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IMPROVING PROCESS HEATING PERFORMANCE - VOL 2 OF 2

Main Category:	Chemical Engineering
Sub Category:	-
Course #:	CHE-135
Course Content:	44 pgs
PDH/CE Hours:	4

OFFICIAL COURSE/EXAM
(SEE INSTRUCTIONS ON NEXT PAGE)

CHE-135 EXAM PREVIEW

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Instructions:

- At your convenience and own pace, review the course material below. When ready, click "Take Exam!" above to complete the live graded exam. (Note it may take a few seconds for the link to pull up the exam.) You will be able to re-take the exam as many times as needed to pass.
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Exam Preview:

1. 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.
   a. True
   b. False

2. Using the Percent Fuel Savings Gained from Using Preheated Combustion Air table in the reference material, what percentage of fuel savings may be seen if the system has a furnace exhaust temp of 1,800 °F and a preheated air temperature of 1,200 °F?
   a. 20%
   b. 28%
   c. 33%
   d. 40%

3. In an oxygen-enriched heat-governed furnaces, the furnace gas velocity may increase because the convective heat transfer coefficient may decrease in a larger proportion than the increase in gas temperature.
   a. True
   b. False

4. 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 ____ British thermal units (Btu) in complete combustion.
   a. 100
   b. 250
   c. 500
   d. 1,000

5. 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 10% in 10,000 hours.
    a. True
    b. False

6. Using Table 2. Comparison of Cast and Wrought Alloys, which of the following advantages belongs to cast alloys?
    a. Availability—fabrications are quickly procured
    b. Inherently greater creep strength
    c. Usually free of the internal and external defects, such as shrink and porosity
    d. Thinner sections permit significant weight reduction

7. 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 ____°F are sufficient to strain metals beyond the yield point.
    a. 750
    b. 500
    c. 200
    d. 100

8. According to the reference material, 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.
    a. True
    b. False

9. According to the reference material, which element is the one element present in all heat-resistant alloys, and its protective scale is the basis for high-temperature environmental resistance.
    a. Aluminum
    b. Silicon
    c. Nickel
    d. Chromium

10. Using Table 1. High Temperature Alloys (in order of increasing performance), which alloy matches the following description: A nickel-chromium alloy. Good oxidation resistance through 2,200°F, good carburization resistance and ductility?
    a. RA333® 6 alloy (N06333)
    b. 600 alloy (N06600)
    c. 321 (S32100) stainless
    d. Alloy 800HT® 1 (UNS N08811)

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The tip sheets can also be downloaded from ITP's BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

Preheated Combustion Air

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

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

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

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

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

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

Payback Guidelines

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

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

References

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

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

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

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

Example

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

Suggested Actions

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

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Check Burner Air to Fuel Ratios

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

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

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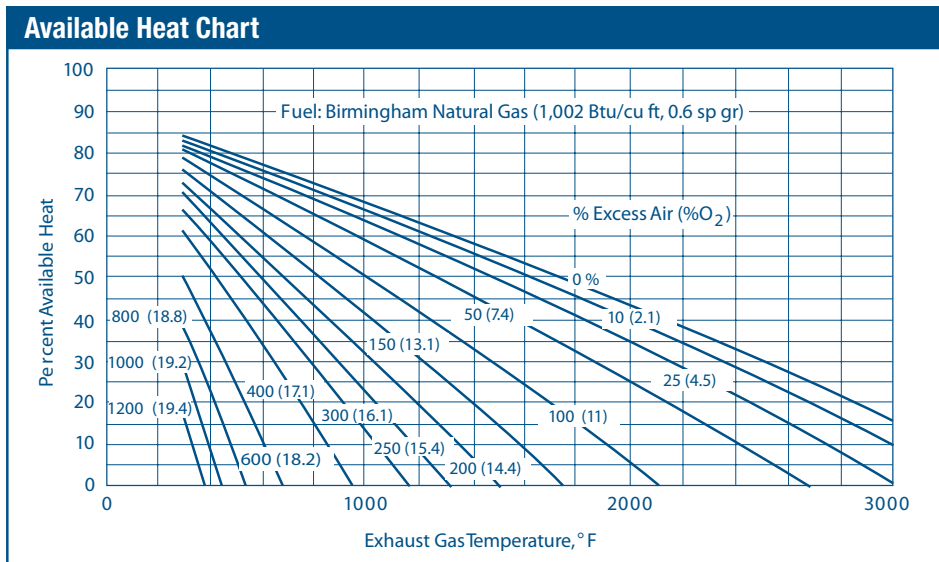
Source: Calculations by Mr. Richard Bennett, published in *Process Heating* magazine, September 1997.

To figure potential savings, you need to know:
• The temperature of the products of combustion as they leave the furnace
• The percentage of excess air or oxygen in flue gases, at which the furnace now operates
• The percentage of excess air or oxygen in flue gases, at which the furnace could operate.

Factors Affecting Excess Air Level Requirements

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

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

References

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

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

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

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

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

Example

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

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

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

Suggested Actions

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

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

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

3. Check and adjust ratio settings regularly.

Oxygen-Enriched Combustion

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

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.

Figure 1. Oxygen-enriched burner

Air
Oxygen
Fuel

Courtesy Air Products
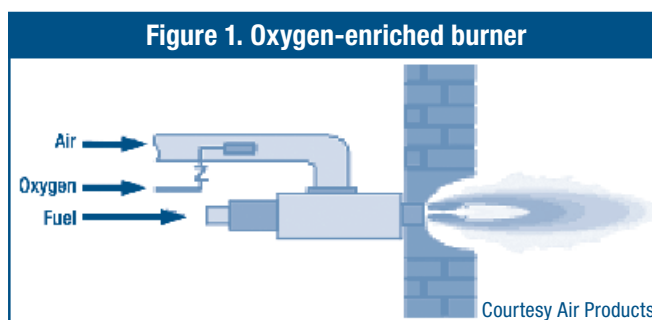
Suggested Actions

- 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.

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.

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

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
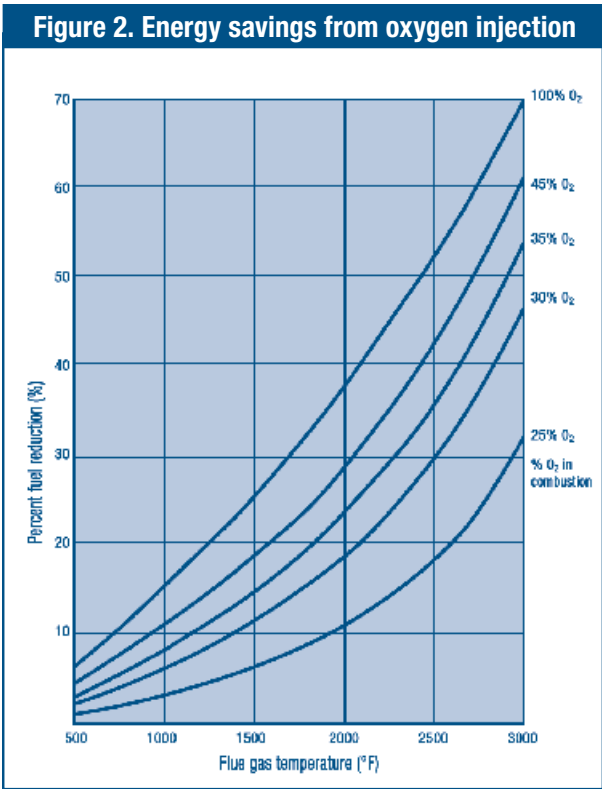
Potential Applications

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

Reference

Improving Process Heating System Performance: A Sourcebook for Industry.
DOE and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices.

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

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

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.

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

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

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

Suggested Actions— Flue Gases

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

Suggested Actions— Water Supplies

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

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

Table 1. Efficiency Reductions Caused by Soot Deposits*		
Soot Layer Thickness		
1/32 inch	1/16 inch	1/8 inch
2.5%	4.5%	8.5%

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

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

Contamination from Water Supplies

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

Reference

Improving Process Heating System Performance: A Sourcebook for Industry.
U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices.

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.

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

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

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

Secondary parameters that affect the amount of air leakage include these:
- The furnace firing rate
- The flue gas velocity through the stack or the stack cross-section area
- The burner operating conditions (e.g., excess air, combustion air temperature, and so on).

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

Flue

H
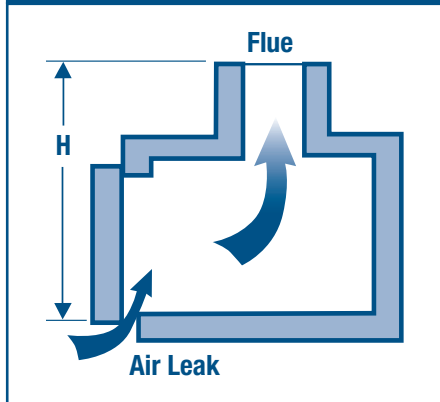
Air Leak

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.

Resources

See also *Improving Process Heating System Performance: A Sourcebook for Industry.* Washington, D.C.: U.S. Department of Energy and Industrial Heating Equipment Association, 2004.

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

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

Example

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

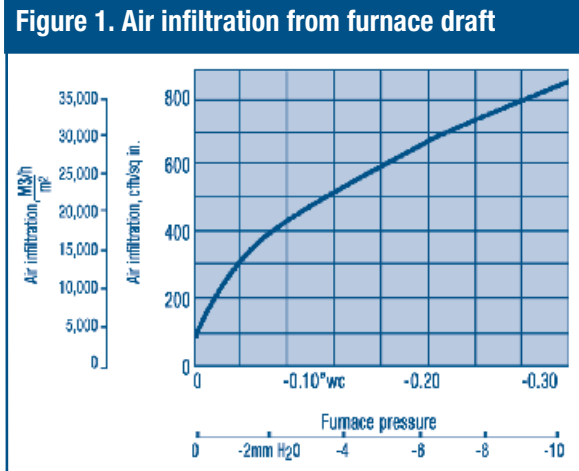| Cost of Air Infiltration in a Furnace	
Stack height (ft)	8
Stack diameter (ft)	3
Opening size, area (in.^{2})	36
Gross input (MMBtu/hr)	20
Combustion air temperature (°F)	70
Oxygen in flue gases (%)	2
Temperature of flue gases (°F)	2,300
Fuel cost ($/MMBtu)	8
Operating hr/yr	6,000
Air infiltration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

Furnace Pressure Controllers

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

References

Fan Engineering. Robert Jorgensen, ed. New York: Buffalo Forge Company. 1961.
Gas Engineers Handbook. George C. Segeler, ed. New York: The Industrial Press. 1968.
W. Trinks et al. *Industrial Furnaces, Sixth Edition.* New York: John Wiley & Sons, Inc. 2003.

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Furnace Pressure Controllers

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

Figure 1. Air infiltration from furnace draft

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

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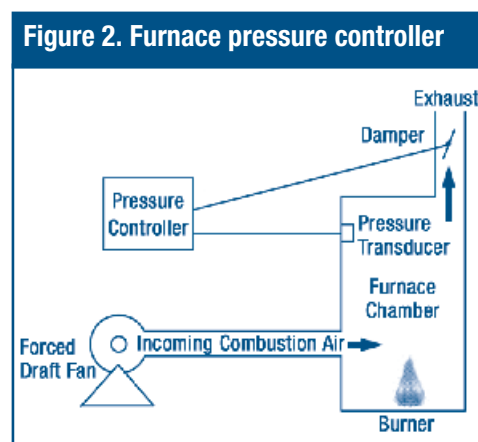
Figure 2. Furnace pressure controller

Suggested Actions

- Work with process heating specialists to estimate energy savings from using precise furnace pressure control.

- Contact furnace or combustion system suppliers to obtain cost estimates so you can calculate payback or return on investment.

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

Four types of draft systems are used in industrial furnaces:

- **Natural.** Uses the chimney effect. Gases inside the stack are less dense and will rise, creating a vacuum that draws air into the furnace.

- **Induced.** A fan draws air from the furnace to the stack.

- **Forced.** A fan pushes air into the furnace.

- **Balanced.** Uses an induced and a forced draft fan.

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

Benefits

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

- **Energy savings.** Positive pressure eliminates cold air infiltration, which reduces fuel consumption.

- **Improved product quality.** Process heating equipment with regulated pressure control will help maintain a more uniform temperature in the furnaces and avoid cold and hot spots, which can improve product quality. For heat treating applications, positive furnace pressure can reduce oxidation, and for processes like carburizing, create a more stable atmosphere for the diffusion process.

- **Maintenance savings.** Pressure control prevents excessive fluing through cracks and doors in process heating equipment, which can minimize corrosion and crack enlargement.

- **Emissions Reductions.** Improved combustion control can reduce emissions.
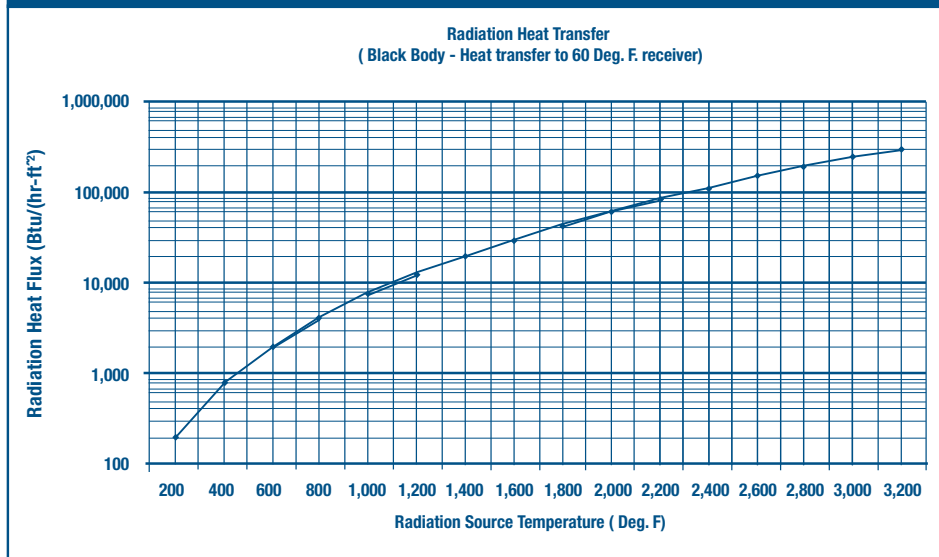
Reference

Improving Process Heating System Performance: A Sourcebook for Industry.
U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices.

Reduce Radiation Losses from Heating Equipment

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

Figure 1. Radiation heat transfer rates[1]

Radiation Heat Transfer
(Black Body - Heat transfer to 60 Deg. F. receiver)

(x-axis: Radiation Source Temperature (Deg. F); y-axis: Radiation Heat Flux (Btu/(hr-ft²)))

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

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

Suggested Actions

The following actions can prevent or reduce radiations losses:

• Eliminate the furnace opening or keep the furnace door open the shortest possible time.

• For a continuous furnace in which opening size cannot be reduced, you can use flexible materials such as ceramic strips, chains, or ceramic textiles as "curtains." These generally reduce heat loss by half and help reduce infiltration of air into the furnace and leakage of hot furnace gases into the atmosphere. Tunnel-like extensions on the end of the furnace can also reduce the effective opening; shallow inclines in extension tunnels can direct radiation into furnace insulation or incoming cold work. These methods still allow the load to enter the furnace.

• Repair or plug fixed openings. If that is not possible, use a radiation shield such as an alloy sheet or ceramic board. Use proper refractory or insulation to plug holes. For openings such as a sight glass, use a damper or slide valve to block radiation when using the sight glass.

Resources

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

Figure 2. Calculation of effective area for openings in a furnace[2]
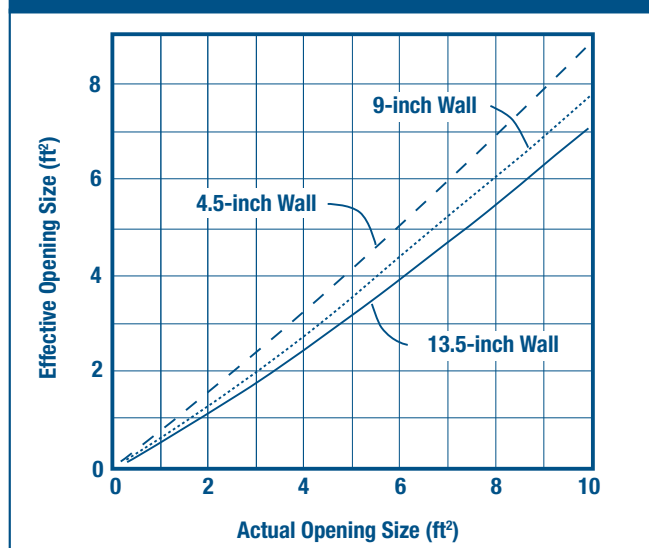
Technically, the temperature of the colder (receiving) surface also plays a part. However, this surface is usually the area surrounding the furnace, which can range from 20°F for an outdoor furnace up to 120°F for a hot factory building, and it has little effect on radiation losses.

Estimating Radiation Heat Losses

Radiation losses can be estimated by using a simple formula:

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

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

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

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

Install Waste Heat Recovery Systems for Fuel-Fired Furnaces

For most fuel-fired heating equipment, a large amount of the heat supplied is wasted as exhaust or flue gases. In furnaces, air and fuel are mixed and burned to generate heat, some of which is transferred to the heating device and its load. When the heat transfer reaches its practical limit, the spent combustion gases are removed

Figure 1. Heat in flue gas

Fuel: Birmingham Natural Gas (1002 Btu/cu ft, 0.6 sp gr)

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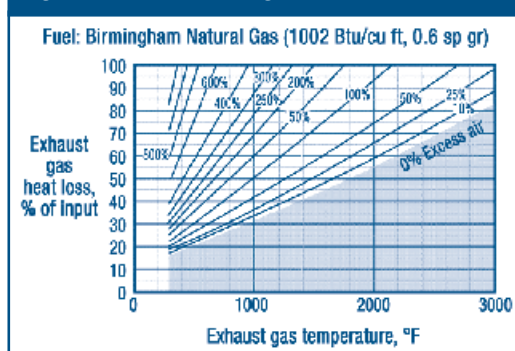
For natural gas-based systems, the amount of heat contained in the flue gases as a percentage of the heat input in a heating system can be estimated by using Figure 1. Exhaust gas loss or waste heat depends on flue gas temperature and its mass flow, or in practical terms, excess air resulting from combustion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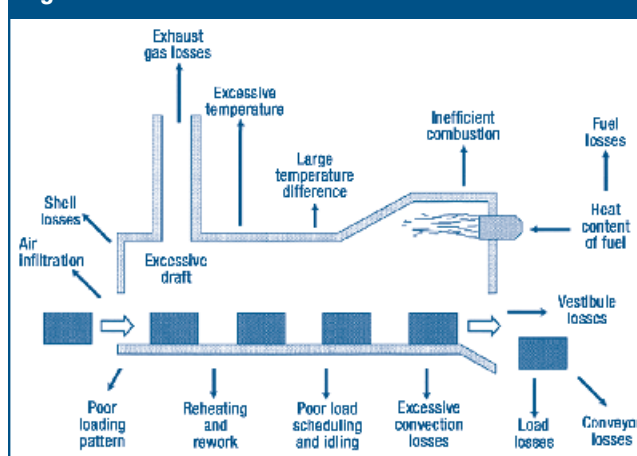
Suggested Actions

- Use PHAST with current and projected energy costs to estimate energy savings from waste heat recovery.

- Contact furnace or combustion system suppliers to calculate payback or return on investment.

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

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

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

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

Benefits

Benefits of waste heat recovery include:

- **Improved heating system efficiency.** Energy consumption can typically be reduced 5% to 30%.

- **Lower flue gas temperature in chimney.** Less heat is wasted.

- **Higher flame temperatures.** Combustion air preheating heats furnaces better and faster.

- **Faster furnace startup.** Combustion air preheating heats furnaces faster.

- **Increased productivity.** Waste heat used for load preheating can increase throughput.

Potential Applications

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

References

Improving Process Heating System Performance: A Sourcebook for Industry.
U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices

Waste Heat Reduction and Recovery for Improving Furnace Efficiency. DOE and IHEA. This document can be obtained from www.eere.energy.gov/industry/bestpractices

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

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

- Use of an *unfired load preheat section*, in which furnace flue gases are brought in contact with the incoming load in an extended part of the furnace.

- Use of an *external box*, in which high-temperature furnace flue gases are used to dry and/or preheat the charge before loading in a furnace.

- Use of a *counter-current* flow design in a furnace or a kiln, in which the burner gases flow in the opposite direction of the load being heated.

Figure 1. Available Heat Chart
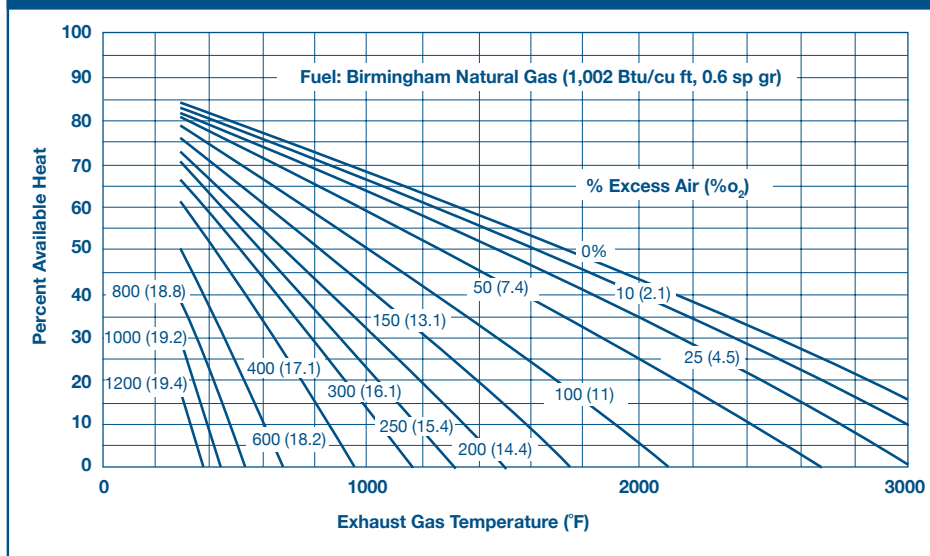
The amount of energy savings obtained by using load preheating is *higher* than the amount of actual heat transferred to the load. The "net" heat delivered to the load has to account for the efficiency of the furnace. Since the furnace efficiency is always less than 100%, the resulting energy savings exceed the energy picked up by the load. Load preheating can result in higher production from the same furnace.

Suggested Actions

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

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

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

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

Example

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

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

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

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

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

Reference

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

Using Waste Heat for External Processes

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

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

Fuel: Birmingham Natural Gas (1002 Btu/cu ft, 0.6 sp gr)
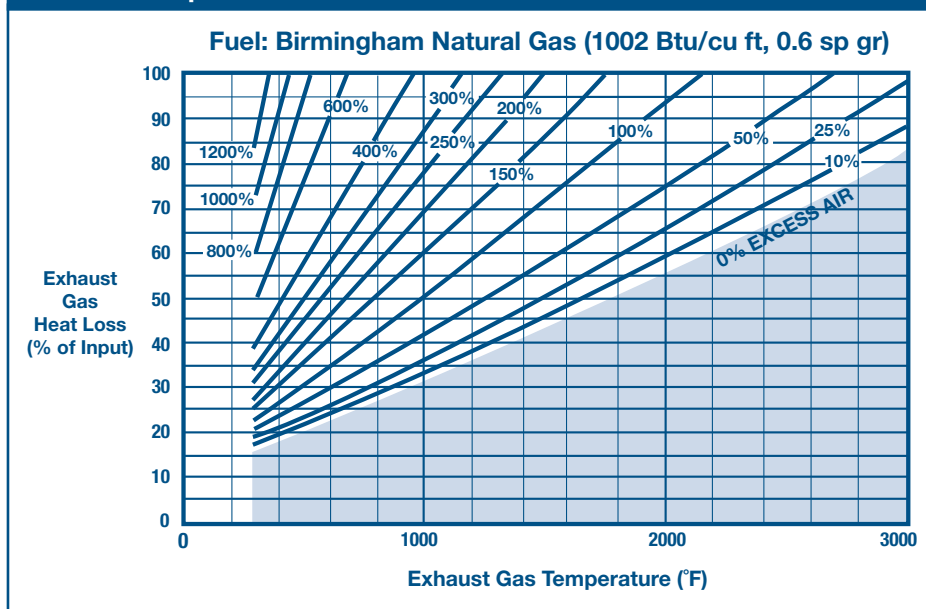
Before attempting to use energy from higher temperature flue gases in lower temperature processes, engineers should take the following technical issues into consideration:

- **Nature or quality of the flue gases.** Flue gases from the primary processes should be clean and free of contaminants such as corrosive gases and particulates. Contaminants pose special handling problems for the gases and might affect the quality of work in the secondary process.

- **Temperature of primary process flue gases.** The temperature difference between the primary and secondary process should be high enough (at least 200°F), and there should be a sufficient amount of usable waste heat.

Suggested Actions

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

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

Resources

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

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

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

• **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.

Example

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

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

[1] Calculations by Richard Bennett, Janus Technology Group.
[2] Figure by Richard Bennett, Janus Technology Group.
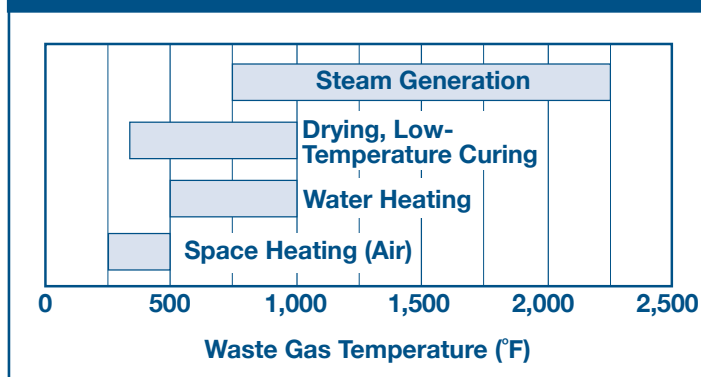
Use Lower Flammable Limit Monitoring Equipment to Improve Process Oven Efficiency

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

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

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

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

LFL Monitoring Equipment

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

Suggested Actions

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

Resources

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

Improving Process Heating System Performance: A Sourcebook for Industry. U.S. Department of Energy and Industrial Heating Equipment Association. This document can be obtained from *http://www1.eere.energy.gov/industry/bestpractices/techpubs_process_heating.html*

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

Example

The NFPA safety ventilation ratios are significantly lower when LFL monitoring equipment is used than when such equipment is absent. This lowers the energy requirements for the process because less air needs to be exhausted to keep the process from becoming flammable. For a continuous strip coating process requiring 46 gallons of xylol with a maximum oven temperature of 800° F and ambient air temperature of 70° 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.

Technical Briefs

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

The technical briefs can also be downloaded from ITP's BestPractices Web site at www.eere.energy.gov/industry/ bestpractices.

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. 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.

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

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℉ (649℃); above 950℉ (510℃) 304H is stronger, and of course, more resistant to oxidation.
409, and 410S stainless (UNS S40900, S41008) 1,200℉ (650℃)	Limited by oxidation. Both are subject to embrittlement after several years of service above 600℉ (315℃).
430 stainless (S43000), with useful oxidation resistance to about 1,600℉ (870℃)	Subject to embrittlement when exposed to the 600˚-1,100℉ (315˚-600℃) range.
304/304H & 316L stainless (S30400/ S30409, & S31600), cast HF	This is limited by oxidation to 1,500℉ (816℃). If product contamination by scale particles is a concern, consider 1,200℉ (650℃) as limitation.
321 (S32100) stainless	This has an advantage of about 100℉ (55℃) over 304, and is used to 1,600℉ (1202℃).
309S (S30908), cast HH-2 (J93633)	Useful up to the 1,850-1,900℉ (1010-1038℃) range. Above 1,900℉, 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℉ (1,093℃).
RA 253 MA® [2] alloy (UNS S30815)	Has superior oxidation resistance up to 2,000℉ (1,100℃). Above this temperature, the oxidation resistance may be adequate, but not exceptional
310 (S31008), and cast HK (J94204)	Very good oxidation resistance to 2,000℉ (1,093℃), but drops off considerably by 2,100℉ (1,150℃). 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℉ (1,200℃). 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℉/1,360℃) 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.
Alloy HR-120® [5]	One of the strongest available wrought alloys up to about 1,900℉ (1040℃), and is used through 2,100℉ (1,150℃).
RA333® [6] alloy (N06333)	In open-air use has a practical limit of about 2,200℉ (1,204℃). 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℉ (980℃).
600 alloy (N06600)	A nickel-chromium alloy. Good oxidation resistance through 2,200℉, good carburization resistance and ductility.
601 (N06601)	Is very oxidation resistant to 2,200℉ (1,204℃). 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℉. Applications include CVD retorts, vacuum furnace fixturing, rotary calciners
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℉ (1,177℃).
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.

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 N08830 and N08811 do not perform well in metal dusting environments.

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® 60[10] (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.

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10 Registered trade name of AK Steel Corporation

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.
	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

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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.

Acknowledgements

Special thanks to Dr. James Kelly 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.

This technical brief supports or complements the software tool Process Heating Assessment and Survey Tool (PHAST) developed jointly by the Industrial Heating Equipment Association (IHEA) and the U.S. Department of Energy's (DOE) Industrial Technologies Program.

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 ITP's Process Heating Tip Sheets, available on the DOE's BestPractices Web site at www. eere.energy.doe.gov/industry/bestpractices.

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 (NO_x) 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.

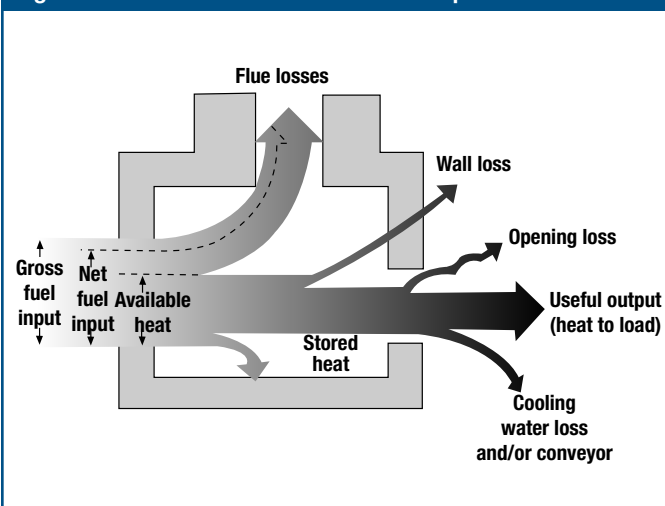Figure 1. Heat losses in industrial heat processes.
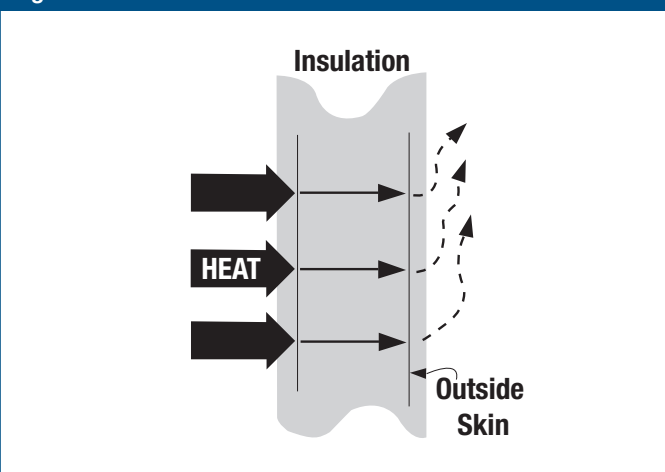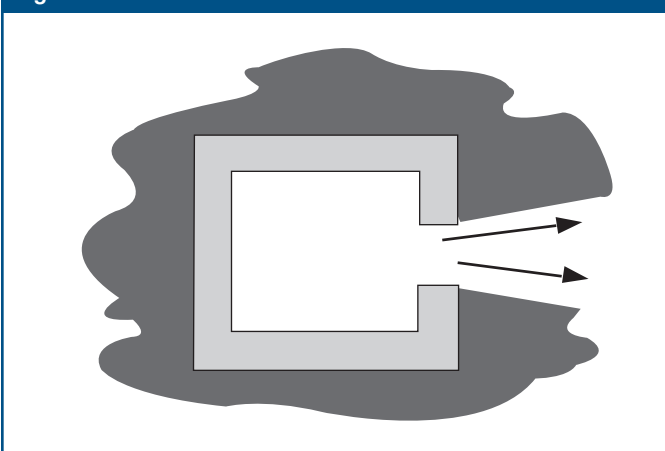

Figure 2. Wall loss.

Figure 3. Radiation loss from heated to colder surface.

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.

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.

Figure 1. Heat losses in industrial heat processes.
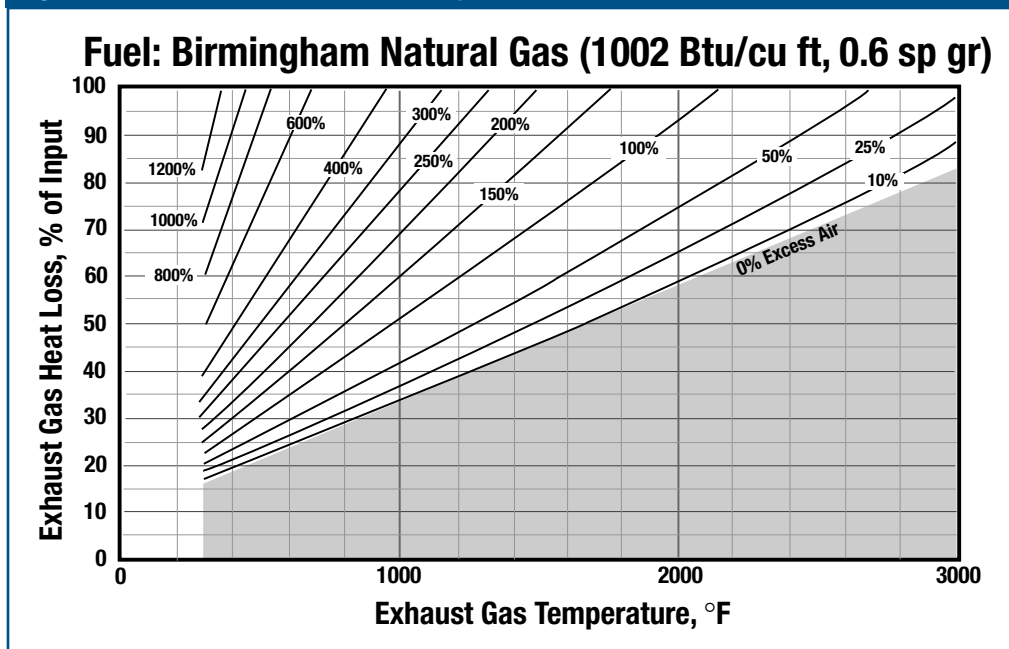
This makes it obvious that the temperature of a process, or more correctly, of its exhaust gases, is a major factor in its energy efficiency. The higher that temperature, the lower the efficiency.

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 (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).

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 ITP tip sheet, "Reduce Air Infiltration in Furnaces," for guidelines on estimating infiltration losses.[1]

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[1] The tip sheet is available online on the ITP BestPractices Web site at www.eere.energy.gov/industry/bestpratices.

Figure 6. Air infiltration from furnace opening.
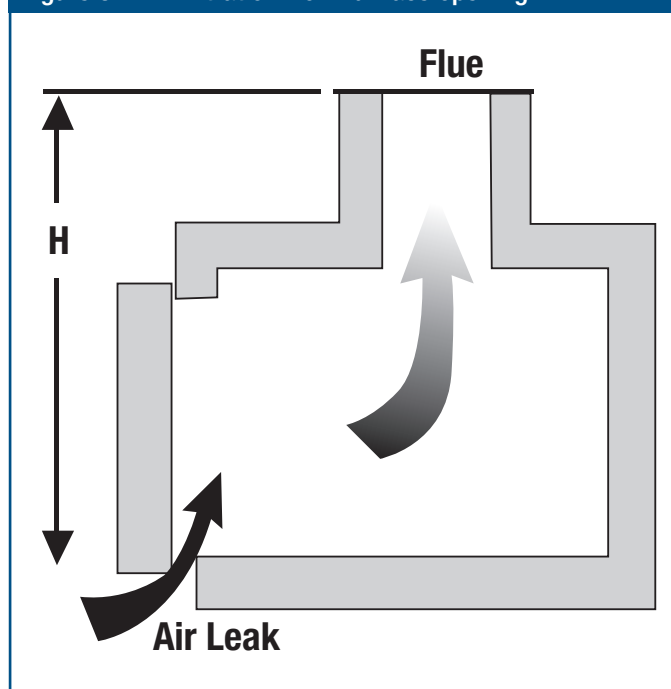
The bottom line is that to get the best possible energy efficiency from furnaces and ovens, reduce the amount of energy carried out by the exhaust and lost to heat storage, wall conduction, conveying and cooling systems and radiation.

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).

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.

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.

Figure 7. Impact of production rate on energy consumption per unit of production.
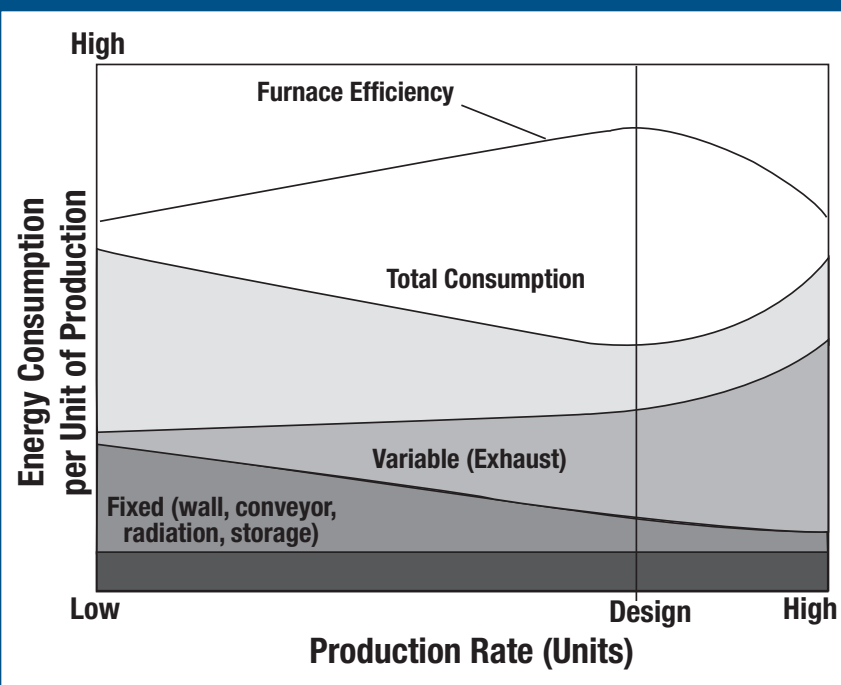
Minimize exhaust gas temperatures. Excessive exhaust gas temperatures can be the result of poor heat transfer in the furnace. If the combustion gases are unable to transfer the maximum possible heat to the furnace and its contents, they will leave the furnace at higher temperatures than necessary. Optimizing heat transfer within the furnace requires different methods for different situations. The ITP tip sheet "Check Heat Transfer Surfaces" will provide greater insight into how transfer takes place and what can be done to improve it.[2]

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

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[2]   The tip sheet is available online on the ITP Best Practices Web site at www. eere.energy.gov/industry/bestpractices.

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 ITP 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.

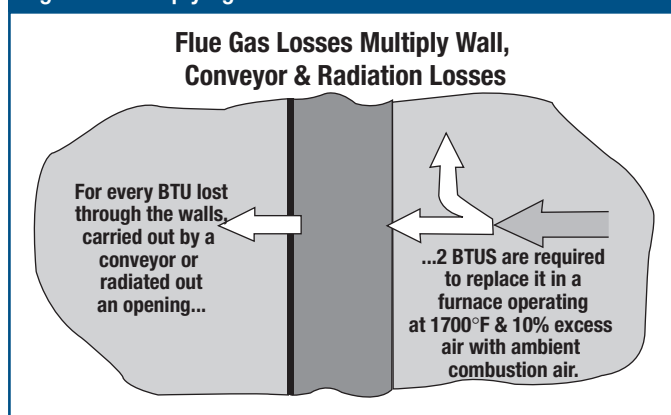**Figure 8. Multiplying effect of available heat on furnace losses.**

Flue Gas Losses Multiply Wall, Conveyor & Radiation Losses

For every BTU lost through the walls, carried out by a conveyor or radiated out an opening...

...2 BTUS are required to replace it in a furnace operating at 1700°F & 10% excess air with ambient combustion air.

Figure 9. Direct preheating of incoming work.
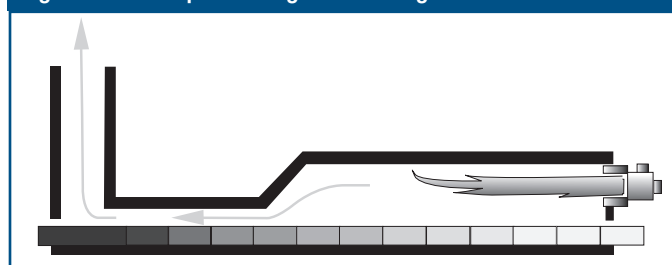
Figure 10. Exhaust gas losses with ambient and preheated air.

Fuel: Birmingham Natural Gas (1002 Btu/cu ft, 0.6 sp gr) with 10% Excess Air

70°F Air
400°F Air
600°F Air
800°F Air
1000°F Air

Exhaust Gas Heat Loss, % of Input

Furnace Exhaust Temperature, °F
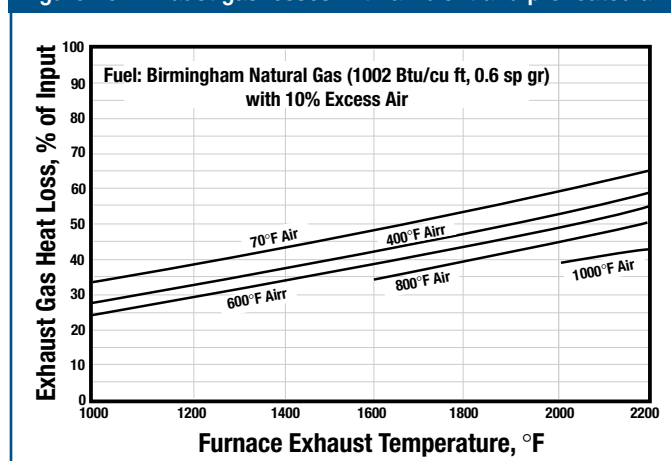
Waste heat recovery. Reducing exhaust losses should always be the first step in a well-planned energy conservation program. Once that goal has been met, consider the next level – waste heat recovery. Waste heat recovery elevates furnace efficiency to higher levels, because it extracts energy from the 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.

   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.

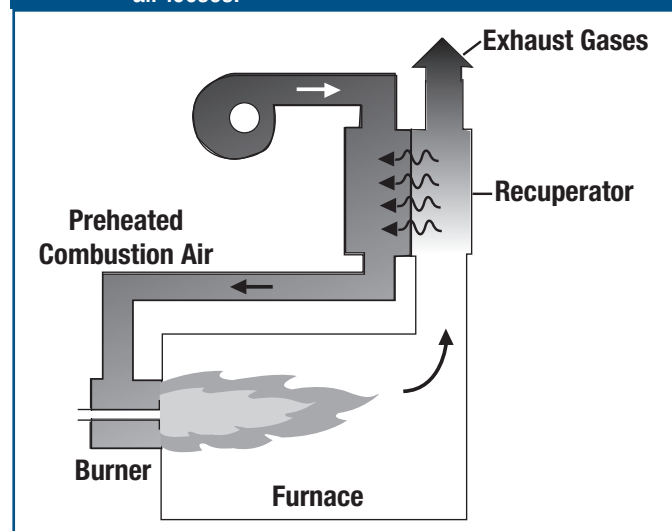Figure11. Recuperator system for preheating combustion air looses.

| 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.

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 ITP 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.

Figure 12. Regenerator system for storing thermal energy.
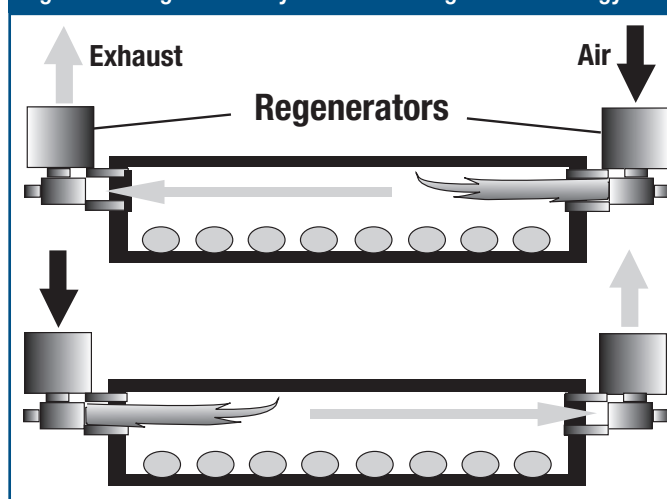
Summary

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
on the ITP BestPractices Web site at www.eere.energy.gov/
industry/bestpractices.

Acknowledgements

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.

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 6.24×10^{18} 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 H_2, 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.

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.