
21 Oxy-Fuel Burners

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21.1 INTRODUCTION

Burners using industrial-purity oxygen (typically 90 to 99.9+% O₂) are conventionally called “oxy-fuel” burners. Because of the high cost of oxygen in the early days of air separation technologies, oxy-fuel burners were originally developed only for special high-flame-temperature applications that air burners could not perform. Welding with an oxy-acetylene flame, flame polishing of glass surfaces, and oxygen cutting of steel plates are some examples. The development of oxy-fuel burners has historically been driven by the oxygen manufacturers, as a special burner is needed for each new oxygen combustion application developed. As the oxygen manufacturers improved the air separation technologies and reduced the cost of oxygen, large-volume oxygen applications requiring on-site oxygen production plants were introduced for high-temperature industrial processes such as steel refining and copper smelting to improve the productivity and the product quality. Oxygen pipelines have been built in certain industrial areas to supply large amounts of oxygen to multiple users, and the resulting availability of low-cost oxygen further encouraged oxy-fuel burner applications. Today, oxy-fuel burners are used in a wide range of industrial furnaces to improve productivity and fuel efficiency and to reduce pollutant emissions.

As with air burners, there are many different oxy-fuel burner designs available to end users. Each different design was developed to overcome a problem or achieve a certain goal, depending on the application. These could include various flame shapes, low NO_x production, or dual fuel capability. Understanding the attributes of an oxy-fuel burner and overlaying them with the requirements of the process and the needs of the end user are key to selecting the proper burner for a particular application. In many situations, seeking advice from the burner manufacturers, who have significant design and hands-on experience with each burner type, is the best way to ensure that the selected burner will perform satisfactorily in the application.

21.2 MOTIVATIONS TO USE OXY-FUEL BURNERS AND APPLICATIONS

Oxy-fuel combustion creates an obvious increase in operating costs as the end user now must purchase the oxidant in addition to the fuel. The benefits achieved with oxy-fuel burners must be greater than the cost of oxygen. The following points briefly review some of the major motivators for using oxy-fuel burners in an industrial heating or melting process. Some of the benefits are applicable in all cases, while others may be application specific. Chapter 20 discusses changes in combustion conditions with oxygen enrichment and generic benefits. More detailed discussions on the applications and benefits of oxy-fuel combustion can be found in References 1 through 5.

21.2.1 POTENTIAL BENEFITS

21.2.1.1 High Flame Temperature and Heat Transfer

High adiabatic flame temperature and high heat release rate and transfer are the main benefits for which traditional applications of oxy-fuel burners were developed. Welding with an oxy-acetylene flame, flame polishing of glass surfaces, and oxygen cutting of steel plates are some of examples of applications that take advantage of these oxy-fuel flame characteristics.

21.2.1.2 Fuel Savings

The use of oxygen in a heating process eliminates the nitrogen introduced with combustion air from the process and hence eliminates the energy required to heat the nitrogen from inlet temperature to outlet temperature. For high-temperature processes (>2200°F or 1200°C) with no heat recovery, fuel savings when using oxygen can exceed 50%. As heat recovery is employed with the air combustion system, the savings achievable when switching to oxy-fuel combustion are reduced. A simple heat and mass balance on the furnace under each operating condition can provide accurate

information as to the fuel consumption using oxygen. The key parameters to consider are the flue gas temperatures and air preheat temperatures for the process.

21.2.1.3 Production Increase

Oxy-fuel flames are more compact than air flames and more energy can be released in a given furnace space, which often permits greater productivity from an existing furnace. The value of production increase would normally justify the additional cost associated with the oxygen. The amounts of additional fuel and oxygen required and the increase in production achievable are the key parameters for evaluating this benefit of oxy-fuel burners. The fuel and oxygen requirement can be determined via furnace energy balance calculations. However, the amount of production increase achievable requires a much more detailed study of the furnace conditions and its current limitations. Fan capacity or flue gas handling limitations can easily be overcome using oxygen, but maximum furnace temperature or heat flux limits require careful selection and placement of oxy-fuel burners to yield productivity improvements.

21.2.1.4 Reduction of Pollutants

Reduction of pollutants such as particulates and NO_x has become an increasingly important objective for using oxy-fuel combustion in recent years. When applied properly, and with proper control of flame temperature and localized stoichiometric conditions through burner design, oxy-fuel burners can reduce NO_x emissions by 80 to 95% due to the elimination of nitrogen from the furnace atmosphere. Particulate emissions are often reduced due to reduced carryover or volatilization caused by the reduction in flue gas volume. With reduced flue gas volumes, existing flue gas cleanup equipment such as electrostatic precipitators and scrubbers can run more efficiently and the size of new equipment can be reduced.

21.2.1.5 Capital Reduction

When a furnace is converted to oxy-fuel combustion, many of the auxiliary systems for preheating or delivering air to the furnace are eliminated. The size of the flue gas handling system is reduced substantially. The capital costs of installing, replacing, and disposing of large gas handling systems is no longer required; this can favorably influence the economics, especially if these systems require replacement periodically. An example is the elimination of regenerators used for glass-melting furnaces.

21.2.1.6 Yield and Quality Improvements

The yield and quality of products may change in some heating or melting processes as a result of higher furnace temperatures and higher concentrations of combustion products such as H₂O and CO₂. For example, oxy-fuel fired glass-melting furnaces often result in a reduced number of gas bubbles (seeds) in the product. On the other hand, a higher concentration of H₂O and CO₂ in the furnace gas increases the oxidation potential and could potentially increase metal oxidation loss. The impacts of oxy-fuel burners on product yields and quality are very process specific and must be evaluated for each application.

21.2.1.7 Other Considerations

Other factors that need to be considered for oxy-fuel combustion include:

1. Reduced flue gas volume often results in reduced maintenance for oxy-fuel fired furnaces as it relates to furnace doors and dampers.
2. Higher productivity typically results in higher furnace wall temperature. The life of refractory wall may diminish as a result.

3. Air blower and burner noise is reduced significantly with oxy-fuel burners.
4. Elimination of air preheating systems results in more space around the furnace, which could be utilized to increase the size and capacity of the furnace without expanding the rest of the plant.
5. Better flame stability is achieved with oxy-fuel combustion, which provides wider operating ranges and faster response to load changes.
6. Degradation of furnace efficiency of an air-fired system caused by the deterioration of recuperators and regenerators is avoided.

21.2.2 APPLICATIONS OF OXY-FUEL BURNERS

Oxy-fuel burners are widely used in high-temperature industrial furnaces to improve productivity and fuel efficiency, to reduce emissions of pollutants, and to eliminate the capital and maintenance costs of an air preheater. Significant fractions of glass melting furnaces, steel scrap melting furnaces (electric arc furnaces), steel reheat furnaces, soaking pits, forging furnaces, ladles, aluminum melting furnaces, copper smelting and anode furnaces, hazardous waste incinerators, rotary enamel frit furnaces, and rotary lead melting furnaces are fired with oxy-fuel burners (see [Figure 21.1](#)).

Glass melting furnaces require a well-controlled temperature profile to produce a proper molten glass flow pattern for melting batch materials and fining gas bubbles. Wall and roof temperatures approach the upper limit of allowable refractory material temperatures, so a nearly uniform refractory temperature is critical to avoid refractory damage. Water-cooled burners often experience corrosion and fouling problems due to condensation of alkali vapors present in the furnace. Non-water-cooled oxy-fuel burners producing a long and wide flame are generally preferred. Relatively low momentum burners are used as high flame velocities tend to accelerate volatilization of alkali compounds. Multiple burners are placed in the side walls to provide good flame coverage over the molten glass surface and to avoid flame impingement and hot spots on refractory walls and crown. Both cylindrical and flat-flame burners are used.^{6,7}

Electric arc steel scrap melting furnaces require high intensity and high flame temperature burners to accelerate the melting of scrap steel by high-momentum impinging flames. Typically, three burners are mounted on the cylindrical side wall to fire between the three electrodes. These burners are used to supplement the main source of energy provided by electric arc and also provide extra oxygen with carbon injection for foamy slag operation and for post-combustion of CO. Because of extreme temperature conditions in these furnaces, the burners are usually water cooled and of rugged design. The burners are typically designed to provide an oxygen lancing mode of operation to reduce the carbon content of molten steel.^{8,9}

Steel reheating furnaces, soaking pits, and forging furnaces require uniform heating of steel ingots, slabs, blooms, or billets to the rolling temperature. Burners for this application need to be able to produce uniform furnace temperatures and adapt to the various geometry changes associated with differently shaped steel pieces. High-momentum, low flame temperature oxy-fuel burners are often used to provide uniform heating and low NO_x emissions.¹⁰

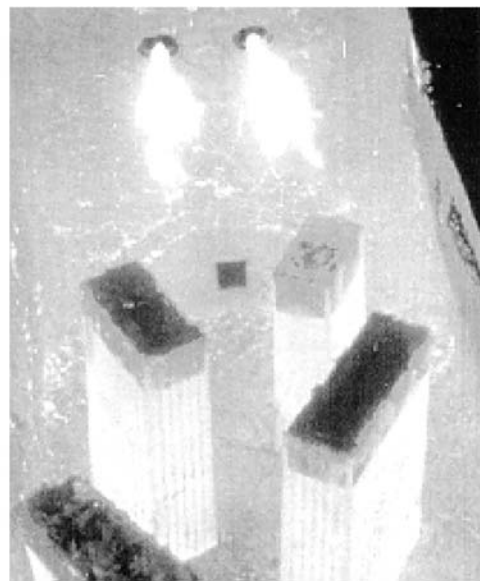
Aluminum melting furnaces require rapid melting of scrap with minimal formation of dross (mixture of metal and metal oxides). Oxy-fuel burners are used in reverberatory furnaces and rotary melters to improve productivity and to reduce fuel consumption.¹¹

High-intensity oxy-fuel burners are used in copper reverberatory furnaces for smelting operations. Most copper smelting, however, is done by flash smelting processes using specially designed oxy-fuel burners. Oxy-fuel burners are also used in copper converters and anode furnaces.

In hazardous waste incinerators, organic waste materials are oxidized to carbon dioxide and water vapor, and halogens, metallic, and other impurities are either scrubbed out or transformed into nonhazardous solids. The small flue gas volume of oxy-fuel combustion provides a longer residence time and substantially reduces the size of the flue gas cleaning system. High-momentum oxy-fuel burners are used to provide good mixing and rapid combustion in rotary kiln incinerators.



(a)



(b)

FIGURE 21.1 Examples of furnaces fired with Praxair oxy-fuel burners: (a) aluminum melting furnace and (b) steel soaking pit.

Specially designed oxygen waste burners are used for special incinerators for chemical waste streams.^{12,13}

Rotary enamel frit melting furnaces and rotary lead melting furnaces are small batch furnaces typically fired with a single oxy-fuel burner. The small furnace size and high productivity requirement are met by applying a burner designed to provide a compact flame of the length needed to impinge on the surface of the batch materials.

Some furnaces in the steel, glass, aluminum, copper, and cement industries are heated primarily with conventional air-fuel combustion systems and also equipped with supplementary oxy-fuel burners. Production rate increase is the most common objective and the improvement of product quality is also important. Reduction of pollutants such as particulates and NO_x has also become an important objective in recent years. Supplemental oxygen combustion has also been successfully applied to waste incinerators and chemical process furnaces such as the Claus sulfur reactor, sulfuric acid recovery furnaces, and the fluidized bed catalyst regenerator for the fluid catalytic cracking process of petroleum. The economics of these applications are dominated by the value of the increased production and generally can support the high cost of oxygen delivered as bulk liquid.

There are many small oxy-fuel burners used in welding metals and fire-polishing glass surfaces. These special burners are unique in design and described in Chapter 21.6.

21.3 GENERAL DESIGN CONSIDERATIONS FOR OXY-FUEL BURNERS

Combustion with oxygen is characterized by a higher adiabatic flame temperature, a higher flame speed, a lower ignition temperature, and a wider flammability range than is the case in combustion with air. Traditional rapid nozzle-mix oxy-fuel burners produce stable, short, very intense, high-temperature flames. Many of the original oxy-fuel burner applications, such as welding and melting of steel scrap, were designed specifically to take advantage of the high temperature and high heat transfer properties of oxy-fuel flames. For burners of this type, water cooling of burner components is often required to protect the burner face from intense radiation from the flame and furnace walls. In the applications of oxy-fuel burners for common industrial furnaces such as glass melting and steel reheating furnaces, the high intensity of the traditional oxy-fuel flame is considered undesirable to the process and to the furnace refractory, and also raises concerns related to high thermal NO_x formation. New types of oxy-fuel burner have been developed to provide more uniform heating of the entire furnace while retaining the main benefits of oxy-fuel combustion: high heat transfer, fuel savings, and reduced emissions. In this section, general combustion characteristics of air and oxygen combustion and general design considerations for oxy-fuel burners are discussed.

21.3.1 OXYGEN SAFETY

Many materials used for air burners are not compatible for oxygen service. Special safety considerations are required in selecting materials, designing, fabricating, and operating oxy-fuel burners. These considerations are discussed in Chapter 21.7.

21.3.2 FUEL INPUT

In combustion with air, about 70% of the volume of the flue gas is nitrogen. Thus, most of the sensible heat loss in the flue gas is due to heating the nitrogen contained in air. When oxygen is used in place of air for combustion, most nitrogen in the flue gas is eliminated and the flue gas heat loss is reduced substantially. As a result, the useful heat to the furnace or the available heat of combustion is increased substantially with oxy-fuel combustion and the required fuel input is reduced. To size oxy-fuel burners properly for a process, it is important to be able to predict the fuel savings that will be achieved with oxy-fuel combustion. The higher the flue gas temperature, the greater the

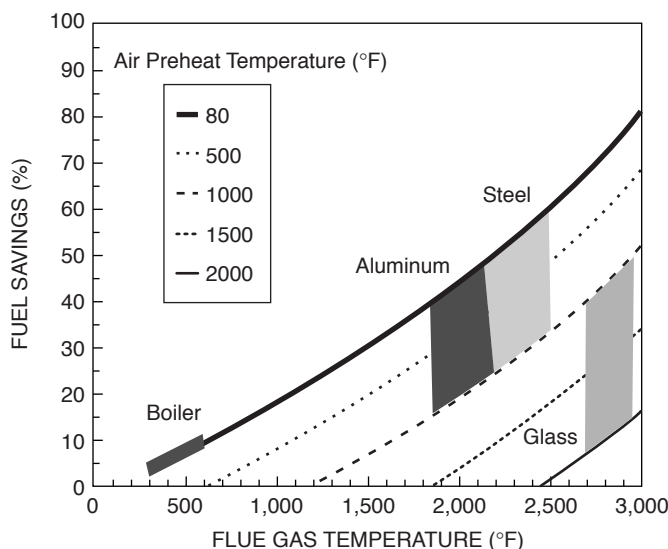


FIGURE 21.2 Fuel savings with oxy-fuel combustion (fuel = methane, 2% O_2 in flue gas).

fuel savings that will result from converting from air to oxygen combustion. As compared with the flue gas temperature, the type of fuel and the excess air level have a relatively small influence on fuel savings. Because most air combustion systems for high-temperature furnaces are equipped with heat recovery systems to preheat combustion air, the temperature of combustion air also has a large influence on fuel savings. Figure 21.2 shows percent fuel savings as a function of flue gas temperature in a natural gas-fired furnace when preheated combustion air is replaced by pure oxygen. Each curve represents a different air preheat temperature. The uppermost curve shows the case of replacing combustion air at ambient air temperature, that is, when no air preheating is employed.

Typical fuel savings achieved for glass melting furnaces, steel heating furnaces, aluminum melting furnaces, and boilers are indicated by the shaded areas. The glass melting furnaces operate at about 2700 to 3000°F and inherently represent high potential for fuel savings. However, most large glass melting furnaces for manufacture of containers and flat glass are equipped with efficient regenerators to preheat combustion air to 2000 to 2400°F. As a result, predicted fuel savings with oxygen combustion for these glass furnaces based only on exhaust sensible heat loss are typically 10 to 20%. (Actual fuel savings are significantly greater than indicated in this graph due to the reduction of radiative heat loss through regenerator ports.) Fiberglass furnaces equipped with recuperators and other smaller glass furnaces are less efficient and fuel savings of 30 to 50% are typically achieved with oxygen combustion. Steel reheat furnaces and soaking pits operate at flue gas temperatures of about 2100 to 2400°F. The air preheat temperature is typically less than 1000°F and fuel savings of 30 to 60% are achieved with oxygen combustion. Aluminum melting furnaces operate at lower flue gas temperatures of about 1800 to 2100°F, but often no heat recovery is used. Consequently, fuel savings of 30 to 50% are typically achieved. By comparison, boiler furnaces are very efficient with extensive convective heat transfer surfaces to heat feedwater and to raise steam temperature. Flue gas temperatures of 300 to 600°F are typical. As a result, fuel savings of only about 5 to 10% are achievable by reducing sensible heat with oxygen combustion.

21.3.3 FLAME TEMPERATURE

High flame temperature is one of the most prominent features of traditional oxy-fuel combustion. Oxy-combustion is significantly different from air combustion in dissociation phenomena, radiant heat transfer, and formation of NO_x in the flame. The extremely high temperatures of oxy-fuel

flames cause dissociation of part of the combustion products into CO, H₂, OH, and other radicals. These chemical species can be measured in large amounts in oxy-flames even if the burner operates at fuel-lean conditions. Table 21.1 provides the molar fraction of dissociated species in the combustion products of a stoichiometric methane/oxygen flame at different temperatures.

With methane and pure oxygen at ambient temperature, the adiabatic flame temperature is about 5000°F (2760°C), as compared about 3520°F (1940°C) for methane-air combustion. The theoretical flame temperature simply represents the practical upper limit of flame temperature when the fuel and oxidant are mixed rapidly and ignited. The actual flame temperature of oxy-fuel burners can be controlled to a desired level by burner design. As discussed further in Chapter 21.4.4, internal or external flue gas recirculation (FGR) is one of the most effective ways of reducing the flame temperature for reduction of thermal NO_x emissions.

Figure 21.3 shows the adiabatic flame temperature of methane burned with a mixture of pure oxygen and flue gas containing 2% oxygen concentration as a function of the oxygen concentration in the oxygen-flue gas mixture at different oxidant preheat temperatures. The bottom curve represents the case of oxygen mixed with flue gas cooled to ambient temperature. The other curves represent various degrees of mixing of hot flue gas with oxygen, especially by in-furnace FGR.

TABLE 21.1
Molar Fractions of Dissociated Species from Adiabatic Equilibrium
Stoichiometric Combustion of Methane with Oxygen

Temp. (°C)	1600	1800	2000	2200	2500	2780
CO ₂	0.328	0.322	0.304	0.271	0.194	0.114
H ₂ O	0.658	0.651	0.636	0.605	0.518	0.390
CO	0.001	0.006	0.020	0.046	0.102	0.152
H ₂	0.0	0.003	0.008	0.017	0.040	0.071
OH	0.001	0.004	0.01	0.021	0.054	0.096
O	0.0	0.0	0.0	0.002	0.012	0.040
H	0.0	0.0	0.0	0.003	0.015	0.049
O ₂	0.010	0.014	0.021	0.035	0.064	0.088

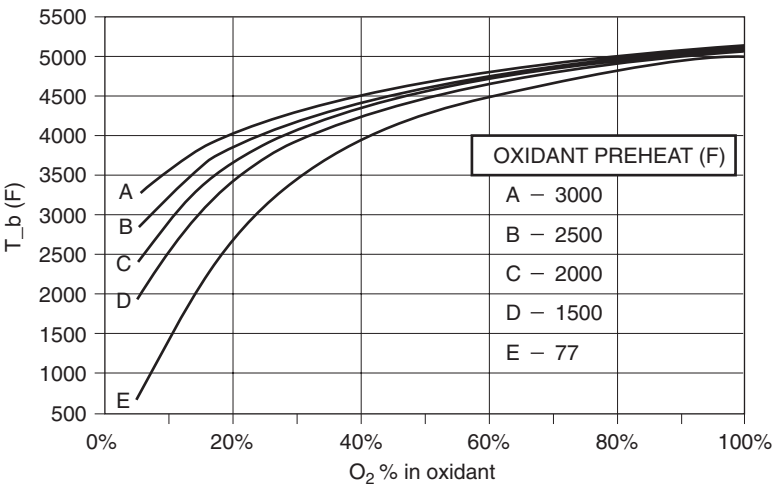


FIGURE 21.3 Adiabatic flame temperature vs. %O₂.

Separated high-velocity oxygen jets are often used to aerodynamically mix hot flue gas into the oxygen jets in a furnace. As more flue gas is mixed into the oxygen jets, the concentration of oxygen in the mixture decreases and the temperature increases. As seen from [Figure 21.3](#), the flame temperature is reduced substantially as the concentration of oxygen is reduced and can be controlled to a temperature even lower than that of a typical air flame. It is interesting to note that at about 25 to 30% O_2 in the oxygen-hot flue gas mixture, or by mixing about 4 volumes of hot flue gas with oxygen, the flame temperature about equals that of a methane-ambient air flame. The reason this occurs at a higher oxygen concentration than the oxygen concentration of air (20.9% O_2) is the higher specific heat of carbon dioxide and water vapor in flue gas compared with that of nitrogen.

21.3.4 HEAT TRANSFER

Heat transfer efficiency is an important consideration for burner and furnace designs. High flame temperature and high luminosity generally improve the heat transfer rate through higher flame radiation. Because of this, a common misunderstanding is that the higher efficiency achieved by oxy-fuel combustion is caused by high oxy-fuel flame temperatures and that reducing the flame temperature would result in lower furnace efficiency. In fact, studies and actual experience show that the overall thermal efficiency of an oxy-fuel fired furnace is very insensitive to the type and temperature of the oxy-fuel flames. The reason for this can be understood by considering the effects of heat transfer on the sensible heat loss to flue gas. A reduction in heat transfer to a furnace load results in an increase in flue gas temperature and increases the amount of sensible heat contained in the flue gas. Because the volume of the flue gas in an oxy-fuel fired furnace is reduced dramatically to 15 to 25% of that of an equivalent air fired furnace, an increase in flue gas temperature causes only a minor increase in the flue gas sensible heat loss under oxygen combustion. On the other hand, a relatively small increase in the bulk furnace gas temperature causes a sharp increase in the gas-to-load radiative heat transfer rate due to the strong temperature dependence of radiative heat transfer. Thus, any loss in heat transfer attributable to a reduction in oxy-fuel flame temperature is naturally compensated by an increase in gas-to-load radiative heat transfer caused by a small increase in the bulk furnace gas temperature. In fact, oxygen combustion is inherently efficient in heat transfer because higher concentrations of CO_2 and H_2O in the furnace atmosphere and the much longer gas residence time enhance radiative heat transfer.

In most industrial furnaces, uniform temperature and heat flux distributions over the furnace heat load are critical requirements. Flame temperature, shape, luminosity, momentum, and burner placement are all important parameters influencing the temperature and heat flux distributions. In converting a furnace fired with air burners to oxy-fuel firing, the number of burners required and their placement on furnace walls may be significantly different from those of the original air-fired configuration. Because the flame characteristics of oxy-fuel burners can vary widely, depending on burner design, detailed heat transfer analysis of the furnace using a CFD model is often performed to determine the optimum burner configuration.

21.3.5 FLAME STABILITY

Oxy-fuel flames are generally very stable due to the high flame velocity and wide flammability range of different fuels in oxygen. For example, the blow-off fuel velocity of a turbulent natural gas free jet in an oxygen atmosphere may exceed 1000 ft/s as compared with that in ambient air, which is in a range of 50 to 200 ft/s, depending on the nozzle configurations. Because of this stability, great flexibility is afforded in oxy-fuel burner design. Very high fuel and oxygen velocities, sometimes exceeding sonic velocities, are used in high momentum oxy-fuel burners. Unlike air burners, the refractory burner port is not required to provide flame stability, and water-cooled burners are often used without a burner port. With nonwater-cooled oxy-fuel burners, however, refractory burner ports are generally required to protect the metallic part of the oxy-fuel burner from furnace heat.

21.3.6 BURNER MATERIALS AND SIZE

The selection of materials for oxy-fuel burners and piping skids requires special safety considerations for oxygen service, as further discussed in Chapter 21.7. High-temperature alloys are typically used for fuel and oxygen nozzles on the burner face, which is exposed to intense radiation from the oxy-fuel flame and hot furnace walls. In air burner design, combustion air provides sufficient cooling of burner components. By comparison, the volume flow rate of oxygen is small and may not provide proper cooling. To prevent burner overheating in some oxy-fuel burner designs, controlled mixing of fuel and oxygen near the burner face to prevent high heat release is combined with a narrow burner port to reduce the radiation heat flux from the flame and the hot furnace walls. Refractory burner materials are used in other burner designs for high-temperature furnace applications. Water-cooled copper and stainless steel are also used in some oxy-fuel burners to provide greater nozzle design flexibility.

The size of an oxy-fuel burner is typically very small compared to the equivalent air burner, due not only to the reduced volume flow rate of the oxidant, but also to the reduced fuel input and the high fuel and oxygen velocities. For example, a typical 10 MMBtu/hr (3 MW) cold air burner may have a diameter of about 15 in. and an equivalent oxy-fuel burner with 6 MMBtu/hr (2 MW) may have a diameter of only 4 in.

21.3.7 BURNER DESIGN TOOLS AND METHOD

Numerical simulation has become an essential tool for the development of new generations of industrial burners. To meet the continuous needs of increasing the energy efficiency and the flexibility of the new combustion systems while reducing their pollutant emissions, better control of the physical phenomena is required. The numerical simulation is not only a major asset to reduce development times and costs, but also to reduce the risks when the experimental developments using pilot-scale facilities are limited. Today, numerical simulation tools are widely used to estimate the flame heat release and the heat transfers to the walls or to the load in various industrial processes and furnaces. They are also used to estimate pollutant emissions such as NO_x emissions. Radiation represents the predominant mode of heat transfer in oxy-fuel combustion systems where the maximum temperature reaches more than 2000K (3140°F). Therefore, in combustion with oxygen, it is essential to use an accurate model to calculate radiative heat transfer in gases. For example, the weighted sum of gray gas (WSGG) model, generally used in industrial configurations (less time consuming than the CK model) could overpredict radiative fluxes in industrial glass melting furnace by more than 10%.¹⁴ In the same way, special models must be used to calculate the formation of NO in high-temperature flames. The classical models available in the commercial codes generally significantly overestimate nitrogen oxides formed in oxygen flames.^{15–16} In the future, numerical simulation tools will be used to predict the flame stability, and to develop the burner closed-loop control systems that will be driven by process information.

21.4 OXY-FUEL BURNERS FOR HIGH-TEMPERATURE INDUSTRIAL FURNACES

There are two types of burners, according to whether the reactants are mixed before (i.e., premixed combustion) or after (i.e., postmixed combustion) injection into the combustion chamber. Premixed combustion is seldom used for high firing rate burners for safety reasons, especially for oxy-fuel combustion. Only postmixed flame burners are described in this section.

The design of oxy-fuel burners depends on the nature of the fuel (gas, liquid, or solid) and the expected shape or characteristics of the flame. In the following sub-sections, the basic technologies

of oxy-gas burners are discussed first, followed by unique design considerations for liquid fuel burners. The two final sub-sections focus on flat-flame and low-NO_x oxy-fuel burners.

21.4.1 CONCENTRIC PIPE OXY-FUEL BURNER

Before providing a detailed description of industrial burners, it is useful to recall the main characteristics of oxy-fuel flames, which differ significantly from the traditional air flames. In addition to the increased flame temperature, the use of oxygen, by removing the ballast of nitrogen, allows a significant increase in the fluid injection velocities in the combustion chamber or in the furnace. Thus, a drastic increase of the mass flow rates of the reactants enables extremely high volumetric heat release rates (Btu/ft³ or W/m³) while keeping a good flame stability. With oxy-fuel combustion, flame stability problems arise in a quite different way from air combustion. Unlike air burners, it is not necessary for industrial oxygen burners to use stabilization devices (flame holders, swirling flows, etc.). Therefore, the first designs of oxygen burners simply consisted of concentric tubes inserted in a protective water-cooled sheath. A practical design is to use two concentric tubes to inject the reactants as two parallel concentric jets. The mixing of fuel and oxygen is carried out close to the burner tip by turbulent shear and diffusion of the two jets. [Figure 21.4](#) illustrates this burner concept.

The expected shapes and dimensions of the flame for a specific process can be obtained by some modifications to the burner tip geometry, such as the relative position of the fluid exits and the direction of the flows. For example, to ensure faster mixing, one of the two gases (oxygen, in general) can be injected at the burner tip from two different sections, as illustrated on [Figure 21.5](#). With this design of burner, a fast mixing leads to a transparent, long, and narrow flame.

A burner dedicated to the combustion of hydrocarbon gases and more specifically to the production of H₂/CO mixtures consists of a jet of oxygen in the center surrounded by an annular converging jet of natural gas (see [Figure 21.6](#)). This ensures a fast and more effective mixing and leads to short flames. The injection velocities of each fluid stand between 20 and 50 m/s and the exit velocity of the mixture in combustion between 60 and 100 m/s.

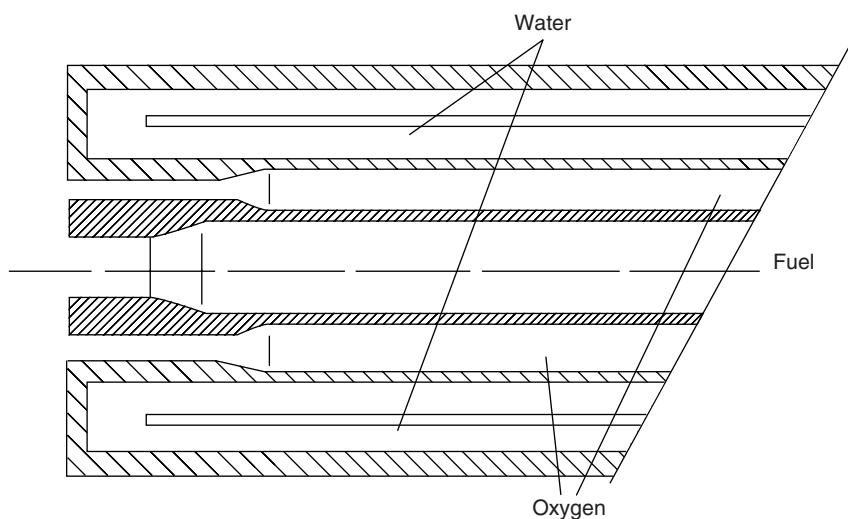


FIGURE 21.4 Oxygen pipe-in-pipe burner.

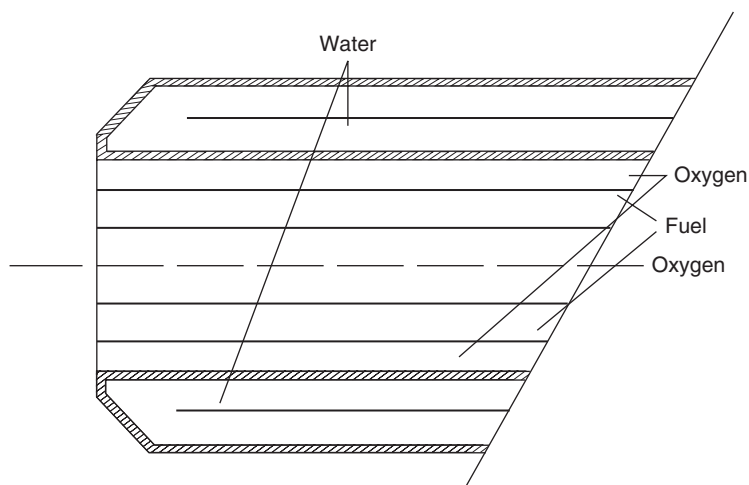


FIGURE 21.5 Oxygen twin impulsion pipe-in-pipe burner.

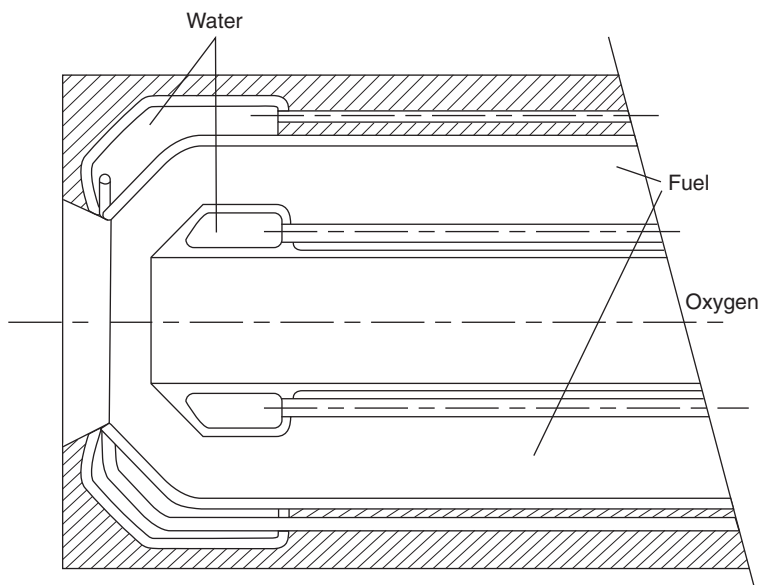


FIGURE 21.6 Texaco oxygen burner.

There is another category of burner design — multiple nozzle burners — in which at least one fluid injection line ends in a series of nozzles of varied forms and sizes. An example of this design of burner is shown in [Figure 21.7](#).

Improvements have been made to these first-generation burners, and the burner water cooling system has been eliminated. Similar to air burners, a ceramic part (burner block) isolates the metallic burner tip from the radiation of the flame and of the furnace walls. The metallic parts are cooled by convection of the fuel and oxygen flows. Examples of this generic burner design include the Praxair J Burner¹⁷ and the Air Liquid's ALGLASS burner,¹⁸ which is shown in [Figure 21.8](#). The ALGLASS concept is shown in [Figure 21.9](#).

Although industrial burners — and particularly oxy-fuel burners — are often based on generic concepts, it is not uncommon to adapt and tune a combustion design to a specific process

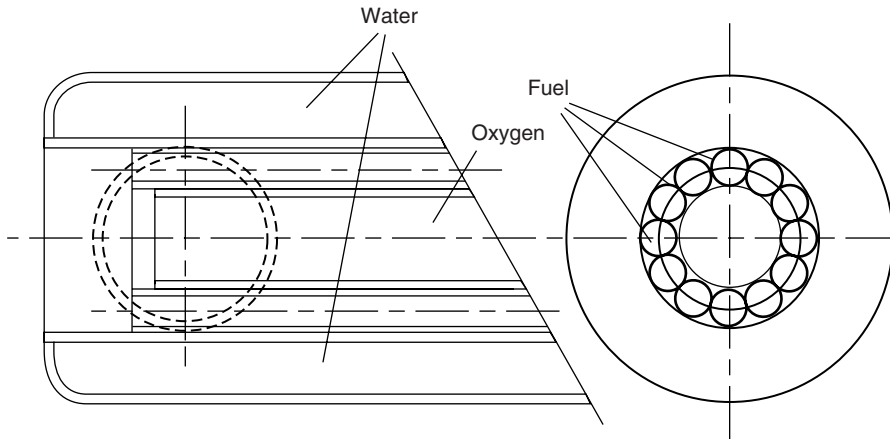


FIGURE 21.7 Chemetron oxygen burner.

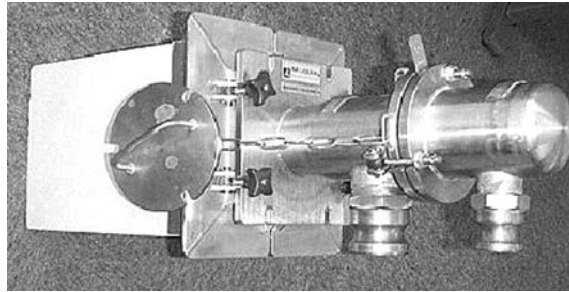


FIGURE 21.8 ALGLASS™ oxygen burner.

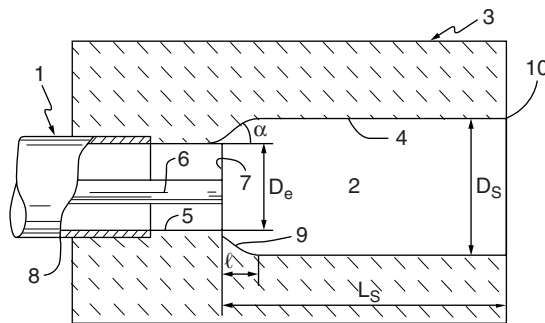


FIGURE 21.9 ALGLASS concept.

in order to optimize heating quality, combustion performances, and flame/process interaction. Such developments have been carried out for the purpose of implementing oxy-fuel combustion technologies within the steel reheating process, particularly in continuous billet or slab reheat furnaces, and also preheat zones of annealing/galvanizing lines or stainless pickling/annealing lines. The benefits of oxy-burners for these types of applications are various, but can be directly linked to the improvement of furnace efficiency, energy optimization, and, above all, capacity increase. In many cases, oxy-burners are used to boost furnace production and are

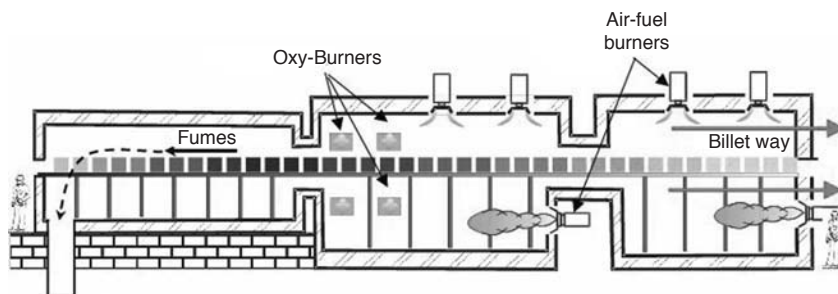


FIGURE 21.10 Walking-beam billet furnace with oxy-fuel burners.

added to complement existing air-fuel burners. New oxy-flame burners are usually installed near the charge end of a furnace (Figure 21.10) and allow the addition of very efficient heating power for furnace de-bottlenecking.

Because side-wall burner positioning is encouraged, oxy-fuel burner design must ensure sufficient development of the flame inside the furnace. Indeed, in such configurations, oxy-flames are influenced by the crosswind of the furnace flue gas, the velocity of which ranges from 2 to 5 m/s in reheat furnaces and 9 to 10 m/s in annealing lines. To avoid flame deflection, a high-momentum jet is recommended, which generates a stable flame, well stabilized at the burner tip. Finally, the oxy-fuel burner specifications for such an application must include the following characteristics:

- High-momentum jet to avoid flame deflection toward the wall
- High flexibility to allow fast ignition and shutdown (i.e., oxy-burners are only used when a production rate increase is needed)
- Large power turndown ratio to follow the setpoint prescribed by the furnace control system
- Compactness and high maintainability without water cooling
- Tunable flame length to adapt radiant heat transfer to the product and optimize temperature homogeneity

The pipe-in-pipe concept can be easily modified to fulfill these requirements and, consequently, is often used for steel reheating applications. Figure 21.11 provides an example of ALROLL™ burners installed in a billet reheat furnace.¹⁹

21.4.2 OXY-OIL BURNERS

Liquid fuel or oil burner development has acquired renewed interest due to the worldwide availability of fuel oil and to the high thermal efficiency and low NO_x emissions of oxygen fuel-oil combustion systems. For oxy-oil burners, scaling rules are based on the characteristic time scales of the physicochemical phenomena that control two-phase combustion;²⁰ that is:

- Droplet vaporization, function of droplets size, and atomization quality
- Reactant mixing, which depends on flow structure (i.e., on burner geometry and injection velocities)
- Chemical reaction time, which depends on the mass diffusivity of reactants and flame velocity

The evaluation of these characteristic time scales shows that for air combustion, the vaporization and chemical time scales are of the same order; and that for oxy-oil combustion, the vaporization time scale is two orders of magnitude larger than the chemical time scale.²¹

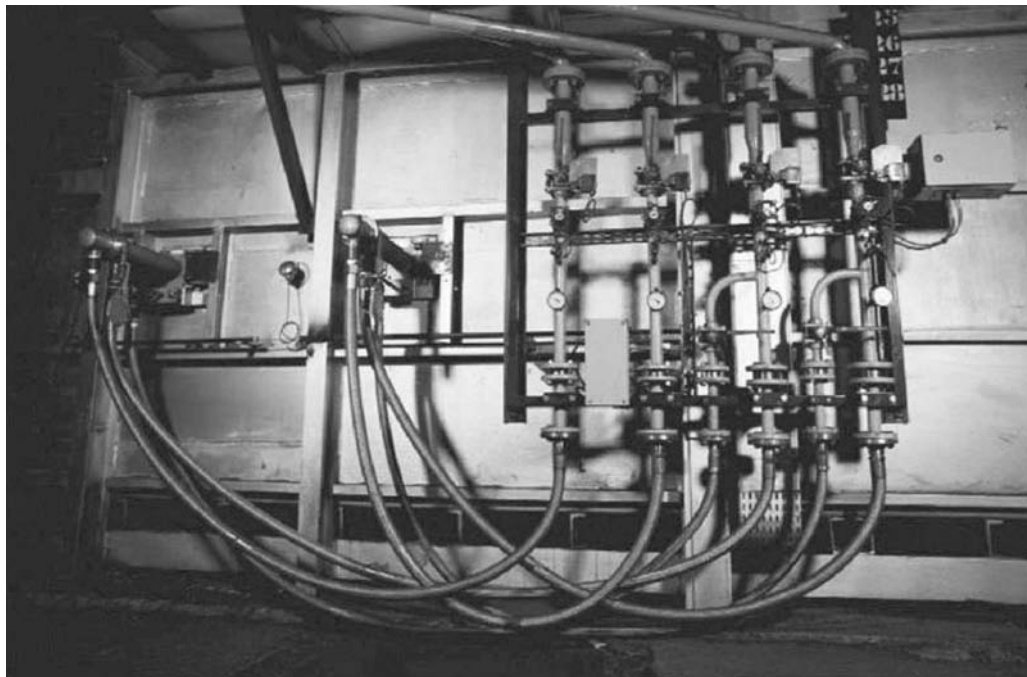


FIGURE 21.11 ALROLL™ oxygen burners installed on the side wall of a billet reheat furnace.

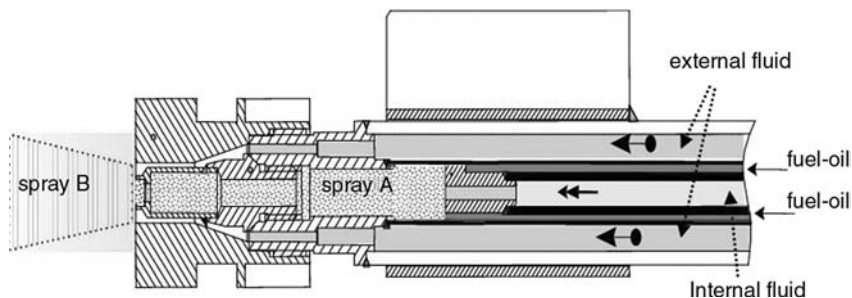


FIGURE 21.12 Air Liquide DUAL™ injector.

Therefore, the atomization technology will have a strong impact on flame structure, flame length or width, or flame stability in the case of oxy-oil combustion.

Two physical phenomena are used to atomize liquid fuels. The first is based on the impact between an atomizing fluid and the liquid flow (and/or liquid against the atomizer wall); the second one is based on the instability developing at the interface between the liquid and the gas when the two flows are parallel. There are two ways to practically make use of the above phenomena: internal and external atomization, whether the atomization takes place inside or outside the nozzle body prior to the injection plane.

In internally mixing twin-fluid atomizers, the atomization stage is achieved in a closed environment. For such configurations, the liquid is often spread on an adapted surface before coming in contact with the gaseous flow, often known as an "pre-filming atomizer." An internal atomizer is very efficient and flexible enough to handle high-viscosity oils, but the main drawback is the risk of flashback, especially when using oxygen as the atomizing fluid. The Air Liquide Dual²² atomizer uses this atomization principle (see Figure 21.12).

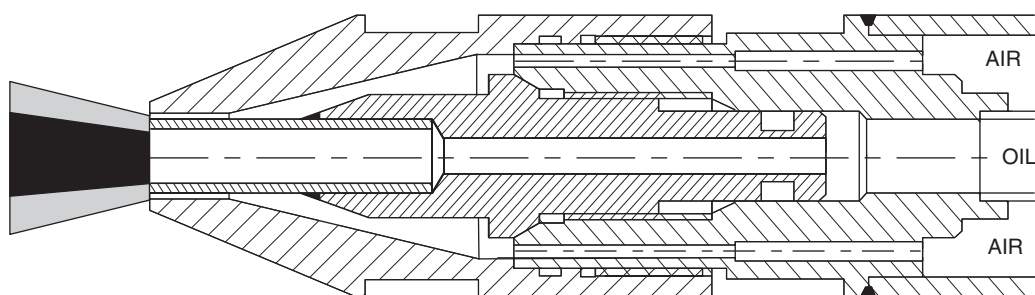


FIGURE 21.13 Air Liquide Robust™ injector.

In this design, the oil circular film is first broken up by the internal atomization gas flow. Then this first mixture is atomized externally by the second, high-velocity gas flow. This two-step atomization process allows a larger flame length range as a function of atomization pressure and to stabilize the flame.

In externally mixing twin-fluid atomizers, a low-velocity (3 ft./s or 1 m/s) liquid jet is broken up by a high-velocity (164 ft./s or 50 m/s) gas flow outside the atomization system. An example is the Air Liquide Robust atomizer shown in [Figure 21.13](#).

The external fluid is also useful for cooling the lance and the injector. This kind of atomizer is recommended to be used flush with the wall or with a small offset with various atomization gas types: air, natural gas, steam, or oxygen. External atomization is less efficient. However, because mixing occurs outside the nozzle, these devices are considered to offer lower risk from a safety perspective.

In mechanical atomization systems (pressure nozzles), a liquid jet submitted to a high pressure flows with high velocity toward a small-diameter nozzle. Mechanical atomization is widely used in fuel-oil burners. It is attractive due to the single fluid requirement for atomization, simplified piping, and simple atomizer construction. Its disadvantages include the low turndown ratio of that atomizer technology, a relatively short life span (due to tip erosion), and more frequent cleaning requirements (due to the small orifice).

Oxy-oil burners are primarily used in continuous melting furnaces (e.g., for glass-type applications). The main motivations of the oil burner users are often the following: reduced maintenance time of the burners, higher energy efficiency, and low pollutant emissions levels. To meet these requirements, oxy-fuel oil burners tend to adopt configurations in which the reactants are brought by separate injections and mixed outside the burner block. This is the case in the ALGLASS FC burner, which is particularly appropriate for most glass-type applications. In this geometry, the oil atomizer is installed at the bottom of refractory burner block, while oxygen is injected at a lower velocity from two injectors located at the top of the block. The oxygen flow is directed toward the fuel oil spray. A wide horizontal spray is achieved using the Trident²³ injector, as illustrated in [Figure 21.14](#), which shows three oil injection orifices with diverging horizontal directions.

21.4.3 FLAT-FLAME BURNERS

Industrial processes often use large-size furnaces and require a long and homogeneous energy transfer to the load. To fulfil this requirement, flat-flame burners have been developed by several manufacturers. The principal idea that guides the design of these burners is to maximize the flame coverage over the furnace heat load, by developing a long and wide flame close to the load. A design option to achieve this goal consists of distributing the fuel injections in a plane parallel to the load and also injecting oxygen in a separate parallel plane. The number of injections, the relative position, or the distance between the planes of injection of fuel and oxidant are the main parameters that control the shape of the flame and the heat release. [Figure 21.15](#) provides an example of this

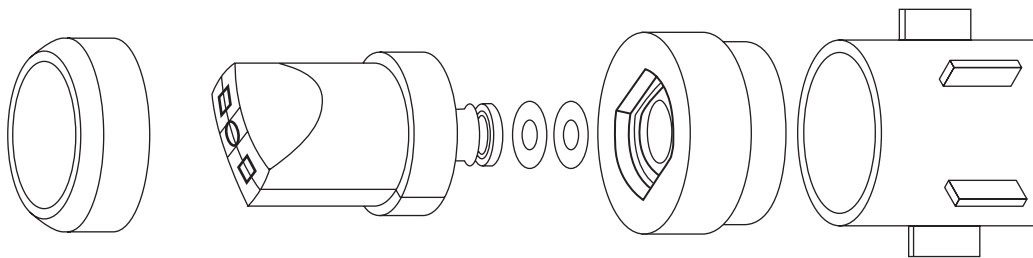


FIGURE 21.14 Trident injector for ALGLASS FC™ burner.

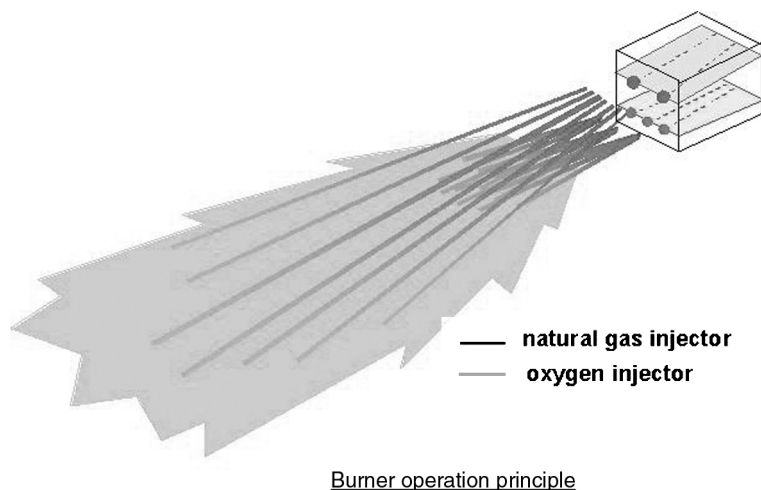


FIGURE 21.15 Schematic of ALGLASS FC™ oxygen burner.²⁴

concept of burner. The oxygen flow is placed above the fuel flow and slopes toward the load so as to bring the flame closer to the load.

The concepts of a flat-flame burner can be classified in two main categories according to whether the root of flame is confined in a pre-combustion chamber or established directly in the furnace. The principal reasons to confine the root of flame is to make the flame less sensitive to the aerodynamic conditions inside the furnace and to provide better control of flame characteristics and stability. A potential concern with this design concept is thermal stress and potential damage to the refractory material due to the heat release in the confined space of the pre-combustion chamber.

Flat-flame burners were originally developed several years ago for wide glass melting furnaces and then applied to many other industrial fields, such as melting of enamel frits and ferrous or nonferrous metals. Experience from these applications showed better transfer to the load and lower fuel consumption. Moreover, by maximizing the volume of flame and by increasing the transfer of energy to the load, the flat-flame burners showed low NO_x emissions.

21.4.4 LOW-NO_x OXY-FUEL BURNERS

The reduction of NO_x emissions has become an important requirement in many burner applications. Due to the high flame temperature of oxy-fuel combustion, it is often viewed as producing high NO_x emissions. Contrary to conventional wisdom, oxy-fuel combustion actually provides an inherent advantage in NO_x reduction, because nitrogen contained in combustion air is largely eliminated. In key NO-forming reactions, both the rate of formation of NO from nitrogen molecules (thermal

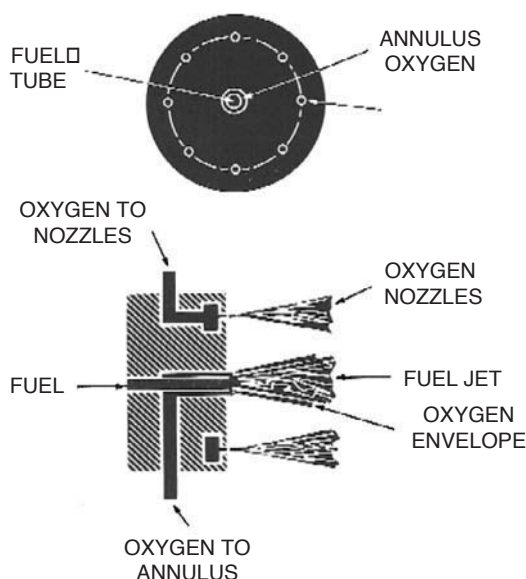


FIGURE 21.16 Praxair “A” Burner using in-furnace FGR.

NO_x) and that from fuel radicals (prompt NO_x) are proportional to the concentration of N₂. Advanced oxy-fuel burners described in this section are designed to control flame temperature and stoichiometric conditions to achieve very low NO_x emissions.

21.4.4.1 Burners Using In-Furnace Gas Recirculation

Oxy-fuel burners using in-furnace flue gas recirculation (FGR) were first developed in the late 1970s to provide a high-momentum, low-temperature flame mimicking the traditional air flame.²⁵ Figure 21.16 shows a schematic diagram of Praxair “A” Burner™. The key design principle of the “A” burner is the “aspiration” of furnace gases using high-velocity oxygen jets to produce “simulated hot air” prior to mixing with fuel. The main oxygen nozzles are separated from the central fuel nozzle to prevent direct mixing of fuel and oxygen near the burner face. The concentration of oxygen in the oxygen jet decreases along the jet length due to the entrainment of furnace flue gas according to the turbulent jet theory. By adjusting the diameter of the oxygen nozzle and the separation distance between the fuel nozzle and the oxygen nozzles, the amount of flue gas entrained into the oxygen jets prior to mixing with the fuel jet is controlled. As discussed in Figure 21.3, the flame temperature of this oxy-fuel burner is much lower than that of a direct mix type oxy-fuel burner. In low-NO_x air burners using FGR, flame stability becomes a limiting factor in operating the burner with very high FGR ratios. In the Praxair “A” burner design, a small amount of oxygen, typically less than 5% of the total oxygen flow, is used around the central fuel jet to anchor the fuel jet and provide excellent flame stability. As a result, the burner can operate at very high FGR ratios and at a lower flame temperature than a typical low-NO_x air burner using FGR.

Figure 21.17 shows the effects of oxygen-enriched combustion on NO_x emissions for two commercial air burners (Bloom and Kinemax) and two commercial oxy-fuel burners (Oxytherm and Praxair “A”) in a test furnace.²⁶ Oxygen enrichment of combustion air in the air burners increased the flame temperature and resulted in sharp increases of NO_x emissions. As the oxygen enrichment level was increased, NO_x emissions peaked and started to decrease. At high concentrations of oxygen, NO_x emissions decreased linearly with oxygen concentration. A comparison of the two oxy-fuel burners showed that the Praxair “A” Burner produced NO_x emissions about an order of magnitude less than those from the Oxytherm burner. There are two competing factors in NO_x formation under

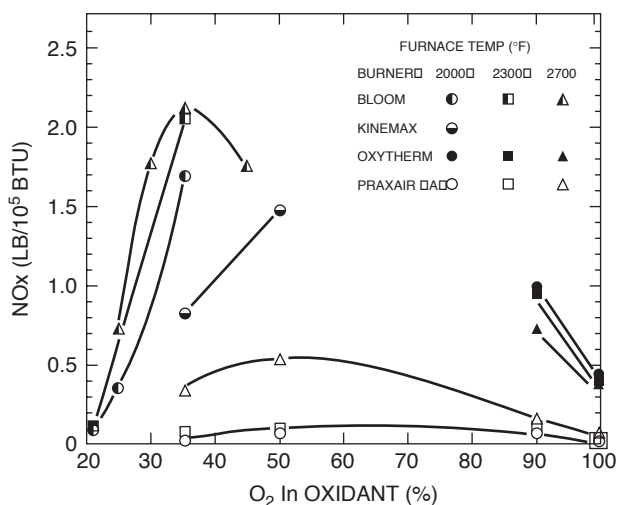


FIGURE 21.17 NO_x emissions under oxygen-enriched conditions.

oxygen-enriched combustion conditions: flame temperature and nitrogen concentration. In air combustion, the nitrogen concentration in the furnace atmosphere is about 70%. When air is enriched with oxygen, the effect of the higher flame temperature dominates and results in a sharp increase in NO_x emissions. As the enrichment level increases and approaches pure oxygen, the effect of the decreasing nitrogen concentration starts to dominate. A peak in NO_x emissions is formed at mid range. In the Zeldovich mechanism of thermal NO_x formation, the rate of NO_x formation is proportional to the nitrogen concentration. For example, if the nitrogen concentration is reduced to 7% with oxygen-enriched combustion and the flame temperature is kept constant, it would result in a tenfold reduction in NO_x formation. This is the reason why the “A” Burner produced very low NO_x emissions for a wide range of oxygen concentrations. By contrast, the Oxytherm oxy-fuel burner produced significant NO_x emissions even when pure oxygen was used, because the natural gas used in the test contained about 2% nitrogen and the flame temperature of the Oxytherm burner was very high. Most industrial furnaces operate at close to atmospheric pressure and normally experience significant ambient air infiltration. It is important to control the flame temperature of oxy-fuel burners to achieve low NO_x emissions even when pure oxygen is used for combustion.

The concept of in-furnace FGR was further advanced in the late 1980s to the conditions approaching those of a “homogeneous reactor” in which the furnace temperature and species concentrations are uniform throughout the furnace. The concept of this unique combustion process, known as “dilute oxygen combustion” (DOC), is shown in Figure 21.18.²⁷ The basic concept is to react fuel with a hot, dilute oxidant containing only 2 to 10% oxygen to produce a low flame temperature “reaction zone.” As shown in Figure 21.3, the flame temperature of DOC can become as low as 500°F (260°C) above the temperature of hot oxidant. An oxygen or air jet is injected into the furnace, separated by some distance from the fuel jet, to produce “hot dilute oxidant” by jet entrainment of furnace gas in a “mixing zone.” The reaction zone and the mixing zone are segregated within the furnace to prevent direct mixing and combustion of the undiluted oxidant and fuel. One or more pairs of oxidant and fuel jets are placed on the furnace walls to create furnace gas recirculation patterns that promote dilution of oxidant and good mixing of fuel. The stability of combustion requires hot furnace gases in this process. A minimum furnace temperature of 1400°F is typically required.

A hybrid technology²⁸ (Figure 21.19) combining a separated jet combustion device with a secondary oxygen injection system has been developed recently. In this design, the secondary oxygen jets

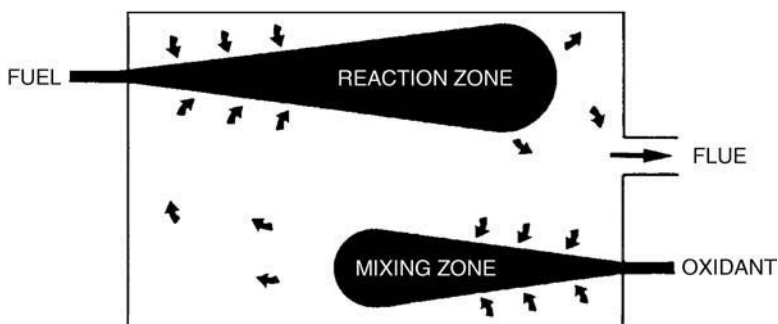


FIGURE 21.18 Dilute oxygen combustion (DOC) process.

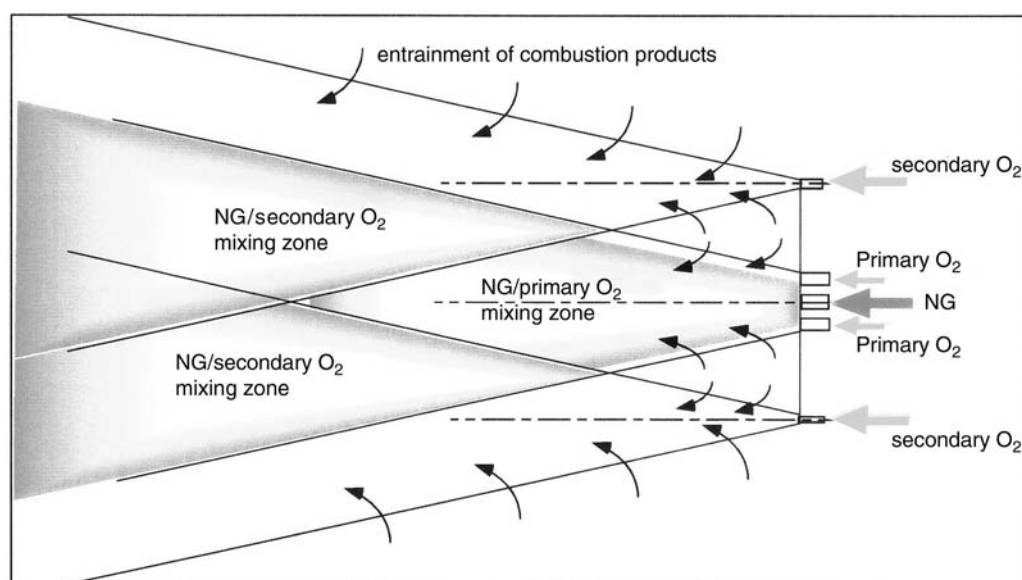


FIGURE 21.19 Diluted jet burner concept.

are positioned far from the primary ones, to produce hot oxidizing mixtures with low oxygen content, before they mix and react with the primary oxygen-fuel mixture. The distribution of oxygen between the two oxygen injection systems allows the combination of the principal advantages of the two preceding technologies; that is, a good flame stability and a very homogeneous temperature in the furnace. [Figure 21.20](#) compares the performance of a 2-MW diluted jet burner with those of other oxy-fuel burners in a pilot-scale furnace at high temperatures ($1420^{\circ}\text{C} = 2588^{\circ}\text{F}$ and $1500^{\circ}\text{C} = 2732^{\circ}\text{F}$). NO_x emissions from the diluted jet combustion technology²⁸ are very low and also show a very weak dependence on the nitrogen concentration in the furnace atmosphere.

21.4.4.2 Burners Using Oscillating Combustion

Oscillating combustion²⁸ for an oxy-fuel burner was developed in the 1990s to improve the energy efficiency and environmental performance of industrial combustion technologies. The basic idea of this low- NO_x primary technique is to create successive fuel-rich and fuel-lean zones within the flame, while operating the burner globally at stoichiometric conditions. The concept is schematically shown in [Figure 21.21](#).

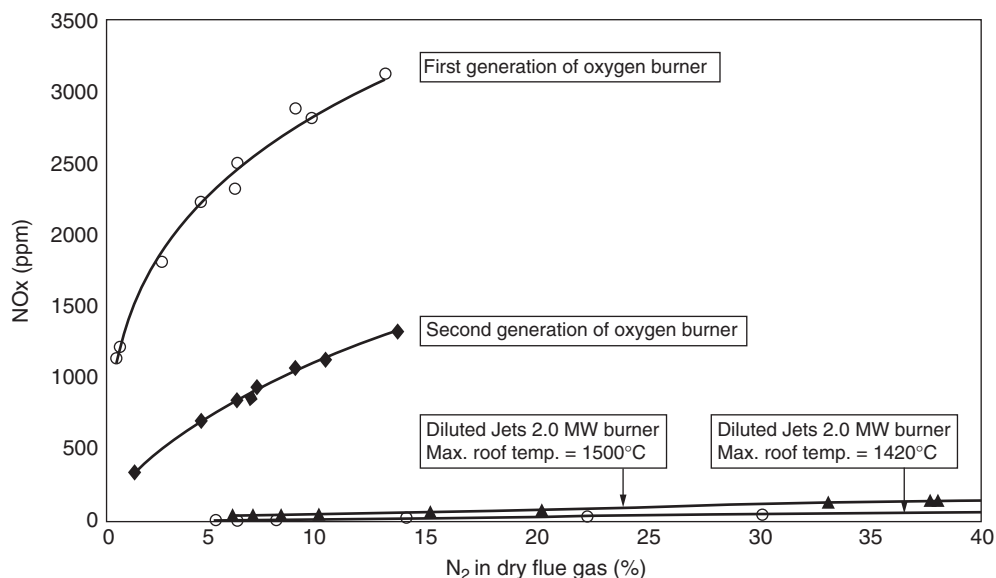


FIGURE 21.20 NO_x emissions in pilot-scale furnace of 1-MW oxygen combustion technologies.

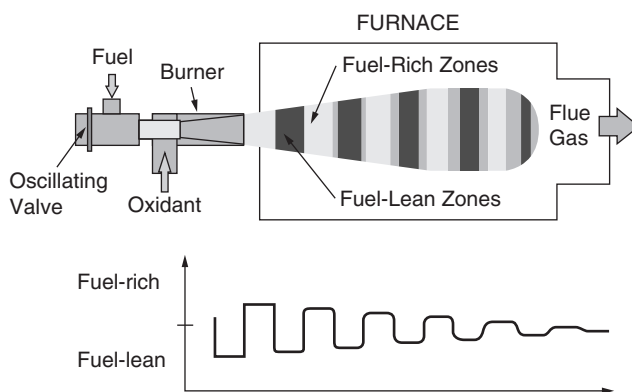


FIGURE 21.21 Oscillating combustion burner.

The pulsated flame is achieved by forced oscillation of the fuel flow rate, using a special valve. It is a solid-state proportioning (SSP) valve. A schematic drawing is shown in [Figure 21.22](#).

An elastomer disk is sandwiched between the fixed and movable pistons. The actuator is energized and oscillated at the required oscillating frequency. The force exerted by the moving piston on the elastomer disk causes it to plug and restrict the flow passage, which provides required flow oscillations. It is well known that NO_x formation is sensitive to temperature, especially in high-temperature flames such as pure oxygen flames

As shown in [Figure 21.23](#), an excess of either fuel or oxygen reduces the flame temperature and thus the NO_x formation rate. Early experiments on pilot furnaces have shown that up to 90% NO_x reduction can be achieved without lowering heat transfer, when pulsating both gases in opposite phases. This technology is designed to easily retrofit existing combustion systems, by the installation of oscillating valves and associated electronics to control the frequency and amplitude of the flow oscillations. The pulsating frequency and amplitude should be adjusted for each combustion system, and the phases of the oscillating flames in multi-burner systems

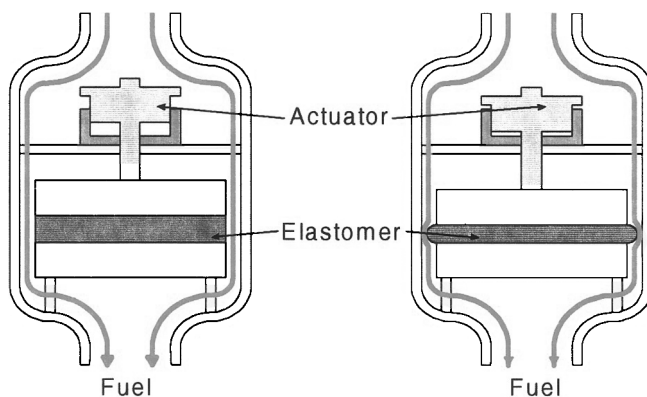


FIGURE 21.22 SSP valve operation schematic.

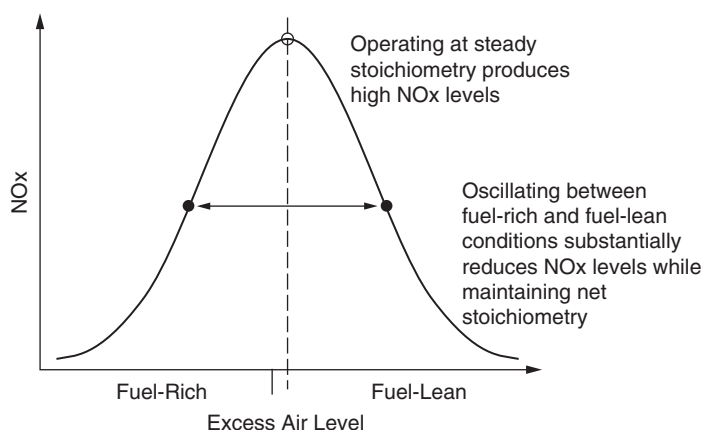


FIGURE 21.23 NO_x vs. stoichiometry.

should be staggered in sequence to avoid pulsating the whole flow in the furnace. Several years of field tests and application to different industrial processes showed that oscillating combustion is a competitive technology to reduce NO_x emissions, which allows 20 to 40% NO_x reduction for existing combustion systems. It has wide applicability and provides a cost-effective NO_x reduction option for steel, glass, aluminum, and other applications.

21.4.4.3 Burners Using Staged Combustion

Staged combustion is one of the primary reduction techniques of the emissions of nitrogen oxides for the industrial combustion systems. This technique consists of staging in the flame injection of one of the reactants (usually the oxidant) so as to create a primary combustion zone in fuel excess, and then a secondary zone in which additional oxygen is provided to complete combustion. In general, the primary combustion zone is the site of maximal heat release in the flame. The fuel excess in this zone limits the flame temperature at a level significantly lower than that of the stoichiometric flame. A lower temperature generally contributes to the reduction of thermal NO_x emissions, but the lack of sufficient oxygen in this primary zone is the principal element leading to a significant NO_x reduction, regardless of origin (i.e., either thermal NO or prompt NO). The simplest way to implement this technique on industrial furnaces, when the furnace wall space is available, is to add secondary oxygen lances to a traditional burner, in such a way that the flows

from the lances meet the primary zone flame only at a sufficient distance inside the furnace. Burner operation must be regulated in a fuel-rich condition and the supplemental oxygen is injected from the lances to complete the combustion. A good knowledge of the flow pattern inside the furnace, as well as good control of the injection conditions of the fluids, are essential to maximize the reduction of NO_x emissions. For a good performance evaluation of any combustion system, it is recommended that one simultaneously measure NO_x and CO emissions. The optimum for the operating condition of the combustion system is normally obtained for the intersection point of the two emission curves vs. the level of staging of the oxidant (i.e., the primary zone stoichiometric ratio). An example of a staged combustion oxy-fuel system consists of placing an oxygen lance under an oxygen burner and diverting part of oxygen feeding the burner to the lance. A valve arrangement to enable variable oxygen flows to the main burner and the lance is preferred. There are many other design options, but they all follow the same concept of two combustion zones with different stoichiometric conditions.

21.5 CUSTOMIZED OXY-BURNERS FOR CHEMICAL PROCESS APPLICATIONS

Combustion with pure oxygen is not only used for the traditional industrial processes such as glass or metal melting or the reheating of steel products, but is also used for chemical processes such as fly ash vitrification, reprocessing of chlorinated or sulfurized products, or the incineration of aqueous residues. Three of these specific applications of oxy-combustion are described in the following sub-sections.

21.5.1 OXY-BURNERS FOR SULFURIC ACID RECOVERY

Sulfuric acid recycling in a methyl methacrylate monomer (MMA) plant is an example of an industrial process for which a special oxygen combustion technology was developed. Stringent anti-pollution regulations and high production capacity requirement for a monomer production plant led to the development of an oxygen combustion system that was combined with other advanced technologies (two-staged, steam-heated vacuum evaporator; waste heat boiler; gas cleaning system; etc.) to double the sulfuric acid regeneration capacity of the plant.

The MMA product boils off in the esterifier vessels, leaving an aqueous solution known as by-products acid (BPA). Approximately 3 tons of BPA are generated for every ton of MMA produced, so the quantity of spent acid generated is substantial. Initially, the spent acid is preconcentrated in a two-stage, steam-heated vacuum evaporator. Then the concentrated acid is burned, using oxygen burners. Finally, the resulting SO₂ gas is cleaned and recovered as acid and oleum in a gas cleaning system. Burning the BPA in a pure oxygen atmosphere reduces the equipment size by a factor of about 2 compared to operation in air only. This saves cost, permits a large degree of vessel shop fabrication, avoids gas distribution problems in very large equipment, and avoids structural limitations on furnace brickwork. Pure oxygen combustion also allows energy savings — about 30% of the energy required for air-based operation, taking into account the energy consumed in producing oxygen itself.

The preconcentrated BPA containing ammonium sulfate and heavy organics is decomposed in the furnace at over 1832°F (1000°C). The chamber is lined with refractory brick. Natural gas is fired with oxygen to provide the energy required to decompose the acid. Operating conditions in the furnace must be controlled within narrow limits. If the oxygen excess in the flue gases is too high, sulfur trioxide will form, resulting in yield loss. If reducing conditions are approached, the organics will not be completely oxidized and elemental sulfur will form, which will sublime and block downstream equipment as the gases are cooled. Application of oxygen combustion burners to a SAR furnace with its highly corrosive atmosphere posed particular problems. In particular, it was

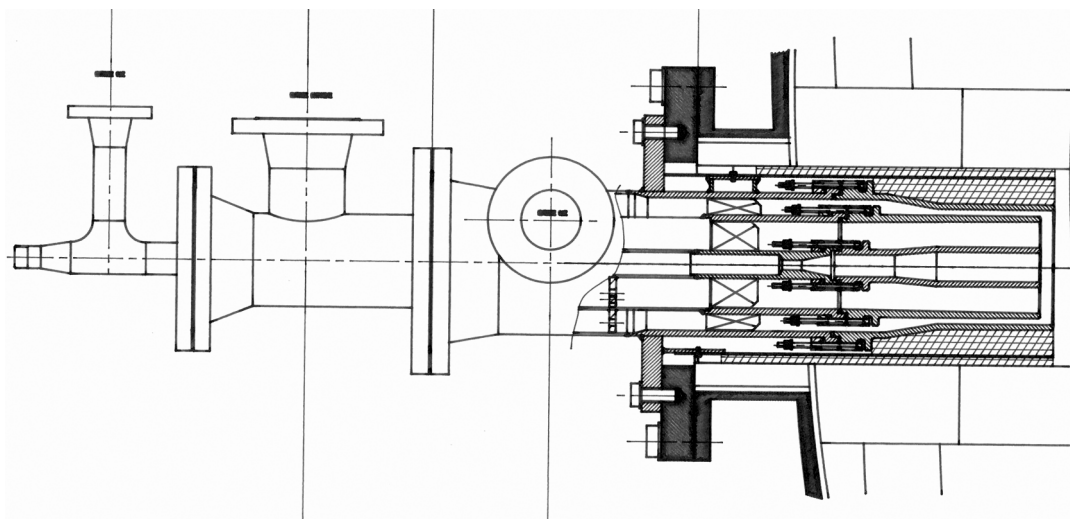


FIGURE 21.24 Oxygen burner scheme.

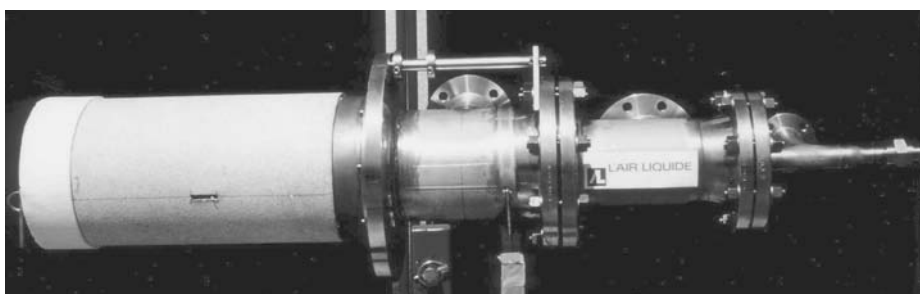


FIGURE 21.25 25-MW oxygen burner.

necessary to ensure that sufficient mixing occurs and that the kinetics of the various decomposition reactions are not adversely affected by the use of pure oxygen.

At the start of the development program, it was not known whether the oxygen/fuel burners could provide the required mixing and residence time necessary to achieve the desired conversions. In addition, there was a concern that radiation from the high-temperature flame would result in damage to the furnace refractories, and to the burner itself, in a highly acidic environment. It was therefore necessary to optimize and test the detailed mechanical configuration of the burner.

An 85-MMBtu/hr (25-MW) burner was developed (see [Figure 21.24](#)). This combustion technology (see [Figure 21.25](#)) enabled the required conversion of sulfur to SO_2 without producing undesirable by-products. Its performance primarily depends on burner design, BPA feed positions and droplet sizes, and flame stoichiometry.

21.5.2 OXY-BURNERS FOR WASTE INCINERATION AND FLY ASH VITRIFICATION

The use of oxygen in waste incineration is mostly driven by the incineration of low calorific value liquid waste, the possibility to design mobile incineration units or by vitrification applications, as well as new oxygen production technologies. The removal of the ballast of nitrogen in oxy-combustion improves the kinetics of combustion (i.e., increases the oxygen partial pressure and combustion temperature), increases the flammability range, and lowers the self-ignition temperature. For example, methylene chloride is nonflammable with air under atmospheric conditions; whereas

with oxygen, the lower and upper flammability limits are 16 and 66%, respectively. Combustion with oxygen allows increases in the performance of incineration processes. For example, combustion with oxygen allows one to minimize common problems of the incineration processes, such as flame instabilities or pyrolytic pockets. The most important benefit, however, is to enable incineration of aqueous wastes with low calorific values ($\text{LHV} < 1800 \text{ Btu/lb}$ or 1000 kcal/kg). In incineration with air, the lowest LHV values allowing for flame stabilization are close to 3600 Btu/lb (2000 kcal/kg). The removal of the ballast of nitrogen allows the stabilization of flames for LHV above 1530 Btu/lb (850 kcal/kg); this leads to auxiliary fuel savings and the elimination of waste evaporation or concentration stages preliminary to the incineration.

Another example is the possibility offered by oxy-combustion to treat waste with a low volatile content, such as irradiated graphite. Tests showed the feasibility to incinerate with pure oxygen in a cyclone furnace or with enriched air in a fluidized bed reactor. A final example of chemical process applications of oxygen burner technology concerns vitrification applications. Vitrification (homogenization by melting) is a form of chemical stabilization while reducing the volume. It is a process that requires large quantities of concentrated energy. Plasma, electric arc melting, and oxy-fuel combustion have been successfully applied. Recent progress in fume filtration has generated new and more residual wastes of different kinds, such as fly ash, bottom ash, and sludge. All of these materials have a common characteristic of containing a rather hazardous part, basically heavy metals, chlorides, and sulfurous compounds, with the major part of mineral oxides (e.g., SiO_2 , CaO , Al_2O_3). Vitrification technology takes advantage of the similarity between the chemical composition of ash and that of common glass, and transforms the incoming ash into a glass product. When ash is transformed into vitrified state, the treated ash performs very well in a leaching test under the recently passed laws concerning maximum leaching values for landfill waste disposal. An effective vitrification demands a strong thermal gradient, while keeping a smooth flame; the oxygen burner shows excellent performance in these two aspects.

An advantage of an oxy-fuel flame as an energy source in vitrification is lower NO_x emissions compared with high-temperature air flames. Ash often contains some organic residues (carbon, hydrocarbons, dioxins, etc.) and the use of an oxy-fuel flame enables full combustion of most residual organic components in ash. It is also possible to separate heavy metals from the mineral matrix by the action of oxy-fuel flames.

21.6 SMALL-SIZE OXY-FUEL BURNERS FOR SPECIALIZED FUNCTIONS

For many years, the glass industry has been using combustion with pure oxygen for the finishing process of glass products (polishing, forming, etc.) or for lubricating moulds. The burners used for these applications are small firing rate burners (typically several thousand Btu/hr or few kilowatts), and their design characteristics and operating conditions are specific to the dedicated process. More recently, another technology of small-size oxygen burners was developed for temperature control on glass distribution systems in forehearth. Small-size burner technologies developed for some of these specific applications are described below.

21.6.1 POLISHING BURNERS

Burners used for flame polishing rough edges on glass bottles usually require hot, intense flames that burn in a small area. They utilize gaseous fuels and may employ other unconventional fuels such as hydrogen if ordinary fuels do not produce the proper flame temperature. The approaches in burner design focus on flame shape and usually try to match the hot point of the flame to the passing object's geometry to perform the polishing. Burners typically consist of long, slot-type geometries or multiple conical burners whose positioning can be adjusted. An example of this burner technology is shown in [Figure 21.26](#) and [Figure 21.27](#), which provide examples of flame polishing production lines.



FIGURE 21.26 Glass flame polishing burner.



FIGURE 21.27 Glass flame polishing production line.

21.6.2 FOREHEARTH BURNERS

In the production of glass objects, molten glass is produced in a glass melting furnace from raw materials (batch) and recycled glass (cullet). The molten glass is transferred from the glass melting furnace through a glass distribution system, to the processing section, to a forming machine in which molten glass is processed into the desired glass shape or article. The glass distribution system may include distribution channels, feeders, and forehearth. Typical forehearths are designed to receive molten glass from the furnace and condition the glass to make it suitable for processing, and then convey it to the glass processing section or machine. Forehearths generally include a refractory trough along which the molten glass flows and which is covered with an insulating roof.

Traditional systems for heating glass in a forehearth system use combustion burners of premixed design in which the fuel (e.g., natural gas) and combustion air are premixed together in the correct stoichiometric ratio before they enter the burners. However, the use of premixed air-fuel burners for glass distribution systems such as channels and forehearths is not totally satisfactory. Such burners provide very poor fuel efficiency and, due to the high volume of combustion gases, the associated emissions are quite high. Moreover, most forehearth systems require precise temperature control of the glass, as small as 1°C, which is difficult to attain with air-fuel burners. Another disadvantage of the premixed air-fuel firing system is the very limited turndown ratio, which, in turn, limits the level of control on the forehearth when responding to a temperature control signal to either increase or decrease fuel input. The turndown ratio (i.e., the high firing rate of the burner divided by the low firing rate of the burner) for typical premixed air-fuel burners is only 4:1, due to flashback or blow-off phenomena.

To overcome these problems, some of premixed air-fuel burners have been replaced with post-mixed oxy-fuel burners. There are various arrangements of tube-in-tube design oxy-fuel burners for forehearth applications.

21.6.3 MOULD LUBRICATION IN GLASS PROCESS

Lubricating technologies are used in the glass industry and more specifically for the manufacturing of hollowware, such as bottles and containers. One of the more important steps in the manufacturing of hollowware is the forming of hot glass gob. This happens in individual section (IS) or rotary machines, in which a red-hot glass gob is filled in a mould, where it gets shaped by blowing air and is then taken out. This gob then becomes a so-called “parison,” which is a pre-form of the final hollowware. During this operation, strongly nonreversible thermal transfers take place between the hot glass (~920°F or 1200K) and the relatively cold mould (~670°F or 750K). To prevent any sticking of the glass to the mould, to obtain a good skin quality of the glass article (i.e., to prevent surface defects), and to avoid a quick damaging of the mould, the inside surfaces of the mould must be lubricated before the glass gob comes in contact. The conventional technology commonly used is manual swabbing, consisting of an oil-based soot graphite solution being deposited on the mould surface by an operator using a saturated swab. An alternative method for mould lubrication is to deposit a carbon black layer on the internal mould surface that is in contact with the glass, using a specific technique. Different techniques using fuel-rich flames are available; for example, the LINDE, OWENSBROCKWAY, or T.A. Seeman’s process. Air Liquide has developed a specific technology (ALBLACK™) that uses a natural gas/oxygen pilot flame to initiate cracking of an acetylene pulse, as shown in [Figure 21.28](#) and [Figure 21.29](#).

This technology deposits a thin carbon film on the metallic casting mould surface by acetylene gas decomposition at high temperature, providing mould lubrication for automated manufacturing operations. Some of the advantages of this process include:

- Improved skin quality of the glassware
- Easy automation of the forming machine
- Complete elimination of pollution caused by oil lubricants

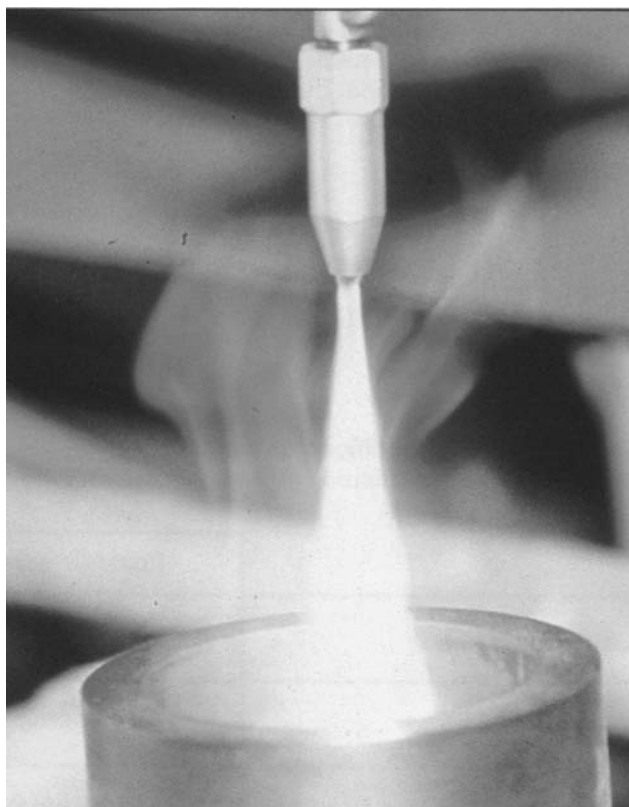


FIGURE 21.28 ALBLACK[™] oxygen burner.



FIGURE 21.29 ALBLACK[™] process.

- Improvement in working conditions by eliminating oil fumes
- Improvement in product quality
- Mould loading (glazing) reduction
- Regular and reproducible carbon film deposit

21.7 OXYGEN AND COMBUSTION SAFETY

Safety and reliability are very important requirements for any combustion system. The use of oxygen enrichment or high-purity oxygen for combustion requires special design considerations due to the high reactivities of oxygen and oxygen-enriched air with various materials. Two different aspects of safety need to be addressed: (1) the safety of the oxygen supply and flow control system, and (2) the safety of oxygen-enriched combustion and burner management.

Many materials that do not burn with air can be ignited and burn vigorously in an oxygen atmosphere. For example, carbon steel pipes, especially when not properly cleaned for oxygen service, can ignite and cause an “oxygen pipe fire.” For safe storage and distribution of oxygen, proper selection, sizing, and cleaning of all materials for oxygen service, including storage tanks, pipes, piping components, valves, flanges, gauges, gaskets, and sealing compounds, are required. The design and manufacturing guidelines for oxygen storage and distribution systems are, for the most part, well established and available from the publications of the Compressed Gas Association.^{30–35} However, the design and engineering of oxygen systems should always be performed by qualified engineers with proper safety training, education, and experience. Industrial gas oxygen suppliers, who have excellent safety records in the operation of numerous bulk oxygen storage and distribution systems, provide turnkey installations for various industrial applications.

For combustion safety and burner management, the basic design principles of the safety interlock systems are the same for both air and oxygen enriched systems. Prevention of combustibles or explosive mixtures in the furnace, monitoring of flame, and detection and correction of off-stoichiometric conditions, are among the most important design features. It is recommended that all safety standards for air burner systems also be incorporated into the design of oxygen enriched combustion systems. In addition, special design considerations should be given to prevent accidental accumulation of oxygen enriched air in or near the furnace. With oxygen enrichment, the minimum ignition temperature of a fuel-oxidant mixture is reduced and the higher flammability limit is significantly widened compared to those of the equivalent fuel-air mixture. Thus, the likelihood of potential formation and ignition of flammable mixtures tends to increase in the event of accidental accumulation of both fuel and oxygen enriched air in the furnace.

Proper purging of a furnace prior to initiating the ignition sequence is an important safety step. In air-fired furnaces, combustion air is available for use as the purge gas. In an oxy-fuel-fired furnace, a separate purge gas stream, typically blower air or nitrogen, is required to ensure proper purging. Further details on oxygen combustion safety can be found in National Fire and Protection Agency’s (NFPA) Standard 86, “Ovens and Furnaces,” which is generally considered the accepted standard for regulating the safe design of combustion equipment.³⁶ With proper design, construction, and a good in-plant safety program, the operation of the oxygen combustion system is as safe and reliable as a well-designed air combustion system.

21.8 SUMMARY

Oxy-fuel burners have been adopted in a wide range of industrial furnaces to improve productivity and fuel efficiency, to reduce emissions of pollutants, and, in some applications, to improve product quality and yield or to eliminate the capital and maintenance costs of air preheaters. Significant fractions of glass melting furnaces, steel scrap melting furnaces, electric arc furnaces, steel reheat furnaces, soaking pits, forging furnaces, ladles, aluminum melting furnaces, copper smelting and

anode furnaces, hazardous waste incinerators, rotary enamel frit furnaces, and rotary lead melting furnaces are fired with oxy-fuel burners.

As with air burners, many different oxy-fuel burner designs have been developed and are available to end users. Each different design was developed to overcome a problem or achieve a certain goal, depending on the application. Traditional oxy-fuel burners produce a high flame temperature and intense heat transfer, and are typically used in high-temperature melting processes. Low-NO_x oxy-fuel burners are designed to produce low flame temperatures comparable to those of low-NO_x air burners, while retaining the other benefits of oxy-fuel combustion. These burners use one of three design features: (1) in-furnace recirculation of flue gas, (2) off-stoichiometric oscillating combustion, or (3) staged combustion. As the concentration of nitrogen molecules in the combustion space is reduced with full oxy-fuel combustion to less than one tenth that of air combustion, NO_x emissions as low as one tenth of those from low-NO_x air burners have been demonstrated.

Customized oxy-fuel burners are available for specific applications such as the Claus sulfur recovery process, the sulfuric acid recovery process, waste incineration processes, and ash vitrification processes. Also, small oxy-fuel burners are available for special applications such as glass surface polishing and uniform heating in glass forehearth. New sensor and control technologies have been adapted for some oxy-fuel burner systems to enhance and to optimize burner performance.

Understanding the attributes of an oxy-fuel burner and overlaying them with the requirements of the process and the needs of the end user are key to selecting the proper burner for a particular application. In many situations, seeking advice from the burner manufacturers, who have significant design and hands-on experience with each burner type, is the best way to ensure that the selected burner will perform satisfactorily in the application. In addition, the use of oxygen enrichment for combustion requires special design considerations due to the high reactivities of oxygen and oxygen-enriched air with various materials. The design and engineering of oxygen systems should always be performed by qualified engineers with the proper safety training, education, and experience. Industrial gas oxygen suppliers, who have excellent safety records of numerous bulk oxygen storage and distribution systems, provide turnkey installations for various industrial applications.

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