The Diesel Engine and the Environment

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The diesel engine and the environment
- rules and regulations
- emission reduction technologies
### Typical composition of diesel engine exhaust gas

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N\textsubscript{2}</td>
<td>76%</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>O\textsubscript{2}</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO\textsubscript{2}</td>
<td>5%</td>
<td>Low due to high efficiency</td>
</tr>
<tr>
<td>Water</td>
<td>H\textsubscript{2}O</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Sulphur oxides</td>
<td>SO\textsubscript{x}</td>
<td></td>
<td>Fuel choice related</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td></td>
<td>Low due to good combustion</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>C\textsubscript{x}H\textsubscript{y}</td>
<td></td>
<td>Low due to good combustion</td>
</tr>
<tr>
<td>Particles</td>
<td></td>
<td></td>
<td>Low at steady state operation</td>
</tr>
<tr>
<td>Visible smoke</td>
<td>FSN</td>
<td></td>
<td>Low load related (&lt;25% load)</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>NO\textsubscript{x}</td>
<td></td>
<td>To be controlled</td>
</tr>
</tbody>
</table>
Exhaust compounds and their environmental impact

\( \text{NO}_x : \)
- acid rain, acidification
- ozone/smog formation in the lower atmosphere
  (potential damage on vegetation and human health)

Particulates:
- some considered carcinogenic
- blackening with soot

\( \text{SO}_x : \)
- acid rain, acidification
- potential detrimental effect on human health

CO:
- ozone/smog formation in the lower atmosphere

Hydrocarbons:
- ozone/smog formation in the lower atmosphere
- some considered carcinogenic
- contribute to the greenhouse effect

\( \text{CO}_2 : \)
- the major greenhouse gas
Annex VI to MARPOL 73/78

- **Applies to:** Ships of 400 GRT or above, Platforms and Drilling Rigs

- **Enters into force:** 12 month after the date on which not less than 15 states, constituting not less than 50% of the gross tonnage of the world’s merchant fleet, have signed the protocol.

- It is important to note that the NOx emission regulation is linked to the date, 1st of January 2000. Ships constructed after this date will be required retroactively to comply with these requirements when Annex VI enters into force.
IMO MEPC Proposal for Global Marine NO$_x$ Legislation

ISO 8178 Test Procedure
Reference Fuel: Marine Diesel Oil
Diesel NO\textsubscript{x} Formation

- Thermal NO\textsubscript{x} formation (65-75%)
- Nitrogen source: combustion air
- Formation process: extremely complex including hundreds of different reactions
- Strong temperature influence (exponential)
Thermal NO\textsubscript{x} Formation

![Graph showing the relationship between local temperature (K) and relative NO\textsubscript{x} concentration. The graph indicates an exponential increase in NO\textsubscript{x} equilibrium concentration as the local temperature increases.](image-url)

**NO\textsubscript{x} Equilibrium Concentration**
Typical NO$_x$-Emissions for Different Types of Engines

Typical NO$_x$ Emissions in g/kWh:

- Diesel: 13 g/kWh
- Liquid Fuel: 8 g/kWh
- Gas: 4 g/kWh
- Diesel: 8 g/kWh
- Lean Burn Gas Engine: 1.3 g/kWh
- Liquid Fuel: 0.65 g/kWh
NOx emissions of different prime movers operating on MGO

- Diesel engine with Selective Catalytic Reduction
- Aeroderivative gas turbine
- Diesel engine with Direct Water Injection
- Diesel engine
Technologies to reduce emissions:

• Primary Methods - During Combustion
• Secondary Methods - After Combustion
Primary NO\textsubscript{x} control - diesel engines

Available today - Combustion Modification

- Emission rating
  - Adjustment of fuel injection timing/TC specification
  - NO\textsubscript{x} reduction potential: 10 - 20 %
  - Simple and cheap
  - Increased fuel consumption and thermal load

- Low NO\textsubscript{x} combustion
  - Rearranged diesel cycle
  - NO\textsubscript{x} reduction typically: 25 - 35 %
  - NO\textsubscript{x} well below the IMO limit
  - Unchanged or improved fuel consumption
Primary NO\textsubscript{x} control - diesel engines

Available today - Water Injection

- Water-in-fuel emulsions
  - Humidification of the combustion process
  - NO\textsubscript{x} reduction potential typically: 20 %
  - Limitations
    - emulsion stability
    - fuel injection system capacity
    - poor engine performance in “non-water” operational mode
    - cavitation risk in injection system

- Direct water injection
  - Humidification of the combustion process
  - NO\textsubscript{x} reduction typically: 50 - 60 %
  - Improved thermal load and engine cleanliness

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Low NOₓ Combustion Engine Design

- Rearranged diesel cycle
  - Very late fuel injection start
  - Higher compression ratio
  - Early inlet valve closing (4-stroke)
  - Late exhaust closing (2-stroke)
  - Optimized combustion chamber
  - Optimized fuel injection pressure

- Results
  - Lower combustion temperatures
  - Shorter duration at high temperatures

- Conclusions
  - NOₓ reduction typically 25-35%
  - Unaffected fuel consumption
Low NO\textsubscript{x} Combustion

Application: All Fuel Types

Conventional Design
Engine Maximum Firing Pressure

- Pressure rise induced from combustion
- Pressure rise induced from compression

Low NO\textsubscript{x} Design
Engine Maximum Firing Pressure

- Pressure rise induced from combustion
- Pressure rise induced from compression
Implementation of Low NO\textsubscript{x} Combustion on Wärtsilä Vasa 32b

Relative NO\textsubscript{x} Emissions

100%

WV32
Compr. Σ = 12

80%

WV32LN
Σ = 13.8


100%

WV32
Σ = 12

97%

WV32LN
Σ = 13.8
Features of fuel-water emulsions

Disadvantages

– Increased camshaft torque and cam load.
– Full load of engine not possible at high water ratios due to limitations in the fuel injection equipment.
– Same nozzles not optimal for operation with and without emulsion.
– Negative impact on injection equipment reliability and lifetime.
– Increased fuel viscosity, higher preheating temperatures needed.

Advantages

– Improved low load smoke.
– Lower NOx. The NOx limitation is limited to about 20%, because unlimited water amounts cannot be kept in a stable emulsion.
MEC Test on W6L46CR, Vaasa
2-19 December 2002

INFLUENCE OF WATER EMULSION ON FSN
Standard Nozzle: 12x0.64x160°, Fuel: HFO

Engine load [%]

FSN

- W/F ratio = 0, without MEC
- W/F ratio = 0, with MEC
- W/F ratio = 0.1
- W/F ratio = 0.2
- W/F ratio = 0.3

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MEC Test on W6L46CR, Vaasa
2-19 December 2002
INFLUENCE OF WATER EMULSION ON NOx EMISSIONS
Standard Nozzle: 12x0.64x160°, Fuel: HFO
Reference NOx Without MEC

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The principle of Direct Water Injection

Water needle and fuel needle in the same injector
Direct Water Injection

Water tank

High pressure water pump

Flow fuse

Control unit

Solenoid valve

Fuel needle

Water needle

Fuel
Direct Water Injection

typical water/fuel timing and duration
Future Technologies:

- CASS (Combustion Air Saturation System)
The hot air after the compressor is cooled to the saturation point by injecting water mist. After heating in the "charge air cooler" the mixture is again saturated by injecting more water. Heating of the air by HT-water.
Efficiency of humidification methods

Relative NO\textsubscript{x} formation

Direct Water Injection

Combustion Air Humidification

Water/Fuel flow ratio

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Predicted NOx behavior with different control methods on Wärtsilä 46

- Fuel Water Emulsion
- CASS
- FWE + CASS

Water amount as % of fuel consumption
Secondary NO\textsubscript{x} control - diesel engines

Available today

- Selective catalytic reduction (SCR)
  - NO\textsubscript{x} reduction typically: 85 - 95 %
  - Urea/water solution injected
  - Integrated part of the engine package
  - Exhaust temperature window 330 - 450 °C at HFO operation
  - Investment and operating costs relatively high

- Compact SCR
  - Combined silencer and SCR unit
  - Minimized size
Principle of Selective Catalytic Reduction

NO\textsubscript{x} Reduction Typically: 85 - 95%
SCR Reactions With Urea

- Before Entering the Reactor:
  \[(\text{NH}_2\text{)}_2\text{CO} + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2\]

- In the Reactor:
  \[4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}\]
  \[6\text{NO}_2 + 8\text{NH}_3 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}\]
Retrofit of Compact SCR

**Birka Princess at Lloyd Werft**

SCR plants have been retrofitted in several passenger ships in existing engine casing = no lost space!

A Compact SCR occupies a little more space than a normal silencer which it replaces.
Particle Emissions
- Particle emissions are seen as smoke
- More prevalent at low loads and start-up

Smoke Reduction Methods
- Common rail fuel injection
Targets for the Smokeless Engine

- No visible smoke at start-up
- No visible smoke at any load
- NO\textsubscript{x} emissions to be reduced
- CO\textsubscript{2} emissions to be reduced even lower by further improvements in efficiency
Conventional vs common rail fuel injection

Conventional injection system

Mechanical/hydraulic control at the injectors

Fuel pressure produced each time by the injection pump

Common Rail Injection

Electronic/hydraulic control of injection

Constant fuel pressure
Common Rail advantages

- Smokeless operation at all loads and speeds.
- Smokeless start of the engine.
- Smokeless load pick-up ramps.
- NOx reduction down to 3…4 g/kWh with humidification possible without visible smoke.
- Improved total fuel economy.
- Flexibility for different fuels without hardware modifications (heavy fuel, diesel oil, gas turbine fuel, water-fuel emulsion).
- Improved safety and comfort because more engines can be kept running with still good fuel economy and no smoke.
FSN status at engine laboratory and delivery test run

Production engines May 2002 and for upgrading

Conventional injection

Best lab. results with modified piston shape

THIS IS SMOKELESS