

Common Rail

Design & Field Experience

Engineering the Future – since 1758.

MAN Diesel & Turbo



Introduction

MAN Diesel & Turbo Common Rail

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 years will see a sharp increase in the ecological and economical requirements placed on combustion engines. Evidence of this trend is the further 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.

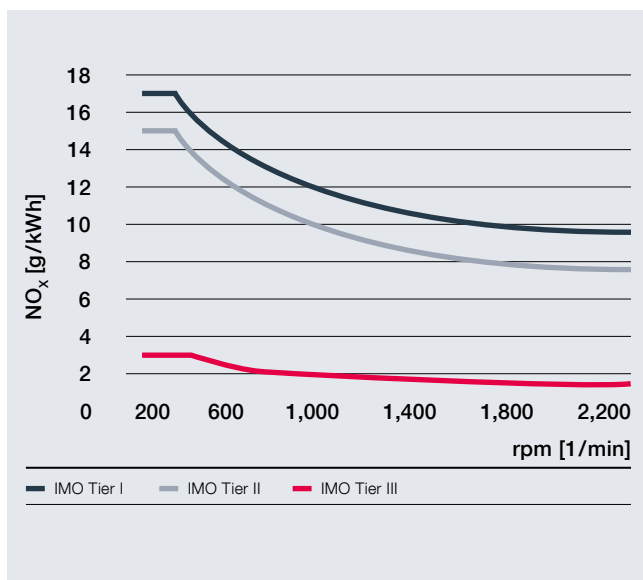
Compliance with existing and upcoming emission regulations with best possible fuel consumption is becoming an

increasingly important success factor for marine and power 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.

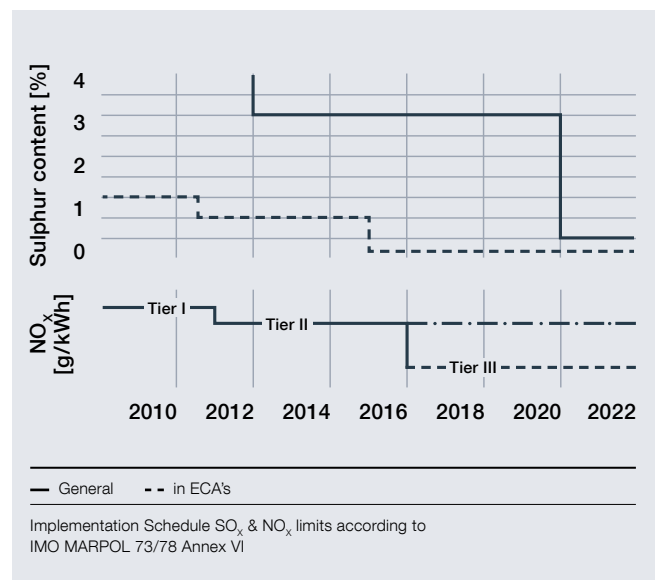
MAN Diesel & Turbo's common rail technology (CR) severs this link in medium speed four-stroke engines. CR permits

continuous and load-independent control of injection timing and injection pressure. This means that common rail technology achieves, for a given engine, 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).



IMO NO_x limit curves according to engine speed



Implementation schedule

System Description

General considerations

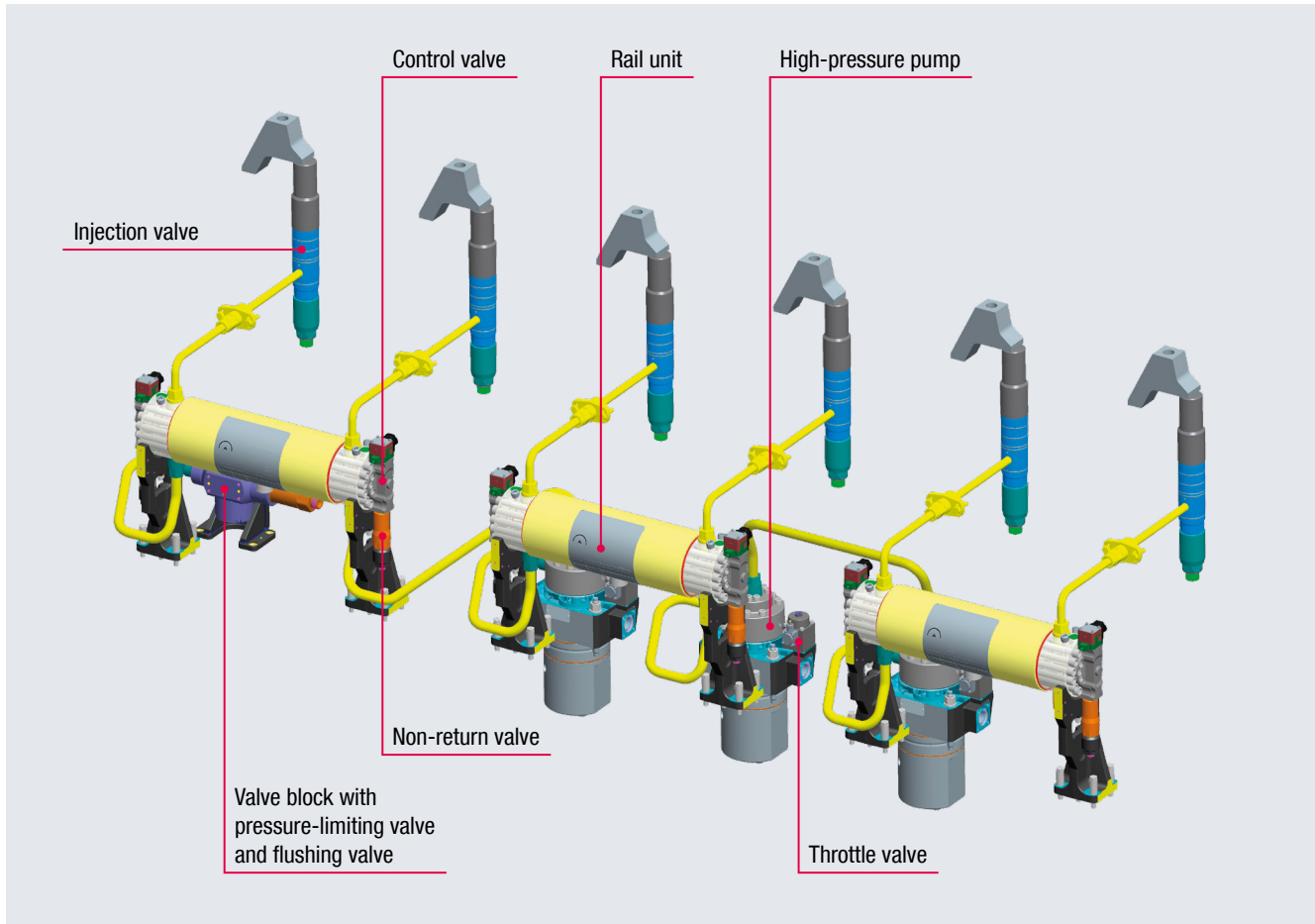


Fig. 1: CR injection system MAN 32/44CR

The MAN Diesel & Turbo CR system (Fig. 1, Fig. 2) 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.

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 counter-measures therefore increase proportionally with 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 also lead to various common rails.

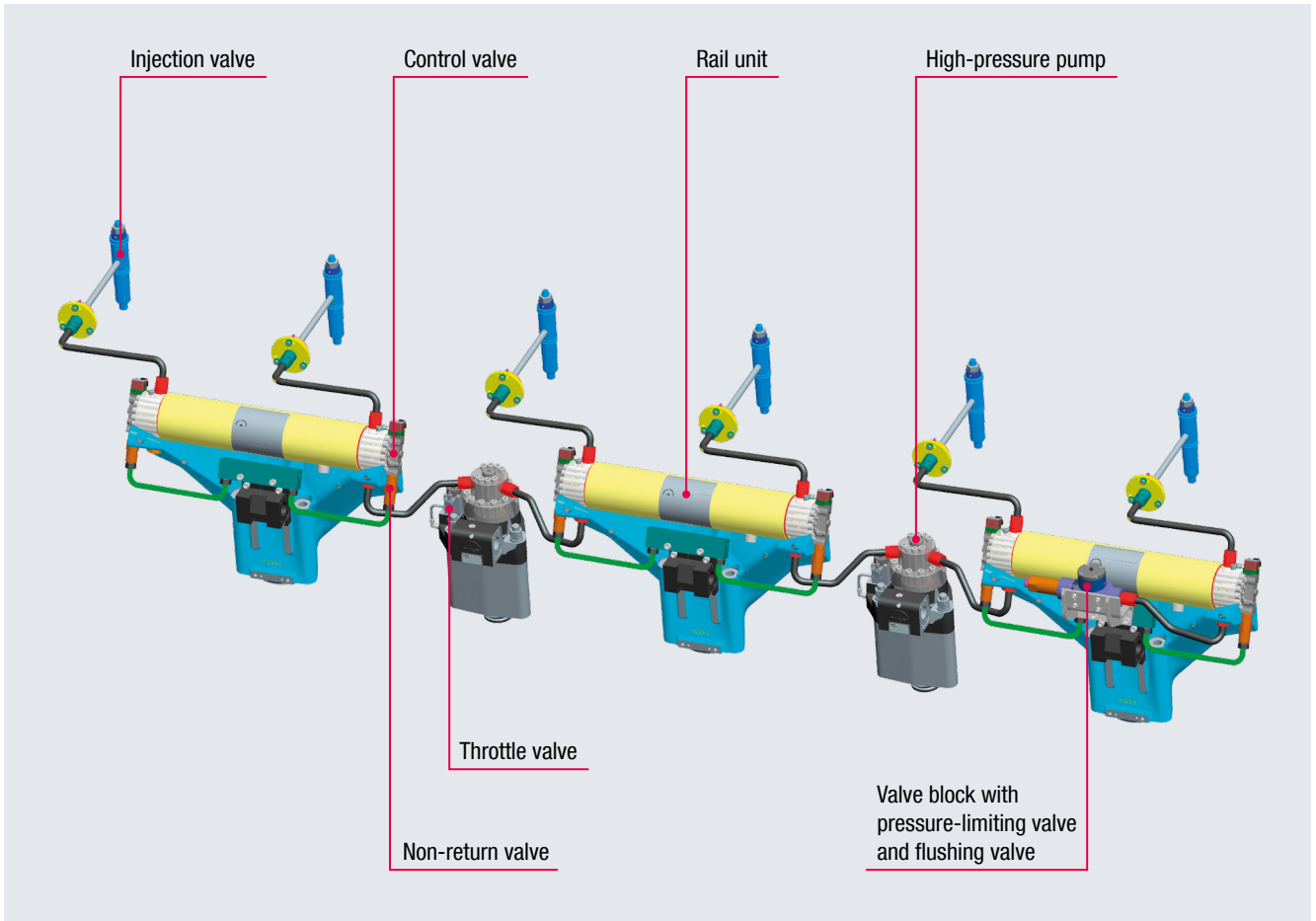


Fig. 2: CR injection system MAN 48/60CR

- 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 separate the accumulator into several rail units of suitable volume (Fig. 1, Fig. 2) 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 by means of proven modular system components. 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 and handling 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

Well thought-out and proven

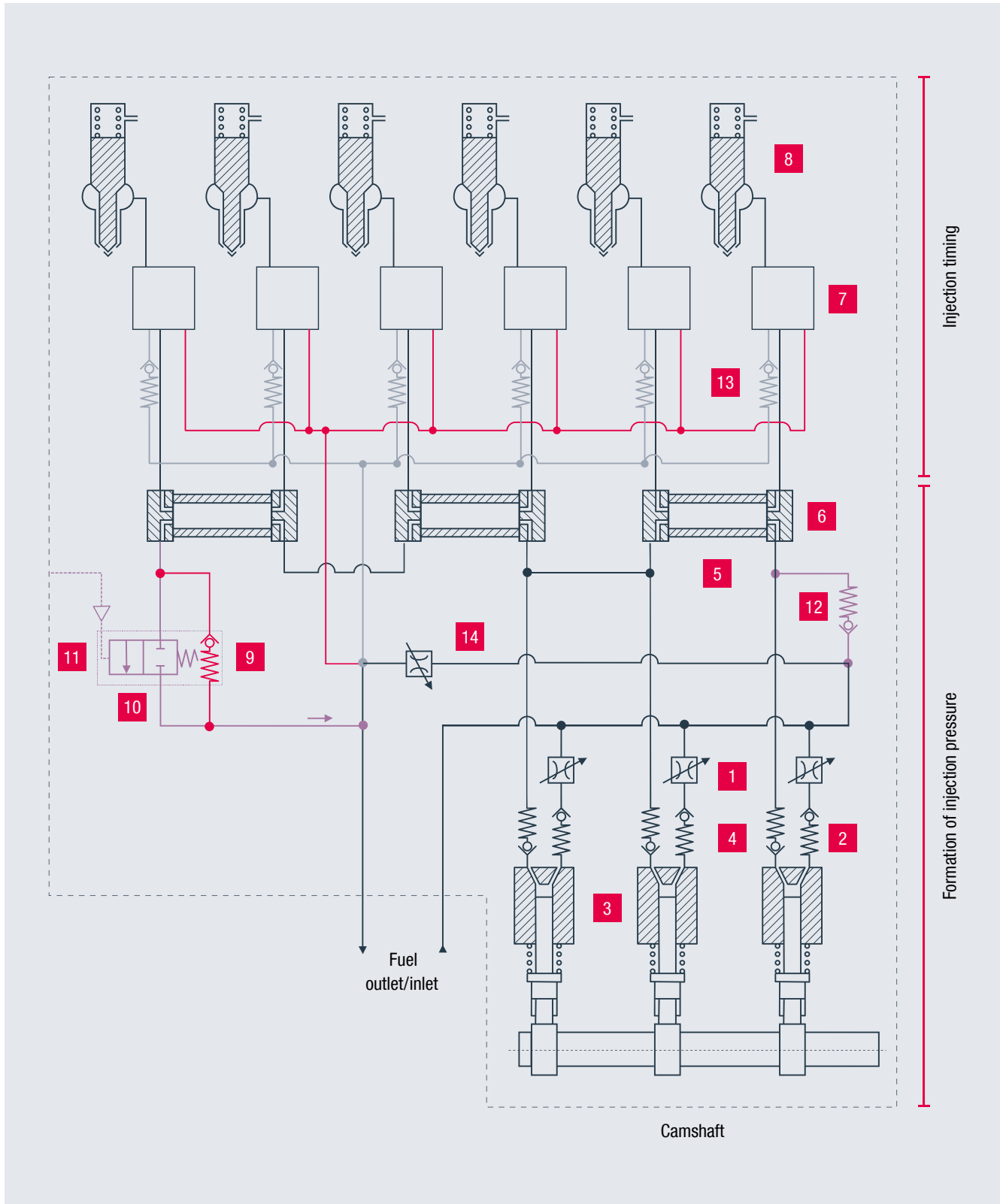


Fig. 3: CR injection system – general layout and functionality

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, the fuel supply is fed through electromagnetically 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 delivery valves **4**.

The rail units **5**, which function as a pressure and volume accumulator for fuel, consist of a high-strength tube sealed 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 injection valves **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. The required amount of fuel 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, on the basis of 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.

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 injection valve. The flow limiter consists of a spring-loaded piston which carries out one stroke for each injection, whereby the piston stroke is proportional to the injected fuel quantity. The piston then returns to its original position. However, should the injection quality exceed a specific limit value, the piston will be pressed against a sealing seat at the outlet side at the end of the stroke and will thus prevent permanent injection at the injection valve.

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 injection valve.

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).

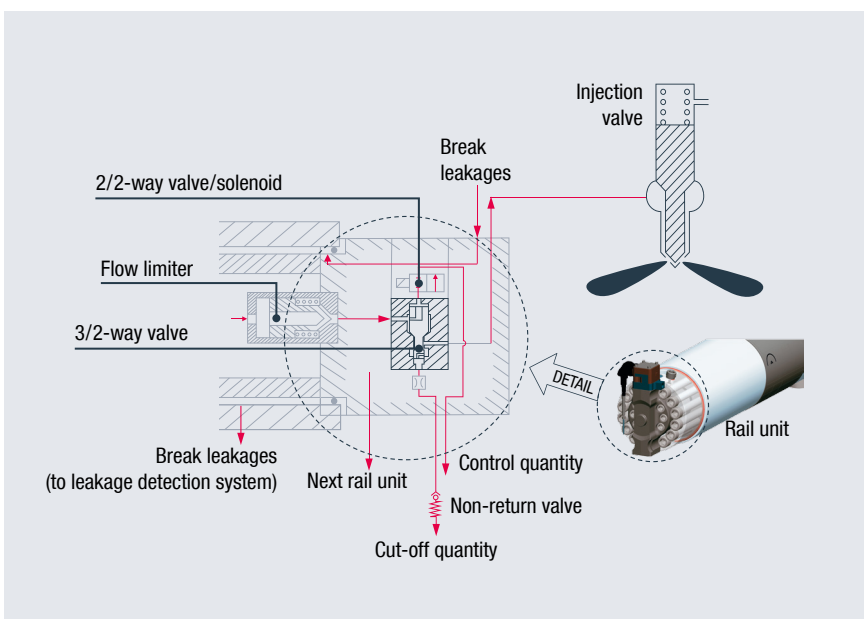


Fig. 4: Control valve and integrated components

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 pre-heated 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 pressure-control 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 (rail units 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 (LDS), enabling the rapid and specific detection of any leaks that may occur.

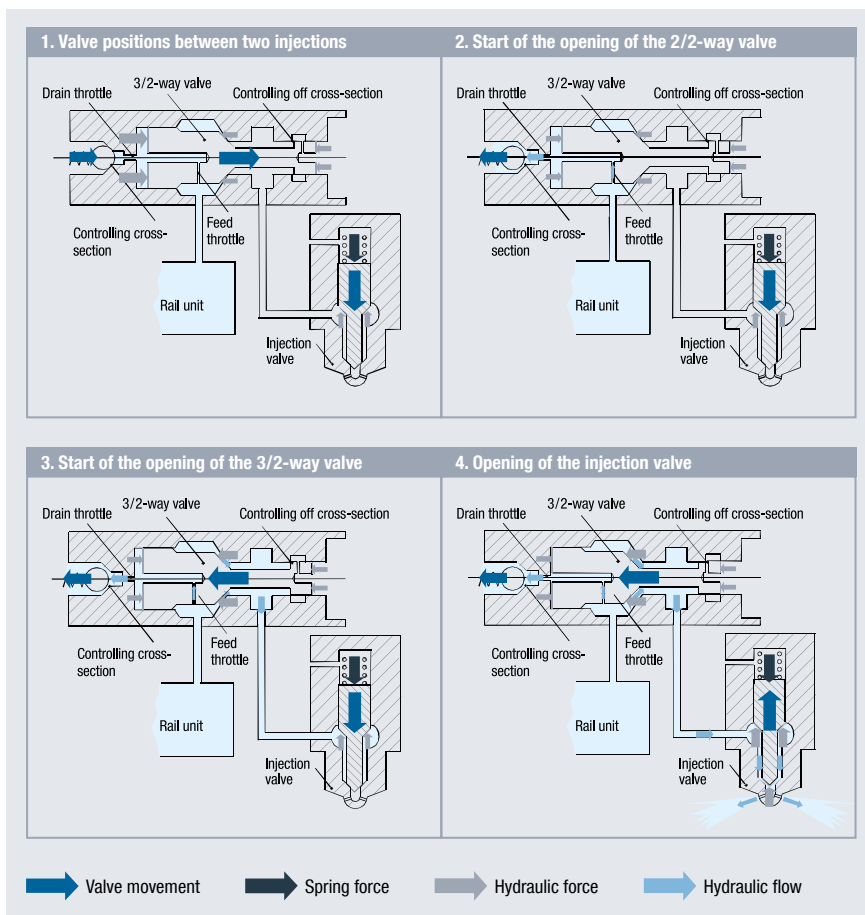


Fig. 5: Positions of control valve during injection

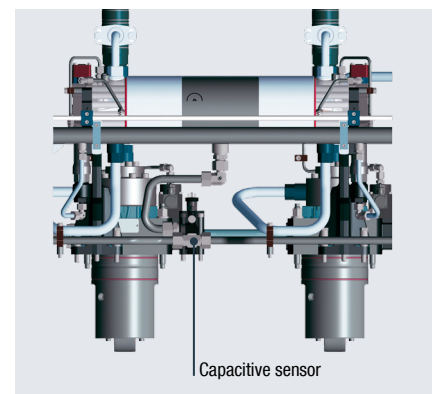


Fig. 6: Leakage detection system (LDS) – capacitive sensors

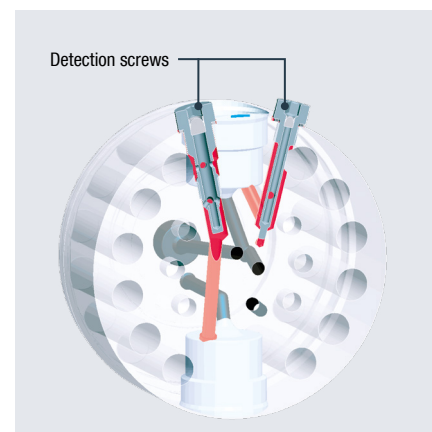


Fig. 7: LDS – detection screws

Advantages

Decisive criteria for operators

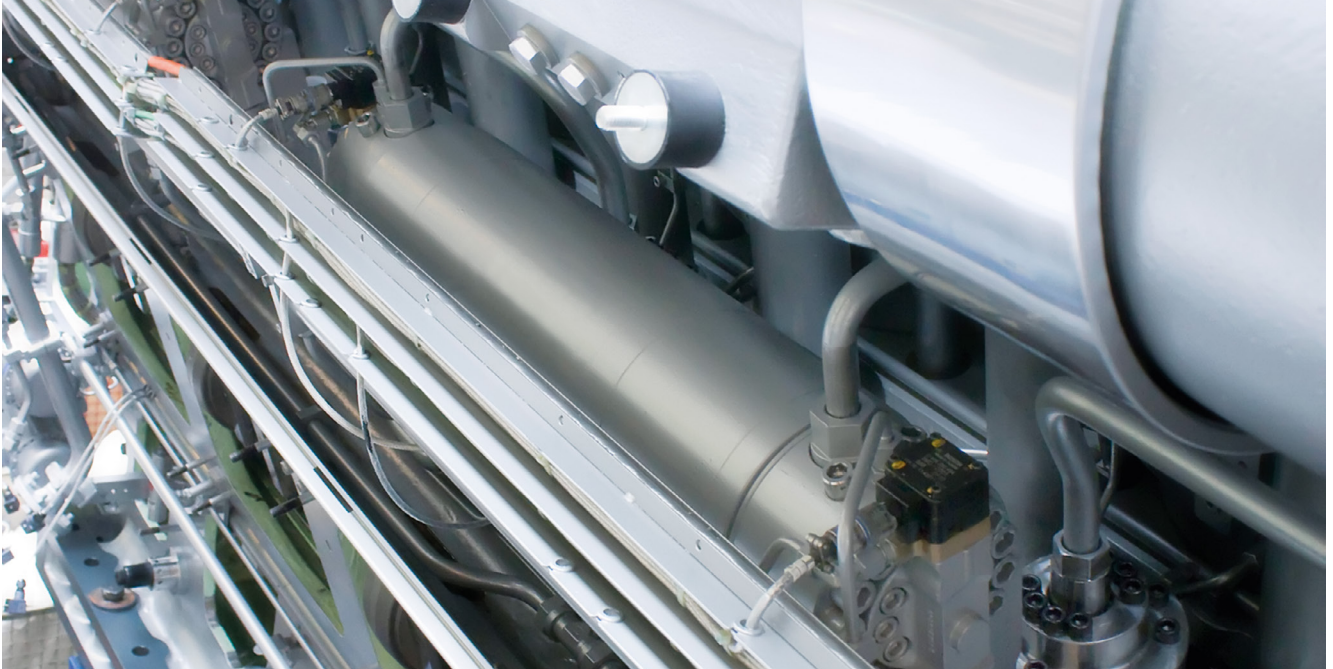


Fig. 8: Common rail system MAN V32/44CR

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 injection valves are used and control 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 valves. The use of the separate 3/2-way valves ensures

that the injection valves 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 all marine applications and the MAN 32/44CR is also released for stationary installations.

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 prevents pressure waves in the high-pressure pipes between the rail unit and the injection valve – 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, have the best potential to meet more stringent emission regulations that may be imposed in future with best possible fuel consumption. The design ensures that smoke emissions stay below the visibility limit even in cases of extreme low load.

Irrespective of the application (marine or power), the life cycle costs of a CR engine are comparable to those of a conventional system.

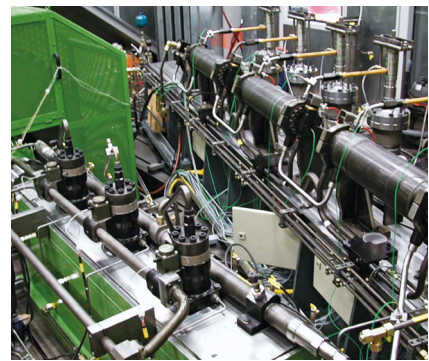
Safety Concept

Established method, smart features

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 carried out 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 integrated into the system, 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:

- **Injection valves 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 limiter (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**
Emergency operation is possible should one pump fail.
- **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.



Test rig installation of the complete CR system



Stena Hollandica, MAN 48/60CR engines



Bartolomeu Dias, MAN 48/60CR engines

Electronics

Fully embedded into SaCoS_{one}

The challenge for electronics was to design a simple and redundant CR system for single-engine main-propulsion applications. The result of this research was a flexible and reliable CR solution, which has meanwhile been extensively proven in practice.

For single-engine main-propulsion systems, classification organizations require a fully 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 operate the control 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.

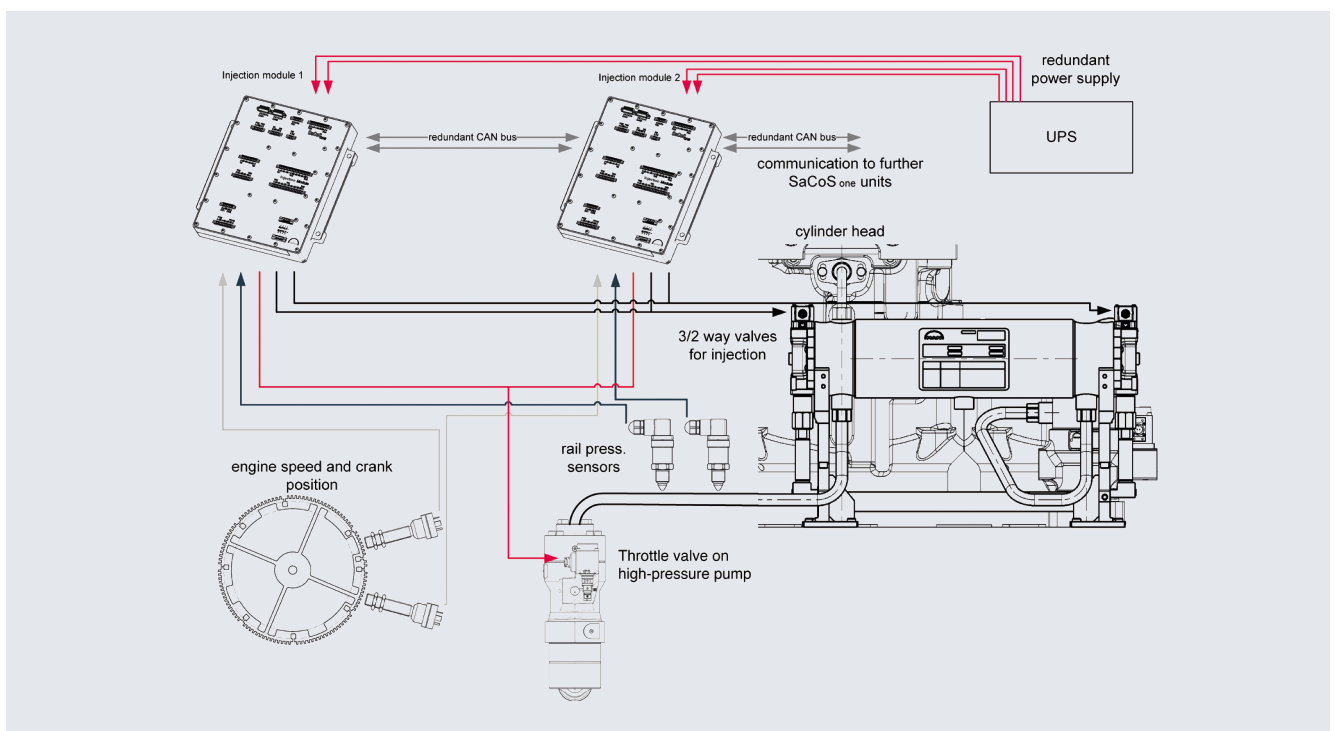


Fig. 9: Redundancy of electronic control system

Development Process

Design, simulation, and testing

The complete development process ensures the market launch of a new product with a high level of maturity, so a well-proven product with low technical risk will be available from start of series production. With continuous development after series release, experience from the field is taken into account.

Fig. 10 gives a general impression of the development process which the new MAN Diesel & Turbo product needs to go through. Some important stages of the development of the CR system are described below.

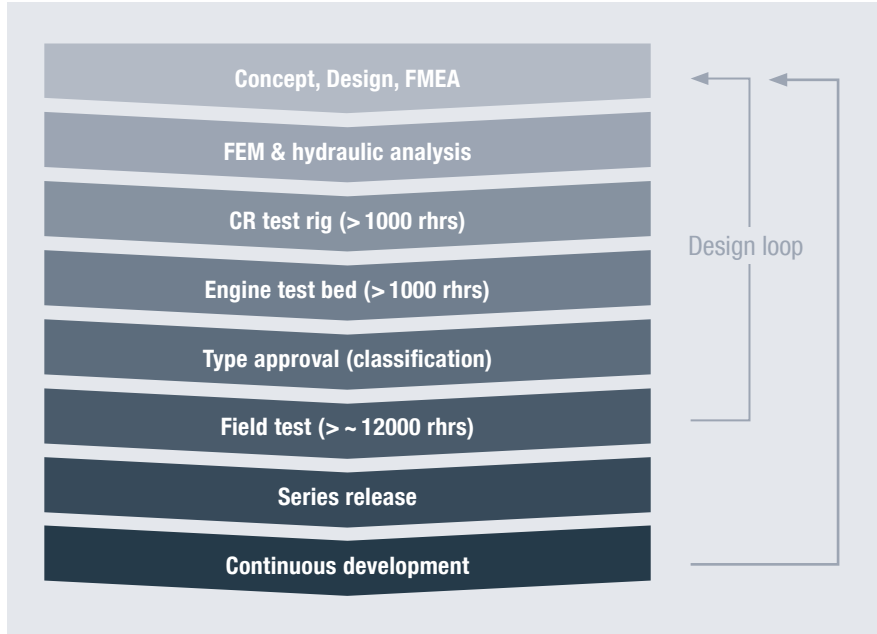


Fig. 10: Development process

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.

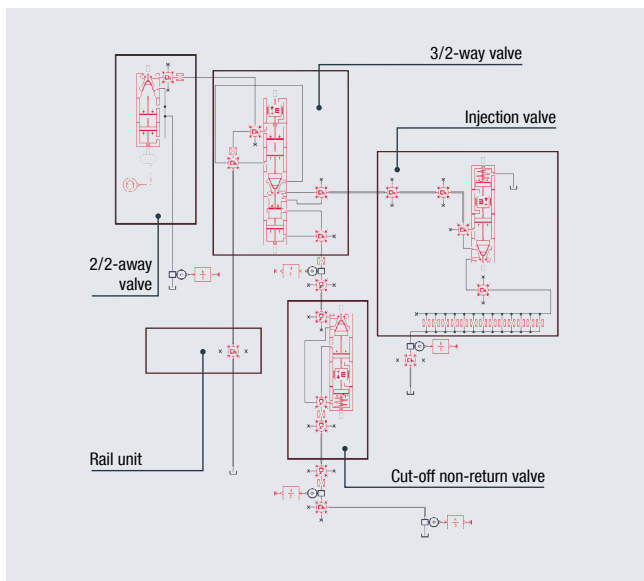


Fig. 11: Simulation model for one-cylinder unit

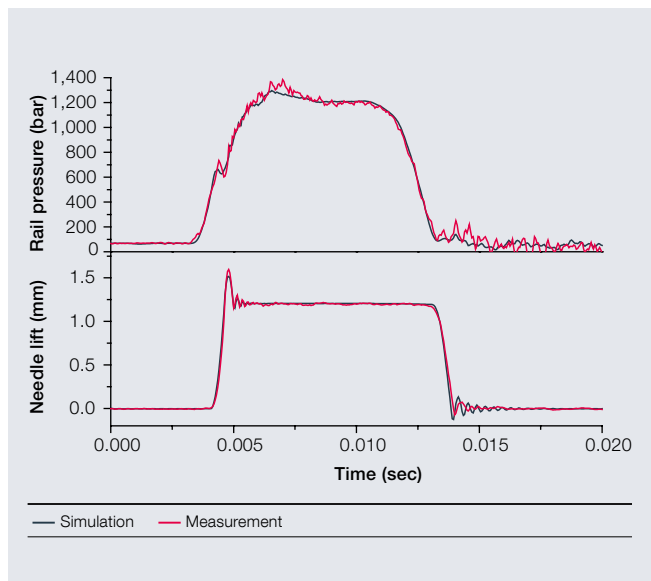


Fig. 12: Comparison of simulation and measurement

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 uses test rigs where the hydraulic optimization and endurance testing of the CR injection systems has been carried out under almost realistic conditions. These test rigs are characterized by the following main features:

- Possible installation of complete CR systems for up to 10 cylinders;
- 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. However, 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. 13 shows one of these test rigs with the MAN Bore 32 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 are 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.

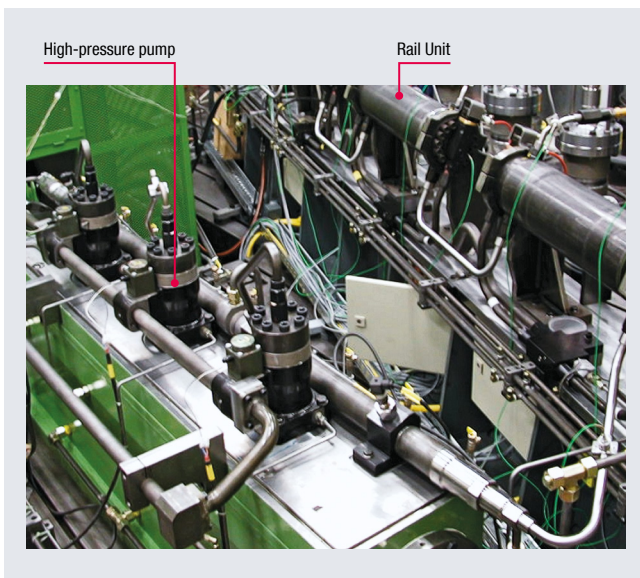


Fig. 13: Test rig installation of the complete CR system

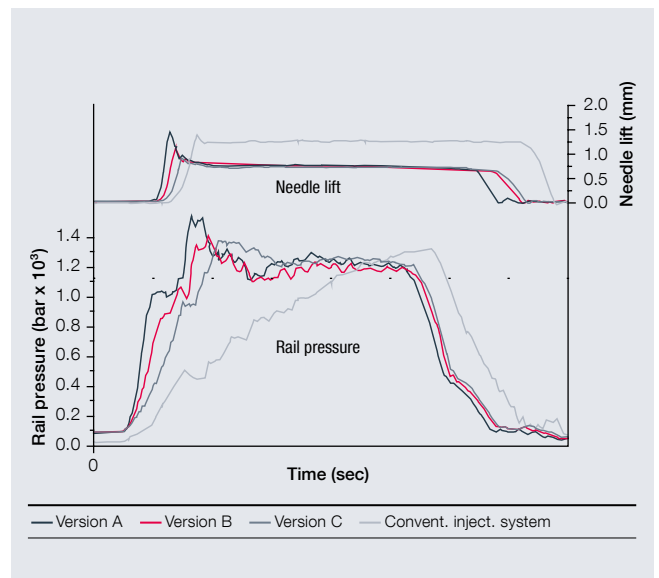


Fig. 14: Matching of the rate of injection

Continuous Development

Driving competitiveness

The aim of continuous development is to improve the reliability and lifetime of CR components in order to achieve the best possible performance. Based on our field experience since 2001, new features have been developed and validated for every single CR component.

To prevent damage to the CR components by particles, an additional 10µm automatic filter needs to be installed in the booster circuit of the HFO fuel oil supply system upstream from the engine. This filter reduces wear and stabilizes the lifetime of CR components.



Fig. 15: Additional 10µm automatic filter in booster circuit of HFO fuel oil supply system

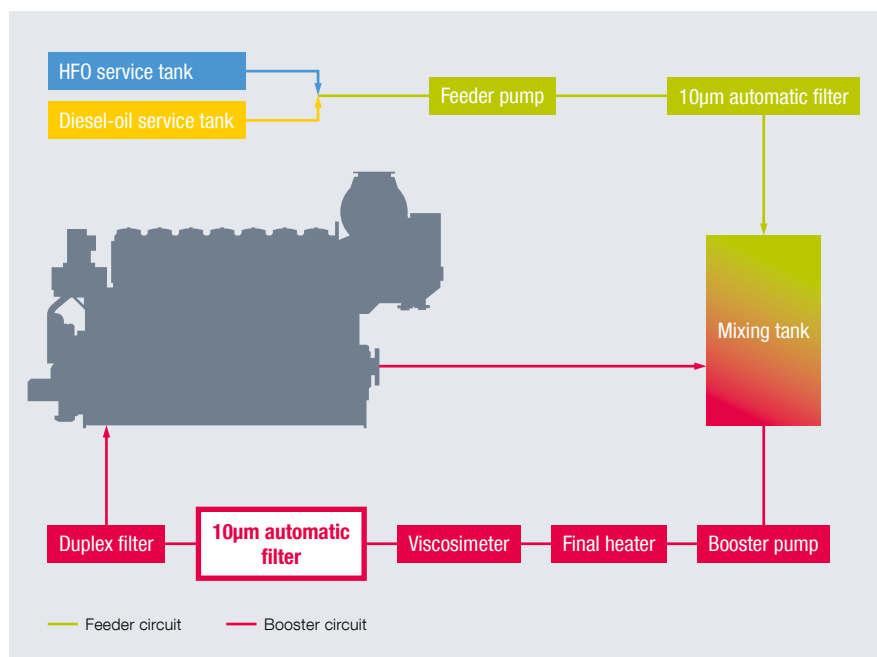


Fig. 16: Fuel oil supply system (simplified)

Adaption to a New Engine

The ease of parametrization

ECOMAP

ECOMAP is a new innovative feature for our fully electronically controlled engines. The unrivalled flexibility of the CR-System permits the engine to be programmed to run along different SFOC / power characteristics, each of them having its efficiency optimum at different load points. This, without the need to modify anything in the engine's hardware. Hence, the customer is provided with the potential to realize better fuel economy with changing operating profiles of his installation. Especially, on vessels with multi-engine installations, the combination of such CR engines with an intelligent power management system permits to exploit the flexibility potential of such engines to the best permissible level.

The ECOMAP concept has received "Approval in Principle" (AIP) from several major classification societies. For details on the operating boundary conditions and map selection principles that need to be respected, please contact MAN Diesel & Turbo.

Boost injection

A special, patented feature for common rail engines, called boost injection, was introduced in parallel with the release of the IMO Tier II engines.

SaCoS_{one} is able to detect a request for engine load increase at an early stage and to improve the load response of the engine significantly by activation of a so-called boost injection in the common rail control.

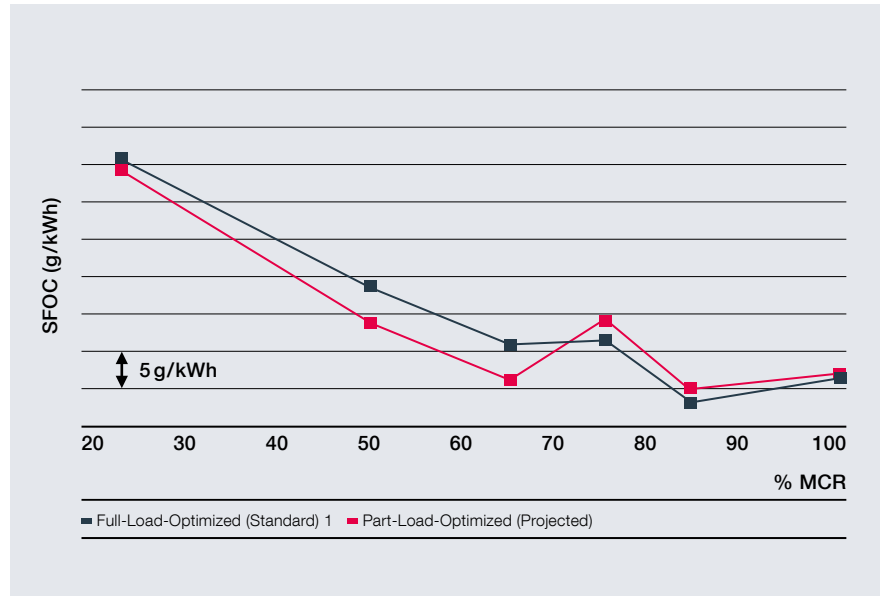


Fig. 17: ECOMAP – example of a set of maps with different SFOC / power characteristics

Operation and Maintenance

Supported by MAN PrimeServ

The operation and maintenance of the CR system are supported by:

1. Updated working cards

- implement the design updates of the continuous development
- improve the assessment of the condition of CR components
- integrate the handling and testing procedures based on field experience

2. Working tools

Special tools have been created for the replacement, assembly and testing of the CR components. With the combination of working cards and tools, the customer is able to do the necessary work on the CR system without MAN service personnel.

3. Training

In the PrimeServ Academies, MAN offers training courses (basic and advanced levels) for personnel working with the CR system. During training, the customer learns all about operation and maintenance with the purpose of gaining confidence in handling the CR system. For a realistic approach, practical training is carried out on a full functional test model of the CR system.

4. Guided troubleshooting tool

The guided troubleshooting tool is a fault detection tool that assists the customer in CR troubleshooting. This tool provides easy-to-use graphically designed fault detection by means of multiple choice questions and is self-explanatory. The fault detection tool represents the full MAN experience concerning CR troubleshooting from development, field test, system automation and service. The alarm codes and additional indications are implemented.

5. MAN PrimeServ Online Service

Engines which are equipped with the PrimeServ Online Service package can automatically and continuously be monitored. MAN PrimeServ experts analyze the engine data and provide valuable advice for maintenance, operation and repairs of the engine. At the event of irregularities the customer will be informed immediately to avoid downtimes. Furthermore a non-efficient operation mode can be adjusted earlier. If necessary the experts can support the customer in troubleshooting via remote access.

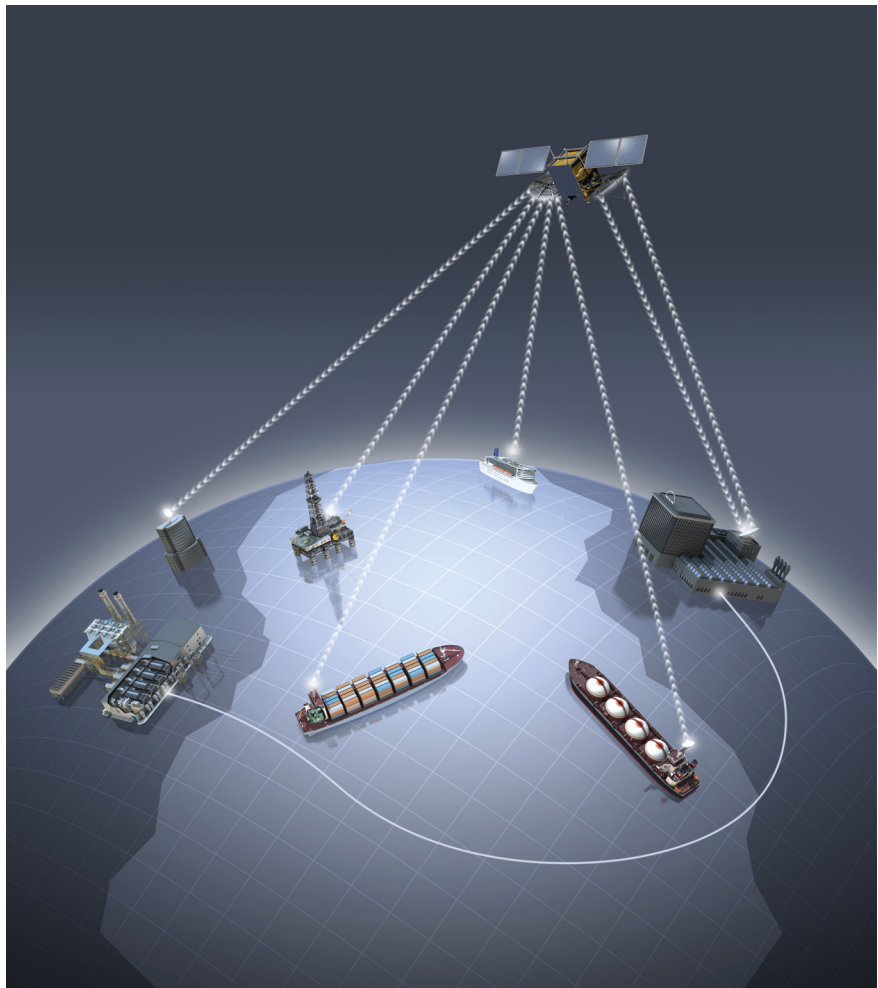


Fig. 18: MAN Diesel & Turbo's Online Service in principle

Conclusion

Significance of a broad installed base

The advantage of the CR injection system, through its freely adjustable injection parameters, has been comprehensively presented in this paper. The design of the CR system with its extensive 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 programs and the corresponding component development, a remarkable level of maturity has been achieved and confirmed by field experience of different applications totaling approximately 2,110,000 operating hours (01/2015).

As per Status of 01/2015, more than 180 engines are in commercial operation, thereof more than 80 MAN 32/44CR and more than 90 MAN 48/60CR engines.

Excerpt of engine references with CR Technology	Engine type
A.P. Moeller - Maersk A/S, Denmark, Charlotte Maersk	1x 7L32/40CR
John T. Essberger GmbH & Co. KG, Germany, DAL Kalahari	1x 6L32/40CR
Norwegian Curise Line, USA, Norwegian Jewel	1x 12V48/60CR
Scandlines Danmark A/S, Denmark, Prinsesse Benedikte	1x 6L32/44CR
Harren & Partner Schifffahrts GmbH, Germany, Combi Dock III	2x 8L32/44CR
Hermann Buss GmbH & Cie KG, Germany, CSAV Rio de Janeiro	1x 8L32/40CR
Pesqueria Vasco Montanesa S.A., Spain, Playa de Azkorri	1x 8L32/44CR
Orophil Shipmanagement Corp, Philippines, Yang A	1x 9L32/44CR
V.Ships Ltd., Cyprus, OIG Giant II	2x 8L32/44CR
Stena North Sea Ltd., United Kingdom, Stena Hollandica	2x 8L48/60CR 2x 6L48/60CR
Hermann Buss GmbH & Cie KG, Germany, CSAV Brasilia	1x 8L32/40CR
Stena Rederi AB, Sweden, Stena Britannica	2x 8L48/60CR 2x 6L48/60CR
Columbus Shipmanagement GmbH, Germany, Paranagua Express	2x 9L32/40CR
Disney Cruise Line, USA, Disney Dream	2x 14V48/60CR 3x 12V48/60CR
P&O Ferries Limited, United Kingdom, Spirit of Britain	4x 7L48/60CR
Naviera Armas SA, Canary Islands, Volcan del Teide	4x 7L48/60CR
Hamburg-Süd, Germany, Santa Catarina	2x 9L32/40CR
Nova Star Cruises Ltd., Canada, Nova Star	4x 10L32/44CR
Naviera Armas SA, Canary Islands, Volcan de Tinamar	4x 7L48/60CR
Celebrity Cruises Inc., USA, Celebrity Silhouette	4x 14V48/60CR
Columbus Shipmanagement GmbH, Germany, Santa Rosa	2x 9L32/40CR
China Yantai Salvage, China, De Qi	2x 9L32/44CR
P&O Ferries Limited, United Kingdom, Spirit of France	4x 7L48/60CR
Seatruck Ferries Limited, United Kingdom, Seatruck Power	2x 7L48/60CR
Disney Cruise Line, USA, Disney Fantasy	2x 14V48/60CR 3x 12V48/60CR
Northern Marine Management Limited, United Kingdom, Stena Performer	2x 7L48/60CR
Yangtze Estuary Waterway, China, Chang Jiang Kou 01	2x 7L48/60CR
Celebrity Cruise Lines, Inc., USA, Celebrity Reflection	2x 14V48/60CR 2x 12V48/60CR
Norwegian Cruise Line, USA, Norwegian Breakaway	2x 14V48/60CR 2x 12V48/60CR
Dredging Corp. of India Ltd., India, DCI Dredge XX	2x 8L32/44CR
Huta Marine Works Ltd., Saudi Arabia, Al Bahar	2x 9L48/60CR
Allseas Engineering B.V., Netherlands, Pioneering Spirit	8x 20V32/44CR 1x 9L32/44CR



Combi Dock III, MAN 32/44CR engines

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