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C O N T E N T S

MEAN PRESSURE OF MECHANICAL LOSSES EQUATION FOR MARINE SLOW SPEED TWO-STROKE DIESEL ENGINE

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Abstract: *During the engine experimental investigation usually was obtained engine effective power and rotational speed. In order to obtain engine mechanical efficiency and engine indicated power from experimental data, must be used equation for calculation of engine mean pressure of mechanical losses along with its proper coefficients. This equation gives correct values if engine mechanical efficiency and engine indicated power was obtained in the range ±1.5%, when compared with experimentally obtained ones. For marine slow speed two-stroke diesel engine 6S50MC MAN B&W was analyzed this equation along with its coefficients during the whole range of engine loads. The mean pressure of mechanical losses equation, when obtained coefficients was applied, gives a percentage difference in the range ±0.79% for the engine mechanical efficiency and percentage difference in the range ±0.85% for the engine indicated power when compared with experimentally obtained values. For the higher engine loads presented equation is even more accurate and precise.*

Keywords: *TWO-STROKE DIESEL ENGINE, MEAN PRESSURE OF MECHANICAL LOSSES, MECHANICAL EFFICIENCY, INDICATED POWER*

1. Introduction

Marine slow speed two-stroke diesel engines, compared to the other diesel engines, are characterized by their construction, dimensions and operating process. For a large number of engine components, the materials used in such engines cannot be of conventional type [1].

Development of numerical models for marine two-stroke diesel engine simulation is nowadays one of the goals for scientists [2] to be able to predict their operating parameters during the propulsion [3] or to get an insight into the details of in-cylinder processes [4] such as convective heat transfer [5].

To improve marine two-stroke diesel engine operating parameters and reduce their emissions, numerous investigations were performed in order to implement alternative fuel combustion [6], using bio-fuel blends for combustion [7] or using standard diesel fuels with some additives [8] in this type of engines.

For marine two-stroke diesel engines were also investigated some of the known techniques from automotive diesel engines for reducing nitrogen oxides (NO_x) emissions, as for example EGR (Exhaust Gas Recirculation) [9]. It is also important to know maximum NO_x reduction potential of two-stroke marine diesel engines [10] by using EGR. Along with nitrogen oxides, for marine slow speed two-stroke diesel engines was also investigated soot emission [11] and possibilities of soot emission reduction.

In this paper was investigated mean pressure of mechanical losses equation for calculating analyzed marine slow speed two-stroke diesel engine 6S50MC MAN B&W mechanical efficiency and indicated power. During the engine measurements, usually obtained parameters are engine effective power and rotational speed, for a wide range of engine loads. By using engine effective power, engine rotational speed and engine geometrical specifications along with the equation proposed in this paper can be calculated indicated engine power and engine mechanical efficiency. For the whole observed range of the engine loads, engine mechanical efficiency and indicated power calculated by proposed equation can deviate in the range of ±1.5% in comparison with values obtained during the experiment (usual deviation range of engine operating parameters calculation). For the analyzed engine was obtained measurement results of both effective and indicated engine power, for each observed engine load [12]. The calculated values were compared with experimentally obtained ones in order to analyze the accuracy and precision of the proposed equation for the mean pressure of mechanical losses calculation. Analyzed engine is used for propulsion on the chemical tanker, which specifications are presented in Table 1.

Table 1. *Main characteristics and parameters of chemical tanker with analyzed propulsion engine*

Dead weight tonnage	46000 DWT
Overall length	82.90 m
Max breadth	32.20 m
Design draft	12.00 m
Maximum draft	17.20 m
Guaranteed speed	15.5 knots

2. Marine two-stroke slow speed diesel engine main characteristics

Marine diesel engine analyzed in this paper is a slow speed turbocharged two-stroke engine with direct fuel injection 6S50MC MAN B&W. The main engine specifications are presented in Table 2.

Table 2. *Specifications of marine slow speed two-stroke diesel engine 6S50MC MAN B&W [12]*

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

Cross section of marine diesel engine 6S50MC MAN B&W is presented in Fig. 1. In Fig. 1 can be seen all 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.

The ambient conditions during the measurements were:

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

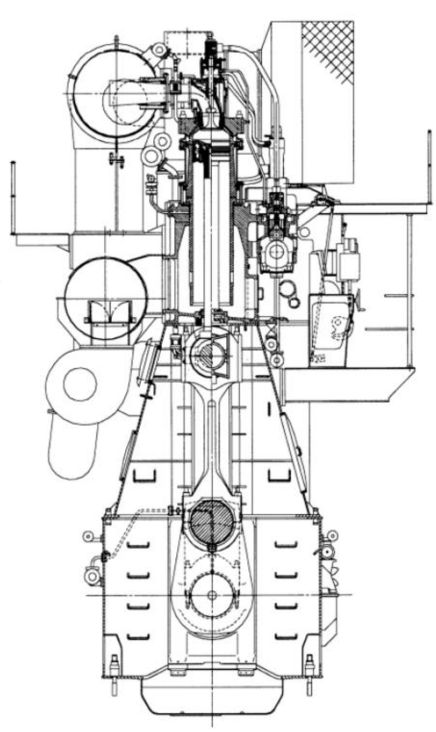

Fig. 1. Cross section of marine slow speed two-stroke diesel engine 6S50MC MAN B&W [13]

The engine measurements were performed 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 42.625 MJ/kg.

Engine load was presented in percentage of maximum continuous rating (MCR), Table 2. The measured values for the engine steady state operation at engine loads 25%, 50%, 75%, 93.5% and 100% of MCR was presented in Table 3.

***Table 3.** 6S50MC MAN B&W measured data [12]*

Load (% of MCR)	Indicated power (kW)	Effective power (kW)	Rotational speed (rpm)	Fuel mass flow (kg/h)
25%	2401	2142	76.5	400.2
50%	4406	4099	96.0	713.5
75%	6580	6160	110.4	1054.5
93.5%	8170	7667	118.5	1317.3
100%	8656	8182	121.4	1429.1

4. The equation for the mean pressure of mechanical losses calculation

4.1. Mechanical efficiency according to experimental measurements

For the analyzed slow speed two-stroke marine diesel engine, during the measurements, Table 3, was obtained indicated and effective engine power. Engine indicated power was developed in the engine cylinders in comparison with engine effective power which is used for propulsion propeller drive. Therefore, engine effective power can be measured much easier at the engine crankshaft outlet. Measurements with obtained both indicated and effective engine powers for a range of engine loads are very rare.

If the indicated and effective engine power were obtained during the experimental measurements, it is easy to obtain engine power of mechanical losses and engine mechanical efficiency according to equations:

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

where P_{ml} is power of engine mechanical losses, P_{ind} is measured engine indicated power and P_{eff} is measured engine effective power,

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

where η_{m} is engine mechanical efficiency, η_{eff} is engine effective efficiency and η_{ind} is engine indicated efficiency.

According to measured indicated and effective power, Table 3, and by using equation (2), was calculated engine real (experimentally obtained) mechanical efficiency. This real mechanical efficiency was compared with mechanical efficiency for the same engine obtained by using the equation for the mean pressure of mechanical losses, for each observed engine load.

4.2. Mechanical efficiency by using the equation for mean pressure of mechanical losses

Usually, during the experimental measurements of any engine was obtained only engine effective power (by using engine braking) and engine rotational speed. If not measured, engine indicated power can be calculated from engine mechanical efficiency, in order to get an insight into the engine mechanical losses and to determine the amount of energy transferred from the fuel to the engine pistons. It will be assumed that engine indicated power, for any observed engine load, is not known, so it will be calculated by using measured engine effective power and engine measured rotational speed along with known engine geometrical parameters.

Engine mechanical efficiency can also be defined as:

$$\eta_{\mathrm{m}} = \frac{\eta_{\mathrm{eff}}}{\eta_{\mathrm{ind}}} = \frac{p_{\mathrm{me,eff}}}{p_{\mathrm{me,ind}}} = \frac{p_{\mathrm{me,eff}}}{p_{\mathrm{me,eff}} + p_{\mathrm{me,ml}}} \tag{3}$$

where $p_{\mathrm{me,ind}}$ is engine mean indicated pressure, $p_{\mathrm{me,eff}}$ is engine mean effective pressure and $p_{\mathrm{me,ml}}$ is engine mean pressure of mechanical losses.

At any engine load, mean effective pressure can be calculated by using an equation:

$$p_{\mathrm{me,eff}} = \frac{P_{\mathrm{eff}} \cdot \tau}{2 \cdot z \cdot n \cdot V_{\mathrm{op}}} \tag{4}$$

where τ is engine stroke - analyzed engine is two-stroke engine so τ = 2, z is number of engine cylinders, n is measured engine rotational speed and V_{op} is operating volume of one engine cylinder which can be calculated according to the equation:

$$V_{\mathrm{op}} = \frac{D^2 \cdot \pi}{4} \cdot s \tag{5}$$

where D is cylinder bore and s is cylinder stroke.

Engine mean pressure of mechanical losses is not the real, measurable variable, it is just numerical auxiliary variable which allows calculation of engine mechanical efficiency, according to equation (3). Engine mean pressure of mechanical losses can be calculated according to few empirical equations. In any empirical equations all of the input and output variables must be in precisely defined measuring units, which has to be defined under the presented equation. One of the few empirical equations for engine mean pressure of mechanical losses calculation has the form:

$$p_{\mathrm{me,ml}} = k_1 \cdot \left(1 + \frac{1}{z}\right) + \frac{3}{D} + k_2 \cdot p_{\mathrm{me,eff}} + k_3 \cdot c_{\mathrm{s}} \tag{6}$$

From the above equation (6), mean pressure of mechanical losses will be obtained in (MPa) if in the equation was put variables in following measuring units:

- Cylinder bore D in (mm),
- Number of engine cylinders z in (-),
- Engine mean effective pressure $p_{\mathrm{me,eff}}$ in (MPa),
- Medium piston speed c_{s} in (m/s).

Coefficients k_1, k_2 and k_3 are constants which are defined usually for the whole set of similar internal combustion engines. Based on the whole set of diesel engines for the road vehicles drive, these coefficients are:

$$k_1 = 0.06 \quad (7)$$

$$k_2 = 0.03 \quad (8)$$

$$k_3 = 0.015 \quad (9)$$

Medium piston speed c_s should be calculated by using an equation:

$$c_s = 2 \cdot s \cdot n \quad (10)$$

where s is cylinder stroke and n is engine rotational speed.

Equation (6) gives correct values for engine mean pressure of mechanical losses if engine mechanical efficiency and engine indicated power was obtained in the range ±1.5%, when compared with experimentally obtained ones.

The main goal of this paper is to obtain correct coefficients k_1, k_2 and k_3 for the analyzed slow speed two-stroke diesel engine. It is not a problem to obtain correct coefficients for one engine operating load, therefore the aim will be to obtain coefficients for all of the observed engine loads, within the recommended accuracy limits.

After the conducted mathematical analysis, for the marine slow speed two-stroke diesel engine was obtained the following coefficients:

$$k_1 = 0.0384 \quad (11)$$

$$k_2 = 0.018 \quad (12)$$

$$k_3 = 0.004 \quad (13)$$

The accuracy and precision of obtained coefficients for the equation (6) for marine slow speed diesel engine will be tested and compared with the experimentally obtained engine mechanical efficiency and engine indicated power for the complete range of engine loads.

5. Engine mechanical efficiency and indicated power calculated with developed equation - comparison with measurement results

The mean pressure of mechanical losses for marine slow speed two-stroke diesel engine was calculated by using equation (6) and coefficients obtained for the analyzed engine, equations (11), (12) and (13). Engine mean pressure of mechanical losses was calculated for each observed engine load, in order to present a proper analysis of obtained coefficients and to determine accuracy and precision of proposed equation.

The values for the mean pressure of mechanical losses continuously increase during the increase in engine load, Fig. 2. The lowest mean pressure of mechanical losses value was calculated at the lowest engine load 25% of MCR and amounts 0.0837 MPa, while the highest value was calculated at the highest engine load 100% of MCR and amounts 0.1141 MPa. The average value of mean pressure of mechanical losses for the complete range of engine loads is equal to 0.1023 MPa.

Accuracy and precision of mean pressure of mechanical losses values can be seen when this variable is used for calculation of engine mechanical efficiency and engine indicated power for each observed engine load.

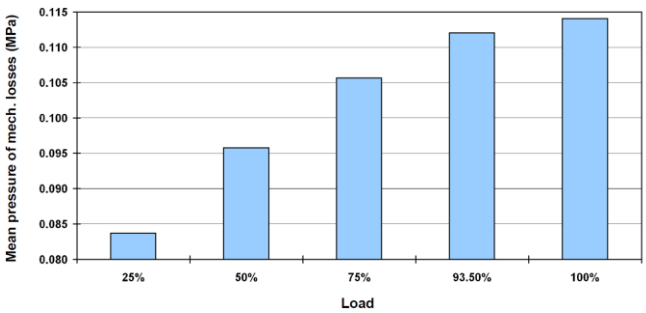

Fig. 2. *Change in engine mean pressure of mechanical losses for analyzed loads*

Marine two-stroke diesel engine mechanical efficiency obtained by experiment and by calculation was presented in Table 4. Experimentally obtained engine mechanical efficiency was calculated according to equation (2) by using measured indicated and measured effective engine power.

Calculated engine mechanical efficiency was obtained by using equation (3). The main parameters of equation (3) are engine mean effective pressure and mean pressure of mechanical losses. Both of these parameters were calculated for each observed engine load.

Table 4. *Engine mechanical efficiency - experimental and calculated values*

Load (% of MCR)	**25%**	**50%**	**75%**	**93.5%**	**100%**
Mechanical efficiency-experiment (%)	89.21	93.03	93.62	93.84	94.52
Mechanical efficiency-calculated (%)	89.92	92.24	93.37	93.90	94.03

Fig. 3 presents the percentage difference between calculated and experimentally obtained mechanical efficiency of the analyzed engine. Percentage difference for all of the observed loads is in the range from -0.79% up to +0.70%, which is within the target range of ±1.5%. According to calculated engine mechanical efficiency, presented equation for the mean pressure of mechanical losses calculation gives a satisfactory accuracy and precision.

The largest deviations between calculated and experimentally obtained engine mechanical efficiency can be seen at the lower engine loads (25% and 50% of MCR), Fig. 3. For the higher engine loads (75%, 93.5% and 100% of MCR) percentage difference between calculated and experimentally obtained engine mechanical efficiency is in the range of ±0.50%. This is an important conclusion because the majority of engine operation, during the ship navigation, will be on the higher engine loads. Therefore, presented equation for the mean pressure of mechanical losses calculation can be used with accuracy and precision much higher than expected ones, for the most of analyzed diesel engine operating time.

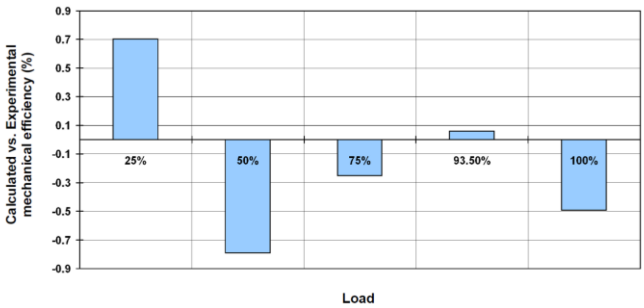

Fig. 3. *Percentage difference between calculated and experimental engine mechanical efficiency for analyzed loads*

Analyzed engine indicated power obtained by experiment and by calculation was presented in Table 5. Experimentally obtained engine indicated power was shown in Table 3, while calculated engine indicated power was obtained by using equation (2). In equation (2) engine effective power was obtained by experiment - Table 3, and engine mechanical efficiency was calculated by using equation (3) where was used the mean pressure of mechanical losses proposed equation and its coefficients.

The percentage difference between calculated and experimentally obtained indicated power of the analyzed engine is presented in Fig. 4. Percentage difference for all of the observed loads is in the range from -0.79% up to +0.85%, which is within the target range of ±1.5%. It is concluded before that according to calculated engine mechanical efficiency, presented equation for the mean pressure of mechanical losses calculation gives a satisfactory accuracy and precision which is also valid for calculated engine indicated power.

__Table 5.__ Engine indicated power - experimental and calculated values

Load (% of MCR)	25%	50%	75%	93.5%	100%
Indicated engine power-experiment (kW)	2401	4406	6580	8170	8656
Indicated engine power-calculated (kW)	2382.2	4443.7	6597.6	8164.9	8701.3

The largest deviations between calculated and experimentally obtained engine indicated power can be seen at the lower engine loads (25% and 50% of MCR), Fig. 4. For the higher engine loads (75%, 93.5% and 100% of MCR) percentage difference between calculated and experimentally obtained engine indicated power is in the range of ±0.53%. Presented equation for the mean pressure of mechanical losses calculation can be used with accuracy and precision much higher than expected ones, for the most of marine two-stroke diesel engine operating time also from the viewpoint of calculated indicated power.

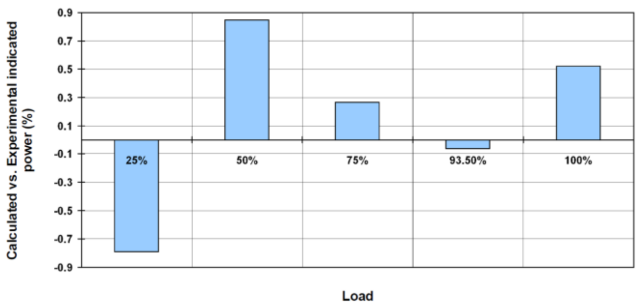

Fig. 4. *Percentage difference between calculated and experimental engine indicated power for analyzed loads*

6. Conclusions

During the internal combustion engine experimental investigation, by using engine braking, was obtained engine effective power (power transferred to power consumer) and engine rotational speed. By using only engine effective power cannot be known engine mechanical losses or the amount of energy transferred from fuel during combustion to engine pistons (indicated engine power).

In this paper was investigated empirical equation for calculating engine mean pressure of mechanical losses. This is not the real, measurable pressure, but auxiliary calculation variable, which can be used for calculation of engine mechanical efficiency and engine indicated power from measured engine effective power, measured engine rotational speed and known engine geometrical parameters.

The equation for the mean pressure of mechanical losses calculation gives correct values if engine mechanical efficiency and engine indicated power was obtained in the range ±1.5%, when compared with experimentally obtained ones. This fact must be valid for the whole engine operating range (for all observed engine loads).

For the analyzed marine slow speed diesel engine, the equation for the mean pressure of mechanical losses calculation, when obtained coefficients was applied, gives a percentage difference in the range ±0.79% for engine mechanical efficiency and percentage difference in the range ±0.85% for the engine indicated power when compared with experimentally obtained values. For the higher analyzed engine loads presented equation for the mean pressure of mechanical losses calculation gives percentage difference for mechanical efficiency and engine indicated power in the range of ±0.53%, what is important fact because the majority of analyzed diesel engine operation can be expected on higher loads.

Presented equation for the mean pressure of mechanical losses calculation can be helpful to the ship crew for easy and fast analysis of the current engine parameters and mechanical losses.

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