New HFO Common Rail System for Medium-speed Diesel Engines

Introduction

The Diesel engine is and will, also in the future, be one of the most economic possibilities for converting chemical fuel energy into mechanical energy. This applies both to the automotive range and the propulsion of large vessels or power plant generators. In order to make use of the Diesel engine's economy also in the future, it will, with regard to environmental aspects, become more and more important to prevent visible and, in particular, pollutant components from being contained in the exhaust gas. Already at an early stage, MAN B&W attached great importance to this requirement , carried out corresponding development work and launched exhaust gas optimised engines [1]. Following the philosophy of environment-friendly engine development, CR will, as a next step, be introduced for MAN B&W engines.

Due to an electronic control system's degrees of freedom, CR now offers engine developers a considerably wider spectrum of injection curve design, i.e. total combustion will prevent harmful constituents from being produced in the exhaust gas. When taking all possibilities of combustion process design into consideration, one must be fully aware of the fact that the injection system and, particularly, CR, is one of the most important components of an engine and that the engine is no longer functional if the injection system fails. The development of CR focused, in addition to functionality and representation of the degrees of freedom, particularly on its reliability.

In order to take a decisive development step forward in engine technology with the help of CR, relevant development targets were precisely fixed. Optimum combustion requires, in addition to the degrees of freedom, i.e. injection start, injection quantity and injection pressure, the realisation of pilot and post injection. As the already existing engine series is to be equipped with CR, the system had to be designed in order to permit mounting on the engine without constructive interventions. Due to this requirement, the mechatronic components could not be accommodated in the cylinder head. As our engines are heavy fuel oil compatible, the fuel-relevant conditions, such as abrasive and corrosive constituents and high temperature, must be fulfilled with the utmost reliability and the usual maintenance intervals.

With regard to the success of a new development, it is of fundamental importance that the courses are already correctly set during the development phase. For this reason, the different system possibilities, including one and two-circuit systems, were tested in pre-studies on an L 16/24 engine [1]. In this connection, it was very soon evident that the final development solution could only be a one-circuit system as it proved that the requirement for a variable design of the injection curve can, system-dependent, not be achieved with a two-circuit system.

Pre-studies

For safeguarding the long term technology planning of MAN B&W 's CR concept different pre-studies were done. At the experimental tests with the single circuit system investigations were done with regard to the materials and the necessary production methods of the control valves. Furthermore the CR system for basic developments at the engine L16/24 was modified with an separate control valve at the rail to pre-test a hydraulic concept as it is described below, where no mechatronic components are installed in the cylinder head.

The tests showed also at a high engine speed of 1200 rpm very good engine performance.

Furthermore extensive simulation were done to compare the hydraulic behaviour of different fuel injection systems. At figure 1 a conventional injection system is compared to two different kind of CR systems. With the lift controlled system the rail pressure continuously is located at the needle seat, with the advantage of fast response behaviour. Such kind of systems are mainly applied at high speed Diesel engines in the truck or automotive market at engine speeds up to 5000 rpm. At another variant of CR systems the needle lift is controlled by pressure increase like at a conventional system. The pressure exists only during the injection period at the needle seat, which is an important safety factor for the application at medium speed diesel engines.

With further matching of the geometry of the throttles inside the control and injection valve it is possible to adjust also a very high pressure inside the sac hole of the injection nozzle (figure 2). This potential of the pressure controlled CR system gives the freedom for best matching results at engine operation values.

System description

The MAN B&W CR injection system is designed for the use of heavy fuel oil with viscosities of up to 700 cSt at 50°C. These fuels have to be preheated to a temperature of up to 150°C in order to reach a suitable injection viscosity. Another problem with heavy fuel in electronic controlled injection systems is the high content of abrasive particles and aggressive components in these fuels. All parts that control the injection therefore have to work under the conditions of high temperature, high viscosity, highly abrasive particles and aggressive components.

For large bore diesel engines the application of a single pressure accumulator along the full length of the engine is problematic due to the following reasons:

- For heavy fuel operated engines there are big differences in the possible fuel temperature from appr. 25°C up to 150°C. This high temperature differences will result in big differences of rail length caused by thermal expansion.
- A long rail always requires radial drillings for the connection to each cylinder. Caused by these drillings very high stresses are unavoidable. The problems and the countermeassures with these stresses increase with the increased inner diameter of the rail necessary for large diesel engines.
- In the case with reduced accumulator volume it would hardly be possible to reach identical injection ratios for all engine cylinders and excessive pressure fluctuations in the system could not be ruled out.
- The possibility to build large bore diesel engines with different cylinder numbers, would lead to a special rail for each cylinder number.
- Also connection to a pressure accumulator of excessive length at one place only via the high-pressure pump will result in deviations of the injection quality.

It was therefore reasonable to divide the accumulator in several units with a suitable volume and to divide the supply to two high-pressure pumps at least for an 6 cylinder engine.

A further advantage of this segmentation is the increased flexibility depending on the engine cylinder number, which is also an interesting factor in the case of retrofit application. The more compact building units ensure

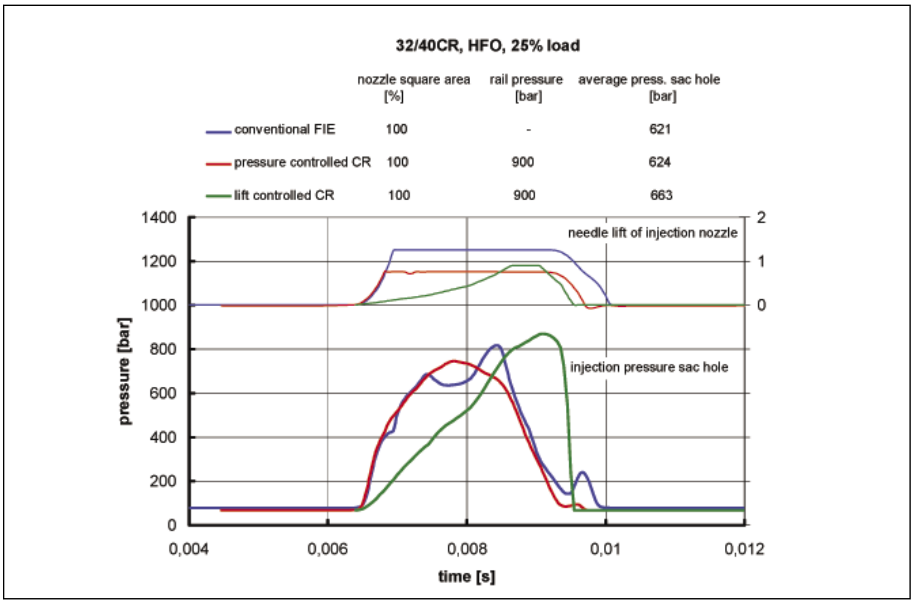

Fig. 1: Comparison of different fuel injection systems

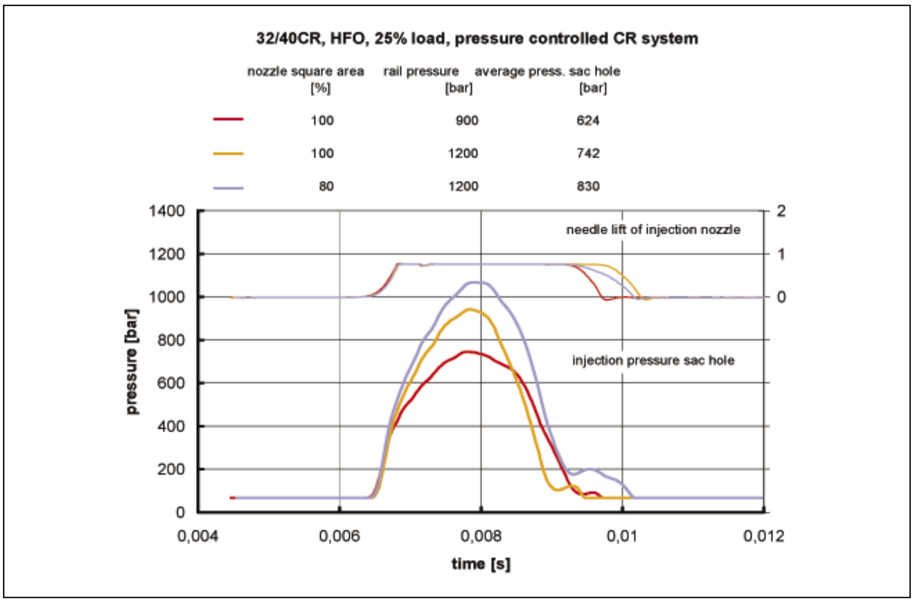

Fig. 2: Matching of sac hole pressure at part load

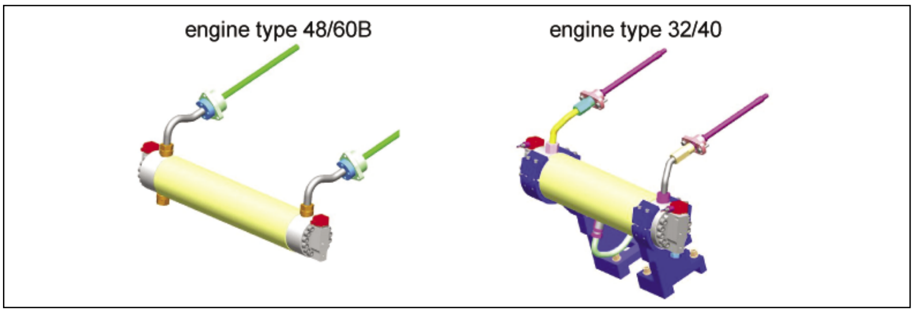

Fig. 3: Modular rail unit with integrated control valves for different engine types

an improved utilisation of the available space on the engine, which results in advantages during assembly and spare parts storing.

Based on the idea of the segmented rail MAN B&W developed a modular system to cover several engine types. Figure 3 shows the rail units for two different engine types 32/40 CR and 48/60B CR. The rail cover including the control valves and further components are very similar or even equal in its geometry.

Layout and functionality

Figure 4 shows the hydraulic scheme of the patented heavy fuel oil CR injection system for the MAN B&W 32/40 engine.

A low-pressure fuel pump (1) delivers the fuel via electromagnetic activated throttle valves (2) and suction valves (3) to the high-pressure pumps (4), which force the fuel into the pump accumulator (6) by means of pressure valves (5).

Each pump is connected to the pump accumulator (6) which samples the fuel delivered by the pumps. From the pump accumulator the fuel flow goes to the accumulator units (7), which are connected in series to the so called common rail. The accumulator units consist of a compact tube, which is on both front sides equipped with an accumulator cover, which is tightly fixed by a number of cylinder screws. The accumulator covers contain radial connections for the high-pressure pipes leading to the injectors (9) as well as for the connecting pipe to the next accumulator unit. The tube itself doesn't contain any radial drillings and is therefore easy to produce and very resistant to high fuel pressures.

Drive of the high-pressure pumps is, as known, effected by cams arranged on the engine camshaft, which are designed as three-lobe-cams in order to increase and equalise delivery. On account of the interposition of the pump accumulator, which is supplied by two to four high-pressure pumps, the dynamic pressure waves can be kept very low. The delivery quantity of the high-pressure pumps is calculated by the electronic control system on the basis of an evaluation of the fuel pressure indicated by the rail pressure sensor and the corresponding operation condition of the engine. The electro-magnetically activated throttle valve (2) in the low-pressure pipe will now suitably meter the fuel quantity supplied to the high-pressure pumps. Each accumulator cover (figure 5) contains components and connections, which serve for fuel supply and transmission as well as for fuel injection timing control of the injectors. On its way from the accumulator unit interior to the 3/2-way valve and then to the injector, the fuel is passed through a flow limiter. A spring-loaded piston in this component carries out a stroke for each injection, which is proportional to the injection quantity and returns in its original position in the time between the injections. Should the injection quantity exceed however a specified

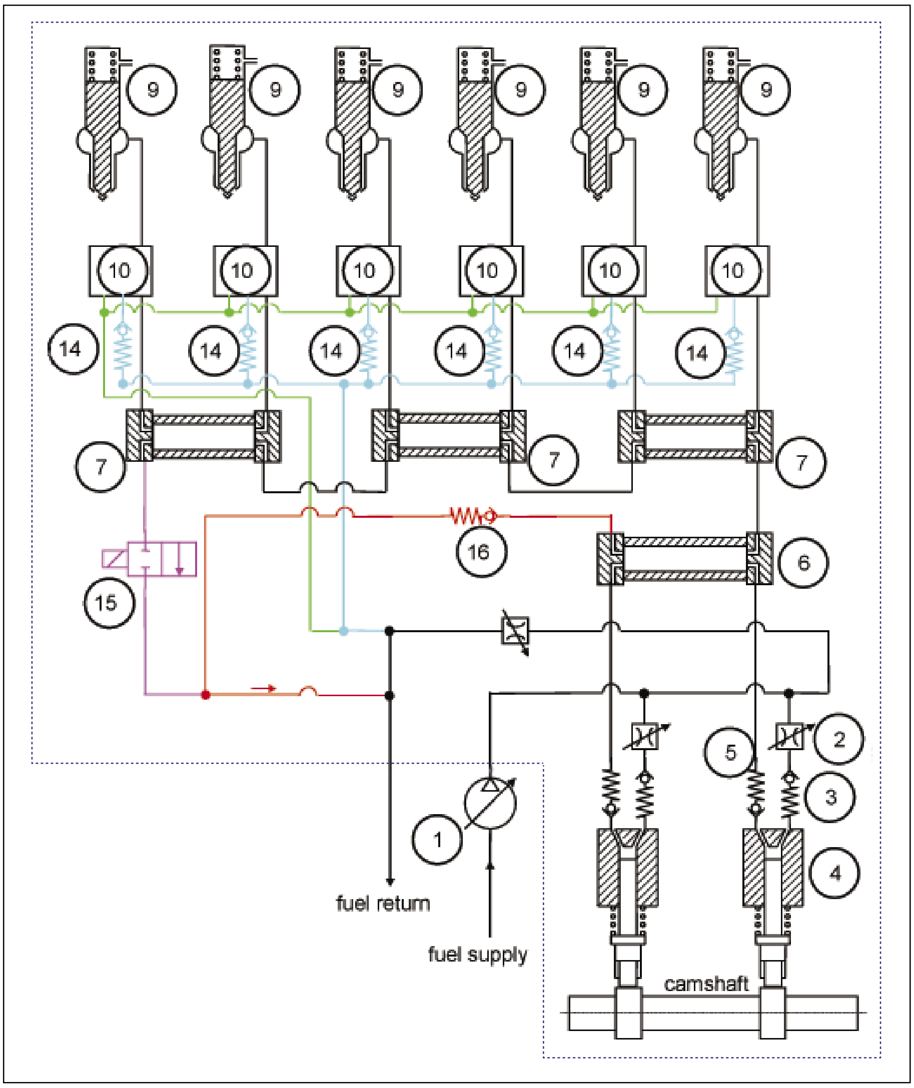

Fig. 4: General layout and functionality

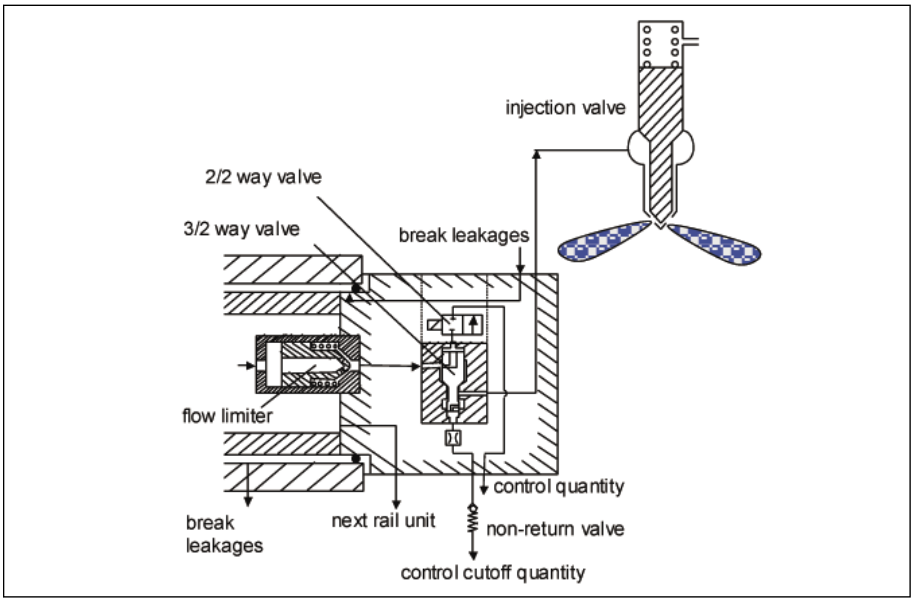

Fig. 5: Rail cover and integrated components

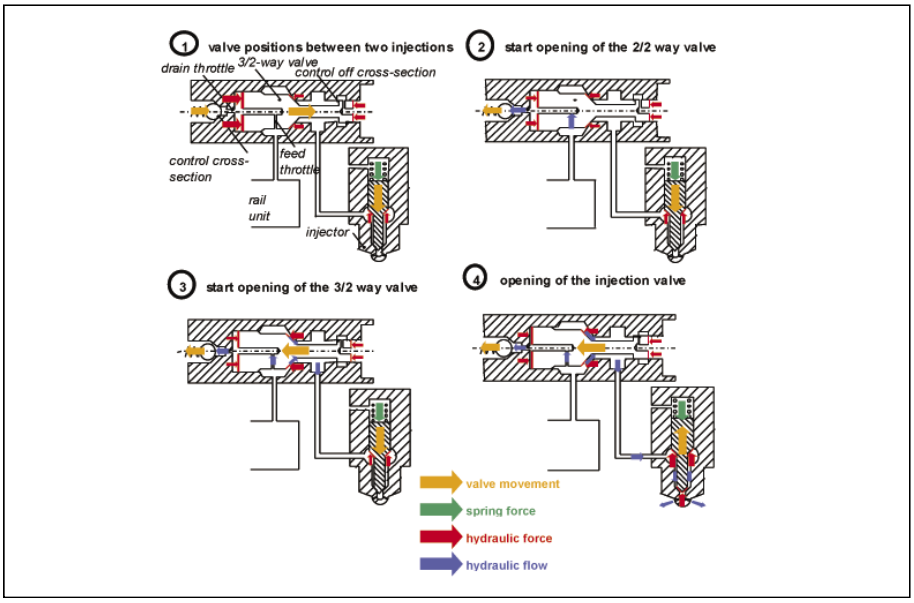

Fig. 6: Positions of control valve during injection

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.

The 3/2-way valve (10) inside the accumulator cover is electro magnetically activated by the control system and permits the high-pressure fuel to be supplied from the accumulator unit, via the flow limiter, to the injector. As shown in figure 6 it is operated and controlled without any additional servo fluid by an additional 2/2-way valve. Therefore it is possible to be actuated much faster than an servo oil controlled valve. By a repeated actuation of the 2/2-way valve during the injection process, pre- and post-injection can be obtained. The general concept of the pressure controlled CR system are described in [2]. The functional leakages arising during the control process of the 3/2-way valve will be discharged via separate pipes back into the low pressure system. To ensure that back flow of fuel from the low pressure system into the cylinder is impossible, for instance in the case of a seized needle, in each of these pipes a non-return valve is installed.

A safety valve (16) is arranged at the pump accumulator (6), which opens if a specified pressure is exceeded and protects the high-pressure system against overload.

The high-pressure pipes and accumulator units are designed with double walls in order to prevent fuel from penetrating to the outside in the case of leakage or break of connections. In this case, the operating personnel will be warned by means of the float lever switch.

The fuel supply system is provided with a heavy fuel oil preheating system. For start-up of the cold engine with heavy fuel oil, the high-pressure part of the injection system is heated by means of circulating hot heavy fuel oil. For this purpose, the flushing valve (15), located at the end of the last accumulator unit connected in series, will be opened pneumatically. The heavy fuel oil will now be pumped back into the fuel tank from the low-pressure fuel pump (1), through the throttle valves (2) and the suction valves (3), through the pump chamber of the high-pressure pumps (4), via the pump accumulator (6), through the accumulator units (7) and the open scavenging valve (15). After sufficient heating of the injection system, the scavenging valve is closed and the engine started.

The scavenging valve serves also for pressure relief of the high-pressure part of the injection system in the case of emergency stop, maintenance, repair work and regular engine stop.

The supply of high-pressure fuel into the pumped accumulator through two ore more high-pressure pumps offers the advantage that part-load or lean home operation is still possible, if one of the pumps fails.

The assembly of the CR system at the engine is shown in figure 7.

Advantages of the MAN B&W CR system

By the use of the separate 3/2-way valve there is only pressure at the injection valve during injection. This ensures the high safety necessary for ship application because uncontrolled injection is avoided even if the control valve or the injection valve is leaking.

By locating the 3/2-way valve in the accumulator cover and using a conventional pressure controlled injector, this CR system is easy to use for actual engine designs with their very limited space in the cylinder head. Also the retrofit of conventional fuel injection equipment to CR at engines in service is considerably easier.

Pressure waves, which occur in the high-pressure pipes of other CR systems between rail and injector, especially at the end of injection, will thus be avoided. This reduces the load of the components which are exposed to pressure.

The modular division of the units and the assignment of the individual engine cylinders reduces the expenditure of material and assembly work and permits short pipe lengths to the injectors.

The concept enables within the hydraulic functionality the features pre- and post-injection (see also figure 13). Furthermore a shaping of the injection rate is possible to adjust the penetration of the fuel jet during the mixture formation (see also figure 12). At future upgrade the concept has also the potential for a transient shaping of the injection rate during the injection period. By matching the combustion with this features the engines equipped with the CR system have the potential to fulfil also future emission limits.

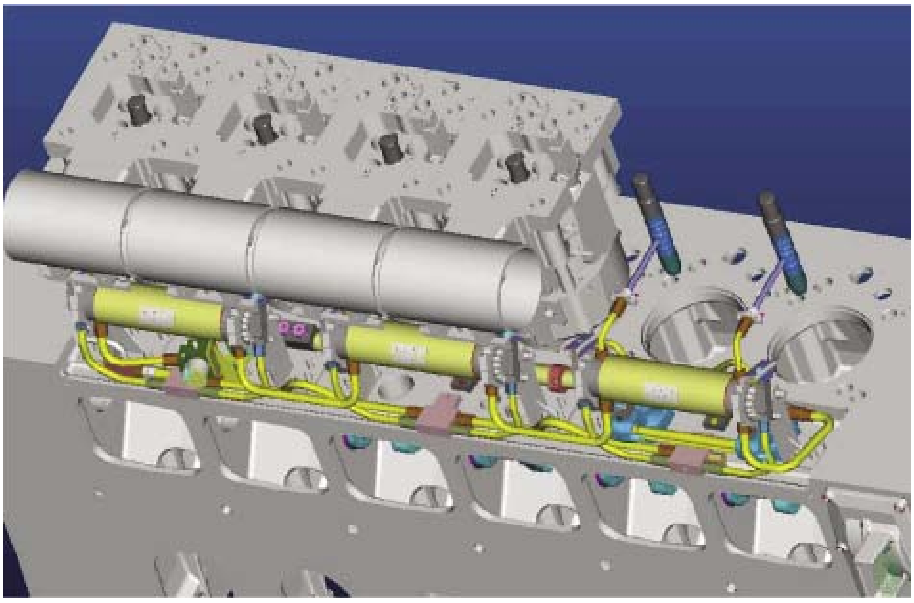

Fig. 7: Assembly of CR system at a 6 cylinder engine

Safety concept

For all applications of medium speed engines but especially for the use of these engines on board of ships, safety is one of the most important items for design and operation.
To ensure that all possible failures which are dangerous for the ship are covered by the safety concept of the CR injection system MAN B&W performed an extensive FMEA (Failure Mode and Effect Analysis) for the mechanical/hydraulical part as well as for the electronic part. For instance in the mechanical/hydraulical part of the CR injection system 142 hypothetical possible failures were identified. To avoid any negative effects of these possible failures 154 detection measures and 232 avoiding measures were developed and introduced.

Based on this FMEA the main points of the safety concept for the MAN B&W Common Rail injection system are:

- Injection pressure only during injection at the injection valve → No danger of uncontrolled fuel injection caused by leaking control or injection valves.
- All high pressure pipes, rails and high pressure connections are shielded → No danger of fuel spray through leaking or broken pipes.
- Fuel limiting valves at each cylinder → No danger of uncontrolled injection length.
- Non return valves at each cylinder → Ensure that fuel back flow from the fuel low pressure system to the cylinder is impossible.
- At least two high pressure pumps → Emergency operation possible in the case of a pump failure.
- Safety valve with additional pres-

sure control valve → Emergency operation possible in the case of a rail pressure control failure.
- 2 Rail pressure sensors and 2 speed / TDC pick ups → Continued operation in the case of a sensor or pick up failure.

The investigation showed that by the introduction of the new CR technology the system itself should be kept as simple as possible including the safety features. One main important item for a safe technology concept are the following validation tests out of the FMEA method. For these tests additional test rig facilities were installed.

Electronics

The introduction of CR is a special challenge for the electronics development as there are no possibilities of having a mechanical redundant backup-system available. While the classification societies allow non redundant solutions for multiple engine installations MAN B&W has directed its focus regarding the layout to single engine main propulsion applications. This requires a full "hot" redundant system layout (figure 8).

The two ECU's (electronic control units) are responsible for the solenoid valve control, the high pressure pump control and therefore the speed governing. Each ECU controls half of the engine but is also able to control the complete engine if the other unit fails. In case of a malfunction the system can continue the control with one ECU without interrupting the engine operation and with full functionality by assigning the actuators to the remaining ECU by means of the switch over modules. All necessary sensors, the power supply and all field bus connections are doubled. So a single failure will never lead to an engine stop. The single PLC is only

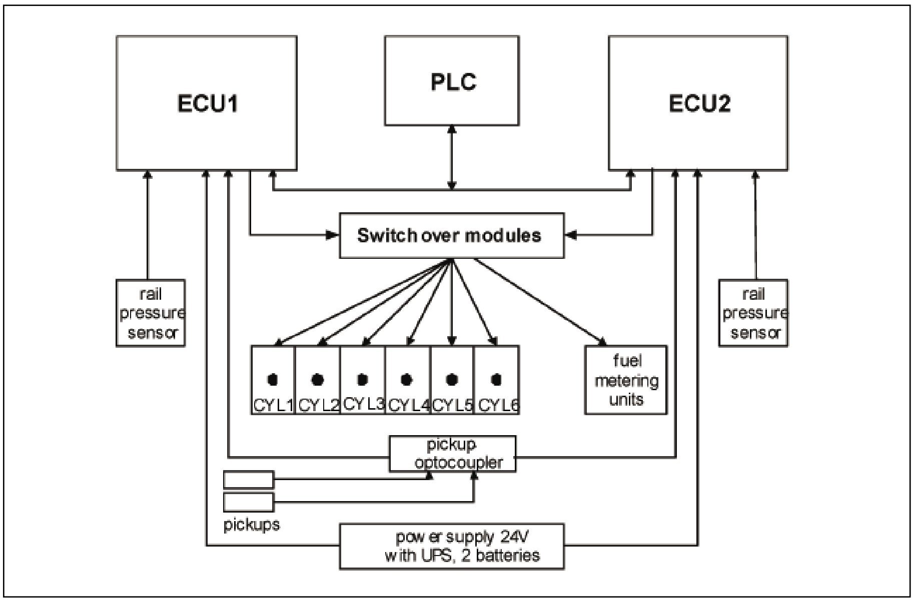

Fig. 8: Redundancy of electronic control system

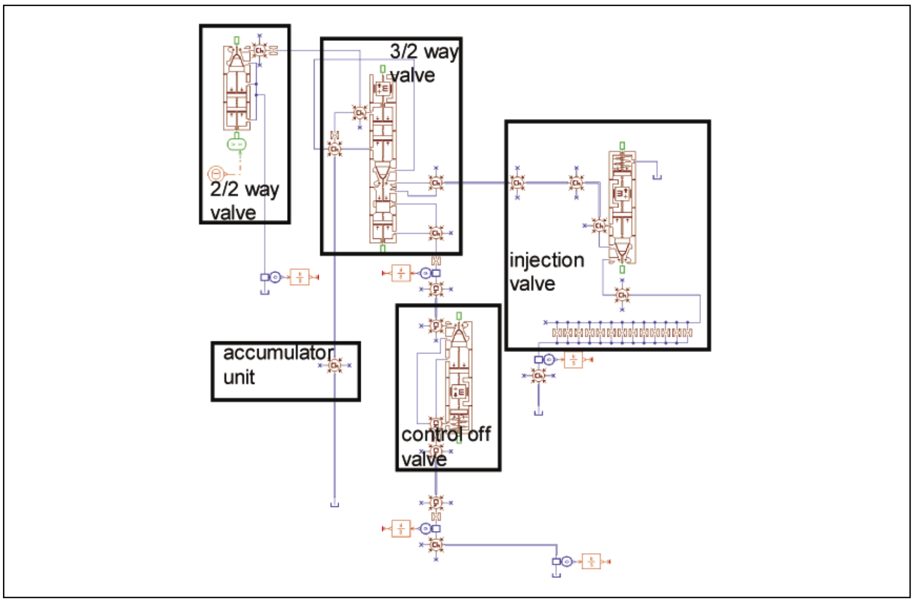

Fig. 9: Simulation model for 1 cylinder unit

responsible for communication with the ship alarm system and for the Man Machine Interface.

For multiple engine applications there exists also a non redundant version of the CR control which improves simplicity and costs.

The CR electronics extend the possibilities of the conventional injection systems by allowing pre- and post-injection and of course by using freely adjustable rail pressure and injection timing. A multitude of characteristic maps and parameters allows to adjust the injection to an optimum for the entire operating range. In the future this will be the heart of an engine management system for a self adapting engine.

Development results

The development of the MAN B&W CR injection system was divided into five main steps:

- Layout and simulation
- Design and FMEA
- Hydraulic optimization and endurance test at injection test rigs
- Test and optimization at the test engine
- Field test on board

Layout and simulation

As already mentioned the development started with intensive studies of the different possibilities to realize a CR injection system. In a very early phase of these studies first simulations were started to evaluate the advantages and disadvantages of these variants. After a preselection the simulation tool was then used to optimize the different parts and to define the frame conditions for the design.

But also after design was started, simulation was a very effective tool to optimize the system already before the first parts were produced.

Figure 9 shows a physical and mathematical model for the simulation of a one cylinder unit including the components between rail segment and injection nozzle. Figure 10 illustrates the comparison between the simulation and the test results to demonstrate the good correlation between simulation and reality.
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 9 cyl. were prepared and verified by measurements.

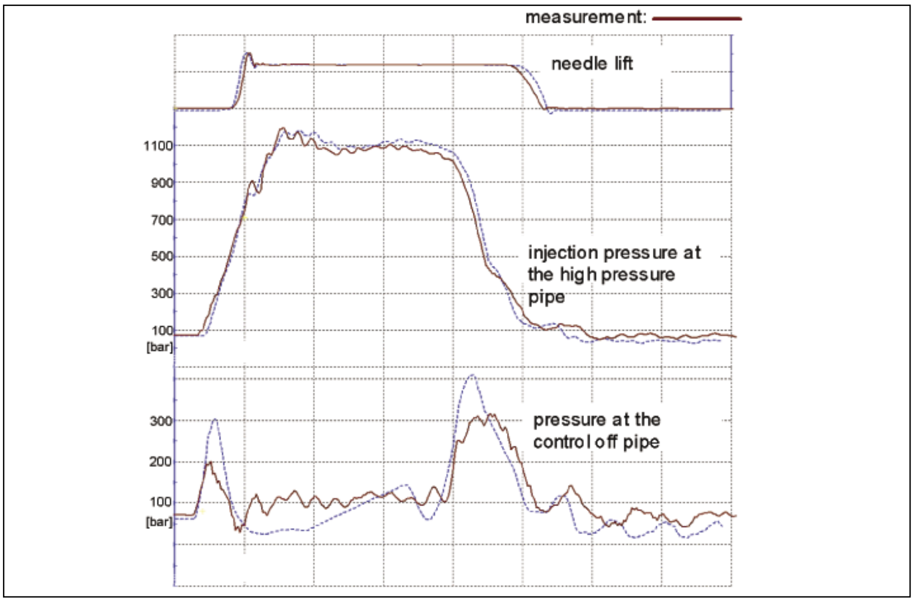

Fig. 10: Comparison of simulation and measurement

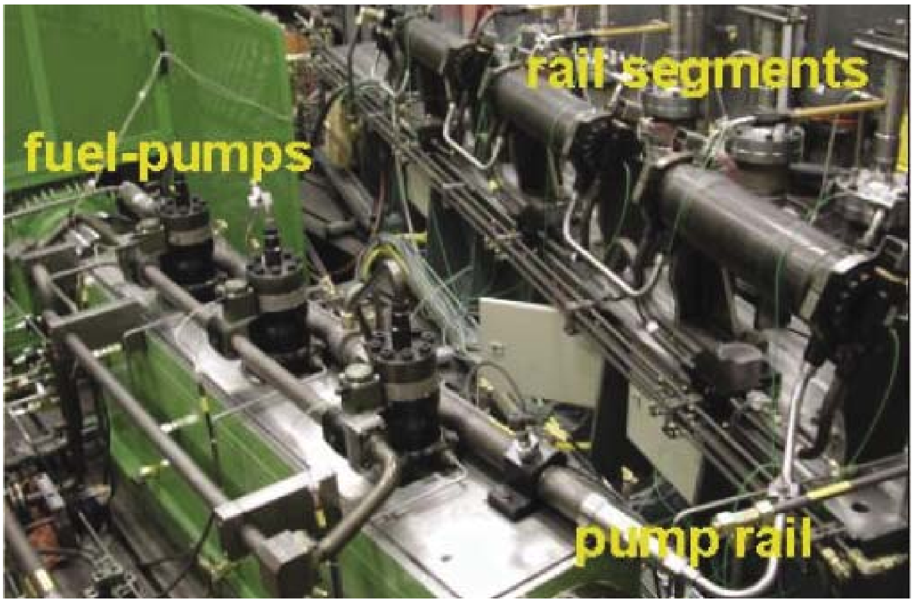

Fig. 11: Test rig installation of the complete CR system

Hydraulic optimization and endurance test at injection test rigs

As already mentioned the heavy fuel operation is a big challenge for all electronic controlled injection systems. Therefore MAN B&W decided to install new test rigs especially for the hydraulic optimization and endurance testing of CR injection systems under as realistic conditions as possible. These test rigs are characterized by the following main features:

- Installation of complete CR systems for up to 9 cyl. possible.
- Fully computerized operation and measurement with the possibility of unmanned endurance runs.
- Operation with different test fuels, especially with real heavy fuel oil for endurance tests.

Figure 11 shows one of these test rigs with the CR injection system 32/40 installed.

Additionally to the test rigs for the hydraulic and endurance test MAN B&W installed an additional test rig to check the calibration of the control valves. Results of the test engine showed the importance of a good calibration of these components. With the precise calibration of the rail covers it was possible to reach the level of exhaust gas temperature deviations of a well adjusted conventional injection system without correction at the electronic side even at very low load points.

The optimization of the CR injection system at the injection test rigs shall be demonstrated at a few examples:

- Figure 12 shows the measured pressure before 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 the NO_x- and the smoke formation with the MAN B&W CR system can be optimized in a big range to match the injection system to the requirements of the engine.
- Also pre- and post-injection was not only simulated but also tested at the injection test rigs. Figure 13 shows the measured pressure and needle lift for a measuring point with pre- and post-injection.
- Not only the electronic control valves are highly loaded and sensitive parts for CR injection systems. Also the high pressure pumps are due to the reduced number of pumps (1 high pressure pump for up to 3 cyl.) and the high possible rail pressure (1600 bar) exposed to a very high load. Therefore they have to be tested and optimized very extensive. For instance figure 14 shows the influence of the rail pressure on the temperature in the pump barrel close to the plunger bore. This temperature is increasing significantly with increased pressure. But by a modified pump element which improved cooling and lubrication it was possible to reduce this temperature peak to an acceptable level.
- The possibility to operate the CR injection system with original heavy fuel oil over long operation periods at the test rigs also showed wear problems far before they would be seen on a test engine or in the field.

Figure 15 shows on the left side the piston of the control valve in the first version. Already after a short operating time cavitation was visible and measurable. To reduce this cavitation the flow geometry was opti-

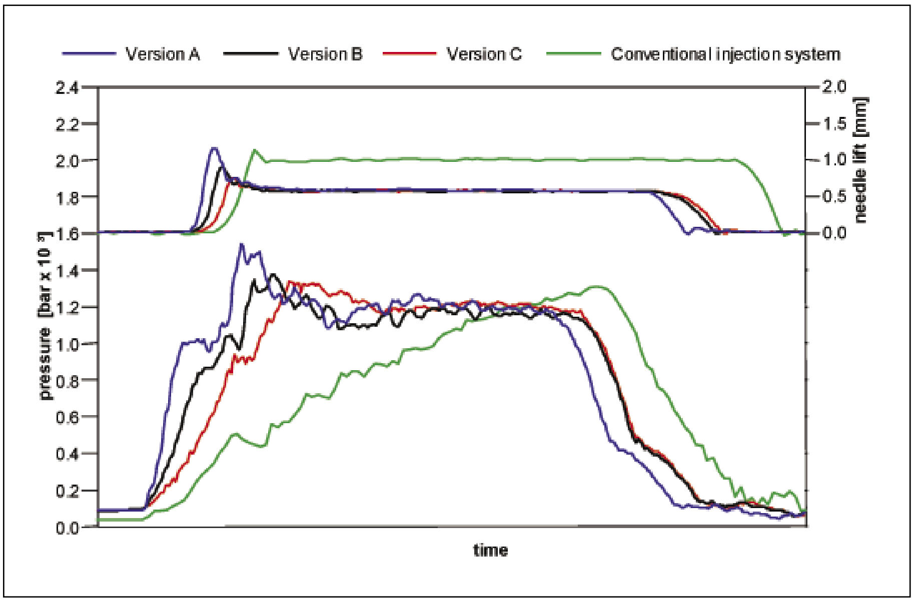

Fig. 12: Matching of the rate of injection

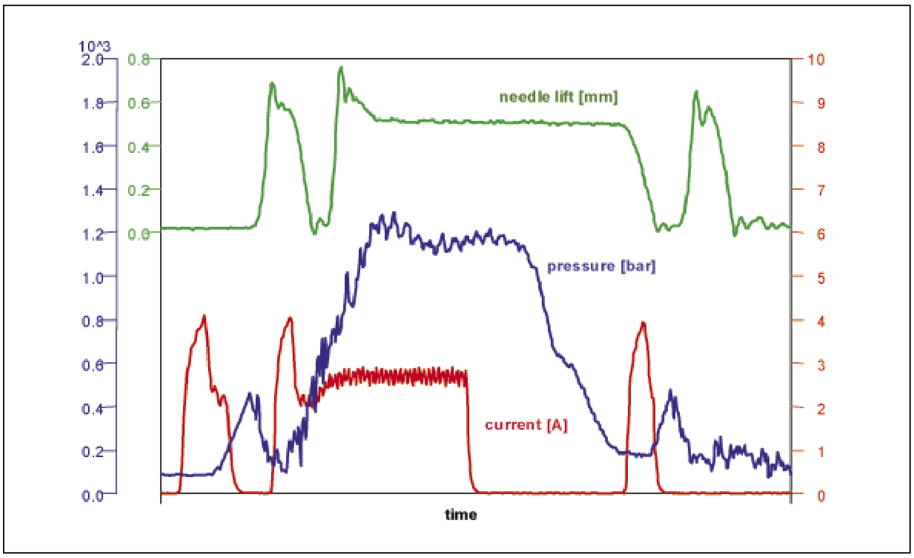

Fig. 13: Pre- and post injection

mized by CFD calculations and the modified parts were tested again. The picture on the right side shows the same area after appr. 2500 h and demonstrates the significant improvement.

Also on the piston which controls the control cut off area unacceptable wear was found at the beginning of the system tests. (figure 16 top). But after some optimizations steps also at this position a good running behavior could be reached (figure 16 bottom)

Enigine results

Demands on exhaust gas emissions of medium-speed Diesel engines

In addition to compliance with IMO regulations, it must, these days, be ensured that the exhaust gas is invisible and cannot be proven as smoke at the funnel. Already at an early stage, MAN B&W Diesel addressed themselves to the development of an engine with invisible exhaust gas over the complete load range.

Performance data of the 32/40CR engine

The 32/40 engine is used as main and auxiliary marine engine, in stationary power generation plants as well as for special applications, e.g., in the offshore range. The engine is generally loaded at a constantly rated engine speed of 750, resp. 720 rpm. In individual cases it can, however, also be operated in the so-called combinator or propeller mode within a speed range of between 450 and 750 rpm. In these operating modes, the engine is increasingly loaded at rising engine speeds.

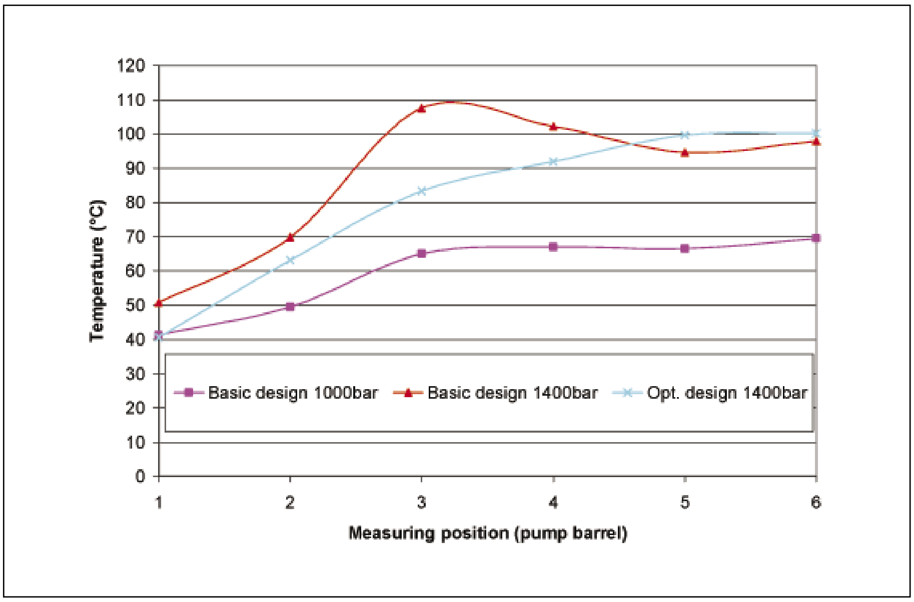

Fig. 14: Thermal load of high pressure pump

Fig. 15: Optimized design of control valve after few thousand operating hours

Fig. 16: Optimized design of control valve without cavitation and wear marks

When the engine is operated on heavy fuel oil of medium quality, the fuel is heated to a supply temperature of approx. 150°C in order to reach a fuel viscosity of 12 cSt upstream of the engine.

As injection pressure and start-up are freely selectable at any load point within the engine characteristic map, the engine is, depending on the load, able to cope with quite a variety of requirements: e.g. smoke reduction at low load and NO_x reduction at medium, resp. full load [3]. Figure 17 shows, based on the example of an injection pressure variation at 100% engine load and an injection pressure of 1000 resp. 1400 bar, how smoke and NO_x emissions as well as the heat release can be influenced by injection pressure variations. In both cases, the exhaust gas at the funnel is invisible.

Injection pressure and injection start variations were carried out at all load points within the engine characteristic field and evaluated in the trade off smoke emissions, SFOC (specific fuel oil consumption) and NO_x emission. In addition, modifications of the injection rate curve were examined and the injection nozzle configuration varied. As matters stand at present, the following intermediate results can be stated.

- Compared to conventional injection systems, CR is able to achieve an advantage in smoke-SFOC-NO_x trade off over the complete engine load range already by means of simple injection, i.e. without pre- or post-injection.
- Figure 18 is a survey of both systems, the conventional injection system and CR, over an engine load range from 0% to 100%. It is to be noted that the engine was loaded in generator operation at a rated engine speed of 750 rpm.
- Due to injection flexibility, NO_x emissions, fuel consumption and exhaust gas opacity could clearly be improved by injection pressure and start adaptation. Exhaust gas opacity can be reduced below to the visibility limit within the critical low-load range. Based on the same fuel consumption, CR was able to clearly reduce the NO_x emissions within the load range from 50 to 85%, while the exhaust gas at the funnel is already invisible.
- It is no surprise that only negligible advantages can be achieved at nominal load, as this engine operation point has for years been optimised for the conventional injection system. The CR injection system is, above all, a tool in order to improve emission and fuel consumption values in particular for part-load operation with a high degree of flexibility within the complete operating range.

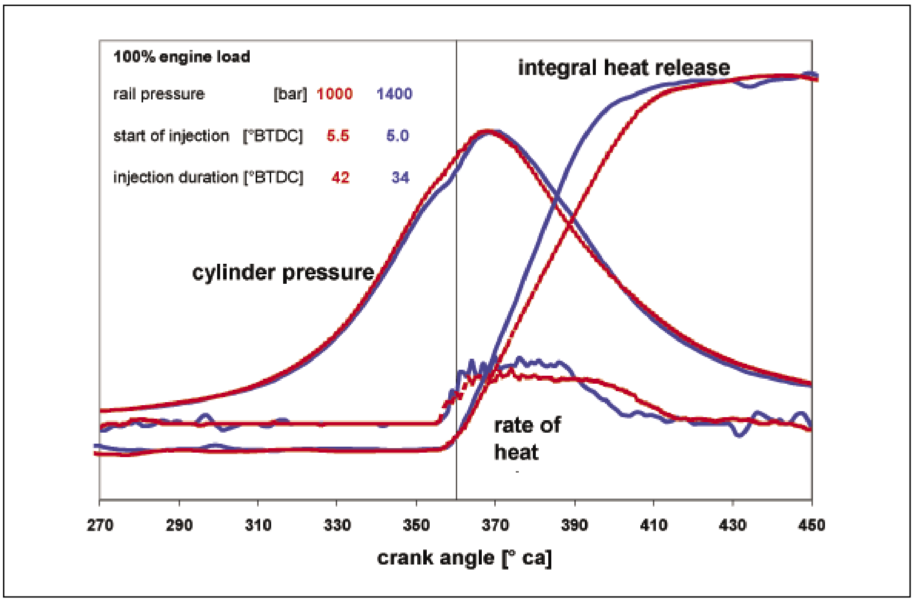

Fig. 17: Combustion characteristics with different injection pressures

Conclusions

Prospects to engine performance

The advantage of flexible injection, even when performing a single injection, by means of a freely selectable injection pressure and injection start could clearly be demonstrated.

With the MAN B&W CR system the rate of injection at the beginning of injection, which is most important for the NO_x- and the smoke formation can be optimized in a big range to match the injection system to the requirements of the engine.
An additional pre or post injection is a further possibility to optimize the combustion process. The application for future engine concepts is also desribed in [4].

Beyond this, a specific post injection can, with regard to Diesel engines with exhaust gas turbocharger, be used for a short-term increase in the enthalpy of the exhaust gas. Contrary to the above-mentioned post injection, with only a very small amount of fuel being injected shortly after the

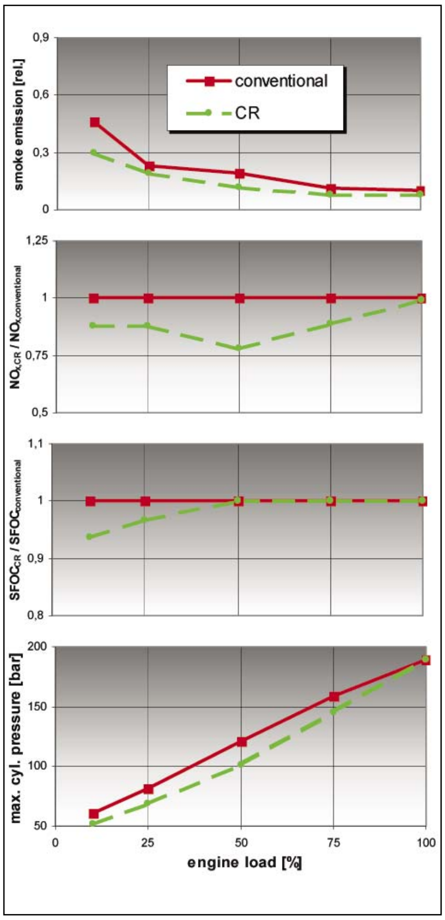

Fig.18: Comparison of engine performance datas with different injection systems

main injection, the MAN B&W patented "boost injection", means that the fuel is injected considerably later (approx. 50° crank angle after the main injection). In addition, a considerably larger amount of fuel is injected in the case of boost injection. This very late post injection results in an increase of energy supply at the exhaust gas turbine and, therefore, the air mass flow rate in the compressor increases. This is requested, in particular for dynamic engine operation, when load is applied with increased tendency of smoke emissions due to insufficient combustion air. Figure 19 shows the increase in the charge air pressure, measured 10 seconds after load application due to the connected boost injection. In this connection, a short-term increase in the fuel consumption is accepted. Additional equipments for dynamic engine operation, as presently used, can be avoided in the future.

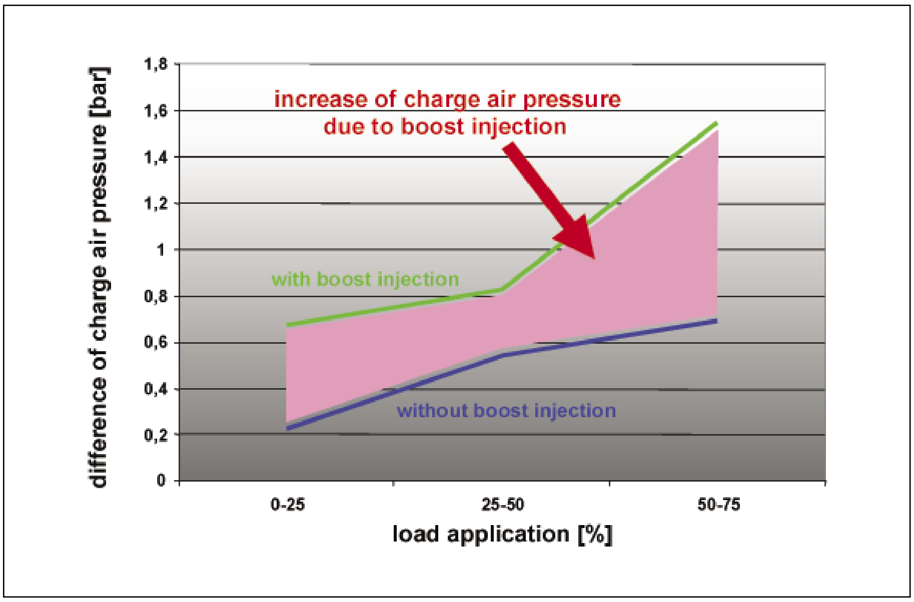

Fig.19: Improved dynamic engine behaviour with post injection

Market introduction

The several development steps of the MAN B&W CR system explained here in detail, emphasised the long term technology planning. The new concept revealed advantages like modular design, simple hydraulic and mechanical layout, easy retrofit of existing engines and high potential for future development steps with this kind of CR fuel injection system at engine implementation. Only with the innovative CR injection system it is possible to reach individual injection rate shaping over the entire operating range and, with it, a high degree of flexibility for matching the combustion and design advantages.

With the results of the test programms and corresponding component development a remarkable level of maturity was achieved, followed by first customer applications in the field.

MAN B&W believes the CR concept has considerable scope for further development, securing today's and future customer requirements.

Acknowledgements

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