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MARINE SLOW SPEED TWO-STROKE DIESEL ENGINE - NUMERICAL ANALYSIS OF EFFICIENCIES AND IMPORTANT OPERATING PARAMETERS

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Abstract: *This paper presents numerical analysis of efficiencies and non-measured operating parameters for the marine two-stroke slow speed turbocharged diesel engine 6S50MC MAN B&W with direct fuel injection. Numerical analysis was based on a measurement set performed at different engine loads. Calculated efficiencies were mechanical, indicated and effective efficiency, while the calculated important operating parameters were power of engine mechanical losses, mean effective pressure, effective engine torque and specific effective fuel consumption. Engine load was presented in percentage of maximum continuous rating (MCR). The highest engine mechanical efficiency of 94.52 % was obtained at the highest engine load, while the highest engine effective efficiency of 49.34 % was obtained at the engine load 75 % of MCR. Available engine effective torque was from 267380 Nm on the lowest up to 643594 Nm on the highest engine load, while effective fuel consumption was between 171.18 g/kWh and 186.83 g/kWh.*

Keywords: *MARINE DIESEL ENGINE, TWO-STROKE PROCESS, EFFICIENCIES, OPERATING PARAMETER ANALYSIS*

1. Introduction

Experimental measurements are the basis of internal combustion engines operating parameters analysis [1], regardless of the engine type. By using several engine measured variables can be obtained a complete insight into engine general operating parameters, in a wide load range [2]. Numerous researchers are involved in the investigation of the diesel engines from the several points of view [3].

Marine slow speed two-stroke diesel engines, compared to the other diesel engines, are characterized by their construction, dimensions, operating processes and start-up process. Because of the high pressures and temperatures, the materials used in such engines for a large number of engine components, cannot be conventional ones [4].

Several researchers were involved in the development of numerical models for marine two-stroke diesel engines [5], in order to predict their operating parameters during the propulsion [6] or to get an insight into the details of in-cylinder processes [7] such as convective heat transfer [8].

Marine two-stroke diesel engines are turbocharged engines and it is interesting to investigate turbocharging process and its influence on engine performance [9].

To improve marine two-stroke diesel engine operating parameters and reduce emissions, numerous investigations were performed in order to implement alternative fuel combustion [10], using bio-fuel blends for combustion [11] or using standard diesel fuels with some additives [12] in this type of engines.

For this type of diesel engines were also investigated some of the known techniques from automotive diesel engines for reducing nitrogen oxides (NO_x) emissions, as for example Exhaust Gas Recirculation (EGR) [13]. It is also important to know maximum NO_x reduction potential of two-stroke marine diesel engines [14] by using EGR. Along with nitrogen oxides, for marine slow speed two-stroke diesel engines was also investigated soot emission [15] and possibilities of soot emission reduction.

This paper presents change in efficiencies and the main operating parameters of marine slow speed two-stroke diesel engine 6S50MC MAN B&W. Operating parameters and efficiency analysis was based on a measurement set performed at different engine loads (from the lowest to the highest load). For each engine operation point, by using measured parameters, was performed calculation of mechanical losses power, mean effective engine pressure, engine effective torque and engine specific effective fuel consumption. On this way was gained an insight into the change of these engine operating parameters during the whole range of observed loads. Calculated engine efficiencies and their change during the change in engine load were engine mechanical efficiency, engine indicated efficiency and on the end engine effective efficiency. This analysis confirmed that marine slow speed two-stroke diesel engines are the internal combustion engines with the highest effective efficiency and the lowest specific effective fuel consumption, during the complete load range.

2. Slow speed marine diesel engine specifications

Analyzed marine diesel engine is a slow speed turbocharged two-stroke engine with direct fuel injection 6S50MC MAN B&W. The main engine specifications are presented in Table 1.

Table 1. *Specifications of marine slow speed two-stroke diesel engine 6S50MC MAN B&W [16]*

Number of cylinders	6 in line
Cylinder bore	500 mm
Cylinder stroke	1910 mm
Firing order	1-5-3-4-2-6
Maximum continuous rating (MCR)	8580 kW
Engine speed at MCR	127 rpm
Maximum mean effective pressure	18 bar
Maximum combustion pressure	143 bar
Compression ratio	17.2
Crank mechanism ratio	0.436
Exhaust manifold volume	6.13 m^3
Inlet manifold volume (with intercooler)	7.179 m^3
Cumulative engine mass	232000 kg

A cross section of the analyzed marine diesel engine 6S50MC MAN B&W is presented in Fig.1. In Fig.1 can be seen all of the housing and cylinder main elements. The engine was built in a diesel engine factory in Split, Croatia, according to the license MAN B&W.

3. Engine measurement results

The main operating data of the marine diesel engine 6S50MC MAN B&W were obtained by test-bed measurements in Shipyard Split, Croatia. Engine load was presented in percentage of maximum continuous rating (MCR), Table 1. The measured values for the engine steady state operation at engine loads 25 %, 50 %, 75 %, 93.50 % and 100 % of MCR was presented in Table 2.

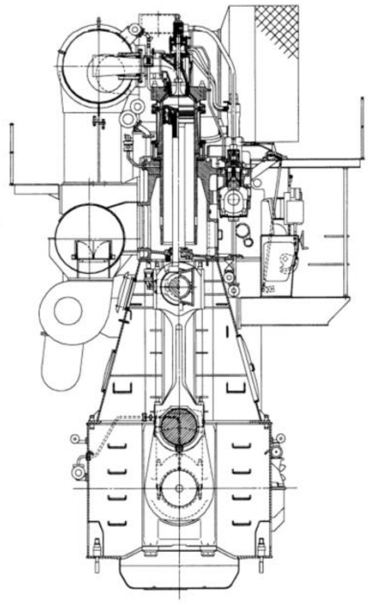

Fig.1. *Cross section of marine slow speed two-stroke diesel engine 6S50MC MAN B&W [17]*

Table 2. *6S50MC MAN B&W measured data [16]*

Load (% of MCR)	Indicated power (kW)	Effective power (kW)	Mean indicated pressure (bar)	Rotational speed (rpm)	Fuel mass flow (kg/h)
25 %	2401	2142	8.37	76.5	400.2
50 %	4406	4099	12.24	96.0	713.5
75 %	6580	6160	15.89	110.4	1054.5
93.50 %	8170	7667	18.38	118.5	1317.3
100 %	8656	8182	19.01	121.4	1429.1

The measurements were performed during the following environmental conditions:

- Ambient temperature 30 °C,
- Ambient pressure 1005 mbar,
- Relative humidity 50 %.

The engine was tested with a standard marine diesel fuel, whose properties are:

- Density 844.7 kg/m^3,
- Kinematic viscosity 3.03 mm^2/s,
- Sulfur content 0.45 %,
- Lower heating value 42625 kJ/kg.

4. Equations for calculating engine efficiencies and operating parameters

Power of mechanical losses for each operating point of the analyzed engine should be calculated as a difference between measured indicated and effective power, Table 2:

$$P_{\mathrm{ml}} = P_{\mathrm{ind}} - P_{\mathrm{eff}} \tag{1}$$

where P_{ml} (kW) is power of mechanical losses, P_{ind} (kW) is measured indicated power and P_{eff} (kW) is measured effective power.

Engine mechanical efficiency was calculated by using an equation:

$$\eta_{\mathrm{m}} = \frac{P_{\mathrm{eff}}}{P_{\mathrm{ind}}} \cdot 100 \tag{2}$$

where η_{m} (%) is engine mechanical efficiency.

Indicated engine efficiency is the ratio of engine indicated power and heat released by fuel. Indicated engine efficiency was calculated according to the equation:

$$\eta_{\mathrm{ind}} = \frac{P_{\mathrm{ind}}}{\dot{m}_{\mathrm{f}} \cdot H_{\mathrm{low}}} \cdot 3600 \cdot 100 \tag{3}$$

where η_{ind} (%) is engine indicated efficiency, $\dot{m}_{\mathrm{f}}$ (kg/h) is measured fuel mass flow - Table 2 and H_{low} (kJ/kg) is used fuel lower heating value.

Effective engine efficiency is the ratio of engine effective power and heat released by fuel. Effective engine efficiency was calculated according to the equation:

$$\eta_{\mathrm{eff}} = \frac{P_{\mathrm{eff}}}{\dot{m}_{\mathrm{f}} \cdot H_{\mathrm{low}}} \cdot 3600 \cdot 100 \tag{4}$$

where η_{eff} (%) is engine effective efficiency.

Engine mean effective pressure was calculated by using an equation:

$$p_{\mathrm{me,eff}} = \frac{P_{\mathrm{eff}} \cdot \tau}{2 \cdot z \cdot n \cdot V_{\mathrm{op}}} \cdot \frac{6}{10} \tag{5}$$

where $p_{\mathrm{me,eff}}$ (bar) is engine mean effective pressure, τ (-) is engine stroke - analyzed engine is two-stroke engine so $\tau = 2$, z (-) is number of engine cylinders - Table 1, n (rpm) is measured engine rotational speed - Table 2 and V_{op} (m^3) is operating volume of one engine cylinder which can be calculated according to the equation:

$$V_{\mathrm{op}} = \frac{D^2 \cdot \pi}{4} \cdot s \tag{6}$$

where D (m) is cylinder bore - Table 1 and s (m) is cylinder stroke - Table 1.

Engine effective torque, which drives the ship's propeller was calculated according to the equation:

$$M_{\mathrm{eff}} = \frac{P_{\mathrm{eff}}}{2 \cdot \pi \cdot n} \cdot 60000 \tag{7}$$

where M_{eff} (Nm) is engine effective torque.

Specific effective fuel consumption was calculated by using an equation:

$$b_{\mathrm{eff}} = \frac{\dot{m}_{\mathrm{f}} \cdot 1000}{P_{\mathrm{eff}}} \tag{8}$$

where b_{eff} (g/kWh) is engine specific effective fuel consumption.

5. Engine calculation results for various observed loads and discussion

Fig.2 presents the power of mechanical losses calculated by using equation (1) and mechanical efficiency calculated by using equation (2) for all observed loads of the analyzed engine.

Engine power of mechanical losses is the lowest at load 25 % of MCR and amounts 259 kW, while the highest power of mechanical losses can be seen at load 93.5 % of MCR where it amounts 503 kW. At the highest engine load 100 % of MCR, power of mechanical losses decrease from the highest value and amounts 474 kW.

The mechanical efficiency of the analyzed engine continuously increases during the increase in engine load. At the lower engine load 25 % of MCR, mechanical efficiency is the lowest and amounts 89.21 %, while on the highest engine load 100 % of MCR mechanical efficiency of the engine is the highest and amounts 94.52 %. This is an important fact, because for the analyzed engine it can be expected that the majority of its operation will be obtained at the highest load. Therefore, during the majority of engine operation, mechanical efficiency will be the highest.

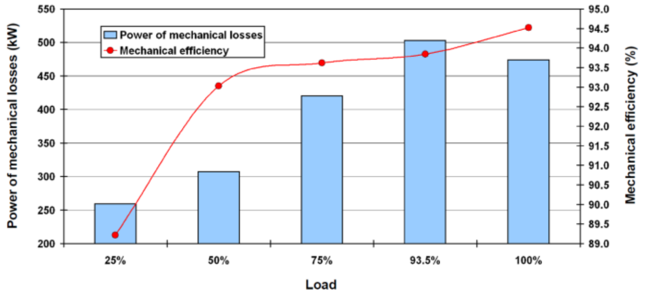

Fig.2. *Change in engine power of mechanical losses and mechanical efficiency for all observed loads*

Analyzed engine indicated efficiency change, calculated according to equation (3) and engine effective efficiency change, calculated according to equation (4) are presented in Fig.3. From the lowest to the highest engine load, both efficiencies have the same trend - they increase until the engine load 75% of MCR after which both of them decreases.

Indicated engine efficiency is the ratio of the engine indicated power and heat released by fuel, so this efficiency presented amount of energy which is transferred from fuel to the engine pistons. At the lowest engine load 25 % of MCR indicated efficiency is the lowest and amounts 50.67 %. Increase in engine load firstly causes an increase of indicated efficiency to a maximum value of 52.70 % at the engine load 75 % of MCR after which follows a decrease in indicated efficiency to 52.38 % (engine load 93.50 % of MCR) and to 51.16 % (engine load 100 % of MCR).

Engine effective efficiency has the lowest value of 45.21 % at the engine load 25% of MCR while the highest effective efficiency amounts 49.34 % at the engine load 75 % of MCR. At the highest engine load 100 % of MCR, effective efficiency amounts 48.36 %. In comparison with all the other types of internal combustion engines, marine slow speed two-stroke diesel engine has significantly higher effective efficiency, which can nowadays reach above 50 % (maximal obtained effective efficiency of marine two-stroke diesel engine is 55 %). Effective efficiency of analyzed diesel engine does not reach 50 % for any observed load, but is very close to that value.

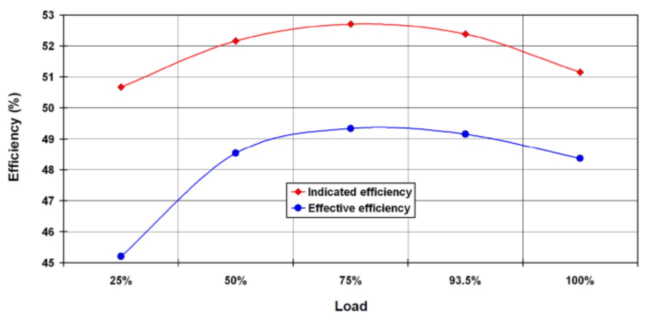

Fig.3. *Change in engine indicated and effective efficiency for all observed loads*

The change in mean effective pressure of the analyzed engine, for all of the observed engine loads was presented in Fig.4. Mean effective engine pressure was calculated according to equation (5) and in Fig.4 was presented along with measured mean indicated engine pressure.

During the increase in engine load, mean effective pressure continuously increases from 7.47 bar at the engine load 25 % of MCR up to 17.97 bar at the engine load 100 % of MCR. At the maximum engine load 100 % of MCR was obtained almost the maximum mean effective pressure, which amounts exactly 18 bar, Table 1.

Measured indicated and calculated effective pressures of the analyzed engine have the same trends during the increase in engine load from the lowest to the highest loads.

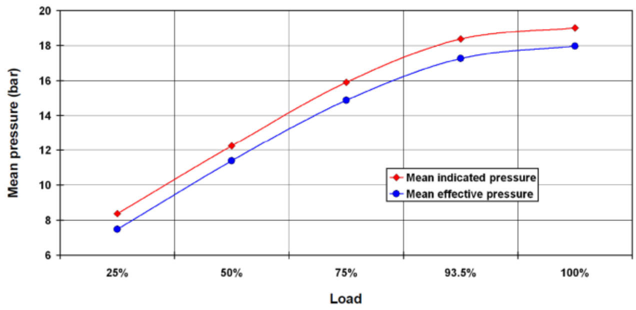

Fig.4. *Change in engine mean indicated and effective pressure for all observed loads*

Engine effective torque, calculated by using equation (7) continuously increases during the increase in engine load, Fig.5. In comparison to other diesel engines, marine slow speed two-stroke diesel engines develop significantly higher engine effective torque which will be used for propulsion propeller drive. One of slow speed marine diesel engine advantages is direct propeller drive, without usage of gearbox, so the developed effective torque was directly transferred to the main ship propeller.

The lowest effective torque analyzed engine develops on the lowest observed load 25 % of MCR, and that effective torque amounts 267380 Nm. On the highest observed engine load 100 % of MCR was developed the highest engine effective torque which amounts 643594 Nm. For marine two-stroke diesel engine, with cylinder bore of 500 mm, this is an expected range of developed effective torque. The highest developed effective torque must be obtained at the highest engine load, because at the highest engine load can be expected the majority of ship operation (maximum ship speed).

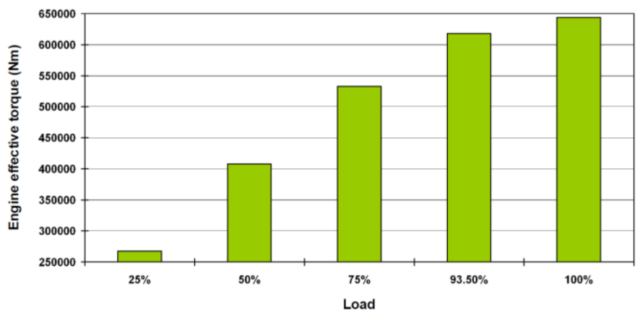

Fig.5. *Change in engine effective torque for all observed loads*

When compared specific effective fuel consumption of the analyzed engine with other diesel engines, for example, with a high speed direct injection turbocharged diesel engine MAN D0826 LOH15 presented in [18], it can be calculated that marine two-stroke diesel engine has much lower specific effective fuel consumption. This is not a fact only for two compared diesel engines, marine two-stroke diesel engines have the lowest specific effective fuel consumption of all diesel engines or of all engines in general. This fact is valid if compared diesel engines which use standard diesel fuel, if diesel engine use the alternative fuels, this conclusion does not have to be correct.

Specific effective fuel consumption of the analyzed engine, calculated by using equation (8), has the same trend like the other diesel engines - during the load increase specific effective fuel consumption firstly decrease to the lowest value, after which follows slight increase, Fig.6. The highest specific effective fuel consumption of the analyzed engine was obtained at the lowest load 25 % of MCR and amounts 186.83 g/kWh. Increase in engine load causes that specific effective fuel consumption decreases and the lowest value were obtained at the engine load 75 % of MCR and amounts 171.18 g/kWh. A further increase in engine load causes an increase in specific effective fuel consumption and at the highest engine load 100 % of MCR specific effective fuel consumption of the analyzed engine amounts 174.66 g/kWh.

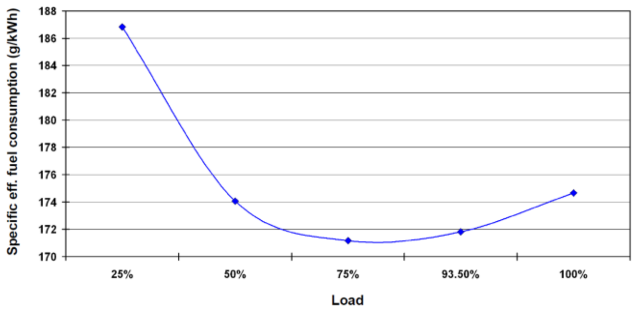

Fig.6. *Change in engine specific effective fuel consumption for all observed loads*

6. Conclusion

Calculated operating parameters and efficiencies of marine slow speed two-stroke diesel engine 6S50MC MAN B&W was analyzed in this paper. Analysis was based on a measurement set performed at different engine loads in order to obtain complete range of main engine parameters and efficiencies change.

Presented calculation method gives for result that the highest engine mechanical efficiency of 94.52 % was obtained at engine load 100 % of MCR. The highest indicated engine efficiency of 52.70 % and the highest engine effective efficiency of 49.34 % were obtained at the engine load 75 % of MCR. In comparison with the other types of internal combustion engines, marine slow speed two-stroke diesel engines have significantly higher effective efficiency which can nowadays reach above 50 %.

The highest power of engine mechanical losses was obtained at engine load 93.50 % of MCR and amounts 503 kW. During the engine load increase, mean effective pressure continuously increases from 7.47 bar at the lowest up to 17.97 bar at the highest observed engine load. The range of available engine effective torque was from 267380 Nm on the lowest up to 643594 Nm on the highest engine load, what is an expected range of developed effective torque for this kind of diesel engine.

The range of analyzed engine specific effective fuel consumption was between 171.18 g/kWh and 186.83 g/kWh. Obtained range of specific effective fuel consumption proves the fact that marine two-stroke diesel engines have the lowest specific effective fuel consumption of all diesel engines or of all engines in general.

7. Acknowledgments

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