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.

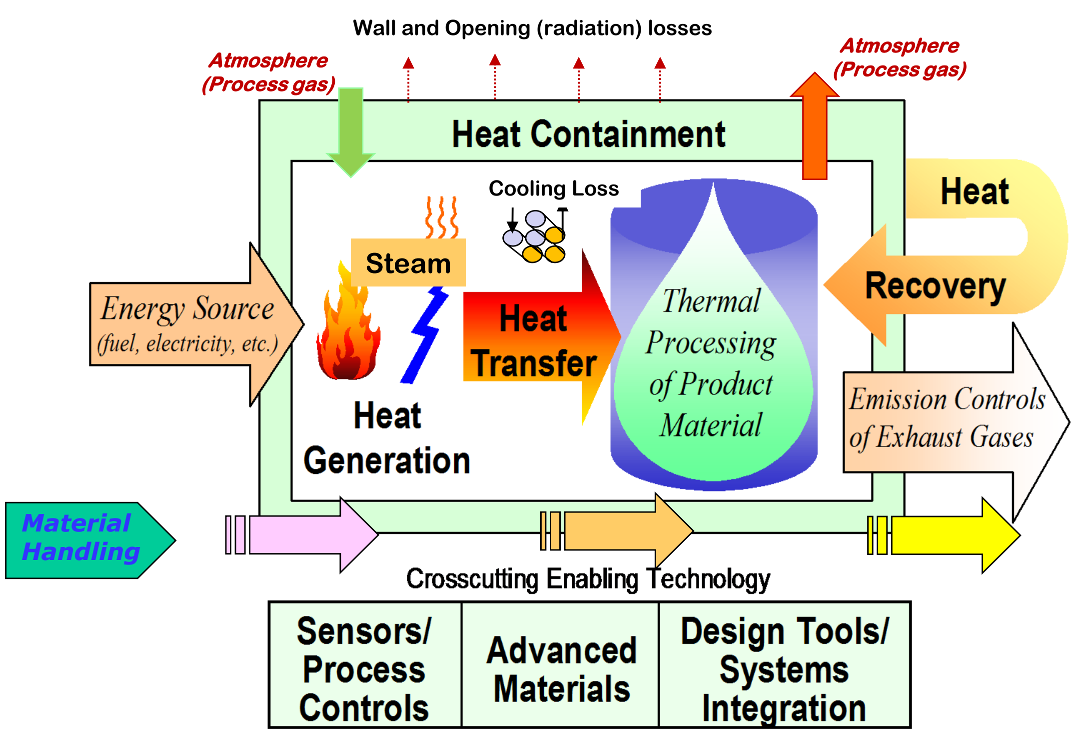

Figure 1. A fuel-based process heating system and opportunities for improvement

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.

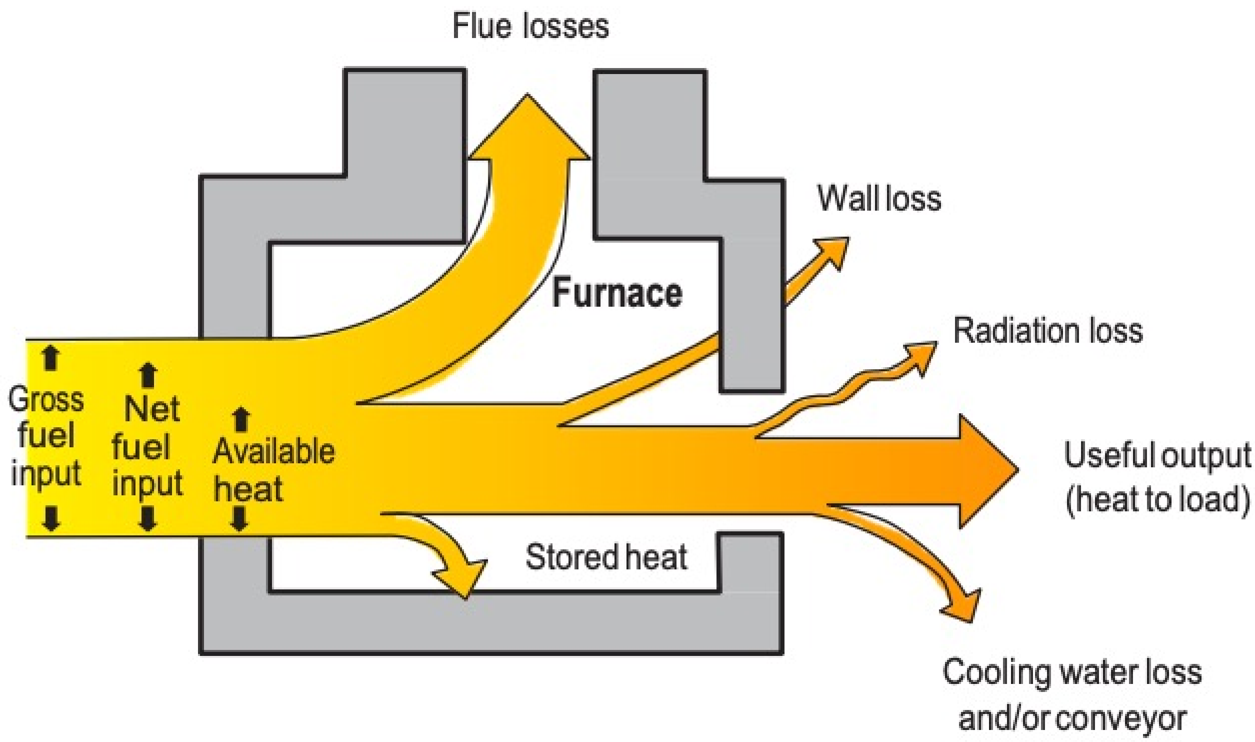

Figure 2. Energy loss diagram in a fuel-based process heating system.

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.

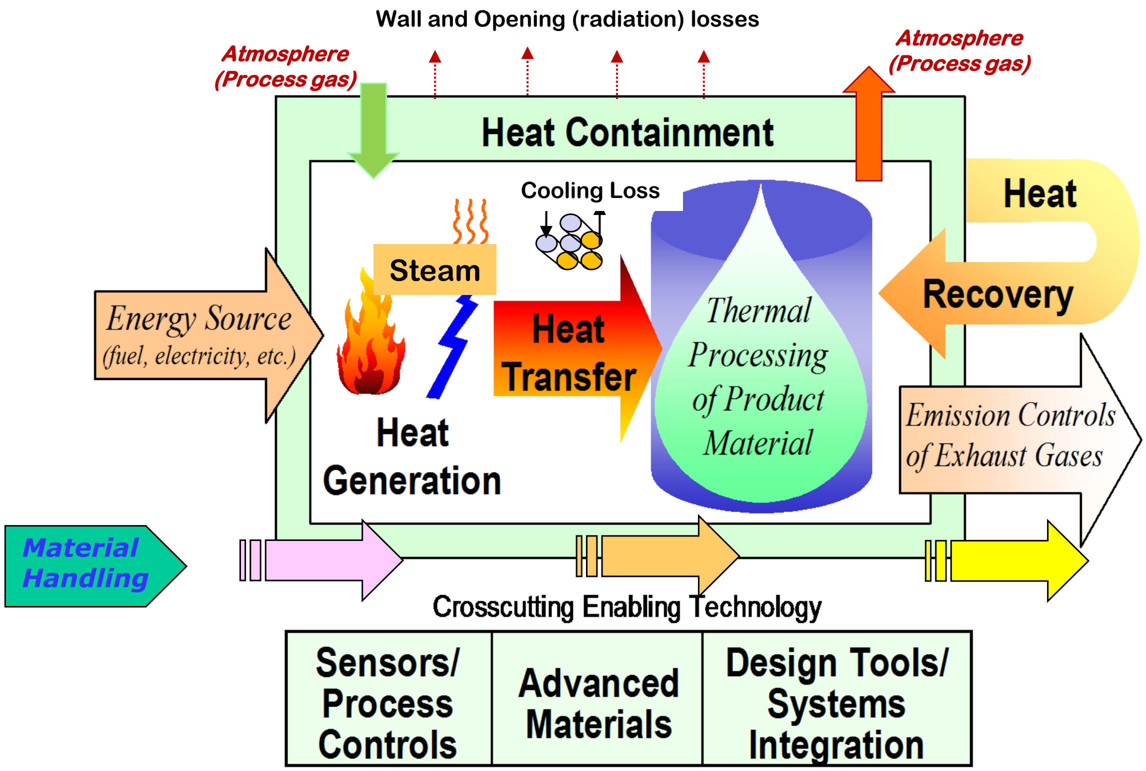

Figure 3. Key opportunities in a fuel-based system

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***

2 – PERFORMANCE IMPROVEMENT OPPORTUNITIES – FUEL-BASED SYSTEMS

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.