DYNAMIC POSITIONING CONFERENCE
September 16-17, 2003

Environment Session

The Diesel Engine and the Environment

Dave Steffens
Wartsila North America, Inc.
16330 Air Center Blvd.
Houston, TX 77032

Introduction

Exhaust emission control has become an important factor in the marine and offshore industry in recent years. The importance of this dimension will increase further in the years ahead as marine environmental regulations become tighter and public awareness of 'green' issues continues to grow. This paper will show the proposed international and local U.S. regulations and when each will enter into force as well as which diesel engines will be affected. The first part of the paper will show the typical composition of diesel engine exhaust with discussions around the environmentally harmful elements. The current legislation is concentrating on the reduction of NO_x emissions. Therefore, most of the remaining part of the paper will concentrate on the industry solutions, both primary and secondary methods, to reduce the NO_x emissions to meet the current and future diesel engine emission regulations. The final part of the paper will look at how particles and smoke emissions are reduced.

Diesel Engine Exhaust Composition

When looking at the effects of diesel engine exhaust on the environment, it is important to first look at the composition of the exhaust gases. Over 99.5% of the exhaust gases are a combination of nitrogen, oxygen, carbon dioxide, and water. With the exception of carbon dioxide, which contributes about 5% of the total volume, the diesel engine exhaust consists of elements which are part of the natural atmosphere and are not harmful to the environment. The remaining 5 ½% (including CO_2) are the elements that can be harmful to the environment and should be controlled.

Carbon dioxide emissions are directly related to the efficiency of the combustion unit. The higher the efficiency, the lower the CO_2 emissions. The diesel engine has a relatively high efficiency and, therefore, the carbon dioxide emissions are lower as compared to other less efficient prime movers. Carbon dioxide is considered the major greenhouse gas in the atmosphere and should be kept at acceptable levels.

Carbon monoxide and hydrocarbons are directly related to the combustion process. The cleaner the overall combustion, the lower the CO and C_xH_y emissions. Carbon monoxide and hydrocarbons contribute to the ozone/smog formation in the lower atmosphere and should be kept at acceptable levels.

Sulphur oxide emissions are directly related to the fuel choice. The higher the sulphur content of the fuel, the higher the SO_x emissions. Sulphur oxides have a potential detrimental effect on human health and can cause acid rain. Therefore, many regulatory bodies are beginning to regulate the SO_x emissions levels in local areas. The only primary method to achieve lower sulphur oxide emissions is to choose a fuel with a lower sulphur content. Low sulphur fuels are becoming more prevalent in the marine and offshore industry. As many operators are finding out, there is a cost impact with using low sulphur fuels. One secondary method of reducing sulphur oxide emissions is to use a deSO_x scrubber. Unfortunately, deSO_x scrubbers are very large and expensive and are not practical for use on board a vessel.

Particles or soot emissions are contributed to low load operation and large load swings causing unburnt fuel in the exhaust. Particle emissions are also influenced by the fuel ash and sulphur content as well as poor combustion. Particle emissions from a diesel engine are typically low during steady state operation. Some particle emissions are considered carcinogenic and can have a detrimental effect on human health.

Nitrogen oxides (NO_x) are formed in the combustion process by the oxidation of nitrogen (from the atmosphere and fuel) to nitrogen monoxides (NO) and nitrogen dioxides (NO_2). The nitrogen oxide emissions are difficult to control due to the complex formation process. The formation rate is highly dependent on the temperature in the combustion chamber. Nitrogen oxide emissions contribute to the ozone/smog formation in the lower atmosphere as well as acid rain and can have a detrimental effect on human health. Nitrogen oxides are the elements of the diesel engine exhaust that the regulatory bodies have chosen to concentrate their efforts in recent years. For that reason, the next few pages of this paper will concentrate on the NO_x regulations and the corresponding reduction methods used in the industry today.

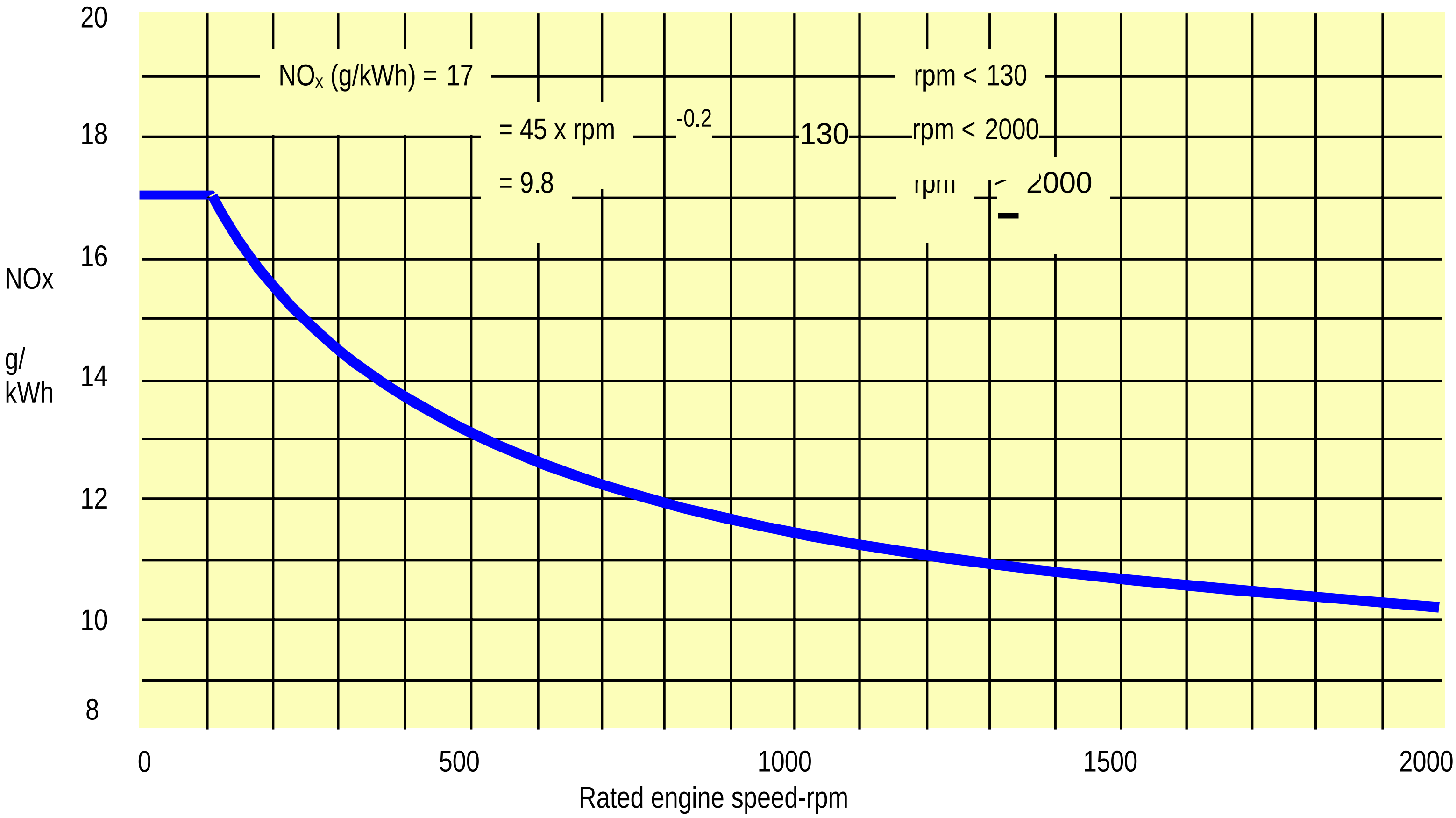
Regulations

The international regulatory body is the IMO. The IMO MARPOL 73/78 Annex VI legislation is a currently proposed NO_x emissions regulation and is on the table for ratification. It will enter into force 12 months after the date on which not less than 15 member states, constituting not less than 50% of the gross tonnage of the world's merchant fleet, have signed the protocol. The ratification process has been ongoing for several years, but now it appears the Annex VI legislation will be ratified by sufficient member states in 2003 and enter into force one year later. Once ratified, the legislation will apply to ships of 400 gross tons or above, platforms, and drilling rigs. The legislation will also be retroactive to January 1, 2000. Vessels constructed after that date will be required to comply with the protocol. Figure 1 shows the proposed NO_x emissions levels based on the speed of the engine along with the equations used to produce the curve.

Other local and regional regulatory bodies are proposing future legislation for more stringent NOx emissions regulations. Locally in the US, the EPA will start to enforce the IMO Annex VI proposed NO_x levels in 2004 as their Tier I levels. The EPA legislation only applies to engines with a cylinder displacement of 30 liters or less. The EPA has also proposed their Tier II regulations for enforcement in 2007. The Tier II regulations set NO_x emission levels at 30% lower than the Annex VI levels. The European Union has also proposed the same legislation.

The NO_x emissions levels of diesel engines are the area where engine manufacturers have concentrated their efforts and research and development monies to evolve systems to reduce NO_x emission levels.

Figure 1 – IMO Annex VI Proposed NO_x Emissions Levels



NO_x Emissions Reduction Methods

As mentioned above, the NO_x formation process is extremely complex and involves hundreds of different reactions in the combustion process. The NO_x formation process is influenced heavily by temperature. The NO_x concentration increases exponentially as the temperature increases. In fact, thermal NO_x formation contributes 65-75% of the total NO_x formation in the combustion process. In addition, time is an important factor in the NO_x concentration. The longer the combustion process at the higher temperatures, the more NO_x formation. With this in mind, the easiest way to reduce the NO_x emission levels are to decrease the length of the combustion process and the temperature at which the combustion process takes place.

There are two types of NO_x reduction methods – primary and secondary methods. The primary methods include those that alter the combustion process to reduce the NO_x emission levels. The secondary methods include those that clean the exhaust gases after they leave the combustion chamber.

Primary NO_x Emission Reduction Methods

The most widely used primary methods of NO_x reduction available today are:

- Emission rating
- Low NO_x combustion
- Water-in-fuel emulsions
- Direct water injection

The emission rating is the most simple and cheap method to reduce the NO_x emission levels. This method consists of retarding the fuel injection timing and modifying the turbocharger specification. This method is limited to a NO_x reduction potential of between 10-20%. The drawback of this method is an increased fuel consumption and thermal load on the engine.

The Low NO_x combustion method involves rearranging the diesel cycle. The diesel cycle is rearranged by increasing the compression ratio and fuel injection pressures, closing the inlet valve sooner, and starting the fuel injection at a very late stage in the cycle. The results of the rearranged cycle are lower combustion temperatures and a shorter combustion duration at high temperatures. This method has a NO_x reduction potential of 25-35%. In addition, with the low NO_x combustion process, the fuel consumption remains the same and, in some cases, is actually improved slightly.

The water-in-fuel emulsions method involves emulsifying water with the fuel and injecting it through the same injection system. The water in the fuel causes a humid combustion process resulting in a lower combustion temperature. The advantages of this system are improved low load smoke emissions as well as lower NO_x emissions. The NO_x emissions reduction is limited to about 20% due to the instability of the emulsion at higher water contents. The disadvantages of this system are it causes an increased camshaft torque and cam load, full load operation is not possible at higher water ratios due to limitations in the fuel injection equipment, the engine performance is poor during "non-water" operation, and the injection equipment reliability and lifetimes are affected by the presence of water in the fuel.

The direct water injection (DWI) method involves injecting water directly into the cylinder through a separate nozzle built into the same injector. The water is injected prior to the injection of the fuel into the cylinder thus having a longer time to reduce the cylinder temperature before the fuel is injected and the combustion starts. The result is a lower combustion temperature and lower NO_x emission levels. The actual amount of reduction is dependent on the amount of water injected. Water amounts vary up to a maximum of around 50% of the consumed fuel volume. With the maximum volume injected, the NO_x emission levels can be reduced by 50-60%. The only disadvantage of this system is a slightly higher fuel consumption (1-2 g/kWh).

The above primary NO_x reduction methods are the systems available today. Another primary system that is not available today, but will be available in the future is the combustion air saturation system (CASS). CASS involves a humidification of the combustion air prior to entering the combustion chamber. This causes a humid combustion process resulting in a lower combustion temperature. The result is a lower NO_x emission level. As with DWI, the actual amount of reduction is dependent on the amount of water injected in the combustion air. With this system, it is possible to inject even more water as compared to DWI. In some cases, it is possible to even inject twice as much water as the consumed fuel volume. This gives a slightly better result as compared to DWI. The NO_x emission levels can be reduced around 60% with the addition of CASS. It is foreseen that CASS is the future standard system to ensure that engines can meet the more stringent local and regional proposed NO_x emission levels.

Secondary NO_x Emission Reduction Methods

The most common and most effective method of secondary NO_x emission control is the selective catalytic reduction (SCR). This method involves injecting a urea/water solution in the exhaust system after the exhaust gas leaves the engine. The urea/water solution mixes with the exhaust gases before entering the honeycomb reactor. In the reactor, the exhaust gas/urea/water mixture chemically reacts to form nitrogen and water at the outlet of the reactor. The SCR system has a NO_x emission reduction potential of 85-95% or down to about 1-2 g/kWh. The actual amount of reduction is dependent on the amount of urea/water solution injected. The more solution injected, the lower the NO_x emissions outlet to a certain limit. If too much urea/water solution is injected, it can cause what is known as ammonia slip. Ammonia slip causes the smell of ammonia out the exhaust stack.

Today, a compact SCR unit is available that is nearly the same size as a standard exhaust silencer. The compact SCR incorporates both the honeycomb reactor section of the SCR and the silencer into one unit. With the compact SCR, it makes it possible to retrofit an existing installation with an SCR system for secondary cleaning of the exhaust.

With the high degree of NO_x emission reduction, the SCR system is ideal for vessels operating in sensitive areas. The main drawback of the system is the high investment and operating costs. Fortunately, the system can be started and stopped as needed to comply with more stringent regulations in sensitive areas. Another feature of the system is the closed loop control system that continuously samples the exhaust gas as it leaves the reactor and regulates the amount of urea solution injection based on the set point chosen by the operator.

Particle/Soot/Smoke Emissions

Another element of diesel engine exhaust receiving environmental attention is the particle/soot/smoke emissions. As mentioned above, particle emissions are contributed to low load operation and large load swings causing unburnt fuel in the exhaust. Particle emissions are also influenced by the fuel ash and sulphur content as well as poor combustion due to insufficient engine preheating. Particle emissions from a diesel engine are typically low during steady state operation at higher loads, but during start-up, low load operation, and large load swings, it is common to see a puff of black smoke from the exhaust stack. Smoke emissions draw attention in pristine areas such as Alaska. Some local regulations are now prohibiting smoke emissions during operation in coastal areas.

As mentioned previously, water-in-fuel emulsions has some reduction of smoke emissions at low loads, but does not eliminate smoke emissions entirely. The only true method available today to get completely smokeless operation is the common rail fuel injection.

Smokeless Diesel Engine

The targets of the common rail fuel injection are to provide smokeless operation at start-up and during operation at any load or load swing. In addition, the common rail fuel injection provides some increased efficiency resulting in lower fuel consumption, slightly lower NO_x emission levels, and lower CO_2 emissions.

The common rail injection differs from a standard fuel injected engine by providing a constant fuel pressure to the injectors which are, in turn, electronically controlled to inject the proper amount of fuel based on the engine load and the available combustion air. This ensures the full complement of fuel is burnt during combustion. The result is no visible smoke at any load, during load changes, and during start-up. Laboratory and field tests have proved the technology is successful in meeting and exceeding the original targets. Common rail fuel injection coupled with a primary NO_x emission reduction method provides an engine equipped to meet even the most stringent of local emission regulations.

Conclusion

As regulations become increasingly more stringent, engine manufacturers are working to meet the requirements and help our customers be responsible to the environment in a cost effective manner.