

Section I

Industrial Combustion Basics

1 Introduction

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1.1 INDUSTRIAL COMBUSTION

The field of industrial combustion is very broad and touches, directly or indirectly, nearly all aspects of our lives. The electronic devices we use are generally powered by fossil-fuel-fired power plants. The cars we drive use internal combustion engines. The planes we fly in use jet-fuel-powered turbine engines. Most of the materials we use have been made through some type of heating process. While this book is concerned specifically with industrial combustion, all of the above combustion processes share many features in common.

Industrial combustion is complicated by many factors. First, the science of combustion is still developing and has a long way to go until we have a complete understanding of it so it can be better applied and controlled. While fire has been with us since the beginning of time, much remains to be learned about it. The science of combustion combines heat transfer, thermodynamics, chemical kinetics, and multi-phase turbulent fluid flow, to name a few areas of physics. Therefore, the study of industrial combustion is interdisciplinary by necessity.

Combustion has been the foundation of worldwide industrial development for the past 200 years.¹ Industry relies heavily on the combustion process as shown in Table 1.1. The major uses for combustion in industry are shown in Table 1.2. Hewitt et al. (1994) have listed some of the common heating applications used in industry, as shown in Table 1.3.² Typical industrial combustion applications can also be characterized by their temperature ranges as shown in Figure 1.1. As can be seen in Figure 1.2, the demand for energy is expected to continue to rapidly increase. Most of the energy (88%) is produced by the combustion of fossil fuels such as oil, natural gas, and coal. According to the U.S. Dept. of Energy, the demand in the industrial sector is projected to increase by 0.8% per year to the year 2020.³

As shown in Figure 1.3, three elements are required to sustain combustion processes: fuel, oxidizer, and an ignition source (usually in the form of heat). Industrial combustion is defined here as the rapid oxidation of hydrocarbon fuels to generate large quantities of energy for use in industrial heating and melting processes. Industrial fuels can be solids (e.g., coal), liquids (e.g., oil), or gases (e.g., natural gas). The fuels are commonly oxidized by atmospheric air (which is approximately 21% O₂ by volume) although it is possible in certain applications to have an oxidizer (sometimes referred to as an “oxidant” or “comburent”) containing less than 21% O₂ (e.g., turbine exhaust gas⁴) or more than 21% O₂ (e.g., oxy/fuel combustion⁵). The fuel and oxidizer are typically mixed in a device referred to as a burner, which is discussed in more detail below and is the subject of this book. An industrial heating process can have one or many burners, depending on the specific application and heating requirements.

Many theoretical books have been written on the subject of combustion, but they have little if any discussion of industrial combustion processes.^{6–11} Edwards (1974) has written a brief chapter on applications, including both stationary (boilers and incinerators primarily) and mobile sources

TABLE 1.1
The Importance of Combustion in Industry

Industry	% Total Energy From (at the point of use)		
	Steam	Heat	Combustion
Petroleum refining	29.6	62.6	92.2
Forest products	84.4	6.0	90.4
Steel	22.6	67.0	89.6
Chemicals	49.9	32.7	82.6
Glass	4.8	75.2	80.0
Metal casting	2.4	67.2	69.6
Aluminum	1.3	17.6	18.9

Source: U.S. Dept. of Energy.¹

TABLE 1.2
Major Process Heating Operations

Metal Melting
Steel making
Iron and steel melting
Nonferrous melting
Metal Heating
Steel soaking, reheat, ladle preheating
Forging
Nonferrous heating
Metal Heat Treating
Annealing
Stress relief
Tempering
Solution heat treating
Aging
Precipitation hardening
Curing and Forming
Glass annealing, tempering, forming
Plastics fabrication
Gypsum production
Fluid Heating
Oil and natural gas production
Chemical/petroleum feedstock preheating
Distillation, visbreaking, hydrotreating, hydrocracking, delayed coking
Bonding
Sintering, brazing
Drying
Surface film drying
Rubber, plastic, wood, glass products drying
Coal drying
Food processing
Animal food processing
Calcining
Cement, lime, soda ash
Alumina, gypsum
Clay Firing
Structural products
Refractories
Agglomeration
Iron, lead, zinc
Smelting
Iron, copper, lead
Nonmetallic Materials Melting
Glass
Other Heating
Ore roasting
Textile manufacturing
Food production
Aluminum anode baking

Source: U.S. Dept. of Energy.¹

TABLE 1.3
Examples of Processes in the Process Industries Requiring Industrial Combustion

Process Industry	Examples of Processes Using Heat
Steel making	Smelting of ores, melting, annealing
Chemicals	Chemical reactions, pyrolysis, drying
Nonmetallic minerals (bricks, glass, cement and other refractories)	Firing, kilning, drying, calcining, melting, forming
Metal manufacture (iron and steel, and nonferrous metals)	Blast furnaces and cupolas, soaking and heat treatment, melting, sintering, annealing
Paper and printing	Drying

Adapted from Reference 3.

(primarily internal combustion engines).¹² Barnard and Bradley (1985) have a brief chapter on industrial applications.¹³ A book by Turns (1996), which is designed for undergraduate and graduate combustion courses, contains more discussions of practical combustion equipment than most similar books.¹⁴

There have also been many books written on the more practical aspects of combustion. Griswold's (1946) book has a substantial treatment of the theory of combustion, but is also very practically oriented and includes chapters on gas burners, oil burners, stokers and pulverized-coal burners, heat transfer, furnace refractories, tube heaters, process furnaces, and kilns.¹⁵ Stambuleanu's (1976) book on industrial combustion has information on actual furnaces and on aerospace applications, particularly rockets.¹⁶ There is much data in the book on flame lengths, flame shapes, velocity profiles, species concentrations, liquid and solid fuel combustion, with a limited amount of information on heat transfer. A book on industrial combustion has significant discussions on flame chemistry, but little on pollution from flames.¹⁷ Keating's (1993) book on applied combustion is aimed at engines and has no treatment of industrial combustion processes.¹⁸ A book by Borman and Ragland (1998) attempts to bridge the gap between the theoretical and practical books on combustion.¹⁹ However, the book has little discussion of the types of industrial applications considered here. Even handbooks on combustion applications have little if anything on industrial combustion systems.^{20–24}

1.2 INDUSTRIAL COMBUSTION APPLICATIONS

Burners are a key component in industrial combustion applications. An understanding of these applications is necessary when selecting the proper burner design. Some of the more common burner designs are considered in this book. The uses of each burner type in specific applications are discussed in relevant chapters. Some of the most common industrial applications are briefly discussed next. Note that not every type of industrial burner is considered in this book as there are numerous special designs for specific applications.

1.2.1 METALS PRODUCTION

Metals are used in nearly all aspects of our lives and play a very important role in society. The use of metals has been around for thousands of years. There are two predominant classifications of metals: ferrous (iron-bearing) and nonferrous (e.g., aluminum, copper, and lead). Ferrous metal production is often high temperature because of higher metal melting points compared to nonferrous metals. Many metal production processes are done in batch, compared to most other industrial combustion processes considered here which are typically continuous. Another fairly unique aspect of metal production is the very high use of recycled materials. This often lends itself

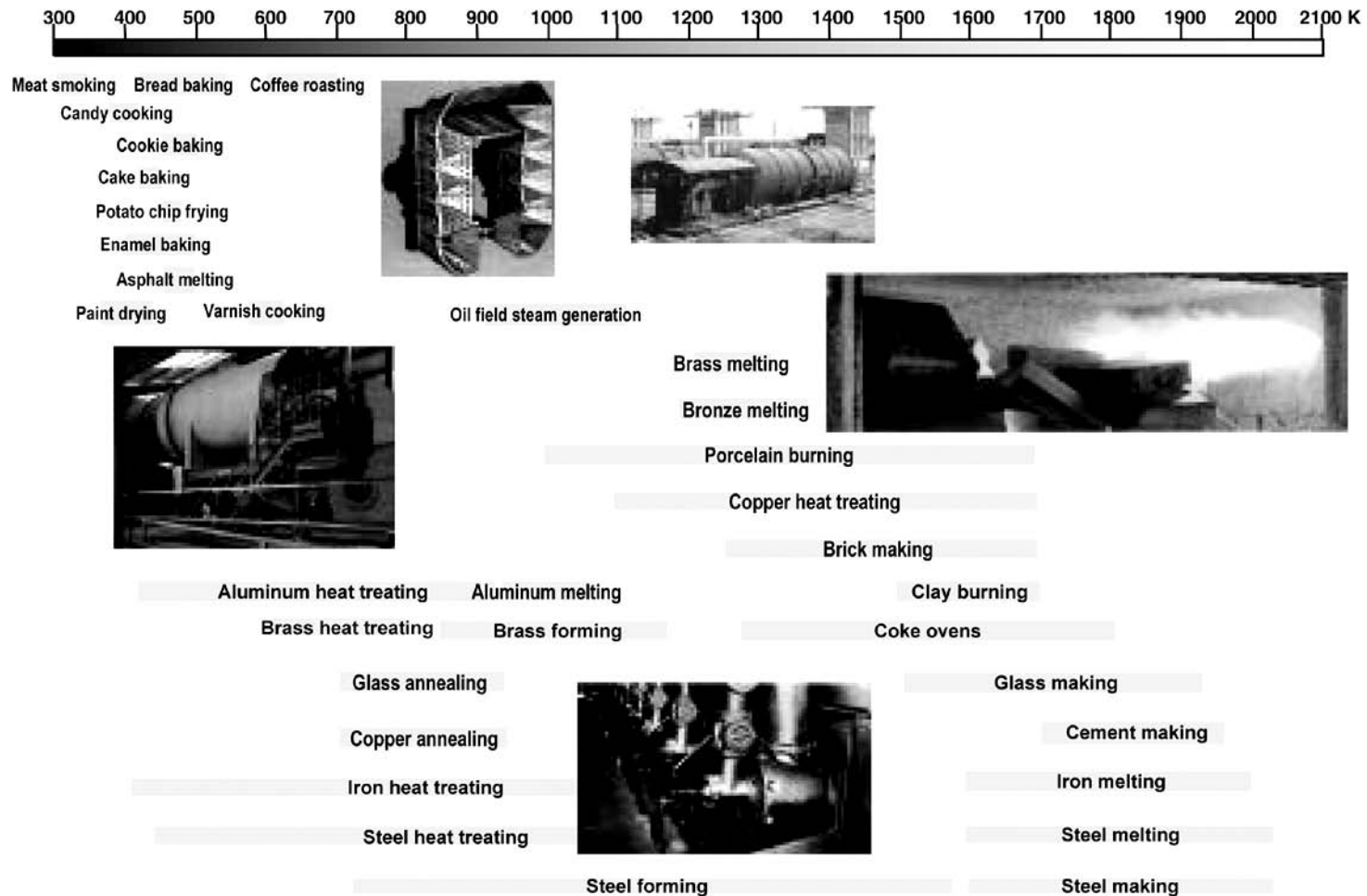


FIGURE 1.1 Temperature ranges of common industrial combustion applications. (Courtesy of Werner Dahm, 1998.)

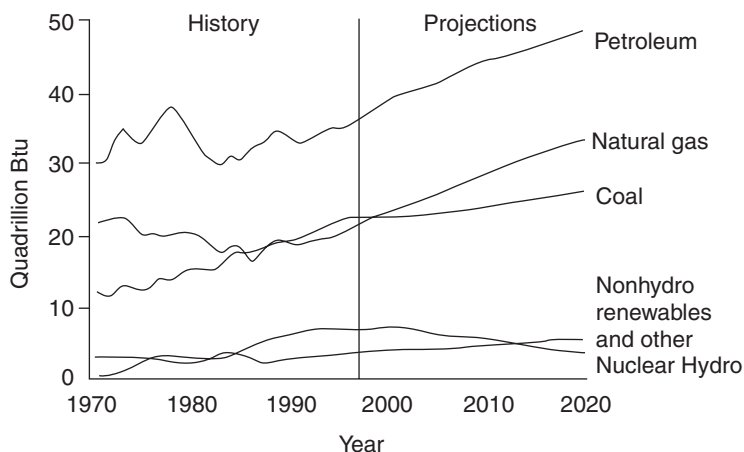


FIGURE 1.2 Historical and projected world energy consumption. (Source: U.S. Dept. of Energy.³)

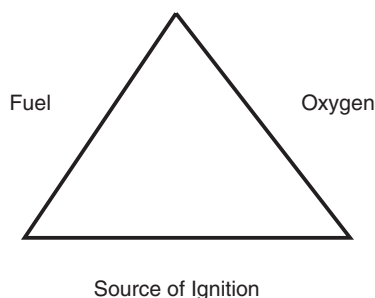


FIGURE 1.3 Combustion triangle.⁵

to batch production because of the somewhat unknown composition of the incoming scrap materials that may contain trace impurities that could be very detrimental to the final product if not removed. The metals are typically melted in some type of vessel and then sampled to determine the chemistry so that the appropriate chemicals can be either added or removed to achieve the desired grade of material. Another unique aspect of the metals industry is that transfer vessels are preheated prior to the introduction of molten metals into the vessel to minimize the thermal shock to the refractory. Figure 1.4 shows an example of preheating a transfer ladle.

Because metals melt at higher temperatures, higher intensity burners are often used in these applications. This includes, for example, oxygen-enhanced combustion^{25,26} and air preheating to increase the flame temperatures and metal melting capability. These higher intensity burners have the potential to produce high pollutant emissions, so burner design is important to minimize these emissions.

Another somewhat unique aspect of metals production is that supplemental heating may be required to reheat the metals for further processing. For example, ingots might be produced in one location and then transported to another location to be made into the desired shape (e.g., wheel castings are often made from remelting aluminum ingots or sows). While this process can be economically efficient, it is energy and pollutant inefficient due to the additional heating. Burners are used in the original melting process as well as in the reheating process. This is something that has begun to attract more attention in recent years, where the entire life cycle of a product is considered rather than just its unit cost and initial energy requirements. For example, aluminum has a low life-cycle cost compared to many other metals because of its high recycle

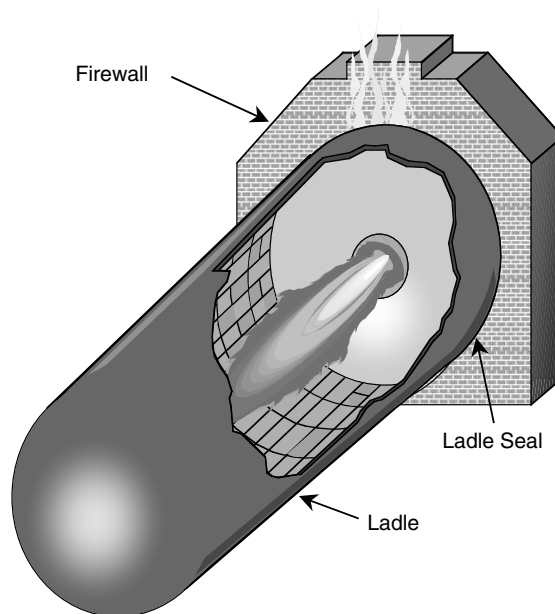


FIGURE 1.4 Ladle preheater.

ratio. While the energy consumption to make aluminum from raw ore is fairly high, remelting scrap aluminum takes only a fraction of that energy, which also means less overall pollution. Burners commonly used in the metals industry include high-velocity burners (Chapter 11), regenerative burners (Chapter 12), radiant tube burners (Chapter 14), air-oxy/fuel burners (Chapter 20), and oxy/fuel burners (Chapter 21).

1.2.2 MINERALS PRODUCTION

Some common minerals processes include the production of glass, cement, bricks, refractories, and ceramics. These are typically high-temperature heating and melting applications that require a significant amount of energy per unit of production. They also tend to have fairly high pollutant emissions as a result of the high temperatures and unit energy requirements. Most mineral applications are continuous processes, but there is a wide range of combustors. Large glass furnaces are typically of rectangular shape and have multiple burners. On the other hand, cement kilns are long refractory-lined rotating cylinders that are slightly inclined so that the materials flow gradually downhill (see [Figure 1.5](#)). A typical cement plant is shown in [Figure 1.6](#).

Many minerals applications employ some type of heat recovery in the form of air preheating to improve energy efficiency. However, the heat recovery typically significantly increases NO_x emissions. While recycling of used glass (referred to as cullet) is practiced in some applications, there is generally much less recycling in the minerals industry compared to the metals industry. Some burners used in minerals applications include regenerative burners (Chapter 12), air-oxy/fuel burners (Chapter 20), and oxy/fuel burners (Chapter 21).

1.2.3 CHEMICALS PRODUCTION

This is a very broad classification that encompasses many different types of production processes that have been loosely sub-categorized into chemicals (organic and inorganic) and petrochemicals (organic) applications. A typical refinery is shown in [Figure 1.7](#). There is some overlap in terms

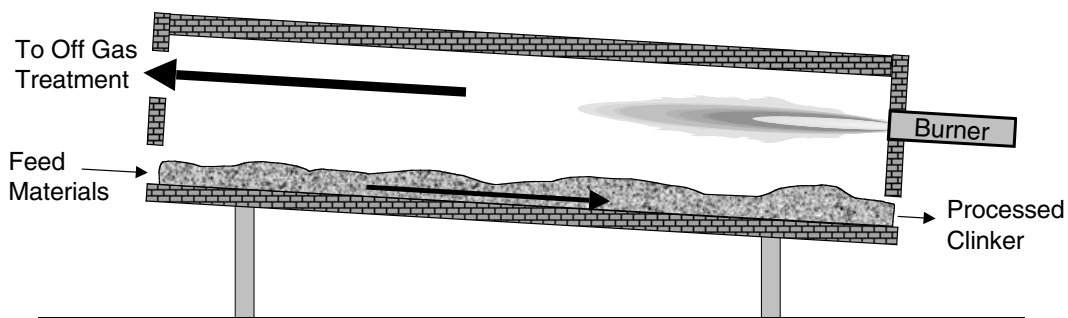


FIGURE 1.5 Counter-current rotary cement kiln schematic.



FIGURE 1.6 Cement plant.



FIGURE 1.7 Refinery.

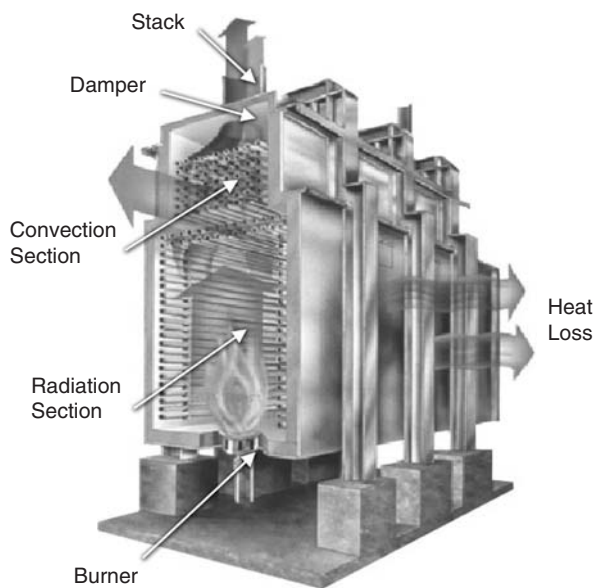


FIGURE 1.8 Process refinery heater. (Courtesy of John Zink Co., LLC.³⁶)

of the types of heating equipment used where many of the incoming feed materials are in liquid form (e.g., crude oil) that are processed in heaters with tubes running inside them. These are generally lower temperature applications ($<2300^{\circ}\text{F}$ or $<1300^{\circ}\text{C}$) that incorporate heat recovery to preheat the incoming feed materials. Nearly all chemicals heating applications employ multiple burners, but in a much more diverse configuration compared to many other industries. Burners may be fired horizontally, vertically up, vertically down, or at some angle in between, depending on the specific process. There are numerous configurations for fired process heaters (see [Figure 1.8](#)).

There are some aspects that make this industry unique compared to others. The first and one of the most important is the wide range of fuel compositions used to fire the heaters. These are mostly gaseous fuels that are by-products of the production process. These gaseous fuels often contain significant quantities of hydrogen, methane, and propane, and may include large quantities of inert gases such as nitrogen and carbon dioxide. A given heater might need to be able to fire on multiple fuels that may be present during various times in the production process. Another unique aspect of this industry is that many of the heaters are fired with natural-draft burners (see Chapter 16) where no blower is used to supply the combustion air. These burners are designed differently than conventional forced-draft burners and are more susceptible to variations in ambient conditions such as air temperature, humidity, and wind speed. A specific type of burner used in petrochemical applications is the radiant wall burner (see Chapter 15).

1.2.4 WASTE INCINERATION

The objective of waste incineration processes is to reduce or eliminate waste products, which involves combusting those materials. Not only is the incinerator (see [Figure 1.9](#)) fired with burners, but the waste material itself is often part of the fuel that generates heat in the process. However, the waste usually has a very low heating value, and hence the need for supplemental fuel. Compared to most other industrial combustion processes, by the very nature of the variability of the feed material, incineration is a more complicated and dynamic process. [Figure 1.10](#) shows a schematic



FIGURE 1.9 Municipal waste incinerator.

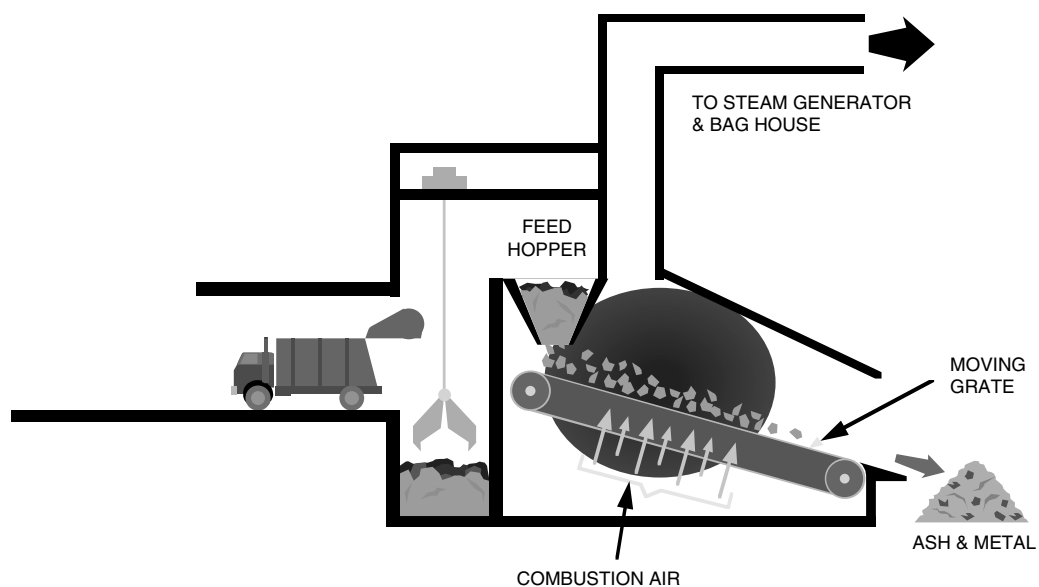


FIGURE 1.10 Schematic of municipal solid waste incinerator.

of a municipal solid waste incinerator. The waste may be very wet after a rain storm, which may put a huge extra heat load on the incinerator. In some locations where waste materials are separated for recycling, the waste actually fed into the incinerator may have a much higher heating value compared to other incinerators where there is no separation of the waste.

A complicating factor with incinerators is that the end product (e.g., the noncombustible waste) must also be disposed of, which means that one of the goals of most incineration processes is to produce minimal waste output. Because of waste material variability, other pollutants can be generated that are not normally associated with industrial combustion processes. An example is the burning of plastics, which can produce dioxins and furans. The types of incinerators can vary greatly, depending on a variety of factors. In some cases, waste materials to be destroyed can be fed through the burners. This is particularly true of waste hydrocarbon liquids. Some of the burners used in incineration include air-oxy/fuel (Chapter 20) and oxy/fuel (Chapter 21).

1.2.5 INDUSTRIAL BOILERS AND POWER GENERATION

Boilers are used for a variety of purposes in an assortment of applications. Common uses include producing hot water or steam for heating, producing steam for use within a plant such as atomizing oil for oil-fired burners, and producing steam to generate power in large power plants. Applications range from small single-burner uses in hospitals, schools, and small businesses, up to large multi-burner boilers in power plants. The burners used in boilers are typically regulated because of their proliferation and widespread use in applications involving the general public. The burners are normally required to have a full complement of safety controls to ensure safe operation. These burners are often highly regulated to minimize pollutant emissions, particularly in large power plants because of the size of the source. The types of burners used in smaller single-burner boiler applications are considered in Chapter 17. Boiler burners used in larger applications requiring multiple burners are considered in Chapter 18.

A special category of burners sometimes used in large power generating plants with gas turbines are called duct burners (see [Figure 1.11](#)). A schematic of the typical location of duct burners downstream of the turbine is shown in [Figure 1.12](#). These burners are unique because they use the combustion products from a turbine as their combustion “air.” The turbine exhaust gas (TEG) is at an elevated temperature and contains significant quantities of carbon dioxide and water, which are the products of the upstream combustion process. The TEG is also at a depleted oxygen level, so duct burners are designed to operate under these conditions. They are treated in detail in Chapter 19.

1.2.6 DRYING

Burners are used in a wide variety of lower-temperature drying applications to remove water from products that was added during the manufacturing process. These are lower-temperature applications that include paper manufacturing, printing and publishing, textile manufacturing, and food processing. Drying is defined as “a process in which a wet solid is heated or contacted with a hot gas stream, causing some or all of the liquid wetting the solid to evaporate.”²⁷ Kudra and Mujumdar (2002) have written a new book²⁸ on advanced drying technologies that covers a wide range of industries. One example is the drying of paper produced from a wet slurry. A typical paper mill is shown in [Figure 1.13](#).

In many drying processes, moisture is removed from webs that may be traveling at high speeds. Radiant heating is often used to supplement steam-heated cylinders or high-velocity hot air dryers.²⁹ The radiant heaters are either electric or fired with a fuel gas such as natural gas. Thermal radiation burners used in many of these applications are discussed in Chapter 13.

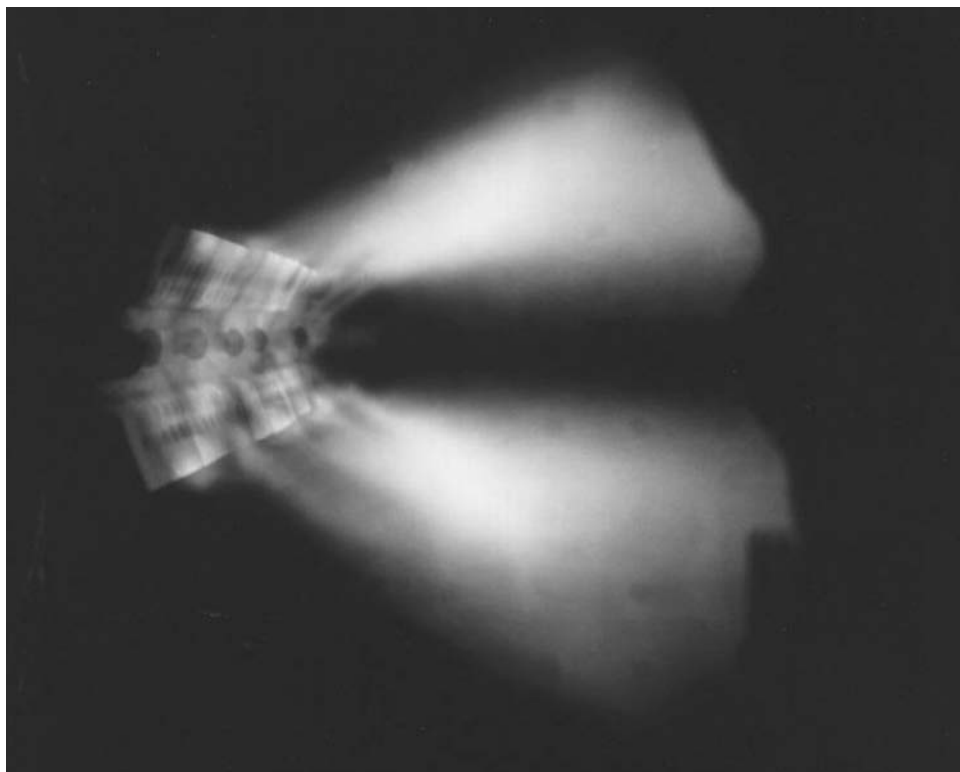


FIGURE 1.11 Duct burner flame. (Courtesy of John Zink Co., LLC.³⁶)

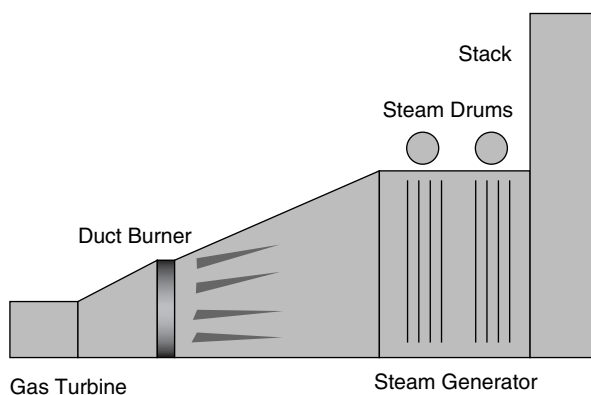


FIGURE 1.12 Duct burner process schematic. (Courtesy of John Zink Co., LLC.³⁶)

1.3 COMBUSTION SYSTEM COMPONENTS

There are six components that may be important in industrial combustion processes (see [Figure 1.14](#)). One component is the burner, which combusts the fuel with an oxidizer to release heat. Another component is the load itself, which can greatly affect how the heat is transferred from the flame. In most cases, the flame and the load are located inside a combustor, which may be a furnace, heater, or dryer and constitutes the third component in the system. In some cases, there may be some type



FIGURE 1.13 Paper mill.

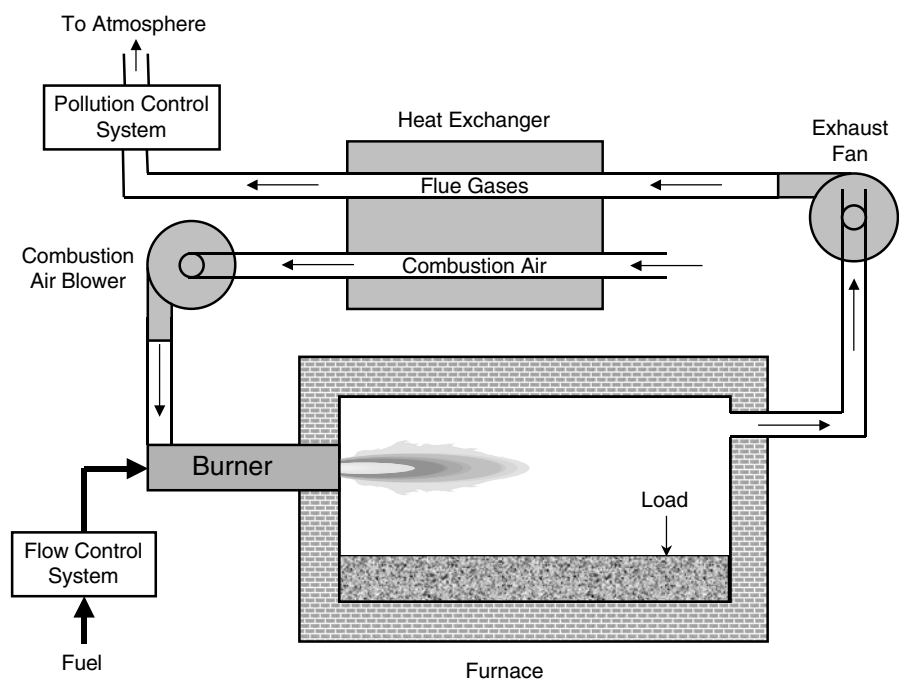


FIGURE 1.14 Schematic of an industrial combustion process.

of heat recovery device to increase the thermal efficiency of the overall combustion system, which is the fourth component of the system. The fifth component is the flow control system used to meter the fuel and the oxidant to the burners. The sixth and final component is the air pollution control system used to minimize the pollutants emitted from the exhaust stack into the atmosphere. Various aspects of these components are discussed in more detail in other sections of the book.

1.4 BURNER DESIGN FACTORS

The burner is the device used to combust the fuel with an oxidizer to convert the chemical energy in the fuel to thermal energy. A given combustion system may have a single burner or many burners, depending on the size and type of the application. For example, in a rotary kiln, a single burner is located in the center of the wall on one end of a cylindrically shaped furnace (see [Figure 1.15](#)). The heat from the burner radiates in all directions and is efficiently absorbed by the load. However, the cylindrical geometry has some limitations concerning size and load type, which make its use limited to certain applications such as melting scrap aluminum or producing cement clinker. A more common combustion system has multiple burners in a rectangular geometry (see [Figure 1.16](#)). This type of system is generally more difficult to analyze because of the multiplicity of heat sources and because of the interactions between the flames and their associated products of combustion.

There are many factors that go into the design of a burner. This section briefly considers some of the important factors that are taken into account for a particular type of burner. These factors affect things such as heat transfer and pollutant emissions. There have been many changes in the traditional designs used in burners, primarily because of the recent interest in reducing pollutant emissions. In the past, the burner designer was primarily concerned with efficiently combusting the fuel and transferring the energy to a heat load. New and increasingly more stringent environmental regulations have added the requirement to consider the pollutant emissions produced by the burner. In many cases, reducing pollutant emissions and maximizing combustion efficiency are at odds with each other. For example, a well-accepted technique for reducing NO_x emissions is known as staging, where the primary flame zone is deficient in either fuel or oxidizer.³⁰ The balance of fuel or oxidizer can be injected into the burner in a secondary flame zone or, in a more extreme

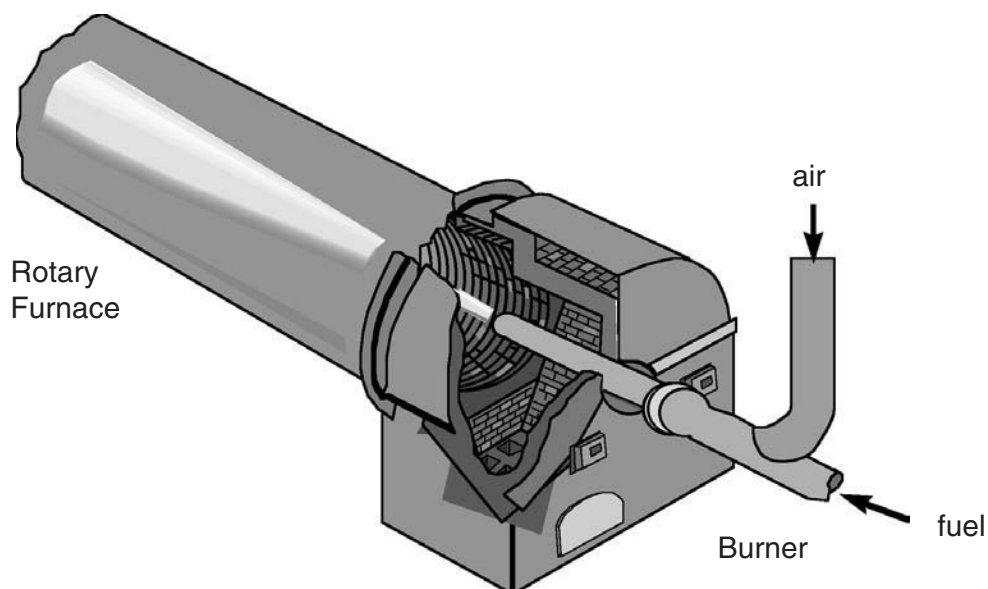


FIGURE 1.15 Rotary kiln with single burner.²⁹

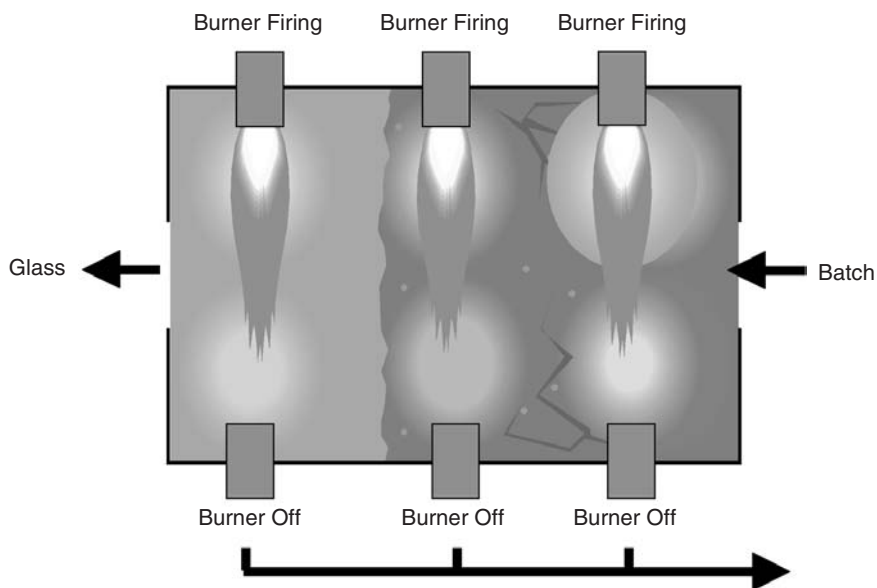


FIGURE 1.16 Plan view of multiple burners in a glass furnace.²⁹

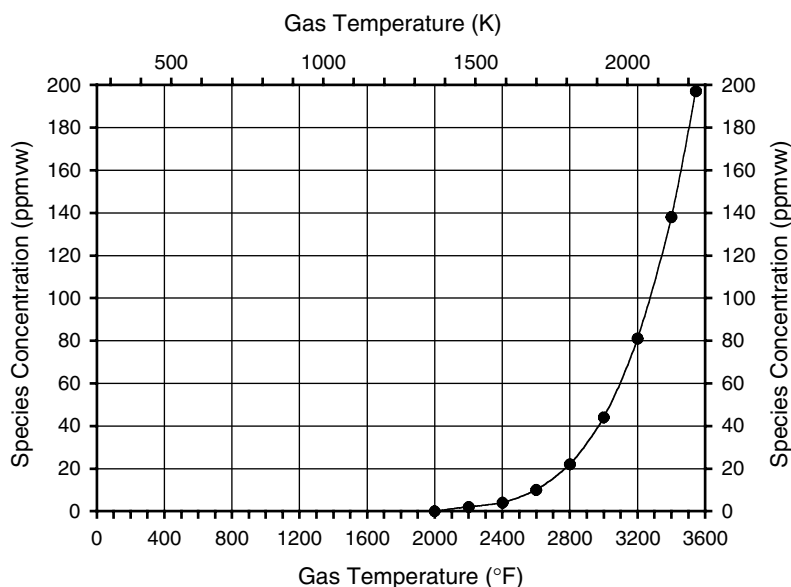


FIGURE 1.17 NO_x as a function of gas temperature.²⁹

case, can be injected somewhere else in the combustion chamber. Staging reduces the peak temperatures in the primary flame zone and also alters the chemistry in a way that reduces NO_x emissions because fuel-rich or fuel-lean zones are less conducive to NO_x formation than near-stoichiometric zones. Figure 1.17 shows how the NO_x emissions are affected by the exhaust product temperature. Because thermal NO_x is exponentially dependent on the gas temperature, even small reductions in the peak flame temperature can dramatically reduce NO_x emissions. However, lower flame temperatures often reduce the radiant heat transfer from the flame because radiation is

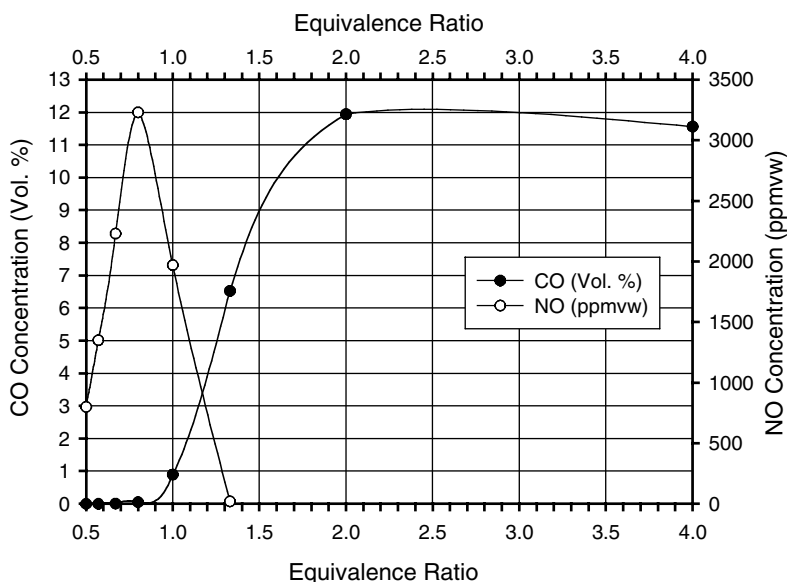


FIGURE 1.18 NOx and CO as a function of stoichiometry.²⁹

dependent on the fourth power of the absolute temperature of the gases. Another potential problem with staging is that it may increase CO emissions, which is an indication of incomplete combustion and reduced combustion efficiency. However, it is also possible that staged combustion can produce soot in the flame, which can increase flame radiation. The actual impact of staging on the heat transfer from the flame is highly dependent on the actual burner design.

In the past, the challenge for the burner designer was often to maximize the mixing between the fuel and the oxidizer to ensure complete combustion, especially if the fuel was difficult to burn, as in the case of low heating value fuels such as waste liquid fuels or process gases from chemicals production. Now, the burner designer must balance the mixing of the fuel and the oxidizer to maximize combustion efficiency while simultaneously minimizing all types of pollutant emissions. This is no easy task as, for example, NO_x and CO emissions often go in opposite directions, as shown in [Figure 1.18](#). When CO is low, NO_x may be high and vice versa. Modern burners must be environmentally friendly, while simultaneously efficiently transferring heat to the load.

Many types of burner designs exist due to the wide variety of fuels, oxidizers, combustion chamber geometries, environmental regulations, thermal input sizes, and heat transfer requirements (including flame temperature, flame momentum, and heat distribution). Some of these design factors are briefly considered here. Other important design factors, such as heat transfer ([Chapter 6](#)), noise ([Chapter 7](#)), and controls ([Chapter 8](#)), are discussed elsewhere in the book. Some of the tools used to optimize burner design include computational fluid dynamic modeling ([Chapter 5](#)), testing ([Chapter 9](#)), and physical modeling ([Chapter 10](#)).

1.4.1 FUEL

Depending on many factors, certain types of fuels may be preferred for certain geographic locations due to cost and availability considerations. Gaseous fuels, particularly natural gas, are commonly used in most industrial heating applications in the United States. In Europe, natural gas is also commonly used along with light fuel oil. In Asia and South America, heavy fuel oils are generally preferred although the use of gaseous fuels is on the rise. Fuels also vary depending on the application. For example, in incineration processes, waste fuels are commonly used either by themselves or with other

fuels such as natural gas. In the petrochemical industry, fuel gases often consist of a blend of several fuels, including gases such as hydrogen, methane, propane, butane, and propylene.

The fuel choice has an important influence on the heat transfer from a flame. In general, solid fuels (e.g., coal) and liquid fuels (e.g., oil) produce very luminous flames that contain soot particles that radiate like blackbodies to the heat load. Gaseous fuels such as natural gas often produce nonluminous flames because they burn so cleanly and completely without producing soot particles. A fuel such as hydrogen is completely nonluminous as there is no carbon available to produce any soot. In cases where highly radiant flames are required, a luminous flame is preferred. In cases where convection heat transfer is preferred, a nonluminous flame may be preferred in an effort to minimize the possibility of contaminating the heat load with soot particles from a luminous flame. Where natural gas is the preferred fuel and highly radiant flames are desired, new technologies are being developed to produce more luminous flames. These include pyrolyzing the fuel in a partial oxidation process,³¹ using a plasma to produce soot in the fuel,³² and generally controlling the mixing of the fuel and oxidizer to produce fuel-rich flame zones that generate soot particles.³³ Therefore, the fuel itself has a significant impact on the heat transfer mechanisms between the flame and the load. In most cases, the fuel choice is dictated by the customer as part of the specifications for the system and is not chosen by the burner designer. The designer must make the best of whatever fuel has been selected. In most cases, the burner design is optimized based on the choice for the fuel.

The fuel also has a large impact on pollutant emissions. For example, gaseous fuels generally contain little or no sulfur so SO_x emissions are usually small. However, heavy oils often contain significant quantities of sulfur and therefore SO_x emissions are of concern and need to be controlled. Another example is particulate emissions. Gaseous fuels generally burn very cleanly and produce negligible particulates. However, heavy liquid oil fuels can generate high levels of particulate emissions. Therefore, burner design is important in minimizing pollutant emissions, depending on the fuel.

In some cases, the burner may have more than one type of fuel. An example is shown in Figure 1.19.³⁴ Dual-fuel burners are typically designed to operate on either gaseous or liquid fuels. These burners are used where the customer may need to switch between a gaseous fuel (e.g., natural gas) and a liquid fuel (e.g., oil), usually for economic reasons. These burners normally operate on one fuel or the other, and occasionally on both fuels simultaneously. Another application in which

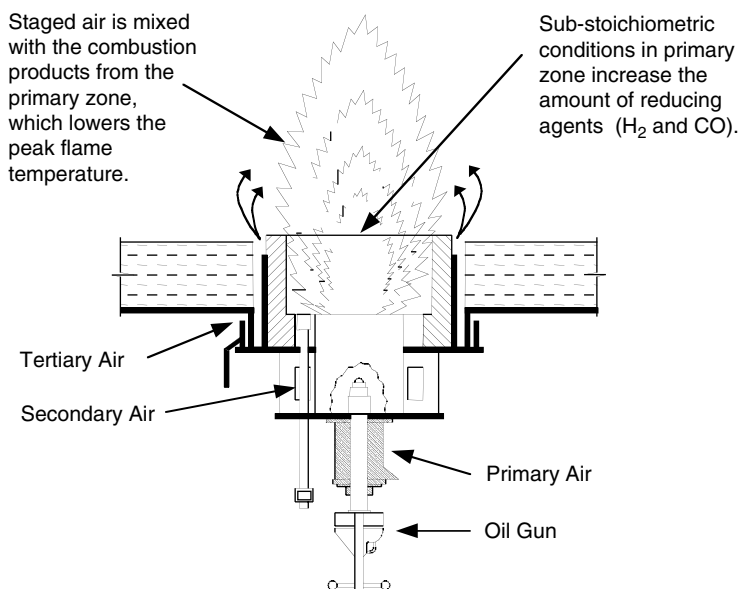
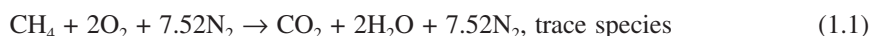


FIGURE 1.19 Dual fuel burner. (Courtesy of John Zink Co., LLC.³⁶)

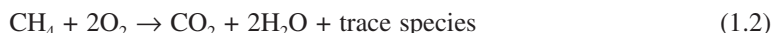
multiple fuels might be used is in waste incineration. One method of disposing of waste liquids contaminated with hydrocarbons is to combust them by direct injection through a burner. The waste liquids are fed through the burner, which is powered by a traditional fuel such as natural gas or oil. The waste liquids often have very low heating values and are difficult to combust without auxiliary fuel. This further complicates the burner design, where the waste liquid must be vaporized and combusted concurrently with the normal fuel used in the burner.

1.4.2 OXIDIZER

The predominant oxidizer used in most industrial heating processes is atmospheric air. This can present challenges in some applications where highly accurate control is required due to the daily variations in the barometric pressure and humidity of ambient air. The combustion air is sometimes preheated and sometimes blended with some of the combustion products, which is usually referred to as flue gas recirculation (FIGR). In certain cases, preheated air is used to increase the overall thermal efficiency of a process. FIGR is often used to both increase thermal efficiency and to reduce NO_x emissions. The thermal efficiency is increased by capturing some of the energy in the exhaust gases that are used to preheat the incoming combustion oxidizer. NO_x emissions may also be reduced because the peak flame temperatures are reduced, which can reduce the NO_x emissions, which are highly temperature dependent. There are also many high-temperature combustion processes that use an oxidizer containing a higher proportion of oxygen than the 21% (by volume) found in normal atmospheric air. This is referred to as oxygen-enhanced combustion (OEC) and has many benefits, including increased productivity and thermal efficiency while reducing the exhaust gas volume and pollutant emissions.⁵ A simplified global chemical reaction for the stoichiometric combustion of methane with air is given as follows:



This compares to the same reaction where the oxidizer is pure O₂ instead of air:



The volume of exhaust gases is significantly reduced by the elimination of N₂. In general, a stoichiometric oxygen-enhanced methane combustion process can be represented by:



where $0 \leq x \leq 7.52$, depending on the oxidizer. The N₂ contained in air acts as a ballast that may inhibit the combustion process and have negative consequences. The benefits of using oxygen-enhanced combustion must be weighed against the added cost of the oxidizer, which in the case of air is essentially free except for the minor cost of the air handling equipment and power for the blower. The use of a higher-purity oxidizer has many consequences with regard to heat transfer from the flame and pollutant emissions generated. These are considered elsewhere in the book. Oxygen-enhanced combustion is considered in more detail in Chapters 20 and 21.

1.4.3 GAS RECIRCULATION

A common technique used in combustion systems is to design the burner to induce furnace gases to be drawn into the burner to dilute the flame, usually referred to as furnace gas recirculation (FuGR). Although the furnace gases are hot, they are still much cooler than the flame itself. This dilution may accomplish several purposes. One is to minimize NO_x emissions by reducing the peak temperatures in the flame, as in FIGR (see [Figure 1.20](#)). However, furnace gas recirculation may be preferred to FIGR because no external high-temperature ductwork or

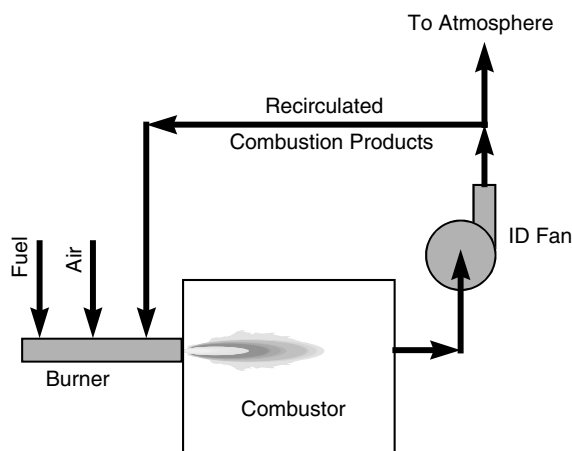


FIGURE 1.20 Schematic of flue gas recirculation.²⁹

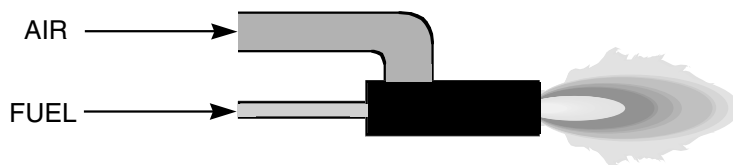


FIGURE 1.21 Diagram of a premixed burner.²⁹

fans are needed to bring the product gases into the flame zone. Another reason to use furnace gas recirculation may be to increase the convective heating from the flame because of the added gas volume and momentum. An example of flue gas recirculation into the burner is given in Figure 1.20.³⁵ A specific type of burner incorporating furnace gas recirculation is called a regenerative burner (see Chapter 12).

1.5 GENERAL BURNER CLASSIFICATIONS

There are numerous ways to classify burners. Some common ones are discussed below, with a brief consideration as to how burner performance is impacted.

1.5.1 MIXING TYPE

One common method for classifying burners is according to how the fuel and the oxidizer are mixed. In premixed burners, shown in the diagram in Figure 1.21 and schematically in Figure 1.22, the fuel and the oxidizer are completely mixed before combustion begins. Thermal radiation burners (Chapter 13) and radiant wall burners (Chapter 15) usually are of the premixed type. Premixed burners often produce shorter and more intense flames, as compared to diffusion flames. This can produce high-temperature regions in the flame, leading to nonuniform heating of the load and higher NO_x emissions, although this is very dependent on the specific design. However, in flame impingement heating, premixed burners are useful because the higher temperatures and shorter flames can enhance the heating rates.

In diffusion-mixed burners, shown schematically in Figure 1.23, the fuel and the oxidizer remain separated and unmixed prior to combustion, which begins where the oxidizer/fuel mixture is within the flammability range (assuming the temperature is high enough for ignition). Oxygen/fuel burners (see Chapter 21) are usually diffusion burners, primarily for safety reasons, to prevent flashback

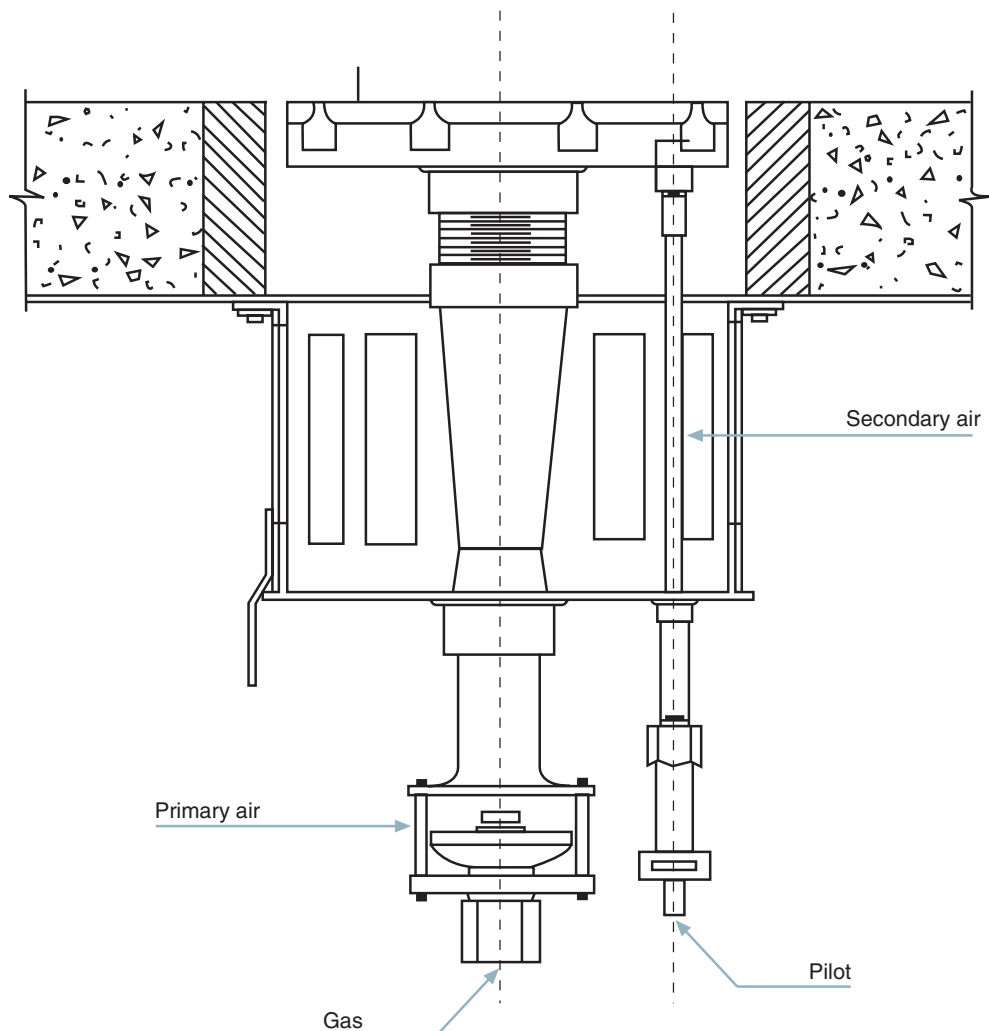


FIGURE 1.22 Schematic of a premixed burner. (Courtesy of John Zink Co., LLC.³⁶)



FIGURE 1.23 Schematic of a diffusion-mixed burner.²⁹

and explosion in a potentially dangerous system. Diffusion gas burners are sometimes referred to as “raw gas” burners, as the fuel gas exits the burner essentially intact with no oxidant mixed with it. Diffusion burners typically have longer flames than premixed burners, do not have as high temperature a hot spot, and usually have a more uniform temperature and heat flux distribution. They may also have lower NO_x emissions although, again, this is design dependent.

It is also possible to have partially premixed burners, shown schematically in [Figure 1.24](#) and [Figure 1.25](#), where a portion of the fuel is mixed with the oxidizer prior to exiting the burner. This is often done for stability and safety reasons, wherein the partial premixing helps anchor the flame, while

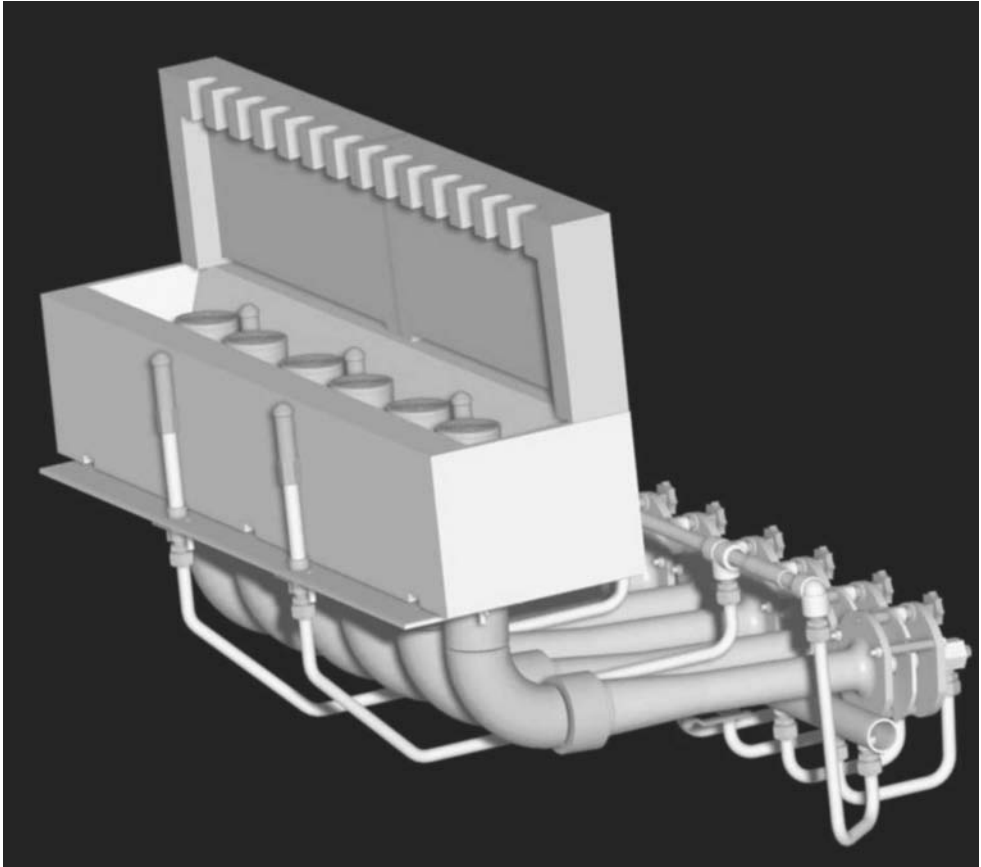


FIGURE 1.24 Partially premixed burner (Courtesy of John Zink Co., LLC).

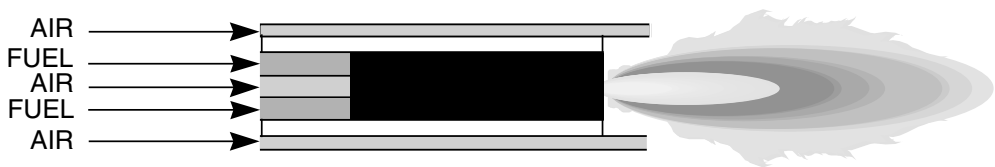


FIGURE 1.25 Schematic of a partially premixed burner.²⁹

not fully premixing lessens the chance for flashback. This type of burner often has a flame length and temperature and heat flux distribution that is between the fully premixed and diffusion flames.

Another burner classification based on mixing is known as staging: staged air and staged fuel. A staged air burner is shown in the diagram in [Figure 1.26](#) and schematically in [Figure 1.27](#). A staged fuel burner is shown in the diagram in [Figure 1.28](#) and schematically in [Figure 1.29](#). Secondary and sometimes tertiary injectors in the burner are used to inject a portion of the fuel and/or the oxidizer into the flame, downstream of the root of the flame. Staging is often done to control heat transfer, produce longer flames, and reduce pollutant emissions such as NO_x. These longer flames typically have a lower peak flame temperature and more uniform heat flux distribution than nonstaged flames. However, an additional challenge is that multiple longer flames might interact with each other and produce unpredictable consequences compared to single shorter flames.

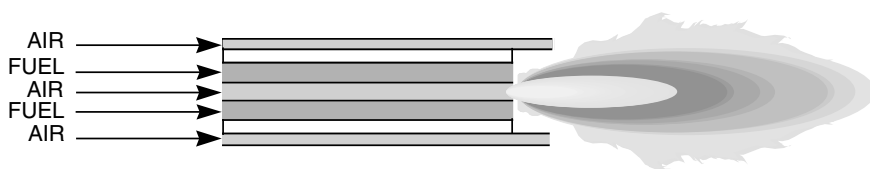


FIGURE 1.26 Diagram of a staged-air burner.²⁹

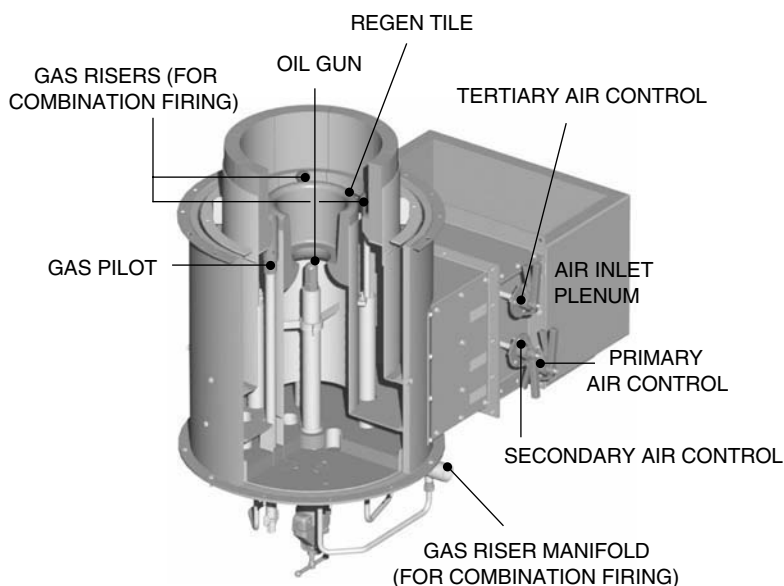


FIGURE 1.27 Schematic of a staged-air process. (Courtesy of John Zink Co., LLC.³⁶)

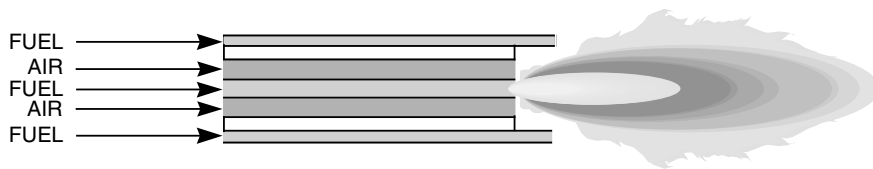


FIGURE 1.28 Diagram of a staged fuel burner.²⁹

1.5.2 FUEL TYPE

Burners can also be classified according to fuel type. Gaseous fuel burners are the predominant type used in most of the applications considered here. In general, natural gas is the predominant gaseous fuel used because of its low cost and availability. However, a wide range of gaseous fuels are used in, for example, the chemicals industry.³⁶ These fuels contain multiple components such as methane, hydrogen, propane, nitrogen, and carbon dioxide and are sometimes referred to as refinery fuel gases. Figure 1.30 shows an example of a typical nonluminous gaseous flame from a burner used in the petrochemical industry. Gaseous fuels are among the easiest to control because no vaporization is required, as is the case for liquid and solid fuels. They are also often simpler to control to minimize pollution emissions because they are more easily staged compared to liquid and solid fuels. Table 1.4 shows typical data for the combustion of common hydrocarbons.

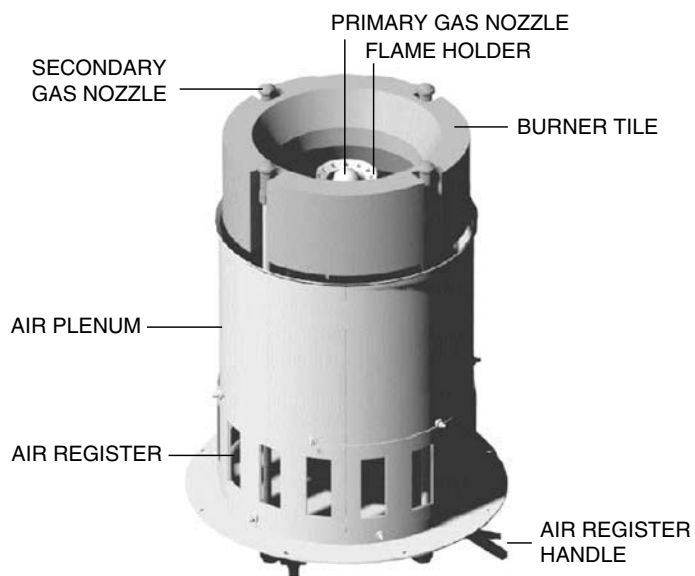


FIGURE 1.29 Schematic of a staged fuel burner.²⁹

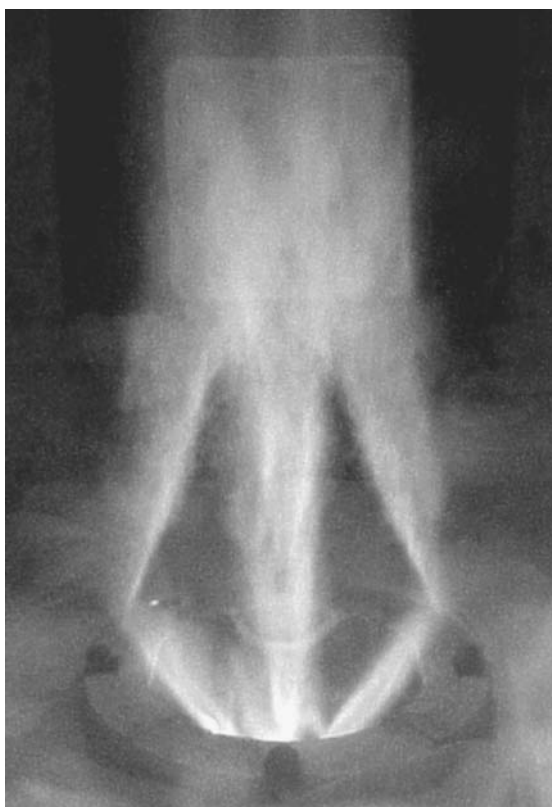


FIGURE 1.30 Typical nonluminous flame. (Courtesy of John Zink Co., LLC.³⁶)

TABLE 1.4
Combustion Data for Common Hydrocarbons²

Hydrocarbon	Formula	Higher Heating Value, Vapor (Btu/lb _m)	Theor. Air/Fuel Ratio, by mass	Max. Flame Speed (ft/s)	Adiabatic Flame Temp., in Air (°F)	Ignition Temp., in Air (°F)	Flash Point (°F)	Flammability Limits, in Air (% by volume)	
Paraffins or Alkanes									
Methane	CH ₄	23875	17.195	1.1	3484	1301	(gas)	5.0	15.0
Ethane	C ₂ H ₆	22323	15.899	1.3	3540	968–1166	(gas)	3.0	12.5
Propane	C ₃ H ₈	21669	15.246	1.3	3573	871	(gas)	2.1	10.1
<i>n</i> -Butane	C ₄ H ₁₀	21321	14.984	1.2	3583	761	−76	1.86	8.41
<i>Iso</i> -Butane	C ₄ H ₁₀	21271	14.984	1.2	3583	864	−117	1.80	8.44
<i>n</i> -Pentane	C ₅ H ₁₂	21095	15.323	1.3	4050	588	<−40	1.40	7.80
<i>iso</i> -Pentane	C ₅ H ₁₂	21047	15.323	1.2	4055	788	<−60	1.32	9.16
Neopentane	C ₅ H ₁₂	20978	15.323	1.1	4060	842	(gas)	1.38	7.22
<i>n</i> -Hexane	C ₆ H ₁₄	20966	15.238	1.3	4030	478	−7	1.25	7.0
Neohexane	C ₆ H ₁₄	20931	15.238	1.2	4055	797	−54	1.19	7.58
<i>n</i> -Heptane	C ₇ H ₁₆	20854	15.141	1.3	3985	433	25	1.00	6.00
Triptane	C ₇ H ₁₆	20824	15.141	1.2	4035	849	—	1.08	6.69
<i>n</i> -Octane	C ₈ H ₁₈	20796	15.093	—	—	428	56	0.95	6.20
<i>iso</i> -Octane	C ₈ H ₁₈	20770	15.093	1.1	—	837	10	0.79	5.94
Olefins or Alkenes									
Ethylene	C ₂ H ₄	21636	14.807	2.2	4250	914	(gas)	2.75	28.6
Propylene	C ₃ H ₆	21048	14.807	1.4	4090	856	(gas)	2.00	11.1
Butylene	C ₄ H ₈	20854	14.807	1.4	4030	829	(gas)	1.98	9.65
<i>iso</i> -Butene	C ₄ H ₈	20737	14.807	1.2	—	869	(gas)	1.8	9.0
<i>n</i> -Pentene	C ₅ H ₁₀	20720	14.807	1.4	4165	569	—	1.65	7.70
Aromatics									
Benzene	C ₆ H ₆	18184	13.297	1.3	4110	1044	12	1.35	6.65
Toluene	C ₇ H ₈	18501	13.503	1.2	4050	997	40	1.27	6.75
<i>p</i> -Xylene	C ₈ H ₁₀	18663	13.663	—	4010	867	63	1.00	6.00
Other Hydrocarbons									
Acetylene	C ₂ H ₂	21502	13.297	4.6	4770	763–824	(gas)	2.50	81
Naphthalene	C ₁₀ H ₈	17303	12.932	—	4100	959	174	0.90	5.9

Liquid fuel burners are used in some limited applications, but are more prevalent in certain areas of the world such as South America. No. 2 and no. 6 oil are the most commonly used liquid fuels. Waste liquid fuels are also used in incineration processes. One of the specific challenges of using oils is vaporizing the liquid into small enough droplets to burn completely. Improper atomization produces high unburned hydrocarbon emissions and reduces fuel efficiency. Steam and compressed air are commonly used to atomize liquid fuels. The atomization requirements often reduce the options for modifying the burner design to reduce pollutant emissions. Another challenge is that liquid fuel oils often contain impurities such as nitrogen and sulfur that produce pollution emissions. In the case of fuel-bound nitrogen, so-called fuel NO_x emissions increase. In the case of sulfur, essentially all of the sulfur in a liquid fuel converts to SO_x emissions.

Solid fuels are not commonly used in most industrial combustion applications. The most common solid fuels are coal and coke. Coal is used in power generation and coke is used in some primary metals production processes. However, neither is considered a traditional industrial combustion process and therefore is not considered here. Another type of pseudo solid fuel is sludge that is processed in incinerators. Solid fuels also often contain impurities such as nitrogen and sulfur that can significantly increase pollutant emissions. Some solid fuels may also contain hazardous chemicals that can produce carcinogenic pollution emissions. Because solid fuels are not used frequently in the applications considered, they are only discussed in those specific cases.

There are some applications that require the burner to be able to fire on a gaseous fuel such as natural gas, a liquid fuel such as fuel oil, or both simultaneously. This is generally due to the economics of the fuel costs. In some locations, a more favorable fuel cost rate can be obtained, for example, on natural gas, if the supply can be interrupted with sufficient notice. The backup fuel is typically fuel oil. These dual-fuel burners have special challenges because of significant differences in the design of gaseous and liquid burners.

1.5.3 OXIDIZER TYPE

Burners and flames are often classified according to the type of oxidizer that is used. The majority of industrial burners use air for combustion. In many of the higher-temperature heating and melting applications, such as glass production, the oxidizer is pure oxygen. These burner types are discussed in Chapter 21. In other applications, the oxidizer is a combination of air and oxygen, often referred to as oxygen-enriched air combustion. These burner types are discussed in Chapter 20.

Figure 1.31 shows a schematic of an air/fuel burner, which is the most commonly used type in industrial combustion applications. In most cases, the combustion is supplied by a fan or blower, although there are many applications in the petrochemical industry where natural-draft burners are commonly used (see Chapter 16). There are numerous variations of air/fuel burners and these are discussed throughout this book.

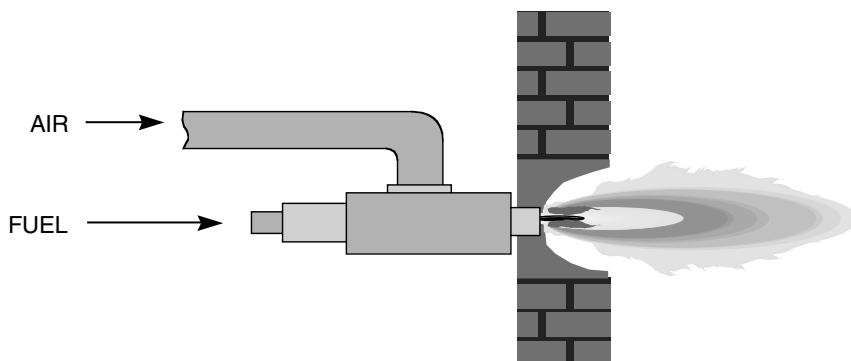


FIGURE 1.31 Schematic of an air/fuel burner.²⁹

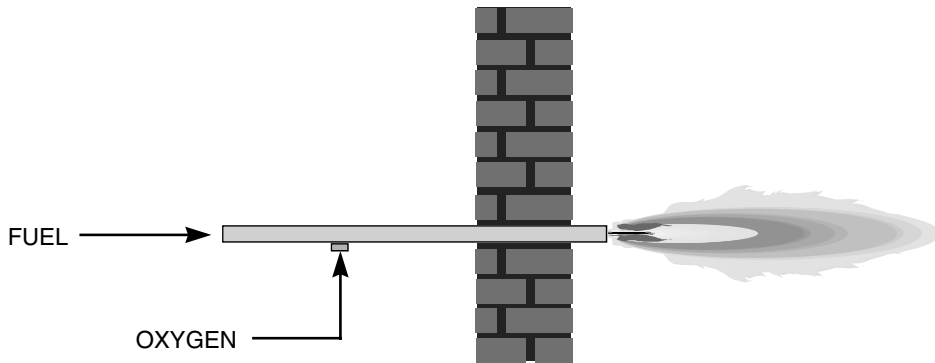


FIGURE 1.32 Schematic of an oxy/fuel burner.⁵

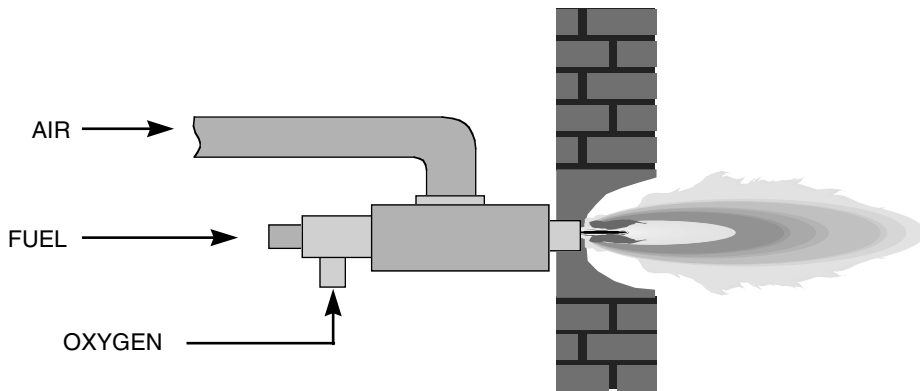


FIGURE 1.33 Schematic of an air-oxy/fuel burner.⁵

Figure 1.32 shows a method of using OEC and commonly referred to as an oxy/fuel burner. In nearly all cases, the fuel and the oxygen remain separated inside the burner. They do not mix until reaching the outlet of the burner. This is commonly referred to as a nozzle-mix burner, which produces a diffusion flame. For safety reasons, there is no premixing of the gases. Because of the extremely high reactivity of pure O_2 , there is the potential for an explosion if the gases are premixed. In this method, high-purity O_2 (>90% O_2 by volume) is used to combust the fuel. As discussed later, there are several ways of generating the O_2 . In an oxy/fuel system, the actual purity of the oxidizer will depend on which method has been chosen to generate the O_2 . As shown later, oxy/fuel combustion has the greatest potential for improving a process, but it also may have the highest operating cost.

Figure 1.33 shows an air/fuel process in which the air is enriched with O_2 . This can be referred to as low-level O_2 enrichment, or premix enrichment. Many conventional air/fuel burners can be adapted for this technology.³⁷ The O_2 is injected into the incoming combustion air supply, usually through a diffuser to ensure adequate mixing. This is usually an inexpensive retrofit that can provide substantial benefits. Typically, the added O_2 will shorten and intensify the flame. However, there may be some concern if too much O_2 is added to a burner designed for air/fuel. The flame shape may become unacceptably short. The higher flame temperature may damage the burner or burner block. The air piping may need to be modified for safety reasons to handle higher levels of O_2 .

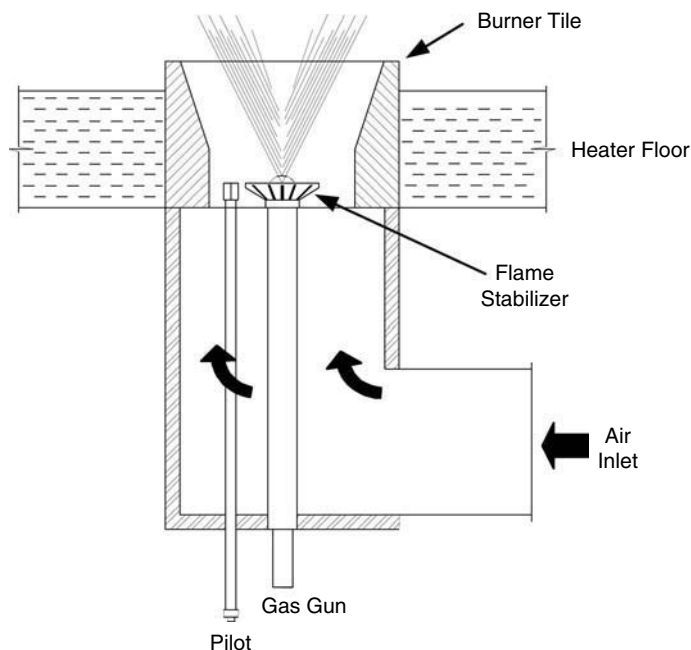


FIGURE 1.34 Schematic of a natural-draft burner. (Courtesy of John Zink Co., LLC.³⁶)

1.5.4 DRAFT TYPE

Most industrial burners are known as forced-draft burners. This means that the oxidizer is supplied to the burner under pressure. For example, in a forced-draft air burner, the air used for combustion is supplied to the burner by a blower. In natural-draft burners (see Chapter 16), the air used for combustion is induced into the burner by the negative draft produced in the combustor and by the motive force of the incoming fuel, which may be at a significant pressure. A schematic is shown in Figure 1.34 and an example is shown in Figure 1.35. In this type of burner, the pressure drop and combustor stack height are critical in producing enough suction to induce sufficient combustion air into the burners. This type of burner is commonly used in the chemical and petrochemical industries in fluid heaters. The main consequence of the draft type on burner performance is that the natural-draft flames are usually longer than the forced-draft flames so that the heat flux from the flame is distributed over a longer distance and the peak temperature in the flame is often lower.

1.5.5 HEATING TYPE

Burners are often classified as to whether they are of the direct (see Figure 1.36) or indirect heating type (see Figure 1.37). In direct heating, there is no intermediate heat exchange surface between the flame and the load. In indirect heating, such as radiant tube burners (see Chapter 8), there is an intermediate surface between the flame and the load. This is usually done because the combustion products cannot come in contact with the load because of possible contamination.

Radiation heat transfer (see Chapter 2) from the flame to the product is the primary mode used in many industrial combustion systems (see Chapter 6). There are a variety of burner designs that rely primarily on this mechanism. Thermal radiation burners are discussed in Chapter 13. Radiant tube burners are discussed in Chapter 14. Radiant wall burners are discussed in Chapter 15. Other burner designs discussed throughout this book also use thermal radiation as the primary heat transfer mechanism.

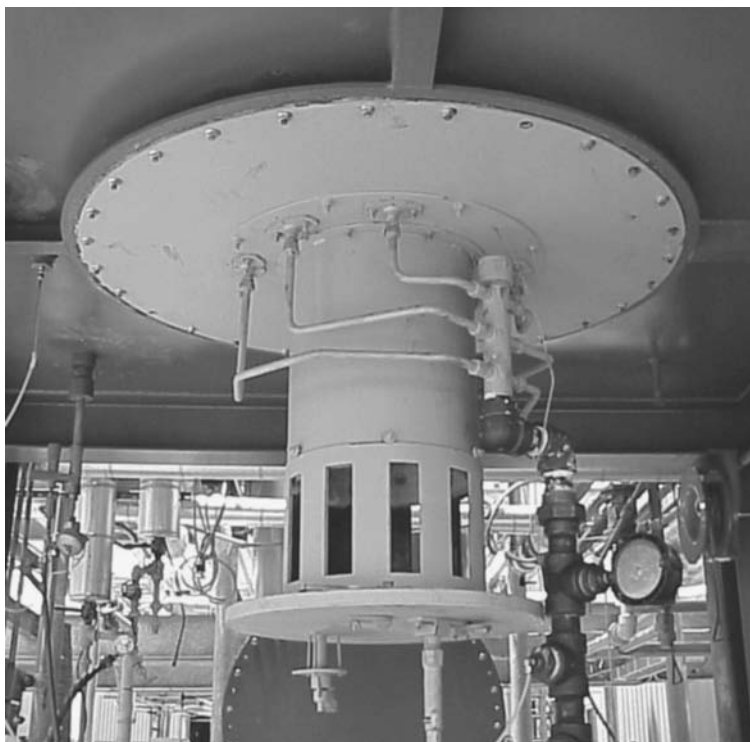


FIGURE 1.35 Photo of a natural-draft burner. (Courtesy of John Zink Co., LLC.²⁹)

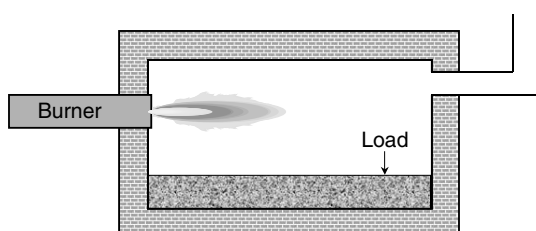


FIGURE 1.36 Direct fired process.

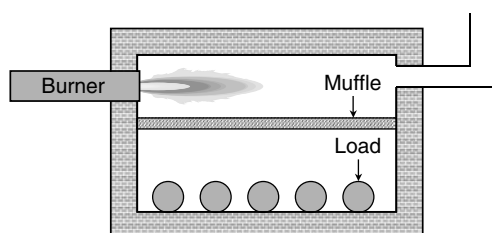


FIGURE 1.37 Indirect fired process.

Forced convection (see Chapter 2) is the other predominant mechanism for transferring heat from flames to a load. For example, high-velocity burners are considered in Chapter 11. These are particularly useful in applications where primarily radiant heating may overheat the surface with much less energy getting inside the load. An example would be heating a pile of scrap metal. Highly radiant heating could melt the outside of the pile and cause excessive oxidation, leading to

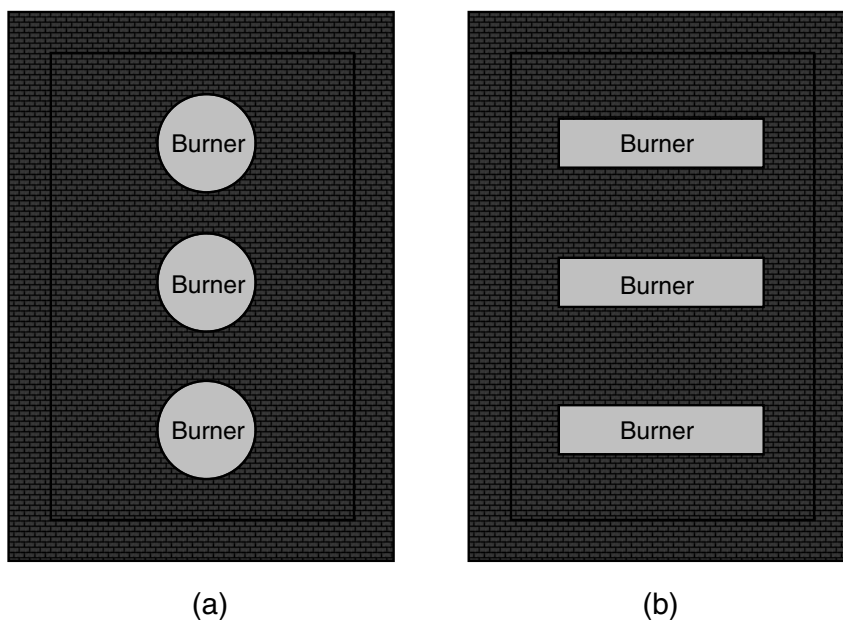


FIGURE 1.38 Round (a) and rectangular (b) burner shapes in identical combustors.

high metal yield losses. Convective heating can penetrate inside the load to cause more uniform heating. In certain applications, high-velocity burners may not be preferred because the materials being heated may contain fine particles that can easily become airborne. An example is glass manufacturing, where the incoming batch materials contain fine powders.

1.5.6 BURNER GEOMETRY

There are two primary shapes for the outlet nozzle of industrial burners: round or rectangular. [Figure 1.38](#) shows identical heaters with the same number of burners but with different burner shapes: round flame and flat flame. These are briefly considered next.

Round flames are the predominant shape used in industry. Most of the burners discussed in this book are predominantly round. This is often due to the lower cost of making round shapes compared to making rectangular shapes. It is also often due to the burner tile; round shapes generally require less maintenance compared to rectangular tiles, which have corners that are more susceptible to cracking. Another reason may be due to more preferred flow patterns inside round burner plenums compared to rectangular shapes.

Rectangular shapes are sometimes preferred in certain applications, depending on the geometry of the combustor and the load. Burners with a fairly high aspect ratio (length to width) are sometimes referred to as “flat” flame burners because the flame shape appears to be flat. One example is in ethylene cracking furnaces where flat-shaped burners fire up along a refractory wall to heat the wall to radiate to tubes opposite that wall. Another example is in glass furnaces where flat-shaped flames fire over the molten glass; these flat shapes often give better flame coverage, more uniform heating, and better thermal efficiency.

1.6 BURNER COMPONENTS

There are several important components briefly considered here that impact the burner design.

The *ignition system* is an important component in the burner system to ensure safe and reliable operation. The ignition system is often built into the burner, but in some cases it may be separate

from the burner. The system may be fully automatic or completely manual. Different types of ignitors are available. In many cases, a pilot is used to ignite the main flame. This may be continuous or interruptible, depending on the system design. The pilot may be permanent or removable, and may be ignited by something like a spark-ignitor or by an external torch. Pilots require a separate fuel supply and are typically premixed.

Plenums are used to homogenize the incoming gas flows to evenly distribute them to the outlet of the burner. This is important to ensure proper operation of the burner over the entire range of operating conditions, especially at turndown. These gases may include combustion air, premixed fuel and air, or partially premixed fuel and air. If the plenum is too large, then the flows may be unevenly distributed across the burner nozzle outlet. If the plenum is too small, then the pressure drop through the plenum may be excessive.

The *burner tile*, sometimes referred to as a *block* or *quarl*, is an important component because it helps shape the flame and protects the internal parts from overheating. In the majority of designs, the burner tile is made of some type of ceramic that often contains alumina and silica, depending on the temperature requirements. The burner tile can also play an important role in the ignition and fluid dynamics of the combustion process. The tile may have bluff body components that enhance flame stability. There may be holes through the tile to enhance mixing of furnace gases with the gases fed into the burner. Advances in ceramics and manufacturing processes have led to increasingly more complicated burner tiles.

Controls refer not to the control equipment for the flows coming to the burner, but to controls that may be on the burner. For example, there is often a damper built into natural-draft burners (see Chapter 16) to control the incoming air flow and the furnace draft. Other controls on a burner may be for adjusting the distribution of fuels or air throughout the burner. For example, if a burner has multiple fuel injectors, particularly for fuel staging, controls on the burner can be used to control how much fuel goes to each injector. Chapter 8 has a detailed discussion of the controls leading up to the burner.

The *flame safety system* is critical to the safe operation of the combustion system. This may include some type of flame scanner or flame rod to ensure that either the burner or the pilot is operating. These are connected to the fuel supply system so that the fuel flow will be stopped if the flame goes out to prevent a possible explosion for unignited fuel gases contacting a hot surface somewhere in the combustor. This is also discussed in Chapter 8.

1.7 COMBUSTORS

This section briefly introduces the combustors that are commonly used in industrial heating and melting applications.

1.7.1 DESIGN CONSIDERATIONS

There are many important factors that must be considered when designing a combustor. This section only briefly considers a few of those factors and how they might influence the heat transfer in the system.

1.7.1.1 Load Handling

A primary consideration for any combustor is the type of material that will be processed. The various types of loads are considered later in this chapter. One obvious factor of importance in handling the load and transporting it through the combustor is its physical state — whether it is a solid, liquid, or gas. Another factor is the transport properties of the load. For example, the solid may be granular or it might be in the form of a sheet (web). Related to that is how the solid will be fed into the combustor. A granular solid could be fed continuously into a combustor with a

screw conveyor or it could be fed in with discrete charges from a front-end loader. The shape of the furnace will vary according to how the material will be transported through it. For example, limestone is fed continuously into a rotating and slightly downward-inclined cylinder.

1.7.1.2 Temperature

Industrial heating applications can be divided into two categories: higher and lower temperatures. The division between the two is somewhat arbitrary but mainly concerns the different types of applications used in each. For example, most metal and glass melting applications fall into the higher-temperature categories as the furnace temperatures are often well over 2000°F (1400K). They use technologies such as air preheating and oxygen enrichment (see Chapters 20 and 21) to achieve those higher temperatures. Lower-temperature applications include dryers, process heaters, and heat treating and are typically below about 2000°F (1400K). Although many of these processes use air preheating, it is primarily employed to improve the thermal efficiency and not to get higher flame temperatures. Those processes rarely use oxygen enrichment, which usually only works economically for higher-temperature processes. Both the combustors and the burners are designed differently for higher- and lower-temperature processes. The heat transfer and pollutant generation mechanisms are often different as well. In higher-temperature processes, the primary mode is often radiation, while in lower-temperature applications, convection often plays a significant role. NO_x emissions, for example, are much more significant at higher temperatures compared to lower temperatures.

1.7.1.3 Heat Recovery

When heat recovery is used in an industrial combustion process, it is an integral part of the system. The two most popular methods are regenerative and recuperative. The heat recovery system is important in the design of the combustor as it determines the thermal efficiency of the process and the flame temperatures in the system. It also influences the heat transfer modes, as it can increase both the radiation and convection because of higher flame temperatures. Another type of heat recovery used in some processes is furnace or flue gas recirculation, where the exhaust products are recirculated back through the flame. This also influences the heat transfer and furnace design because it can moderate the flame temperature but increase the volume flow of gases through the combustion chamber.

1.7.2 GENERAL CLASSIFICATIONS

There are several ways that a combustor can be classified and these are briefly discussed in this section. Each type has an impact on the heat transfer mechanisms in the furnace.

1.7.2.1 Load Processing Method

Furnaces are often classified as to whether they are *batch* or *continuous*. In a batch furnace, the load is charged into the furnace at discrete intervals where it is heated. There may be multiple load charges, depending on the application. Normally, the firing rate of the burners is reduced or turned off during the charging cycle. On some furnaces, a door may also need to be opened during charging. This significantly impacts the heat transfer in the system as the heat losses during the charge cycle are very large. The radiation losses through open doors are high and the reduced firing rate may not be enough to maintain the desired furnace temperature. In some cases, the temperature on the inside of the refractory wall, closest to the load, may actually be lower than the temperature of the refractory at some distance from the inside, due to the heat losses during charging. The heating process and heat transfer are dynamic and constantly changing as a result of the cyclical nature of the load charging. The burners may cycle on and off or between high-fire

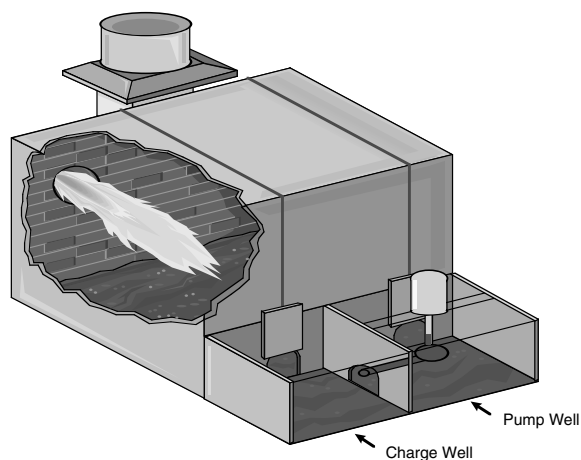


FIGURE 1.39 Aluminum reverberatory furnace.²⁹

and low-fire. This makes analysis of these systems more complicated because of the need to include time in the computations.

In a continuous furnace, the load is constantly fed into and out of the combustor. The feed rate can change, sometimes due to conditions upstream or downstream of the combustor or to the production needs of the plant, but the process is nearly steady-state. This makes continuous processes simpler to analyze, because there is no need to include time in the computations. It is often easier to make meaningful measurements in continuous processes due to their steady-state nature.

There are some furnaces that are semicontinuous, wherein the load can be charged in nearly continuous fashion, but the finished product can be removed from the furnace at discrete intervals. An example is an aluminum reverberatory furnace that is charged using an automatic side-well feed mechanism (see [Figure 1.39](#)). In that process, shredded scrap is continuously added to a circulating bath of molten aluminum. When the correct alloy composition has been reached and the furnace has a full load, some or all of that load is then tapped out of the furnace. The effect on heat transfer is somewhere between that for batch and continuous furnaces.

1.7.2.2 Heating Type

As described above for burners, combustors are often classified as *direct* (see [Figure 1.36](#)) or *indirect* (see [Figure 1.37](#)) heating. In indirect heating, there is some type of intermediate heat transfer medium between the flames and the load that keeps the combustion products separate from the load. One example is a muffle furnace where there is a high-temperature ceramic muffle between the flames and the load. The flames transfer their heat to the muffle, which then radiates to the load, which is usually some type of metal. The limitation of indirect heating processes is the temperature limit of the intermediate material. Although ceramic materials have fairly high temperature limits, other issues such as structural integrity over long distance spans and thermal cycling can still reduce the recommended operating temperatures. Another example of indirect heating is in process heaters, where fluids are transported through metal tubes that are heated by flames. Indirect heating processes often have fairly uniform heat flux distributions because the heat exchange medium tends to homogenize the energy distribution from the flames to the load. The heat transfer from the heat exchange surface to the load is often fairly simple and straightforward to compute because of the absence of chemical reactions in between. However, the heat transfer from the flames to the heat exchange surface and the subsequent thermal conduction through that surface are as complicated as if the flame was radiating directly to the load. Indirect heating may

also have the advantage of reducing pollutant emissions when contact of the high-temperature exhaust gases with the load could possibly generate pollutants.

As a result of the temperature limits of the heat exchange materials, most higher-temperature processes are of the direct heating type where the flames can directly radiate heat to the load.

1.7.2.3 Geometry

Another common way of classifying combustors is according to their geometry, which includes their shape and orientation. The two most common shapes are rectangular and cylindrical. The two most common orientations are horizontal and vertical, although inclined furnaces are commonly used in certain applications such as rotary cement furnaces. An example using the shape and orientation of the furnace as a means of classification would be a vertical cylindrical heater (sometimes referred to as a VC) used to heat fluids in the petrochemical industry. Both the furnace shape and orientation have important effects on heat transfer in the system. They also determine the type of analysis that will be used. For example, in a VC heater, it is often possible to model only a slice of the heater due to its angular symmetry, in which case cylindrical coordinates would be used. On the other hand, it is usually not reasonable to model a horizontal rectangular furnace using cylindrical coordinates, especially if buoyancy effects are important.

Some furnaces are classified on the basis of what they look like. An example is a shaft furnace used to make iron. The raw materials are loaded into the top of a tall, thin, vertically oriented cylinder. Hot combustion gases generated at the bottom, via combustion of coke, flow up through the raw materials, which get heated. The melted final product is tapped out of the bottom. The furnace looks and acts almost like a shaft because of the way the raw materials are fed in through the top and exit at the bottom. A transfer chamber used to move molten metal around in a steel mill is often referred to as a ladle because of its function and appearance. These ladles are preheated using burners before the molten metal is poured into them; this is done to prevent the refractory-lined vessels from thermally shocking.

Another aspect of the geometry that is important in some applications is whether or not the furnace is moving. For example, in a rotary furnace for melting scrap aluminum, the furnace rotates to enhance mixing and heat transfer distribution. This again affects the type of analysis that would be appropriate for that system and can add some complexity to the computations.

The burner orientation with respect to the combustor is also sometimes used to classify the combustor. For example, a wall-fired furnace has burners located in and firing along the wall.

1.7.2.4 Heat Recuperation

In many heat processing systems, energy recuperation is an integral part of the combustion system. Often, the heat recuperation equipment is a separate component of the system and not part of the burners themselves. Depending on the method used to recover the energy, the combustors are commonly referred to as either *recuperative* or *regenerative* (see discussion later in this chapter). The heat transfer in these systems is a function of the energy recovery system. For example, the higher the combustion air preheat temperature, the hotter the flame and the more radiant heat that can be produced by that flame. The convective heat transfer might also be increased due to the higher gas temperature and to the higher thermal expansion of the gases, which increases the average gas velocity through the combustor.

1.8 HEAT LOAD

This section is a brief introduction to some of the important issues concerning the heat load in a furnace or combustor. In petrochemical production processes, process heaters are used to heat petroleum products up to operating temperatures. The fluids are transported through the process heaters in process tubes. These heaters often have a radiant section and a convection section.

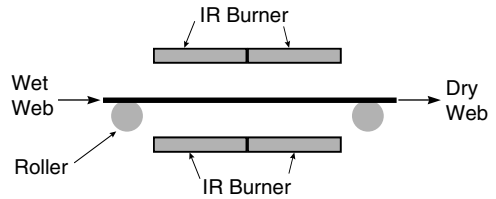


FIGURE 1.40 Elevation view of infrared burner heating a moving web.²⁹

In the radiant section, the radiation from burners heats the process tubes. In the convection section, the combustion products heat the tubes by flowing over the tubes. The design of the radiant section is especially important as flame impingement on the tubes can cause premature failure of the tubes or cause the hydrocarbon fluids to coke inside the tubes, which reduces the heat transfer to the fluids.

In some applications, heaters and burners are used to heat or dry moving substrates or webs. An example is shown in [Figure 1.40](#). One common application is the use of gas-fired infrared (IR) burners (see Chapter 13) to remove moisture from paper during the forming process.³⁸ These paper webs can travel at speeds over 300 m/s (1000 ft/s) and are normally dried by traveling over and contacting steam-heated cylinders. IR heaters are often used to selectively dry certain portions of the web that may be wetter than others. For example, if the target moisture content for the paper is 5%, then the entire width of the paper must have no more than 5% moisture. Streaks of higher moisture areas often occur in sections along the width of the paper. Without selectively drying such areas, the streaks would be dried to the target moisture level, which means that the rest of the sheet would be dried to even lower moisture levels. This creates at least two important problems. The first is lost revenue, because paper is usually sold on a weight basis. Any water unnecessarily removed from the paper decreases its weight and therefore results in lost income. Another problem is a reduction in the quality of the paper. If areas of the paper are too dry, they do not handle as well in devices such as copiers and printers, and are not nearly as desirable as paper of uniform moisture content. Therefore, selective drying of the paper only removes the minimum amount of water from the substrate. The challenge of this application is to measure the moisture content profile across the width of a sheet that may be several meters wide and moving at hundreds of meters per second. That information must then be fed to the control system for the IR heaters, which then must be able to react almost instantaneously. This is possible today because of advances in measurement and controls systems.

Another example of a moving substrate application is the use of IR burners to remove water during the production of fabrics in textile manufacturing.³⁹ Moving substrates present unique challenges for burners. Often, the material being heated can easily be set on fire if there is a line stoppage and the burners are not turned off quickly enough. This means that the burner control system must be interlocked with the web handling equipment so that the burners can be turned off immediately in the event of a line stoppage. If the burners have substantial thermal mass, then they may need to be retracted away from the substrate during a stoppage, or heat shields may need to be inserted between the burners and the substrate to prevent overheating.

Convection dryers are also used to heat and dry substrates. Typically, high-velocity heated air is blown at the substrate from both sides so that the substrate is elevated between the nozzles. In many cases, the heated air is used for both heat and mass transfer, to volatilize any liquids on or in the substrate such as water, and then carry the vapor away from the substrate.

An important aspect of heating webs is how the energy is transferred into the material. For example, dry paper is known to be a good insulator. When steam cylinders are used to heat and dry paper, they become less and less effective as the paper becomes drier because the heat from the cylinder cannot conduct through the paper as well as when it is moist (because the thermal conductivity of the paper increases with increasing moisture content). Infrared burners are effective for drying paper because the radiant energy transfers into the paper and is absorbed by the water. The radiant penetration into the paper actually increases as the paper becomes drier, unlike with

steam cylinders, which become less effective. Another important aspect related to burner design is the ability to cool down rapidly to prevent causing a fire, for example, when a paper web stops unexpectedly during processing due to some type of problem. An alternative is to shield the burner from the web in the event of a sudden line stoppage.

1.8.1 OPAQUE MATERIALS

This type of load encompasses a wide range of materials, including granular solids such as limestone and liquids such as molten metal. For this type of load, the heat transfers to the surface of the load and must conduct down into the material. This process can be enhanced by proper mixing of the materials so that new material is constantly exposed to the surface, as in rotary kilns or in aluminum reverberatory furnaces, which have molten metal pumps to continuously recirculate the metal through the heating zone. The potential problems with this method include overheating the surface materials or having lower thermal efficiencies by limiting the heat transfer to the surface to prevent overheating.

1.8.2 TRANSPARENT MATERIALS

The primary example of this type of load is glass, which has selective radiant transmission properties. In glass melting processes, the primary mode of heat transfer is radiation. As shown in Chapter 6, flames have specific types of radiant outputs that vary as a function of wavelength. If the flame is nonluminous, it usually has higher radiant outputs in the preferred wavelengths for water and carbon dioxide bands. If the flame is luminous, it has a broader, more graybody-type spectral radiant profile. Chapter 6 shows that luminous flames are preferred in melting glass because of the selective transmission properties of molten glass. This allows a significant portion of the radiation received at the surface of the glass to penetrate into the glass, which enhances heat transfer rates and reduces the chances of overheating the surface that would reduce product quality.

1.9 HEAT RECOVERY DEVICES

Heat recovery devices are often used to improve the efficiency of combustion systems. Some of these devices are incorporated into the burners, but more commonly they are another component in the combustion system, separate from the burners. These heat recovery devices incorporate some type of heat exchanger, depending on the application. The two most common types include *recuperators* and *regenerators*, which are briefly discussed next. Reed (1987) predicts an increasing importance for heat recovery devices in industrial combustion systems for increasing heat transfer and thermal efficiencies.⁴⁰

1.9.1 RECUPERATORS

A recuperator is a low- to medium-temperature (up to about 1300°F or 700°C), continuous heat exchanger that uses the sensible energy from hot combustion products to preheat the incoming combustion air. These heat exchangers are commonly counterflow, where the highest temperatures for both the combustion products and the combustion air are at one end of the exchanger and the coldest temperatures are at the other end. Lower-temperature recuperators are normally made of metal, while higher-temperature recuperators can be made of ceramics. Recuperators are typically used in lower-temperature applications because of the limitations of the metals used to construct these heat exchangers.

1.9.2 REGENERATORS

A regenerator is a higher-temperature, transient heat exchanger used to improve the energy efficiency of high-temperature heating and melting processes, particularly in high-temperature processing industries such as glass production. In a regenerator, energy from the hot combustion

products is temporarily stored in a unit constructed of refractory firebricks. This energy is then used to heat the incoming combustion air during a given part of the firing cycle up to temperatures in excess of 2000°F (1000°C).

Regenerators are normally operated in pairs. During one part of the cycle, the hot combustion gases are flowing through one of the regenerators and heating the refractory bricks, while the combustion air is flowing through and cooling the refractory bricks in the second regenerator. Both the exhaust gases and the combustion air directly contact the bricks in the regenerators, although not both at the same time because each is in a different regenerator at any given time. After a sufficient amount of time (usually from 5 to 30 min.), the cycle is reversed so that the cooler bricks in the second regenerator are then reheated while the hotter bricks in the first regenerator exchange their heat with the incoming combustion air. A reversing valve is used to change the flow from one gas to another in each regenerator. The burners used in these systems must be capable of not only handling the high-temperature preheated air, but also the constant thermal cycling.

1.10 CONCLUSIONS

Burners can be thought of as the engine for the industrial combustion system. They are responsible for taking the incoming fuel and oxidizer, mixing them in proper proportions, shaping the resulting flame, and transferring heat from the flame to the load, while simultaneously minimizing pollutant emissions. There are numerous burner designs that are tailored to specific operating conditions and applications. Some of the more common designs are considered in this book. There are many factors that influence burner design, including the fuel, oxidizer, heat release rate, flame shape, primary mode of heat transfer, load type, emission requirements, draft type, and geometry of the combustor, to name a few. As relevant, these factors are considered in more detail in the chapters that follow.

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