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Shipping in Coastal Regions – State of the Art and Current Research for Emission Reduction

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Abstract

Shipping generally is an environmentally-friendly means of transport with relatively low CO_2 emissions. Due to concentration of ship traffic in coastal areas and due to the emission behaviour of ship diesel engines at low and instationary loads, a further reduction of emissions from shipping is desirable and necessary. The formation of emissions inside diesel engines is of a complex nature. Measures which reduce a certain emission component will increase another component at the same time. The EMI-MINI project at the University of Rostock investigates fuel sprays from modern common-rail diesel injectors for ship engines in order to find measures that reduce emissions and maintain the already existing advantages of modern ship diesel engines. Within the project, state-of-the-art laser measurements are applied to determine the influence of injection parameters on the properties of fuel sprays inside the cylinders of large diesel engines.

1 Shipping in coastal regions of the Baltic Sea

1.1 Shipping in the Baltic Sea

The Baltic Sea is an area of high ship traffic density. The total number of port calls in the Baltic Sea (including ferries) was estimated to be 426,000 in 1998. Due to the annual increase in ship traffic, this number is expected to double by the year 2017 compared to 1995 (Rytkönen et al. 2002). For obvious reasons shipping activities are concentrated in coastal areas.

Shipping plays a key role in the economic and social life in coastal zones. It is often a central column for local industry and tourism at the same time. Ports and industries connected with them form the economic backbone of many cities along the Baltic coast line. Besides industrial goods, ferries attract and transport considerable numbers of tourists and are, therefore, an important factor for the tourist industry. In 2002, 7954 ships called at the port of Rostock, 5774 of them were ferries. The ship traffic in and out of the port is surely part of the tourist attractions of Rostock and other Baltic port cities, with the large cruise liners, visiting for instance the passenger quay in Warnemünde, being a particular highlight.

From an environmental point of view shipping has the advantage of relatively low CO_2 emissions due to the outstanding efficiency of modern ship diesel engines and due to the general efficiency of the transport system “ship”.

Nevertheless, shipping contributes significantly to the air pollution, especially in the coastal regions as can be seen in Figure 2. Regarding acidifying gases, ships belong to the major emitters within the European Community. The pressure to reduce these emissions from shipping will increase due to increasingly reduced emission limits imposed on other sources and due to increasing demands, not only from the tourist industry, for improved air quality in coastal regions (e.g. spas, climatic health resorts etc.).

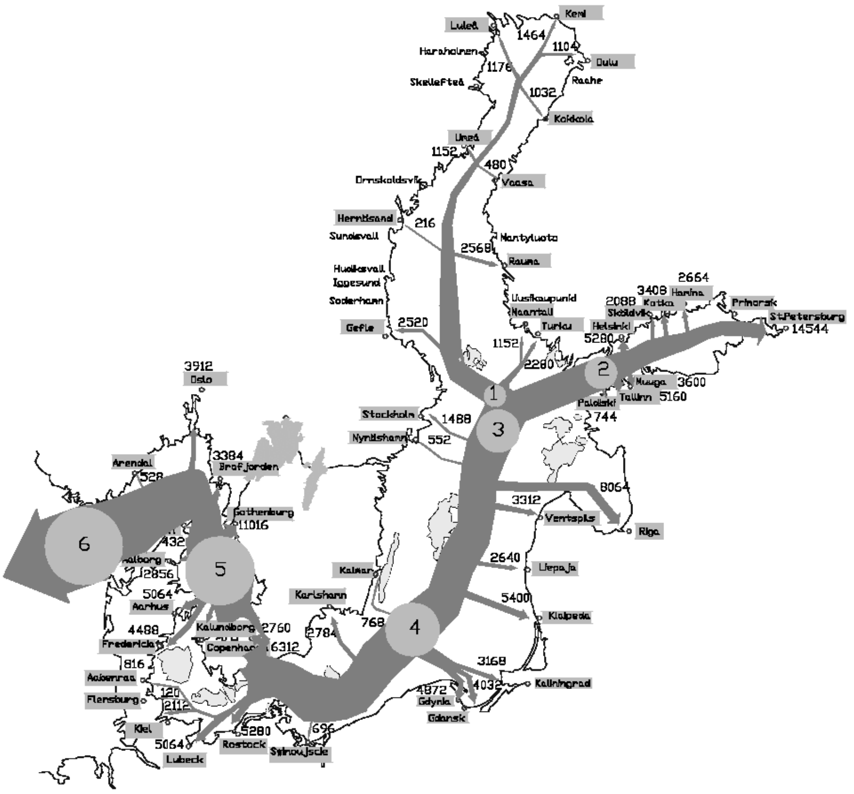

Figure 1: Main ship traffic routes in the Baltic, excluding ferries (Rytkönen et al. 2002).

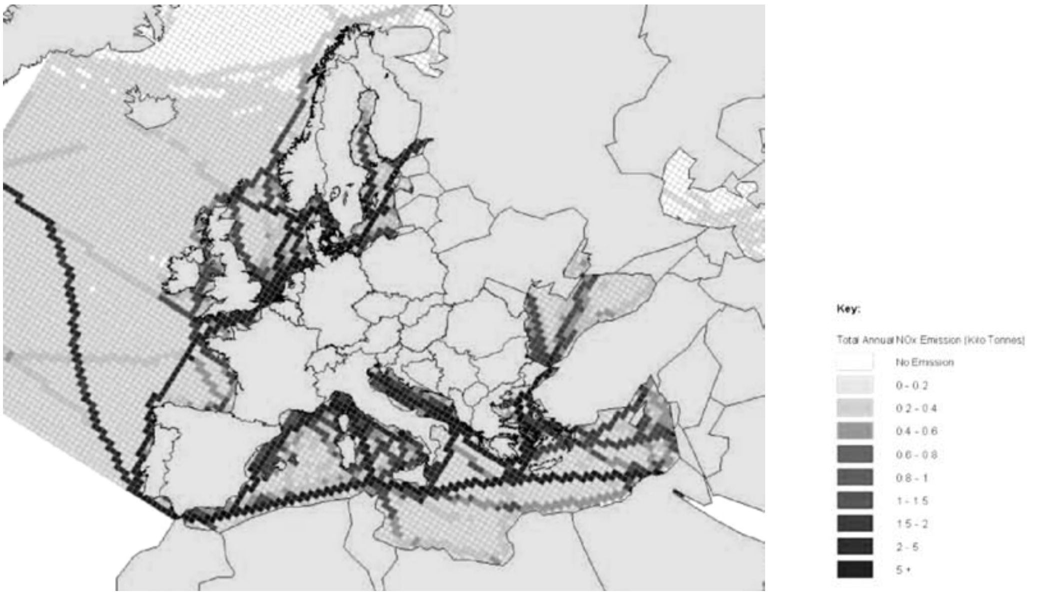

Figure 2: Total annual NOX-emissions from shipping in European seas in 2000 (Chris Whall et al. 2002).

1.2 Modern ship diesel engines

The vast majority of merchant ships uses diesel engines to supply the propulsion energy as well as all electric energy for shipboard use. These engines have outputs from 1 MW up to 60 MW, piston diameters from 15 cm up to nearly 1 meter and rotation speeds from up to 1000 rpm down to less than 100 rpm. This is a very broad range of engines, representing an even broader range of specific design data and technical solutions. Nevertheless, the basic emission behaviour of these engines and the general emission generation processes are comparable.

Modern large diesel engines are still the most efficient supplier of mechanical and (in combination with a generator) electrical energy. These engines reach efficiency values of up to and above 50%. A modern, large ship diesel engine requires approximately 170 grams of fossil fuel (i.e. diesel or heavy fuel oil) per kWh output, whereas a modern diesel engine of a passenger car requires a minimum of approximately 210 grams of diesel oil per kWh. A state-of-the-art gasoline-engine consumes around 245 grams per kWh. This outstanding efficiency of modern ship diesel engines needs to be kept in mind when discussing the overall environmental balance of such engines.

1.3 Fuel quality

Fuel quality is of central importance when discussing emissions from large ship diesel engines. Large merchant ships and ferries are operated with Marine Diesel Oil (MDO) or Heavy Fuel Oil (HFO) which is essentially a residual oil formed from the final fractions of the crude oil.

MGO is available with sulphur contents between 0.05% and 0.2 %. HFO can have sulphur contents of up to 4.5%. In the Baltic Sea the permitted maximum sulphur content in HFO is 1.5%.

Tough economic competition in international shipping and increasing fuel prices led to the use of HFO as the main shipping fuel in the period after the oil crisis. Generally, HFO represents the final residue of the crude oil after all “light” components (gasoline, on-road diesel fuel, gas oil etc.) have been extracted in the refinery process. HFO is not a standardised fuel quality with clearly defined properties. It is simply the category name for a broad range of residual oils and oil blends from various sources and locations. The chemical and physical properties of HFO can very considerably. HFO needs to be processed aboard the ships (heated up to 150°C, separated and filtered) before it can be used in the engine. Apart from the use in ship diesel engines, there are only few alternative applications for HFO.

2 Airborne emissions from ship diesel engines

2.1 Emission of carbon dioxides

The emission of CO_2 is directly linked to the amount of fossil fuel which is burnt in an engine to produce a certain power output. A reduction of CO_2 emissions can be obtained either by reducing the power which is required for a certain task (e.g. the propulsion of the ship), or by improving the engine’s efficiency, i.e. reducing the amount of fuel which is required to produce a certain output.

As already discussed in Section 1.2, the major advantage of modern, large ship diesel engines is their outstanding thermodynamic efficiency which leads to relatively small CO_2 emissions.

During the combustion process, the temperature and pressure levels inside the cylinders of marine diesel engines are extremely high. Compression temperatures (before the start of combustion) reach up to 900 K, whereas flame temperatures during combustion can reach 2700 K at combustion peak pressures of 175 bar and above (compared to maximum pressures of approx.135 bar in car diesel engines). Due to thermodynamic laws, these extremely high process temperatures are the reason of the engines’ outstanding efficiency (Buchholz et al. 1999).

2.2 Emission of nitrogen oxides

Unfortunately, the high process temperatures, which lead to low CO_2 emissions, are at the same time responsible for increased NO_X emissions. NO_X is formed during the combustion process in those zones inside the cylinder where high temperatures (above 1800 K) and air excess are found for certain periods of time. In these zones, the following continuous reaction cycle takes place:

$$O + N_2 \leftrightarrows NO + N$$

$$N + O_2 \leftrightarrows NO + O$$

$$N + OH \leftrightarrows NO + H$$

This reaction-kinetic law of NO_X generation was named after its founder Zeldovich (1946).

2.3 Particulate emissions

Exhaust gas components which can be caught on a filter and do not vaporise at temperatures below 52°C are described as particulate matter (PM). In case of diesel engines, particulate emissions consist mainly of soot (unburnt carbon and longer or cyclic hydrocarbons) and ashes (oxidised metallic components, especially in case of heavy fuel oil operation).

The particulate emissions from large marine diesel engines can generally be low, at least when the engine is in stationary operation mode at increased load levels (50% of nominal output or higher). This is typically the case if the ship is sailing across the sea/ocean.

Increased, clearly visible particulate emissions can appear if large marine diesel engines are operated at very low load (during and immediately after engine start-up and during slow speed), when the engine is accelerated or the load is increased (manoeuvring). As can easily be seen, such operation modes are typical for ships sailing close to the shore or within ports and rivers, i.e. within coastal zones.

Other reasons for increased particle emissions can be poor fuel quality and increased sulphur content in the fuel (Prescher et al. 2000). These cannot be influenced by engine design. Here, the same comments as made in Section 2.5 Emissions of sulphuric oxides apply.

2.4 Emission of CO and unburnt, gaseous hydrocarbons

Hydrocarbon and CO emissions are the result of incomplete combustion processes. For large diesel engines these emissions are typically low, due to the high temperature and pressure level of the internal combustion process and due to the relatively slow process frequency. An increase in these emissions can occur during low load and during transient engine operation. New fuel injection technology in combination with improved engine management can reduce hydrocarbon and CO emissions during these engine operation modes.

2.5 Emission of sulphuric oxides

Fuel oil for ship diesel engines has significantly higher sulphur contents than fuel for land-based traffic. In the European Community, a maximum sulphur content of 0.035 % (to be reduced to 0.005% in 2005) is permitted in diesel fuel for on-road applications. Marine Gas Oil (MGO) can have up to 0.2% and HFO up to 4.5% sulphur (for shipping in the Baltic Sea limited to 1.5%).

During combustion in the cylinder of the diesel engine, virtually all sulphur from the fuel is converted to SO_2 and subsequently emitted into the atmosphere. This cannot be prevented by any engine internal measures. External measures to scrub the exhaust gas from the SO_2, although available for land-based power stations, are hardly technically feasible aboard ships.

The only efficient measure to reduce SO_2 emissions from shipping is the reduction of the sulphur content in the marine fuels. At the moment, availability and price of such fuels prevent their broad application. Major investments in the petrol-chemical industry seem to be necessary to supply sufficient quantities of low-sulphur fuel without significant price penalty.

3 Basic strategies for emission reduction

First NO_X emission limits for ship engines were introduced by the IMO in 2000. Although not ratified by a sufficient number of member states, the IMO “Technical code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines” (IMO 1997) became a virtual standard for all ships built after the 1st January 2000. The IMO code basically requires a 30% reduction in NO_X emission compared to the engine-specific NO_X emissions levels of 1997.

During a period of intense research and development, a number of engine internal measures were developed and applied to obtain the required reduction in NO_X emission without any or without significant fuel penalty. Such measures are: improved injection nozzles, improved engine control systems and adapted engine settings, adapted turbo-charger matching, changes in combustion chamber design. Today, IMO compliant marine diesel engines are available from all engine manufacturers.

Additional engine internal measures are generally known and are also applied aboard some ships, when further reduction in NO_X emission is necessary. Examples for such measures are the use of fuel-water emulsions instead of pure fuel which can reduce NO_X emissions by up to 30% without significant increase in fuel consumption or the injection of pure water during the combustion process. Further research in this field is taking place at the University of Rostock, too.

External measures, i.e. exhaust gas after treatment, are very difficult to apply aboard large merchant vessels. Due to the properties of HFO, its high contents of sulphur, and the varying quality of HFO a reliable operation of any kind of catalyst is very difficult and costly. The only proven technology available is the SCR-catalyst for the reduction of the NO_X emissions. Urea or ammonia is used inside these catalysts to reduce the NO by producing N_2 and H_2O. The installation of these bulky catalysts within engine rooms of ships is often difficult. The costs for the reducing agent (urea or ammonia) are significant. In order to guarantee a reliable operation of the catalysts over longer periods the use of better-quality, low-sulphur HFO is recommended which also increases operation costs. However, using such catalysts, the NO_X emissions can be reduced by well over 90%. In Swedish ports the use of such environmentally friendly technology is rewarded with reduced port fees.

The research carried out to fulfil the IMO requirements on NO_X emissions showed the potential of engine internal measures for further emission reductions. Better understanding of the emission generation processes and new technology to control the combustion process could lead to even more reduced emissions levels at unchanged engine efficiency. Regarding the reduction of NO_X, it will be necessary to find means to reduce local and temporal temperature peaks during combustion without reducing the overall temperature levels in order to maintain engine efficiency. Emissions of particulate matter (especially soot), unburnt hydrocarbons and CO could be reduced by improved injection and air supply especially at low load and instationary engine operation.

Emission reduction techniques which are until now primarily developed for normal, stationary engine operation at upper load levels (the most important operation mode of ship diesel engines) need to be extended onto low load conditions and instationary operations, as these load conditions are especially important for shipping in coastal zones.

4 Current research at Rostock University

The Chair for Combustion Engines at Rostock University has a long tradition in research for modern, environmentally-friendly combustion engines and marine diesel engines in particular. Several test beds are available for the experimental investigation of new engine and engine operation concepts, for the investigation of new, alternative fuels (e.g. fuel-water emulsions, rape seed oil, natural gas etc.) and the analysis of engine internal combustion processes (Hassel et al. 2003). Equipped with modern measurement technology and state-of-the-art simulation tools, basic research projects are carried out to broaden the understanding of engine internal processes and emission generation. Since spring 2004, a state-of-the-art four-stroke medium-speed ship diesel engine has been available for basic and applied research projects. This engine can be operated with heavy fuel oil to investigate emission reduction measures and other engine developments under conditions which are relevant for standard marine applications.

4.1 Influence of the injection process on combustion and emission generation

The fuel injection process has a decisive influence on the combustion process and, therefore, on the emission generation inside diesel engines. Emissions from ship diesel engines can be further reduced if new injection technology allows to control and to “design” the injection process according to the specific requirements of an environmentally optimised combustion process.

This approach requires three basic prerequisites: a flexible injection system, the definition of the requirements on environmentally improved combustion processes and the definition of the injection parameters which are necessary to obtain such combustion processes over the whole engine operation range. With the development of the common-rail diesel injection system a major step to fulfil the first prerequisite has been made. The second prerequisite, the definition of the requirements on environmentally improved combustion processes is subject to many research projects not only at the University of Rostock but at many research institutes and at engine manufacturers world-wide.

Target of the current EMI-MINI-project at the University of Rostock is the investigation of the influence of injection parameters on the fuel sprays generated inside the engine’s cylinder. It contributes to the fulfilment of the third prerequisite mentioned above.

4.2 EMI-MINI Project

To get a better understanding about the influence of injection parameters on the fuel spray properties and on the subsequent combustion, laser based measurement technologies have been applied during various recent research projects at the University of Rostock (Hopp et al. 2003).

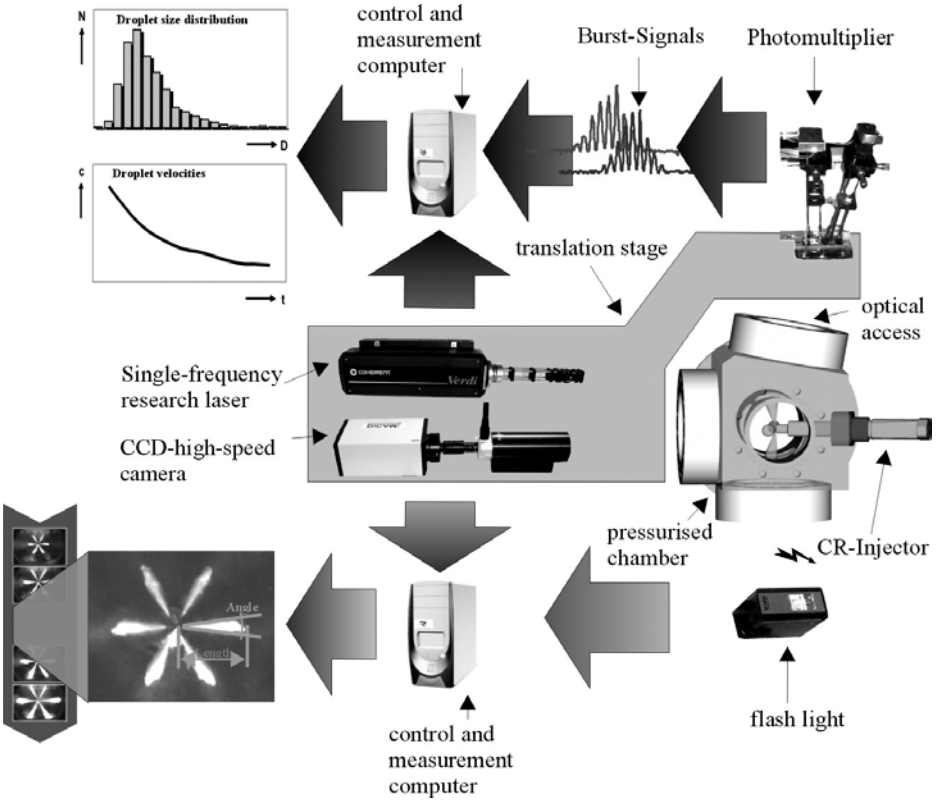

Figure 3: Experimental setup for the measurements of fuel spray parameters within the EMI-MINI Project.

Within the EMI-MINI Project modern laser-based PDA-measurement technology (phase-doppler-anemometry) is applied to investigate the fuel droplet sizes and velocities inside a fuel spray of a modern common-rail diesel-injector for large ship engines. In addition, photographs taken by a high-speed CCD camera are used to determine the macroscopic spray parameters, such as spray cone angle, spray length, spray tip velocity and spray volume. The common-rail injector is mounted to a special pressurised research chamber to investigate the fuel spray under conditions comparable to those inside a cylinder of a large diesel engine. The research chamber has 3 optical accesses (quartz glass windows). Through these optical accesses the spray can be investigated using the CCD camera or a laser beam. Temperature and pressure inside the chamber can be controlled within a broad range. The basic experimental set-up can be seen in Figure 3.

After a period of intensive redesign and construction of the experimental set-up, the first experiments were carried out. The results which are gathered now and in the immediate future will be evaluated and systemised. Figure 4 shows photographs of the diesel fuel spray that was generated from a common-rail ship diesel injector inside the research chamber. Local segments of the spray, for instance the fuel jet close to the nozzle, can be visualised using a far-field microscope and extremely short closure-times for the camera. More results from latest measurements are shown during the oral presentation at the conference.

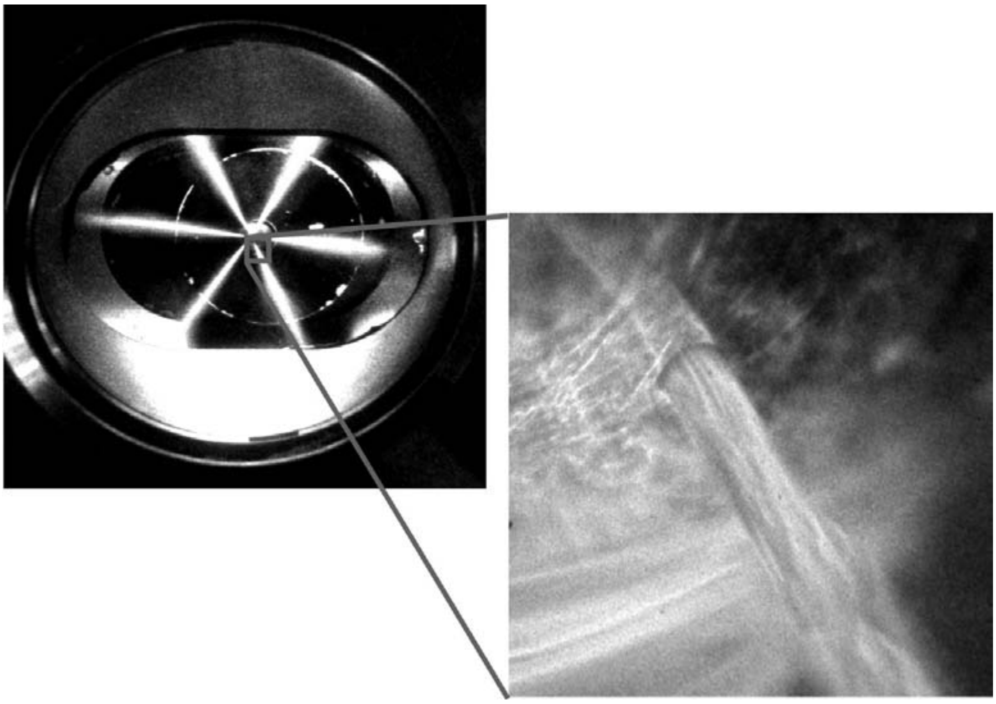

Figure 4: High-speed camera photographs of diesel fuel sprays from a common-rail diesel injector.

The EMI-MINI Project is a joint research project funded by the German Ministry for Education and Research. Apart from the University of Rostock the following research partners are involved:

Caterpillar Motoren GmbH & KG in Kiel

Caterpillar operates a 6-cylinder, medium-speed ship diesel engine equipped with a modern common-rail diesel injection system on their research test bed. The reduction of emission from turbo-charged ship diesel engines at instationary operation mode is Caterpillar’s the task within the joint project.

WTZ Roßlau gGmbH in Roßlau

WTZ carries out fundamental studies regarding soot production at large diesel engines depending on the fuel qualities. WTZ operates a single-cylinder research engine equipped with sophisticated measurement technology.

AVL Deutschland GmbH in Mainz-Kastel

It is AVL’s task to use the data from the other partners involved to develop and verify their engine simulation tools. These modern design and development tools will be offered to the engine builders to support them in their increasingly complex task of developing and producing the next generation of environmentally-friendly ship diesel engines.

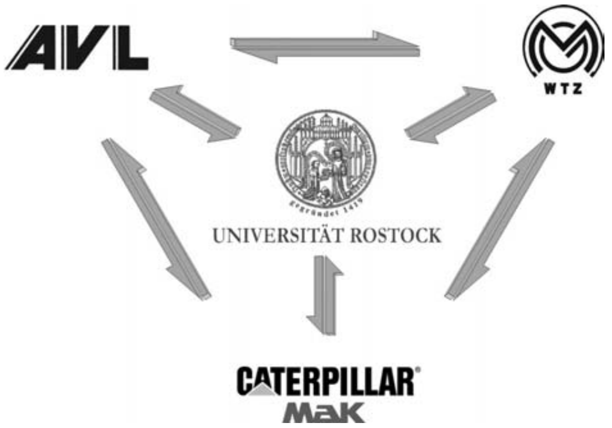

Figure 5: EMIN-MINI Project consortium.

5 Summary

Future emission reduction measures must target the drawbacks of modern ship diesel engines without reducing their advantages. To achieve this demanding target detailed research on all areas of the engine internal combustion process is necessary. The University of Rostock carries out several research projects dealing with emission reduction and use of alternative fuels.

The emissions from ship diesel engines are generated during the combustion of the fossil fuel inside the engine’s cylinders. The emissions of sulphur oxides are directly linked to the sulphur in the fuel and can only be reduced by reducing the sulphur content of the fuel. All other emission components can be influenced by controlling the technical combustion process inside the cylinder. CO_2 generation is directly linked to the engine’s thermodynamic efficiency, i.e. the amount of fuel needed to produce a certain output power. Here, the outstanding efficiency of ship diesel engines is a major advantage. Unfortunately, due to physical and chemical laws the combustion conditions which lead to this outstanding efficiency cause, at the same time, increased NO_X emissions. This effect is known as diesel dilemma or NO_X - fuel consumption trade-off.

Particulate emissions from ship diesel engines are generally low, but increase during low engine load and instationary engine operation (manoeuvring of the ship). These operation conditions are typically found when the ship is sailing close to the coast or within ports. Therefore particulate emissions from ship diesel engines are a specific “coastal zone problem”.

The EMI-MINI Project at the University of Rostock, funded by the German Ministry for Education and Research, applies state of the art laser measurement techniques to the investigation of fuel sprays from modern common-rail injectors for ship diesel engines. An improved understanding of the interaction between injection parameters and fuel spray properties is target of these investigations. Together with the results obtained by other EMI-MINI partners, it will allow to utilise the increased flexibility of modern injection systems to reduce emissions from marine diesel engines especially during low and instationary load without sacrificing their advantages. Following this approach, large diesel engines could become an efficient and environmentally-friendly ship propulsion system of the future having reduced emissions also in coastal zones.

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