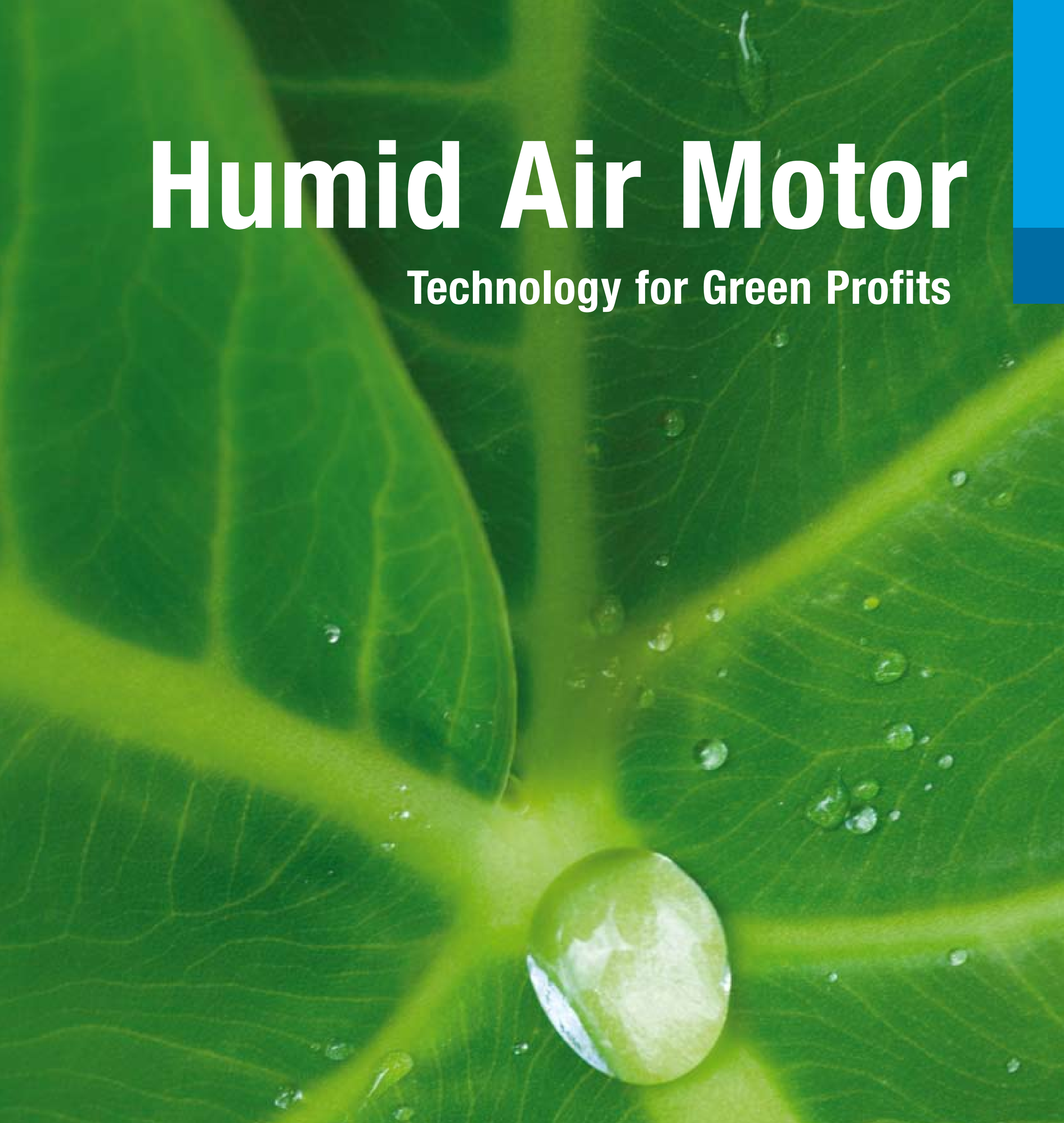
Humid Air Motor

Technology for Green Profits



MAN Diesel

250 years

MAN

Adding Ecology to Economy

Throughout its history the diesel engine has always maintained its status as the most efficient system for converting fuels into mechanical energy, and this situation is expected to continue for the foreseeable future. This assertion applies in all areas of application: the automotive sector, off-highway equipment, and in marine propulsion and electrical power generation.

In recent years, global and local regulations covering exhaust gas emissions from heavy duty medium speed diesel engines have become progressively more stringent. They cover all applications i.e. power generation and propulsion systems on land and at sea. In particular, emissions of oxides of nitrogen (NO_x) have become a major issue.

Since the 1980s, emissions reduction has been a major development aim at MAN Diesel and has resulted in the progressive introduction of exhaust gas optimised engines.

In general today, modern marine diesel engines are capable of meeting the requirements of the first and second stages of the MARPOL 73/78 Annex VI regulations – commonly called IMO Tiers 1 and 2 – using only on-engine and in-cylinder modifications. In 2015/2016, however, the NO_x limitation of IMO Tier 3 will come into force and is so stringent that additional devices will be needed *(see figure 1)*.

Moreover, there are already regional regulations such as those in Norway and Sweden which reward every kg of NO_x

not emitted. In response to these regulations, ship owners have an incentive to adopt NO_x reduction systems on their fleets. Exhaust gas treatment such as "Selective Catalytic Reduction" (SCR) is one way to meet the requirement.

SCR uses a reducing agent (ammonia or urea) in a catalytic reaction to reduce harmful NO_x back to nitrogen (N_2). SCR technology thus implies a relatively heavy additional tank for this additional consumable, which has to be refilled regularly in port. There is presently no appropriate supply infrastructure for the reducing agents, resulting in further increased operating costs.

HAM

A second, widely acclaimed technology for reducing NO_x pollution from diesel engines is the "Humid Air Motor" (HAM). This technology is able to reduce NO_x formation by up to 65%. In the HAM system the turbocharged combustion air is saturated with water vapour produced aboard the ship using sea water and engine heat.
This lowers the temperature peaks in the combustion chamber, which are normally the main reason for NO_x formation. HAM is characterised by extremely low operating costs due to sea water usage, decreased lube oil consumption, very low maintenance costs and a very high availability factor.

Consequently, following its philosophy of environmentally-friendly engine development, MAN Diesel now offers the HAM system. The company's decision to offer this technology is based, in particular, on the economics of the HAM system, which create favourable conditions for profitable engine operation.

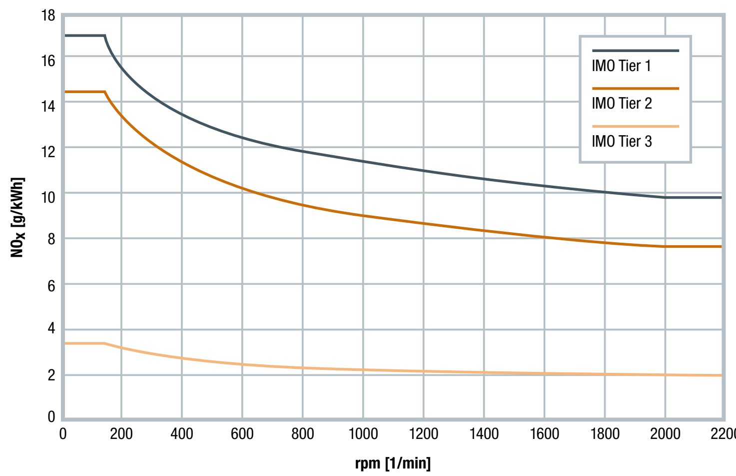


Figure 1: NO_X limit curve of IMO

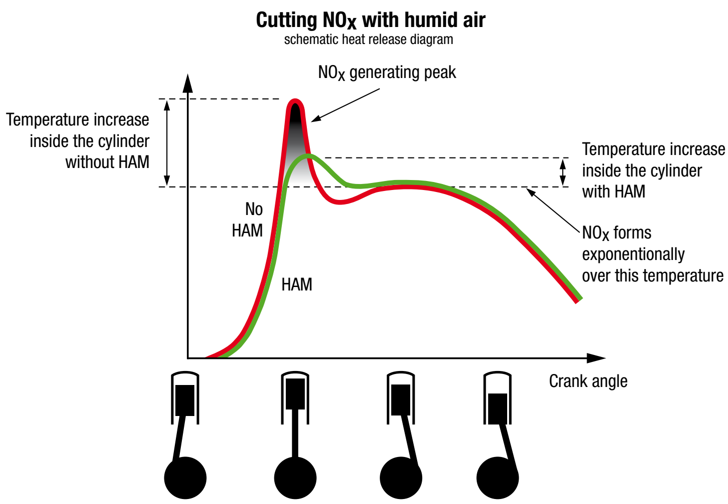


Figure 2: Cutting NO_X with humid air – schematic heat release diagram

Humid Air Motor Technology

H_2O against NO_x

It is well known that the cooling effect of water can prevent NO_x formation during the combustion process. Well proven methods employing water to reduce NO_x are fuel-water emulsification and humidification of inlet air (HAM principle).

HAM principle

Over 90% of NO_x formation results from combustion temperature peaks. The principle of HAM is to humidify the inlet air in order to lower these temperature peaks. The HAM system humidifier produces saturated air.

The ability of water to decrease the formation of NO_x is exploited in the same way as with fuel water emulsification, but the quantity of water added is much higher and the heat for water vaporisation is taken from the compressed air after the turbocharger or other engine-related heat sources.

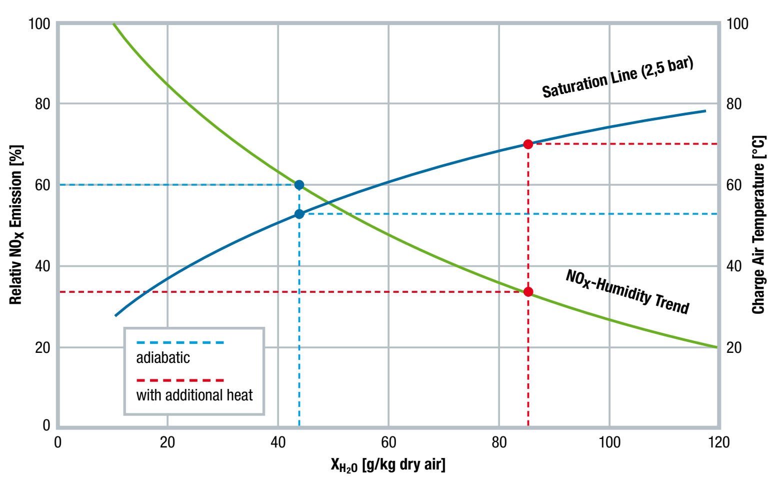


Figure 3: NO_x-Humidity Trend

When the water vapour is mixed with the compressed charge air, two mechanisms can be identified:

>> Increase of the specific heat capacity of the mixture,
>> Dilution of the charge air: water vapour replaces air.

The quantity of water (in g/kg dry air) which can be injected into the inlet air depends on the temperature and the pressure of the mixture.

As shown in the diagram in *figure 3*, when the air temperature rises so does the quantity of water it is possible to vaporise.

In this area HAM has an outstanding advantage, since it uses the heat of the engine to bring the saltwater up to temperature. No external energy source is needed. In addition to the heat of the charge air after the turbocharger, in many applications heat from the engine coolant and exhaust gases can be introduced into the charge-air to increase its capacity to absorb moisture.

With the HAM method a NO_x reduction level of 40% is achieveable without using additional heating of the intake air and a level of 65% when additional heat is introduced from the engine coolant or exhaust gases.

How HAM works

The functional principle of HAM is quite simple.
Figure 4 illustrates the HAM Process:

1. Filtered saltwater is pumped to the catch tank to replace evaporated and purged loop water.

2. The HAM system itself cycles water in a loop between the catch tank and the Humidification tower ("HAM vessel")

3. A heat exchanger between the catch tank and the HAM vessel heats the saltwater using an on-engine heat source.

4. Three injection stages spray the heated saltwater into the charge air.

5. At the same time the compressed charge air from the exhaust turbocharger bypasses the charge air cooler and is piped into the HAM vessel air inlet.
   Flowing through the HAM vessel, the charge air absorbs the water. Due to the high loop capacity of the water all particles (incl. salt) fall back into the catch tank and, over a certain salinity level, are purged. Thus no salt from the saltwater can enter the engine.

6. To avoid tiny droplets reaching the combustion chamber, the humidified charge air passes through a high-performance mist catcher at the end of the humidification tower.

7. This humidification leads to saturated charge air which is fed into the engine.

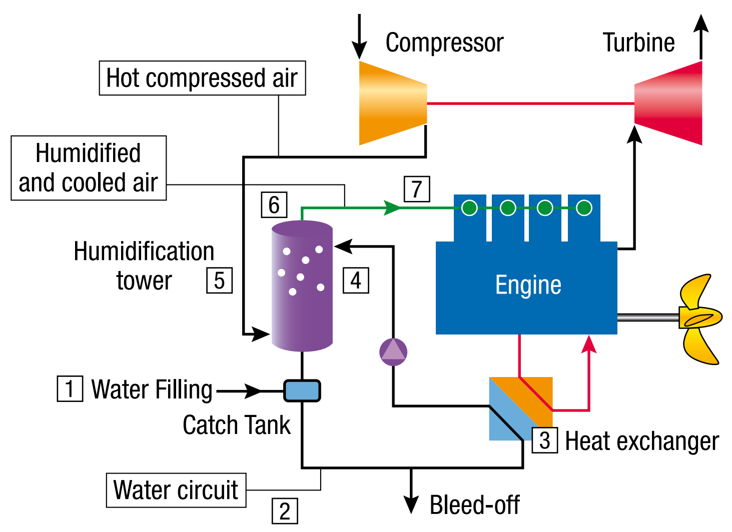


Figure 4: Engine with HAM principle

HAM versus SCR – the Economics

As mentioned above there are special economic advantages with the Humid Air Motor compared to engines with the SCR system.

Below is a detailed look at the economic aspects of both systems under three scenarios depicting new or existing regulations covering NO_x reduction: Norwegian and Swedish NO_x reduction incentives and Standard operation under IMO legislation.

The scenarios consider only the environmental costs and costs related to NO_x reduction technologies.

In general the purchase costs of the HAM system are higher than SCR and other NO_x reduction technologies. However, the situation is totally different in terms of operating costs. Thanks to the use of seawater and no need for a reducing agent (urea/ammonia), the HAM method produces the most economical NO_x reduction in €/ton.

Conditions Norway

The first comparison relates to conditions in Norway. To reduce tax costs most effectively both HAM and SCR work at their maximum NO_x emissions reduction rate, i.e. HAM at 65% reduction rate and SCR at 80%.

In practical use on a ship and in a power station HAM has proven more cost effective than SCR and demonstrated better long term performance. SCR has operating costs including taxes approximately 30% higher than HAM.

Conditions Sweden

The second comparison is under Swedish conditions. Here the cost calculation for NO_x emissions is more difficult. The costs depend on the weight of the ship, the number of calls and the category in the Swedish NO_x reduction table. For this scenario an oil tanker of 11,935 gross tons and 60 calls per year is taken as the basis.

As can be seen, such a ship will be more cost effective with HAM. After 2 years of operation at the latest HAM performs better than SCR. In this case the operating costs including taxes for HAM are half as high as for SCR.

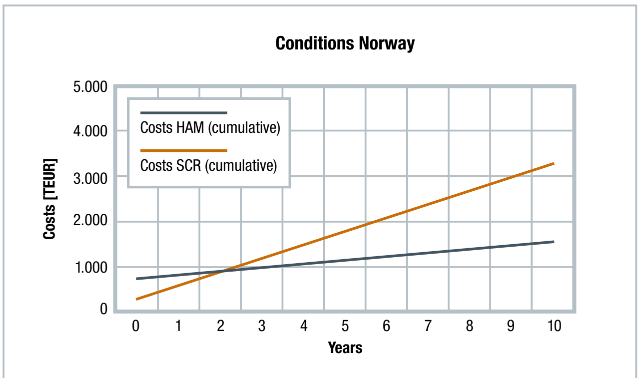


Figure 5: Cost comparison HAM vs. SCR over time

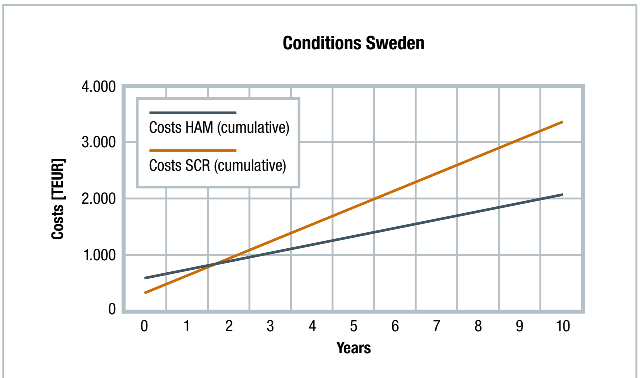


Figure 6: Cost comparison HAM vs. SCR over time

Burning HFO outside Emission Control Areas

The third comparison looks at standard marine operation to the emissions limits expected in IMO Tier 3 legislation due 2015/2016 *(figure 7)*. It is foreseen that an 80% reduction in NO_x will be prescribed for coastal waters compared to IMO Tier 1. The following assumptions are hence made for this case study:

- >> MAN Diesel will achieve the prescribed NO_x reduction level using a combination of HAM and primary, in-cylinder measures.
- >> HAM and SCR work on the same NO_x reduction rate of 65%. As a result, the reducing agent costs for SCR are lower.
- >> The time horizon is 10 years, with the assumption that no NO_x taxes will be levied.

HAM operating costs are lower than SCR by a factor of about 12. The Humid Air Motor thus performs better than the engine equipped with SCR after only 18 months of operation.
In spite of HAM's higher investment costs, its lower operating costs lead to a considerably shorter amortisation period than for an SCR system.

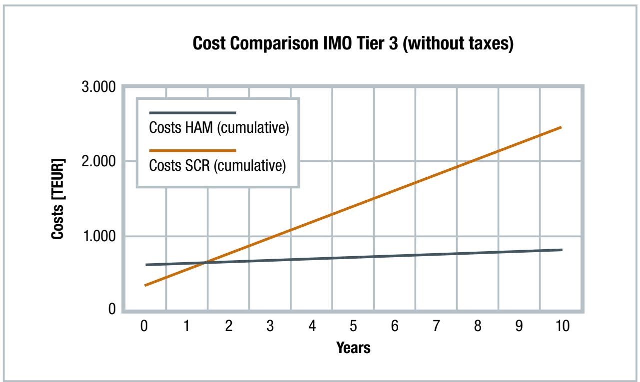


Figure 7: Long term performance HAM vs. SCR

HAM versus SCR – Summary Table

HAM		SCR
Low maintenance and operation Costs	⟷	Low Investment Costs
NO_x reduction up to 65%	⟷	NO_x reduction up to 80%
Safe and ecological process	⟷	Possible ammonia slip, high risk of N_2O formation
Part load operation dependent on available heat	⟷	Part load operation dependent on exhaust gas temperature
"Lighter" system	⟷	Heavy system reduces the total payload of the ship
No fuel quality limitation: engine can run on high sulphur fuel oil (HSFO) at all times	⟷	Engine needs low sulphur fuel oil (LSFO) during SCR operation (additional costs, except in SECA)
No additional reducing agent (uses sea water only), water decalcification agent necessary	⟷	Urea transport + storage aboard ship

References

Proven in Practice –

To prove the theoretical results of HAM technology, field tests under real conditions were carried out.

Marine

Viking Line took the decision to equip all four engines aboard its vessel "Mariella" with the HAM system. This car ferry crosses daily between Helsinki and Stockholm. The main characteristics of the vessel are:

- >> Length: 177 m, Breadth: 29 m, Weight: 37,800 t
- >> 2200 passengers, 540 vehicles
- >> 4 main engines: 12 PC2-6.2
  each rated 5,750 kW at 500 rpm

The system was installed on main engine number one in July 1999 (all engines were subsequently equipped with HAM) and since then it has been operating with seawater. The installation was carried out without interrupting vessel operation.

One of Viking Line's requirements was to be able to switch from the standard intake air system with charge air cooler to HAM with the engine running. This requirement was met by using butterfly valves.

The ship-owner now considers that this condition is no longer required since the charge air cooler is no longer necessary. In case of emergency, without HAM and without charge air cooling, it has been verified that available power is still 50% to 60%. System installation in the engine room is illustrated in *figure 9*.

Figure 8: Viking Line's "Mariella" © Viking Line

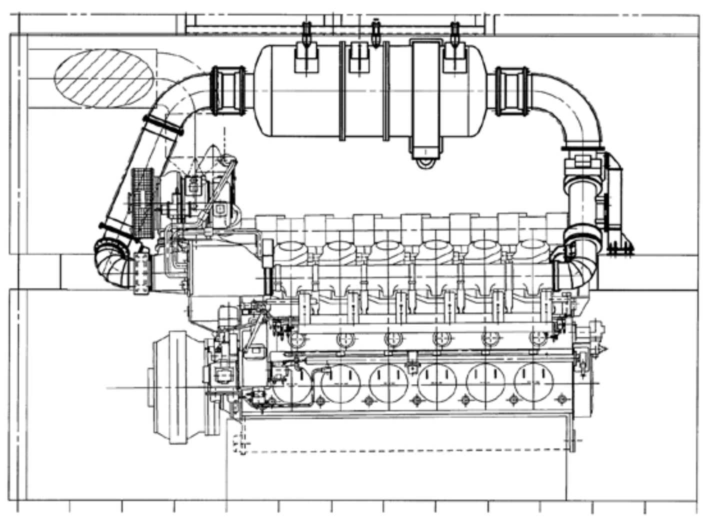


Figure 9: HAM Installation on "Mariella"

Since July 1999 the systems have logged about 100,000 operating hours without any major problems. The following list presents the results over that time:

>> $\triangle NO_x = -65\%$ is confirmed
>> No trace of water or other compounds in lube oil
>> No corrosion
>> Decrease of cylinder and valve temperatures
>> Engine is cleaner (deposits are “washed” away)
>> Decreased lube oil consumption
>> Availability over 99% in the last 7 years
>> No need for turbocharger washing

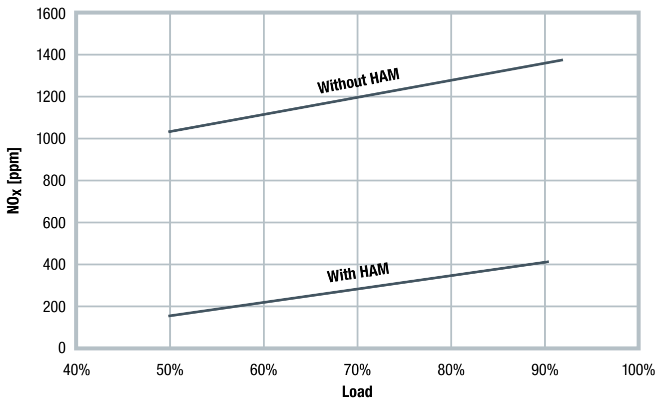


Figure 10: NO_X decrease on engine number 1 onboard “Mariella”

Stationary

On Corsica, one PC3 engine (12 MW) was equipped with HAM to test it under power plant conditions. The following data are available on this configuration:

>> Specific fresh water consumption: 410 g/kWh

The following results were confirmed during the test:

>> $\triangle NO_x = -65\%$ is confirmed
>> 650 mg/Nm^3 CO limit

Figure 11: Power plant, Corsica

Conclusion

To meet the challenge of reducing oxides of nitrogen during diesel engine combustion, the HAM system is an efficient solution with the following advantages:

Efficient NO_x reduction

The targeted NO_x reduction of 65% was confirmed during HAM usage on the car ferry “Mariella” and a power station on Corsica.

Very low operating costs

Seawater may be used as the consumable for the HAM system, meaning operating costs are very low. The use of an additive to prevent calcium deposit does not significantly increase operating costs. The heat to vaporise the water can be taken from on-engine sources i.e. engine coolant and exhaust gases, without affecting the ship’s overall energy recovery levels. Even with no additional input of heat, a NO_x reduction level of 40% is achieved at nominal load.

Best practice to fulfill regulations from an economic standpoint

All three case studies showed that under the specific conditions of existing regulations, and taking account of the balance of investment to operating costs, HAM always demonstrated extremely short amortisation periods.

Engine operation optimisation

Addition of water vapour to the charge air has a beneficial effect:

>> Exhaust gas temperatures and valve temperatures are lower, leading to a decrease in thermal loading.

Simple operation

The use of HAM is simple as shown by experience on the “Mariella”:

>> Simultaneous start for both HAM and engine.
>> 15 minutes before stopping the engine: engine at idle speed and water circulation shut off in order to dry the air system.

System reliability

The system is intrinsically self-controlled without any need of a load-related control loop. The system is stable and responsive.

>> Longevity: Even after 100,000 hours of operation, HAM has demonstrated consistently high effectiveness in NO_x reduction.
>> Stable: No abrupt changes in engine operating parameters if water circulation is shut-off.
>> Responsive: favourable response to load variations.

The HAM system is thus an economically and ecologically viable way to effectively reduce NO_x while optimising engine operation.

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