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# ANALYSIS AND EVALUATION OF THE WORKING CYCLE OF THE DIESEL ENGINE

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***Abstract***

*The paper presents a proposal to apply a quantitative evaluation of the diesel engine with regard to the phenomena occurring during of a working cycle. The proposed procedure when analyzing test results from diesel engine is an attempt to transfer an engine activity evaluation methods in the operational time scale (exploit time), eg. in hours, to the micro-scale (dynamic time) relating only to the execution time of one (several) working cycles.*

***Keywords:*** *diesel engine, working cycle, operation*

## 1.Introduction

The objective evaluation of every piston engine reliability requires evaluative (quantitative) approach to issue and searching measures that would describe the feature most reliably.

Analyzing the matter of piston engines reliability, it's important to focus on following important fact. According to the fact, that from user's point of view, the most important issue is the quality of the task realized by the engine, the concept of reliability is associated with unambiguous definition of the task. In other words, the imprecise definition of the task makes puts the sense of describing any engines reliability indicators into question, due to its little usefulness and possibility of making wrong decisions while basing on them.

On the other hand, precise definition of the task requires not only creating conditions of its performing, but also the duration. The importance of the issue is so great, because the specificity of task in naval transport is generally related to necessity of long-term functioning of main ship's devices, especially main propulsion.

Ipso facto, especially important becomes not only the amount of energy that can be enacted using main propulsion engine, but also the time in which it can be provided.

Aside from commonly used reliability indicators, it seems reasonable to analyze engine's work (its functional systems) in a way, so that it could be described by both energy and time.

Operation (D) in time interval (0, t) in this case can be interpreted as a physical quantity described by multiplication of time - dependent energy $E = f(t)$ and time $t$ [1].

Presented description that in case of ship's marine task realization can be schematically shown as in fig. 1, applies to engine's work in some time scale that for the purposes of this analysis was called “the macro scale” (assuming that in time interval [0, $t_{AB}$] Mo=idem and n=$n_{śr}$=idem are true).

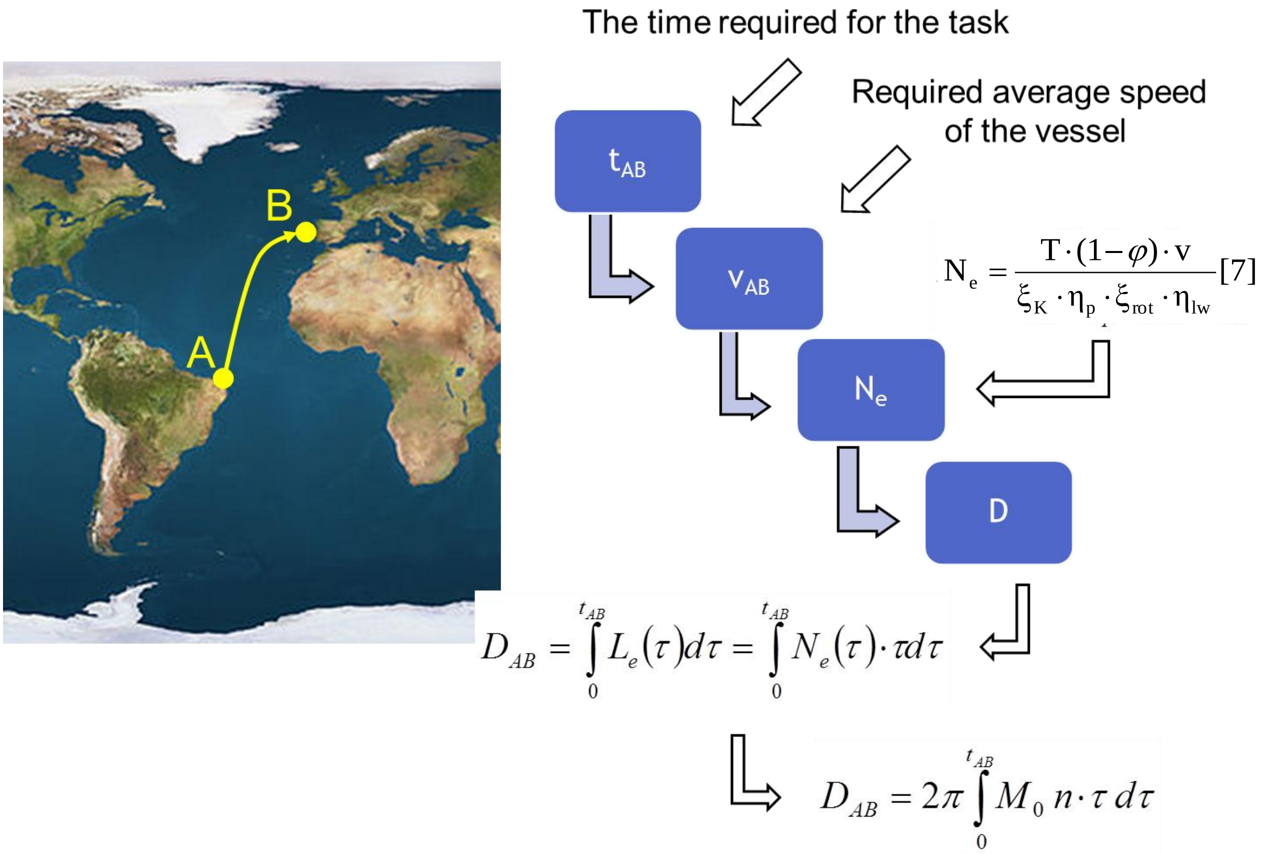



*Fig.1 Operation of main propulsion engine in the aspect of marine task realization. $D_{AB}$ –engine’s work in time $t_{AB}$, $N_e$ – engine’s useful power, Mo – engine’s torque, n – engine’s rotational speed, T – required value of thrust force for created conditions and speed $\varphi$ – value of suction force indicator, v – ship’s speed, $\eta_{lw}$ – shafting efficiency, $\eta_p$ – open water propeller efficiency, $\xi_{rot}$ – propeller rotational efficiency, $\xi_k$ – hull efficiency*

This description results from the fact that time “$t_{AB}$” in marine transport reaches very high values, making definite integral value (fig. 1) that for made assumptions is a measure of engine’s work, will be very high as well.

Having this conditions, comes up a question about possibility of transferring the method of evaluation to “micro” scale i.e. limit the analyzed time to single engine’s operation cycle time realization.

## 2. The evaluation of engine’s operation cycle using indicator graphs

In engine’s work – related scientific researches as well as in exploit time, the major role in operation cycle evaluation of every diesel engine play indicator graphs and their analysis.

Information pictured in the indicator graph (fig. 2) allows to make the evaluation of the quality of conversion of petrol’s chemical energy into mechanical energy in a complex way. Additional measures during the identification of cylinder (eg. vibrations in the area of cylinder head – fig. 2a) simultaneously allow to complete the evaluation by a series of observations eg. current values of timing angles and “hardness” of engine work (fig. 2b).

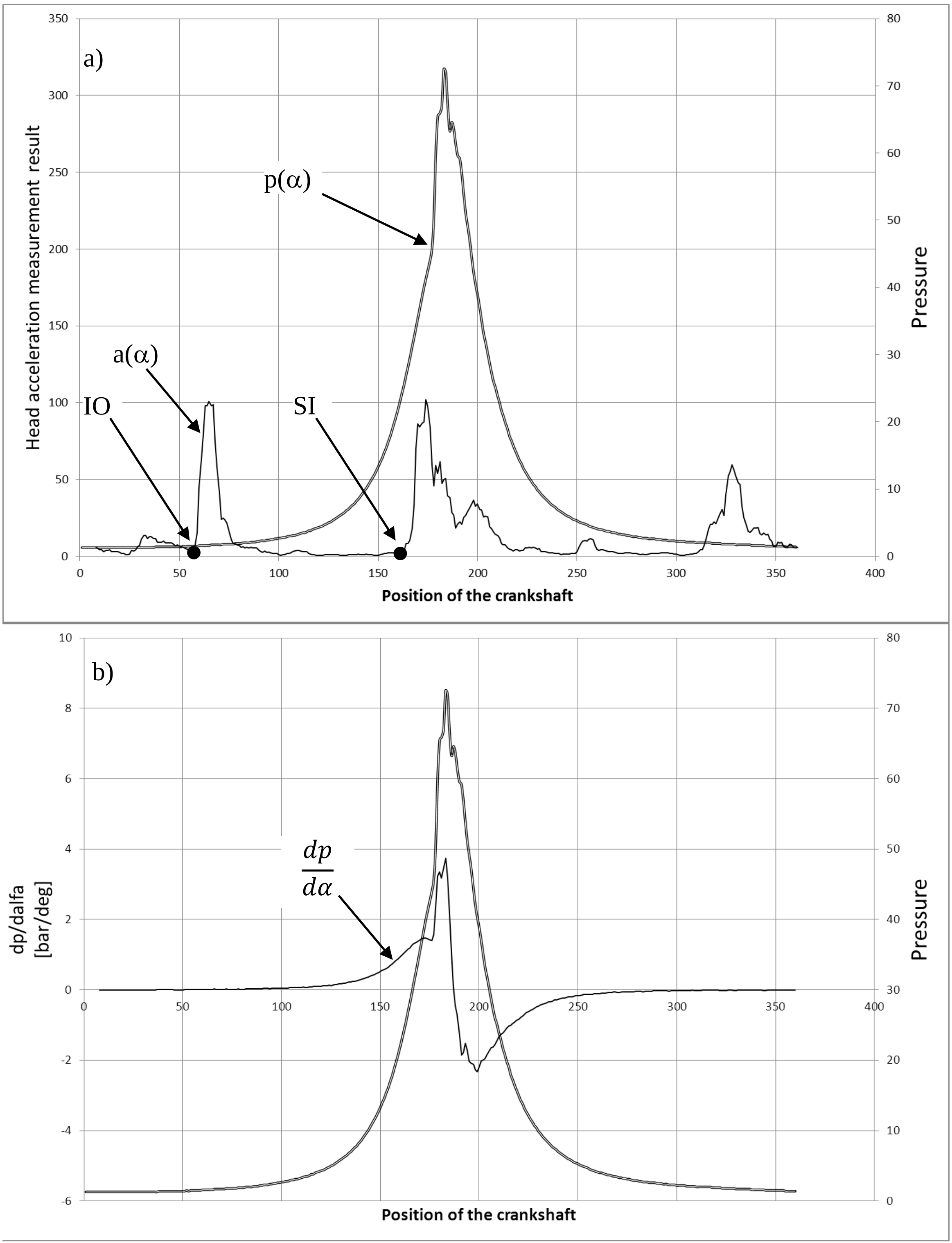
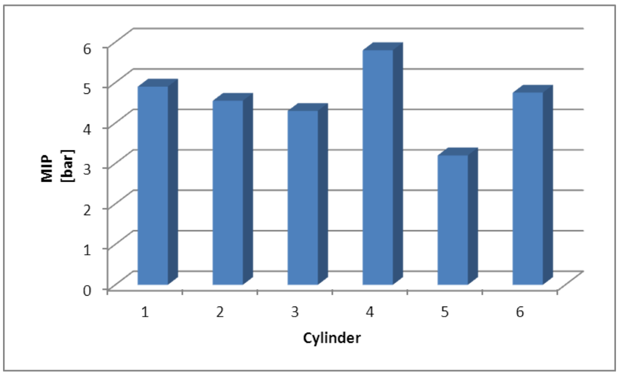



*Fig.2 The engine's extended indicator graph. p($\alpha$) – pressure as a function of crankshaft rotation, a($\alpha$) – accelerations of a cylinder head in the area of inlet valve, SI – the beginning of injection, IO – the beginning of the opening of inlet valve*

The analysis of data received in particular time, allows to calculate some more important work indicators, eg. mean indicated pressure – $p_i$ (fig. 3a) and indicated power – $N_i$ (fig. 3b) in relation to all cylinders of the engine.



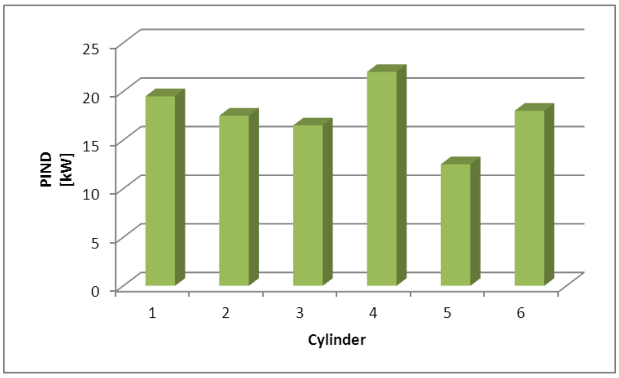




*Fig.3 Values of mean indicated pressure (MIP) and indicated power (PIND) for specific cylinders of 6 – cylinder engine.*

These additional information about the values of pi and Ni in particular moment t, are necessary for predicting both future values of these indicators in time interval [t, t+Δt] and estimation of the interval length.

Analysis of values and deviations from the mean of these, and others (eg, the maximum combustion pressure) quantities allows a fairly good comment on the quality of the implementation of energy transformation process.

On the one hand, it seems, therefore, that there is no need to introduce further parameters that would serve the present evaluation. On the other hand, each assessment and analysis, which is based on a larger number of variables is more complete and leads to more appropriate expertise and the resulting decisions.

As indicated earlier, further discussed among others in the works [4, 5, 6], quantitative assessment of the engine work using the *D(t)* indicator creates the possibility of another study examining the results of the research presented, it seems appropriate that the quantitative description of the engine work in macro scale time be extended on processes (on the same engine) on a scale "micro". In this case possible effects of $D_M(t)$ can be also distinguished and the action required by $D_W(t)$ of the engine. It is obvious that if the inequality of $D_M(t) < D_W(t)$, appears, the engine cannot operate reliably in time *t*.

This seems all the more evident that the source of engine torque is rapidly changing the piston power, which largely depends on the instantaneous change in pressure in the cylinder.

## 3. The evaluation of the diesel engine work cycle using quantitative description of the operation D(t)

Because engine work is identified with physical quantity *D(t)* defined as [2]:

$$D(t) = \int_0^t E(\tau)dt \tag{1}$$

where:

*D(t)* – operation in time [0, t],

*E(τ)* – energy changeable in time eg. in the form of work,

*t* – analyzed time,

and task execution time in the marine transport can be measured in hours, processing cycle scale of the work (even low-speed engines) requires:

- change the upper limit of integration in equation (1) for the duration of a cycle – $t_{1ob}$,
- a decision which component-associated quantity of the actual cycle can be considered as time-variable energy according to equation (1).

The first of the above problems, of course, does not pose any difficulties since, in accordance with generally known that the time dependence can be expressed as [8]:

$$t_{1ob} = \varsigma \cdot t_{1obr} = \frac{\varsigma}{n} \tag{2}$$

where:

$t_{1ob}$ – time of a one working cycle,
$t_{1obr}$ – time of a one rotation of a crankshaft,
n – engine's rotational speed,
$\zeta$ - engine's type factor ($\zeta$ = 1 – two-stroke engines, $\zeta$ = 2 – four-stroke engines),

The issue of choice of the value that corresponds to energy variable in time can raise some doubts, because the very concept of energy, as the scalar quantity describing the state of the system creates a rather wide possibilities of interpretation.

In the context of earlier analyzed results of cylinder inner pressures and opportunities of their presentation in the coordinate system p - V (volume - pressure), it seems appropriate to examine the work (a form of energy transfer), as a searched quantity.

Adoption of the convention allows for the transformation of equation (1) to the form:

$$D_{1ob} = \int_0^{t_{1ob}} E(\tau)dt = \int_0^{t_{1ob}} L(\tau)dt \tag{3}$$

where:

$D_{1ob}$ – engine's operation during one cycle,
$L(\tau)$ – cycle's work up to the $\tau$ moment,

Dependence (3) follows from the fact that the value of work L is equal to the energy E, which was worn on the execution of this work.

Limiting to the concept of absolute work [3] and assuming the contractual rule that the work done by the working factor has a positive sign, and the work associated with the impact of environment on the factor - a negative sign, a work of a two-stroke engine during a operation cycle, or during the successive moments of duration of this cycle, can be determined by solution to the following equations:

- compression stroke - the work is done on the working factor (by convention, a negative sign), which can be interpreted as "negative" operation of engine - the need to provide energy:
    - operation analyzed during the whole stroke:

$$D_{CS} = \int_0^{t_{1ob}/2} L(\tau)dt = \int_0^{t_{1ob}/2} \left( \int_{V_1}^{V_2} p(V)dV \right) dt, \tag{4}$$

    - operation analyzed as a function of time – time in the interval $\left[0, \frac{t_{1ob}}{2}\right]$:

$$D_{CS}(t) = \int_0^{t \le \frac{t_{1ob}}{2}} L(\tau)dt = \int_0^{t \le \frac{t_{1ob}}{2}} \left( \int_{V_1}^{V_2} p(V)dV \right) dt, \tag{5}$$

- the expansion and decompression stroke - the work is done by the working factor (by convention, a positive sign), which also can be interpreted as "positive" operation of the engine
    - operation analyzed during the whole stroke:

$$D_{ES} = \int_{t_{1ob}/2}^{t_{1ob}} L(\tau)dt = \int_{t_{1ob}/2}^{t_{1ob}} \left( \int_{V_2}^{V_1} p(V)dV \right) dt \,, \tag{6}$$

- operation analyzed as a function of time – time in the interval $\left[\frac{t_{1ob}}{2}, t_{1ob}\right]$ :

$$D_{ES}(t) = \int_{t_{1ob}/2}^{t \le t_{1ob}} L(\tau)dt = \int_{t_{1ob}/2}^{t \le t_{1ob}} \left( \int_{V_2}^{V_1} p(V)dV \right) dt \tag{7}$$

- engine's operation during the whole cycle

$$D_{CS} = D_{ES} + D_{CS} = \int_{t_{1ob}/2}^{t_{1ob}} \left( \int_{V_2}^{V_1} p(V)dV \right) dt + \int_{0}^{t_{1ob}/2} \left( \int_{V_1}^{V_2} p(V)dV \right) dt \tag{8}$$

Dependencies above can also be represented graphically in the form of the following procedure (Fig. 4 - 6):

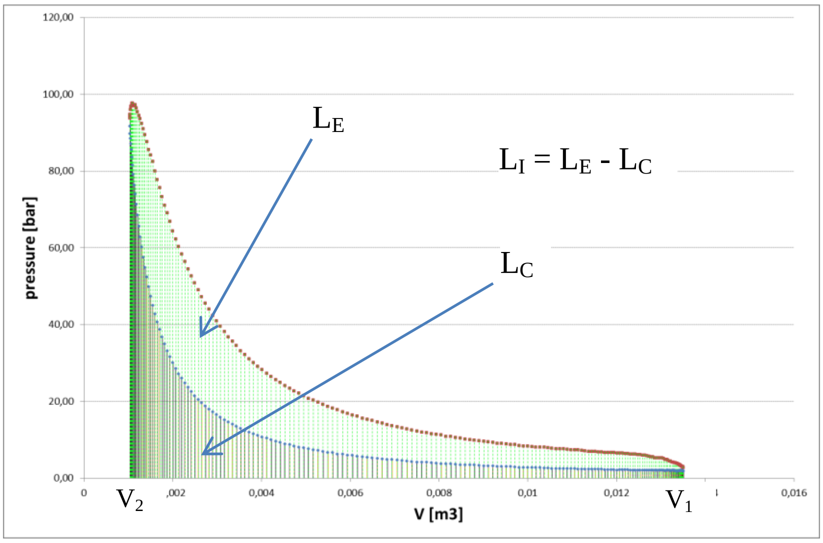



*Fig.4 Closed engine indicator graph. $L_E$ – expansion work, $L_C$ – compression work, $L_I$ – indicated work*

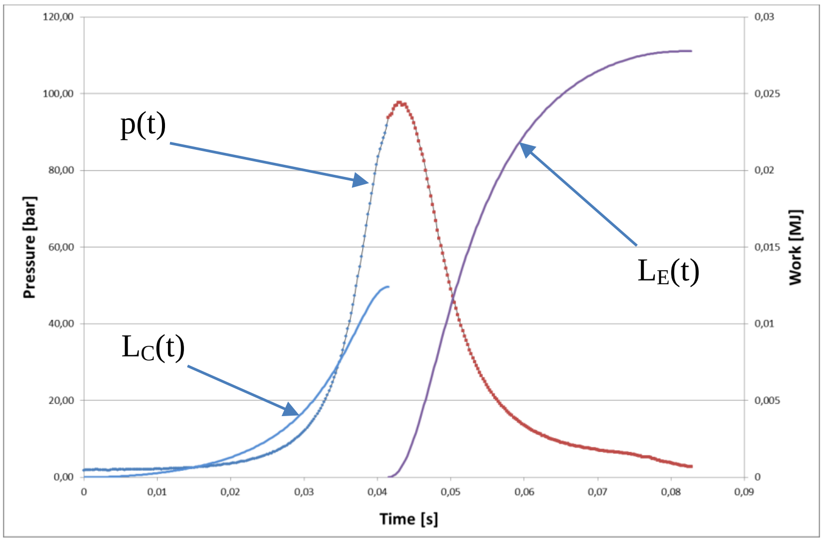
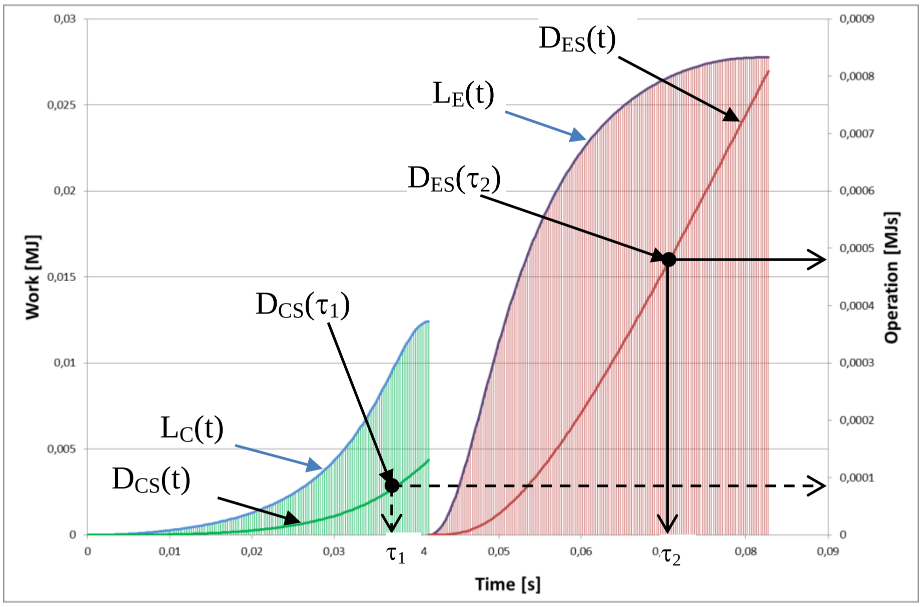



*Fig.5 Dependence of work and pressure during compression and expansion strokes. $L_E(t)$ – expansion work until the t moment, $t \in \left[\frac{t_{1ob}}{2}, t_{1ob}\right]$, $L_C(t)$ – compression work until the t moment, $t \in \left[0, \frac{t_{1ob}}{2}\right]$*




*Rys.6 Określenie działania $D_{CS}(t)$ i $D_{ES}(t)$ silnika w czasie suwów sprężania i rozprężania wynikającego z prac $L_c(t)$ oraz $L_e(t)$. $D_{ES}(t)$ – działanie silnika w czasie suwu rozprężania do chwili t, $t \in \left[\frac{t_{1ob}}{2}, t_{1ob}\right]$, $D_{CS}(t)$ – działanie silnika w czasie suwu sprężania do chwili t, $t \in \left[0, \frac{t_{1ob}}{2}\right]$*

The analysis (especially from functional process $L_C = f_1(t)$ and $L_E = f_2(t)$) shows that the analysis and assessment of these types of work must be done with reference to the time of their implementation. This implies the need for research of engines during the dynamic time, which is the load compression and exhaust gas expansion time in each cylinder.

From the analysis of dependences (4) – (8) and pictures 4 – 6, following conclusions arise:

- periodicity of compression and decompression processes prevents a simple analysis of the engine (during time limited to $t_{1ob}$) as a function of time. Such an analysis, is not impossible, but requires an additional, secondary index that takes into account the number of compression and expansion strokes executed up to the moment t,
- the value of engine operation at the time the operation cycle should be analyzed (in this case two - stroke engine) separately for compression and expansion stroke,
- separation of evaluation of cases of compression and expansion strokes allows accurate evaluation of their progress at any time, eg. in relation to the theoretical ($pV^{\kappa}$ - idem) the implementation of these changes. This indicator can be defined as follows (eg. compression stroke):

$$\psi(t) = \frac{D_{CS}(t)}{D'_{CS}(t)} = \frac{\int_0^{t \le \frac{t_{1ob}}{2}} \left( \int_{V_1}^{V_t} p(V) dV \right) dt}{\int_0^{t \le \frac{t_{1ob}}{2}} \left( \int_{V_1}^{V_t} p_1 \cdot \left( \frac{V_t}{V_1} \right)^{\kappa} dV \right) dt} = \frac{\int_0^{t \le \frac{t_{1ob}}{2}} \left( \int_{V_1}^{V_t} p(V) dV \right) dt}{\frac{p_1 \cdot \left( V_1^{\kappa+1} - V_t^{\kappa+1} \right)}{V_1^{\kappa} \cdot (\kappa+1)} \cdot \int_0^{t \le \frac{t_{1ob}}{2}} dt}, \tag{9}$$

gdzie:

$\psi(t)$ – engine's operation evaluation indicator during the compression stroke (as a function of time)

$D_{CS}(t)$ – operation during the compression stroke in the real engine,

$D'_{CS}(t)$ – operation during the compression stroke during the implementation of the theoretical cycle

$p_1$ – pressure at the beginning of the compression stroke
$V_1$ – volume of working space in the piston BDC
$V_t$ – volume of working space at the moment *t* ($V_{TDC} = V_2 \leq V_t \leq V_1$)
$\kappa$ – isentrope exponent

- determination of the value of performance indicators - $D_{CS}$ and $D_{CS}(t)$ for the reference state, ie. a new engine capable of full technical efficiency and fitness, allows for ongoing evaluation of the quality of the implementation cycle (in this case compression). This can be illustrated as shown below (Fig. 7), which presents a two processes of compression job instantaneous values $L_C$ (t) – for a reference state and in case of excessive leakage in the piston - cylinder system – $L''_C$ (t) and the corresponding change in action compression stroke time - $D_{CS}$ (t) and $D''_{CS}$ (t).

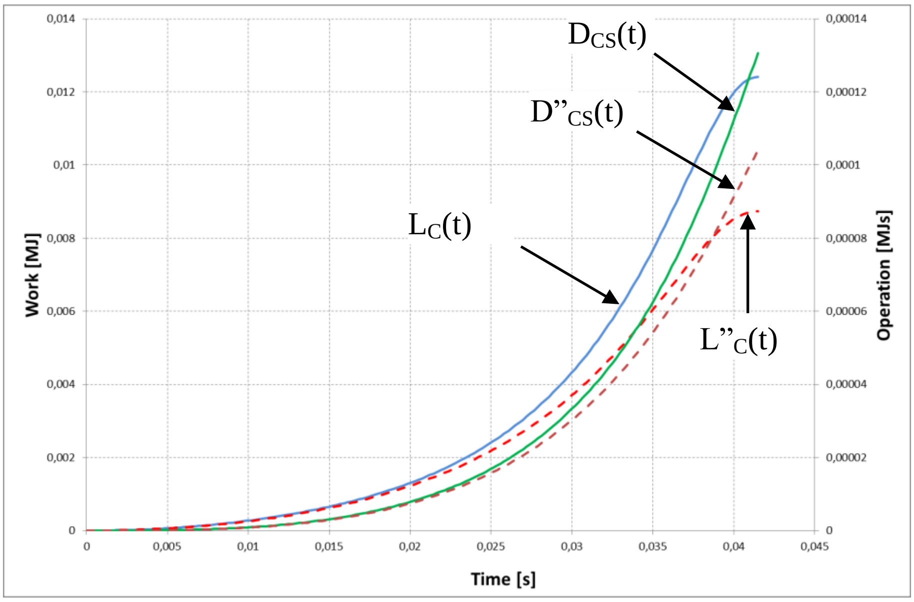



*Fig.7 Engine operations in the time of compression strokes for an engine in the reference technical state - $D_{CS}(t)$ and in case of excessive use of piston – cylinder system elements - $D''_{CS}(t)$. $L_C(t)$ – compression work up to the t moment (reference engine), $L''_C(t)$ – compression work p to the t moment (engine in the state of technical inefficiency of piston – cylinder system), $t \in \left[0, \frac{t_{1ob}}{2}\right]$*

Similarly the size of $L_E$ (t) and the $L_E$ '(t) and $D_{ES}$ (t) and $D_{ES}$' (t) can be determined, where $L_E$ (t) and $D_{ES}$ (t) are illustrated in figure 6

Regardless of the proposed method of the evaluation performance of the engine in the so-called the dynamic (short) time, this activity can be seen in the reliability having possible action $D_{CS(M)}(t)$ and $D_{ES(M)}(t)$ as well as required action $D_{CS(W)}(t)$ and $D_{ES(W)}(t)$.

## 4. Summary

The proposed procedure when analyzing test results from diesel engine is an attempt to transfer an engine activity evaluation methods in the operational time scale (exploit time), eg. in hours, to the micro-scale (dynamic time) relating only to the execution time of one (several) working cycles.

The presented method seems to be acceptable supplement for already used methods of realization of operation cycle in diesel engine evaluation. Its possible usefulness requires, of course, further theoretical studies and research supplies. In view of the fact that the induction of marine engines is a common and general routine operating practice, access to the results of such studies is quite easy, and thus conducive to the development of the presented evaluation method tools.

The basic advantage of this method is the link between evaluation of the work and the time the task is done - in this case during operation cycle of the engine.

Not without significance is the fact that all the necessary calculations are relatively simple and can be made only on the basis of the indicator graph received. The development of modern electronic indicators, so called pressure analyzers, allows for seamless implementation of these calculations in the software environment of such a device

The practical usefulness of the results obtained at the present time may be questionable - but further empirical studies of piston engines operation understood this way can lead to practical application of the proposed method of performance evaluation of such engines.

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