
20 Air-Oxy/Fuel Burners

Charles E. Baukal, Jr., Ph.D., P. E.

CONTENTS

- 20.1 Introduction
- 20.2 Typical Use Methods
 - 20.2.1 Air Enrichment
 - 20.2.2 O₂ Lancing
 - 20.2.3 Oxy/Fuel
 - 20.2.4 Air-Oxy/Fuel
 - 20.2.5 Low-Purity O₂
- 20.3 Basics
 - 20.3.1 Definitions
 - 20.3.2 Operating Regimes
 - 20.3.3 Combustion Products
 - 20.3.4 Properties
 - 20.3.4.1 Flame Temperature
 - 20.3.4.2 Available Heat
 - 20.3.4.3 Ignition Characteristics
 - 20.3.4.4 Flue Gas Modification
- 20.4 General Benefits
 - 20.4.1 Increased Productivity
 - 20.4.2 Higher Thermal Efficiencies
 - 20.4.3 Improved Flame Characteristics
 - 20.4.3.1 Higher Turndown Ratio
 - 20.4.3.2 Increased Flame Stability
 - 20.4.3.3 Better Ignition Characteristics
 - 20.4.3.4 Flame Shape Control
 - 20.4.4 Lower Exhaust Gas Volumes
 - 20.4.5 Higher Heat Transfer Efficiency
 - 20.4.6 Reduced Costs
 - 20.4.7 Increased Flexibility
 - 20.4.8 Improved Operations
- 20.5 Potential Problems
 - 20.5.1 Refractory Damage
 - 20.5.1.1 Overheating
 - 20.5.1.2 Corrosion
 - 20.5.2 Nonuniform Heating
 - 20.5.2.1 Hot Spots
 - 20.5.2.2 Reduction in Convection
 - 20.5.3 Flame Disturbance

20.5.4	Increased Pollutant Emissions
20.5.4.1	NO _x
20.5.4.2	Noise
20.5.5	Flashback
20.6	Industrial Heating Applications
20.6.1	Metals
20.6.2	Minerals
20.6.3	Incineration
20.6.4	Other
20.7	Conclusions
	References

20.1 INTRODUCTION

Most industrial heating processes require substantial amounts of energy, which is commonly generated by combusting hydrocarbon fuels such as natural gas or oil. Most combustion processes use air as the oxidant. In many cases, these processes can be enhanced using an oxidant that contains a higher proportion of O₂ than that in air. This is known as *oxygen-enhanced combustion* or OEC.¹ Air consists of approximately 21% O₂ and 79% N₂ (by volume). One example of OEC is using an oxidant consisting of air, blended with pure O₂. Another example is using high-purity O₂ as the oxidant, instead of air. This is usually referred to as *oxy/fuel* combustion (see Chapter 21).

New developments have made oxy/fuel combustion technology more amenable to a wide range of applications. In the past, the benefits of using oxygen could not always offset the added costs. New oxygen-generation technologies, such as pressure and vacuum swing adsorption,² have substantially reduced the cost of separating O₂ from air. This has increased the number of applications where using oxygen to enhance performance is cost justified. Another important development is the increased emphasis on the environment. In many cases, OEC can substantially reduce pollutant emissions.³ This has also increased the number of cost-effective applications. The Gas Research Institute in Chicago, IL⁴ and the U.S. Dept. of Energy⁵ sponsored independent studies which predict that OEC will be a critical combustion technology in the very near future.

Historically, air/fuel combustion has been the conventional technology used in nearly all industrial heating processes. Oxygen-enhanced combustion systems are becoming more common in a variety of industries. When traditional air/fuel combustion systems have been modified for OEC, many benefits have been demonstrated. Typical improvements include increased thermal efficiency, increased processing rates, reduced flue gas volumes, and reduced pollutant emissions.

Many industrial heating processes can be enhanced by replacing some or all of the air with high-purity oxygen.^{4,6} Typical applications include metal heating and melting, glass melting, and minerals calcining. In a report for the Gas Research Institute, the following applications were identified as possible candidates for OEC:⁷

- Processes that have high flue gas temperatures, typically in excess of 2000°F (1400K)
- Processes that have low thermal efficiencies, typically due to heat transfer limitations
- Processes that have throughput limitations which could benefit from additional heat transfer without adversely affecting product quality
- Processes that have dirty flue gases, high NO_x emissions, or flue gas volume limitations

When air is used as the oxidizer, only the O₂ is needed in the combustion process. By eliminating N₂ from the oxidizer, many benefits can be realized.

20.2 TYPICAL USE METHODS

Oxygen has been commonly used to enhance combustion processes in four primary ways: (1) adding O_2 into the incoming combustion air stream, (2) injecting O_2 into an air/fuel flame, (3) replacing the combustion air with high-purity O_2 , and (4) separately providing combustion air and O_2 to the burner. These methods are discussed next.

20.2.1 AIR ENRICHMENT

Figure 20.1 shows an air/fuel process where 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.⁸ 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 temperatures 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 .

20.2.2 O_2 LANCING

Figure 20.2 shows another method for enriching an air/fuel process with O_2 . As in the first method, this is also generally used for lower levels of O_2 enrichment. However, oxygen lancing may have

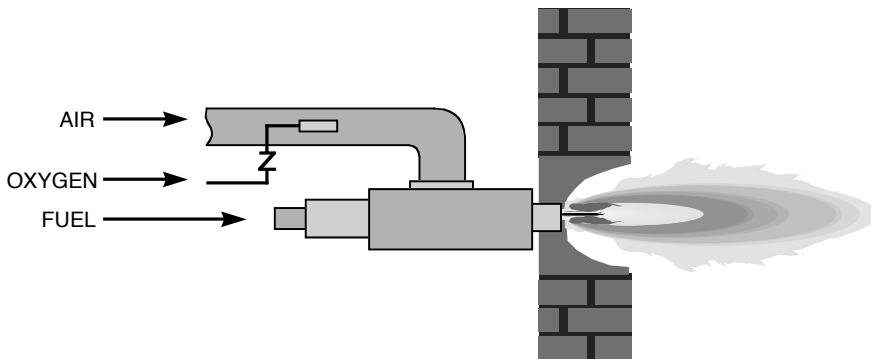


FIGURE 20.1 Schematic of an oxygen-enriched air/fuel burner.¹

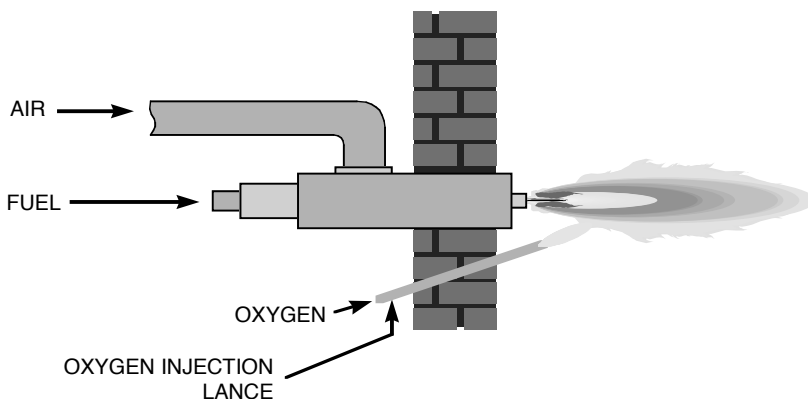


FIGURE 20.2 Schematic of oxygen lancing into an air/fuel burner.¹

several advantages over air enrichment. No modifications to the existing air/fuel burner need to be made. Typically, the NO_x emissions are lower using O₂ lancing compared to premixing because this is a form of staging, which is a well-accepted technique for reducing NO_x.⁹ Depending on the injection location, the flame shape can be lengthened by staging the combustion reactions. The flame heat release is generally more evenly distributed than with premix O₂ enrichment. Under certain conditions, O₂ lancing between the flame and the load causes the flame to be pulled toward the load. This improves the heat transfer efficiency. Therefore, there is less likelihood of overheating the air/fuel burner, the burner block, and the refractory in the combustion chamber. Another variant of this staging method involves lancing O₂, not into the flame, but somewhere else in the combustion chamber. One example of this technique is known as oxygen-enriched air staging or OEAS (see Figure 20.47 and Figure 20.49). In that technology, O₂ lancing is an inexpensive retrofit for existing processes. One potential disadvantage is the cost to add another hole in the combustion chamber for the lance. This includes both the installation costs and the lost productivity. However, the hole is typically very small.

One specific embodiment of O₂ lancing is known as undershot enrichment, where O₂ is lanced into the flame from below. The lance is located between the burner and the material being heated. While air enrichment increases the flame temperature uniformly, the undershot technique selectively enriches the underside of the conventional flame, thereby concentrating extra heat downward toward the material being heated. While the mixing of oxygen and combustion air is not as complete with undershot oxygen as with premixing, this disadvantage is often outweighed by the more effective placement of the extra heat. Another benefit is that the refractory in the roof of the furnace generally receives less heat compared to air enrichment. This usually increases the life of the roof.

20.2.3 OXY/FUEL

Figure 20.3 shows a third method using OEC, commonly referred to as oxy/fuel combustion. 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. There is no premixing of the gases for safety reasons. Because of the extremely high reactivity of pure O₂, there is the potential for explosion if the gases are premixed. In this method, high-purity oxygen (>90% O₂ by volume) is used to combust the fuel. As will be discussed later, there are several ways of generating the O₂. In an oxy/fuel system, the actual purity of the oxidizer will depend on which method has been chosen to generate the O₂. Oxy/fuel combustion has the greatest potential for improving a process, but it also may have the highest operating cost. Oxy/fuel technology is discussed in more detail in Chapter 21.

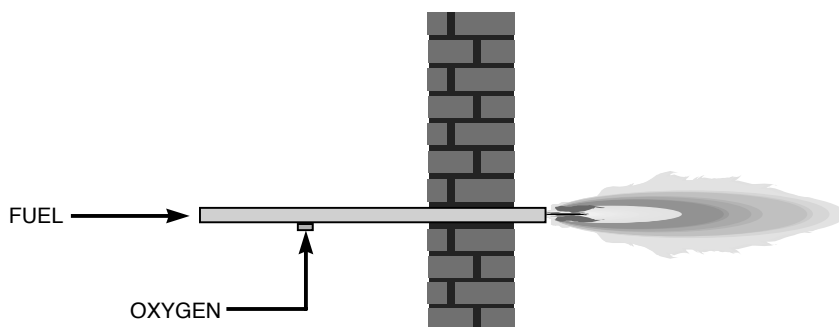


FIGURE 20.3 Schematic of an oxy/fuel burner.¹

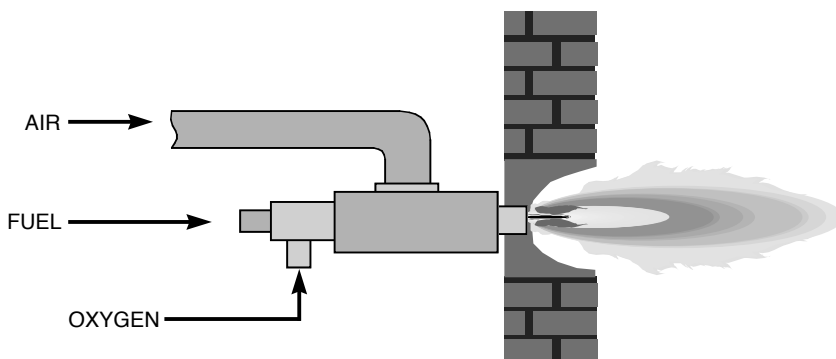


FIGURE 20.4 Schematic of an air-oxy/fuel burner.¹

20.2.4 AIR-OXY/FUEL

The fourth common method of using OEC involves separately injecting air and O_2 through a burner, as shown in [Figure 20.4](#). It is sometimes referred to as an air-oxy/fuel burner. This is a variation of the first three methods. In some cases, an existing air/fuel burner can be easily retrofitted by inserting an oxy/fuel burner through it.¹⁰ In other cases, a specially designed burner can be used.¹¹ This OEC method can have several advantages. It can typically use higher levels of O_2 than the air enrichment and O_2 lancing methods, which yields higher benefits. However, the operating costs are less than for oxy/fuel, which uses very high O_2 levels. The flame shape and heat release pattern can be adjusted by controlling the amount of O_2 used in the process. It is also a generally inexpensive retrofit. Many air/fuel burners are designed for dual fuels, usually a liquid fuel-like oil, and a gaseous fuel-like natural gas. The oil gun in the center of the dual fuel burner can usually be easily removed and replaced by either an O_2 lance or an oxy/fuel burner.

With this OEC method, the oxidizer composition can be specified in an alternate way. Instead of giving the overall O_2 concentration in the oxidizer, the oxidizer can be given as the fraction of the total oxidizer that is air and the fraction of the total oxidizer that is pure O_2 . The equivalent overall O_2 in the oxidizer can be calculated as:

$$\Omega = \frac{20.9}{0.209(\text{vol.\% } O_2) + (\text{vol.\% air})} \quad (20.1)$$

This conversion in Equation 20.1 is graphically shown in [Figure 20.5](#). For example, the oxidizer can be specified as a blend of 60% O_2 and 40% air. That ratio of O_2 to air produces an equivalent of 39.8% overall O_2 in the oxidizer.

20.2.5 LOW-PURITY O_2

In some cases, it may be advantageous to use a technique such as vacuum or pressure swing adsorption (VSA/PSA) to produce oxygen because of significant cost reductions compared to cryogenic production methods. PSA/VSA methods use much less power-per-unit of oxygen produced. However, the oxygen purity is somewhat less than 100% in order to gain this power advantage. Typical purities are in the range of 90 to 95%, although they can be higher or lower depending on the design. Nearly all the benefits are achieved compared to using 100% purity, but at a much reduced cost. The main disadvantage is the potential to produce higher NO_x emissions.

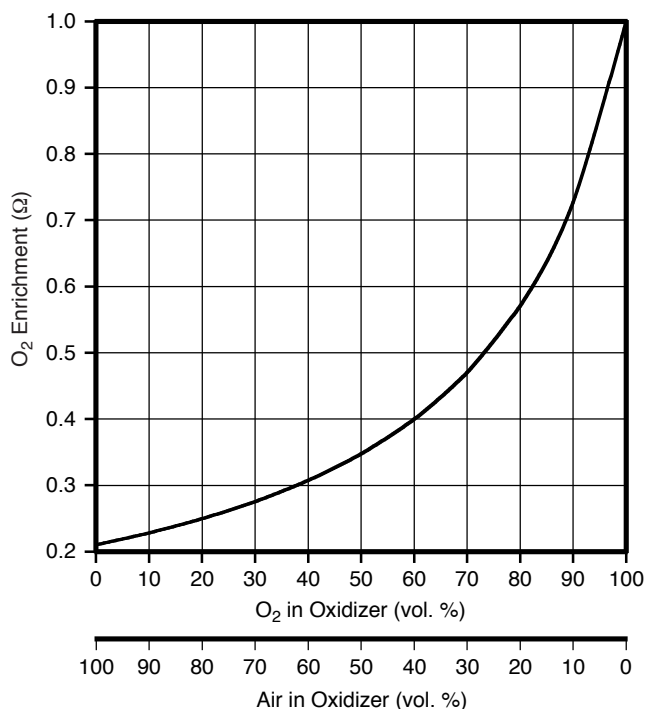


FIGURE 20.5 Oxidizer compositions for blends of air and pure O₂.¹

20.3 BASICS

In this section, methane (CH₄) is used to represent a typical fuel in a heating process. The analysis would be similar for other fuels.

20.3.1 DEFINITIONS

A generalized CH₄ combustion reaction can be written as:



The stoichiometry can be defined as:

$$S = \frac{\text{volume flow rate of O}_2 \text{ in the oxidizer}}{\text{volume flow rate of CH}_4} \quad (20.3)$$

Note that this definition differs slightly from the one commonly used in industry, where the stoichiometry is usually defined as the total oxidizer flow divided by the fuel flow. The problem with the definition commonly used in industry is that the stoichiometry must be recalculated whenever the oxidizer composition changes and stoichiometric conditions change for each oxidizer composition. This is not a concern if air is always used as the oxidizer, which is the case for the vast majority of combustion processes. The benefit of the definition used here is that stoichiometry is independent of the oxidizer composition, so stoichiometric conditions are the same for any oxidizer composition. In Equation 20.2, $S = x/1 = x$. Theoretically, for the complete combustion of CH₄, $S = 2.0$. Actual flames generally require some excess O₂ for complete combustion of the fuel. This is due

to incomplete mixing between the fuel and oxidant. For the fuel-rich combustion of CH₄, $S < 2.0$. For the fuel-lean combustion of CH₄, $S > 2.0$.

The O₂ mole fraction in the oxidizer can be defined as:

$$\Omega = \frac{\text{volume flow rate of O}_2 \text{ in the oxidizer}}{\text{Total volume flow rate of oxidizer}} \quad (20.4)$$

Using Equation 20.2, $\Omega = x/(x + y)$. If the oxidizer is air, $\Omega = 0.21$. If the oxidizer is pure O₂, $\Omega = 1.0$. The O₂ enrichment level is sometimes used. This refers to the incremental O₂ volume above that found in air. For example, if $\Omega = 0.35$, then the O₂ enrichment would be 14% (35% to 21%).

20.3.2 OPERATING REGIMES

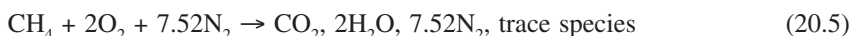
There have been two common operating regimes for oxygen-enhanced combustion. The first or lower regime is usually referred to as *low-level enrichment* ($\Omega < 0.30$). This is commonly used in retrofit applications where only a few modifications need to be made to the existing combustion equipment. It is used when only incremental benefits are required. For example, in many cases, the production rate in a heating process can be significantly increased even with only relatively small amounts of oxygen enrichment. In most cases, air/fuel burners can successfully operate up to about $\Omega = 0.28$ with no modifications.¹² For $\Omega > 0.28$, the flame may become unstable or the flame temperature may become too high for a burner designed to operate under air/fuel conditions. In some cases, it may be possible to make minor burner modifications to permit operation at slightly higher O₂ concentrations.

The other common operating regime is usually referred to as *high-level enrichment*, where high-purity oxygen ($\Omega > 0.90$) is used. This is used in higher temperature applications where the benefits of higher purity oxygen justify the added costs. The heating process is greatly intensified by the high-purity oxygen. In a retrofit situation, existing air/fuel burners are replaced by burners specifically designed to use the higher levels of O₂.

It has only been in the past decade that a significant number of combustion systems have been operated in the intermediate oxygen regime or *medium-level enrichment* ($0.30 < \Omega < 0.90$). Again, these usually require specially designed burners or retrofits of existing burners.

20.3.3 COMBUSTION PRODUCTS

The stoichiometric combustion of CH₄ with air can be represented by the following global equation:



It can be seen that more than 70 vol% of the exhaust gases is N₂. Similarly, a stoichiometric O₂/CH₄ combustion process can be represented by:



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 actual composition of the exhaust products from the combustion reaction depends on several factors, including the oxidizer composition Ω , the temperature of the gases, and the stoichiometry S .

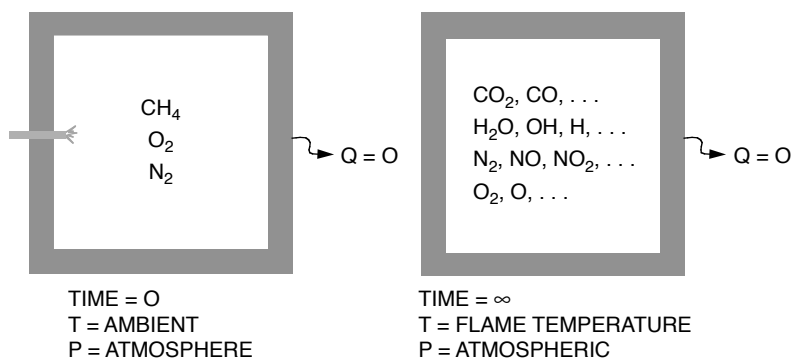


FIGURE 20.6 Adiabatic equilibrium reaction process.¹

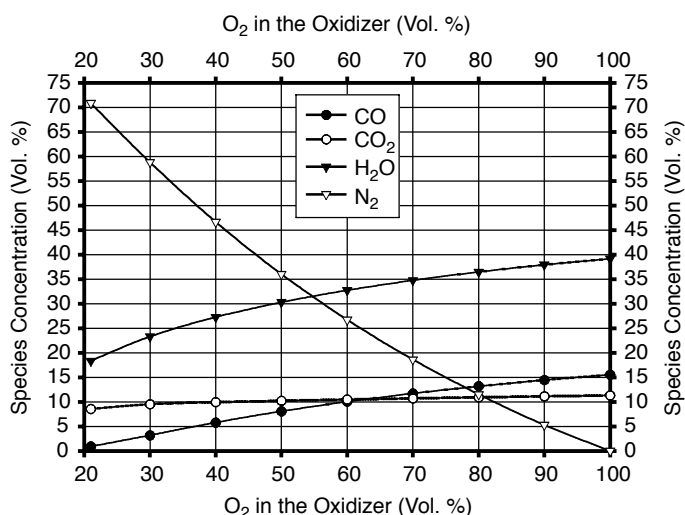


FIGURE 20.7 Predicted major species concentrations vs. oxidizer composition for an adiabatic equilibrium stoichiometric CH₄ flame.¹

A diagram showing an adiabatic equilibrium combustion reaction is shown in [Figure 20.6](#). This is not the case in an actual combustion process where heat is lost from the flame by radiation. [Figure 20.7](#) shows the predicted major species for the adiabatic equilibrium combustion of CH₄ as a function of the oxidizer composition. The calculations were made using a NASA computer program that minimizes the Gibbs free energy of a gaseous system.¹³ An equilibrium process means that there is an infinite amount of time for the chemical reactions to take place, or the reaction products are not limited by chemical kinetics. In actuality, the combustion reactions are completed in fractions of a second. An adiabatic process means that no heat is lost during the reaction, or that the reaction occurs in a perfectly insulated chamber. As expected, [Figure 20.7](#) shows that as N₂ is removed from the oxidizer, the concentration of N₂ in the exhaust products decreases correspondingly. Likewise, there is an increase in the concentrations of CO₂ and H₂O. For this adiabatic process, there is a significant amount of CO at higher levels of O₂ in the oxidizer. [Figure 20.8](#) shows the predicted minor species for the same conditions as [Figure 20.7](#). Note that trace species have been excluded from this figure. The radical species H, O, and OH all increase with the O₂ in the oxidizer. Unburned fuel in the form of H₂ and unreacted oxidizer in the form of O₂ also increase

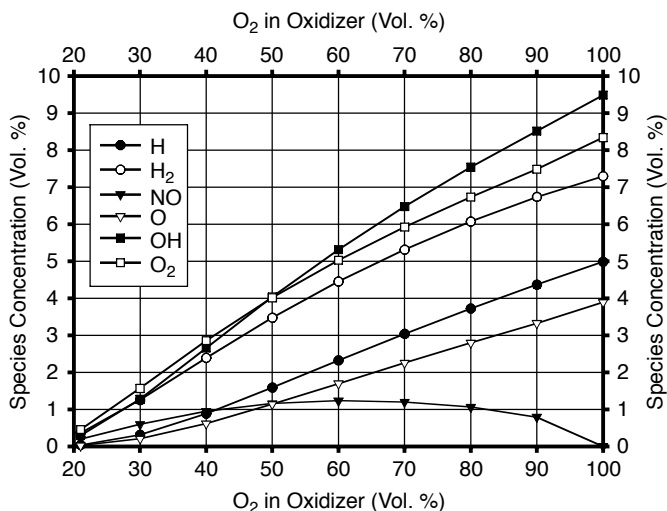


FIGURE 20.8 Predicted minor species concentrations vs. oxidizer composition for an adiabatic equilibrium stoichiometric CH_4 flame.¹

with the O_2 concentration in the oxidizer. This increase in radical concentrations, unburned fuel in the form of CO and H_2 , and unreacted O_2 are all due to chemical dissociation, which occurs at high temperatures.

The actual flame temperature is lower than the adiabatic equilibrium flame temperature due to radiation from the flame. The actual flame temperature is determined by how well the flame radiates its heat and how well the combustion system, including the load and the refractory walls, absorbs that radiation. A highly luminous flame generally has a lower flame temperature than a highly nonluminous flame. The actual flame temperature will also be lower when the load and the walls are more radiatively absorptive. This occurs when the load and walls are at lower temperatures and have higher radiant absorptivities. These effects are discussed in more detail in Chapter 2. As the gaseous combustion products exit the flame, they typically lose more heat by convection and radiation as they travel through the combustion chamber. The objective of a combustion process is to transfer the chemical energy contained in the fuel to the load, or in some cases to the combustion chamber. The more thermally efficient the combustion process, the more heat that is transferred from the combustion products to the load and to the combustion chamber. Therefore, the gas temperature in the exhaust stack is desirably much lower than in the flame in a thermally efficient heating process. The composition of the combustion products then changes with gas temperature.

Figure 20.9 shows the predicted major species for the equilibrium combustion of CH_4 with “air” (21% O_2 , 79% O_2) and with pure O_2 as a function of the gas temperature. The highest possible temperature for the air/ CH_4 and the O_2 / CH_4 reaction is the adiabatic equilibrium temperature of 3537°F (2220K) and 5038°F (3054K), respectively. For the air/ CH_4 reaction, there is very little change in the predicted gas composition as a function of temperature. For the O_2 / CH_4 reaction, there is a significant change in the composition as the gas temperature increases above about 3000°F (1900K). Figure 20.10 shows the predicted minor species for the same conditions as in Figure 20.9. Again, NO has been specifically excluded. For air/ CH_4 , none of the minor species exceeds 1% by volume. As the gas temperature increases, chemical dissociation increases. For the O_2 / CH_4 flame, significant levels of unreacted fuel (CO and H_2), radical species (O , H , and OH), and unreacted O_2 are present at high gas temperatures.

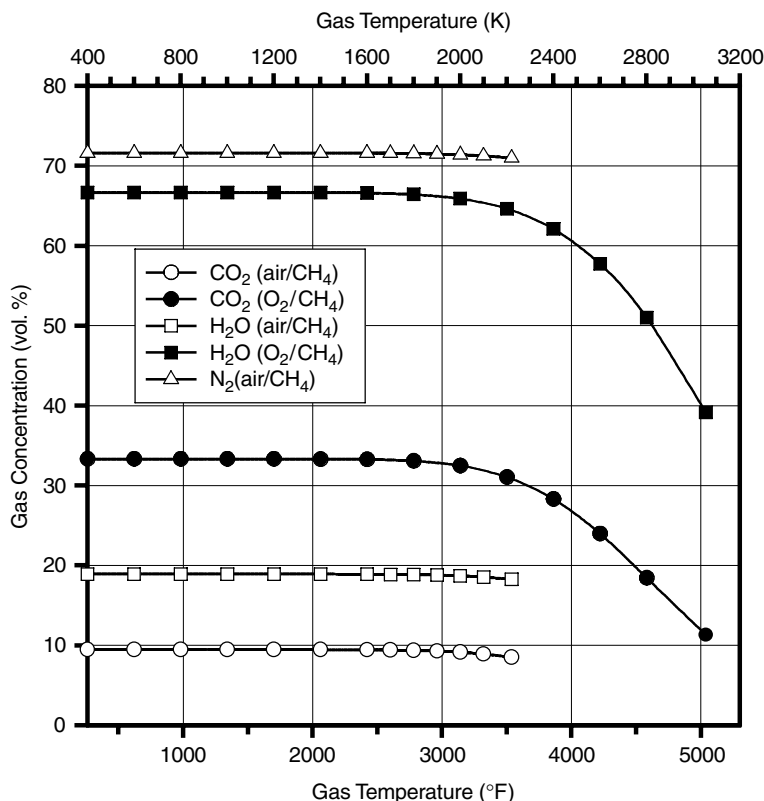


FIGURE 20.9 Equilibrium calculations for the predicted gas composition of the major species as a function of the gas temperature for air/CH₄ and O₂/CH₄ flames.¹

Figure 20.11 shows the predicted major species for the adiabatic equilibrium combustion of CH₄ with “air” (21% O₂, 79% N₂) and with pure O₂ as a function of the stoichiometry. For the air/CH₄ flames, the N₂ concentration in the exhaust gases strictly increases with the stoichiometry. The H₂O and the CO₂ concentrations peak at stoichiometric conditions ($S = 2.0$). For the O₂/CH₄ flames, the peak H₂O concentration occurs at slightly fuel-rich conditions ($S < 2.0$). The predicted CO₂ concentration strictly increases with stoichiometry for the range of stoichiometries shown. Similarly, Figure 20.12 shows the predicted minor species.

20.3.4 PROPERTIES

20.3.4.1 Flame Temperature

The flame temperature increases significantly when air is replaced with oxygen because N₂ acts as a diluent that reduces the flame temperature. Figure 20.13 is a plot of the adiabatic equilibrium flame temperature for H₂, CH₄, and C₃H₈ combustion, as a function of the oxidizer composition, for a stoichiometric combustion process.¹⁴ The flame temperature varies from about 3600 to 5000°F (2255 to 3033K) for air and pure oxygen, respectively. The graph shows a rapid rise in the flame temperature from air up to about 60% O₂ in the oxidizer. The flame temperature increases at a slower rate at higher O₂ concentrations. Table 20.1 shows the adiabatic flame temperature for some common gaseous fuels.

Figure 20.14 is a similar plot of the adiabatic equilibrium flame temperature for CH₄ flames as a function of the stoichiometry, for four different oxidizer compositions ranging from air to pure O₂.

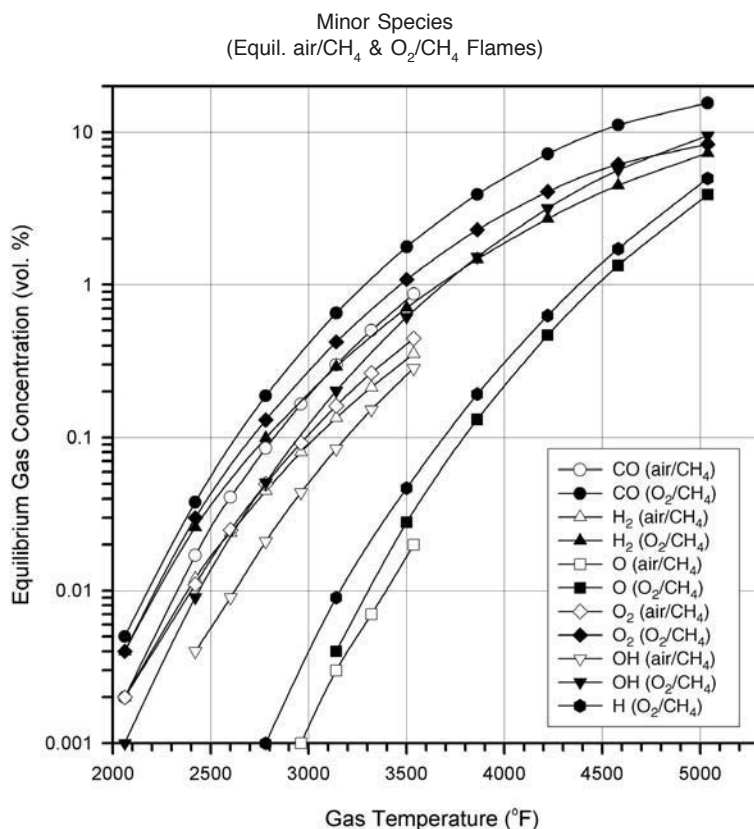


FIGURE 20.10 Equilibrium calculations for the predicted gas composition of the minor species as a function of the gas temperature for air/CH₄ and O₂/CH₄ flames.¹

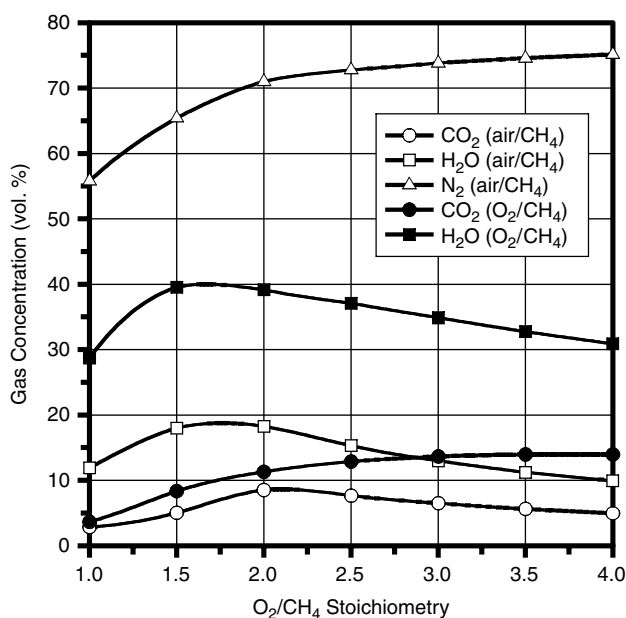


FIGURE 20.11 Adiabatic equilibrium calculations for the predicted gas composition of the major species as a function of the stoichiometry for air/CH₄ and O₂/CH₄ flames.¹

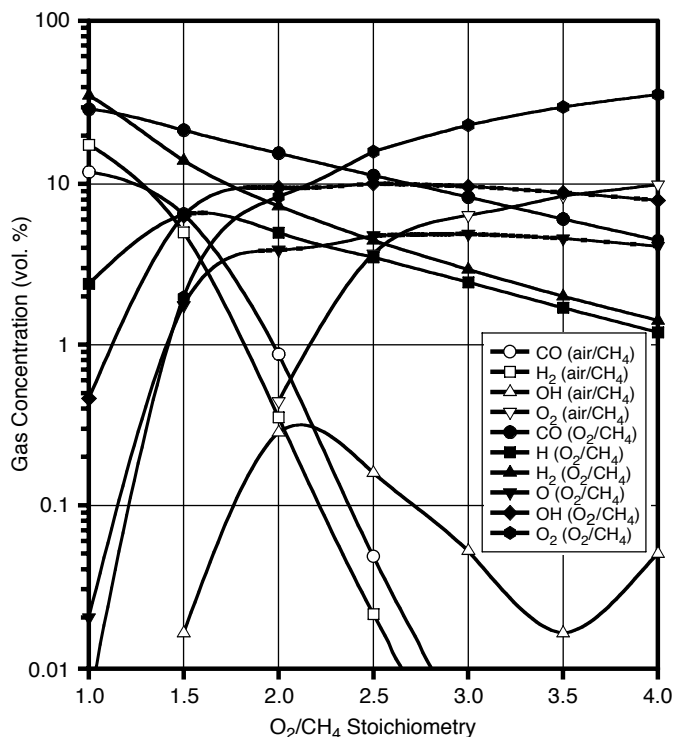


FIGURE 20.12 Adiabatic equilibrium calculations for the predicted gas composition of the minor species as a function of the stoichiometry for air/ CH_4 and O_2/CH_4 flames.¹

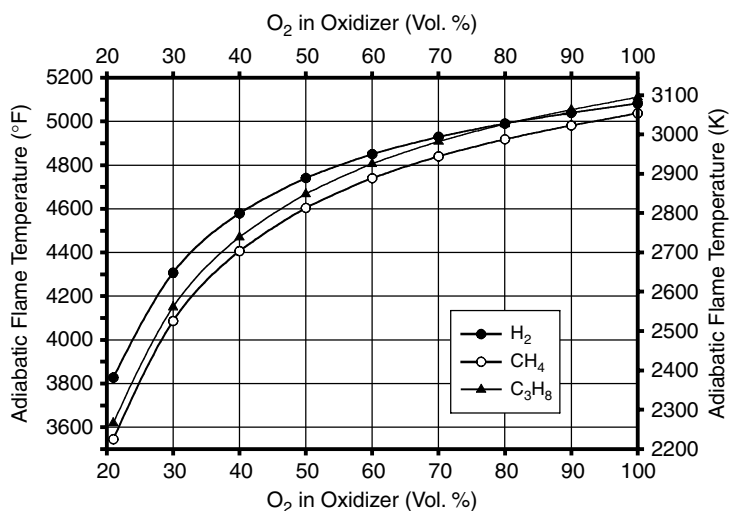


FIGURE 20.13 Adiabatic flame temperature vs. oxidizer composition for adiabatic equilibrium stoichiometric H_2 , CH_4 , and C_3H_8 flames.¹⁴

TABLE 20.1
Adiabatic Flame Temperatures¹

Fuel	Air		O ₂	
	(°F)	(K)	(°F)	(K)
H ₂	3807	2370	5082	3079
CH ₄	3542	2223	5036	3053
C ₂ H ₂	4104	2535	5556	3342
C ₂ H ₄	3790	2361	5256	3175
C ₂ H ₆	3607	2259	5095	3086
C ₃ H ₆	4725	2334	5203	3138
C ₃ H ₈	3610	2261	5112	3095
C ₄ H ₁₀	3583	2246	5121	3100
CO	3826	2381	4901	2978

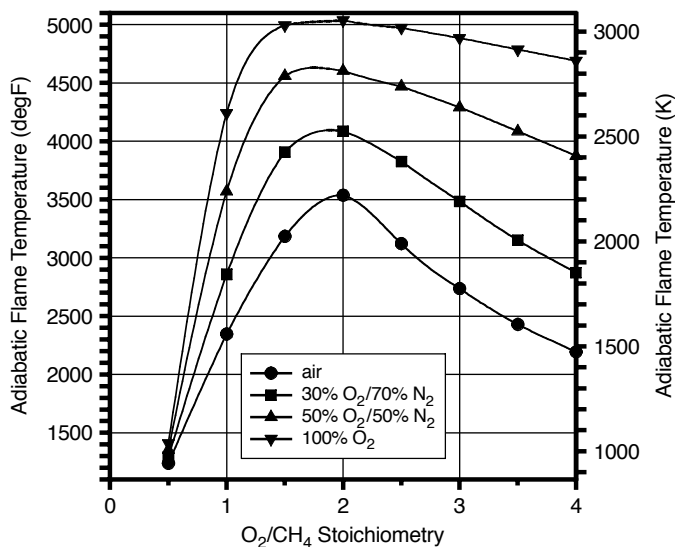


FIGURE 20.14 Adiabatic flame temperature vs. stoichiometry for a CH₄ flame and various oxidizers.¹

The peak flame temperatures occur at stoichiometric conditions. The lower the O₂ concentration in the oxidizer, the more the flame temperature is reduced by operating at nonstoichiometric conditions (either fuel-rich or fuel-lean). This is due to the higher concentration of N₂, which absorbs heat and lowers the overall temperature. Actual flame temperatures will be less than those given in Figure 20.13 and Figure 20.14 because of heat losses from the flame, which is not an adiabatic process.

Figure 20.15 shows how the adiabatic flame temperature varies as a function of the oxidizer preheat temperature. The increase in flame temperature is relatively small for the O₂/CH₄ flame because the increased sensible heat of the O₂ is only a fraction of the chemical energy contained in the fuel. For the air/CH₄ flames, preheating the air has a more dramatic impact because the increase in sensible heat is very significant due to the large mass of air in the combustion reaction.

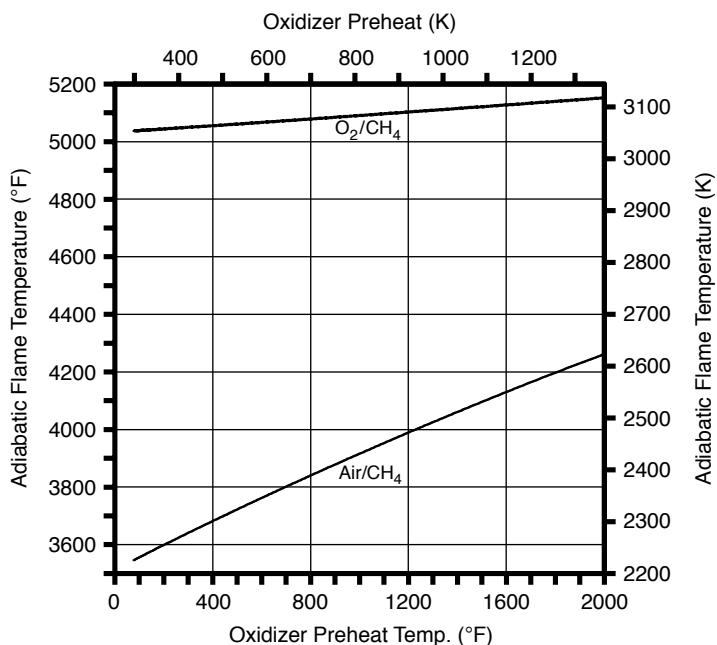


FIGURE 20.15 Adiabatic flame temperature vs. oxidizer preheat temperature for stoichiometric air/CH₄ and O₂/CH₄ flames.¹

20.3.4.2 Available Heat

Available heat is defined as the gross heating value of the fuel, less the energy carried out of the combustion process by the hot exhaust gases. N₂ in air acts as a ballast that carries energy out with the exhaust. Figure 20.16 is a graph of the available heat for the combustion of CH₄ as a function of the O₂ concentration in the oxidizer, for three different exhaust gas temperatures. As the exhaust gas temperature increases, the available heat decreases because more energy is carried out of the exhaust stack. There is an initial rapid increase in available heat as the O₂ concentration in the oxidizer increases from the 21% found in air. That is one reason why O₂ enrichment has been a popular technique for using OEC because the incremental increase in efficiency is very significant.

Figure 20.17 shows how the available heat, for stoichiometric air/CH₄ and O₂/CH₄ flames, varies as a function of the exhaust gas temperature. As the exhaust temperature increases, more energy is carried out of the combustion system and less remains in the system. The available heat decreases to zero at the adiabatic equilibrium flame temperature where no heat is lost from the gases. The figure shows that even at gas temperatures as high as 3500°F (2200K), the available heat of an O₂/CH₄ system is still as high as 60%. The figure also shows that it is usually not very economical to use air/CH₄ systems for high-temperature heating and melting processes. At an exhaust temperature of 2500°F (1600K), the available heat for the air/CH₄ system is only a little over 30%. Heat recovery in the form of preheated air is commonly used for higher temperature heating processes to increase the thermal efficiencies.

Figure 20.18 shows how the available heat increases with the oxidizer preheat temperature. The thermal efficiency of the air/CH₄ doubles by preheating the air to 2000°F (1400K). For the O₂/CH₄ flames, the increase in efficiency is much less dramatic by preheating the O₂. This is because the initial efficiency with no preheat is already 70% and because the mass of the O₂ is not nearly as significant in the combustion reaction as compared to the mass of air in an air/fuel flame. There are also safety concerns when flowing hot O₂ through piping, heat recuperation equipment, and a burner.

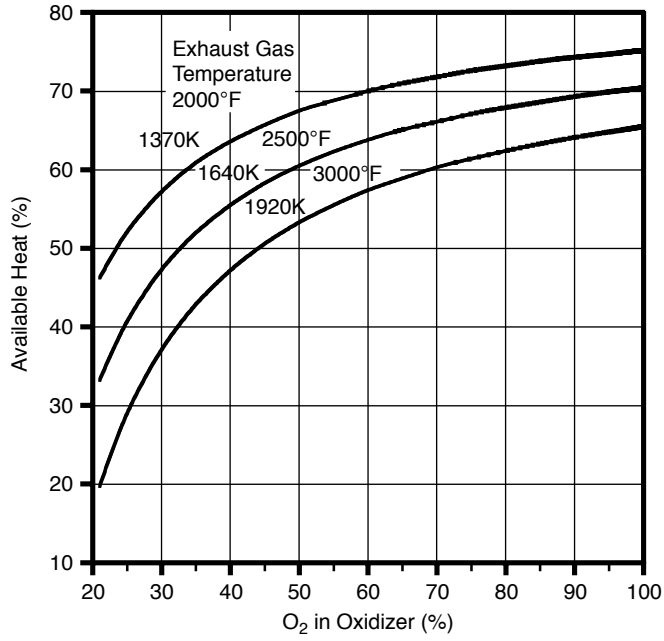


FIGURE 20.16 Available heat vs. oxidizer composition for a stoichiometric CH₄ flame at exhaust temperatures of 2000, 2500, and 3000°F (1370, 1640, 1920K).¹

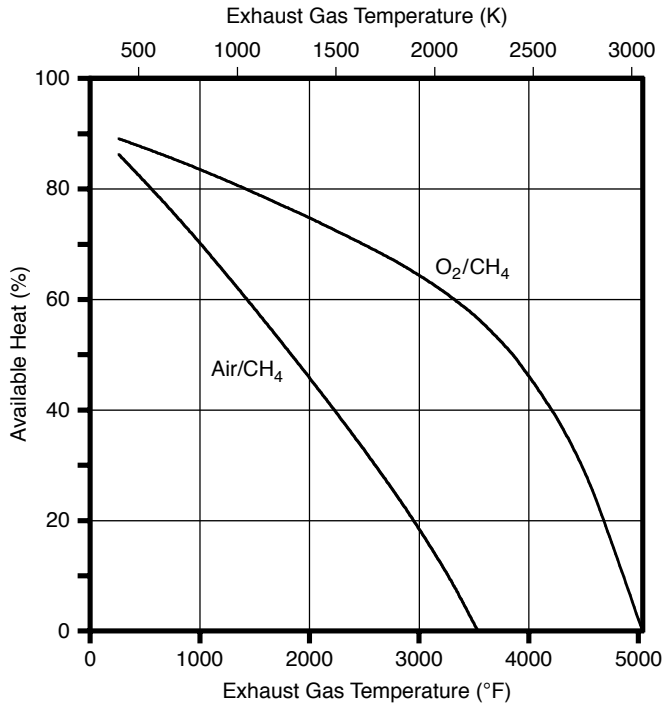


FIGURE 20.17 Available heat vs. exhaust gas temperature for stoichiometric air/CH₄ and O₂/CH₄ flames.¹

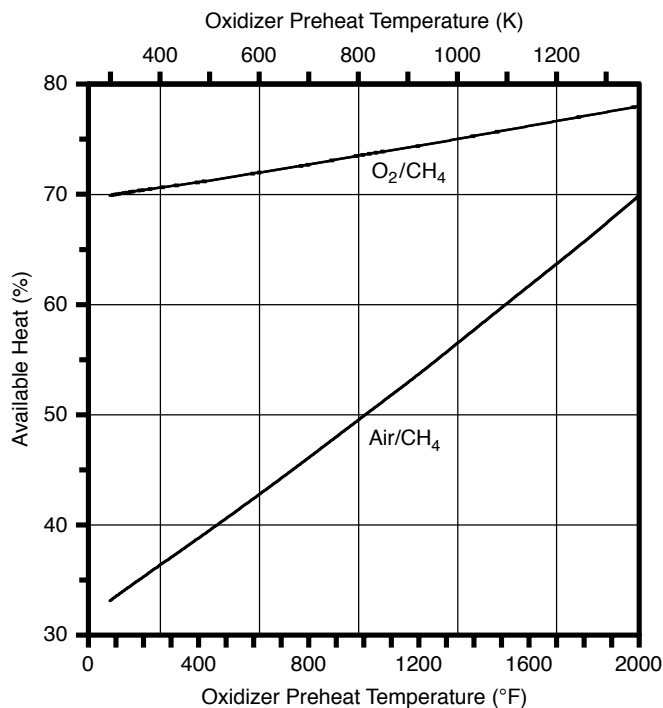


FIGURE 20.18 Available heat vs. oxidizer preheat temperature for stoichiometric, equilibrium air/CH₄, and O₂/CH₄ flames at an exhaust gas temperature of 2500°F (1644K).¹

The fuel savings for a given technology can be calculated using the available heat curves:

$$\text{Fuel Savings (\%)} = \left(1 - \frac{AH_2}{AH_1} \right) \times 100 \quad (20.8)$$

where AH_1 is the available heat of the base case process and AH_2 is the available heat using a new technology. For example, if the base case process has an available heat of 30% and the available heat using the new technology is 45%, then the fuel savings = $(1 - 45/30) \times 100 = -50\%$, which means that 50% less fuel is needed for process 2 compared to process 1.

20.3.4.3 Ignition Characteristics

20.3.4.3.1 Flammability Limits

As the oxygen concentration in the oxidizer increases, the flammability limits for the fuel increase. Figure 20.19 shows the increase for CH₄ combustion with oxidizers having a range of O₂ concentrations.¹⁵ The upper flammability limit increases linearly with the O₂ concentration in the oxidizer, while the lower flammability limit is nearly constant for oxidizers with more than about 35% O₂ in the oxidizer. Table 20.2 shows examples of how using O₂ instead of air widens the flammability range for a given fuel.

20.3.4.3.2 Flame Speeds

OEC increases the flames speed as shown in Figure 20.20. In a flame, the flame front is located where the gas velocity going away from the burner equals the flame velocity going toward the burner.

TABLE 20.2
Flammability Limits (Vol.% Fuel in Fuel/Oxidizer Mixture) of Common Fuels in Air and in O₂¹

Fuel	Limit in Air		Limit in O ₂	
	Lower	Upper	Lower	Upper
H ₂	4.1	74	4.0	94
CH ₄	5.3	14	5.4	59
C ₂ H ₆	3.2	12.5	4.1	50
C ₃ H ₈	2.4	9.5	—	—
C ₂ H ₄	3.0	29	3.1	80
C ₃ H ₆	2.0	11	2.1	53
CO	12.5	74	16	94

Adapted from Turin and Huebler.¹⁵

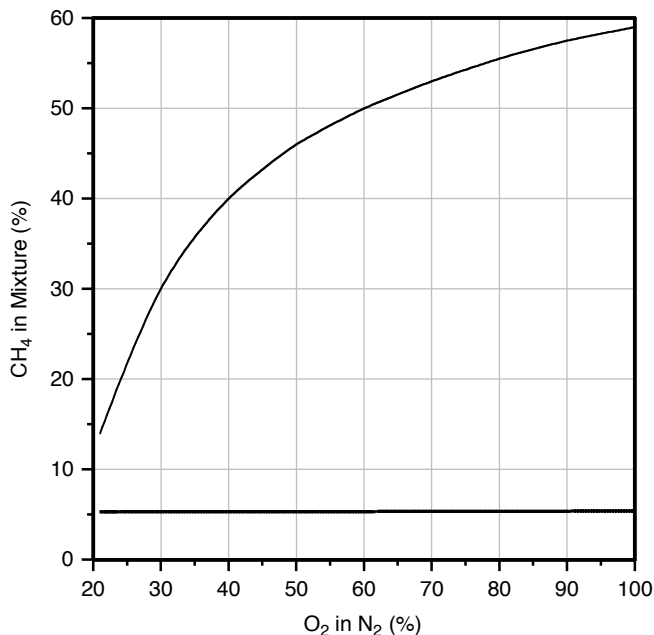


FIGURE 20.19 Upper and lower flammability limits vs. oxidizer composition for a CH₄ flame.¹

The gas velocity exiting the burner must be at least equal to the flame speed. If not, the flame will flashback inside the burner, leading to either flame extinguishment or to an explosion. Because flame speeds are higher using OEC, the burner exit velocities in an oxygen-enhanced combustion system are usually higher than in air/fuel systems.

20.3.4.3.3 Ignition Energy

Less energy is required for ignition using OEC, as shown in Figure 20.21.¹⁶ This means that it is easier to ignite flames with OEC compared to air/fuel flames where much of the ignition energy is absorbed by the diluent nitrogen. The disadvantage is that it is also easier to inadvertently ignite an OEC system, which is why the proper safety precautions must be followed.

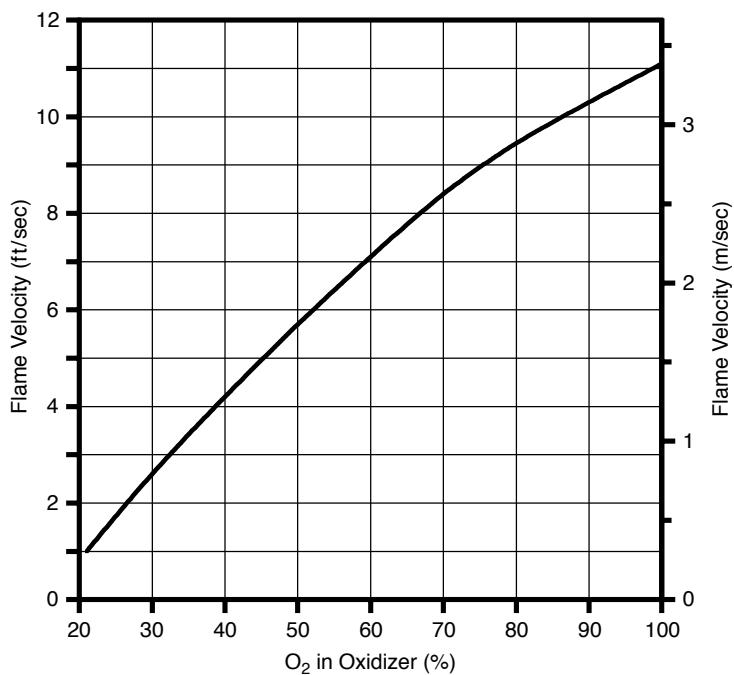


FIGURE 20.20 Normal flame propagation velocity vs. oxidizer composition for a stoichiometric CH₄ flame.¹

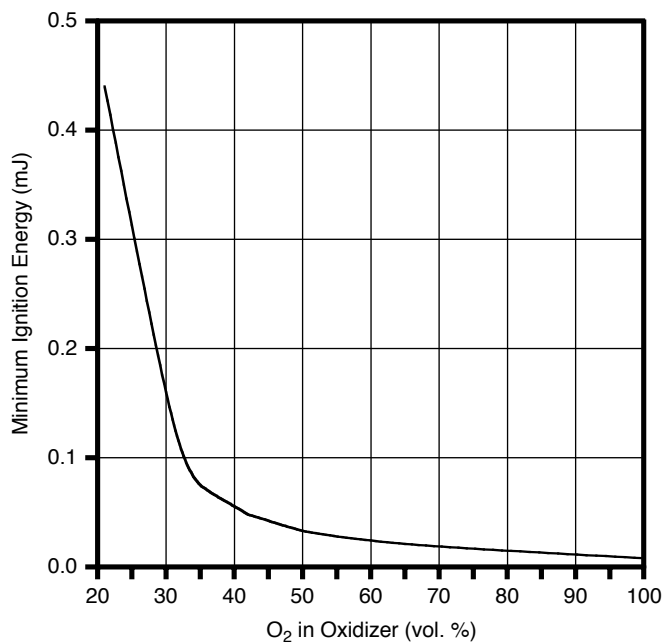


FIGURE 20.21 Minimum ignition energy vs. oxidizer composition for an atmospheric pressure, stoichiometric CH₄ flame.¹

20.3.4.3.4 Ignition Temperature

Using OEC also reduces the ignition temperature. Figure 20.22 shows the ignition temperature for CH₄ as a function of the O₂ concentration in the oxidizer ranging from 15 to 35% O₂.¹⁷ Table 20.3 shows ignition temperatures for gaseous fuels combusted with air and with pure O₂.¹⁸ The graph and the table both show that it is easier to ignite flames that are enhanced with oxygen.

20.3.4.4 Flue Gas Modification

20.3.4.4.1 Reduced Volume

Oxygen-enhanced combustion basically involves removing N₂ from the oxidizer. One obvious change compared to air/fuel combustion is the reduction in the flue gas volume. Figure 20.23 shows the exhaust gas flow rate, normalized to the fuel flow rate, for the stoichiometric combustion of CH₄ where it has been assumed that all the combustion products are CO₂, H₂O, and N₂ (except when the oxidizer is pure O₂). This means that for each unit volume of fuel, 3 normalized volumes of gas are produced for oxy/fuel compared to 10.5 volumes for air/fuel. The reduction in flue gas volume is even larger when considering the increased fuel efficiency using OEC. Less fuel is required to process a given amount of material; therefore, fewer exhaust products are generated.

TABLE 20.3
Ignition Temperatures in Air and in Oxygen¹

Fuel	Air		O ₂	
	(°F)	(K)	(°F)	(K)
H ₂	1062	845	1040	833
CH ₄	1170	905	1274	829
C ₃ H ₈	919	766	874	741
C ₄ H ₁₀	766	681	541	556
CO	1128	882	1090	861

Adapted from Reference 18.

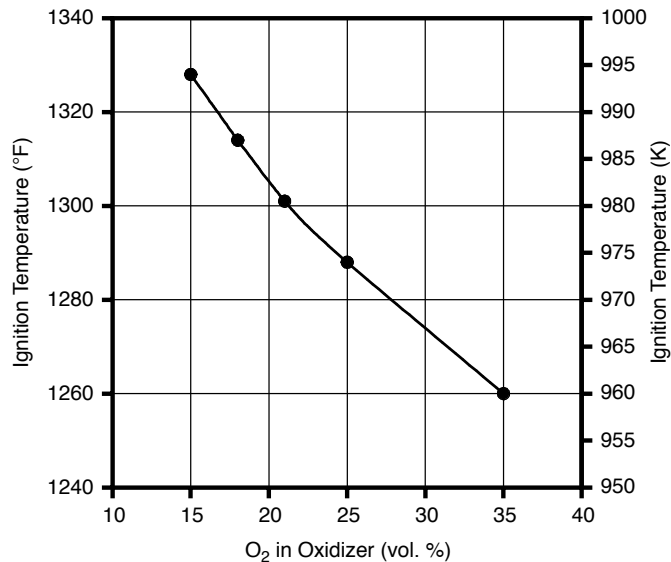


FIGURE 20.22 Ignition temperature vs. oxidizer composition for a stoichiometric CH₄ flame.¹

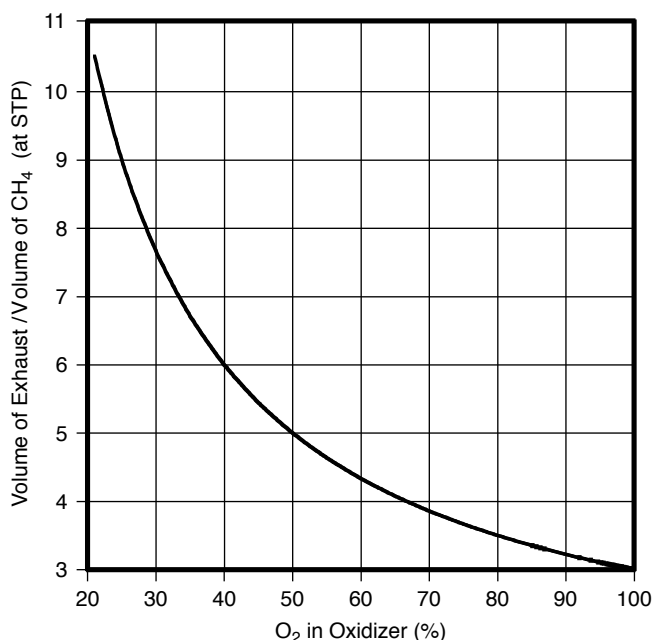


FIGURE 20.23 Normalized flue gas volume vs. oxidizer composition for a stoichiometric CH₄ flame.¹

20.3.4.4.2 Different Composition

Another potential benefit of OEC related to the flue gas is that the composition is significantly different than that produced by air/fuel combustion, as was shown in Figure 20.7. The products of combustion of a stoichiometric oxy/methane flame are approximately one-third CO₂ and two-thirds H₂O by volume compared to air/methane, which has about 71% N₂, 10% CO₂, and 19% H₂O. Any pollutants, such as NO_x or SO_x, are easier to remove in an oxy/fuel exhaust, because they are in much higher concentrations compared to the air/fuel exhaust stream, which is highly diluted by N₂. If the water is condensed from the exhaust products, the remaining gas is nearly all CO₂ for an oxy/fuel exhaust. Because CO₂ has been identified as a global warming gas, it can be more easily recovered from an oxy/fuel combustion system compared to an air/fuel system. The CO₂ can then either be used in another process, such as deep well injection for oil recovery, or it can be “disposed” of, such as by deep ocean injection.

20.4 GENERAL BENEFITS

Air consists of approximately 79% N₂ and 21% O₂, by volume. Only the O₂ is needed in the combustion reaction. By eliminating N₂, many benefits can be realized. These benefits include increased productivity, energy efficiency, turndown ratio, and flame stability, with reduced exhaust gas volume and pollutant emissions. These benefits are discussed next.

20.4.1 INCREASED PRODUCTIVITY

In most high-temperature heating processes, flame radiation is the dominant mode of heat transfer (see Chapter 6). Radiation is dependent on the fourth power of the absolute temperature. The higher temperatures associated with OEC increase the radiation from the flame to the load. This then increases the heat transfer to the load, which leads to increased material processing rates through

the combustion chamber. Therefore, more material can be processed in an existing system, or new systems can be made smaller for a given processing rate. This is particularly important where space in a plant is limited. The environment benefits because of the reduction in the size of the equipment since less material and energy are needed in fabricating the combustion system. To take advantage of increased processing rates, the rest of the production system must be capable of handling the increased throughput. For example, the material handling system may need to be modified to handle the increased material flow rates.

The incremental costs of adding OEC to an existing combustion system are usually small compared to the capital costs of either expanding an existing system or adding new equipment to increase production. This has historically been one of the most popular reasons for using OEC. The advantage of OEC is that it can also be used intermittently to meet periodic demands for increased production. For example, if the demand for aluminum cans increases during the summer because of increased beverage consumption, OEC can be used at that time to meet the increased demand for aluminum. If the demand decreases in the winter, then the OEC system could be throttled back or turned off until it is needed again. In most cases, using OEC would be much more economical than adding new equipment for increased capacity if the increased production demands are only temporary.

20.4.2 HIGHER THERMAL EFFICIENCIES

By using oxygen instead of air, more energy goes into the load, instead of being wasted in heating N_2 . The energy needed to make O_2 from air is only a small fraction of the energy used in the combustion process. Therefore, the overall process uses less energy for a given amount of production due to the higher available heat. In some instances, the cost of the oxygen can be offset by the reduction in fuel costs because of the increase in energy efficiency. This is often the case when OEC is used to supplement a process that uses electricity, which is generally more expensive than fossil fuel combustion. In some cases, it is possible to substitute a less expensive source of energy for an existing source of energy. For example, in the glass industry, the furnaces are fueled primarily by oil or natural gas and commonly “boosted” with electrical energy. It has been shown that some or all of the more expensive electrical energy can be eliminated by the proper use of OEC.

One common reason for using OEC is a reduction in the specific fuel consumption where less fuel is required for a given unit of production because of the improvement in available heat. A recent study projects that, for example, the cost of natural gas was expected to rise by about 10% from 1993 to the year 2000.⁷ At the same time, the cost of oxygen was expected to decrease by 10% due to lower electricity costs and improvements in oxygen production technology. The rising cost of fuel and the lowering cost of oxygen both make OEC a more attractive technology based solely on fuel savings.

Oxy/fuel combustion has been used in many applications in the steel industry, including both continuous and batch reheat furnaces, soaking pits, and ladle preheaters. Fuel savings of up to 60% have been reported.¹⁹ Typical fuel savings achieved by converting from air/fuel to oxy/fuel combustion are given in Table 20.4.²⁰ Another example, from the glass industry, is Spectrum Glass, which reported fuel savings of 50% when it converted from air/fuel to oxy/fuel in its glass melting furnaces.²¹

20.4.3 IMPROVED FLAME CHARACTERISTICS

20.4.3.1 Higher Turndown Ratio

As previously shown in Figure 20.19 and Table 20.2, as the oxygen concentration in the oxidizer increases, the flammability limits for the fuel increase. This leads to an increased turndown ratio for the combustion system. A flame can exist under a wider range of conditions. For example, an air/ CH_4

TABLE 20.4
Fuel Savings by Retrofitting Air/Fuel
Systems with Oxy/Fuel¹

Industry	Fuel Savings (%)
Steel	40–60
Aluminum, lead	40
Copper	40–60
Glass	30–40
Waste incineration	50
Sulfuric acid recovery	50

Adapted from Reference 20.

flame could exist at stoichiometries between about 1.3 and 3.8. An O_2/CH_4 flame could exist at stoichiometries between about 0.7 and almost 18. This is a consequence of removing the diluent N_2 .

20.4.3.2 Increased Flame Stability

Oxygen-enhanced flames have higher flame speeds than air/fuel flames. This means that to prevent either flashback or flame extinguishment, the minimum gas exit velocities for an OEC flame must be higher than those for an air/fuel flame. The potential for flashback is discussed further in Section 20.5.5.

Lewis and von Elbe have defined the critical boundary velocity gradient for a cylindrical tube as follows:

$$g = \frac{4V}{\pi R^3} \quad (20.9)$$

where V is the volumetric flow of a premixed mixture of fuel and oxidizer and R is the radius of the tube.²² For flashback, V is the minimum flow rate before the flame is extinguished due to flashback. The critical boundary velocity gradients for flashback were experimentally determined for premixed methane flames using a round tube. At stoichiometric conditions, the gradient was approximately 2100 and 510,000 s^{-1} for oxidizers of air and pure oxygen, respectively. This shows that much higher exit velocities can be used with OEC without blowing off the flame. These higher velocities generally produce more stable flames that are not as easily disturbed by flow patterns within a combustion chamber.

20.4.3.3 Better Ignition Characteristics

As shown in Figure 20.21 and Figure 20.22, another benefit of using OEC compared to air is that less energy is required for ignition which occurs at a lower temperature. This means that it is easier to ignite flames with OEC compared to air/fuel flames. The disadvantage is that it is also easier to inadvertently ignite an OEC system, which is why the proper safety precautions must be followed. This improvement in ignition characteristics can be especially important when using liquid or solid fuels, which are generally more difficult to ignite compared to gaseous fuels.

20.4.3.4 Flame Shape Control

OEC can be used to control the shape of a flame for an existing air/fuel system. For example, premix enrichment of oxygen into a combustion air stream has been used to shorten the flame length. Undershot enrichment can be used to lengthen a flame. Retrofitting an air/fuel system with

oxygen in an air-oxy/fuel configuration has also been used to control the flame to produce a desired shape. Controlling the flame shape may be done to avoid overheating the refractory in a given location, or to change the heat flux and temperature profiles within the combustion chamber.

20.4.4 LOWER EXHAUST GAS VOLUMES

Eliminating ballast N_2 from air can reduce the exhaust gas flow rate by as much as 96%.²³ In glass manufacturing processes, flue gas reductions from 93 to 98% by mass have been measured.²³ This reduction in the flue gas volume has several advantages. The size of the exhaust gas ductwork can be reduced. Alternatively, OEC has been used effectively to increase production in combustion systems, which are at the limit of their exhaust gas capacity. Normally, increasing capacity would also require a larger flue gas treatment system. However, the flue gas volume actually decreases with OEC, so no new ductwork and treatment equipment are required. Another benefit of the reduction in the flue gas volume is that it can increase the efficiency of the existing flue gas treatment equipment.²⁴ This is because it is easier to treat the exhaust gases since the pollutant emissions are in higher concentrations and therefore easier to remove. The size of the post-treatment equipment can be proportionately reduced, due to the lower flow rates. This saves space, energy, materials, and money.

For a given combustion chamber, the flue gas volume reduction has the added benefit of reducing the average gas velocity by almost an order of magnitude. Lower gas velocities entrain fewer fine particles from the waste. This reduces particulate emissions. Another potential advantage of the reduced velocity in the combustor chamber is the increased residence time. In an incinerator, increased residence time usually increases the level of destruction of undesired organic species in the off gases.

20.4.5 HIGHER HEAT TRANSFER EFFICIENCY

It has been argued that the efficiency of transferring heat from the flame to the load can be increased using OEC.²⁵ In a nonluminous flame, the flame emissivity is higher for an oxygen-enhanced flame, compared to an air/fuel flame. This is due to the higher concentrations of CO_2 and H_2O , which are the gases that radiate in a flame.²⁶ There is no radiation from the N_2 in the flame. These effects are discussed in Chapters 2 and 6.

20.4.6 REDUCED COSTS

Because OEC intensifies the combustion process and reduces the volume of flue gases, many combustion chambers and the associated equipment can be significantly reduced in size. OEC can be used to reduce the cost of the off-gas treatment system.²⁴ Reducing the equipment size can reduce the construction costs and the space required for the heating system.

In some cases, OEC can be used to reduce the costs of raw materials used in a process. Processes that have raw materials containing fine particles generally require some type of baghouse or scrubbing system to remove any particulates that might be entrained in the flue gases so they are not emitted into the atmosphere. For a given size combustion system, replacing air/fuel combustion with OEC can dramatically reduce the amount of particles entrained in the exhaust gases because the gas velocities are much lower, as some or all of the nitrogen is removed from the system. Not only does this reduce the cost of cleaning up the exhaust gases, but it also reduces raw material costs because less is carried out of the system. Specific examples are given in the application sections of this book.

Another type of raw materials saving is an improvement in the process where less material is needed for a given product. One example is in the glass industry where colorants are used to color the glass. Spectrum Glass reported savings of \$20,000/year in colorants when it converted from air/fuel to oxy/fuel because of the improvement in color stabilization using OEC.²¹

20.4.7 INCREASED FLEXIBILITY

There are many other benefits specific to a given process that can be achieved. OEC can increase the flexibility of a heating system.²⁷ In some cases, a wider range of materials can be processed with OEC compared to air/fuel combustion. In other cases, OEC may be required if very high melting temperatures are required. For example, some ceramic and refractory products require firing temperatures of 2900°F (1900K) and higher.²⁸ Those temperatures are difficult if not impossible to achieve with standard air/fuel combustion with no air preheating. A heating system can also be brought up to operating conditions more quickly with OEC compared to air/fuel systems because of the higher heating intensity. For example, it has been shown that using OEC in metal reheat furnaces can substantially improve the ability to start up and shut down quickly.²⁹

A combustion process can react more quickly to changes because of the higher heating intensity. This reduces the time, for example, that it takes to change processing rates or to change the product mix. OEC can give tighter control of the heating profile because of the higher intensity.

20.4.8 IMPROVED OPERATIONS

OEC can improve product quality. For example, the proper use of OEC in a glass furnace can reduce the number of rejects. Quality improvements have been documented in nonferrous smelting, lamp-making, chemical incineration, enamel fritting, and in both ceramic and lime kiln operations.³⁰

By adding oxygen to an existing air/fuel combustion system, the flame length usually shortens. Some oxy/fuel burners are specifically designed to have a short flame length to either intensify the heat release or to better fit into a given furnace geometry to prevent flame impingement on the refractory wall opposite the burner. Shortening existing air/fuel flames or using short flame-length oxy/fuel burners can reduce wear on the refractory by reducing the effects of direct flame impingement on the walls.³¹ As discussed in the next section, however, the improper use of oxygen in a combustion system can lead to refractory damage due to the higher flame temperatures associated with OEC.

20.5 POTENTIAL PROBLEMS

There are potential problems associated with the use of oxygen-enhanced combustion if the system is not properly designed. Many of the potential problems can be generally attributed to the increased combustion intensity.

20.5.1 REFRACTORY DAMAGE

20.5.1.1 Overheating

As previously shown, oxygen-enhanced flames generally have significantly higher flame temperatures compared to conventional air/fuel flames. If the heat is not properly distributed, the intensified radiant output from the flame can cause refractory damage. Today's OEC burners are designed for uniform heat distribution to avoid overheating the refractory surrounding the burner. The burners are normally mounted in a refractory burner block, which is then mounted into the combustion chamber. The burner blocks are made of advanced refractory materials, such as zirconia or alumina, and are designed for long, maintenance-free operation.

If the burner position and firing rate in the furnace are improperly chosen, refractory damage can result. For example, if the flame from an OEC burner is allowed to impinge directly on the wall of a furnace, most typical refractory materials would be damaged. This can be prevented by the proper choice of the burner design and positioning. The flame length should not be so long

that it impinges on the opposite wall. The burner mounting position in the furnace should be chosen to avoid aiming the flame directly at furnace refractories.

20.5.1.2 Corrosion

Another potential refractory problem can result from the increased volatile concentration in the combustion chamber by using OEC. This is a particular problem in the glass industry, for example, where corrosive volatile species are emitted during the glassmaking process. By removing the large quantity of diluent N_2 normally present in air/fuel combustion, these volatile species are now at much higher concentrations in the gas space. This can cause damage to the refractories by corrosion.

20.5.2 NONUNIFORM HEATING

This is an important concern when retrofitting existing systems that were originally designed for air/fuel combustion. By intensifying the combustion process with OEC, there is the possibility of adversely affecting the heat and mass transfer characteristics within the combustion chamber. These issues are only briefly discussed here.

20.5.2.1 Hot Spots

OEC normally increases the flame temperature, which also increases the radiant heat flux from the flame to the load. If the increased radiant output is very localized, then there is the possibility of producing hot spots on the load. This could lead to overheating, which might damage or degrade the product quality. Today, burners for OEC have been specifically designed to avoid this problem.

20.5.2.2 Reduction in Convection

As shown in [Figure 20.23](#), the total volume flow rate of exhaust products is significantly reduced using OEC. However, the average gas temperature is usually higher, but not by enough to offset the reduced gas flow rate. The convective heat transfer from the exhaust gases to the load may be reduced as a result. Another important aspect of convection is mass transfer. In some heating processes, especially those related to drying or removing volatiles, the reduced gas flow rate in the combustion chamber could adversely affect the mass transfer process. This can be offset using a burner that incorporates furnace gas recirculation, which increases the bulk volume flow inside the combustion chamber to help in removing volatiles that evolve from the load during the heating process.

20.5.3 FLAME DISTURBANCE

In recent years, the trend in burner design for OEC has been toward lower momentum flames. One example is the Cleanfire[®] burner (see [Figure 20.24](#)³²), which has been used extensively in the glass industry.³³ These lower momentum flames tend to be longer and more luminous than the high-intensity burners that have traditionally been used in the past. One issue that needs to be considered is that these low momentum flames can be more easily disturbed than the high momentum flames. One example is when low momentum OEC flames are added or partially retrofitted into a furnace containing high momentum air/fuel burners. The high momentum flames can adversely affect the combustion characteristics of the low momentum flames if the geometry is not properly designed. This may be a problem especially if a high momentum burner is directly opposed to and firing at a low momentum burner. Another example of possible flame disturbance is where low momentum flames are located near the exhaust of the furnace. If there are many burners in the furnace, the large exhaust gas flow past a low momentum flame can again disturb those flames. The problem

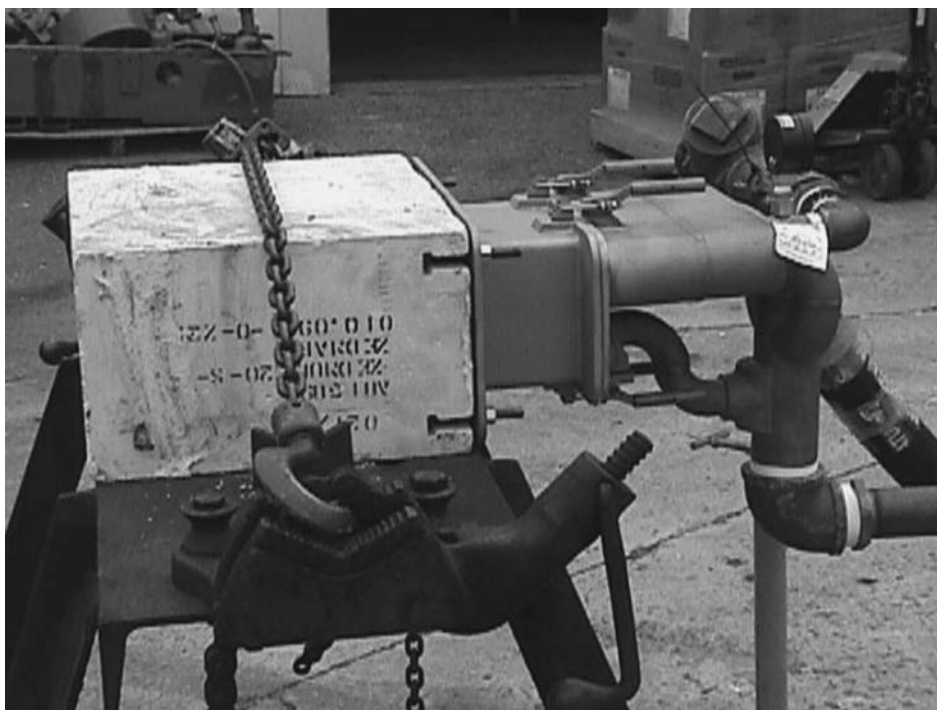


FIGURE 20.24 Cleanfire burner.³²

of flame disturbance can be eliminated by the proper choice of burners, burner mounting positions, and burner operating conditions.

20.5.4 INCREASED POLLUTANT EMISSIONS

20.5.4.1 NO_x

When O₂ enrichment is used in an existing air/fuel combustion system, there may be an increase in NO_x emissions.³⁴ This is due to the increased flame temperature, which increases thermal NO_x formation.

20.5.4.2 Noise

As shown in [Figure 20.20](#), the flame velocity increases with OEC compared to air/fuel combustion. This means that the gas velocities exiting the burner must be increased to compensate for the higher flame speed. These higher gas velocities can increase the jet noise of the burner. The older-style, high-intensity oxy/fuel burners used in metal melting applications were generally very noisy in the open air. However, the noise was generally muffled by the refractory-lined combustion chamber. Also, although the gas velocities were high, the total volume flow rate was much lower by removing N₂ from the oxidizer, which also was a mitigating factor for the noise. Today, the low momentum oxy/fuel burners are actually quieter than many air/fuel burners. Noise is discussed in more detail in Chapter 7.

20.5.5 FLASHBACK

The use of OEC intensifies the combustion reactions. One consequence of this higher reactivity is the increased risk of flashback. Flashback occurs when the gas velocity exiting the burner is less than the flame velocity. This causes the flame front to move toward the burner. If the fuel and the

oxidizer are premixed, the flame can burn inside the burner housing, which creates the potential for an explosion. As shown in Figure 20.25, the gradient for flashback increases rapidly as the oxygen concentration in the oxidizer increases. This means that the minimum volumetric flow rate increases with OEC to prevent flashback. For blowoff, V is the maximum flow rate before the flame is extinguished due to blowoff.

In premixed systems, there is often a provision for arresting the flame if it should flash back. It may be a separate device known as a flame arrestor, or it may simply be incorporated into the burner design. The general idea in most flame arrestors is to remove enough heat from a flame that is flashing back to cool the flame down below its ignition point. In essence, the third leg of the combustion triangle (Figure 20.26) is removed to extinguish the flame because neither the fuel nor the oxidizer can be removed quickly enough to prevent the flame from flashing back.

In virtually all combustion systems using OEC, the fuel and the oxidizer are not mixed until they exit the burner. This is commonly known as a nozzle-mix burner. This essentially eliminates the potential for an explosion caused by flashback. If the flame were to flash back toward the burner, it would be extinguished at the burner nozzle. The flame would not continue to travel into the

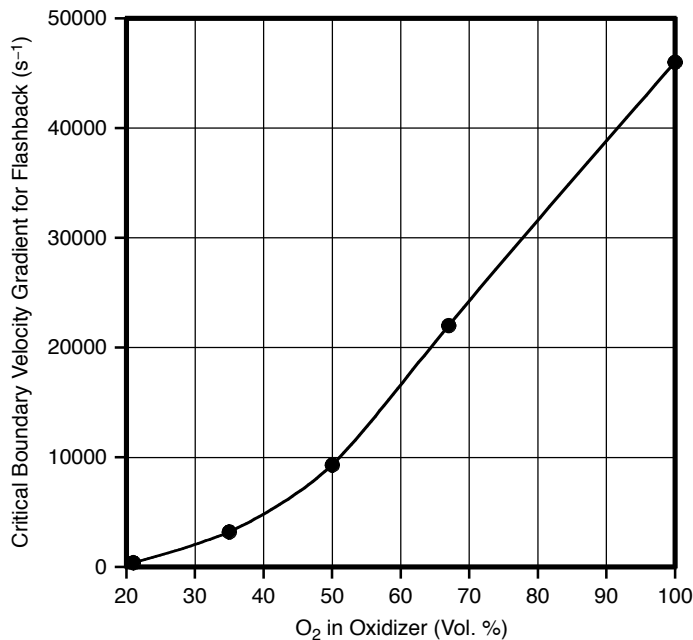


FIGURE 20.25 Critical boundary velocity gradient for flashback vs. oxidizer composition for a stoichiometric premixed methane flame through a cylindrical tube.¹

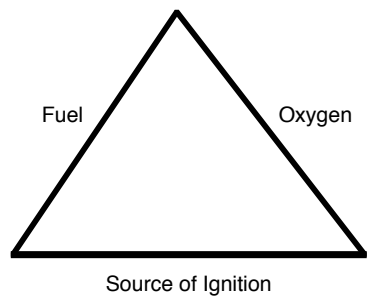


FIGURE 20.26 Combustion triangle.¹

TABLE 20.5
Industrial Applications of Oxygen-Enhanced Combustion

Industry	Furnaces/Kilns	Primary Benefits ^a
Aluminum	Remelting	1, 2
	Coke calcining	1
Cement	Calcining	1
Chemical	Incineration	1, 2, 3, 4
Clay	Brick firing	1, 2, 3
Copper	Smelting	1, 2, 3
	Anode	2
Glass	Regenerative melters	1, 2, 4
	Unit melters	1, 2, 4
	Day tanks	1, 2, 4
Iron and steel	Soaking pits	2, 1
	Reheat furnaces	2, 1
	Ladle preheat	1
	Electric arc melters	1, 2
	Forging furnaces	1, 2
Petroleum	FCC regenerator	1
	Claus sulfur	1
Pulp and paper	Lime kilns	1, 2, 3
	Black liquor	1, 2

^aBenefits of oxygen: 1 = productivity improvement, 2 = energy savings, 3 = quality improvement, 4 = emissions reduction.

With permission from North American Mfg. Co.³⁵

burner as there would no longer be a stoichiometric mixture because the fuel and the oxidizer are separated inside the burner. Therefore, the potential risk of flashback is eliminated by not premixing the fuel and the oxidizer inside the burner.

20.6 INDUSTRIAL HEATING APPLICATIONS

Oxygen-enhanced combustion is used in a wide range of industrial heating applications. In general, OEC has been used in high-temperature heating and melting processes that are either very inefficient or not possible with air/fuel combustion. Table 20.5 shows some of the common reasons why OEC has been used in a variety of industrial applications.³⁵ This section is only intended to give a brief introduction to those applications that are broadly categorized as metals, minerals, incineration, and other. Such applications are briefly discussed here.

20.6.1 METALS

Heating and melting metal was one of the first industrial uses of oxygen-enhanced combustion and continues to be an important application today. OEC has been widely used in both large, integrated steel mills as well as in smaller mini-mills.³⁶ It has also been used in the production of nonferrous metals such as aluminum, brass, copper, and lead.³⁷

The concept of using an oxygen/fuel burner within an air/fuel burner provides the aluminum melter with the flexibility of using either burner, or a combination of both burners (see Figure 20.27). This innovative approach, developed by Air Products and Chemicals, Inc. (Allentown, PA) under the trade name of EZ-Fire[™], has proved to be very successful in the aluminum industry.¹⁰

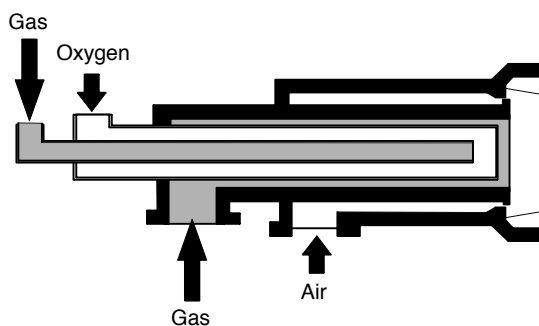


FIGURE 20.27 Air-oxy/fuel burner used in aluminum melting applications.¹

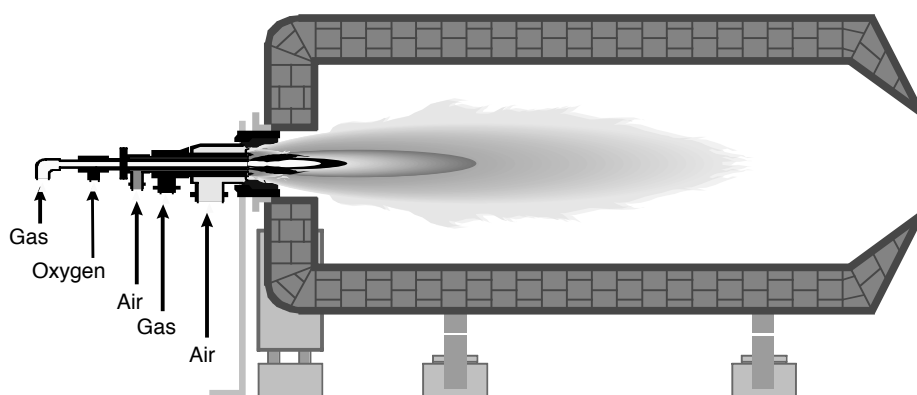


FIGURE 20.28 Air-oxy/fuel burner in a rotary aluminum processing furnace.¹

This differs considerably from both conventional oxygen-enriched techniques and the oxy/fuel burners typically used for melting in the metals industries. This technology is retrofittable on existing air/fuel combustion systems. As shown in Figure 20.28, an oxy/fuel burner is installed in the center of the conventional air/fuel burner. This approach marries the existing air/fuel burner with a retrofitted nonwater-cooled oxy/fuel burner, providing the more efficient heat transfer and available heat benefits of oxy/fuel while maintaining the external flame characteristics of air/fuel. The result is a low-capital-cost, air-oxygen/fuel combustion system that improves the furnace efficiency and lowers production costs.

During meltdown, the oxygen/fuel burner is used along with the air/fuel burner to provide maximum melt rates and minimum flue gas volumes, while during holding and casting, only the air/fuel burner is used. For the melting of aluminum, a combination of air-oxy/fuel combustion provides the best results. The outer air/fuel flame envelope provides a shielding effect for the hot oxygen/fuel inner flame. By firing the oxygen/fuel inner burner on a fuel-rich mixture, flame luminosity is increased as combustion radicals and gas particles are heated to incandescence by the hot oxy/fuel flame. This, in turn, improves the radiative heat transfer of the flame to the charge material and furnace wall while preventing excess oxygen from contacting the load and causing metal oxidation.

Some specific examples of the effects of burner design on NO_x emissions in air-oxy/fuel burners will be used to illustrate the importance of the burner itself, in addition to its operating

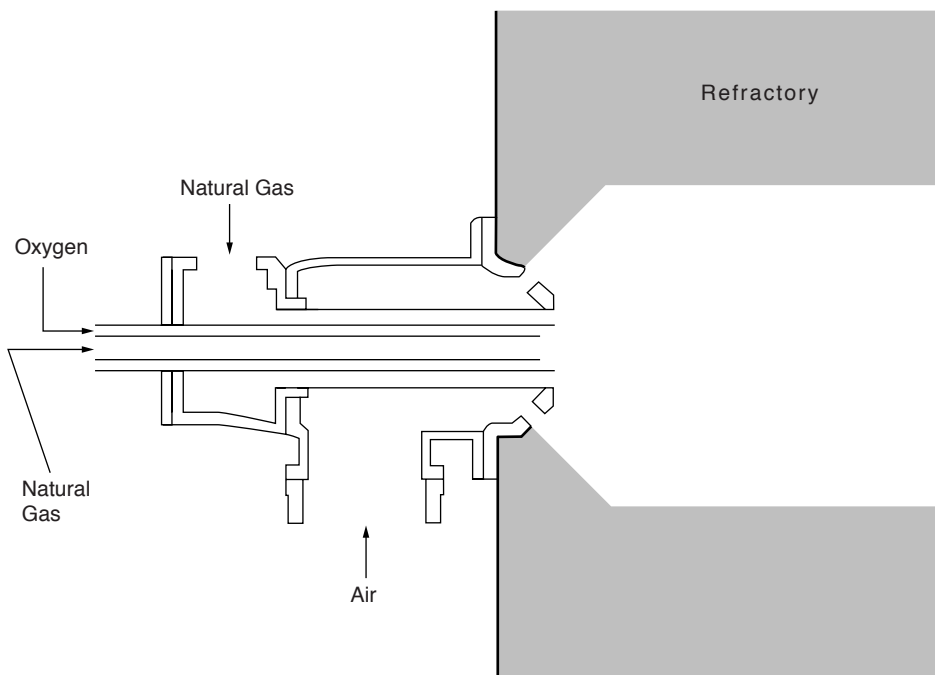


FIGURE 20.29 EZ-0 burner drawing. (Source: U.S. Patent and Trademark Office.³⁹)

conditions. A series of burner designs known as EZ-Fire™ were developed by Air Products and Chemicals, Inc. (Allentown, PA). Figure 20.29 shows a drawing of a first-generation model (referred to here as EZ-0) designed to use a gaseous fuel such as natural gas and a combined oxidant of air and pure oxygen.¹⁰ This design was designed for easy retrofitting of an existing air/fuel burner to increase the throughput of industrial combustion processes, particularly aluminum production. It was not designed for low-NOx emissions and, in fact, increased NOx compared to air/fuel-only combustion. The increased emissions were unacceptable, which led to the development of a second-generation model (referred to here as EZ-1) shown in Figure 20.30.⁴⁰ Two variants of this design are shown in Figure 20.31 and Figure 20.32, referred to here as EZ-1A and EZ-1B, respectively.

During the development of the EZ-1, another series of burner designs (referred to here as EZ-3) was developed and tested. As will be shown, these did not reduce NOx emissions as much as the EZ-1 configuration. Figure 20.33 is a drawing of the EZ-3A configuration consisting of an annular design with a full flare between the middle oxygen passage and the outer air passage. Figure 20.34 shows the effect of the length of the burner block on NOx emissions. For this design, the shorter the block, the lower the NOx. Figure 20.35 shows a similar burner design with only a half flare between the oxygen and air passages. Figure 20.36 shows that the larger internal burner block diameter and the shortest internal burner block length generally produced lower NOx emissions. Figure 20.37 is a drawing of the same burner shown in Figure 20.35, except with seventeen 0.5-in. holes in the half flare. Figure 20.38 again shows that the burner with no burner tile produced less NOx than the 7-in.-long tile. In Figure 20.39, the flare was completely removed. Figure 20.40 again shows that for a fixed internal burner block diameter of 8 in., the shorter the burner block, the lower the NOx emissions. Figure 20.41 shows that the EZ-1 design produced less NOx than any of the EZ-3 designs. This figure also shows that the addition of the flare increased NOx emissions.

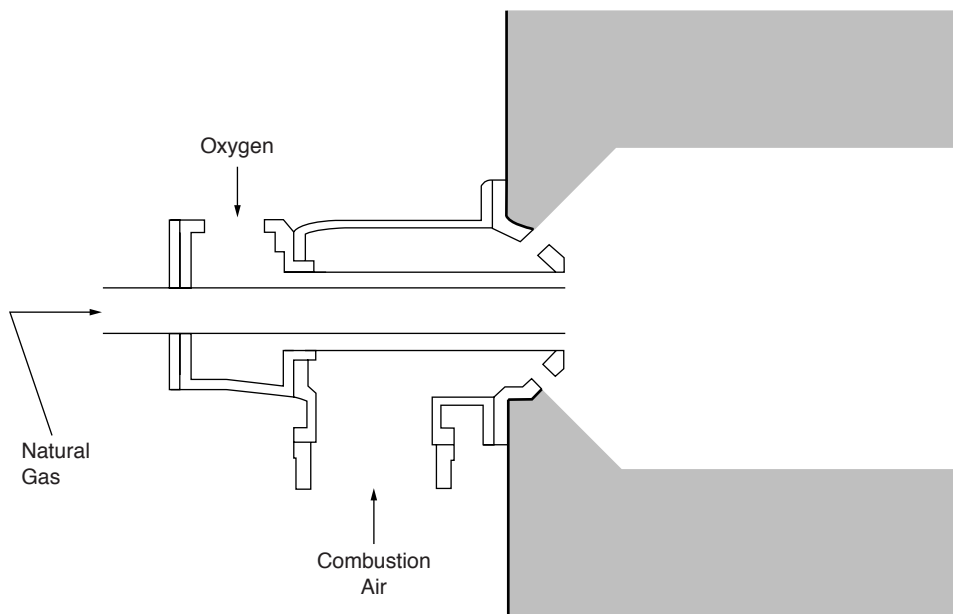


FIGURE 20.30 EZ-1 burner drawing. (Source: U.S. Patent and Trademark Office.³⁸)

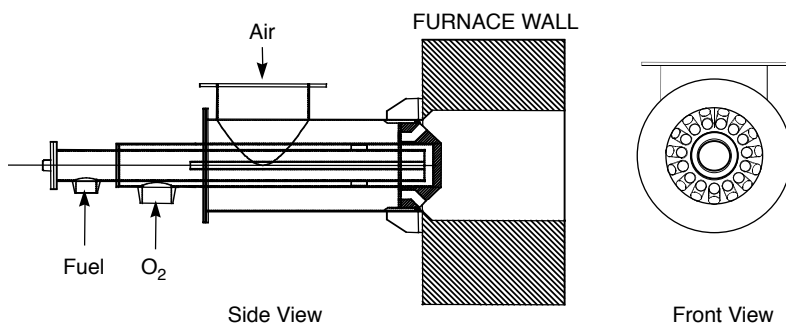


FIGURE 20.31 EZ-1A burner drawing. (Source: U.S. Patent and Trademark Office.³⁸)

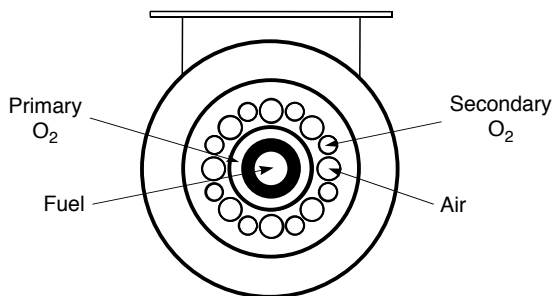


FIGURE 20.32 EZ-1B burner drawing. (Source: U.S. Patent and Trademark Office.³⁸)

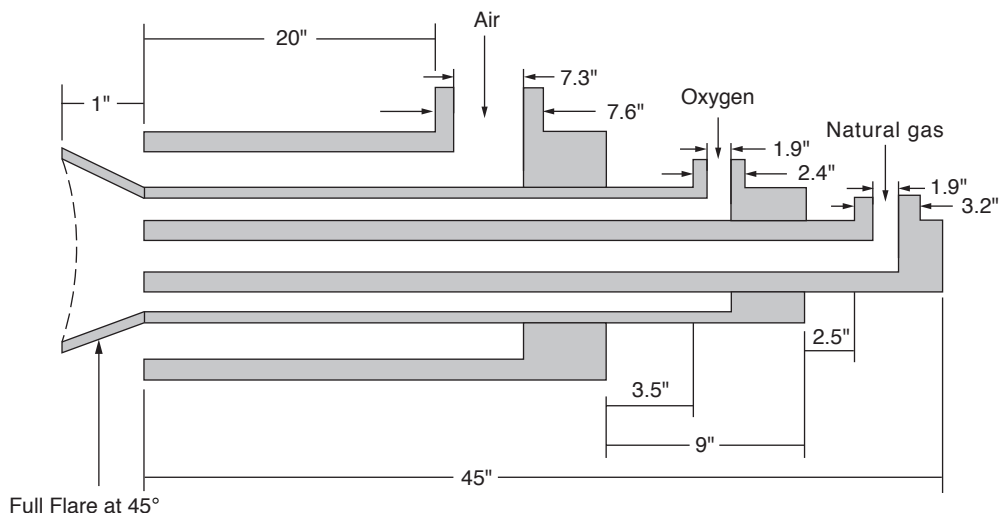


FIGURE 20.33 EZ-3A burner drawing. (Source: U.S. Patent and Trademark Office.³⁸)

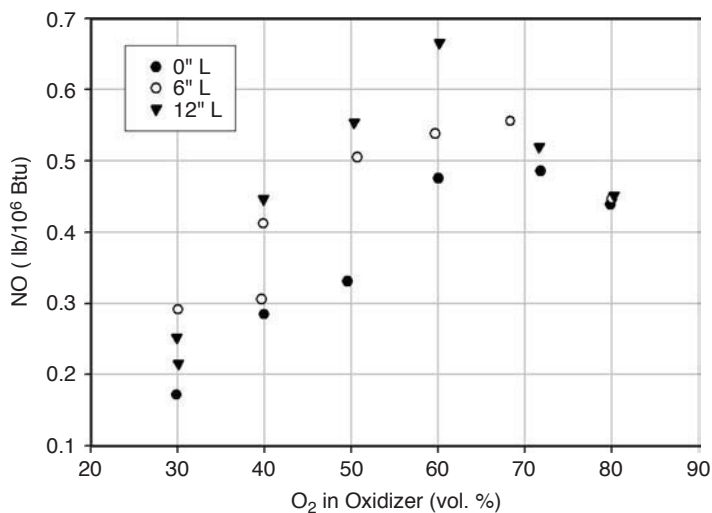


FIGURE 20.34 Measured NO vs. oxidant composition and burner block length for an EZ-3A with an 8-in. ID burner block. (Source: U.S. Patent and Trademark Office.³⁸)

A third-generation EZ-Fire design (referred to here as EZ-4) was developed and tested.³⁹ A drawing of this model is shown in Figure 20.42. As can be seen, the half-moon-shaped air passages are significantly different than the previous designs. In addition, oxygen lances were added in the middle of the air passages. This design was tested to vary the amount of oxygen injected through these lances compared to the amount injected through the central oxygen annulus. Figure 20.43 shows field measurements of the NO_x from the EZ-1A (Figure 20.31), EZ-1B (Figure 20.32), and EZ-4 (Figure 20.42) designs. The EZ-4 produced considerably less NO_x compared to the EZ-1 designs. Figure 20.44 shows that lancing some of the oxygen through the air passage can significantly reduce NO_x compared to no O₂ lancing.

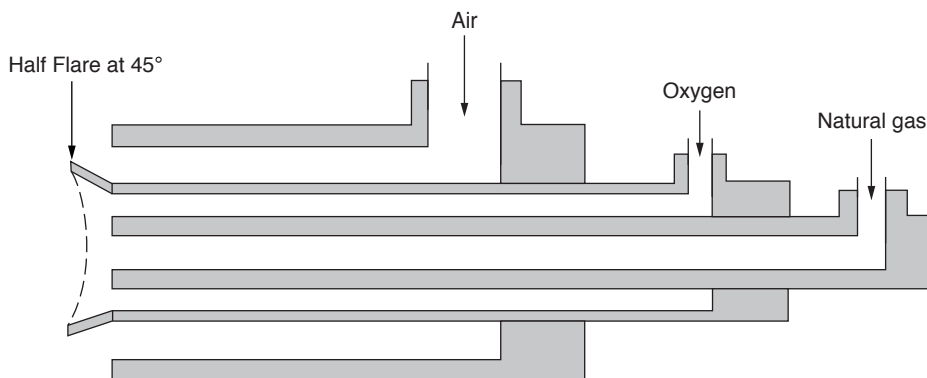


FIGURE 20.35 EZ-3B burner drawing. (Source: U.S. Patent and Trademark Office.³⁸)

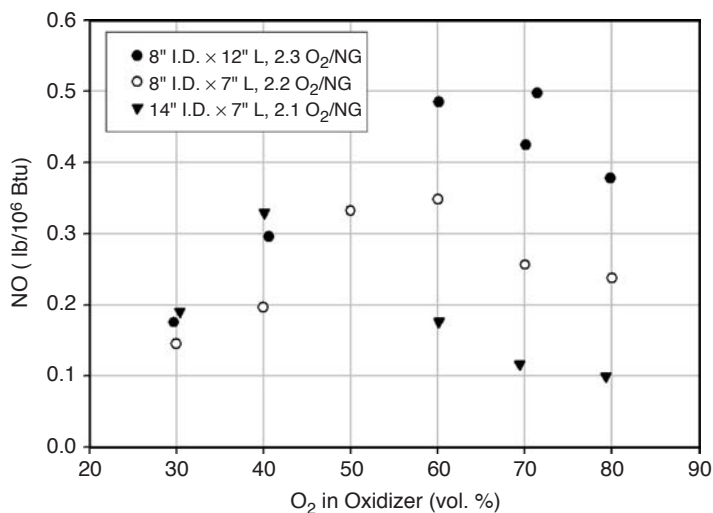


FIGURE 20.36 Measured NO vs. oxidant composition and burner block shape for an EZ-3B with no holes in the half flare. (Source: U.S. Patent and Trademark Office.³⁸)

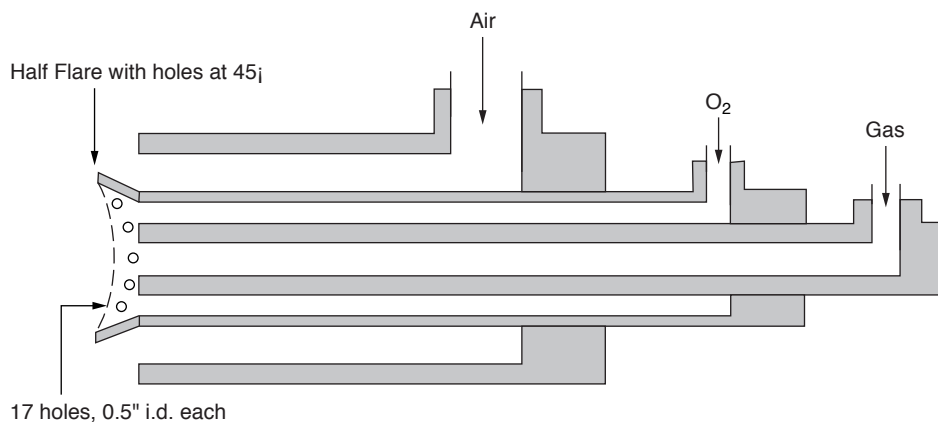


FIGURE 20.37 EZ-3B burner with holes in the flare. (Source: U.S. Patent and Trademark Office.³⁸)

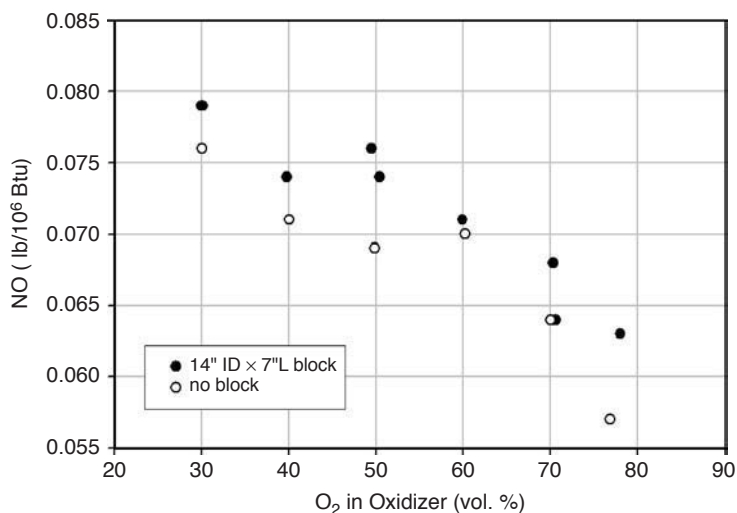


FIGURE 20.38 Measured NO vs. oxidant composition and burner block shape for an EZ-3B with holes in the half flare. (Source: U.S. Patent and Trademark Office.³⁸)

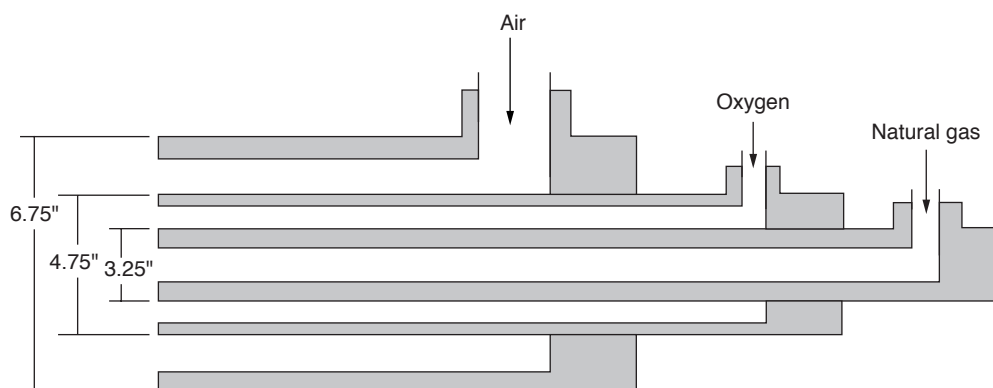


FIGURE 20.39 EZ-3C burner drawing. (Source: U.S. Patent and Trademark Office.³⁸)

20.6.2 MINERALS

Here, minerals refers to glass, cement, lime, bricks, and other related materials that require high-temperature heating and melting during their manufacture. OEC has been used in all of these applications.

Due to the very low energy efficiency and the use of individual burners, the air/fuel unit melters are very amenable to oxygen-enhanced combustion techniques, including supplemental oxy/fuel boosting (see Figure 20.45⁴⁰), premix oxygen enrichment, and full oxy/fuel combustion. Oxy/fuel unit melters have been built as large as 350 tons (320 metric tons) per day of glass to as small as 500 pounds (230 kg) of glass per day.

Abbasi et al. (1996) described a new process known as oxygen-enriched air staging (OEAS).⁴¹ A schematic of the process for an endpoint furnace (see Figure 20.46) is shown in Figure 20.47.⁴²

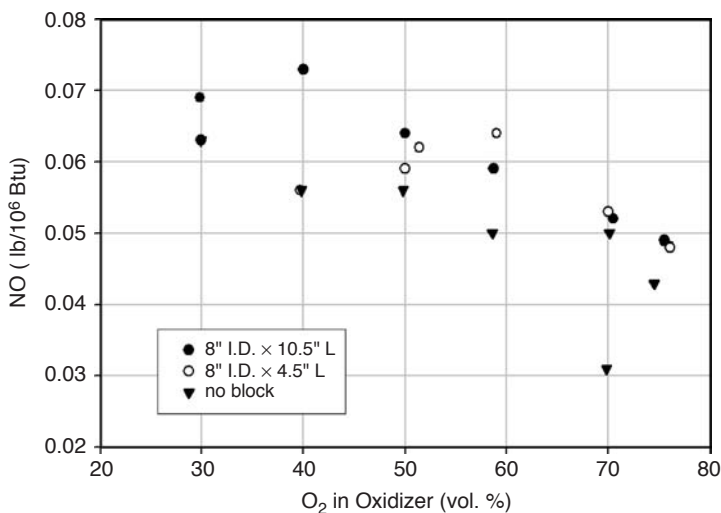


FIGURE 20.40 Measured NO vs. oxidant composition and burner block length for an EZ-3C with an 8-in. ID burner block. (Source: U.S. Patent and Trademark Office.³⁸)

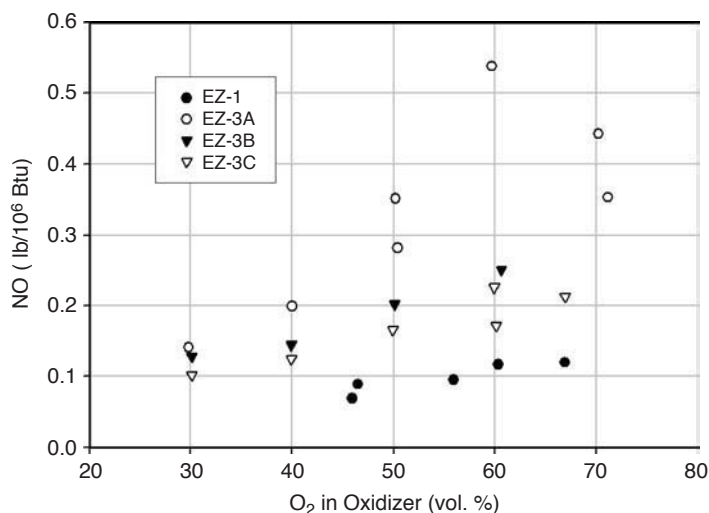


FIGURE 20.41 Measured NO vs. oxidant composition and burner design where the burners had no burner block, the O₂:NG stoichiometry was approximately 2.3, and the firing rate was 3×10^6 Btu/hr. (Source: U.S. Patent and Trademark Office.³⁸)

A schematic for application of the process on a sideport furnace (see [Figure 20.48](#)) is shown in [Figure 20.49](#). While the primary objective of the technology is to reduce NO_x emissions (50 to 70% reduction was measured), there are also some effects on heat transfer. Because the preheated air flames are now initially fuel-rich, they are more luminous and, therefore, more radiative. The secondary oxygen added to the exhaust products completes the combustion before the gases exit the furnace. This secondary combustion zone helps to spread the heat transfer over a wider region in the furnace, which helps to make the heat flux more uniform.

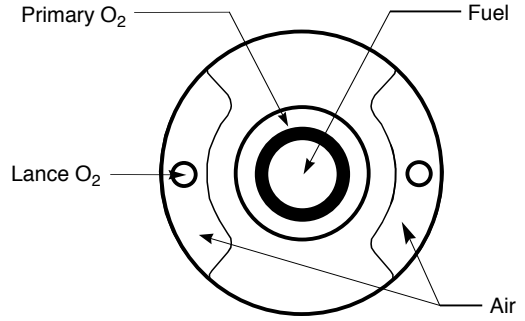


FIGURE 20.42 EZ-4 burner drawing. (Source: U.S. Patent and Trademark Office.³⁹)

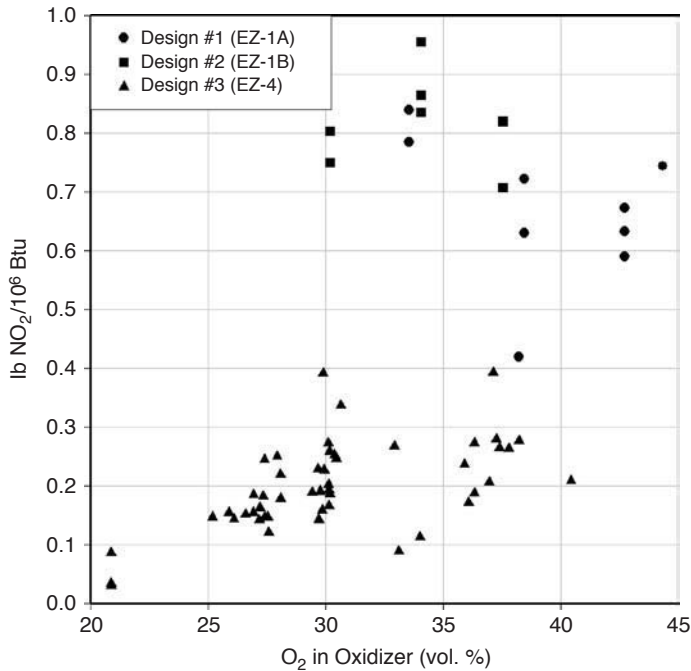


FIGURE 20.43 Measured NO₂ vs. oxidant composition and burner design (EZ-1A, EZ-1B, EZ-4) where the burners had no burner block and the O₂:NG stoichiometry was approximately 2.0; the firing rate and the O₂ flow through the lances of EZ-4 varied. (Source: U.S. Patent and Trademark Office.³⁹)

OEC has been used in a variety of ways in the glass industry. Figure 20.50 shows the use of oxygen-enhanced combustion in a glass furnace by lancing oxygen into the flames of the burners. Figure 20.51 shows oxygen-enhanced combustion in a glass furnace. Figure 20.52 shows the effect on the economics of using oxygen-enhanced combustion to control NO_x and particulate emissions.⁴³

Another technique for controlling dust emissions is through the use of oxygen-enhanced combustion. This is done by replacing a substantial amount of the air used for combustion with high-purity oxygen. Figure 20.53 shows oxygen-enhanced combustion applied to a rotary kiln. Essentially, this amounts to removing large quantities of inert nitrogen from the system. This has two positive effects on dust emissions. The first is that the overall system thermal efficiency is

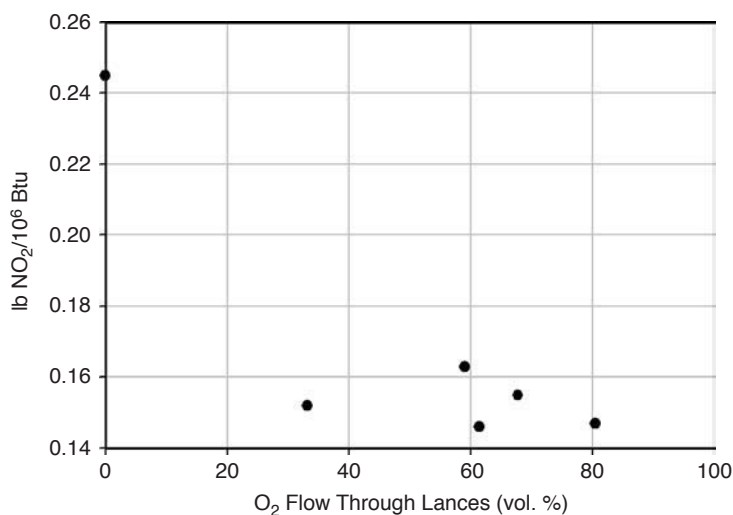


FIGURE 20.44 Measured NO₂ vs. the fraction of oxygen through the lances in the EZ-4 burner for an overall O₂:NG stoichiometry of approximately 2.0 and approximately 27% O₂ in the combined oxidizer. (Source: U.S. Patent and Trademark Office.³⁹)

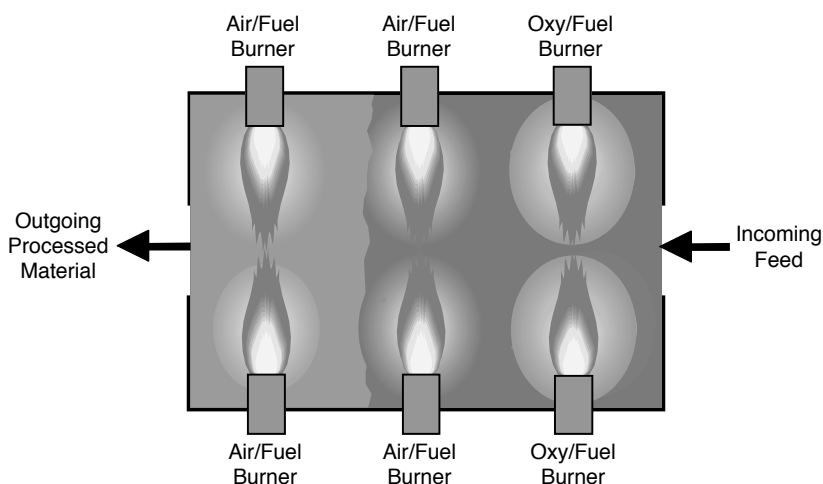


FIGURE 20.45 Plan view of oxy/fuel boosting in a glass furnace.⁴⁰

improved so that less fuel needs to be fired for a given production rate. Less fuel means less flue gas and therefore less particle entrainment. The second positive effect is also related to particle entrainment. By removing large quantities of nitrogen, the flue gas volume decreases, which reduces particle entrainment. Low levels of oxygen enrichment, however, can increase NO_x emissions so there may be a trade-off of one emission for another. Often, oxygen-enhanced combustion is used in this application to increase throughput for a given size kiln and auxiliary equipment. This means that the firing rate may not be decreased, but the material processing rate is increased. The overall

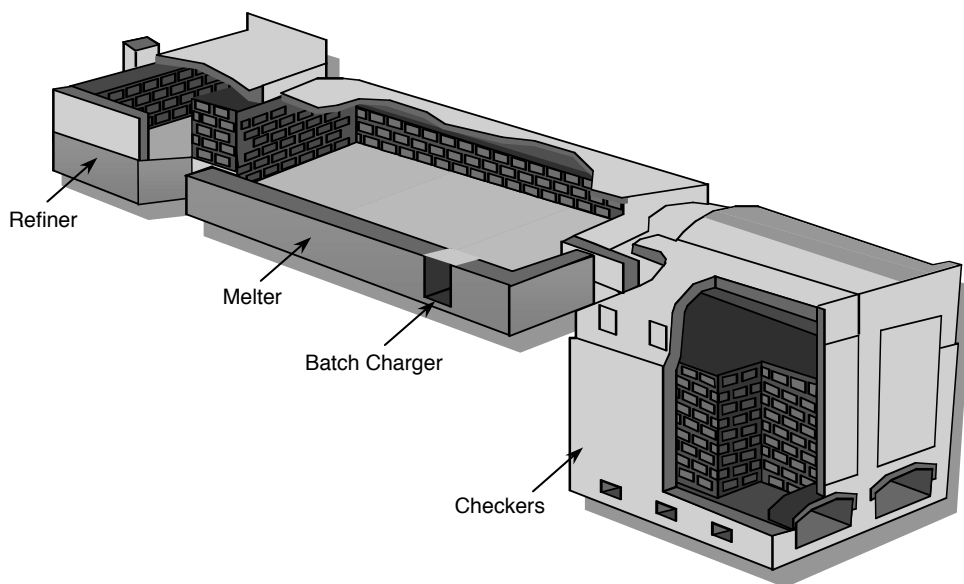


FIGURE 20.46 End-port regenerative melter.⁴³

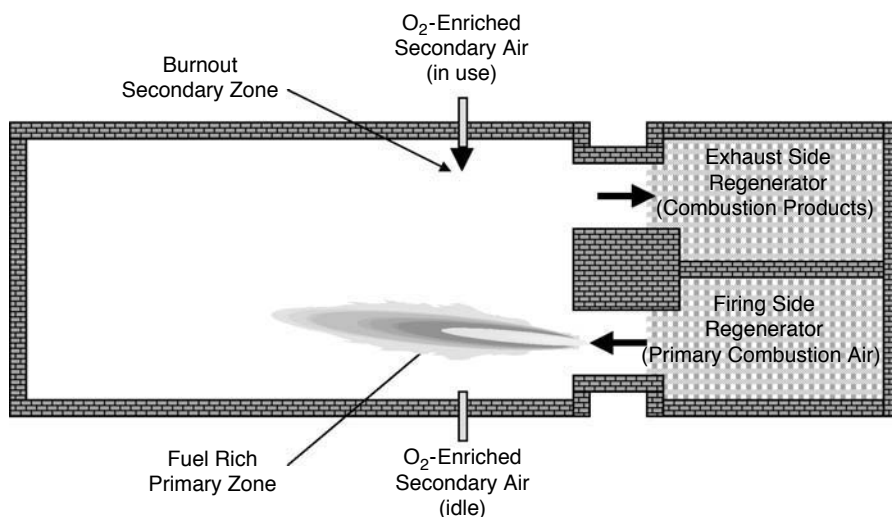


FIGURE 20.47 Oxygen-enriched air staging in an end-port regenerative furnace.

dust emissions may actually increase, although they may decrease on a unit production basis (e.g., tons of clinker).

20.6.3 INCINERATION

OEC has been used to enhance the performance of portable incinerators used to clean up contaminated soil.⁴⁴ It has also been used in municipal solid waste incinerators and in boilers burning waste fuels. Many of the benefits associated with oxygen-enhanced combustion (OEC) relate to

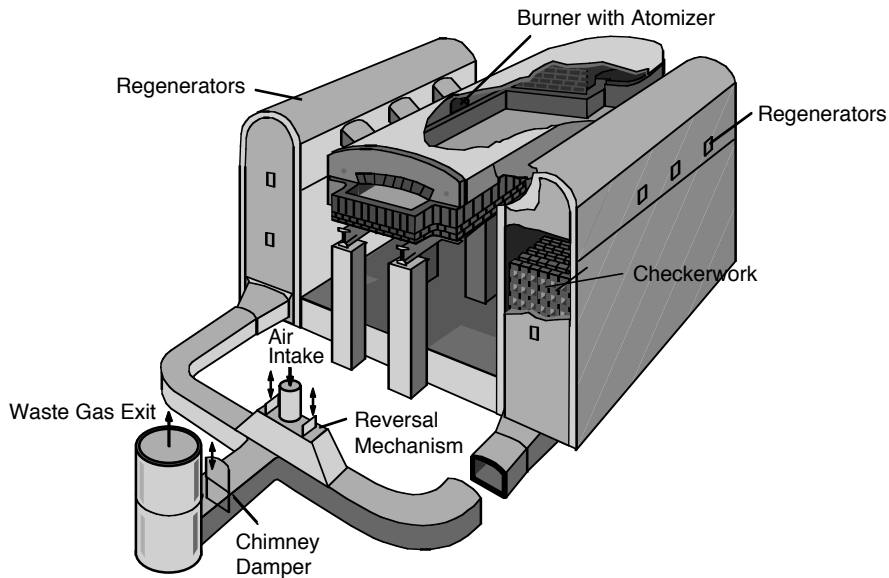


FIGURE 20.48 Side-port regenerative melter.⁴³

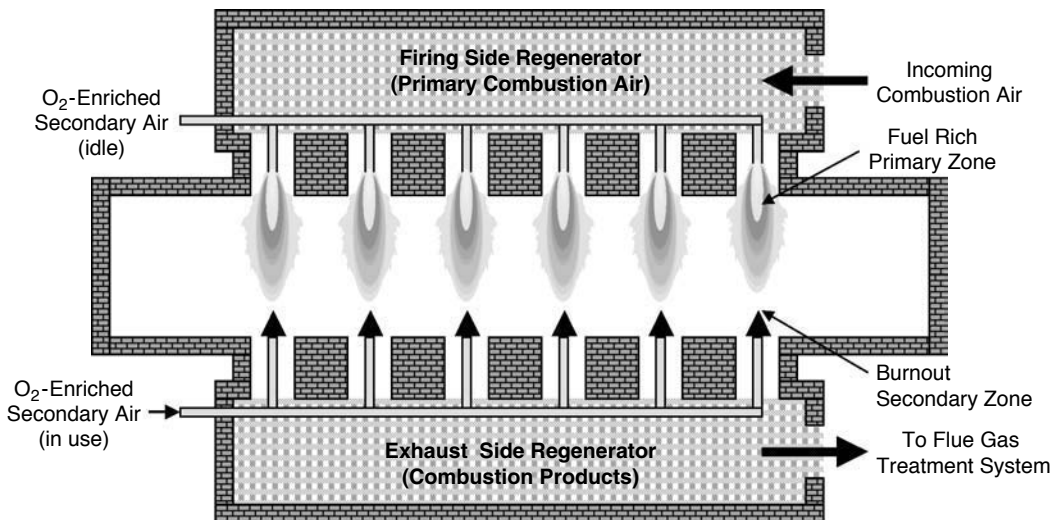


FIGURE 20.49 Oxygen-enriched air staging in a side-port regenerative furnace.

increasing the partial pressure of O_2 in the incinerator. The combustion process becomes more reactive, which tends to increase the destruction efficiency of any hydrocarbons in the system. This lowers the pollutant emissions. A schematic of some of the benefits of using OEC is shown in [Figure 20.54](#). Figure 20.55 shows a schematic of oxygen lancing used to enhance the performance of an incinerator. Figure 20.56 shows the use of oxygen enrichment to enhance the performance of a municipal solid waste incinerator. [Figure 20.57](#) shows the use of oxygen enrichment in a sludge incinerator.

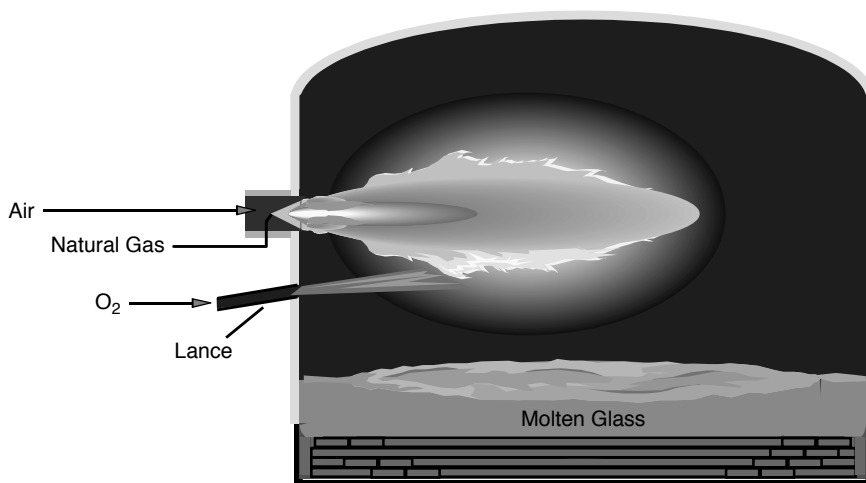


FIGURE 20.50 Oxygen lancing into the flames in a glass furnace.

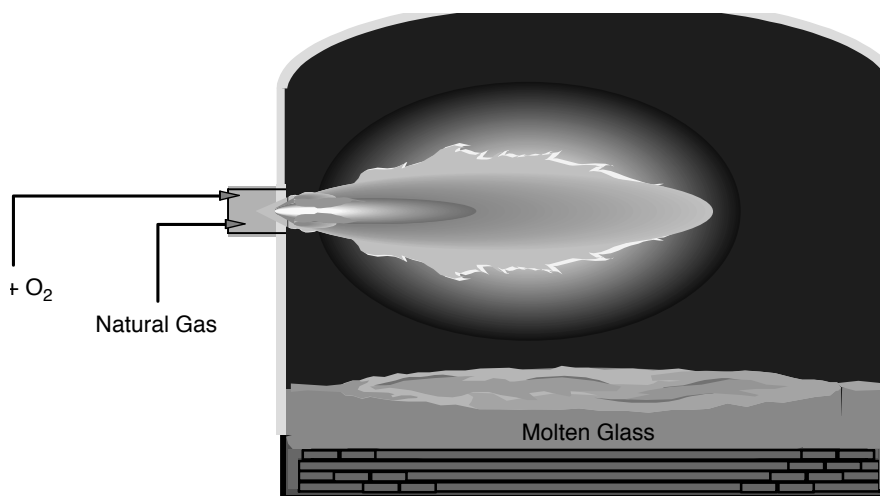


FIGURE 20.51 Oxygen-enhanced combustion in a glass furnace.

20.6.4 OTHER

OEC has been used in a wide variety of specialty applications that are not discussed in detail in this book. Some of these include gasifying organic materials and vitrifying residual ash,⁴⁵ removing unburned carbon from fly ash,⁴⁶ and oxygen enrichment of fluid catalytic crackers.⁴⁷

20.7 CONCLUSIONS

There are a number of factors that make the future look bright for OEC. Separate reports on the industrial uses of OEC sponsored by the U.S. Department of Energy in 1987²⁵ and the Gas Research Institute in 1989⁴ have been published. New advancements are continually being made in existing and new (e.g., Reference 48) oxygen generation technologies. This should

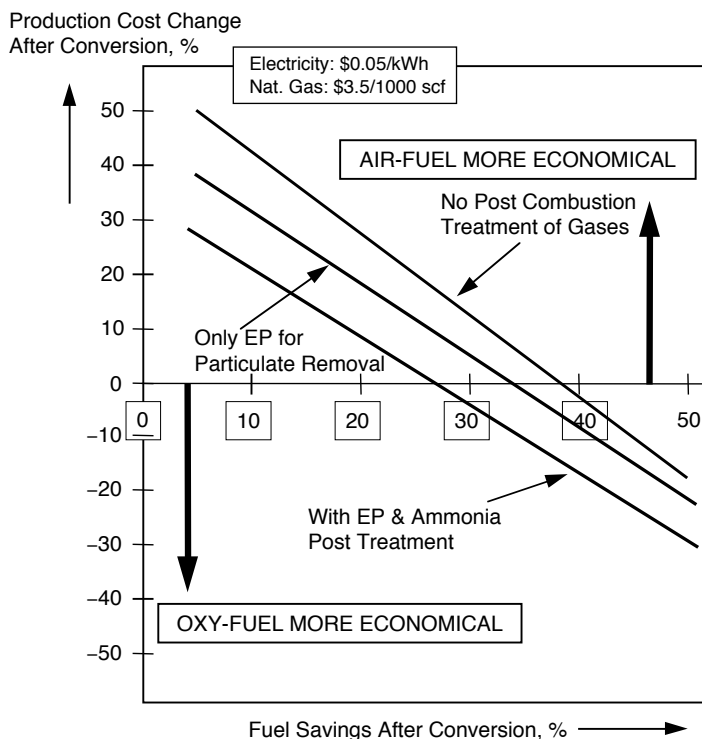


FIGURE 20.52 Effect of NO_x and particulate controls on process economics for air/fuel vs. oxy/fuel combustion.⁴³

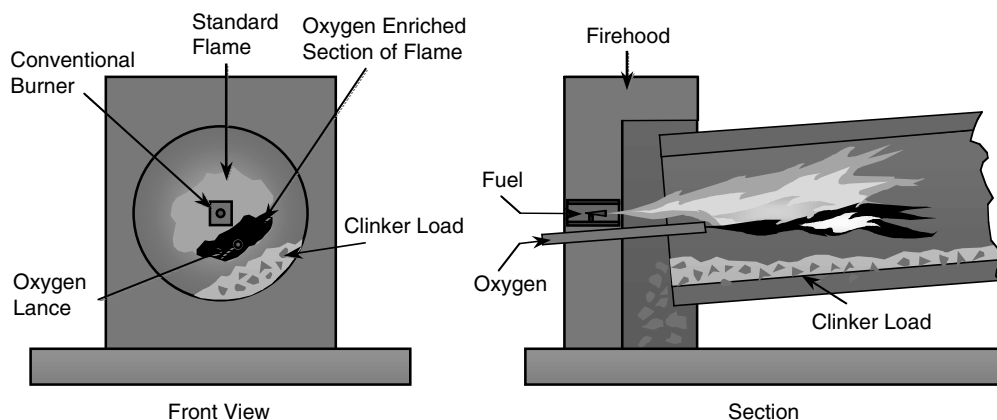


FIGURE 20.53 Oxygen-enhanced combustion in a rotary kiln.

reduce the cost to the end user, which should expand the number of amenable applications. Studies are being conducted to further improve the energy efficiency of OEC processes using novel methods of heat recovery⁴⁹ and integrating the air separation process with the combustion system.²⁰

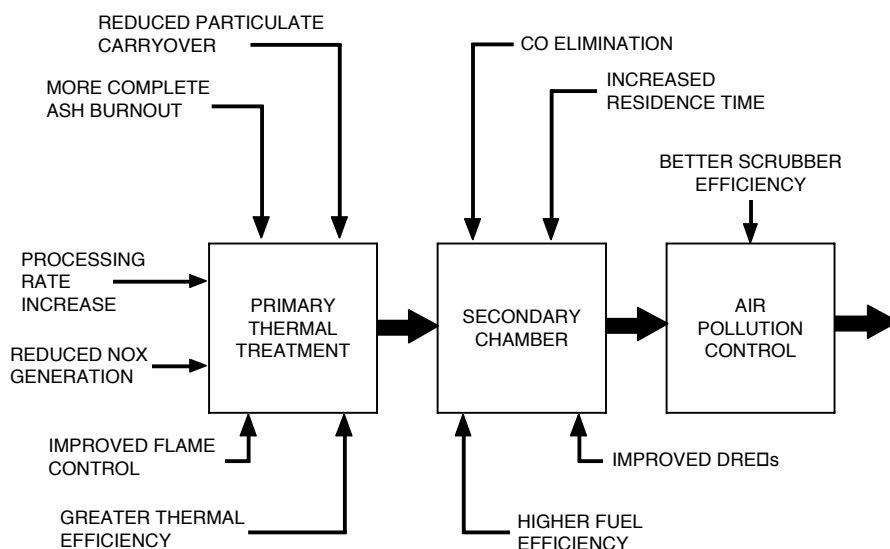


FIGURE 20.54 Benefits of using oxygen in waste incineration applications.¹

There are many areas related to the use of OEC that need further research. In a recent report for the U.S. Department of Energy, the following were recommended for further research:⁵⁰

- Use oxygen enrichment to increase furnace efficiency in the petroleum industry
- Investigate the benefits and disadvantages of varying the oxidizer composition ranging from air to pure O₂
- Measure the NO_x from oxygen-enriched burners in steel reheat furnaces
- Optimize the amount of O₂ injection into cupolas used in the foundry industry to recuperate energy from the CO produced in the process
- Optimize glass-melting processes that use oxygen/fuel combustion, including the development of computer models
- Quantify furnace efficiency and productivity improvements using OEC in aluminum melting
- Develop NO_x reduction technologies for OEC in aluminum processes

Another major area for further research in the use of OEC is the design of the combustion chambers. In nearly all cases, OEC has been adapted and retrofitted to existing furnace designs. In the future, the design of new furnaces that will use OEC should be investigated to optimize the increased radiant heat transfer, reduced convective heat transfer, and reduced gas volume flow rates.

There are numerous examples of using oxygen-enhanced combustion in a wide variety of industrial heating applications. In some cases, low level O₂ enrichment of an existing air/fuel combustion system can have dramatic results. In other cases, oxy/fuel burners may be used to provide needed solutions.

Lower cost O₂, coupled with the significant environmental and operating benefits of OEC, make OEC an attractive technology. Research continues to assess its effectiveness in a wide range of applications.

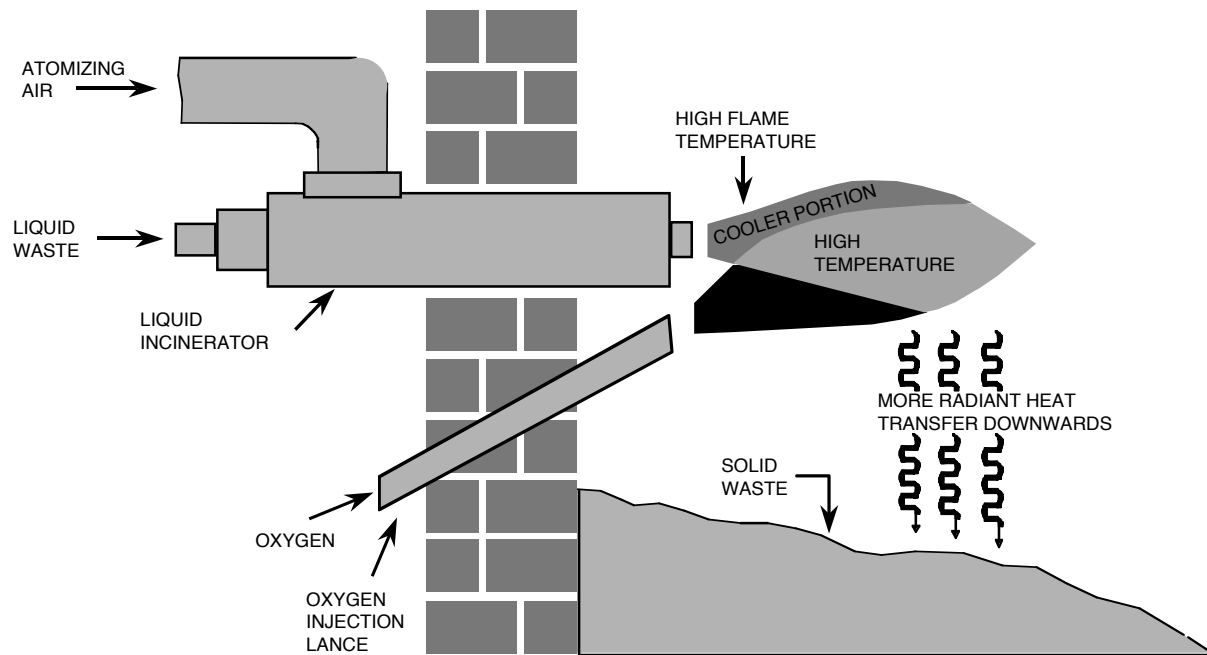


FIGURE 20.55 Oxygen lancing into an incinerator.¹

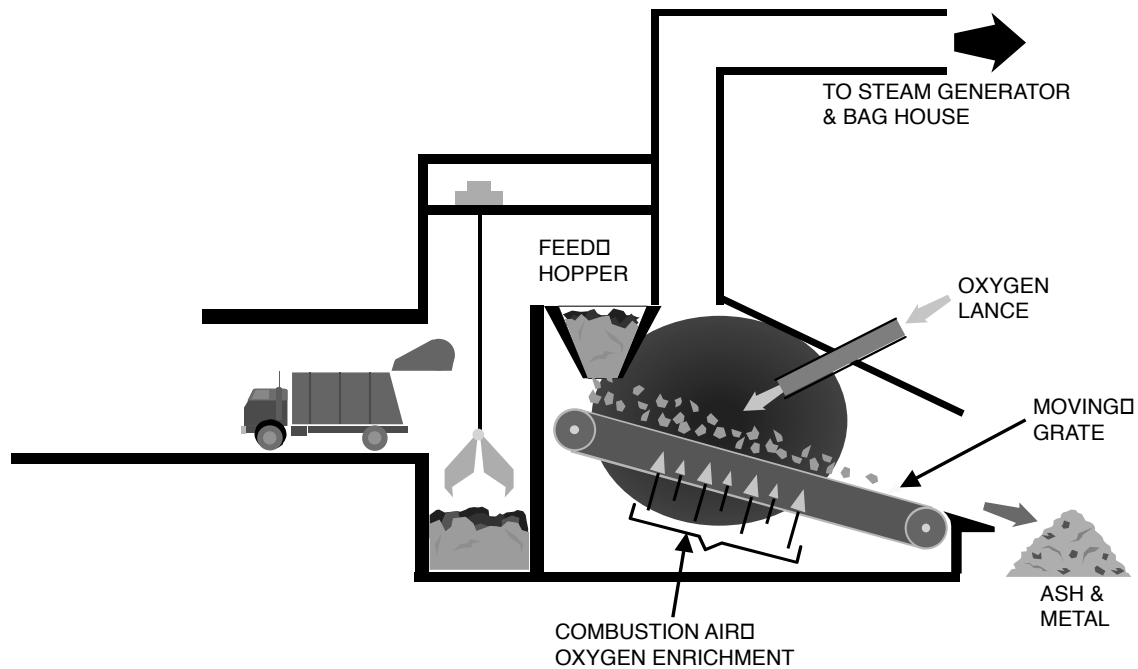


FIGURE 20.56 Oxygen enrichment of a municipal solid waste incinerator.¹

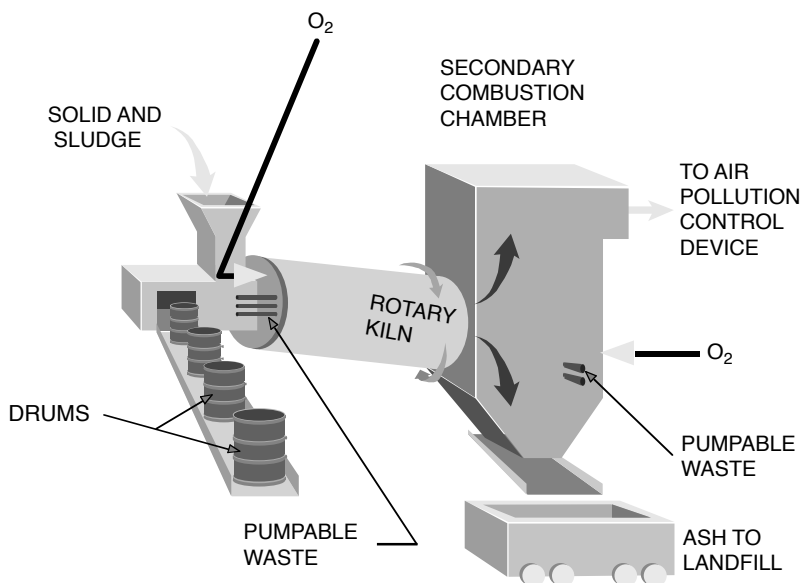


FIGURE 20.57 Oxygen enrichment of a sludge incinerator.¹

REFERENCES

1. Baukal, C.E., Ed., *Oxygen-Enhanced Combustion*, CRC Press, Boca Raton, FL, 1998.
2. McGuinness, R.M. and Kleinberg, W.T., Oxygen Production, Chapter 3 in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998.
3. Baukal, C.E., Pollutant Emissions, Chapter 2 in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998.
4. Williams, S.J., Cuervo, L.A., and Chapman, M.A., High-Temperature Industrial Process Heating: Oxygen-Gas Combustion and Plasma Heating Systems, Gas Research Institute Report GRI-89/0256, Chicago, IL, July 1989.
5. Chace, A.S., Hazard, H.R., Levy, A., Thekdi, A.C., and Ungar, E.W., Combustion Research Opportunities for Industrial Applications — Phase II, U.S. Dept. of Energy report DOE/ID-10204-2, Washington, D.C., 1989.
6. Baukal, C.E., Eleazer, P.B., and Farmer, L.K., Basis for Enhancing Combustion by Oxygen Enrichment, *Industrial Heating*, LIX (2), 22, 1992.
7. Benedek, K.R. and Wilson, R.P., The Competitive Position of Natural-Gas in Oxy-Fuel Burner Applications, Gas Research Institute Report GRI-96-0350, Chicago, IL, September 1996.
8. Joshi, S.V., Becker, J.S., and Lytle, G.C., Effects of Oxygen Enrichment on the Performance of Air-Fuel Burners, in *Industrial Combustion Technologies*, Lukasiewicz, Amer. Soc. Metals, 165, 1986.
9. U.S. Environmental Protection Agency, Alternative Control Techniques Document — NO_x Emissions from Utility Boilers, EPA Report EPA-453/R-94-023, Research Triangle Park, NC, 1994.
10. Bazarian, E.R., Heffron, J.F., and Baukal, C.E., Method for Reducing NO_x Production During Air-Fuel Combustion Processes, U.S. Patent 5,308,239, 1994.
11. Gitman, G.M., Method and Apparatus for Generating Highly Luminous Flame, U.S. Patent 4,797,087, 1989.
12. Dalton, A.I. and Tyndall, D.W., Oxygen Enriched Air/Natural Gas Burner System Development, NTIS Report PB91-167510, Springfield, VA, 1989.
13. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations, NASA Report SP-273, 1971.
14. Baukal, C.E., Ed., *The John Zink Combustion Handbook*, CRC Press, Boca Raton, FL, 2001.

15. Turin, J.J. and Huebler, J., Gas-Air-Oxygen Combustion Studies, Report no. I.G.R.-61, American Gas Association, 1951.
16. Lewis, B. and von Elbe, G., *Combustion, Flames and Explosions of Gases*, third edition, Academic Press, New York, 1987.
17. American Gas Association, *Gas Engineers Handbook*, Industrial Press Inc., New York, 2/72, 1965.
18. Gibbs, B.M. and Williams, A., Fundamental Aspects on the Use of Oxygen in Combustion Processes—A Review, *J. Inst. Energy*, June, 74, 1983.
19. Farrell, L.M., Pavlack, T.T., and Rich, L., Operational and Environmental Benefits of Oxy-Fuel Combustion in the Steel Industry, *Iron & Steel Engineer*, March, 35, 1995.
20. Ding, M.G. and Du, Z., Energy & Environmental Benefits of Oxy-Fuel Combustion, *Proceedings of the 1995 International Conference on Energy & Environment*, Shanghai, China, May 1995, Begell House Inc., New York, 674.
21. Grisham, S., Oxy-Conversion for a Smaller Furnace Yields Big Results, *American Glass Review*, May–June, 12, 1997.
22. Harris, M.E., Grumer, J., Von Elbe, G., and Lewis, B., Burning Velocities, Quenching, and Stability Data on Nonturbulent Flames of Methane and Propane with Oxygen and Nitrogen, *Third Symposium on Combustion, Flame and Explosion Phenomena*, Williams & Wilkins Co., Baltimore, 1949, 80.
23. Brown, J.T., Glass Melting: The Elegance of Direct-Fired Oxy-Fuel, *Ceramic Industry*, March 1992, 47.
24. Gill, J.H. and Quiel, J.M., *Incineration of Hazardous, Toxic, and Mixed Wastes*, North American Mfg. Co., Cleveland, 1993.
25. Kobayashi, H., Oxygen Enriched Combustion System Performance Study, Phase I Interim/Final Report, Volume I: Technical and Economic Analysis, U.S. Dept. of Energy report DOE/ID/12597, Washington, D.C., March 1987.
26. Hottel, H.C. and Sarofim, A.F., *Radiative Transfer*, McGraw-Hill, New York, 1967.
27. DeLucia, M., Oxygen Enrichment in Combustion Processes: Comparative Experimental Results from Several Application Fields, *J. Energy Resources Tech.*, 113, 122, 1991.
28. Industrial Heating Equipment Association, *Combustion Technology Manual*, fifth edition, Arlington, VA, 1994.
29. Becker, J.S. and Farmer, L.K., Rapid Fire Heating System Uses Oxy-Gas Burners for Efficient Metal Heating, *Ind. Heating*, 62(3), 74–78, 1995.
30. Dafoe, B.M., *Report of Committee F: Industrial and Commercial Utilization of Gases*, International Gas Union, Switzerland, 1991.
31. Cornforth, J.R., *Combustion Engineering and Gas Utilisation*, third edition, E & FN Spon, London, 1992.
32. Gershtein, V.Y. and Baukal, C.E., CFD in Burner Development, Chapter 7 in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998.
33. Slavejkov, A.G., Baukal, C.E., Joshi, M.L., and Nabors, J.K., Oxy-Fuel Glass Melting with a High-Performance Burner, *Ceramic Bulletin*, 71(3), 340, 1992.
34. Guerrero, P.S., Rebello, W.J., Ally, M.R., and Jain, R., Combustion Characteristics of Fuels with Preheated Oxygen Enriched Air, in *Industrial Combustion Technologies*, Lukasiewicz, M.A., Ed., American Society of Metals, 1986, 187.
35. Reed, R.J., *North American Combustion Handbook*, third edition, Vol. II, Part 13, 1997.
36. Kistler, M.D. and Becker, J.S., Ferrous Metals, Chapter 5 in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998.
37. Saha, D. and Baukal, C.E., Nonferrous Metals, Chapter 5 in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998.
38. Baukal, C.E., Slavejkov, A.G., and Monroig, L.W., Method and Apparatus for Reducing NO_x Production During Air-Oxygen-Fuel Combustion, U.S. Patent 5,611,683 issued March 18, 1997.
39. Baukal, C.E., Gershtein, V.Y., Heffron, J.F., Best, R.C., and Eleazer, P.B., Method and Apparatus for Reducing NO_x Production during Air-Oxygen/Fuel Combustion, U.S. Patent 5,871,343, issued February 16, 1999.
40. Baukal, C.E., *Heat Transfer in Industrial Combustion*, CRC Press, Boca Raton, FL, 2000.

41. Abbasi, H.A., Grosman, R.E., Donaldson, L.W., Youssef, C.F., Joshi, M.L., and Hope, S.R., A Low-NO_x Retrofit Technology for Regenerative Glass Melters, *Proc. 1995 International Gas Research Conf.*, Vol. II, Dolenc, D.A., Ed., Government Institutes, Rockville, MD, 1996, 2322–2331.
42. Baukal, C.E., *Industrial Combustion Pollution and Control*, Marcel Dekker, New York, 2004.
43. Eleazer, P.B. and Hoke, B.C., Glass, in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998, 215–236.
44. Baukal, C.E., Waste Incineration, Chapter 8 in *Oxygen-Enhanced Combustion*, Baukal, C.E., Ed., CRC Press, Boca Raton, FL, 1998.
45. Bishop, N.G. and Taylor, G., Method and Apparatus for Gasifying Organic Materials and Vitrifying Residual Ash, U.S. Patent 5,584,255, issued Dec. 17, 1996.
46. Martinez, M.P., Apparatus and Process for Removing Unburned Carbon in Fly Ash, U.S. Patent 5,555,821, issued Sept. 17, 1996.
47. Tamhankar, S., Menon, R., Chou, T., Ramachandran, R., Hull, R., and Watson, R., Enrichment Can Decrease NO_x, SO_x Formation, *Oil & Gas J.*, 94(10), 60, 1996.
48. U.S. Dept. of Energy, Assessment of Thermal Swing Absorption Alternatives for Producing Oxygen Enriched Combustion Air, Report DOE/CE-040762T-H1, U.S. Dept. of Energy, Washington, D.C., April 1990.
49. Air Products and Chemicals, Inc., Development of an Advanced Glass Melting System: The Thermally Efficient Alternative Melter “Team,” U.S. Dept. of Energy Report DOE/CE/40917, February 1992.
50. Keller, J.G., Soelberg, N.R., and Kessinger, G.F., Industry-Identified Combustion Research Needs, U.S. Dept. of Energy Report INEL-95/0578 (DE96003785), 1995.