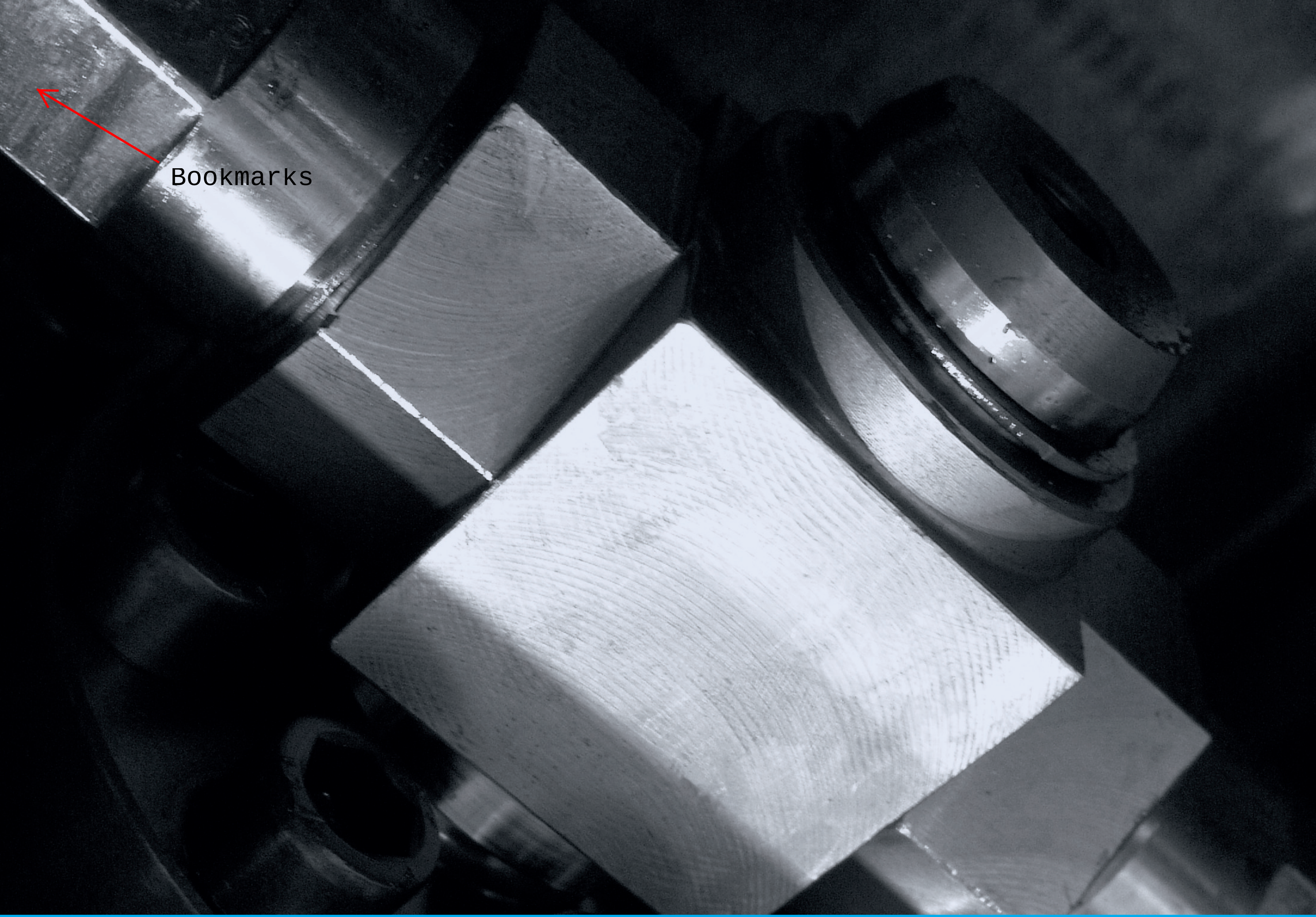

Common Rail

Design and maturity

Engineering the Future – since 1758.

MAN Diesel & Turbo

Introduction

MAN Diesel & Turbo is the world's leading designer and manufacturer of low and medium speed engines – engines from MAN Diesel & Turbo cover an estimated 50% of the power needed for all world trade. We develop two-stroke and four-stroke engines, auxiliary engines, turbochargers and propulsion packages that are manufactured both within the MAN Diesel & Turbo Group and at our licensees.

The coming decades will see a sharp increase in the ecological and economic demands placed on internal combustion engines. Evidence of this trend is the yearly tightening of emission standards worldwide, a development that aims not only at improving fuel economy but above all at achieving clean combustion that is low in emissions.

Large reductions in NO_X, CO_2 and soot emissions are a strategic success factor for HFO diesel engines. Special emphasis is placed on low load operation, where conventional injection leaves little room for optimization, as the injection process, controlled by the camshaft, is linked to engine speed. Thus, possibilities for designing a load-independent approach to the combustion process are severely limited.

MAN Diesel & Turbo's common rail technology (CR) severs this link in medium speed four-stroke engines. CR permits continuous and load-independent control of injection timing, injection pressure and injection volume. This means that common rail technology achieves the highest levels of flexibility for all load ranges and yields significantly better results than any conventional injection system.

A reliable and efficient CR system for an extensive range of marine fuels has been developed, and is also able to handle residual fuels (HFO).

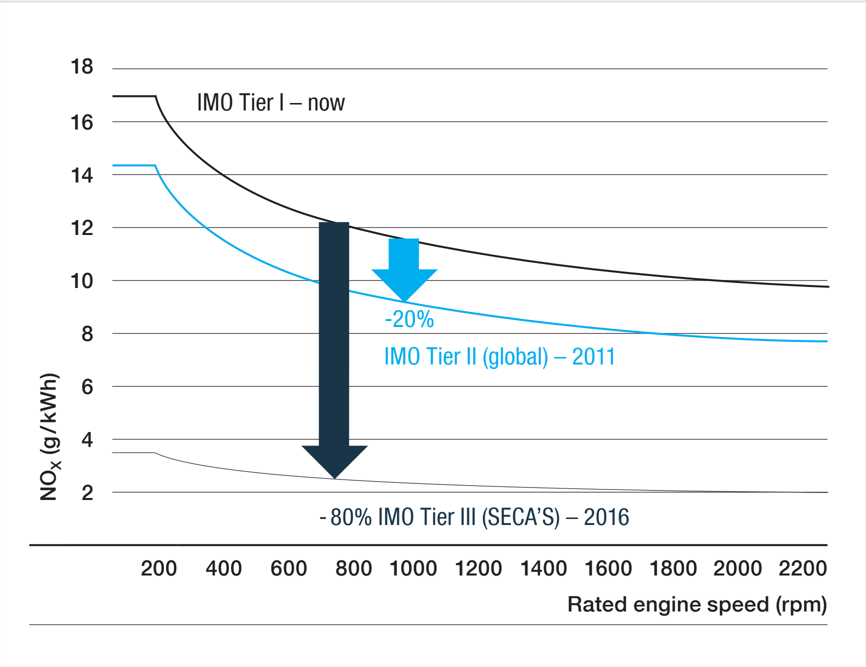

Fig. 1: IMO NO_X-legislation

System Description

The MAN Diesel & Turbo CR system was designed for operation with HFO in accordance with specification DIN ISO 8217 (viscosities up to 700 cSt at 50°C) and fuel temperatures of up to 150°C (to achieve the required injection viscosity). In addition to high viscosity, this fuel also typically has a high content of abrasive particles and very aggressive chemical components.
The injection system must be able to withstand these conditions in a failsafe way, including starting and stopping the engine during HFO operation.

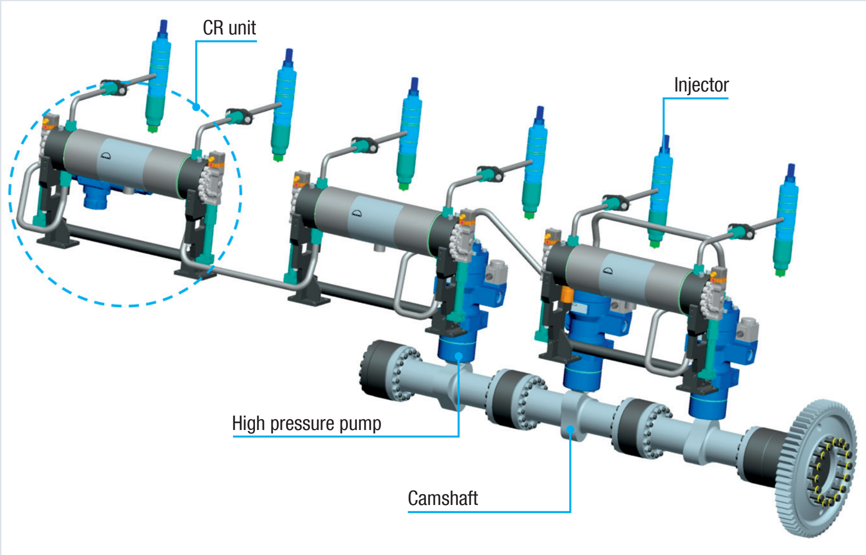

Fig. 2: CR injection system

Using just one pressure accumulator (common rail) for large bore diesel engines, extended over the entire engine length, is problematic for the following reasons:

- The different fuels that the engine can run on is reflected in the required fuel temperature (25°C to 150°C), and this in turn causes significant differences in the linear thermal expansion of the rail.
- A long rail requires radial drillings for the connection to each cylinder unit. Very high material stresses caused by these drillings are unavoidable. The problems and the scope of countermeasures therefore increase proportionally to the increased inner diameter of the rail in larger engines.
- In the case of reduced accumulator volumes, it would hardly be possible to achieve identical injection ratios for all engine cylinders, and excessive pressure fluctuations in the system could not be ruled out.
- Different numbers of cylinders would lead to various common rails, too.
- Supplying a pressure accumulator of excessive length by connecting it to the high-pressure pump at one point only will result in deviations in injection quality.

It is therefore reasonable to divide the accumulator into several units of suitable volume and to divide the supply into at least two high-pressure pumps for a six-cylinder engine. A further advantage of this segmentation is the increased flexibility to adapt the CR system to different numbers of cylinders, which is also an interesting factor when considering retrofit applications. The more compact design of the CR units ensures improved utilization of available space in the engine, which is beneficial for assembly. It also has advantages regarding the storage of spare parts.

Based on the concept of segmented rails, MAN Diesel & Turbo has developed a modular CR system which is applied to several engine types. For instance, a seven-cylinder engine is supplied by four rail units, whereby three rails each supply two cylinder units and one rail unit supplies one cylinder unit.

Layout and Functionality

Fig. 3 shows the hydraulic layout of the patented heavy fuel oil CR injection system for the MAN 32/44CR engine.

From the fuel system, delivered fuel is led through electromagnetic activated throttle valves 1 and suction valves 2 to the high-pressure pumps 3, which supply the rail units 5 with fuel under high pressure up to 1,600 bar by means of pressure valves 4.

The rail units 5, which function as a pressure and volume accumulator for fuel, consist of a high-strength tube closed with end covers in which a control-valve carrier 6 is integrated. The control valves 7 are fixed on to the control-valve carrier. Connections for high-pressure pipes are radially arranged on the control-valve carrier; these connections lead to the injectors 8, as well as to the next rail unit. This design means the tube itself requires no drilling and is therefore highly pressure-resistant. To guarantee uniform fuel injection, pressure fluctuations in the system must remain at a very low level. This is achieved by using rail units of optimum volume, several (two to four) high-pressure pumps instead of one single pump, and a camshaft with a carefully arranged triple cam lobe for optimum drive. The high and uniform delivery volume obtained in this way plays a key role in keeping pressure fluctuations very low. As much fuel as necessary is supplied to the high-pressure pumps, in order to keep the rail pressure at the setpoint. The rail pressure will be calculated by a characteristic map in the injection control, according to the engine load. The electromagnetically activated throttle valve 1 in the low-pressure area will then suitably meter the fuel quantity supplied to the high-pressure pumps.

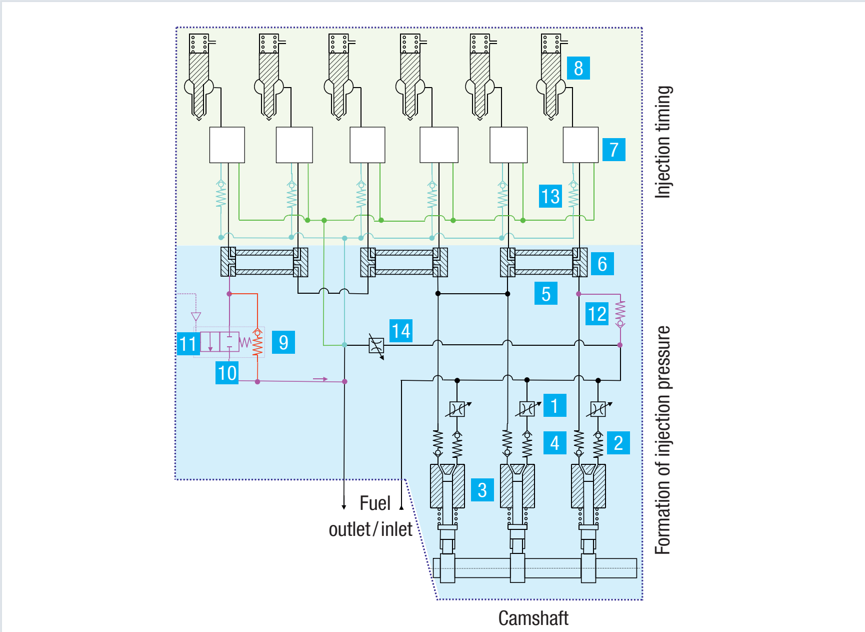

Fig. 3: CR injection system – general layout and functionality

Each rail unit *(Fig. 4)* contains components for fuel supply and injection timing control.

The fuel flow leads from the interior of the rail unit through a flow limiter to the 3/2-way valve and then to the injector. The flow limiter consists of a spring-loaded piston which carries out one stroke for each injection, thereby the piston stroke is proportional to the injected fuel quantity. Afterwards the piston returns to its original position. Should the injection quantity exceed however a specified limit value, the piston will be pressed to a sealing seat at the outlet side at the end of the stroke and will thus avoid permanent injection at the injector.

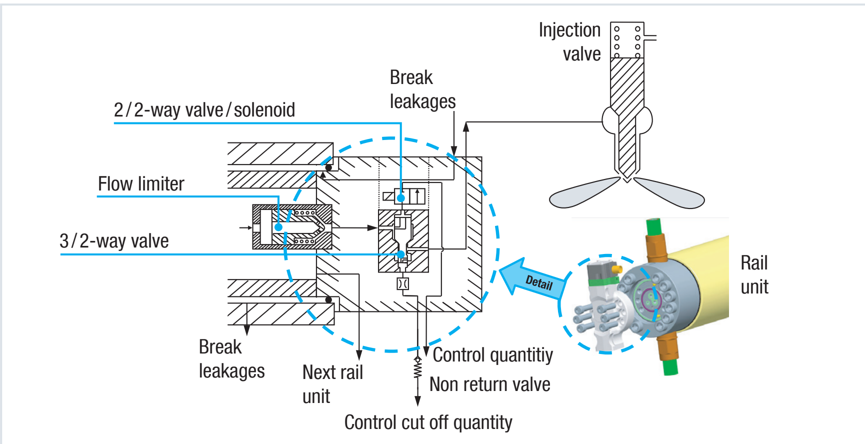

Fig. 4: Control valve and integrated components

The 3/2-way valve *(Fig. 4)* inside the control valve is operated and controlled without any additional servo fluid by an electromagnetically activated 2/2-way valve. It can therefore be actuated much more quickly than a servo-controlled valve. It enables the high-pressure fuel to be supplied from the rail unit, via the flow limiter, to the injector.

Fig. 5 describes the functional principle of the control valve in the pressure-controlled CR system. Functional leakages arising during the control process of the 3/2-way valve will be discharged back into the low-pressure system via the non-return valve (see *Fig. 3* and *Fig. 4*). The non-return valve 13 *(Fig. 3)* also prevents backflow from the low-pressure system into the cylinder, e.g. in case of nozzle needle seizure. A pressure-limiting valve 9 arranged on the valve block 10 protects the high-pressure system against overload *(Fig. 3)*.

The fuel supply system is provided with an HFO preheating system that allows the engine to be started and stopped during HFO operation.

To start the cold engine running with HFO, the high-pressure part of the CR system is flushed by circulating preheated HFO from the low-pressure fuel system. For this purpose, the flushing valve 11, located on the valve block 10 at the end of the rail units will be opened pneumatically. Any residual high pressure in the system is thereby reduced and the fuel passes via high-pressure pumps 3 through the rail units 5; it also passes via the flushing non-return valve 12 (a bypass to ensure a higher flow rate), through the rail units 5 and back to the day tank. The necessary differential pressure for flushing the system is adjusted with the throttle valve 14.

In the event of an emergency stop, maintenance, or a regular engine stop, the flushing valve 11 provides pressure relief for the whole high-pressure rail system.

The high-pressure components (accumulators and high-pressure pipes) are double-walled; the resulting hollow spaces are connected and form, together with the capacitive sensors *(Fig. 6)* and detection screws *(Fig. 7)*, an effective leakage detection system, enabling the rapid and specific detection of any leaks that may occur.

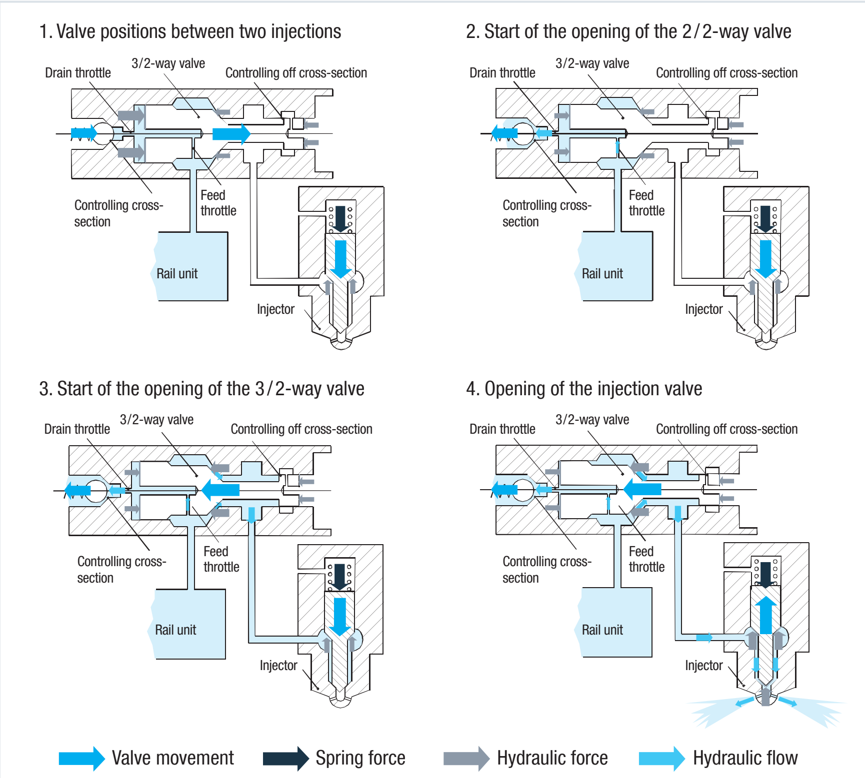

Fig. 5: Positions of control valve during injection

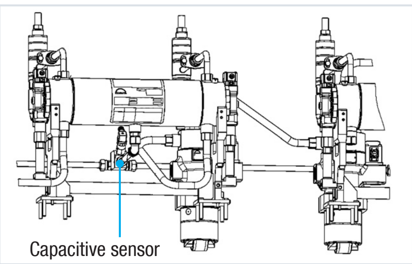

Fig. 6: Leakage detection system – capacitive sensors

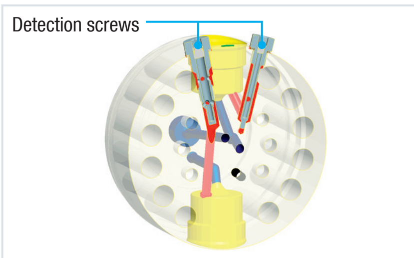

Fig. 7: Leakage detection system – detection screws

Advantages

Fig. 8: Common rail system V32/44CR

The principal advantage of CR injection is the flexibility gained by separating pressure generation and injection control.

MAN Diesel & Turbo has kept its CR technology as simple as possible. For example, there is no separate servo circuit to activate the injection valves. Conventional pressure controlled injectors are used and solenoid valves are integrated into the rail units away from the heat of the cylinder heads, resulting in greater system reliability and easy maintenance.

Different MAN Diesel & Turbo engine types use a very similar CR system design: for instance, the same basic design of 2/2- and 3/2-way valves is used for the control-valve unit.

The use of the separate 3/2-way valves ensures that the injectors are only pressurized during injection. This avoids uncontrolled injection, even if a control valve or injection valve is leaking.

The CR system is released for ships with single propulsion systems.

Modular division of the rail units and their assignment to individual cylinder units reduces material costs and assembly effort and allows for short lengths of high-pressure injection pipes.

The MAN Diesel & Turbo specific CR system design avoids pressure waves in the high-pressure pipes between the rail unit and the injector – a problem that occurs in some other CR systems, especially at the end of injection.

Engines equipped with this CR technology, and thus an optimized combustion process, are also sure to meet more stringent emission regulations (IMO, World Bank) that may be imposed in future. The design ensures that smoke emissions from the funnel stay below the visibility limit.

Safety Concept

Safety in design and operation is one of the most important considerations, especially for marine engines. To ensure that all possible failures are covered by the CR safety concept, MAN Diesel & Turbo has completed an extensive failure mode and effects analysis (FMEA) process.

On the basis of the FMEA, measures for failure detection and error prevention have been developed and system-integrated, but only after the successful completion of extensive validation tests on the test rig, which are vital for any new technology concept. The CR system and its safety concept, as illustrated below, are kept as simple as possible:

- **Injectors are only pressurized during injection**
  No danger of uncontrolled injection, even if a control valve or injection valve leaks.

- **High-pressure components are double-walled**
  No danger of fuel escaping in case of leaking or broken pipes.

- **Flow-limiting valves** *(Fig. 4)* **for each cylinder**
  No danger of excessive injection quantity, even in case of leaking or broken components.

- **Non-return valves** *(Fig. 3,* 13*)* **for each cylinder**
  Prevents backflow from the low-pressure system into the cylinder, e.g. in case of nozzle seizure.

- **Two to four high-pressure pumps**
  Should one pump fail, emergency operation is possible.

- **Pressure-limiting valve** *(Fig. 3,* 9*)* **with additional pressure-control function / safety valve**
  Emergency operation possible, even in case of any failure in rail pressure control.

- **Emergency stop valve / flushing valve** *(Fig. 3,* 11*)*
  The valve, actuated by compressed air, stops the engine in case of emergency.

- **Redundant rail-pressure sensors and TDC speed pick-ups**
  No interruption of engine operation necessary due to pick-up or sensor error.

Electronics

The challenge regarding electronics was to design a simple, redundant, electronic CR system for single-engine main-propulsion applications.

For single-engine main-propulsion systems, classification organizations require a full redundant system layout.
The injection electronics is therefore structured as described below.
The CR control is fully integrated within the SaCoS$_{one}$ (safety and control system on engine). Two injection modules are available *(Fig. 9)* to control the solenoid valves (injection time and injection duration) and the high-pressure pumps (rail pressure generation). Speed governing is performed by means of injection duration. After each engine stop, the control function changes between the two connected injection modules while maintaining full functionality. In case of malfunction of the active injection module, the back-up injection module takes over within milliseconds.
All necessary sensors, the power supply and the field bus system are redundant in design. So a single failure will not lead to an engine shutdown. Via the redundant CAN bus, all necessary information is exchanged between the SaCoS$_{one}$ devices and are displayed on the human machine interface (HMI).

For multiple engine installations, a non-redundant design for CR control is available.

The CR electronics extend the possibilities of the conventional injection system by means of freely adjustable injection parameters. A multitude of characteristic maps and parameters in the injection control allows optimized engine operation over the entire load range.

Redundant arrangement for single main propulsion plants

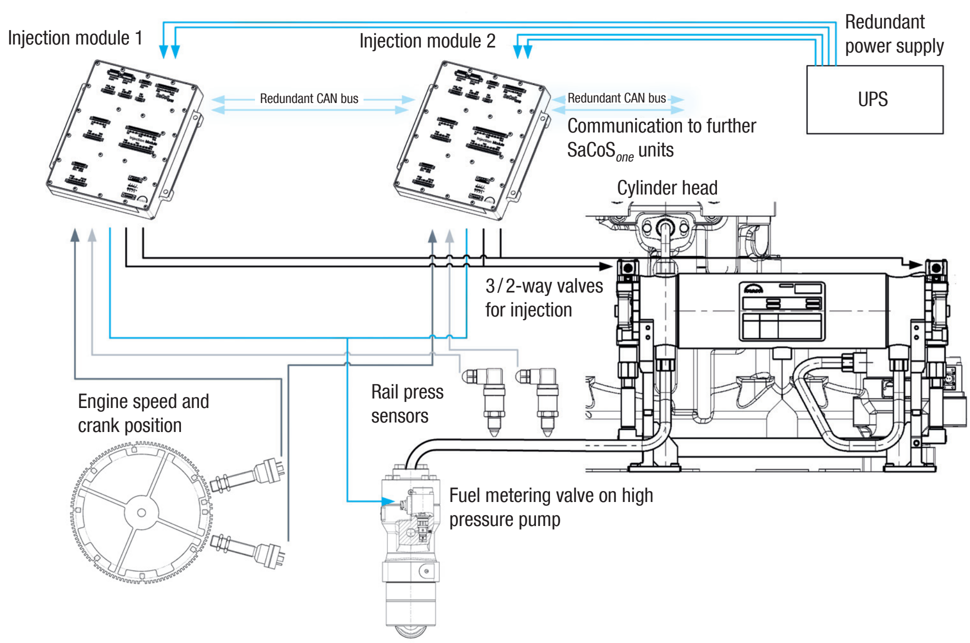

Fig. 9: Redundancy of electronic control system

Development Process

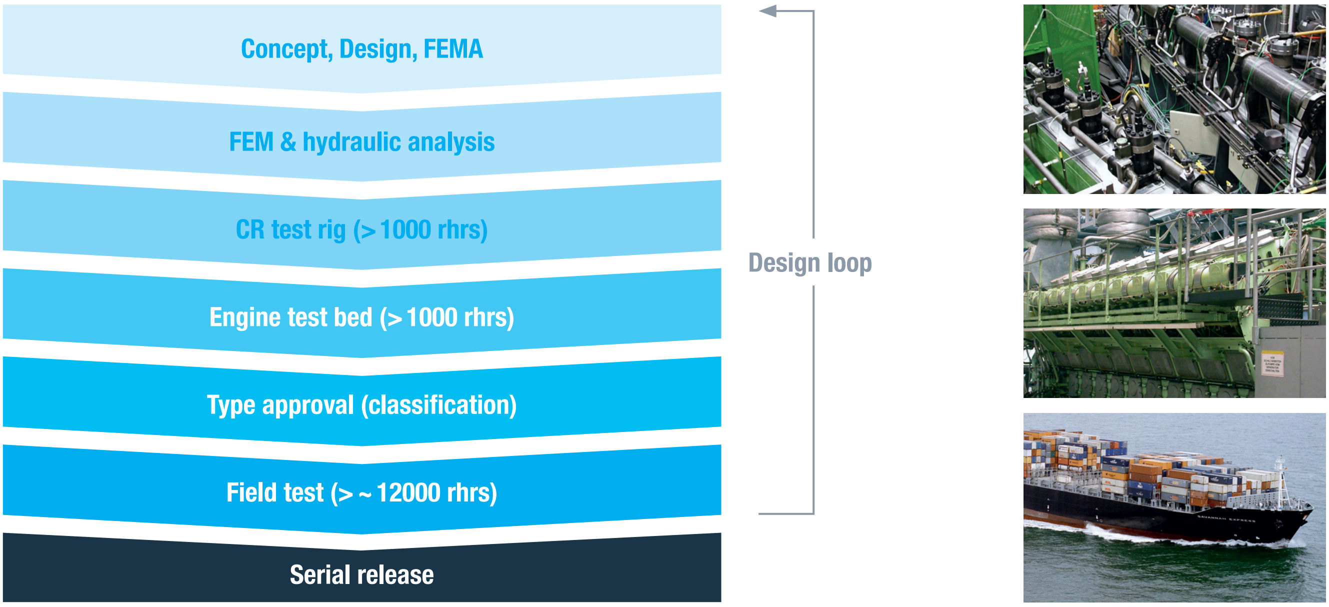

Fig. 10: Development process

The development process ensures the trouble-free market launch of a new product, as it means that a well-proven product with low technical risk will be available from start of series production.

Fig. 10 gives a rough impression of the development which the new product goes through. Some important stages of the development of the CR system are described below.

Simulation

The MAN Diesel & Turbo common rail injection system was simulated to optimize the system before the first components were produced. This simulation tool was also particularly effective for comparing simulated results with real results.

Fig. 11 shows a physical and mathematical model for the simulation of a one-cylinder unit including the components between the unit segment and the injection nozzle.

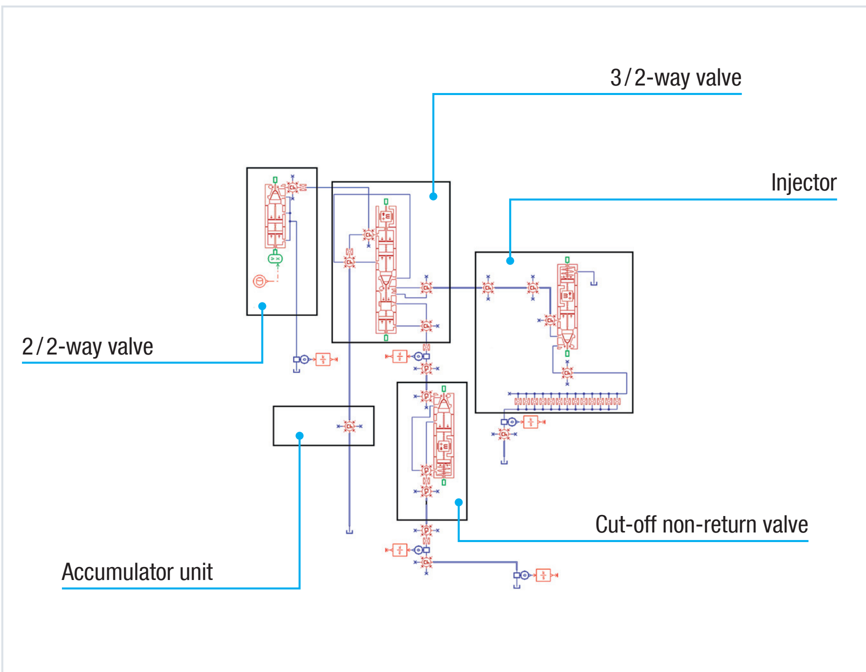

Fig. 11: Simulation model for one-cylinder unit

Hydraulic optimization and endurance testing on injection test rigs

As mentioned above, heavy-fuel operation is a major challenge for all electronically controlled injection systems. MAN Diesel & Turbo therefore decided to install new test rigs especially for the hydraulic optimization and endurance testing of CR injection systems under conditions that are as realistic as possible. These test rigs are characterized by the following main features:

- **Installation of complete CR systems for up to 10 cylinders is possible;**
- **Fully computerized operation and measurement with the possibility of unmanned endurance runs;**
- **Operation with different test fuels, especially with real HFO up to fuel temperatures of 150°C for endurance and hydraulic tests.**

Fig. 12 illustrates the comparison between the simulation and the test results to demonstrate the solid correlation between simulation and measurement. But the simulation was not limited to single cylinder units. To investigate the influence of different cylinder numbers, simulation models of the complete CR system for up to 10 cylinders were prepared and also verified by measurements.

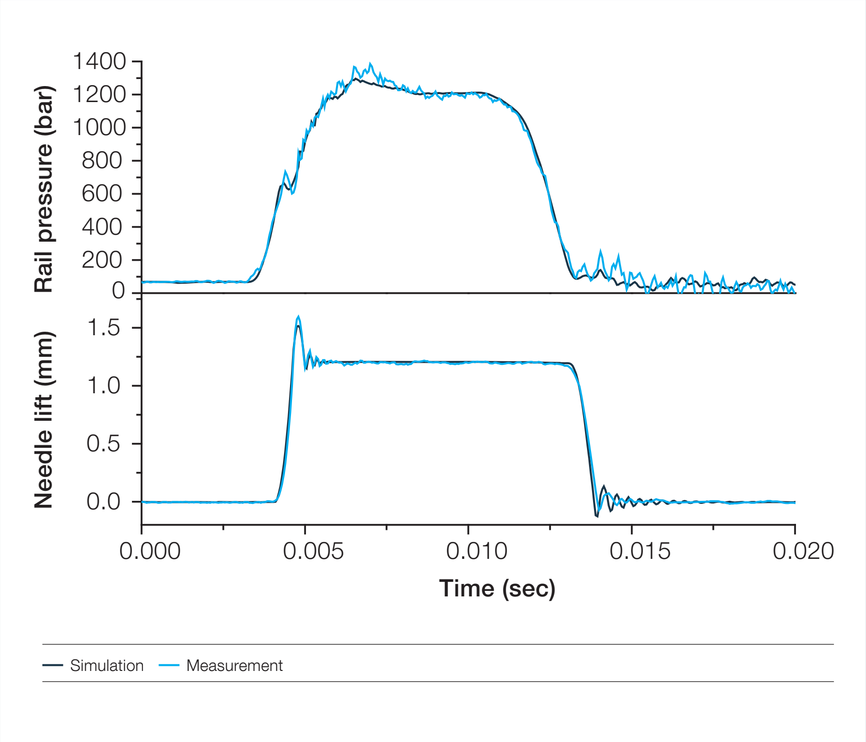

Fig. 12: Comparison of simulation and measurement

Development Process

Fig. 13 shows one of these test rigs with the 32/40 CR injection system installed. In addition to the test rigs for the hydraulic and endurance tests, MAN Diesel & Turbo installed an additional test rig to check the calibration of the control valves. The results from the test engine showed how important it is for these components to be well calibrated. The optimization of the CR injection system on the injection test rigs shall be demonstrated with the example below.

Fig. 14 shows the measured pressure ahead of the injection valve for three different versions of the control valve, compared to the injection pressure curve of the conventional injection system. It is easy to see that the rate of injection at the beginning of injection, which is most important for NO_X- and smoke-formation with the MAN Diesel & Turbo CR system, can be optimized within a broad range in order to match the injection system to the engine's requirements.

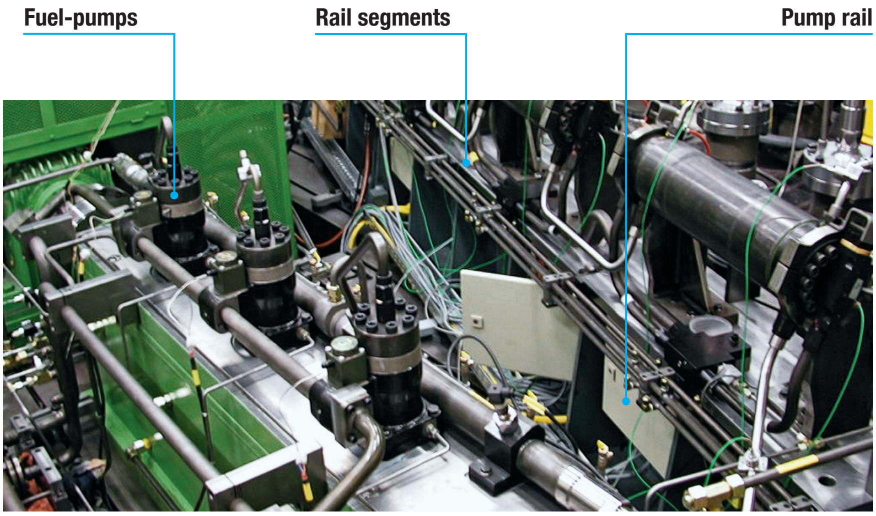

Fig. 13: Test rig installation of the complete CR system

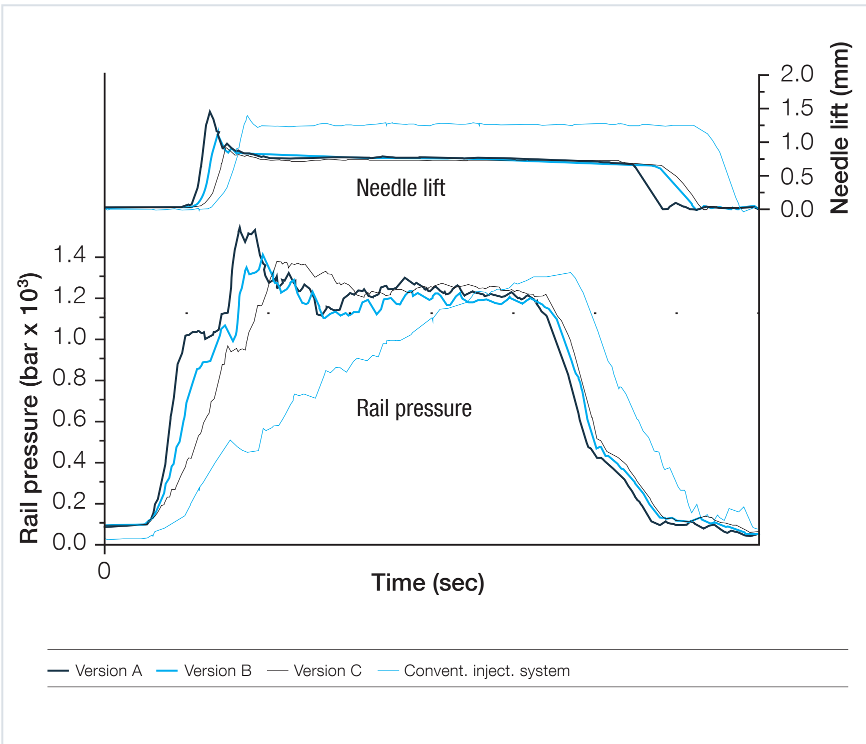

Fig. 14: Matching of the rate of injection

Test Results

CR system – adaptation to a new engine

On the engine test bed, injection pressure and injection start variations are effected at all load points within the characteristic field of the engine. Results are evaluated by taking into account the trade-off between SFOC, NO_X and soot emissions. In addition, the injection quantity curve and the injection nozzle configuration are modified according to the desired effect.

Due to the newly acquired flexibility of the injection parameters, which could be varied, NO_X emissions, fuel consumption and exhaust-gas opacity can be improved significantly. Exhaust-gas opacity can be reduced below the visibility limit within the critical low load range.

It is not surprising that only negligible advantages can be achieved at nominal load, since this operating point has been optimized in recent years in conventional injection systems.

In *Fig. 15*, *the examples* show that the CR system improves the SFOC / NO_X / soot trade-off in comparison to a conventional injection system.

Comparison of engine performance for different injection systems

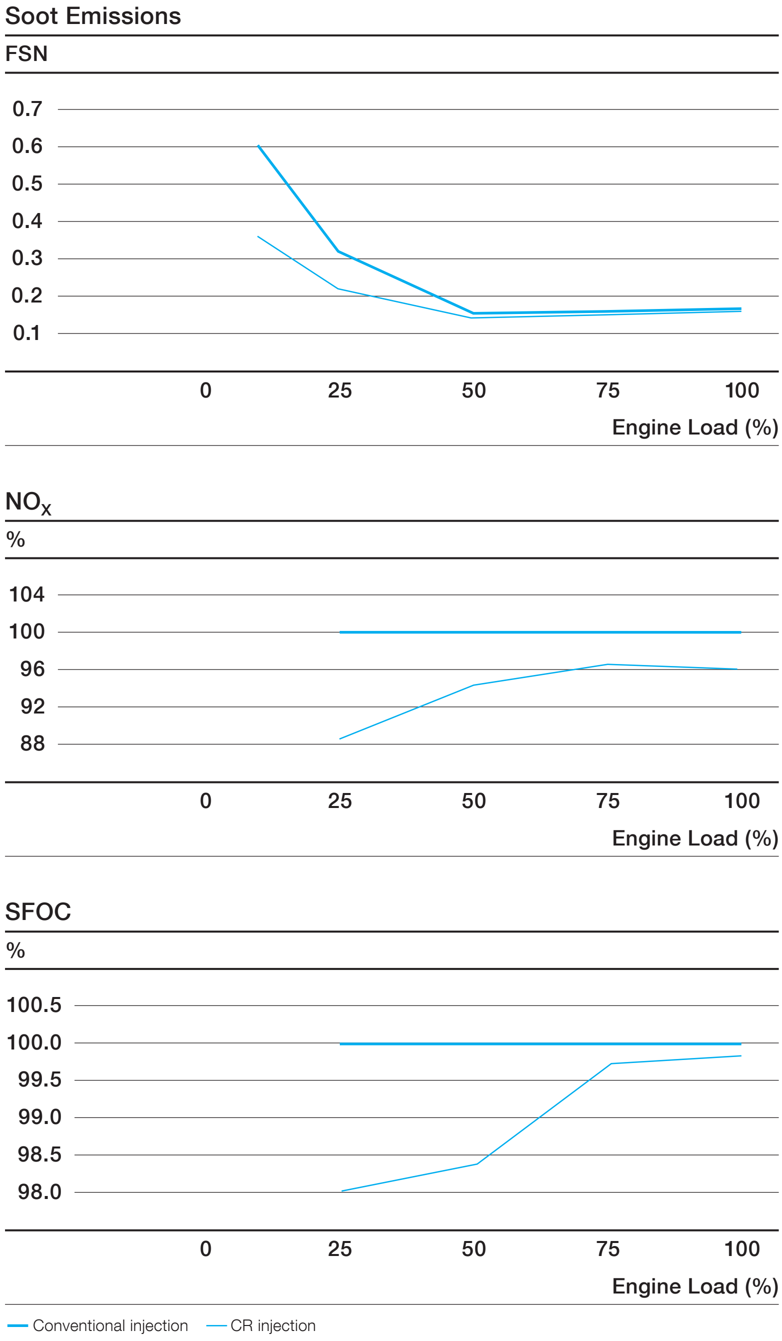

Fig. 15: Comparison CR injection system – conventional injection system

Conclusion

The advantage of the CR injection system, through its freely adjustable injection parameters, has hopefully been clearly demonstrated. The design of the CR system with its comprehensive functionality, control electronics and safety devices required careful long-term technological planning, which equipped the product with the potential to meet future environmental and economic demands.

Thanks to the results of the test programmes and the corresponding component development, a remarkable level of maturity has been achieved and confirmed by field tests of different applications lasting approximately 200,000 operating hours in total.

References	Engine type	Power output	Application	Commissioning
A.P. Moeller, M/S Cornelia Maersk, Sweden	5x7L32/40 thereof 1x7L32/40CR	15,750 kW	Container Vessel	02.2004
A.P. Moeller, M/S Clementine Maersk, Denmark	5x7L32/40 thereof 1x7L32/40CR	15,750 kW	Container Vessel	12.2004
Essberger GmbH, DAL Kalahari, Germany	4x6L32/40 thereof 1x6L32/40CR	8,640 kW	Container Vessel	09.2005
A.P. Moeller, M/S Charlotte Maersk, Denmark	5x7L32/40 thereof 1x7L32/40CR	15,750 kW	Container Vessel	03.2006
A.P. Moeller, M/S Columbine Maersk, Denmark	5x7L32/40 thereof 1x6L32/40CR	15,750 kW	Container Vessel	06.2006
A.P. Moeller, M/S Olga Maersk, Denmark	4x6L32/40 thereof 1x6L32/40CR	11,520 kW	Container Vessel	11.2006
NCL, Norwegian Jewel, USA	5x12V48/60B thereof 1x12V48/60CR	14,400 kW	Cruise Liner	05.2007
DFDS, Tor Petunia, Denmark	4x8L21/31 hereof 1x8L21/31CR	12,800 kW	Ro-Ro / Ferry	05.2008
Scandlines, Prinsesse Benedikte, Denmark	1x6L32/44CR	3,360 kW	Passenger Ferry	04.2007

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