

Chapter 3

Combustion Systems & NO_x

Editor's Note:

Chapter 3 is written by Dr. Brian Doyle and is drawn primarily from personal knowledge and the material developed for the NO_x Emissions course offered by the Rutgers Air Compliance Center from 2000 to 2008.

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3 COMBUSTION SYSTEMS & NOx

NOx emissions can be controlled either by reducing its formation during combustion or by combining reduced formation with post combustion control - such as SCR. In order to discuss reduced formation, we need to understand some basic aspects of combustion as well as the types of combustion systems in common use. Students familiar with specific types of combustion hardware may choose to skip portions of this chapter. However, the discussion of premixed flames is critical to understanding how some low NOx combustion systems work.

Diffusion and Premixed Flames

Combustion involves two distinct processes - (1) mixing of the fuel and air, and (2) chemical reactions that release heat while converting fuel into CO₂ and H₂O. In most types of combustors, mixing and chemical reactions occur simultaneously - the fuel is sprayed into the flame. But there are a few burners where mixing and chemical reactions occur in sequence - in an automobile engine gasoline vapor is mixed with air, then ignited with a spark. In the following discussion we divide the world of combustion devices into two groups:

(a) **Diffusion flames** are those where air-fuel mixing is simultaneous with combustion. Most common burners use diffusion combustion. Examples are flames formed by a spray of liquid oil, or a jet of gas, or by pulverized coal blown into the combustion zone. This includes all systems that burn oil or solid fuel as well as many natural gas burners. It includes most furnaces and nearly all boilers.

(b) If the air and gaseous fuel is completely premixed, blown into a combustion chamber, then ignited, it creates a **premixed flame**. Combustion then occurs in a homogeneous gas mixture. A high gas velocity or valves are used to keep the flame from flashing back into the mixing zone. Spark ignition engines are an example - a homogeneous mixture of air and natural gas (or evaporated gasoline) is drawn into a closed cylinder and ignited by a spark. Since liquids (or solids) cannot be mixed with air at a molecular level, all premixed flame burners must use gas phase fuel such as natural gas, propane or a vaporized liquid.

Since about 1990 the difference between the diffusion and premixed combustion has been highlighted by the evolution of low NOx combustion systems that rely on the use of premixed combustor designs in applications once dominated by diffusion flames.

Premixed flame burners are generally more challenging to operate than diffusion flame burners because they can only be ignited and flame can only be maintained when the air/fuel ratio is kept within a relatively narrow range close to stoichiometric. The flame goes out if the ratio deviates from the ideal range and flame-outs can be very dangerous. Diffusion flames are quite different. They can maintain stable combustion over a wide range of air/fuel ratios.

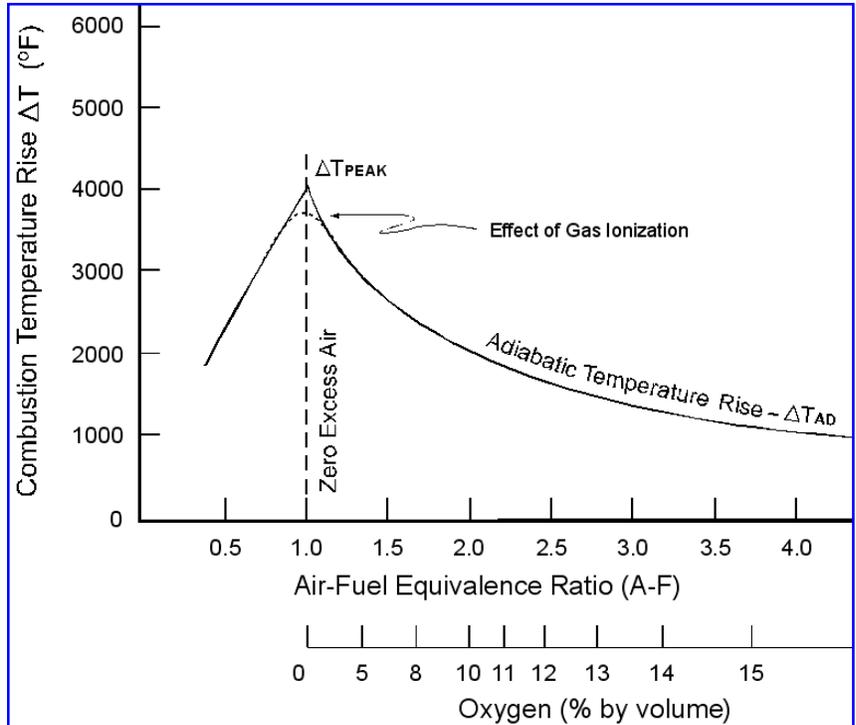


Figure 3-1 - Adiabatic Temperature versus Excess Air

Diffusion burners can operate at very high air/fuel ratios, e.g. where a small flame exists in a large air flow. They provide an inherent protection against flame-out that is not possible with a premixed flame.

Temperatures

Average flame temperature is generally not a critical parameter except in the extreme case where the flame starts to go out or in high temperature furnaces (such as cement kilns) where very high temperatures are essential to production. NOx

formation is driven by temperature - so local hot spots in the flame can cause high emissions even when the overall flame temperature isn't very high. Figure 3-1 shows the theoretical maximum temperature for a generic fuel as a function of excess air. It's derived by setting the amount of energy released by burning the fuel equal to the amount of energy absorbed by the gas in the combustion zone. Peak temperature occurs with zero excess air (where amounts of fuel and air are chemically balanced). Left of that point combustion is incomplete - not all the fuel energy is released and temperature drops. To the right of the peak there is excess air in the combustion zone that absorbs some energy and the temperature drops in proportion to the amount of extra gas present. So, for example, the maximum flame temperature at 100% excess air - corresponding to double the amount required for combustion (equivalence ratio = 2.0) - is about half the temperature at 0% excess air. A conceptual way to understand this curve is that it's the temperature of the exhaust of an insulated furnace - specify the excess air and the curve gives the temperature (actually the increase above the inlet air temperature). But the curve also shows the maximum possible temperature at any point in the flame for the air-fuel ratio at that point.

In actual combustors, temperatures are lower than the theoretical maximum, because heat is continuously lost by radiation to the furnace walls. However, the relationship between excess air and maximum possible temperature - as shown in Figure 3.1 - prevails in all combustion systems. In a premixed burner, the curve shows the maximum temperature everywhere in the flame which is the exhaust temperature of an adiabatic furnace. Except for the effect of radiative heat loss, premixed combustion is isothermal.

But with a diffusion flame the picture changes. Consider a typical boiler or industrial furnace with one or more burners. If the furnace is operating at a high excess air level, the exhaust might be 2000°F or less. But the actual burner flame temperature are much higher - the average furnace exit conditions aren't the same as conditions in the flame. This is because fuel-air mixing occurs in the flame, making rich and lean areas that are hotter and cooler than the final average exit temperature. Consider a small particle of fuel (oil droplet or tiny puff of gas) as it moves into the furnace. As it mixes with air and burns, its air/fuel mixture ratio goes from zero (pure fuel), through one (stoichiometric air), to the final average value. In so doing, it passes through the zero excess air point and through a peak temperature that could be close to 4000°F. Hence, as a consequence of mixing fuel and air in the combustion zone, all the fuel must pass through the point where equivalence ratio equals one and hence through the peak temperature region - even though the average exhaust temperature is much lower.

The down side of diffusion combustion, as we will see later, is that NO_x emissions are difficult to control because all of the fuel goes through a high temperature region at some point during combustion. On the up side, high local temperatures make it possible to have complete combustion and stable fires in a system that operates at fairly low exit temperatures. As an example, combustion turbines typically operate with very hot primary zones, but with combustor exit (turbine inlet) temperatures in the range of 1200°F to 2400°F.

Before leaving Figure 3.1, remember that the curve was derived using air that is about 79% inert nitrogen that absorbs most of the combustion energy. The height of the theoretical peak depends on the oxygen content (normally 20.9%) of the combustion air. A higher or lower peak will be generated if the air is oxygen enriched or vitiated. An increased percentage of inert gas will reduce the flame temperature. We will discuss vitiated combustion in the context of flue gas recirculation used to reduce NO_x emissions in Chapter 4..

Solid & Liquid Fuels

Most burners use diffusion combustion in which case the flame, size, shape and several emission species are substantially governed by the exact manner in which fuel and air are mixed together in the combustion zone. Air constitutes 90-95% of the mass of flame, so the overall flow pattern is controlled by the air flow hardware. Fuel is injected into this flow pattern - with jets of gas, a conical oil spray, etc - resulting in a flame pattern. Adjusting the fuel injection or the air flow pattern can change the stoichiometry and temperature patterns and hence the emissions. On a microscopic scale, the mixing of gas fuel with air is quite rapid as are the chemical reactions of combustion - generally milliseconds or less. Liquid fuel must evaporate before it can mix with air, so liquids burn slower than gas fuels - tens of milliseconds - and the atomizer design becomes important. Both #6 oil and bituminous coal evaporate only partially, leaving a residue of solid carbon (coke). Solid carbon doesn't evaporate at all so combustion must occur on the surface the fuel particles - meaning that the combustion rate is relatively slow - and it is proportional to the amount of exposed surface area. If solid fuel is converted to a powder - as with pulverized coal and sander dust, it can burn almost as fast as atomized oil - hundreds of milliseconds - because the tiny particles have so much surface area.

But non-powdered solid fuels (wood chips or crushed coal) burn very slowly - minutes to hours. Combustion times shorter or longer than about 1 second leads to the distinction between systems that burn fuel in suspension (gas, oil, pulverized coal) compared to stokers that burn solid fuel on a grate. The vast majority of large coal fired boilers are suspension fired. However, we still have stokers, because that's almost the only way to burn wood chips, solid waste or any fuel that cannot be converted to a powder.

Types of Combustion Systems

Until about 1990 most of the NO_x control efforts on stationary sources involved changes to combustion systems to reduce NO_x formation. Although back-end NO_x controls are becoming increasingly important, the design of *low NO_x combustion systems* will continue to be important element in NO_x control. There are many types and configurations of combustion systems and low NO_x systems are site specific. In this section we provide a very general introduction to combustion systems and their NO_x emission characteristics.

First we will divide combustors into three general categories:

1. Furnaces & boilers
2. Reciprocating engines
3. Combustion turbines

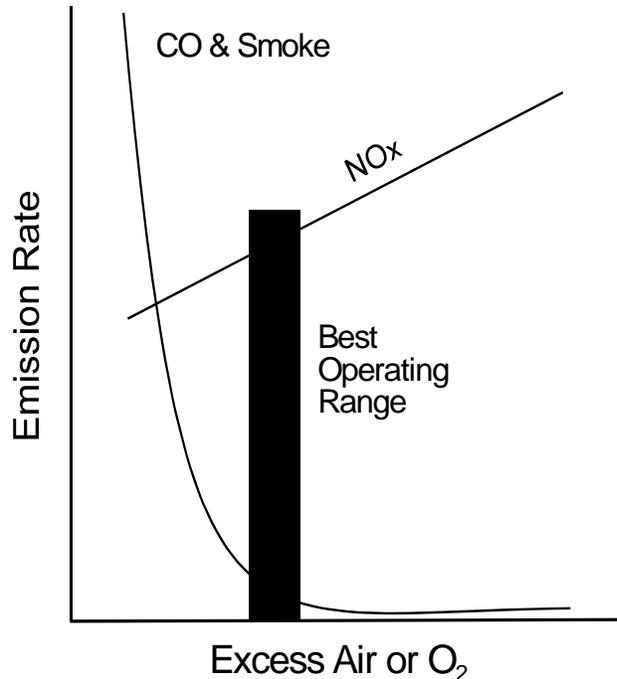
These combustion systems are all very different as are the NO_x control strategies. In all cases NO_x is formed in the combustion zone, then emitted to atmosphere through a stack or exhaust pipe. All the NO_x formation is in the combustion zone - there is almost no formation or destruction after the gases leave the hottest parts of the flame.

All these systems operate continuously over some load range and most have continuous operator supervision. Regulated stationary sources are not "off-on" devices like a residential furnace or water heater. This means that emissions may be an issue not just at full load, but over the load range. In some systems the emissions during start-up or shut-down, which can be a lengthy time period, can constitute a majority of the emissions.

Boiler Characteristics

Boilers produce steam or hot water and they can be designed to burn virtually any fuel. In practice, they burn a wide variety of fuels and nearly all operate at atmospheric pressure. They range in size from a home furnaces that would fit in the back of a small van to electric utility boilers that stand 200' high and burn pulverized coal at a rate of 400 tons/hr. A boiler consists of a firebox where the fuel is burned followed by banks of tubes where heat from the combustion gases is transferred to water or steam. Combustion temperatures are in the range of 3500°F and the flue gases are cooled to about 300°F at the stack.

Figure 3.2. Trade-off of NOx vs. CO & Smoke



Boilers have feed systems to supply fuel and combustion air and automatic controls for these systems. Fuel is supplied at a sufficient rate to satisfy boiler load demand. Air is supplied at a rate that matches the fuel flow. If the controls supply insufficient air, combustion will be incomplete and the boiler will smoke. So as the boiler controls always supply a bit more air than the minimum needed for complete combustion. Air flow to the boiler is generally characterized by the amount of excess air - which is the amount above and beyond that which is theoretically required for complete combustion. It is measured by the amount of O_2 in the flue gas. This O_2 is the air which wasn't consumed during combustion - so by definition it is "excess". Figure 3-2 shows the general relationship between excess air (or stack O_2) and emissions of NOx and CO. This shows the general form of the data if one were to systematically vary the excess air while measuring NOx, CO and O_2 in the flue gas. This is characteristic of diffusion flame emissions and will be observed on all boilers and furnaces. It would also hold true for combustion turbines and diesel engines, except that it is not practical to systematically vary the excess air levels on those sources.

Figure 3-2 illustrates several important points. First note that CO and smoke emissions are negligible at high excess air levels. As excess air is reduced, CO and/or smoke appears abruptly and increases rapidly - this is commonly referred to as the knee in the curve. NOx on the other hand decreases almost linearly as excess air is reduced. One can see that there is an optimum excess air operating point near the knee in the curve where NOx is minimized, but CO (and/or smoke) is not excessive. Any reduction in excess air would reduce NOx at the expense of significantly increased CO, smoke and/or carbon in the fly ash. In general on nearly all combustion systems, emissions control will be a compromise between NOx and CO or smoke emissions. To some degree we almost always trade decreased NOx emissions for increased emissions of CO, smoke and sometimes organic species.

This highlights the need to control air flow precisely on any combustion system,

particularly one that is attempting to minimize NO_x. With diffusion burners air flow needs to be maintained near the minimum practical (not quite smoking) level. The automatic air flow control system needs to do this continuously as load and fuel flow vary. Precise control of excess air is the first and most important step in controlling emissions from boilers and furnaces. This can only be achieved by using an exhaust O₂ monitor tied into an intelligent (microprocessor based) control system.

Fuel Effects on Boiler Emissions

It is useful, from a NO_x perspective, to characterize boilers and furnaces by fuel type:

1. Clean fuels (natural gas and distillate oils)
2. Residual oil, pulverized (powder) coal, and sander dust
3. Solid fuels.

Clean fuels contain very little nitrogen, which means that NO_x from these sources is generated only by the heat of combustion (thermal NO_x). NO_x can be reduced by simply lowering the flame temperature. Note that nearly all engines and combustion turbines only burn clean fuels, so they are in category #1. Fuels in categories #2 and #3 contain enough nitrogen that it accounts for much or most of the NO_x emissions from these sources. Flame temperature based NO_x controls are much less effective with these fuels, so effective NO_x reduction requires some form of staged combustion (*low NO_x burners*) or back end controls.

We have separated solid fuels (coal, wood, etc) into two categories because there are two very different types of combustor. When fuel is divided into fine particles - a powder or atomized spray - it burns very rapidly; typical times are less than ½ second. By contrast a lump of coal, a wood chip, or the material in solid waste may take several minutes to burn. Category #2 fuels are sprayed into the combustion chamber and **burn in suspension** with no significant settling of fuel particles. Category #3 fuels take more than a couple of seconds to burn, so the fuel settles to the floor of the furnace where it **burns on a grate** - similar to the fire in a home fireplace.

Suspension fired boilers all operate similarly regardless of whether the fuel is gas, oil or pulverized coal. The burners look quite similar except for the fuel injection hardware, and in many cases a single burner is capable of firing two or three different fuels - sometimes simultaneously. The main differences between boilers designed for different fuels lie in provisions for handling the large amount of ash present in coal and hence their physical size. Coal fired boilers need to be about 50% larger than gas fired boilers for the same steam capacity.

From the perspective of NO_x control, suspension burning (category #1 or #2) offers the opportunity to control the fuel and air mixing in the flame in a way that affects NO_x formation. Grate burning (category #3) offers very little ability to control the combustion. Hence stoker furnaces (stoker coal, wood chips & solid waste) offer very limited opportunity to minimize

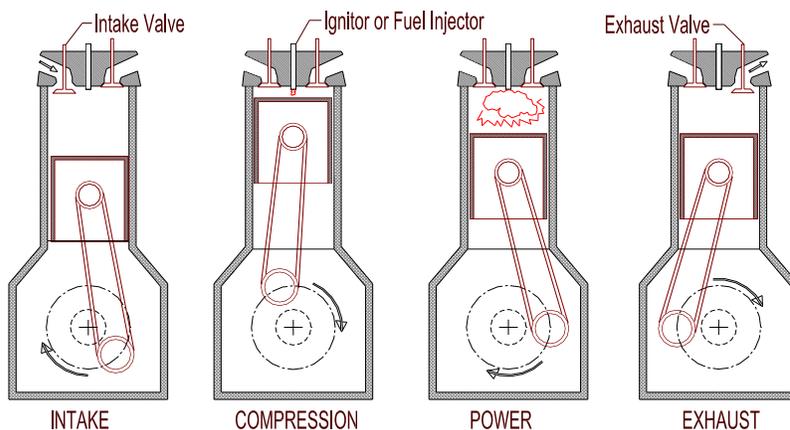
NOx formation. They may be amenable to *reburning* with supplemental suspension burning(discussed later) but for the most part NOx reduction from these units is achieved by back end controls.

Although boilers come in all sizes, many of the basic features are common to all of them. Size does have some influence on NOx emissions and NOx controls. First, small boilers usually burn clean fuels, while larger boilers burn the least expensive fuel available - which usually means high fuel nitrogen content and higher NOx emissions. Second, while industrial boilers generally have only a single burner, large utility boilers have multiple burners - up to several dozen. This has both advantages and disadvantages when it comes to NOx control. The advantage is that low NOx staged combustion firing can frequently be achieved by taking one or more burners out of service - which doesn't reduce the full load capability. The disadvantage is that low NOx operation requires that each burner get the same amount of fuel and air - each one needs to operate at the same air/fuel ratio. While this seems like a straightforward requirement, it can prove very difficult to achieve in practice.

Figure 3-3. Reciprocating Engine Operating Cycle

Reciprocating Engines

Reciprocating engines, similar to a car or truck engine, are used for small to medium size stationary power sources. Generally the largest size is 15-20 MW, but a few much larger engines have been built. Most reciprocating engines fire natural gas as the primary fuel, but many are equipped to fire liquid fuel, #2 or diesel oil, as an alternative. Combustion in reciprocating engines is not steady state. Typically each cylinder fires once for each two revolutions of the crankshaft. Figure 3-3 shows a piston and cylinder cross section and the typical sequence of events.



(1) As the piston moves down it draws in an air-fuel mixture; (2) the mixture is compressed on the up stroke and ignition occurs when the piston is near the top; (3) the power stroke follows

as combustion drives the piston down; (4) exhaust gases are pushed out on the final up stroke. Combustion occurs at very high pressure (over one hundred psi) and at relatively high temperature. As a consequence of the high temperatures, NO_x emissions are high - roughly 10x the emissions from a boiler burning the same amount of fuel. (Note that transportation vehicles generate more NO_x in this country than do large stationary sources.)

Spark Ignition versus Compression Ignition

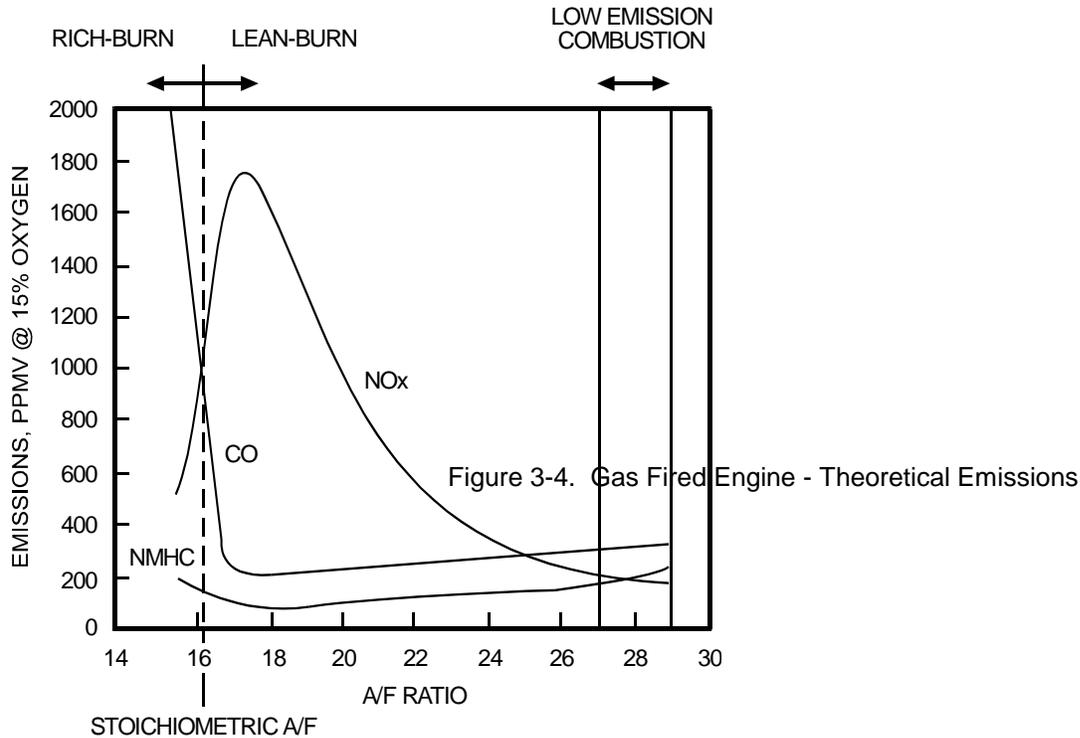
There are basically two ways to get fuel into the cylinder of a reciprocating engine. (1) *Spark ignition* means that air and fuel gas are premixed, drawn into the cylinder on the downstroke and ignited with an electric spark - premixed combustion. (2) *Compression ignition (Diesel)* means that pure air is drawn into the cylinder and fuel oil is injected as the piston approaches the top - diffusion combustion. Diesel engine compression (typically above 12:1) is high enough that the fuel auto-ignites as it is sprayed into the chamber. The auto-ignition point of diesel fuel in the cylinder is approximately 1300°F at 44 atm. The critical difference from a combustion and NO_x control perspective is that natural gas (or gasoline) burns in a premixed mode, while diesel fuel burns in a diffusion mode. As a result, diesel peak combustion temperatures cannot be controlled as effectively as they can be for gas fired engines, so the options for reduced NO_x formation are more limited.

We noted in the discussion of diffusion and premixed combustion that premixed combustion only occurs over a limited range of air-fuel ratios. This means that gas (or gasoline) fired engines all operate with a air-fuel ratio near stoichiometric. How lean the air-fuel ratio can be depends on several factors including spark intensity, type of fuel and combustion chamber design. The higher the spark intensity the leaner the air/fuel ratio that can be ignited. Chapter 6 explores these factors in more detail.

Ignition Timing

One of the variables for either gas or diesel engines is ignition timing. Injection is normally timed for maximum power which means shortly before the piston reaches the top of its stroke - typically up to 20° of crankshaft rotation. Delaying (retarding) the timing reduces both power and NO_x emissions. This method of reducing NO_x formation will be discussed in Chapter 6.

Air/Fuel Ratio



Spark ignited engines are characterized as *lean burn* or *rich burn* depending on whether the exhaust O₂ level is more or less than 1% (corresponding to about 5% excess air). Figure 3-4 shows the theoretical relationship between air/fuel ratio and emissions for a gas fired engine. Rich burning (low excess air) invariably generates a certain amount of CO, hydrocarbons and smoke. Figure 3-4 suggests that a gas fired engine could operate very lean (high excess air) with low emissions of all pollutants. This is discussed later, but conventional engines can't run very lean because very lean mixtures won't ignite with a conventional spark ignition system. So operation is limited to air/fuel ratios where either NO_x or CO is relatively high.

Since a diesel engine operates with diffusion combustion there isn't a limit on the fuel air ratio and Figure 3-4 does not apply. Air flow depends on engine speed while fuel flow depends on power level. At low power, with minimum fuel flow, the excess air and exhaust O₂ are very high. At full power the fuel air ratio is close to stoichiometric, the exhaust O₂ is close to zero, and the engine is beginning to smoke.

Compression Ratio

As the piston moves from the bottom of the cylinder to the top it compresses the air and the ratio of cylinder volume at the bottom of the stroke to the volume at the top of the stroke is called the compression ratio. Increasing an engine's compression ratio increases its efficiency as well as the power available from a given engine size. Maximum compression ratio in a spark ignition engine is generally less than 9:1 and is limited by fuel "knock". If the heat of compression reaches the auto-ignition temperature of the fuel-air mixture, it explodes rather than burning smoothly.

Figure 3-5 Combustion Turbine Schematic

In automobile engines high octane fuel allows a higher compression ratio (up to 12:1), giving more power. In stationary engines, where the fuel is natural gas, the compression ratio can be raised by raising the air/fuel ratio - leaner operation. While this approach potentially improves engine efficiency and lowers NO_x simultaneously, it is limited by the ability to ignite the fuel - as discussed above. In Chapter 6 we look at low NO_x concepts based on lean operation.

Reciprocating engines are factory built as opposed to many boilers which are built on site. In contrast to boilers, their combustion systems and operating controls are built-in and not amenable to simple adjustment or alteration. Thus, when properly maintained, they tend to have more predictable NO_x emissions than does a boiler.

Combustion Turbines

Combustion turbines are basically aircraft "jet" engines adapted for stationary power sources. These engines are physically small, but power levels range up to about 250 MW (330,000 HP). Combustion in turbines is steady state - starting the engine corresponds to establishing a stable fire in the combustor. Figure 3-5 is a schematic diagram of the turbine operation. Air is drawn in and compressed to 10 or 20 atmospheres in an axial flow compressor (like a turbine operating in reverse). Fuel is added in a combustor to raise the temperature to anywhere from 1500°F to 2400°F. This increases the gas volume which is then expanded through a turbine. Part of the power from the turbine runs the compressor and the remainder is the output shaft power.

Combustion turbines can, in concept, burn any liquid or gaseous fuel. In practice they only burn clean fuels - the cleaner the better. Any contaminants in the fuel tend to deposit on the turbine blades leading to frequent expensive maintenance. The availability of cheap natural gas in the late 1900's is part of the reason for the proliferation of these units in power plants.

Originally all turbine combustors used diffusion combustion. About 1990 low NO_x combustors began to appear that operated with premixed combustion when firing natural gas at high loads. This will be discussed further in Chapter 7.

Uncontrolled NO_x emissions from turbines are higher than from boilers, but as discussed in Chapter 7, water injection has kept NO_x emissions relatively low since the mid 1970's. *Low NO_x* combustors have lowered CT emissions even further and the technology continues to

evolve.

Catalytic Combustion

Combustion invokes a mental image of flames and intense temperatures. However, the oxidation of organic material occurs over a broad range of temperatures - for example, rotting vegetation yields the same end products as combustion, but it goes on slowly at ambient temperature. Catalysts allow combustion reactions to occur at temperatures much lower than typical flames. So passing organic vapor over a platinum surface at 500°F will result in combustion of the vapor. Essentially the chemical reaction occurs on the surface of the catalyst. Catalytic combustion is attractive in regard to NO_x control because thermal NO_x formation can be suppressed by reducing the flame temperature. There are a number of limitations or conditions on where and how catalytic combustion can be used.

First, the fuel must be a gas premixed with air so that individual molecules of fuel and oxygen can react on the catalyst surface. Some liquid fuels, gasoline is an example, can be vaporized, but for the most part catalytic combustion is limited to natural gas or propane. Combustors designed to vaporize kerosene or diesel fuel have generally encountered durability problems.

Second, the fuel-air mixture must be preheated to the active range of the catalyst. There are various ways to achieve this preheat, but unlike flame combustion, you can't just light it and expect it to sustain itself.

Third, while the catalyst entry temperature must be above a minimum level, the temperature coming out of the catalyst needs to be below a level that would destroy the catalyst. This can put an upper limit the fuel-air ratio of the catalytic burner - typically a stoichiometric ratio less than 0.5. This makes catalytic burners well suited to vapor incinerators, but challenges the design of systems intended for commercial burners or combustion turbines.

We will look at some catalytic combustors in Chapter 4 - NO_x Control by Reducing Temperature.

Review Exercises

1. What is the basic difference between diffusion and premixed combustion?
2. Can liquid fuels burn in a premixed combustor?
3. What is the approximate maximum flame temperature of hydrocarbon fuels burning in air?
4. Will average flame temperature increase or decrease as excess air is increased?
5. Which will have higher local flame temperatures: diffusion or premixed burners?
6. When operating a typical boiler, increased excess air will: increase or decrease NO_x emissions?
7. What is the effect on CO emissions of reducing excess air to near zero?
8. What is the difference between suspension and grate firing? What types of fuel can be fired by each method?
9. Why is it easier to control NO_x formation in a suspension fired boiler than in a stoker boiler?
10. Do spark ignition engines use diffusion or premixed combustion? Same question for compression ignition (diesel) engines?
11. Typical spark ignition engines operate over a wide or narrow range of air-fuel ratios?
12. Does the fuel-air ratio in a diesel engine vary significantly as the load changes?
13. In a combustion turbine how does the primary zone temperature compare to the turbine inlet temperature?
14. Describe the key elements of catalytic combustion.

Answer Key – Review Exercises – Chapter 3

1. *With diffusion combustion fuel and air mix simultaneously with combustion. With premix, combustion starts only after the fuel and air are completely mixed.*
2. *No – unless the fuel is vaporized completely to a gas during or before premixing.*
3. *4000°F.*
4. *The average will decrease. Local temperatures in a diffusion flame might increase or decrease.*
5. *Diffusion flame burner.*
6. *NO_x always increases with excess air in a diffusion flame.*
7. *Reducing excess air beyond some critical point will create smoke, CO and maybe hydrocarbons.*
8. *Grate combustion burns solid fuel in pieces larger than about 1 mm with residence times measured in minutes. Suspension firing applies to fuel particles smaller than 1 mm including solids, liquid sprays and gases. Combustion times are two seconds or less.*
9. *In suspension firing the design of air and fuel jets gives much more control of the combustion process than is available with air feeding through a bed of solid fuel resting on a grate.*
10. *Spark ignited engines, by definition, use premixed fuel and air. Diesel engines spray a liquid into the combustion zone – mixing and combustion are simultaneous – the definition of diffusion combustion.*
11. *Fuel-air mixtures (for most fuels) can only be ignited when the mixture is somewhere near stoichiometric, so SI engines operate in a narrow range of air-fuel ratios.*
12. *Air flow to a diesel engine depends mostly on engine speed, while fuel flow depends on load. Since speed and load are more or less independent, the fuel-air ratio varies widely.*
13. *The primary zone must stay hot enough to keep stable combustion – typically above 3000°, while the turbine inlet must be cool enough to avoid damage to the nozzle and turbine blades. So there is a lot of cooling dilution air introduced between the primary zone and the turbine.*
14. *A catalyst allows ignition and combustion at temperatures as low as 700°F. An air-gas mixture must be preheated to the catalyst activation temperature and the final catalyst temperature cannot exceed 1800°F. Part of the fuel may burn after the catalyst if an exhaust*

temperature above 1800°F is required.