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Impact of Late and Early Fuel Injection on Main Engine Efficiency and Exhaust Gas Emissions

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ABSTRACT: Exhaust gas emissions from ships are an aspect of the global maritime industry which has been given great importance in recent years. Increasing the efficiency of maritime transport regarding fuel consumption and exhaust gas emissions is an ongoing effort which requires a detailed analysis of all ship systems that have an effect on the aforementioned issue. One aspect that can be analyzed in this regard are the various machinery faults which influence the ships exploitation efficiency. This paper will focus on the analysis of the two stroke slow speed diesel main engine with early and late fuel injection faults. This analysis is based on a set of data acquired from a simulation model of a LCC tanker vessel including fuel consumption and emission pollutants such as carbon monoxide (CO), sulphur oxides (SO_X) and carbon dioxide (CO_2) as a greenhouse gas with early and late fuel injection fault introduced to different number of main engine cylinders. This methodology of research has the advantage of analyzing various scenarios which are not as easily reproduced on actual vessels.

1 INTRODUCTION

The marine diesel engine is the main propulsion of the ship due to high efficiency, power and reliability. Also, it is the main source of harmful emissions, so ship owners and engine manufacturers are forced to find new solutions for reducing pollutants in the combustion process. The emission regulations required by International Maritime Organization (IMO), especially for NO_X and SO_X pollutants, are more stringent with each new amendment and they present a greater challenge for shipowners. One of the methods for reducing emissions in exhaust gases is the modification of the combustion process in the engine. This method includes optimization of the fuel injection with adequate injection timing (split injection, early and late injection) and optimization of exhaust and inlet valve closing/opening timing. Emission reduction with split injection is presented in article [1], where authors simulated split injection with the Miller cycle with exhaust gas recirculation. Stratsianis V., et al. in research [2] concluded that with injection strategies (post-injection) on a marine engine, the reduction of emissions could be achieved, however in terms of NO_X emissions this reduction is far from meeting IMO NO_X Tier III Regulation.

The pre-injection strategy with different pre-injection timing and mass ratio is explained in article [3], which provided a better understanding of the combustion process and the phenomenon of knock in the cylinder. Nemati A., et al. [4] conducted a study on the influence of pilot fuel injection timing on combustion process and emissions formation. The technical condition of the main engine is also highly important for the efficiency of the combustion process and the percentage of pollutants in exhaust gases. The fuel pump fault (leakage) and delay of fuel pump injection by 5° of crankshaft angle are simulated in the article [5]. The results have revealed the changes in specific fuel consumption (SFC), the increase of exhaust temperature and the reduction of fuel injection pressure. Other articles [6, 7] provided insight into the faults of the turbocharger system and its effects on the main engine. The exhaust temperature will increase with the fouling of turbine wheel or blockage of the air filter, which will consequently affect the exhaust emissions. The adequate maintenance of fuel system components and optimization of fuel injection is crucial for an efficient combustion process.

2 METHODOLOGY

The data used for the research in this paper was obtained on the Wärtsilä ERS-LCHS 5000 TechSim engine room simulator, owned by the Maritime department of the University of Zadar. The modelled vessel is a LCC tanker with a MAN B&W 6S60MC-C, two strokes, slow speed, turbocharged, reversible main diesel engine [8]. The vessel simulated in this model is shown in figure 1.

Figure 1. Simulator model vessel - LCC tanker with a MAN B&W 6S60MC-C main engine [8]

The diesel engine, type MC, is a two-stroke diesel engine with direct injection and centrally located exhaust valve. MAN Diesel & Turbo is one of the world's leading designers and manufacturers of engines with low and medium speed. Engine trial test report, the so-called shop test report, MAN 6S60MC was used during the analysis of operating parameters and recording the indicator diagram of the engine in real conditions [9]. These data were compared with data obtained on the ship simulator ERS 5000 TechSim. Obtained values for: mean effective pressure, maximum combustion pressure, fuel pump index recorded in the trial test were compared with ship simulator in normal conditions at a speed of 105 min-1 and they are almost identical. Therefore, it can be concluded that the ship simulator is valid for this research [9]. The basic main engine particulars are shown in table 1.

Some of the many features of the simulator model are introducing various environmental and fault variables during vessel navigation such as environmental loads, late and early fuel injection, piston ring wear, damaged fuel nozzle, turbocharger air filter blockage etc. The faults used for the research in this paper are late fuel injection, early fuel injection and turbocharger air filter blockage. The limitations of using simulated data for scientific research is the possible inaccuracy of the mathematical model used for simulator programming. This can only be validated using data from onboard measurements on actual vessels.

Table 1. Main engine particulars [8]

Main Engine Particulars	
Type	MAN B&W model 6S60 MC-C
Rated power	13 736 kW
Cylinder number	6
Bore	600 mm
Stroke	2400 mm
Rated speed	105 Rpm
Nominal MCR	13 736 kW at 105 RPM

Area of navigation chosen for the simulations is the Adriatic Sea, however since environmental loads i.e., wind, waves, wave spectrum and sea current, were not simulated for the purposes of this research the area of navigation is of little importance and of no impact. Fuel used for the combustion process in the main engines is a distillate marine diesel oil (MDO) with less than 0.5 % of sulphur content. The simulated parameters recorded for the purpose of this research were average cylinder exhaust gas temperature shown in degrees Celsius (°C), main engine fuel oil consumption (FOC) shown in litres per hour (L/h), carbon dioxide emission (CO_2) shown in percentage by volume (%), sulphur oxides emission (SO_x) and carbon monoxide emission (CO) shown in parts per million (ppm). The degree of late or early injection timing was chosen based on experience in this field of research and was set at values expressed in negative or positive degrees of crankshaft position (°) relative to its position at normal injection timing [0 (all cyl)] as is shown in table 2. the degree chosen was the maximum possible setting in the simulator model and is thus only expressed in later text with respective abbreviations 'EI' for early injection and 'LI' for late injection. Early and late fuel injection fault parameters were introduced in three stages at specific time intervals chosen to give the parameters recorded enough time to stabilize at a relatively constant value. The first stage was early or late fuel injection on one cylinder [EI or LI (1 cyl)], the second stage was early or late fuel injection on three cylinders [EI or LI (3 cyl)] and the third stage was early or late fuel injections in all cylinders [EI or LI (all cyl)]. The turbocharger air filter blockage fault parameter was introduced in four stages at specific time intervals same as the early and late fuel injection fault parameter. The four stages were 10 %, 20 %, 30 % and 40 % turbocharger air filter blockage shown in table 2. The observed time needed for parameter stabilization was two minutes. All of the above-mentioned parameters were simulated under one engine load setting. The engine load simulated is 85 % of maximum continuous rate (MCR). This engine load was chosen based on usual optimum engine load for the specific engine type used in the referent vessel [8, 10].

Table 2. Injection timing and air filter blockage degree relative to specific simulation time intervals

T (min)	0:00	2:00	4:00	6:00	8:00
Injection Timing (Early)	0 (all cyl)	EI (1 cyl)	EI (3 cyl)	EI (all cyl)	/
Injection timing (Late)	0 (all cyl)	LI (1 cyl)	LI (3 cyl)	LI (all cyl)	/
Turbocharger Air Filter Blockage	0	10	20	30	40

3 RESULTS AND DISCUSSION

The goal of this research is to test whether injection timing has any significant impact on exhaust gas emission and to compare it to another potential main engine fault, in the case of this paper, turbocharger air filter blockage. The results of the research are shown through several different parameters (average cylinder exhaust temperature, $CO/SO_x/CO_2$ emission, fuel oil consumption). The data accumulated in the late injection fault simulation is shown in table 3.

Table 3. Effect of late injection timing (LI) on specific parameters

Injection timing	EG Cyl Avg [°C]	CO [ppm]	SO_x [ppm]	CO_2 [%]	FOC [L/h]
0 (all cyl)	258.50	82.50	28.60	4.49	2142.95
LI (cyl 1)	262.51	82.50	28.60	4.49	2159.47
LI (cyl 1, 2, 3)	274.33	83.51	28.60	4.49	2209.84
LI (all cyl)	293.64	84.51	28.60	4.49	2292.79

In the late injection simulation average cylinder exhaust gas temperature, CO, SO_x, CO_2, and FOC parameters increase, or decrease, was analyzed with respect to their reference values at the normal injection timing (0 all cyl) for all cylinders. While there is no significant effect shown in the three exhaust gas compound emissions there is an increase in both average cylinder exhaust gas temperature and main engine fuel consumption. Average cylinder exhaust temperature increases with every additional cylinder late injection fault and is shown in figure 2. However, a more important effect could be the slight increase in main engine fuel consumption which is also present at every additional late injection fault as is shown in figure 3.

After observing the two afore mentioned parameters it can be concluded that the increase in average cylinder exhaust temperature is proportional to the increase of main engine fuel consumption.

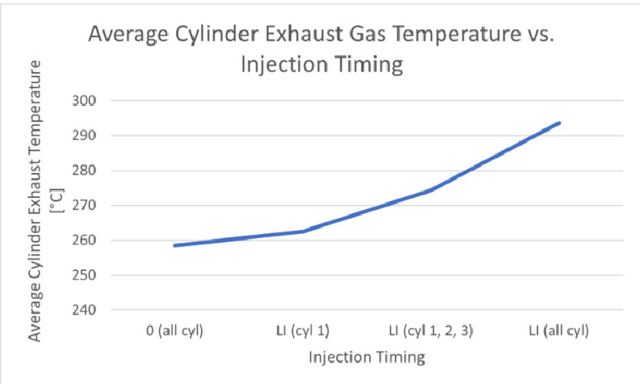

Figure 2. Average cylinder exhaust temperature vs. injection timing in the late injection scenario

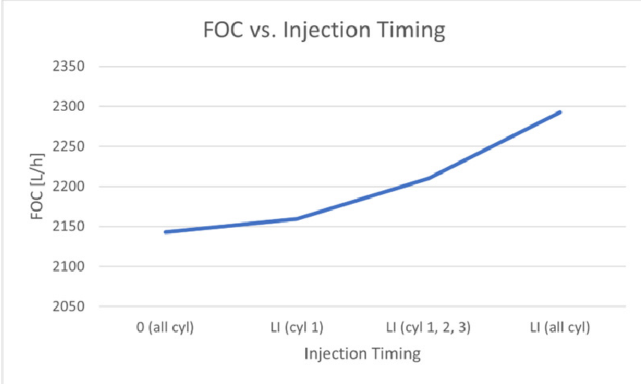

Figure 3. Fuel oil consumption (FOC) vs. injection timing in the late injection scenario

The second simulated scenario is opposite to the first, i.e., early injection simulated for zero, one three and all cylinders. The data accumulated in this simulation is shown in table 4.

Table 4. Effects of early injection timing (EI) on specific parameters

Injection timing	EG Cyl Avg [°C]	CO [ppm]	SO_x [ppm]	CO_2 [%]	FOC [L/h]
0 (all cyl)	258.50	82.50	28.60	4.49	2149.95
EI (cyl 1)	253.63	82.48	28.60	4.49	2115.48
EI (cyl 1, 2, 3)	246.66	82.48	28.60	4.49	2086.93
EI (all cyl)	236.77	80.59	28.60	4.49	2048.66

The parameters are, as before, compared to their respective reference values at normal injection timing for all cylinders (0 all cyl). Again, there is no significant effect on direct exhaust emissions. However, a reversely proportional effect can be seen on exhaust gas temperature and main engine fuel consumption when compared to the late injection simulation parameters. The decrease in exhaust gas temperature seems to be proportional to the decrease in main engine fuel consumption as can be seen in figures 4 and 5.

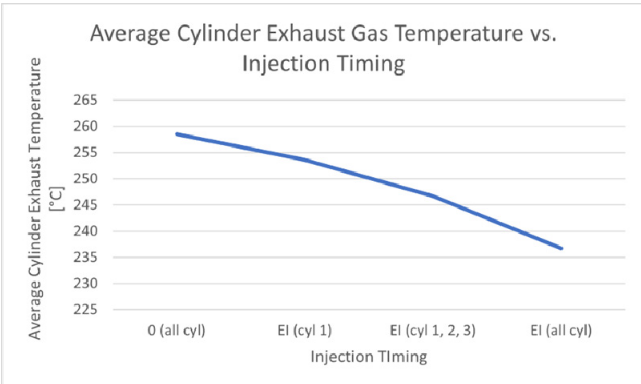

Figure 4. Average cylinder exhaust temperature vs. injection timing in the early injection scenario

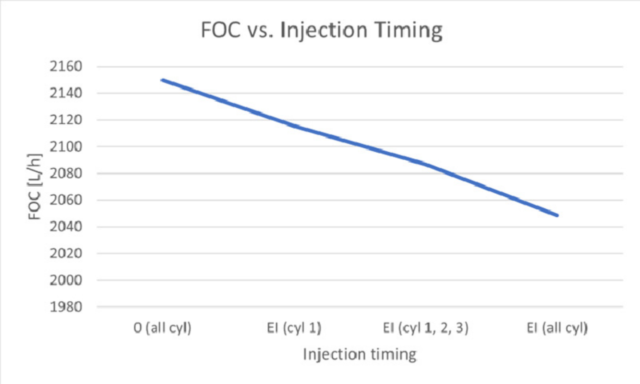

Figure 5. Fuel oil consumption (FOC) vs. injection timing in the early injection scenario

The third and last simulated scenario was that of another main engine fault, more precisely turbocharger air filter blockage. The purpose of this was to compare the emission and other parameters of the first two simulated scenarios to a different situation where there might be a more significant impact on several or all tested parameters. The data accumulated during this simulation is shown in table 5.

Table 5. Effects of turbocharger air filter blockage on specific parameters

Air filter blockage [%]	EG Cyl Avg [°C]	CO [ppm]	SO_X [ppm]	CO_2 [%]	FOC [L/h]
0	258.50	82.50	28.60	4.49	2142.95
10	274.17	92.57	31.08	4.75	2134.77
20	292.42	101.61	33.53	4.75	2137.33
30	353.41	106.60	38.95	5.62	2157.90
40	286.34	64.02	31.70	4.76	917.95

The parameters in this simulation are as well compared to their respective reference values at zero percent (0) turbocharger air filter blockage. In the case of carbon monoxide, sulphur oxide and carbon dioxide direct emissions there is a significant increase in all three compounds as is shown in figures 6 and 7.

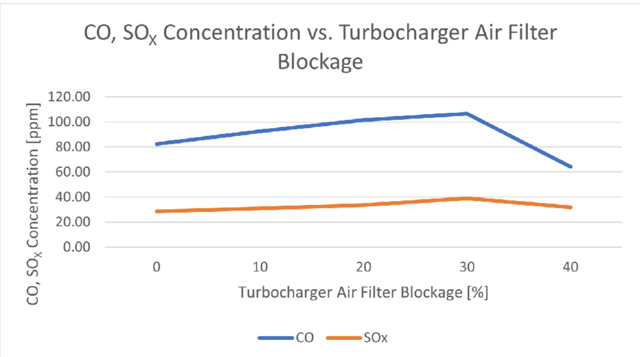

Figure 6. CO, SO_X concentration vs. turbocharger air filter blockage in the air filter blockage scenario

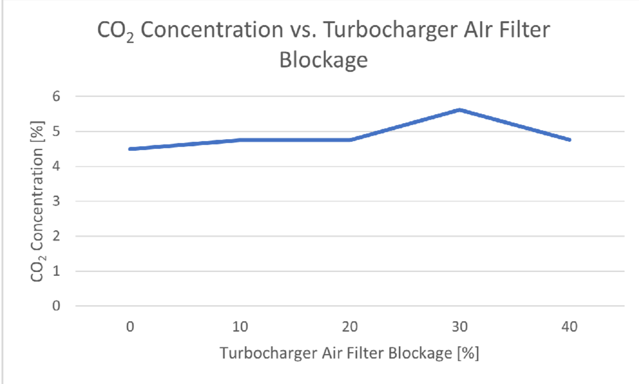

Figure 7. CO_2 concentration vs. turbocharger air filter blockage in the air filter blockage scenario

The decrease shown at 40 % air filter blockage is due to the main engine going into slow down and therefore the average cylinder exhaust temperature and main engine fuel consumption also decrease in this step of the simulation process. Average cylinder exhaust temperature, shown in figure 8, displays a constant increase from 0% to 30 % air filter blockage. Main engine fuel consumption slightly decreases when going from 0 % to 10 % air filter blockage but later steadily increases during the steps from 10 % to 20 % and from 20 % to 30 % air filer blockage. Main engine fuel consumption is shown in figure 9.

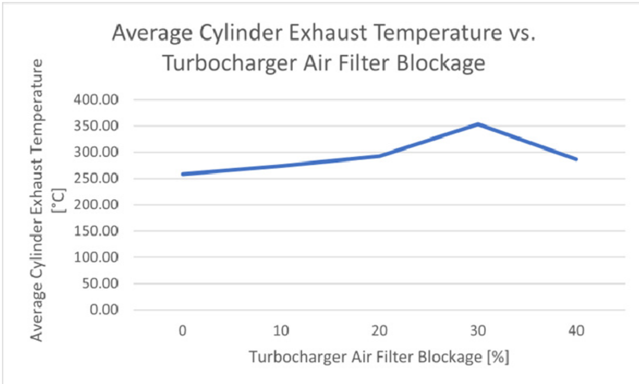

Figure 8. Average cylinder exhaust temperature vs. turbocharger air filter blockage in the air filter blockage scenario

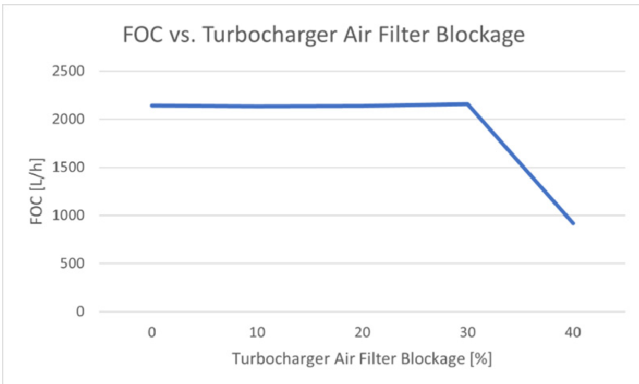

Figure 9. Fuel oil consumption (FOC) vs. turbocharger air filter blockage in the air filter blockage scenario

The large difference this specific fault displays when compared to the first two simulations is the increase in direct measured exhaust gas component emissions.

4 CONCLUSIONS

The results of this research were effective at proving that early and late fuel injection in a slow speed two stroke diesel engine has little to no effect on increased direct exhaust gas emissions. The results of introducing early and late injection fault were compared with the turbocharger air filter blockage fault to present the simulated model where there is a significant effect on direct exhaust gas emission manifested in the increase of emitted harmful and greenhouse compounds. However, it can be argued that the increase in main engine fuel consumption with the late fuel injection condition could lead to overall increased exhaust gas emissions on specific voyages. Considering that the prevalent fuels used in maritime transportation are still fossil fuels this leads to increased greenhouse gas and pollutant emissions. The results have shown that energy efficiency is, therefore, impacted by the degree of late fuel injection. The improved propulsion efficiency and reduced daily fuel consumption could be achieved by planned maintenance and fault diagnostics when taking early and late fuel injection into consideration. Moreover, the optimal frequency of main engine component maintenance could be selected depending on differences in the afore mentioned parameters. The data in this research can be used to further analyze the maritime vessel exploitation economy and to improve main engine maintenance strategies.

REFERENCES

[1] Imperato, M., Kaario, O., Larmi, M. et al. Emission reduction methods and split fuel injection in a marine four-stroke engine. J Mar Sci Technol 23, 94–103 (2018). https://doi.org/10.1007/s00773-017-0458-6

[2] Stratsianis, V., et al., Effects of Fuel Post-Injection on the Performance and Pollutant Emissions of a Large Marine Engine, Journal of Energy Engineering 142(2), DOI: 10.1061/(ASCE)EY.1943-7897.0000337

[3] Huaiyu Wang, Huibing Gan, Gerasimos Theotokatos,;Parametric investigation of pre-injection on the combustion, knocking and emissions behaviour of a large marine four-stroke dual-fuel engine, Fuel, Volume 281, 2020,118744, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2020.118744.

[4] Nemati, A., Ong, J. C., Pang, K. M., Mayer, S., & Walther, J. H. (2022). A numerical study of the influence of pilot fuel injection timing on combustion and emission formation under two-stroke dual-fuel marine engine-like conditions. Fuel, 312, https://doi.org/10.1016/j.fuel.2021.122651

[5] Lewinska, J. The influence of fuel injection pump malfunctions of a marine 4-stroke Diesel engine on composition of exhaust gases. Combustion Engines. 2016, 167(4), 53-57. doi :10.19206/CE-2016-405

[6] Anantharaman, M.; Khan, F.; Garaniya, V.; Lewarn, B. Reliability Assessment of Main Engine Subsystems Considering Turbocharger Failure as a Case Study, TransNav 2018, 12, 271–276

[7] Knežević V, Orović J, Stazić L, Čulin J. Fault Tree Analysis and Failure Diagnosis of Marine Diesel Engine Turbocharger System. Journal of Marine Science and Engineering. 2020; 8(12):1004. https://doi.org/10.3390/jmse8121004

[8] ERS 5000 TechSim MAN B&W 6S60MC-C Diesel Engine – Tanker LCC (Aframax) Trainee Manual, November 2014, Wärtsilä Voyage Limited.

[9] Vukičević M. et. al., Analysis of the Influence of Preventive Maintenance of Main Engines on Working Parameters and Emissions, Fifth conference ˇMaintetnance 2018", Zenica, 10. May 2018.

[10] MAN B&W S60MC-C8-TII Project guide - Camshaft Controlled Two-stroke Engines, 1st Edition, MAN Diesel & Turbo, Augsburg, Germany, 2010.