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THE EFFECT OF MULTIPLE FUEL INJECTION ON COMBUSTION PROFILES IN SLOW-SPEED TWO-STROKE MARINE DIESEL ENGINES

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Summary

This paper presents and explains the results obtained in a study on multiple injections in slow-speed two-stroke marine diesel engines. The study included a simulation model of engine operation processes. The validity of the model was verified by comparing the obtained values with the measured values on three types of engines, Wärtsilä 7 RT Flex 50, MAN B&W MC 50 and ME 60.

Pressure and temperature values in the engine cylinder were obtained for every degree within a single full crankshaft revolution for two types of fuel injection: conventional and multiple fuel injections.

Even though the experiments were carried out with five, six and seven injections, the study has been restricted to three injections for practical purposes.

Pressure and temperature parameters are processed in tables and charts. First and second time derivatives of pressure and temperature were calculated, i.e. the rate of change of pressure and temperature and the acceleration of the rate of change in pressure and in temperature were calculated.

Key words: *slow-speed marine diesel engines, fuel injection, combustion, NOx emissions*

1. Introduction

Multiple injections have been applied in four-stroke high-speed engines in vehicles for some time now. Their application on medium-speed stationary and marine engines is recent. The fuel injection system that enables multiple injections is termed Common *Rail Technology*.

A similar system came into use in slow-speed two-stroke marine diesel engines some 10 years ago. Its application has thus been rather short but has given satisfactory results. It should be pointed out that even though multiple injections can be used in two-stroke engines, they have not been used in the same way as in four-stroke engines (Figure 1).

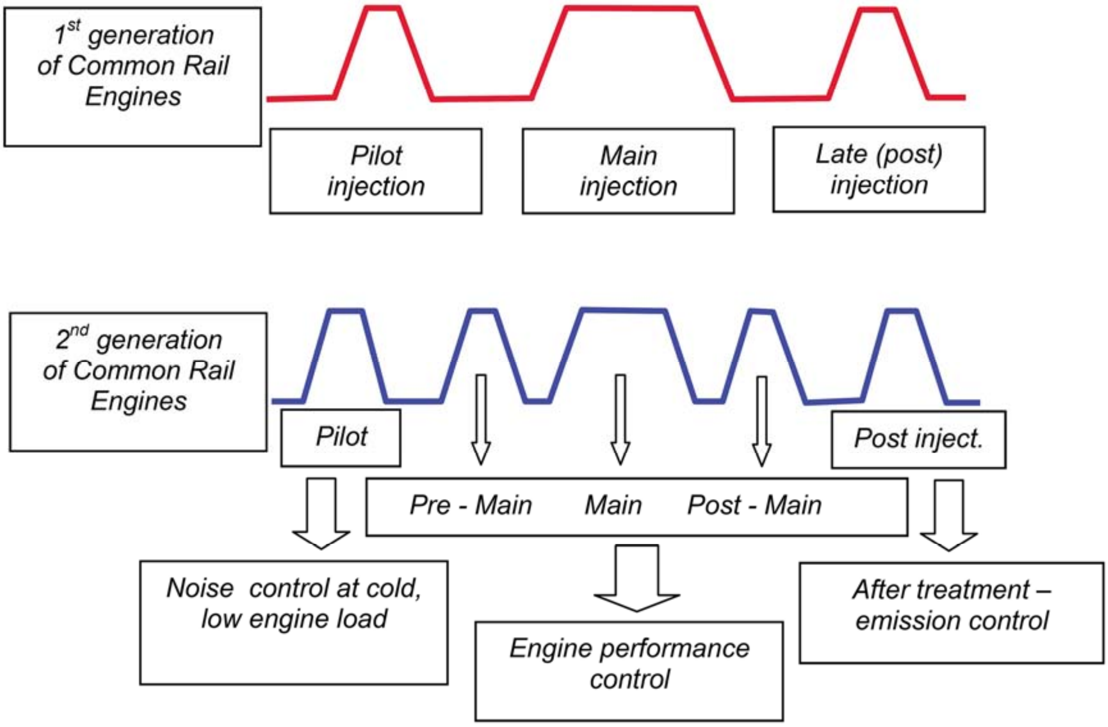

Fig. 1 Diagram of multiple fuel injections in high-speed four-stroke engine [5]

The injection in slow-speed MAN B&W ME engines is shown in Figure 2. A combustion profile of low NOx emissions is not achieved by means of a multiple injection but by metering the amount of fuel supply which is achieved by using a pulsing electro-hydraulic valve. Hence, the desired pressure and temperature curve is obtained, i.e. the desired heat release, and in that way the distribution of pressure and temperature depending on the crank angle. The results are reduced NOx emissions, which is a primary task, along with optimised efficiency and quieter engine operation.

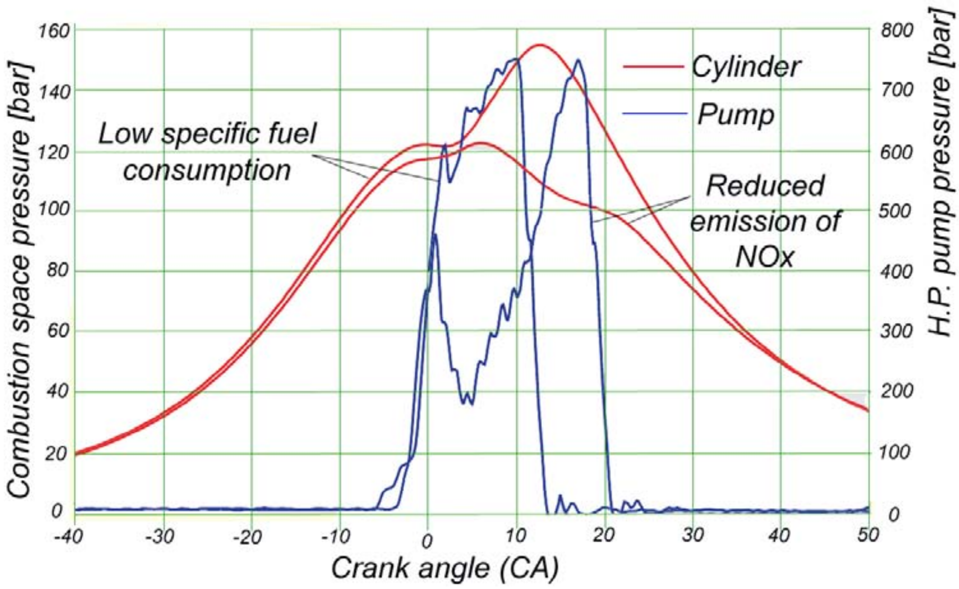

Fig. 2 Comparison of open indicator diagrams and injection profiles on MAN B&W 6 S 60 ME-C engines for two different fuel injections – measured values [3]

2. Description of the simulation model

The simulation of cylinder processes in slow-speed two-stroke marine diesel engines shows all stages that occur in the engine from the moment the exhaust valve is closed until the exhaust valve is opened [1]. The algorithm developed by authors is entered in FORTRAN and MATLAB. The inlet data for the main computer program are basic cylinder parameters as well as the start of combustion values, the end of combustion values and relative fuel amounts. The assumption is that the start of combustion is equal to the start of injection. There is no ignition delay recalculation due to the complexity of such a simulation and there is no need for it in this study. The start and the end of combustion for single injection cases are determined according to the measured values and the heat release rate. In multi-injection cases these parameters were determined by optimisations carried out according to the preset criteria for fuel consumption, maximum combustion temperature, open indicator diagrams and pressure rate of change.

The main computer program simulates compression, combustion and expansion processes. The computer program calculates the most important engine parameters like pressure, temperature, specific heat capacity of mixture, different mixture components, power, efficiency and specific fuel consumption. The operation principle of the simulation model is as follows:

Calculations are made at the commencement of compression, i.e. theoretically at -180° of the crankshaft revolution. The instantaneous cylinder volume at this point is computed from major engine parameters: cylinder diameter, piston stroke, connecting rod length and compression ratio.

The amount of mixture is calculated for that instantaneous cylinder volume and the mixture components which are known at that moment.

A constant amount of mixture is assumed during the entire compression process and until fuel injection commences. It is also assumed that the mixture is composed of fresh air without residues (100 % scavenged cylinder). The air composition is assumed to be that of 79 % nitrogen (N_2) and 21 % oxygen (O_2), while other components are ignored.

Simulations of compression and expansion are made based on Energy and Mass Conservation Equations and the Gas State Equation. The model is a null-dimensional one, and the software computes the most important, the above described parameters, for each degree of the crankshaft revolution.

In the combustion simulation, for single injection the single Vibe functions are used while for multi-injection the multiple Vibe functions are used. The main program uses a subprogramme that is called at particular stages of calculation and serves to calculate the internal energy and enthalpy of the mixture. More detailed information about the simulation model and block diagrams is given in [1].

Three types of slow-speed two-stroke marine diesel engines were chosen for research purposes and for model validation: Wärtsilä 7 RT Flex 50, MAN B&W MC 50 and ME 60. For the Wärtsilä engine 7 RT Flex 50 at 100% of the maximum continuous ratio (MCR) the crank angle ranges from -107° to 125° with reference to top dead centre (TDC). According to the test bed data and trial runs (source MID 3. Maj and Uljanik) these angles are similar for MAN B&W MC 50 and ME 60 engines [3].

As the most important range upon which the simulation depends is around TDC (-10° to 70° CA), the tests and data processing were restricted to the crank angles of -100° to 100° with reference to TDC.

Characteristics of light diesel fuel were included in the analysis since heavy fuel requires a significantly more complex model due to a large number of impurities and its complex chemical composition. Also, it is difficult to ascertain the unique compounds of heavy fuel since it originates from different areas [8].

3. Simulation results for multiple fuel injection

Figure 2 represents real, i.e. the measured values of injection pressure on the high pressure fuel pump in slow-speed two-stroke marine engines. These values are shown in blue for the two engine operation modes. The comparison of indicator diagrams of the same engine with two different injection types is given in red.

Figure 3 shows a similar diagram obtained after processing the simulation results. The conventional mechanical single injection is shown in blue (measured values). Fuel is injected by the mechanical high pressure jerk pump. The red line shows an open indicator diagram obtained from the simulation with a tendency to follow the red curve for the low NOx mode given in Figure 2. A Vibe function has been used for the simulation of all three types of combustion. Parameter values for this particular case with three Vibe functions are:

$C1 = C2 = C3 = 6.901$, (99.9% of fuel is converted into thermal energy)

$m1 = 1$, $m2 = 0.8$, $m3 = 0.6$ (Vibe functions form parameters)

$\varphi PI1 = -1$ [^{0} CA], $\varphi KI1 = 30$ [^{0} KV], fuel amount 15 %

$\varphi PI2 = 1$ [^{0} CA], $\varphi KI2 = 45$ [^{0} KV], fuel amount 25 %

$\varphi PI3 = 9$ [^{0} CA], $\varphi KI3 = 70$ [^{0} KV], fuel amount 60 %,

where *PI1, PI2* and *PI3* are injection starting points, *KI1, KI2* and *KI3* are ends of combustion points, while coefficients *C1, C2, C3, m1, m2, m3* and φPI and φKI define the Vibe function [1].

A comparison of the simulated open indicator diagrams of pressure and rate of pressure change for two different fuel injections at 75 % of engine load is given in Figure 3. One operation mode is the cost-effective mode, with the lowest possible fuel consumption, while the other mode is the reduced NOx emission mode.

Significant differences in the shape of the curve and pressure values can be observed. A more horizontal combustion curve is achieved by the multiple or sequential injection by prolonging the injection time.

The combustion curve obtained from the simulation is more horizontal for multiple injections. This was obtained by combining two pilot injections with a small amount of fuel (15% and 25%) and one main injection with a greater amount of fuel (60% of total amount). The total amount of fuel supply is the same in both diagrams.

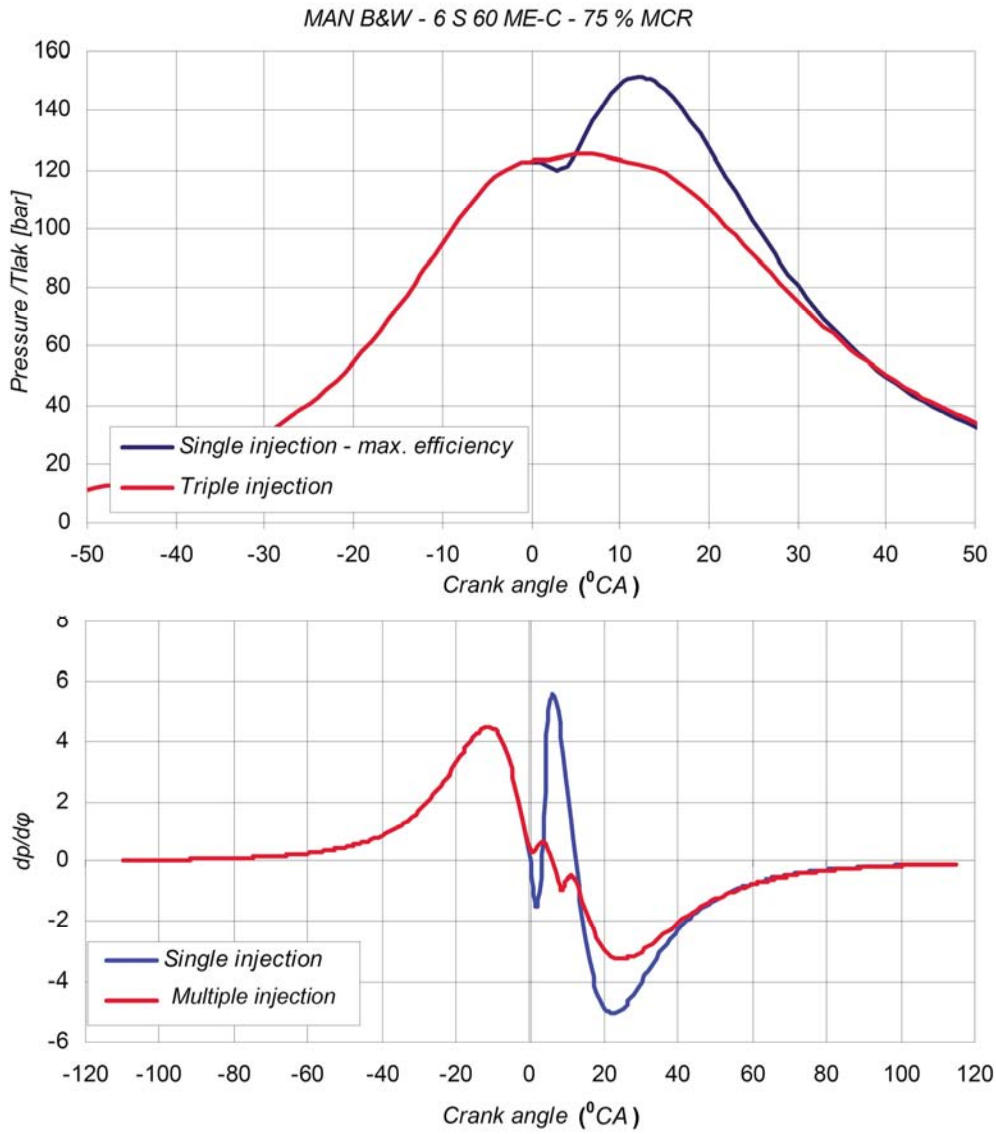

Fig. 3 Comparison of open indicator diagrams of pressure and diagrams of rate of pressure change on MAN B&W 6 S 60 ME-C engine for two different injections – simulated values

It can be observed that the pressure increment after TDC is much smoother during multiple than during single injection.

To avoid engine knocking caused by detonations, the increase in pressure per crank angle degree should remain within boundaries of 2 to 6 [bar/°CA] [7]. For the simulated multiple injection, the increase in pressure is less than 2 [bar/°CA].

A comparison between the measured (Fig. 2) and the simulated values (Fig. 3) can be seen in Figure 4.

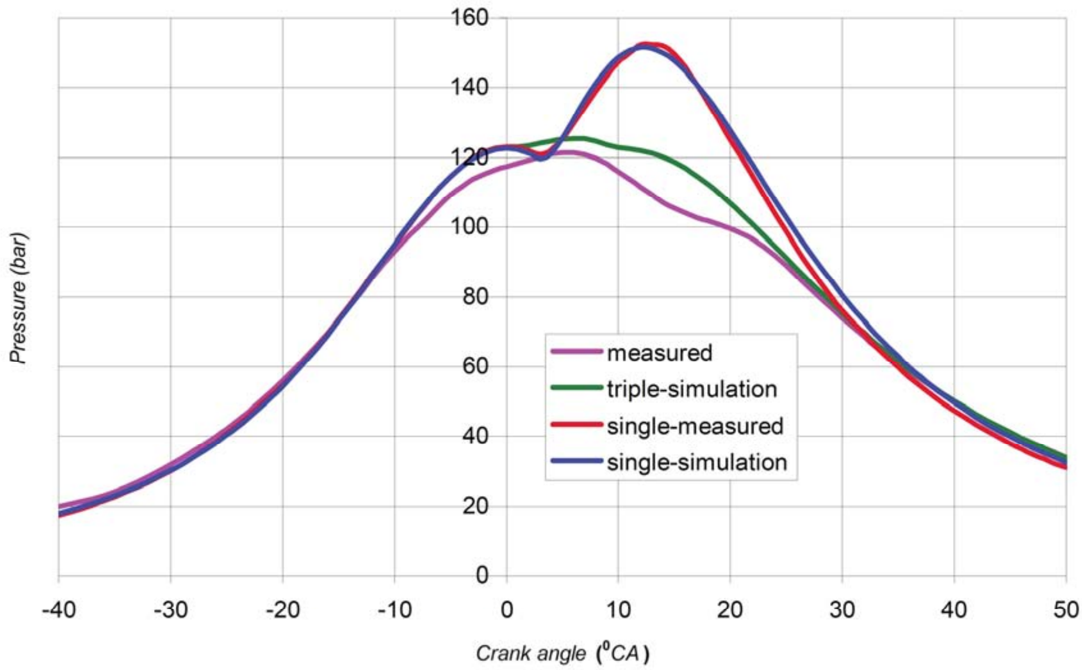

Fig. 4 Comparison between measured and simulated values of open indicator diagrams on MAN B&W 6 S 60 ME-C engine for two different injections

Dozens of cases of multiple injections have been simulated to achieve better overlapping with combustion curves given by the manufacturer and to optimise the process of combustion. According to the preset parameters for optimised efficiency, the lowest possible increase in pressure per crank angle degree and the lowest possible maximum combustion temperature in the cylinder, the simulation results give a good overlap with the measured values (Table 1). The coefficients of determination (R^2) and root mean square errors (RMSE) are:

Table 1 R2 and RMSEs for single and triple injection models

	Single injection	Triple injection
Coefficients of determination (R^2)	0,997891	0,980822
Root Mean Square Errors (RMSE)	1,914723	4,501996

The combustion curve of multiple injection can be even steeper. This means that greater efficiency is achieved, but temperatures are also increased which causes more NOx to be produced and a "harder" engine operation.

A smoother curve and a less rapid increase in pressure (lower rate of pressure change) lead to a smoother engine operation. Maximum combustion temperatures are lower, but fuel consumption is increased.

In the past and up to 19 May, 2005, when MARPOL Annex VI came into force, the commencement of injection in slow-speed two-stroke marine diesel engines began much earlier (in some old slow-speed marine diesel engines it was -15^0 before TDC – SULZER RND, GMT, etc.). The point of injection setting was to achieve the maximum combustion pressure values either at TDC or immediately after TDC with the lowest fuel oil consumption at nominal running speed.

There has always been a tendency to increase the pressure of compression for better efficiency. With electro-hydraulic injection control, combustion can be prolonged to the expansion and thus the maximum pressure and temperature are controlled too, leading to a reduction in the NOx production. The specific fuel consumption is kept at the minimum possible value and NOx emissions and soot are reduced, according to permissible values. Due to better and more efficient combustion, modern slow speed marine diesel engines are more reliable with much less failures and unnecessary costs. The electronic equipment for the fuel injection (combustion) control allows the installation of additional safety devices that significantly improve the safety of the entire propulsion machinery and vessel [6].

Since the maximum combustion temperature is the parameter which has major influence on the NOx production, the mean combustion temperatures were calculated for each case. Diagrams in Figure 5 present the differences in temperature and rate of temperature change for the same case. For multiple injections the highest temperatures are about 200 Kelvin lower than the highest temperature for single injection. Also, at the moment of the exhaust valve opening the temperature is 50 Kelvin higher than in the case of triple injection.

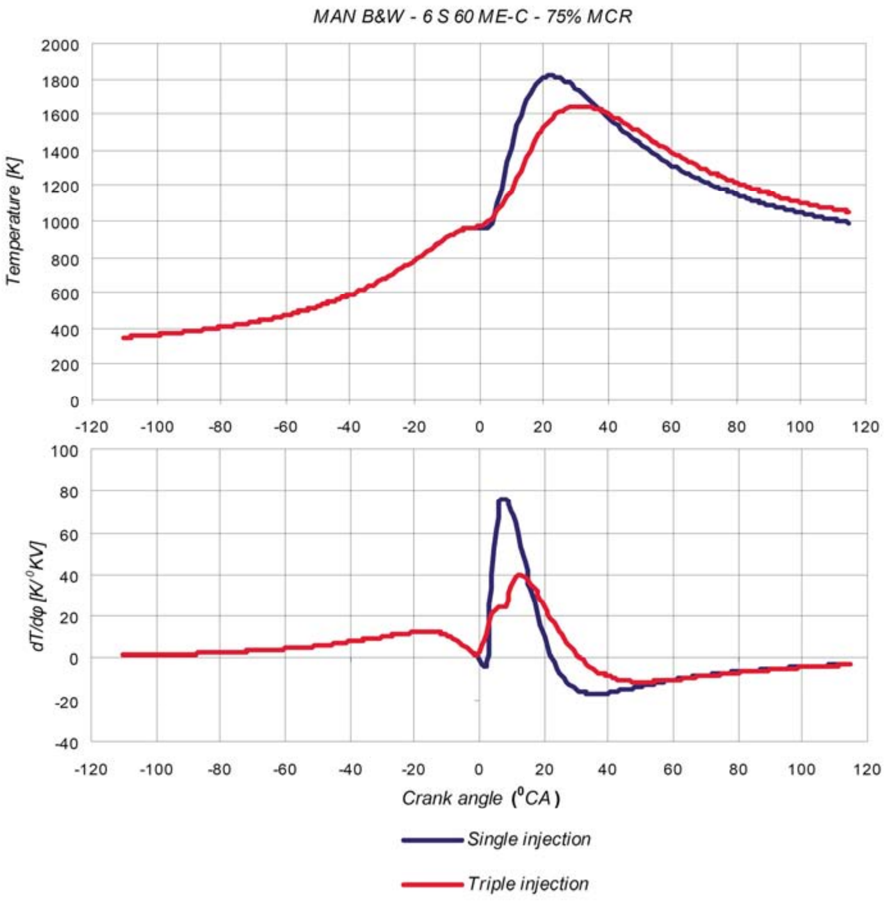

Fig. 5 Comparation of combustion space temperature and temperature change speed for engine type MAN B&W 6 S 60 ME-C at 75 % MCR for two different types of injection – simulated

The influence of temperature on the NOx production was studied in [4] and this temperature value is taken as reference value. Lower maximum combustion temperatures have a direct impact on the reduction in NOx emissions (Fig. 10). By applying the simulation model used in [1], the mean combustion temperature is calculated. If the mean combustion temperatures are higher it can be assumed that the maximum combustion temperatures are higher too, which significantly affects the production of NOx (fig. 9). A multidimensional model that would include complex chemical reactions is necessary for determining real, local areas of high combustion temperatures where nitrogen oxide is created, as well as for analysing the areas where soot is created. Also, for a detailed modelling of chemical reactions an accurate model of heavy fuel oil is necessary. It is very difficult to determine unique features of heavy fuel oil due to its various qualities and unknown chemical composition.

The rate of temperature change is a better indicator of temperature peak values within the cylinder during combustion. It can be seen that these are much smoother when multiple rather than conventional injection is used.

The simulations also included more than three injections in the model. The simulation model supports as many as 10 injections and some research with so many injections has also been made. However, the three-injection model has been chosen for the reason of more practical application.

Quintuple injection[1] is applied in new-generation high-speed diesel engines (Figure 1). Although in two-stroke slow speed marine diesel engines single or pulse injection are in use, double or mostly triple injection can be used as it is proposed in this paper. The reason for the application of single injection lies in engine speed and fuel quality. High-speed engines have less time for creating the mixture and for combustion. Therefore, multiple injection, high quality fuel which is less viscous, and high injection pressures[2] are used to meet the requirements of the international and national regulations on NOx emission, soot and CO_2.

The research in [1] included slow-speed two-stroke marine diesel engines where relatively cheap heavy fuel oil was used. As opposed to high-speed engines, slow-speed engines turn more slowly and thus have more time for creating the mixture and for combustion. In two-stroke engines, the proposed 2 or 3 injections are sufficient, which was confirmed by the simulations. Also, the research showed that there was no need for post-injection like in high-speed diesel engines.

Triple injection was chosen for practical reasons. Multiple injection in high-speed engines requires an adequate electronic system – the „hardware“, i.e. a control unit and final elements, which control the commencement and end of injection, and fuel amount for every engine cycle. A great number of injections in such a short time require powerful processors, and quick response elements[3] for executing the signals [10]. The speed of these components greatly depends on fuel quality. Sulphur-free diesel oil enables the application of quintuple injection and greater engine speed without difficulty. Such an application in slow-speed engines that operate on heavy fuel oil containing a great amount of sulphur is technologically restricted, but not necessary.

Figure 6 shows in parallel the measured and simulated open indicator diagrams of MAN B&W 6 S 60 ME-C engine at 43% of MCR in the low NOx emission mode. The diagram of the measured pressure values with reference to the crank angle degree is obtained from the ship and has been analysed in the same way as the above described diagrams.

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[1] 2 pilot injections, 1 main and 2 post (subsequent) injections.

[2] Even up to 2000 bar.

[3] Electro-hydraulic valve to control the injection, opening and closing of the exhaust valve.

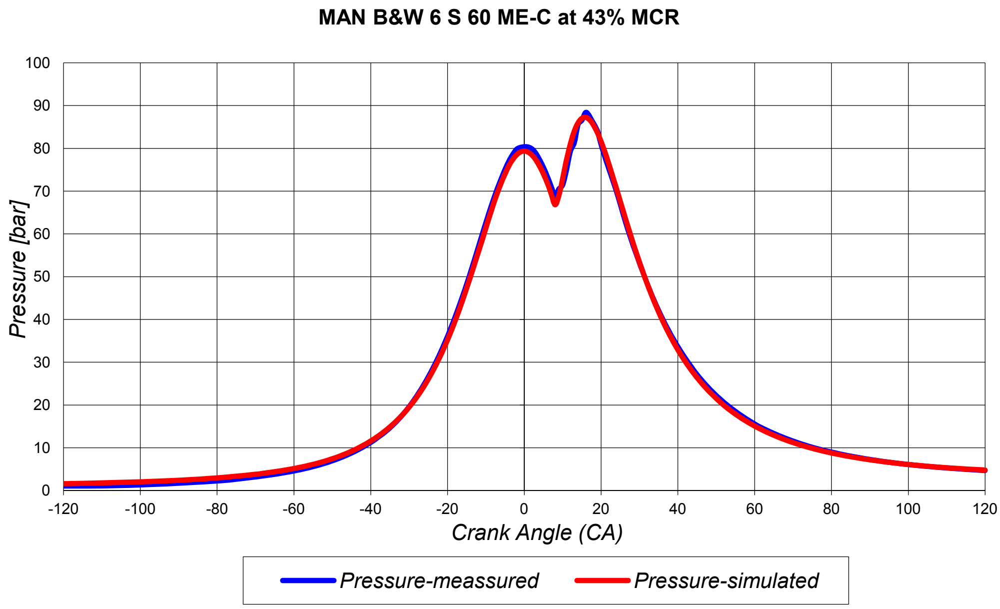

Fig. 6 Comparison of open cylinder indication pressure diagrams for engine type MAN B&W 6 S 60 ME-C at 43% MCR – low NOx emission mode

The diagram in Figure 6 shows that the low NOx emission mode, which has wide application, is programmed in such a way that the commencement of combustion is set at 5° to 7° of the crankshaft revolution after TDC. The calculated values obtained in the simulations by using single injection correspond to the measured values. Discrepancies occur within a boundary of ±4% (Figure 7).

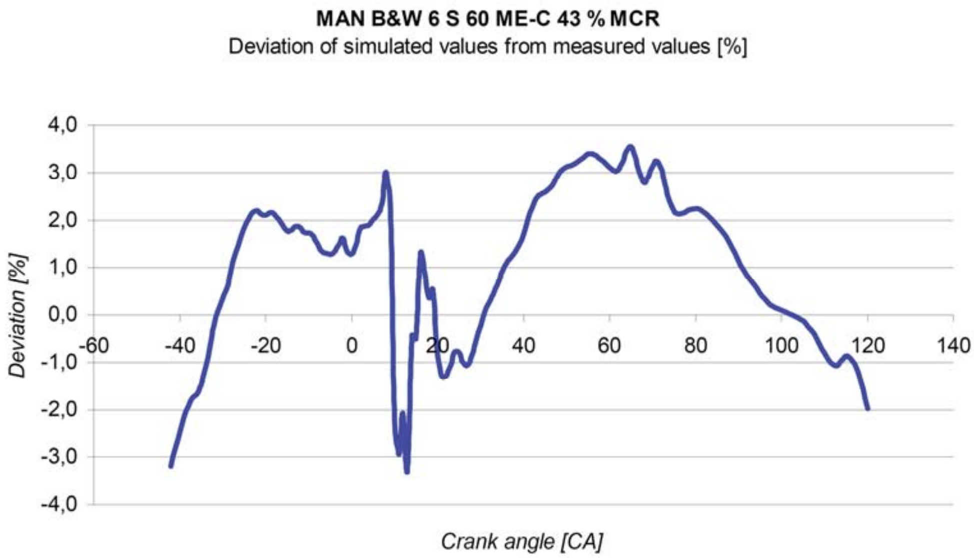

Fig. 7 Discrepancies of calculated and measured pressure values on MAN B&W 6 S 60 ME – C engine at 43 % of MCR

There is a possibility that similar engines on other vessels have a differently programmed control unit and that the combustion profile resembles the one of multiple injection. However, authors of this paper could not obtain any such data.

4. Suggestions for achieving a combustion profile with reduced NOx emissions

Since the main prerequisite for producing harmful nitrogen oxides are high temperatures, suggestions for achieving the lowest possible maximum temperatures in the combustion space were obtained by simulating different combinations of single and multiple fuel injection.

Figure 8 provides two suggestions for reducing NOx emissions. One is raising compression temperature, and commencing injection significantly after TDC (data are presented by the blue line). The other possibility is to reduce compression pressure and start the injection just before TDC. Fuel should be added by initially injecting a small amount, and then metering the fuel supply to the cylinder to prolong the combustion curve till expansion. Maximum pressure and temperature, whereby temperature is the main parameter in the production of nitrogen oxide, are controlled in that way. Both cases are simulated.

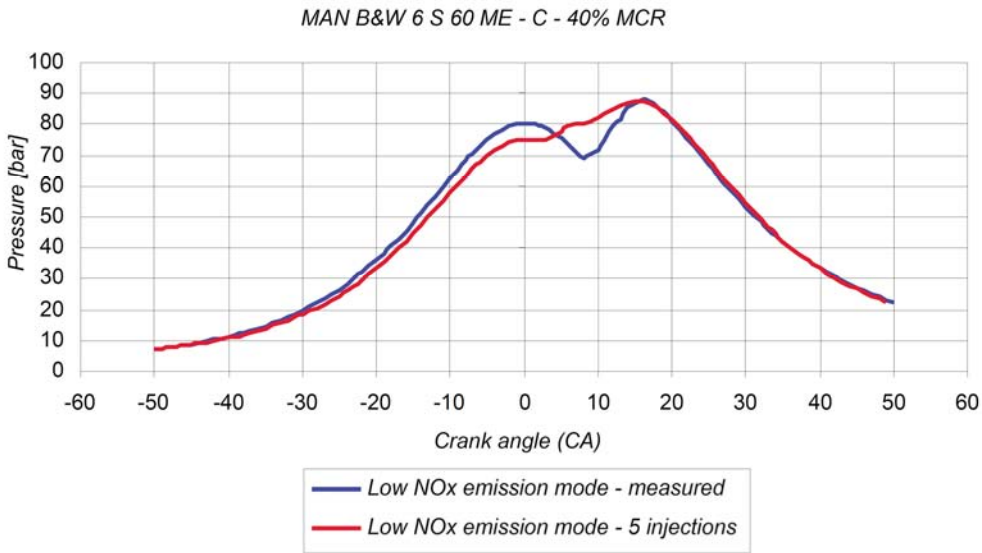

Fig. 8 Comparison of two low NOx emission modes on MAN B&W 6 S 60 ME-C engine

Figure 9 shows curves of indicator pressure, rate of pressure change, change in temperature, and rate of temperature change on the tested engine for different injections. The curve profile can be changed depending on desired results, which are to achieve cost-effectiveness and/or low NOx emissions. The single injection curve shows that this is the most cost-effective mode, whereas curves for 3 or 5 injections show a change in pressure in the low NOx emission mode. The cost-effective operation mode of single injection can also be achieved with multiple injections with significant improvements in thermal efficiency [6].

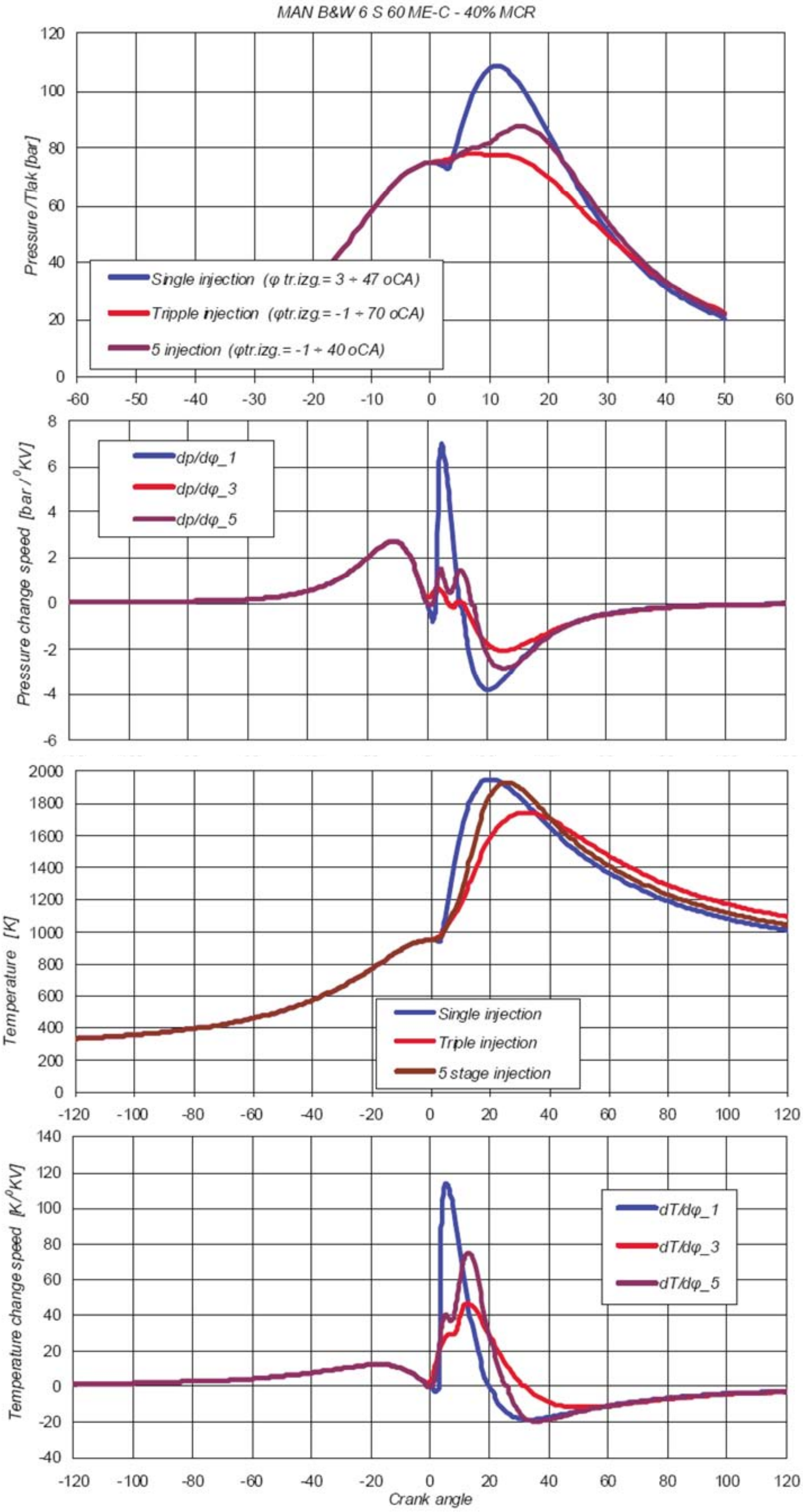

Fig. 9 Comparison of indicator pressures, rate of pressure change, temperature change and rate of temperature change on MAN B&W 6 S 60 ME-C engine from the simulation of different numbers and types of injection (the area of interest is magnified)

The production of thermal NO or its concentration per time unit has been processed in [4], and it can be seen in Figure 10. Chemical balance for $T = 2500$ [K] is achieved only after 10 [ms].

If engine speed for high-speed diesel engines is $n = 1500$ [min^{-1}] and the duration of injection is 80° CA, then the highest temperature is retained for about 9 [ms].

In slow-speed diesel engines, with engine speed of 100 [min^{-1}] and the duration of injection of approximately 20° CA, the highest temperature is retained for approximately 33 [ms], which by far exceeds the time necessary for the production of NO.

The research presented in this paper has proven that maximum mean combustion temperatures for single injection are 1900 [K], and for simulated multiple injection 1700 [K]. It can be predicted that local maximum temperatures around the flame zone will be much higher than 2000 [K]. Higher temperatures, excess air[4] and sufficient time create perfect conditions for the NO production.

Research carried out in [2] has shown that an increase in combustion temperature from 2000 [K] to 2100 [K] quadruples the production of thermal NO.

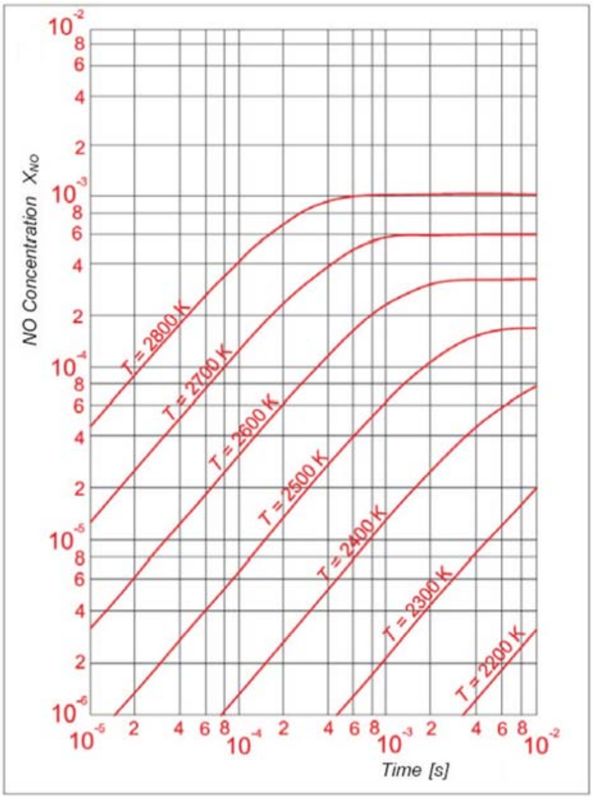

Fig. 10 Thermal NO production where $p = 140$ [bar], $T = 2200 \div 2800$ [K] and $\lambda = 0.8$ [4].

That is why every, even the smallest decrease in the mean combustion temperature is significant. This paper has shown that, by using multiple injection, it is possible to reduce the maximum mean temperature of combustion by 300 [K] or even more. This certainly has an impact on the reduction in local maximum temperatures and the reduction in nitrogen oxides.

[4] The least favourable is the local excess air of $\lambda = 1{,}1$ under adiabatic conditions [9]. If $\lambda = 1{,}1$ production of thermal NO increases, when $\lambda > 1{,}1$ production of thermal NO decreases.

5. Conclusion

The simulation software has been created for research purposes. A great number of simulations have been performed. The results obtained were compared with the real measured values. Open indicator diagrams, which are the main indicators of proper engine operation, were analysed.

Single and multiple injections on the tested engines were performed. Once we determined that the simulation results correspond with satisfactory accuracy to the real state, simulations with other starting conditions and types of injection were carried out. The following elements were varied: start and end of combustion (injection), fuel quality, excess air and Vibe function coefficients. The following conclusions were reached:

For the tested engines, a single Vibe function presents the real change in the pressure of combustion with satisfactory accuracy.

Simulations of multiple injections have yielded a *p-φ diagram* very similar to the one issued by the manufacturer. Since real data on injection for such an operation mode are not known, the paper presents a profile and type of multiple injection with respect to low NOx emission. Data issued by the manufacturer show that such a profile is obtained by a special single injection by acting on the degree and duration of opening of the fuel supply valve. Thus the amount of injected fuel and injection profile are controlled, which directly influences the combustion profile.

Our calculation has also shown that multiple injection for engine operation with the lowest fuel consumption in slow-speed engines is pointless, since the same can be achieved with single injection.

Simulations have verified the hypotheses that the mean and instantaneous maximum temperature in the cylinder greatly depends upon the mode of injection. Maximum temperature is the main factor that leads to the production of NOx. The presented diagrams show why the multiple injection diagram is termed the low NOx emission mode. A multidimensional model is necessary for an accurate simulation of local temperatures in the cylinder.

By commencing injection before TDC, maximum pressure and temperature in the cylinder rise significantly, hence leading to increased efficiency and lower fuel consumption, but increased maximum combustion temperatures affect the production of harmful nitrogen oxides. It is known that the production of nitrogen oxides depends on chemical reactions, but this was not taken into consideration in this paper and could be an idea for further research.

It should be emphasised that nitrogen oxide is produced locally and that it depends on the local distribution of temperatures, and local excess air. However, this paper included the mean maximum combustion temperature only. Locally in the cylinder, temperature values depart from that mean temperature. Therefore, there are no nitrogen oxides in some regions, while there are many in some others. It is during the expansion that gases in the cylinder mix and are then expelled into the atmosphere.

Simulations have also verified the hypothesis that by commencing injection before TDC, the rate of pressure change is increased, thus leading to engine knocking, but the exhaust gas temperatures are significantly lower at the moment the exhaust valve is opened.

For late injection, simulation results were opposite to the results obtained for earlier injection, i.e. the maximum pressure is lower, the maximum mean temperature is lower (less chances of NOx production), and the temperature of exhaust gases is higher when the exhaust valve is opened. Higher output temperature is harmful for the material that will be subjected to greater thermal stresses, but has better enthalpy ratio for admission into the turbocharger. This results in greater power available to the turbocharger and thus greater pressure of scavenge air. This means that a greater amount of fuel could be supplied to the cylinder. Also, higher scavenging air pressure leads to increased compression pressure and improved efficiency, i.e. lower fuel consumption. This effect can be enhanced by the variable opening and closing of the exhaust valve as well as by the new generation of turbo chargers with a variable geometry of stator blades. This mode could be applied in tankers which use up a great amount of steam to heat the cargo during navigation. By increasing the exhaust gas temperature, which is also possible in more cost-effective operation modes, more steam is generated by the exhaust gas boiler. On the contrary, when the amount of exhaust gases is not sufficient, it is necessary to run burners on an auxiliary fuel oil boiler, which in turn reduces the cost-effectiveness of the plant.

Since in 2016 more rigorous regulations for NOx reduction came into force, the results obtained in this study suggest double or triple injection are to be used in future marine two-stroke slow-speed diesel engines. The research also shows that there is no need for post-injection like authors thought before they started the research and like this is a case in high speed diesel engines. The used simulation tool can be used for preliminary, rough engine setting to reduce the setting boundaries and save a lot of working time.

An optimum injection setting should be reached regarding the greatest efficiency, meeting the environmental regulations and keeping the thermal stress of the material within boundaries.

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