RESEARCH ON EXHAUST EMISSIONS REDUCTION TECHNOLOGIES FROM LARGE MARINE DIESEL ENGINES

Prepared by:
Ramani Srinivasan
Matson Navigation Company Inc.

Background

The exhaust emissions from large marine diesel engines on ocean going vessels contains among other pollutants a significant amount of Nitrogen Oxides (NOx). These NOx emissions from ocean going vessels are beginning to represent a significant percentage of the overall NOx emissions in coastal regions and ports located in non-attainment areas.

Marad, under the direction of project coordinator Mr. Bob Behr, has sponsored Matson Navigation for a cooperative joint project to conduct research into available technologies for NOx reduction. The scope of the project entails evaluating various technologies that apply to new engines as well as those that are suitable for a retrofit installation on existing motor vessels.

The project is in 3 phases

- Research and project proposal
- Detailed design, installation and testing
- Incentive programs

This paper discusses various technologies that are available for retrofit on existing engine installations and for new engines. Based on the outcome of this report and availability of funds, Matson under the direction of Marad project coordinator may proceed in the detailed design and installation of a suitable system for NOx reduction on one of our vessels as a technology demonstrator.

Introduction

A diesel engines is type of internal-combustion engine in which atomized fuel oil is sprayed into the cylinder and ignited by the heat generated by compression. Diesel engines are efficient with low carbon di-oxide, carbon monoxide and hydrocarbon emissions. However the emissions are high in nitrous oxides. Additionally marine engines use residual bunker fuels which contains sulphur, asphaltenes and ash. Due to these components in the fuel, the exhaust emissions contain oxides of sulphur and particulate matter which are formed during the combustion process.

Typical concentrations of exhaust emissions are as follows:

Oxygen:	abt.	13%
Nitrogen:	abt.	76%
Carbon di Oxide (CO_2):	abt.	5%
Water vapor:	abt.	5%
Oxides of Nitrigen (NOx):	abt.	1500 ppm
Oxides of Sulphur (SOx):	abt.	600 ppm
Carbon Monoxide (CO):	abt.	60 ppm

Hydrocarbons (HC):	abt.	180 ppm
Particulate matter (PM):	abt.	120 mg/Nm3

Fuel is injected at high pressure (through fuel injectors which atomizes the fuel) into the combustion chamber towards the end of the compression stroke. The fuel ignites, thereby increasing the pressure in the combustion chamber and pushes the piston downward on the power stroke. When the fuel ignites the flame front travels rapidly into the combustion space and uses the compressed air to sustain the ignition. Temperatures at the envelope of the flame can exceed 1300 degrees C, although the mean bulk temperatures in the combustion chamber is much lower. At these localized high temperatures molecular nitrogen in the combustion air is oxidized and Oxides of Nitrogen (NOx) are formed in the combustion chamber. Oxidation of molecular nitrogen in the combustion air comprises of about 90% of all NOx, the other 10% is the result of oxidation of the organic nitrogen present in the residual fuel oil.

Prevention or reduction in NOx formation in the combustion chamber essentially involves lowering the localized peak temperatures. Post treatment of the exhaust gas after the NOx formation in the combustion chamber involves reducing the NOx with ammonia into nitrogen and water vapor in the presence of a catalyst.

Methods for NOx reduction are categorized as follows:

- Pretreatment or conditioning of the fuel and/or the combustion air
- Engine tuning or operational mode
- Hardware design such as modifications and enhancements to the combustion chamber components, fuel system components, engine control system, etc.
- Conditioning the exhaust gas after the combustion process

The first 2 methods can be adopted for existing installations with little or no limitations.

The hardware design is entirely for new engines and most manufacturers are conducting extensive research with the intention of making the engines more eco-friendly without sacrificing fuel economy.

Conditioning the exhaust gas after the combustion for NOx reduction entails installation of a Selective Catalytic Reactor (SCR) unit. Due to size and the prohibitive costs of such an installation, this option is generally considered for new buildings.

1. Pretreatment or conditioning of the fuel and/or the combustion air

1.1 Fuel Pretreatment

Addition of water to the fuel to create a stable and homogeneous emulsion has been successfully employed in many shore side diesel engine power plants. When this emulsified fuel is injected into the combustion chamber, NOx reduction is achieved due to the following reasons:

- The injection time of the emulsified fuel is greater than with fuel for the same load on the engine. Due to this the flame temperatures are lower and thus lower NOx formation.
- The water that is present within the plume of the injected spray creates secondary micro explosions thereby atomizing the injected fuel thoroughly. This relates to a better and a more complete combustion of the fuel and in turn reduces the peak flame temperatures.

Attainable values for NOx reduction is approximately 1 percent reduction of for every percent of water added to the fuel. Some installations have sucessfully tested upto 50% water without any significant operational difficulties. In general 25-30% of water is sustainable throughout the load range of the engine and returns a 25-30% reduction in NOx emissions.

Various types of homogenizers have been employed for fuel emulsification.

- Mill pump homogenizer comprising of a grinding wheel impeller that physically grinds the fuel as it passes through the unit

- Ultrasonic homogenizer employing high power ultrasonic transducers to homogenize the fuel passing through the unit

- High pressure homogenizer comprising of a piston pump to raise the pressure of the fluid to about 100 bar and releasing it through a homogenizing valve that physically pulverizes the fluid passing through.

The added benefit of a homogenizer for residual fuels is that in the process of homogenization, the asphaltenes in the fuel, which can vary widely in size and can be as large as 70-100 microns in size is broken down to about 3-5 microns. This relates to better combustion and thus less deposits in the combustion chamber.

Aside from the NOx reduction benefits derived from a homogenized fuel emulsion, there is marked decrease in particulate matter emissions largely due to the fact that the combustion process is more complete.

1.2 Combustion Air Pretreatment

Injecting water directly in combustion air stream is another method of lowering the peak temperatures of combustion. There are several ways of injecting water depending on the engine type. On 4 stroke trunk piston engines, water can be injected through a spray nozzle in the intake manifold. As with the fuel/water emulsion the NOx reduction attainable is around 25-30%.

However, on 2 stroke engines, as all large marine propulsion engines, there is a risk of engine damage if the injected water washes away the cylinder lube oil film which may lead to excessive wear and/or seizure.

2. Engine tuning or operational mode

2.1 Engine Timing

Compression ignition (diesel) engines and on spark ignition (gasoline) engines, the timing of the fuel ignition is set a few crank degrees before the top dead center. On diesel engines this means that the beginning of fuel injection is started before the top dead center on the power stroke. The advance angle before the top dead center is the pre-ignition angle and is mainly a function of the fuel type and the speed of rotation.

Engine manufacturers optimize this pre-ignition angle for fuel economy and reliability of the engine components.

Retarding the injection timing can lead to lower peak temperatures in the combustion chamber and thus lower NOx emissions. On some engines this timing can be adjusted in service while on others this adjustment is a major undertaking. The NOx reduction potential is limited (about 2-3%) and trade-off is fuel economy. While this may not be a permanent means for NOx reduction, it may be employed while the vessels are trading in environmentally sensitive areas near the coast.

2.2 Operational Mode

With the advent of the electronically controlled engines where the fuel injector is controlled by electronic means, fuel injection rate shaping is possible. This rate shaping can be optimized for fuel economy or low NOx emissions and selecting between the 2 modes of operation is a control panel function and is done in service.

3. Hardware design modifications and enhancements

Over the last several years with the aid of advanced analytical tools such as computational fluid dynamics, engine manufacturers have conducted extensive research into the combustion process.

Optimizing engine inlet valve, exhaust valve and fuel injection timing, injection pressure, injection pattern, lowering excess air ratio, lowering scavenge temperature, modifying the combustion chamber geometry have all led to lower emissions. It is estimated that these measures will reduce NOx from the current levels by 20%. Further decrease in NOx will require conditioning the fuel and/or the combustion air.

3.1 Direct water injection

As an alternative to fuel/water emulsion, direct water injection into the combustion chamber offers certain advantages, the most significant being that large quantities of water can be added at low load operation without disturbing the combustion process thus ensuring reliability during maneuvering. Another advantage is that separate injection timing can be applied to the fuel injection and water injection to optimize NOx reduction.

3.2 Humid Air Motor

Most marine diesel engines are turbocharged engines that utilizes the energy in the exhaust gas to operate a turbocharger. The air outlet from the turbocharger air compressor requires to be cooled before being led to the engine as combustion air. This cooling is traditionally done by water cooled air coolers.

The water emulsified fuel or direct water injection, requires large quantities of fresh water – a precious resource on board vessels. This system employs sea water as the cooling and humidification medium.

Various configurations have been developed for 4-stroke as well as 2-stroke engines. Essentially the humidification and lower scavenge air temperatures reduces the peak flame temperatures within the combustion space and thus reduces NOx formation.

It should be noted that this system can be utilized in conjunction with water fuel emulsion or direct water injection for even greater NOx reduction.

3.3 Exhaust gas recirculation

When a small percentage of exhaust gas is introduced into the combustion air, the oxygen purity of the combustion air is reduced leading to lower NOx emissions. This system is widely employed on smaller car and truck engines, but there are challenges in the marine environment.

Primarily marine diesels operate on residual fuel that contains sulfur. Products of combustion therefore contains corrosive gases that requires to be taken into account while designing an EGR system. Furthermore marine diesels being turbocharged engines, the scavenge pressure is higher than the exhaust pressure. This requires an additional exhaust blower.

Various arrangements have been tested for recirculation, including internal recirculation on 2-stroke engines by timing adjustment, hot and cold exhaust recirculation from the high and low pressure side of exhaust gas turbocharger.

This system is an effective means of NOx reduction. With a 20% EGR NOx reduction is in the order of 50% with very little fuel consumption penalty. However, there many engineering challenges to overcome before this system can be a reliable system for marine diesel engines.

4. **Conditioning the exhaust gas after the combustion process**

An SCR (Selective Catalytic Reduction) unit is an effective means of conditioning the exhaust gas after the combustion process for reducing NOx already formed in the combustion process.

The process essentially involves injecting ammonia in the exhaust stream and in the presence of a catalyst the NOx reacts with the ammonia and forms water vapor and nitrogen. Due to the hazardous properties of ammonia, urea solution is generally used to provide the required ammonia.

Conclusions

This project is primarily focused on the retrofit technologies for existing vessels. The available options are pre-treatment of the fuel and/or the combustion air as described above.

Conditioning the fuel with water to produce a stable water emulsion is considered the most suitable option for large 2-stroke engines. Conditioning the combustion air by water injection is not suitable for 2-stroke engines as there is risk of water droplets carry over to the combustion chamber and washing away the cylinder lube oil film.

The high pressure homogenizer/emulsifier is considered the better alternative to the other designs. The Seaworthy designed system at the Sebring power plant is operating satisfactorily for many years.

It is recommended that the next phase of the demonstration project be approved such that detailed design of the system and installation can be initiated.

Proposal

- Based on information from California regulators, the most typical engine types trading in these waters are the MAN B&W MC type engine and the Wartsila NSD RTA type engines. We propose to install and demonstrate an emission reduction system on board the MV RJ Pfeiffer which is equipped with a MAN B&W MC engine.
- As mentioned, the fuel - water emulsion technology is most promising for large 2 stroke engines. This system is proposed for this uni-fuel ship as the generators may also be operated on the fuel water emulsion during port stays.
- The preliminary cost estimate for design, engineering and installation is around $250,000. This is exclusive of testing protocols and requirements. Matson is also prepared to submit a not to exceed proposal for this technology demonstrator.
- The proposed emulsion system will be based on a high pressure piston pump and a homogenizing valve. This vessel is equipped with a split pressure loop for the fuel system that comprises of a low pressure supply circuit and a high pressure booster circuit. The homogenizer will be installed in the high pressure circuit of the fuel system with monitoring of fuel flow and water content to control the injection of water.
- It is estimated that for a comprehensive design package to be developed including approval from appropriate regulatory agencies is around 12 months. An additional 6 months would be required for procurement of all material and installation.
- The vessel operates between the west coast and Hawaii. The typical main engine operating hours is 6500 hours/year with an average operating horsepower of 26,500. Based on specific NOx generation of 17 gms/bhp/hr, it is estimated that the NOx reduction will be in the order of 600-700 tons/year, provided the system is operating continuously and a reduction of NOx generation by 20-25%.

References

- Various technical papers from MAN B&W
- Various technical papers from Wartsila New Sulzer Diesel
- Sebring power plant system design. Matt Winkler/Seaworthy systems
- Scavenge air direct water injection system. Anatoly Mezheritsky/MA Turbocharger