alloys for industrial heating equipment. The alloy composition contains several elements which are added to iron. The percentages of the elements in each alloy are shown in Table 3.

Table 2. Comparison of Cast and Wrought Alloys		
Alloy	Advantages	Disadvantages
Cast	Inherently greater creep strength	Embrittlement frequently occurs in service, making weld repair difficult
	Availability of shapes that are inconvenient to fabricate	May have soundness issues, such as porosity, shrink and surface integrity
	Chemistries not available as wrought alloys	May incur high costs for creating patterns, if only a few pieces are needed
	Some 35% and 50% chromium castings only available as castings	Delivery time may be long even if only a few pieces are needed
		Cast parts may be thicker and heavier than the equivalent fabrication. This increases the dead weight that is heat treated, and reduces efficiency of thermal transfer through the wall.
Wrought	Availability of broad range of section thicknesses. Wrought alloys are available as thin as foil.	Creep strength—few wrought alloys match the high strength of heat-resistant alloy castings. This must be considered in product design, where creep rupture is a concern. Recent trends towards lighter, thinner sections/components from wrought products somewhat mitigate these differences.
	Thinner sections permit significant weight reduction	Composition—alloys such as 50Cr 50Ni, 28Cr 10Ni or 35Cr 46Ni, all with excellent hot corrosion and/or carburization resistance, are available only as castings.
	Smooth surface helps avoid focal point for accelerated corrosion by molten salts or carbon deposits	
	Usually free of the internal and external defects, such as shrink and porosity, found in castings	
	Availability—fabrications are quickly procured, using stock materials, which minimizes down time.	

Table 3. Material (Alloy) Composition								
Nominal Chemistry, Ferritic Alloys								
Alloy	Unified Numbering System (UNS)	European Normal/ Werkstoff Nummer EN/W.Nr	Chromium (Cr)	Silicon (Si)	Aluminum (Al)	Titanium (Ti)	Carbon (C)	Other
410S	S41008	1.4000	12.0	0.30	--	--	0.05	--
430	S43000	1.4016	16.5	0.50	--	--	0.08	--
MA956® [11]	S67956	--	19.4	0.05	4.5	0.4	0.02	$0.5Y_2O_3$
446	S44600	1.4763	25.0	0.50	--	--	0.05	--
Nominal Chemistry, Fe-Cr-Ni Alloys, Nickel 20% and under								
Alloy	UNS	EN/W.Nr	Cr	Nickel (Ni)	Si	C	Nitrogen (N)	Other
304H	S30409	1.4301	18.3	9	0.5	0.05	--	70Fe
RA253 MA®	S30815	1.4835	21	11	1.7	0.08	0.17	0.04Ce 65Fe
309S	S30908	1.4833	23	13	0.8	0.05	--	62Fe
310S	S31008	1.4845	25	20	0.5	0.05	--	52Fe
Nominal Chemistry, Fe-Ni-Cr Alloys, Nickel 30% to 40%								
Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Other	
800 HT®	N08811	--	21	31	0.4	0.06	45Fe 0.6Ti 0.4Al	
803	S35045	--	25.5	34.5	0.7	0.07	37Fe 0.4Ti 0.3Al	
RA330®	N08330	1.4886	19	35	1.2	0.05	43Fe	
RA353 MA®	S35315	1.4854	25	35	1.2	0.05	36Fe 0.16N 0.05Ce	
HR-160® 12	N12160	--	28	36	2.8	0.05	30Co 2Fe 0.5Ti	
HR-120®	N08120	--	25	37	0.6	0.05	35Fe 0.7Cb 0.1Ti	

Table 3. Material (Alloy) Composition (continued)

Nominal Chemistry, Ni-Cr-Fe Alloys, Nickel 45% to 60%

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Other
RA333®	N06333	2.4608	25	45	1	0.05	3Co 3Mo 3W 18Fe
617	N06617	2.4663	22	54	0.03	0.08	12.5Co 9Mo 1Al 0.4Ti 1Fe
230®	N06230	--	22	60	0.4	0.10	14W 1.5Mo 0.3Al 0.02La

Nominal Chemistry, Nickel over 60%, 15% to 25% Chromium

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Other
601	N06601	2.4851	22.5	61.5	0.2	0.05	1.4Al 14Fe
RA 602	N06025	2.4633	25	63	--	0.2	2Al 0.1Y 0.08Zr
CA®							9.5Fe
214™[13]	N07214	--	16	76	--	0.04	4.5Al 0.005Y 3.5Fe
600	N06600	2.4816	--	15.5	76	0.2	0.08 0.2Ti 8Fe

Nominal Chemistry, Cast Heat Resistant Alloys

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Tungsten (W)	Cobalt (Co)	Other
HC	J92605	--	28	2	0.8	0.3	--	--	67Fe
HD	J93005	--	29	5	1.5	0.4	--	--	63Fe
HE	J93403	1.4339	28	9	1.5	0.3	--	--	61Fe
HF	J	--	21	10	1.4	0.3	--	--	67Fe
HH-2	J93633	1.4837	25	13	1	0.3	--	--	60Fe
HI	J94003	--	28	16	1	0.4	--	--	54Fe
HK	J94204	1.4840	25	20	1.4	0.4	--	--	54Fe
HL	J94614	--	30	20	1.4	0.4	--	--	47Fe
HN	J		21	25	1.4	0.4	--	--	52Fe
Ten-X	--	--	20	30	1.4	0.4	5	8	35Fe
HT	J94605	--	17	35	1.7	0.5	--	--	44Fe
HU	J95405	1.4865	18	38	1.7	0.5	--	--	40Fe
HP	J95705	1.4857	26	35	1.3	0.5	--	--	36Fe
MO-RE® 1[14]	--	--	26	36	1	0.45	1.6	--	33
Supertherm®[15]	--	--	26	35	1.5	0.5	5	15	13Fe
22H®[16]	--	2.4879	28	48	1	0.5	5	--	16Fe
Super 22H[17]	--	--	28	48	1	0.5	5	3	13
MO-RE® 40MA	--	--	35	46	1	0.45	--	--	14Fe 1.3Cb
HX	N06006	--	17	66	2	0.5	--	--	13Fe
IC-221M	--	--	7.7	81	--	0.04	--	--	8Al 1.3Mo 1.7Zr

11 Registered trade name of Special Metals, Inc.
12 Registered trade name of Haynes International.
13 Trade name of Haynes International.
14 Registered trade name of Duraloy Technologies, Inc.
15 Registered trade name of Duraloy Technologies, Inc.
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Acknowledgements

Special thanks to Dr. James Kelly and Marc Glasser of Rolled Alloys, and Arvind Thekdi of E3M, Inc., for their contributions to this technical brief.

Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emissions Performance

Introduction

Thermal efficiency of process heating equipment, such as furnaces, ovens, melters, heaters, and kilns is the ratio of heat delivered to a material and heat supplied to the heating equipment. For most heating equipment, a large amount of the heat supplied is wasted in the form of exhaust or flue gases. These losses depend on various factors associated with the design and operation of the heating equipment.

This technical brief is a guide to help plant operators reduce waste heat losses associated with the heating equipment.

Heat Losses from Fuel-Fired Heating Equipment.

Waste-gas heat losses are unavoidable in the operation of all fuel-fired furnaces, kilns, boilers, ovens, and dryers. Air and fuel are mixed and burned to generate heat, and a portion of this heat is transferred to the heating device and its load. When the energy transfer reaches its practical limit, the spent combustion gases are removed (exhausted) from the furnace via a flue or stack to make room for a fresh charge of combustion gases. At this point, the exhaust flue gases still hold considerable thermal energy, often more than what was left behind in the process. In many fuel-fired heating systems, this waste heat is the greatest source of heat loss in the process, often greater than all the other losses combined.

Reducing these losses should be a high priority for anyone interested in improving the energy efficiency of furnaces and other process heating equipment.

The first step in reducing waste heat in flue gases requires close attention and proper measures to reduce all heat losses associated with the furnace. Any reduction in furnace heat losses will be multiplied by the overall available heat factor. This could result in much higher energy savings. The multiplier effect and available heat factor are explained in greater detail in the following sections.

These furnace losses include:
- Heat storage in the furnace structure
- Losses from the furnace outside walls or structure
- Heat transported out of the furnace by the load conveyors, fixtures, trays, etc.
- Radiation losses from openings, hot exposed parts, etc.
- Heat carried by the cold air infiltration into the furnace
- Heat carried by the excess air used in the burners.

All of these losses can be estimated by using the PHAST software tool or the AMO's Process Heating Tip Sheets.

Reducing waste heat losses brings additional benefits, among them:
- Lower energy component of product costs
- Improved furnace productivity
- Lower emissions of carbon monoxide (CO), nitrogen oxides (NOx) and unburned hydrocarbons (UHCs)
- May contribute to more consistent product quality and better equipment reliability.

What Determines Waste-Gas Losses?

To answer this, the flow of heat in a furnace, boiler, or oven must be understood. The purpose of a heating process is to introduce a certain amount of thermal energy into a product, raising it to a certain temperature to prepare it for additional processing, change its properties, or some other purpose. To carry this out, the product is heated in a furnace or oven. As shown in Figure 1, this results in energy losses in different areas and forms.

First, the metal structure and insulation of the furnace must be heated so their interior surfaces are about the same temperature as the product they contain. This stored heat is held in the structure until the furnace shuts down, then it leaks out into the surrounding area. The more frequently the furnace is cycled from cold to hot and back to cold again, the more frequently this stored heat must be replaced.

In addition, because the furnace cannot run production until it has reached the proper operating temperature, the process of storing heat in it causes lost production time. Fuel is consumed with no useful output.

Wall losses. Additional heat losses take place while the furnace is in production. Wall or transmission losses are caused by the conduction of heat through the walls, roof, and floor of the heating device, as shown in Figure 2. Once that heat reaches the outer skin of the furnace and radiates to the surrounding area or is carried away by air currents, it must be replaced by an equal amount taken from the combustion gases. This process continues as long as the furnace is at an elevated temperature.

Material handling losses. Many furnaces use equipment to convey the work into and out of the heating chamber, and this can also lead to heat losses. Conveyor belts or product hangers that enter the heating chamber cold and leave it at higher temperatures drain energy from the combustion gases. In car bottom furnaces, the hot car structure gives off heat to the room each time it rolls out of the furnace to load or remove work. This lost energy must be replaced when the car is returned to the furnace.

Cooling media losses. Water or air cooling protects rolls, bearings, and doors in hot furnace environments, but at the cost of lost energy. These components and their cooling media (water, air, etc.) become the conduit for additional heat losses from the furnace. Maintaining an adequate flow of cooling media is essential, but it might be possible to insulate the furnace and load from some of these losses.

Radiation (opening) losses. Furnaces and ovens operating at temperatures above 1,000˚F might have significant radiation losses, as shown in Figure 3. Hot surfaces radiate energy to nearby colder surfaces, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. Anyone who has ever stood in front of the open door of a high-temperature furnace can attest to the huge amount of thermal energy beamed into the room.

Anywhere or anytime there is an opening in the furnace enclosure, heat is lost by radiation, often at a rapid rate. These openings include the furnace flues and stacks themselves, as well as doors left partially open to accommodate oversized work in the furnace.

Figure 1. Heat losses in industrial heat processes.

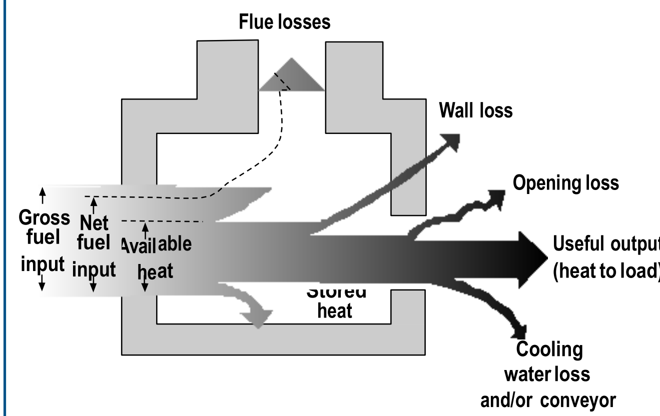


Figure 2. Wall loss.

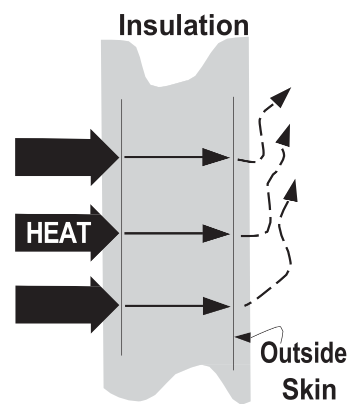


Figure 3. Radiation loss from heated to colder surface.

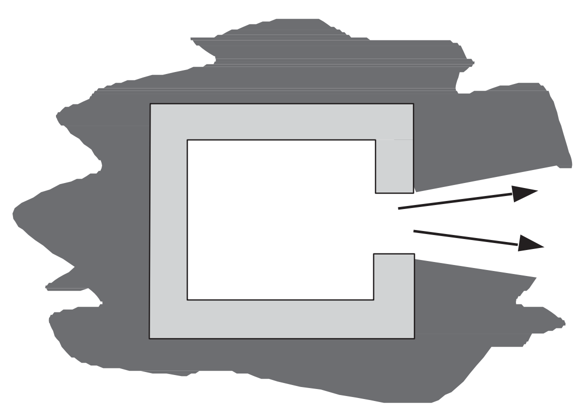
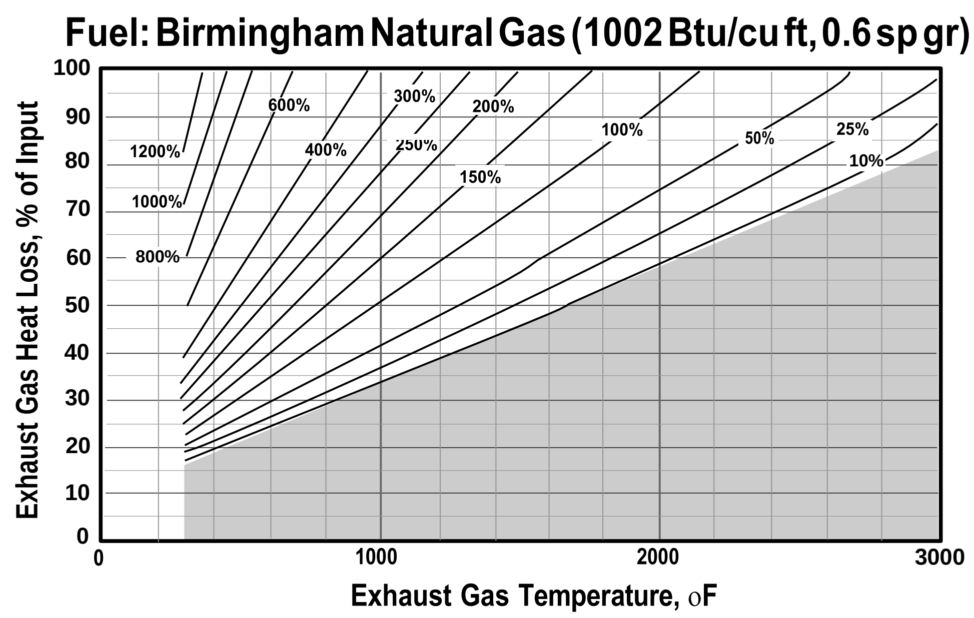


Figure 4. Heat losses in industrial heat processes for different excess air percentages



Waste-gas losses. All the losses mentioned above – heat storage, wall transmission, conveyor and radiation – compete with the workload for the energy released by the burning fuel-air mixture. However, these losses could be dwarfed by the most significant source of all, which is waste-gas loss.

Waste-gas loss, also known as flue gas or stack loss, is made up of the heat that cannot be removed from the combustion gases inside the furnace. The reason is heat flows from the higher temperature source to the lower temperature heat receiver.

In effect, the heat stream has hit bottom. If, for example, a furnace heats products to 1,500˚F, the combustion gases cannot be cooled below this temperature without using design or equipment that can recover heat from the combustion gases. Once the combustion products reach the same temperature as the furnace and load, they cannot give up any more energy to the load or furnace, so they have to be discarded. At 1,500˚F temperature, the combustion products still contain about half the thermal energy put into them, so the waste-gas loss is close to 50% (Figure 4). The other 50%, which remains in the furnace, is called available heat. The load receives heat that is available after storage in furnace walls, and losses from furnace walls, load conveyors, cooling media and radiation have occurred.

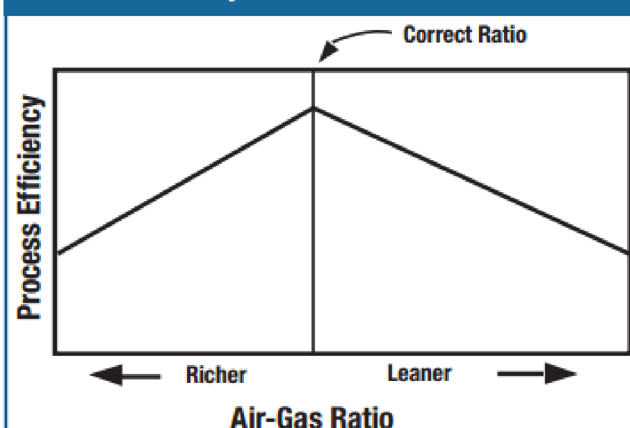
This makes it obvious that the temperature of a process, or more correctly, of its exhaust gases, is a major factor in its energy efficiency. The higher that temperature, the lower the efficiency.

Another factor that has a powerful effect is the fuel-air ratio of the burner system.

Fuel-air ratios. For every fuel, there is a chemically correct, or stoichiometric, amount of air required to burn it. One cubic foot of natural gas, for example, requires about 10 cubic feet of combustion air. Stoichiometric, or on-ratio combustion will produce the highest flame temperatures and thermal efficiencies.

However, combustion systems can be operated at other ratios. Sometimes, this is done deliberately to obtain certain operating benefits, but often, it happens simply because the burner system is out of adjustment. The ratio, as shown in Figure 5, can go either rich (excess fuel or insufficient air) or lean (high percentages of excess air). Either way, it wastes fuel. Because there is not enough air for complete combustion, operating the burners at rich combustion conditions wastes fuel by allowing it to be discarded with some of its energy unused. It also generates large amounts of carbon monoxide (CO) and unburned hydrocarbons (UHCs).

Figure 5. Effect of off-ratio operation on furnace efficiency.



At first glance, operating lean might seem to be a better proposition because all the fuel is consumed. Indeed, a lean operation produces no flammable, toxic by-products of rich combustion, but it does waste energy. Excess air has two effects on the combustion process. First, it lowers the flame temperature by diluting the combustion gases, in much the same way cold water added to hot produces warm water. This lowers the temperature differential between the hot combustion gases and the furnace and load, which makes heat transfer less efficient. More damaging, however, is the increased volume of gases that are exhausted from the process. The products of stoichiometric combustion and the excess are at the same temperature. The excess air becomes one more competitor for the energy demand in the process. Because this is part of the combustion process, excess air goes to the head of the line, taking its share of the heat before the furnace and its contents.

The results can be dramatic. In a process operating at 2,000˚F, available heat at stoichiometric ratio is about 45% (55% goes out the stack). Allowing just 20% excess air into the process (roughly a 12-to-1 ratio for natural gas) reduces the available heat to 38%. Now, 62% of the total heat input goes out the stack, the difference being carried away by that relatively small amount of excess air. To maintain the same temperatures and production rates in the furnace, 18% more fuel must be burned.

Air infiltration. Excess air does not necessarily enter the furnace as part of the combustion air supply. It can also infiltrate from the surrounding room if there is a negative pressure in the furnace. Because of the draft effect of hot furnace stacks, negative pressures are fairly common, and cold air slips past leaky door seals and other openings in the furnace. Figure 6 illustrates air infiltration from outside the furnace.

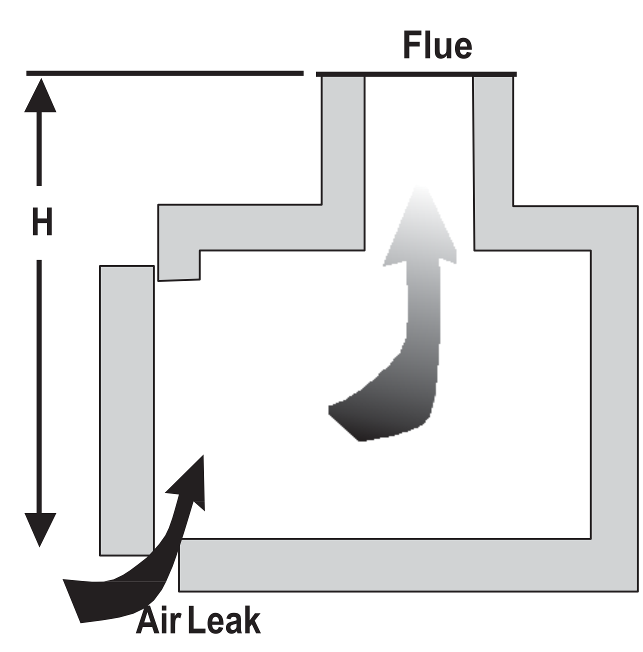
Once in the furnace, air absorbs precious heat from the combustion system and carries it out the stack, lowering the furnace efficiency. A furnace pressure control system may be an effective way to deal with this. See the AMO tip sheet, "Reduce Air Infiltration in Furnaces," for guidelines on estimating infiltration losses.

The bottom line is that to get the best possible energy efficiency from furnaces and ovens, reduce the amount of energy carried out by the exhaust and lost to heat storage, wall conduction, conveying and cooling systems and radiation.

Furnace scheduling and loading

A commonly overlooked factor in energy efficiency is scheduling and loading of the furnace. "Loading" refers to the amount of material processed through the furnace or oven in a given period of time. It can have a significant effect on the furnace's energy consumption when measured as energy used per unit of production, for example, in British thermal units per pound (Btu/lb).

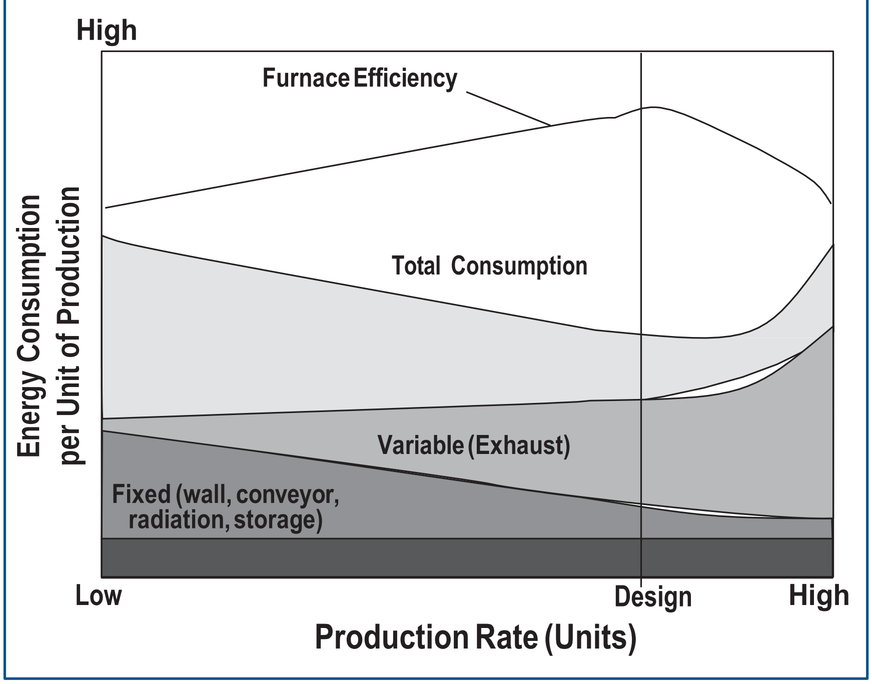
Figure 6. Air infiltration from furnace opening.



Certain furnace losses (wall, storage, conveyor and radiation) are essentially constant regardless of production volume; therefore, at reduced throughputs, each unit of production has to carry a higher burden of these fixed losses. Flue gas losses, on the other hand, are variable and tend to increase gradually with production volume. If the furnace is pushed past its design rating, flue gas losses increase more rapidly, because the furnace must be operated at a higher temperature than normal to keep up with production.

Total energy consumption per unit of production will follow the curve in Figure 7, which shows the lowest at 100% of furnace capacity and progressively higher the farther throughputs deviate from 100%. Furnace efficiency varies inversely with the total energy consumption. The lesson here is that furnace operating schedules and load sizes should be selected to keep the furnace operating as near to 100% capacity as possible. Idle and partially loaded furnaces are less efficient.

Figure 7. Impact of production rate on energy consumption per unit of production.



Steps for increasing energy efficiency through reduction in exhaust gas heat losses. The exhaust gas heat losses can be calculated by the equation:

Furnace exhaust heat losses =
W * Cp * (T exhaust – T ambient)

Where:

- W = Mass of the exhaust gases
- Cp = Specific heat of the exhaust gases
- T exhaust = Flue gas temperature entering the furnace exhaust system (stack)
- T ambient = Ambient temperature (usually assumed 60˚F)

The highest priority is to minimize exhaust gas temperature and mass or volume of exhaust gases.

- The furnace exhaust gas temperature depends on many factors associated with the furnace operation and heat losses discussed above. It can be measured directly or can be assumed to 100˚ to 200˚F above the control temperature for the furnace zone where the flue gases are exhausted.
- The exhaust mass flow depends on the combustion air flow, fuel flow and the air leakage into the furnace. Measurement of fuel flow together with the percentage of oxygen (or carbon dioxide [CO_2]) in the flue gases can be used to estimate mass or volume of exhaust gases.
- The flue-gas specific heat (Cp) for most gaseous fuel-fired furnaces can be assumed to be 0.25 Btu/lb per ˚F) or 0.02 Btu/(standard cubic foot per ˚F) for a reasonably accurate estimate of flue gas heat losses.

Minimize exhaust gas temperatures. Excessive exhaust gas temperatures can be the result of poor heat transfer in the furnace. If the combustion gases are unable to transfer the maximum possible heat to the furnace and its contents, they will leave the furnace at higher temperatures than necessary. Optimizing heat transfer within the furnace requires different methods for different situations. The AMO tip sheet "Check Heat Transfer Surfaces" will provide greater insight into how transfer takes place and what can be done to improve it.

Overloading a furnace can also lead to excessive stack temperatures. To get the proper rate of heat transfer, combustion gases must be in the heating chamber for the right amount of time. The natural tendency of an overloaded furnace is to run colder than optimal, unless the temperature is set artificially high. This causes the burners to operate at higher than normal firing rates, which increase combustion gas volumes. The higher gas flow rates and shorter time in the furnace cause poor heat transfer, resulting in higher temperature for the flue gases. Increased volumes of higher temperature flue gases lead to sharply increased heat losses. Overly ambitious production goals might be met, but at the cost of excessive fuel consumption.

Minimize exhaust gas volumes. Avoiding overloading and optimizing heat transfer are two ways to lower waste gas flows, but there are others.

The most potent way is to closely control fuel-air ratios. Operating the furnace near the optimum fuel-air ratio for the process also controls fuel consumption. The best part is that it can usually be done with the existing control equipment. All that is required is a little maintenance attention. The AMO tip sheet "Check Burner Air-Fuel Ratios" provides a useful chart for figuring exhaust gas losses and shows how to figure the efficiency improvements that can come from controlling ratios more closely.

Some reduction in exhaust volumes will be the indirect result of efficiencies applied elsewhere. As mentioned above, flue gas losses are a fixed percentage of the total heat input to the furnace. As shown in Figure 8, any reduction in heat storage, wall, conveyor or radiation losses will be multiplied by the available heat factor. For example, on a furnace operating at 50% available heat (50% exhaust gas loss), lowering wall losses by 100,000 Btu per hour (Btu/hr) will permit a firing rate reduction of 200,000 Btu/hr. That is 100,000 Btu/hr for the wall loss and 100,000 Btu/hr for the accompanying exhaust gas loss.

Use of oxygen enriched combustion air. Ambient air contains approximately 21% oxygen with nitrogen and other inert gases as balance. The total volume of exhaust gases could be reduced by increasing the oxygen content of combustion air, either by mixing in ambient air or by using 100% oxygen. Reducing exhaust gases would result in substantial fuel savings. The exact amount of energy savings depends on the percentage of oxygen in combustion air and the flue gas temperature. Higher values of oxygen and flue gas temperature offer higher fuel savings. Obviously, the fuel savings would have to be compared to the cost of oxygen to estimate actual economic benefits.

Waste heat recovery. Reducing exhaust losses should always be the first step in a well-planned energy conservation program. Once that goal has been met, consider the next level – waste heat recovery. Waste heat recovery elevates furnace efficiency to higher levels, because it extracts energy from the exhaust gases and recycles it to the process. Significant efficiency improvements can be made even on furnaces that operate with properly tuned ratio and temperature controls. There are four widely used methods:

1. **Direct heat recovery to the product.** If exhaust gases leaving the high-temperature portion of the process can be brought into contact with a relatively cool incoming load, energy will be transferred to the load and preheats the load. This reduces the energy that finally escapes with the exhaust (Figure 9). This is the most efficient use of waste heat in the exhaust.

Figure 8. Multiplying effect of available heat on furnace losses.

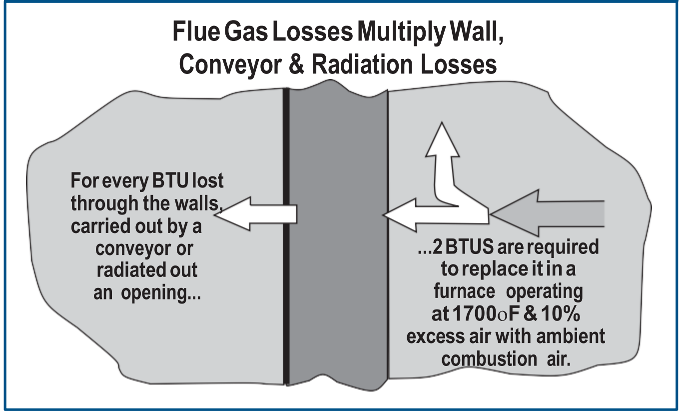


Figure 9. Direct preheating of incoming work.

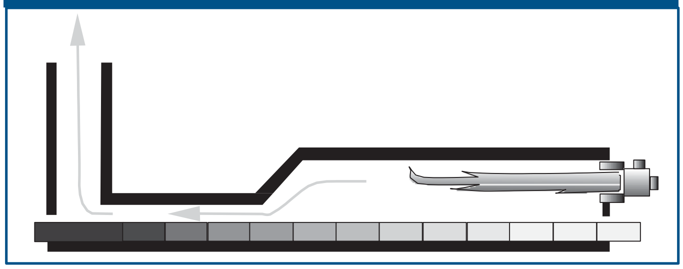
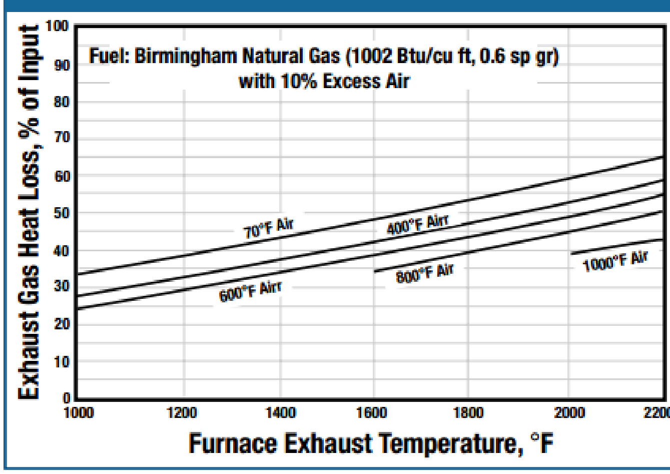


Figure 10. Exhaust gas losses with ambient and preheated air.



Use of waste heat recovery to preheat combustion air is commonly used in medium- to high- temperature furnaces. Use of preheated air for the burners reduces the amount of purchased fuel required to meet the process heat requirements. Figure 10 shows the effect of preheating combustion air on exhaust gas heat losses. Preheating of combustion air requires the use of a recuperator or a regenerator.

2. **Recuperators.** A recuperator (Figure 11) is a gas-to-gas heat exchanger placed on the stack of the furnace. There are numerous designs, but all rely on tubes or plates to transfer heat from the outgoing exhaust gas to the incoming combustion air, while keeping the two streams from mixing. Recuperators are the most widely used heat recovery devices.

3. **Regenerators.** These are basically rechargeable storage batteries for heat. A regenerator (Figure 12) is an insulated container filled with metal or ceramic shapes that can absorb and store relatively large amounts of thermal energy. During the operating cycle, process exhaust gases flow through the regenerator, heating the storage medium. After a while, the medium becomes fully heated (charged). The exhaust flow is shut off and cold combustion air enters the unit. As it passes through, the air extracts heat from the storage medium, increasing in temperature before it enters the burners. Eventually, the heat stored in the medium is drawn down to the point where the regenerator requires recharging. At that point, the combustion air flow is shut off and the exhaust gases return to the unit. This cycle repeats as long as the process continues to operate.

For a continuous operation, at least two regenerators and their associated burners are required. One regenerator provides energy to the combustion air, while the other recharges. In this sense, it is much like using a cordless power tool; to use it continuously, you must have at least two batteries to swap out between the tool and the recharger. An alternate design of regenerator uses a continuously rotating wheel containing metal or ceramic matrix. The flue gases and combustion air pass through different parts of the wheel during its rotation to receive heat from flue gases and release heat to the combustion air.

4. **Use of waste heat boiler.** Use of a waste heat boiler to recover part of the exhaust gas heat is an option for plants that need a source of steam or hot water. The waste heat boiler is similar to conventional boilers with one exception: it is heated by the exhaust gas stream from a process furnace instead of its own burner. Waste heat boilers may be the answer for plants seeking added steam capacity. Remember, however, that the boiler generates steam only when the process is running.

Figure 11. Recuperator system for preheating combustion air losses.

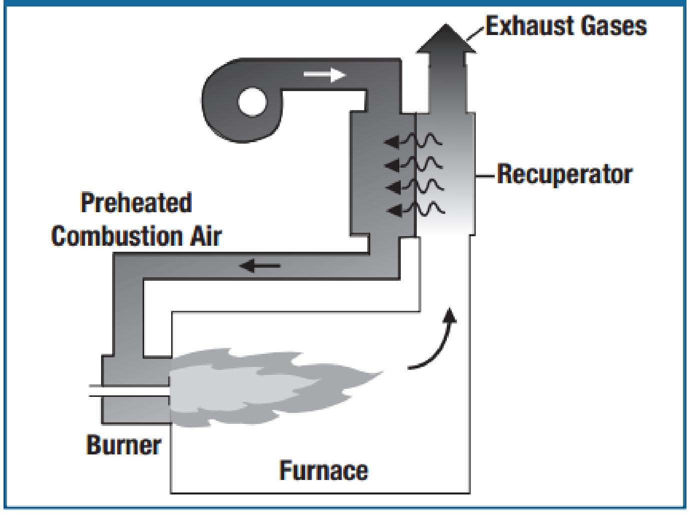
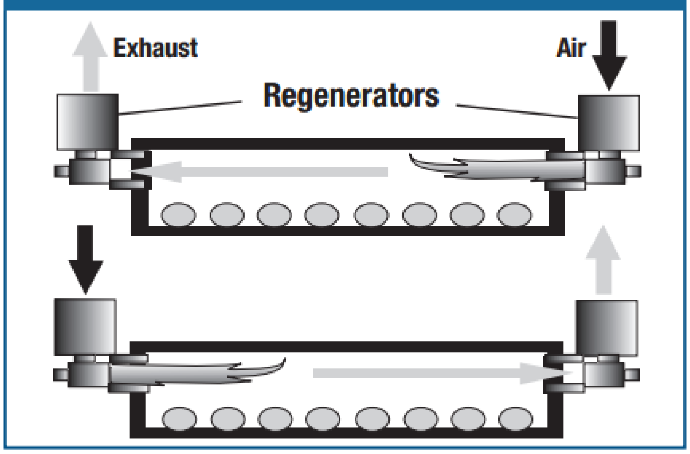


Figure 12. Regenerator system for storing thermal energy.



Not all processes are candidates for waste heat recovery. Exhaust volumes and temperatures may be too low to provide financial justification, but if the exhaust temperature is above 1,000˚F, waste heat recovery is worth investigating.

The AMO tip sheet "Preheated Combustion Air" offers guidance on how to estimate the efficiency and economic benefits of preheating combustion air.

Energy reduction and recovery strategy

A comprehensive program for reducing furnace energy consumption involves two types of activities. The first deals with achieving the best possible performance from the existing equipment. Equipment modifications, if required, are relatively modest. The second involves major equipment modifications and upgrades that can make substantial reductions in energy consumption. These techniques and their benefits are summarized in Table 1.

Table 1. Areas of Potential Waste Heat Reduction and Recovery Improvement

Energy Conservation Technique	Heat Transfer to Load	Reduction of Exhaust Gas Mass	Temperature Uniformity	Productivity
Improving the Performance of Existing Equipment				
Reducing Heat Storage		√		√
Reducing Wall Losses		√		√
Reducing Material Handling Losses		√		√
Reducing Cooling Media Losses	√	√	√	√
Reducing Radiation Losses	√	√	√	√
Optimizing Fuel-Air Ratio	√	√		√
Reducing Air Infiltration	√	√	√	√
Improving Scheduling & Loading		√		√
Modifying and Upgrading Equipment				
Waste Heat Recovery				
- Air Preheating	√	√		√
- Load Preheating		√	√	√
- To External Processes*				
Oxygen-Enhanced Combustion	√	√		√
Improving Heat Transfer with Advanced Burners and Controls	√	√	√	√

* Process is not directly affected, but energy reduction can be achieved at the plant level.

Summary

Obtaining the maximum efficiency and productivity from industrial furnaces and ovens is a two-step process. First, get the equipment up to its peak performance by reducing heat losses, improving production scheduling and closely controlling gas-air ratios. Once the equipment has reached this level of performance, additional significant improvements may come from recapturing waste heat through direct load preheating, combustion air preheating or steam generation.

Additional Process Heating Resources

For additional information on topics referenced in this tech brief, please see tip sheets and case studies in the Process Heating section of the AMO website at www.energy.gov/eere/amo/process-heating-systems.

Acknowledgements

Special thanks to Richard Bennett of Janus Technologies and Arvind Thekdi of E3M, Inc., for their contributions to this technical brief.

Appendix D: References

The following are references used in this Sourcebook.

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Presentation titled, *Process Heating, Review of Processes and Equipment Used by the Industry*, Dr. Arvind Thekdi, E3M, Inc.

Figures 1, 2 and 4. Presentation titled, *Process Heating, Review of Processes and Equipment Used by the Industry*, Dr. Arvind Thekdi, E3M, Inc.

Figure 3. *North American Combustion Handbook*, diagram source; numbers from Arvind Thekdi, E3M, Inc..

Figures and Tables in the Section 4 (Waste Heat Management) were also provided by Dr. Arvind Thekdi, E3M, Inc.

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