

Solutions Reduce Engine Emissions

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FORT COLLINS, CO.—Most U.S. industries have been affected by clean air regulations over the past couple decades, and the oil and gas industry is no exception. Several new clean air regulations that impact oil and gas have been enacted and others will be finalized soon. However, for companies that operate reciprocating engines in their compressor fleets, a number of available and proven retrofit technologies can be applied to installed horsepower to reduce emissions.

The Clean Air Act Amendments of

1990 required significant ozone emission reductions from installed equipment such as large reciprocating engines, turbines, heaters and boilers. In addition, operators were required to maintain records monitoring emissions. Title III of the legislation focused on reducing hazardous air pollutants, but until recently, it was not heavily enforced in the oil and gas industry.

Through a combination of automatic provisions and legal decisions, several new rules and regulations are expected to be put in place in 2010, 2011 and 2012 that will require significant action and investments by oil and gas operators. Moreover, with air quality and emissions reduction remaining key issues on the

federal level as well as the state and local levels, additional mandates and legislation can be expected. Key regulations expected to impact the industry over the next few years include:

- National emission standards for hazardous air pollutants (NESHAP) for reciprocating internal combustion engines;
- Ozone national ambient air quality standards (NAAQs);
- Nitrogen dioxide (NO₂) NAAQS (new one-hour standard); and
- Greenhouse gases (GHGs).

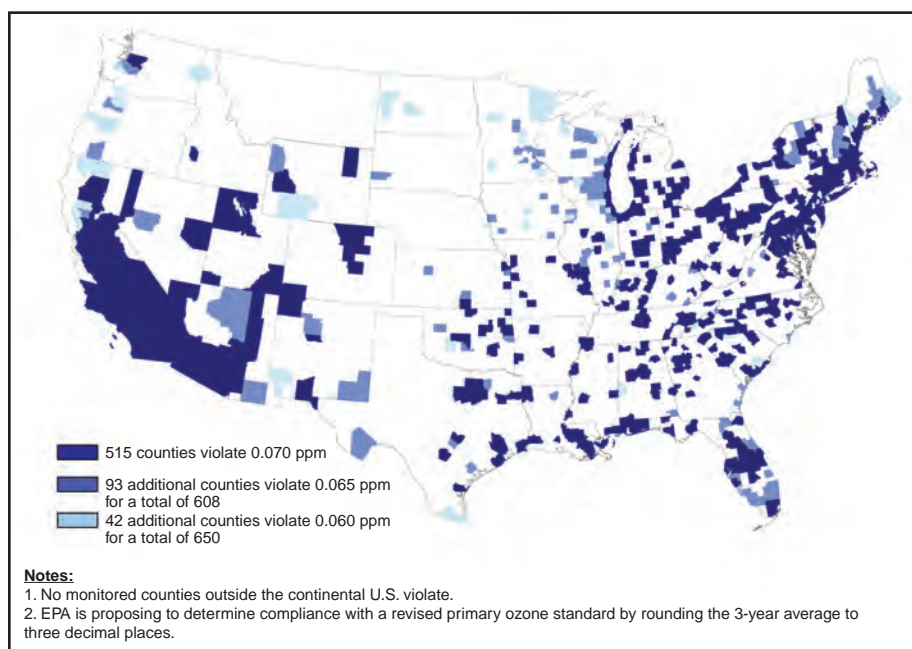
HAP And Ozone Regulations

Title III of the Clean Air Act Amendments calls for controlling and reducing air toxins, and this section was separate and distinct from other sections. The rule was intended to curb emissions of 189 specific hazardous air pollutants, and called for implementing the maximum achievable control technologies (MACT) to reduce HAP emissions. The rule called for identifying and installing MACT controls for a wide range of equipment and processes. Specific guidelines for stationary reciprocating internal combustion engines (RICE NESHAP) refer to technologies for complying with the NESHAP. HAP emissions from stationary reciprocating internal combustion engines include formaldehyde, acrolein, methanol and acetaldehyde, with formaldehyde (CH₂O) being the most prevalent.

The original RICE NESHAP requirements for existing engines were released in 2004 and identified MACT as "no controls." Since then, the rule has been revisited and the MACT approach has been invalidated by the courts. In response, the U.S. Environmental Protection Agency has drafted (and partially published) a

FIGURE 1

Counties Violating Proposed Ground-Level Ozone Standards
(60-70 ppb)



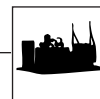
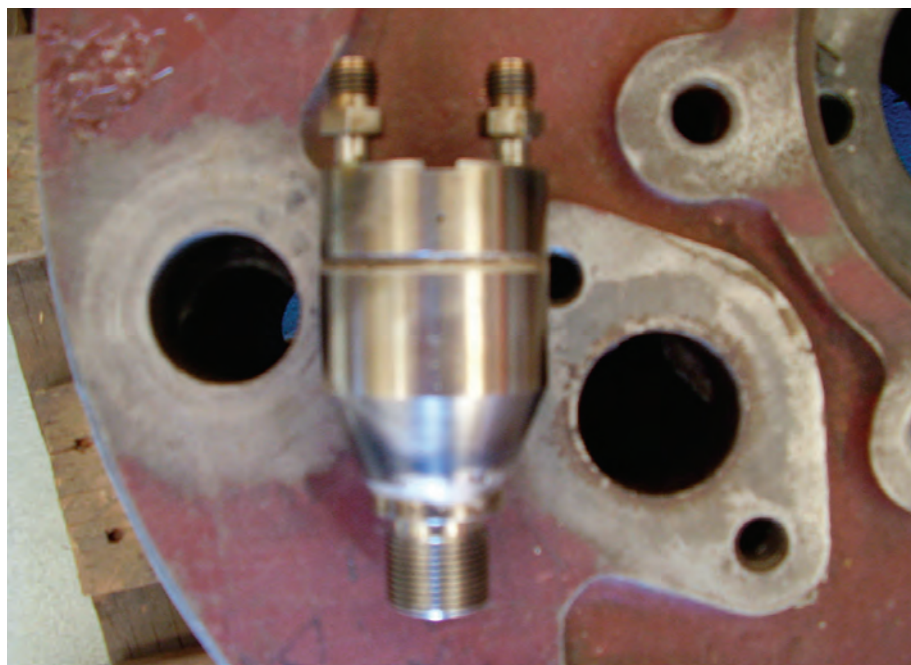


FIGURE 3
Example Screw-In Precombustion Chamber



Subpart W).

As part of the CAIR program, 10 Northeast and Mid-Atlantic states have agreed to implement a market-based effort known as the Regional Greenhouse Gas Initiative (RGGI) to cap and reduce CO₂ emissions from electric generating plants (including gas- and oil-fired facilities). This effort is expected to reduce CO₂ levels 10 percent by 2018.

Looking forward, the new clean air regulations anticipated to be implemented over the next few years will require additional emissions reductions and controls. These rules are expected to have a major impact on existing and new reciprocating engines owned and operated by oil and gas companies.

Controlling Emissions

The most common elements in the exhaust stream created by the internal combustion process in a reciprocating engine are CO₂, water, CO, NO and NO₂ (NO_x), air toxics (formaldehyde, etc.), VOCs, unburned fuel (hydrocarbon), unburned air (N₂ and O₂), and ash or particulate matter (generally from diesel engines).

For gas-fired reciprocating engines, the primary focus of clean air regulations has been on reducing NO_x, CO, VOC and CH₂O emissions. Several factors influence the amount of emissions produced by combustion, including combustion temperature and time, burn stability, and

the amount of fuel and air introduced into the engine.

NO_x is primarily influenced by the air/fuel mixture, combustion temperature and time. NO_x is formed when high temperatures (typically greater than 1,200 degrees Fahrenheit) bond the naturally occurring nitrogen and oxygen found in air. NO_x emissions can be reduced by lowering the combustion temperature (or shortening the burn time). The most common way of lowering combustion temperature is “leaning” the air/fuel mixture with excess air to effectively keep the cylinder temperature down.

CO, VOC and CH₂O are products of incomplete or partial combustion. Incomplete combustion can be caused by many things, including mechanical problems, cool combustion, a poorly mixed air/fuel mixture, combustion quenching at the cylinder walls or in crevice spaces, etc. Some of the most effective ways to reduce or minimize incomplete combustion are to perform regularly scheduled maintenance, increase combustion temperature (burn hotter), and minimize misfires (more powerful ignition source, better mixing of air and fuel, etc.).

A number of proven, available retrofit technologies can reduce emissions on reciprocating engines. There are three categories of emission reduction solutions for stationary reciprocating engines: preventive maintenance, combustion modi-

fications, and after-treatment solutions.

The goal of preventive maintenance is to maintain and operate the engine at or near new operating conditions. Most operating permits for engines require continuous compliance with emissions limits. When the engine and its subsystems are operating properly, exhaust emissions are controllable and predictable. However, as parts wear and controls lose calibration, the engine begins to operate poorly (generally with increased emissions and reduced fuel economy). For emissions compliance, each part or subsystem of the engine that affects the fuel, air, ignition or combustion process must be properly maintained.

The simplest maintenance includes routine air filter changes, regular spark plug changes, oil changes, power cylinder balancing, catalyst washing, and general calibration and maintenance of controls and monitoring devices. For many older engines being retrofitted with emission reduction devices, a mechanical overhaul is a good choice to verify that internal wear parts and clearances are within specifications.

Combustion Modifications

Numerous add-on or retrofit combustion modification technologies have been developed to reduce emissions. The most common proven technologies include open-chamber/high-energy ignition systems, precombustion chambers, air system upgrades to high-energy ignition systems, air/fuel ratio control upgrades, and enhanced mixing technologies.

An open-chamber system is an ignition system directly inside the main chamber, generally a spark plug protruding from the bottom of the power cylinder head into the combustion chamber. When the engine’s air/fuel mixture is lean, the amount of spark required from the ignition system to start combustion is increased. High-energy ignition systems allow more energy to be delivered to a spark plug with a larger gap, thereby increasing the spark energy delivered to the air/fuel mixture and ensuring proper ignition.

Spark plug and ignition systems have been dramatically improved over the past couple decades. Today’s high-energy ignition systems are digitally controlled devices that use crankshaft referenced angle encoders to deliver precise, high-energy ignition sparks. Many industrial engines have two spark plugs per cylinder, and the ignition systems can be set to generate



FIGURE 4

Example Air System Upgrade



multiple, successive sparks during combustion to ensure proper air/fuel light-off.

The extremely lean air/fuel mixtures used on many engines to lower emission levels are very difficult, if not impossible, to ignite using a standard open-chambered spark plug ignition system. In these cases, a prechamber (typically less than 10 percent of the volume of the main chamber) is installed in the power cylinder head and fitted with a conventional spark plug and ignition system (Figure 3).

During the intake process, the precham-

ber is charged with a richer air/fuel mixture than the main chamber. The richer mixture is easily ignited by the spark plug, creating a “fire ball” inside the prechamber. As the burning gas exits the prechamber and enters the main chamber, it acts like a blow torch to ignite the main chamber’s lean air/fuel mixture. As a result, the main chamber will light off easier and burn faster than if the ignition was started by a traditional open-chamber spark plug.

The most common approach to adding

more air to the combustion process for leaner air/fuel mixtures is to upgrade, add or replace the air delivery device with a turbocharger. The turbocharger must be properly designed and built to provide the necessary air supply to maintain emissions and horsepower across the engine’s full operating range. The design specifications are critical and should be done by an expert. Unfortunately, replacing or changing a turbocharger likely will require several other changes to the engine, including air manifold cooling, air inlet piping/manifold modifications, and exhaust piping/manifold and silencer changes.

Figure 4 shows an engine with an air system upgrade. In addition to the physical changes, certain controls must be installed to monitor and adjust air manifold pressure and temperature. Air manifold pressure is important for controlling the air/fuel mixture for proper combustion and emissions control. Air/fuel strategies monitor and vary air manifold pressure based on various engine parameters (charge air temperature, engine speed, fuel flow, etc.) to properly maintain the correct air/fuel ratio necessary for emissions compliance over varying speed and load conditions.

Control Upgrades

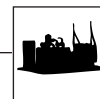
Simple electronic or pneumatic controls can be used to moderate emission controls, but as emission-reduction requirements stiffen, more sophisticated air/fuel ratio and engine parameter controls must be put in place. Most simple controls cannot adjust well for varying load or speed conditions, varying ambient conditions, or startup/shutdown conditions.

Most low-emitting engines are fitted with air/fuel ratio controllers with trapped

FIGURE 5

High-Pressure Fuel Injection Enhanced Mixing System





equivalence ratio (TER) technology. TER uses a sophisticated mathematical model to monitor many engine parameters and atmospheric conditions to determine the correct air/fuel mixture for the operating conditions. By tracking and maintaining the “correct” air/fuel mixture, the engine runs clean and more efficiently. And most importantly, with a good TER-controlled system, the engine can maintain emissions compliance even as operating conditions and ambient conditions change (which is not practical on a traditional air/fuel controller).

Enhanced mixing technologies are another option. Two-stroke engines and direct fuel-injected four-stroke engines have an inherent problem mixing air and fuel well. Unlike a carbureted engine where the air and fuel are premixed and delivered together to the cylinder, two-stroke industrial engines do not mix the air and fuel until it enters the cylinder.

To further complicate things, air generally is delivered through the bottom of the cylinder through the intake ports, while fuel is delivered through an injection valve in the power head. The air and fuel mix by colliding into each other (imagine squirting chocolate syrup into a glass of milk and hoping the two mix with one or two turns of the spoon into perfect chocolate milk).

In the real world, the fuel and air do not mix very well, resulting in a sporadic and unstable burning process as the flame burns through the cylinder filled with different regions of differing air/fuel mixtures. To improve the mixing process, the fuel pressure (typically less than 30 psi) is raised significantly and “jetted” into the cylinder (Figure 5).

Three versions of fuel injection are used in the field, depending on the desired emission reductions and the availability of high-pressure fuel: port-injection (for four-stroke engines), medium-pressure fuel injection (less than 150 psi), and high-pressure fuel injection (~500 psi). High-pressure fuel injection forces a rapid and turbulent interaction between the air and fuel to thoroughly mix both, similar to using a pressure washer to inject the chocolate syrup into the milk.

After-Treatment Solutions

After-treatment solutions are designed to reduce or destroy exhaust emissions after they are created. The most common is catalytic converters, which contain precious metals that help break down exhaust

FIGURE 6

Catalyst Installed on High-Speed Engine



gases into nonpollutants. However, it is important to note that while catalysts work very well in certain temperature and exhaust conditions, they do not work well in others. Three types of catalysts can be used, depending on engine type: nonselective catalyst reduction (NSCR), selective catalyst reduction (SCR), and oxidation catalysts. Figure 6 shows a typical catalyst installation on a high-speed engine.

NSCR catalysts are designed for rich-burn engines with low levels of excess oxygen in the exhaust. Used in automobiles for decades, NSCR catalysts reduce NO_x, CO, VOC and several air toxins (formaldehyde, for example). They work particularly well at high exhaust temperatures, but not as well at low exhaust temperatures (such as those experienced when an engine is starting or cooling), or higher than 0.5 percent exhaust O₂ concentrations. NSCR catalyst efficiency is directly related to the air/fuel mixture and temperature of the exhaust. As such, proper air/fuel ratio (particularly oxygen) control is critical.

Oxidation catalysts are used with lean-burn engines to reduce carbon monoxide, VOCs and air toxins, but they do not reduce NO_x emissions. This catalyst works well in exhaust streams with high levels of excess oxygen, but unfortunately, its efficiency suffers dramatically at exhaust temperatures below 600 degrees F (common for lean-burn engines). The reduction efficiency can be improved, but the surface area or precious metal load of the catalyst elements must be increased.

Greater than 90 percent CO conversion can be achieved at levels at or near 600 degrees, but the catalyst housing and elements tend to get rather large and heavy, requiring highly engineered installation structures, maintenance platforms and element lifting devices to adequately support and provide safe maintenance of the equipment for long-term use. At lower exhaust temperatures, engine operators must be particularly sensitive to oil car-

ry-over into the exhaust, which may lead to premature catalyst masking/fouling.

SCR catalysts are used with lean-burn engines to reduce NO_x emissions only. In addition to high exhaust temperatures, SCR catalysts require the controlled injection of a special reagent (typically ammonia or urea) to keep the NO_x reduction going. The extra requirements related to supplying and controlling the reagent make SCR catalysts difficult and time consuming to operate and maintain.

While SCRs are used only in special cases on industrial engines in the oil and gas industry, they are widely accepted in the power industry. The difference between power units and gas compressors is the varying load and speed, which requires a more sophisticated reagent controller to properly vary with frequent changes in load and speed.

All three types of catalysts have similar maintenance requirements. Over time, the catalyst can be fouled or contaminated with normal engine exhaust (oil, ash, etc.). By monitoring the different pressures and temperatures across the catalyst, the operator can determine when catalyst maintenance is required. Generally, catalysts can be washed with special chemicals and reused two or three times before the element must be replaced. As a general rule, intervals between washing are typically one to two years.

Main Engine Types

The three main types of gas-fired engines used in the oil and gas industry are two-stroke lean-burn engines, four-stroke lean-burn engines, and four-stroke rich-burn engines. Although each engine type is similar in many ways, the emission retrofit technologies differ.

Two-stroke engines complete the combustion process in one revolution of the crankshaft, or two strokes of the piston (one up and one down). The engines have intake ports to introduce air and exhaust

TABLE 1

Emission Control Technologies for Two-Stroke Lean-Burn Industrial Engines

Emission Retrofit Technologies	Typical emission reduction			Technology Introduced on New Equipment
	NOx	Carbon Monoxide	VOC and Air Toxins	
Mechanical overhaul and preventive maintenance	10%	25%	25%	< 1970s
Combustion modifications				
Open-chamber high-energy ignition system	10%	30%	35%	1990s
Air upgrade (turbocharger and air manifold cooling)	75%	may get worse	may get worse	1970s
+ Enhanced mixing (medium- and high-pressure fuel injection)	90%	80%	80%	2000s
+ Precombustion chamber ignition system	90%	85%	85%	1980s
+ TER air/fuel ratio control	Assures continuous compliance at different operating and ambient conditions			2000s
After-treatment				
+ Oxidation catalyst	n/a	90-99%	50-90%	2000s
+ SCR catalyst	50-95%	n/a	n/a	2010s

ports to expel combustion gases. Industrial two-stroke engines are generally fuel injected and require a positive supply of air to feed and purge the combustion process. To supply the necessary air, the engines may have scavenging air compressors, mechanical blowers, turbochargers, or some combination thereof.

The air and fuel are mixed inside the power cylinder and fired by either a spark plug or precombustion chamber. Two-stroke engines generally are set to operate

with a lean mixture to minimize combustion temperatures, and with excess oxygen present in the exhaust, they can be fitted with oxidation or SCR catalysts to reduce emissions. Table 1 shows the types and effectiveness of retrofit technologies for large natural gas-fired, two-stroke lean-burn engines.

Four-stroke engines complete the cycle in two revolutions of the crankshaft. Each of the piston's four strokes has an important function in the engine cycle (intake, com-

pression, power and exhaust). These engines have intake and exhaust valves to introduce and exhaust combustion gases. Most four-stroke engines use open-chamber spark plugs to ignite the air/fuel mixture, and can be configured as rich- or lean-burn, depending on the air/fuel mixture.

Rich-burn four-stroke engines are configured to operate at or near stoichiometric with little or no excess air. The engines generally are carbureted and use the intake stroke of the piston to draw air into the

TABLE 2

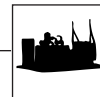
Emission Control Technologies for Four-Stroke Rich-Burn Industrial Engines

Emission Retrofit Technologies	Typical emission reduction			Technology Introduced on New Equipment
	NOx	Carbon Monoxide	VOC and Air Toxins	
+ Mechanical overhaul and preventive maintenance	10%	25%	25%	
Combustion modifications				
+ Open-chamber high-energy ignition system	10%	10%	10%	1990s
After-treatment				
+ NSCR catalyst (with air/fuel ratio controls)	90-99%	90-99%	50-90%	1970s

TABLE 3

Emission Control Technologies for Four-Stroke Lean-Burn Industrial Engines

Emission Retrofit Technologies	Typical emission reduction			Technology Introduced on New Equipment
	NOx	Carbon Monoxide	VOC and Air Toxins	
Mechanical overhaul and preventive maintenance	10%	25%	25%	
Combustion modifications				
Open-chamber high-energy ignition system	10%	30%	35%	1990s
Air upgrade (turbocharger and air manifold cooling)	60-70%	may get worse	may get worse	1970s
+ Enhanced mixing (port injection or carburetor upgrade)	90%	50%	50%	2000s
+ Precombustion chamber ignition system	90%	10%	20%	1980s
+ TER air/fuel ratio control	Assures continuous compliance at different operating and ambient conditions			2000s
After-treatment				
+ Oxidation catalyst	n/a	90-99%	50-90%	2000s
+ SCR catalyst	50-95%	n/a	n/a	2010s



cylinder (naturally aspirated). Manufacturers have added turbochargers to increase the delivery of air, which increases horsepower output. Table 2 shows the types and effectiveness of retrofit technologies for large gas-fired, four-stroke rich-burn engines.

Lean-burn four-stroke engines usually have a fuel injection system near the intake valves or in the power head. They use either open-chambered or precombustion chamber ignition systems to assure ignition of the lean mixture. Engines generally are fitted with a mechanically-driven blower or turbocharger to supply air. Table 3 shows the types and effectiveness of retrofit technologies for large gas-fired, four-stroke lean-burn engines.

Looking forward, environmental regulations likely will require additional exhaust

emission reductions for installed reciprocating gas-fired engines. The NESHAP regulations are expected to impact the oil and gas industry by first requiring emission control technologies to reduce carbon monoxide and formaldehyde, followed soon by ozone regulations requiring additional reductions in NO_x emissions, and then GHG regulations that likely will require reductions in CO₂ or equivalent emissions.

Fortunately, many reliable and proven emission control technologies can be applied to installed engines to meet current and expected future clean air requirements. Furthermore, the engine operator generally can tailor the emissions solution to meet current needs with options to further reduce emissions in the future. □

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