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THE METHOD FOR DETERMINING THE THEORETICAL OPERATION OF SHIP DIESEL ENGINES IN TERMS OF ENERGY AND ASSESSMENT OF THE REAL OPERATION OF SUCH ENGINES, INCLUDING INDICATORS OF THEIR PERFORMANCE

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Abstract

Operation of any diesel engine understood as energy transfer to a receiver at a fixed time during which the energy is converted and transferred into (in the form of) work and heat. Valuation of operation of diesel engines installed in marine power plants, proposed by the author of this paper, consists in equating the operation of this type of engines to a physical quantity of which the unit of measurement is the joule-second. The concept of a theoretical engine operation has been introduced as a standard operation to which the real operation of engines comprising various degrees of wear, could be equaled. It has been shown that calculation of the value of so understood operation needs application of the theoretical work defined on the basis of the ideal Diesel and Sabathe cycles, or their versions modified by heat transfer according to isobaric or isothermal transformation. It has been shown that for calculating the theoretical work for this type of engines the commonly known ideal Diesel and Sabathe cycles can be not always applied.

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Keywords: *operation, energy, diesel engine, marine main engine*

1. Introduction

Operation of diesel engines is interpreted as a transfer of energy E in the form of heat and work to a receiver at a given time *t* (work is a form, way of energy conversion) [1, 2, 3, 8, 9, 10]. So interpreted operation for this type of engines (in valuation approach) is a physical quantity which is a specific numerical value with a unit of measurement called the joule second [joule ×second].

This interpretation of operation for piston internal combustion engines is a result of applying the analogy method (indirect method between induction and deduction) that enables transferring the observations from one object of research (empirical system) to another. The inspiration for the considerations undertaken in this paper were the suggestions by P.L. Maupertius and W.R. Hamilton to regard the operation of mechanical systems as a physical quantity that describes a change in mechanical energy at time. In consequence, in classical physics there is known an interpretation for operation as a result of energy changes over time, expressed as a product of energy and time, which makes that the unit of measurement for the operation is the joule second.

This approach considers the operation [12, 13]:

• of a mechanical system, as a result of change in kinetic and potential energy, which is called the Hamilton's operation (D_H) and

• resulting only from a change in kinetic energy of a mechanical assembly, called the Maupertius' operation (D_M).

A similar interpretation for operation has been adopted to quantum mechanics with reference to the source of electromagnetic radiation [12, 13]. The equivalent to operation in the same sense is here the Planck's constant (*h*), which is also a physical quantity expressed by a number with the unit of measurement [joule × second].

Achievements in classical physics and quantum mechanics in this regard have led the author to an idea to implement such understood operation also to the technique, by providing it with an individual interpretation for particular power systems, including piston diesel engines.

Such engine operation study seems to be useful because considerations on engine power properties, based on analysis and assessment of the way of energy E transfer, being work, do not provide full recognition on the engine usefulness for performing a task. Such recognition is reached through considering the converted energy and the time of its conversion jointly, so the quantity $D = E \cdot t$ which has been called the engine operation. So understood engine operation provides information on how long the energy E is or can be converted. If we narrow down the analysis on energy conversion only to work (*L*) as a way (form) of energy conversion, simultaneously considering the time of its conversion, the engine operation can be defined as $D_L = L \cdot t$. This type of engine operation provides information on how long the work *L* is or can be performed. This information is equally important as this one being provided by engine power (*N*) which can be determined when knowing the work *L* and its performance time *t*. The power, as it is known, provides information on how quickly the work (*L*) can be done.

Over time, diesel engine operation undergoes deterioration. In this connection interesting may be the issue of analysis and evaluation of so understood operation of this type of engines.

The operation estimation for any diesel engine, proposed herein by the author, has this advantage that a descriptive assessment of operation, eg. the operation is good, not too good, worrisome, bad, etc. can be replaced by an evaluation resulting from equaling the operation of a given engine to a standard operation by using numbers, obviously with the unit of measurement which is the joule second.

The meaning of such interpretation for operation of the engine and any each other power machine can be justified by the following reasoning: operation ($D = E \cdot t$) of a diesel engine depends on the form in which the energy is converted by the engine and the conversion time (*t*). It can also be considered a special case of energy transfer, eg in the form of work (*L*) and then the reasoning is as follows: operation ($D_L = L \cdot t$) of a diesel engine depends on how big work (*L*) is performed by this engine and at what time (*t*).

Presentation of the problem of diesel engine operation in this approach is, however, difficult and from this reason the solution - uneasy to accept. This follows from the fact that energy is understood in different ways, for example, in classical physics the energy is defined as the only measure for different forms of motion In thermodynamics, where additionally heat is considered, such definition of energy is not sufficient and therefore the energy is defined as a state function of a thermodynamic system or physical body, which can be evaluated only when being transferred during its conversion. In technique there are known two forms (two ways) of its transfer (conversion), namely heat and work. Further considerations referring to the operation of diesel engines concern the work.

The engine operation understood in the presented way undergoes deterioration when the engine wear increases. This means that the value of the operation, in comparison with the operation of a standard (ideal) engine, decreases with time.

From the above results that important is an analysis of the engine operation and equaling it to a theoretical operation represented by a standard (ideal) engine running in accordance with a theoretical cycle. Therefore, the theoretical operation of the ideal engine needs to be determined. For the considerations we can accept that a real cycle of a low-speed diesel engine is the closest to the Diesel cycle and a real cycle of high-speed diesel engine – to the Sabathe cycle [1, 7].

2. Engine operation in deterministic approach

From considerations in literature follows that in case of diesel engines, conversion of chemical energy (contained in the fuel-air mixture produced in combustion chambers) into thermal energy and then into mechanical energy in a crankshaft-piston assembly enables generating effective power N_e. This power must be generated at time t indispensable for execution of the task by the engine. That means that in order to perform the task at this time, the adequate effective work $L_e = N_e \cdot t$ must be executed by an arbitrary diesel engine. Execution of the work is an effect of the torque (M_o) of the crankshaft at a defined rotational speed (n) of each piston internal combustion engine, including main engine [1, 2, 6, 7, 11]. Therefore, the engine operation interpreted as energy conversion leading to execution of the effective work L_e at time t can be expressed as:

$$D_{L_e} = \int_0^t L_e(\tau)\mathrm{d}\tau = 2\pi \int_0^t n(\tau) M_o(\tau)\tau \mathrm{d}\tau \tag{1}$$

Ccomparison of so defined operation (1) of a diesel engine to the operation of ideal engine requires defining the theoretical operation D_{L_t} for such an engine, depending on the way of realization of its work cycle. Determination of the theoretical operation is possible if the theoretical work L_t, that can be performed by an ideal engine at a given time t is defined. To determine the theoretical work one of the theoretical cycles (Diesel or Sabathe) can be applied, depending on whether the consideration includes low-speed or high-speed engine [1, 7]. A characteristic feature of these cycles is, among others, that compression of the working medium starts from the bottom dead centre (BDC) of the piston. Also in the case of comparable cycles, the working medium compression is considered from BDC. However, it can be or sometimes must be taken into account for theoretical analysis that in real engines compression of fresh charge (air with residual gas remaining in the cylinder from the previous cycle) in the workspace starts from the piston's position finding itself above the BDC. The reason is that, before the compression of fresh charge in the cylinder proceeds,:

- first, the exhaust valve in uniflow two-stroke engines must be closed and in engines comprising other types of scavenge the air intake slots and exhaust slots must be covered, what takes place when the piston is above BDC,
- first, the air intake valve in four-stroke engines must be closed, which also takes place when the piston is already away from BDC and moves to TDC.

It must be therefore assumed that till the moment when the compression of fresh charge starts in a real engine, the heat is transferred to environment. Thus, taking this fact into account, not only isochoric heat transfer should be considered in the theoretical cycles of diesel engines (as it takes place in the Diesel and Sabathe cycles), but additionally the heat transfer, depending on the speed-type engine, at:

- constant pressure (isobaric), in case of low- and medium-speed engines,
- constant temperature (isothermal), in case of medium- and high-speed engines.

This approach can be justified by the fact that in the case of low- and medium-speed engines with lower rotational speeds the flow resistances change in such a way that it can be concluded that the heat transfer process runs at the same pressure. During realization of the process, however, a significant change in temperature occurs due to the longer time (than in the case of high-speed engines) of transferring the heat to environment, which goes by before the compression of the fresh charge becomes initiated.

For medium-speed engines with higher rotational speeds, particularly for high-speed engines, the flow resistances change significantly (in comparison with low-speed engines) and therefore, we cannot assume that the heat transfer process runs at the same pressure. During realization of the process, however, the nonessential change in temperature proceeds due to shorter time (than in the case of low-speed engines) of transferring the heat to environment, which goes by before the compression of the fresh charge is initiated in the cylinder. Consequently, it can be accepted that in engines of this type the isothermal heat transfer process exists (after the end of the isochoric heat transfer process) before the compression process of the fresh charge is initiated.

Thus, in order to evaluate the real operation of engines operated in the given conditions, described in the work [2], we should compare it to the theoretical operation. This issue for low-speed two-stroke engines has been presented in the work [1].

Operation of supercharged high-speed two-stroke diesel engines whose real (indicator) cycles are close to the Sabathe cycle, can be considered in a similar way.

3. Theoretical operation of internal combustion engines and its practical significance

In case of diesel engines, there are important possible operation and demanded operation dependant on the effective work L_e and time t (1). However, in order to determine the operations, also the theoretical operation is needed as the operation enabling assessment on how far the possible engine operation differs from the standard operation. In this case, the knowledge of the theoretical work (L_t) (besides the time τ) is indispensable. This work can be easily determined knowing the average theoretical pressure (p_t). Such theoretical operation, in other words: the theoretically possible operation (D_{L_t}), can be determined in accordance with the formula (1) as:

$$D_{L_t} = \int_0^t L_t(\tau)\mathrm{d}\tau \qquad (2)$$

The theoretical cycles of diesel engines include thermodynamic cycles for this type of engines, such as the Sabathe cycle and the Diesel cycle, where the real cycles of high-speed diesel engines are the closest to the Sabathe cycle and the real cycles of low-speed diesel engines - to the Diesel cycle [7].

Determination of the theoretical work (L_t) requires the knowledge of the work performed during one theoretical working cycle (L_{t1}) of engine.

In case of high-speed two-stroke internal combustion engines whose the real cycle is the closest to the Sabathe cycle, taking into account that the beginning of compression starts above BDC, the theoretical cycle in the form of the modified Sabathe cycle can be applied for calculation of the theoretical work of the cycle $L_{t1,}$ including additionally isobaric heat transfer (Fig. 1). Isobaric heat transfer proceeds on the way of the piston's motion from BDC (p.6) to the position (p.1) at which the compression of the working medium begins.

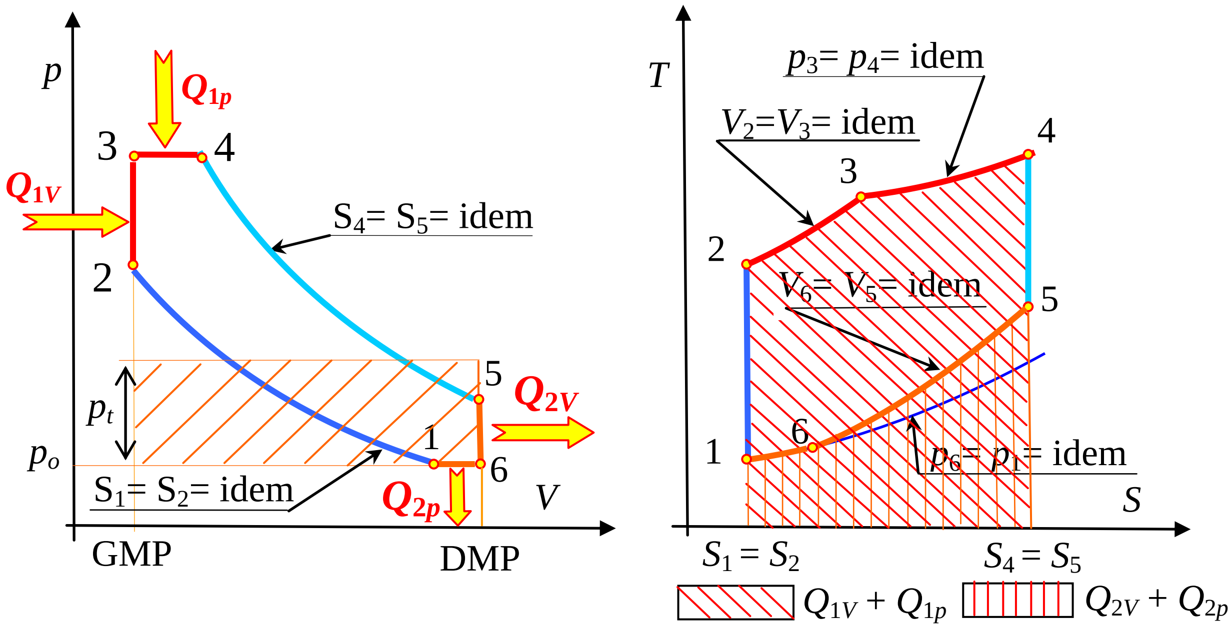

***Fig.1 .** Modified theoretical Sabathe cycle including additionally isobaric heat transfer: **a)** with regard to work, **b)** with regard to heat: $\boldsymbol{L_{t1}}$ – theoretical work of the cycle, **p** – pressure, $\boldsymbol{p_t}$ – average theoretical pressure, **V** – volume, **T** – temperature, **S** – entropy, $\boldsymbol{Q_1}$ – supplied heat, $\boldsymbol{Q_{2v}}$ – heat transferred at constant volume (isochoric), $\boldsymbol{Q_{2p}}$ – heat transferred at constant pressure (isobaric), $\boldsymbol{Q_{2T}}$ – heat transferred at constant temperature (isothermal), **TDC** and **BDC** – top and bottom dead centre of the piston, respectively*

For so modified Sabathe cycle, being the cycle that takes into account first the isochoric and then the isobaric heat transfer, the theoretical work is determined from the formulas [1, 7]:

$$L_{t1} = Q_{1V} + Q_{1p} - (Q_{2V} + Q_{2p}) = m[c_v(T_3 - T_2 - T_5 + T_6) + c_p(T_4 - T_3 - T_6 + T_1)] \qquad (3)$$

or

$$L_{t1} = Q_1 - Q_2 = p_4V_4 + \int_4^5 \mathrm{pd}V - \left(p_6V_6 + \int_1^2 \mathrm{pd}V + p_3V_3 \right) \qquad (4)$$

where: $p_6 = p_1$ = idem.

Obviously, the theoretical work (L_t) indispensable to determine the theoretical work of the engine can be, taking into account the number of realized cycles n and the number of cylinders k, defined in the form of formulas [1, 7]:

$$L_t = k{\cdot}n{\cdot}L_{t1} \qquad (5)$$

or, after determination of the average theoretical pressure p_t (Fig. 2a) from the formulas [1, 7]:

$$L_t = k \cdot n \cdot L_{t1} = k \cdot n \cdot p_t \cdot (V_6 - V_2) = k \cdot n \cdot p_t \cdot \Delta V_{6,2} \qquad (6)$$

where:

$$V_6 - V_1 = \Delta V_{6,2} = V_s$$

where:
k – number of cylinders in the engine, n – number of realized theoretical cycles in the operating time interval $[0, t]$, L_{t1} – work of a single (one) theoretical cycle in cylinder of the ideal engine, p_t – average theoretical pressure, V_s – cylinder displacement volume, V_5, V_2 – cylinder (working space) volumes of the interpretation resulting from the designations in Fig. 2.

In case of high-speed two-stroke internal combustion engines, particularly with higher rotational speed, their real cycles are the closest to the modified Sabathe cycle including additionally isothermal heat transfer. For this type of engines it can be assumed that temperature $T_6 = T_1$ = idem. Such a cycle is shown in Fig. 2.

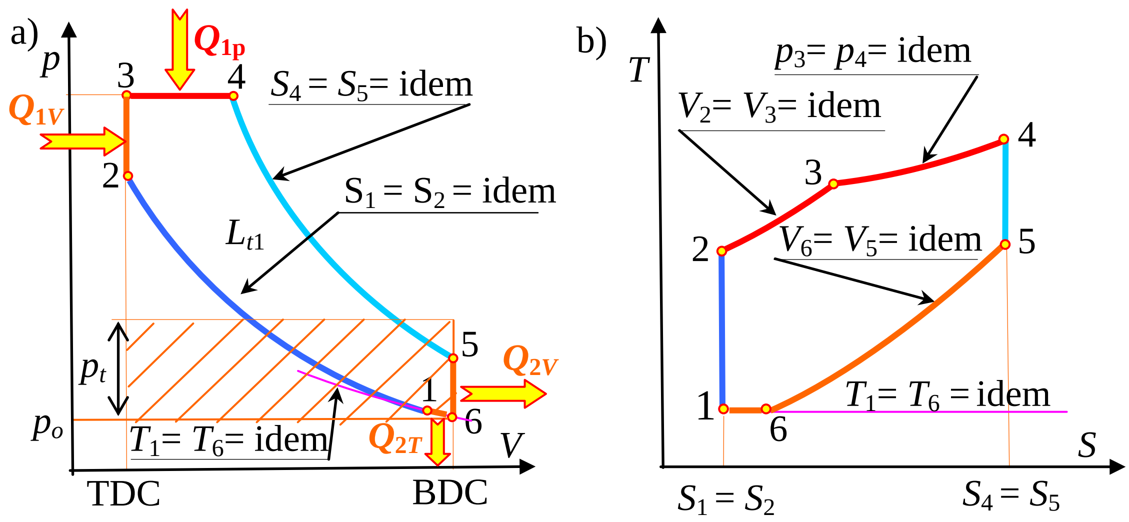

*Fig. 3. Modified theoretical Sabathe cycle including additionally isothermal heat transfer: **a)** with regard to work, **b)** with regard to heat: L_{t1} – theoretical work of the cycle, **p** – pressure, p_t – average theoretical pressure, **V** – volume, **T** – temperature, **S** – entropy, Q_1 – supplied heat, Q_{2V} – heat transferred at constant volume (isochoric), Q_{2p} – heat transferred at constant pressure (isobaric), Q_{2T} – heat transferred at constant temperature (isothermal), **TDC** and **BDC** – top and bottom dead centre of the piston, respectively*

For so modified Sabathe cycle, taking into account first isochoric and then isothermal heat transfer, the theoretical work is determined by the formula::

$$L_{t1} = Q_{1V} + Q_{1p} - (Q_{2V} + Q_{2T}) = mc_v[(T_3 - T_1) + \kappa(T_4 - T_3) - (T_5 - T_6)] - T_6(S_6 - S_1) \quad (7)$$

where: $T_6 = T_1$ = idem

or

$$L_{t1} = Q_1 - Q_2 = p_4V_4 + \int_4^5 \mathrm{pd}V - \left(\int_6^1 pdV + \int_1^2 \mathrm{pd}V + p_3V_3 \right) \quad (8)$$

where: $V_2 = V_3$, $Q_1 = Q_{1V} + Q_{1p}$ and $Q_2 = Q_{2V} + Q_{2T}$

In this case the theoretical work (L_t) indispensable to determine the theoretical engine operation can be, taking into account the number of realized cycles n and the number of cylinders k, also defined as the formula (6).

In order to determine the differences in the values of the theoretical work and the theoretical power of an ideal engine, depending on whether isobaric or isochoric heat transfer is additionally included, and to compare them to the values of a given engine, there were made calculations by using thermodynamic parameters of a working medium, corresponding to the parameters of work of a two-stroke diesel engine type RTA84R4 with 5 cylinders, and the following data: cylinder diameter D = 0,84m, piston stroke S = 2,4 m, rotational speed n = 65 rpm, compression ratio ε =18; rate of increase in volume φ_v = 1,7; compression and expansion proceed isentropically, air is taken as an ideal medium; uniflow scavenge takes place in the engine, the length of air intake slots is $h_d = 0{,}15 \cdot S$, at the end of a filling stroke the pressure is 0,3 MPa and the temperature is 350 K.

As a result of making the above calculations the following differences between the particular works and the differences between the powers corresponding to these works, have been obtained:

$$\Delta L_t = L_{t(T)} - L_{t(p)} = 1690 - 1685 = 5[\text{kJ}] \quad \text{and} \quad \Delta N_t = N_{t(T)} - N_{t(p)} = 1831 - 1825 = 6[\text{kW}]$$

$$\Delta L = L_{t(T)} - L_e = 1690 - 1680 = 10[\text{kJ}] \quad \text{and} \quad \Delta N = N_{t(T)} - N_e = 1831 - 1820 = 11[\text{kW}]$$

$$\Delta L = L_{t(p)} - L_e = 1685 - 1680 = 5[\text{kJ}] \quad \text{and} \quad \Delta N = N_{t(p)} - N_e = 1825 - 1820 = 5[\text{kW}]$$

where:

ΔL_t – difference between theoretical works,
ΔL – difference between theoretical and effective work,
ΔN_t – difference between theoretical powers,
ΔN – difference between theoretical and effective power,
$L_{t(T)}$ – theoretical work of the cycle including isochoric and isothermal heat transfer,
$L_{t(p)}$ – theoretical work of the cycle including isochoric and isobaric heat transfer,
L_e – effective work of engine,
$N_{t(T)}$ – power corresponding to the work $L_{t(T)}$,
$N_{t(p)}$ – power corresponding to the work $L_{t(p)}$,
N_e – power corresponding to the work L_e.

From the obtained data follows that the differences both between the theoretical works $L_{t(p)}$ (ΔL_t = 5kJ) as between the theoretical powers $N_{t(T)}$ and $N_{t(p)}$ (ΔN_t = 6kW) are not considerable. It does not mean however that they may be disregarded. Similarly, not large are the differences between $L_{t(p)}$ and L_e (ΔL = 5kJ) and obviously between $N_{t(p)}$ and N_e (ΔN = 5kW). But, the differences in case of works $L_{t(T)}$ and L_e (ΔL = 10kJ), and powers $N_{t(T)}$ and N_e (ΔN = 11kW) are significant. Hence, such researches can be interesting also for diesel engines other then the engine described above.

4. Characteristics of engine operation

Comparing only the effective work performed by the engine at time t and the theoretical work which can be performed by an ideal engine at the same time we can estimate the excellence degree ($\varepsilon_{Ln(ob)}$) of conversion of the energy leading to performance of effective work (L_e) by the given engine. This degree can be determined by considering two cases. The first case takes place when we cannot assume that during the time t of engine operation the same effective work is generated in each engine cylinder. Then the excellence degree ($\varepsilon_{Ln(ob)}$) of energy conversion in the engine can be defined by the formula:

$$\varepsilon_{Ln(ob)} = \frac{\sum_{k=1}^{m} \sum_{j=1}^{n} L_{e(j)k}}{L_t} \tag{9}$$

where:
$L_{e(j)k}$ – effective work of the j-th cycle in the k-th engine cylinder,
L_t – theoretical work determined by the formula (6).

The excellence degree of energy conversion into work, defined by the formula (9), describes how far the energy conversion into work in the real engine differs from the theoretical work of an ideal engine, after n cycles.

The second case takes place when we can assume that during the time t of engine operation the same effective work is generated in each cylinder. Then the degree of excellence ($\varepsilon_{Ln(ob)}$) can be determined by the formula:

$$\varepsilon_{Ln(ob)} = \frac{L_e}{L_t} = \frac{L_{e1}}{L_{t1}}; \quad L_e = knL_{e1} \tag{10}$$

where:
k – number of engine cylinders, n – number of realized theoretical cycles in the operating time interval [0, t], L_{e1}– effective work of a single (one) real cycle in an engine cylinder.

Also interesting can be how far operation of a real engine differs from the operation of an ideal engine. Analyzing the same cases like for determining the excellence degree ($\varepsilon_{Ln(ob)}$) of energy conversion into effective work (L_e) by the given engine, we can define the excellence degree ($\varepsilon_{Dn(ob)}$) of engine operation. Thus, in the first case when the need is to assume that at the total time t of engine operation different effective work is generated in each cylinder in particular time intervals $t_{(i)k}$,, the excellence degree ($\varepsilon_{Dn(ob)}$) of engine operation can be defined as:

$$\varepsilon_{Dn(ob)} = \frac{\sum_{k=1}^{m} \sum_{j=1}^{n} L_{e(j)k} t_{(j)k}}{L_t t} \tag{11}$$

where:
$L_{e(i)k}$ – effective work of the j-th cycle in the k-th engine cylinder, $t_{(j)k}$ – time of generation of work $L_{e(j)k}$, L_t – theoretical work defined by the formula (6).

In turn in the second case when it can be assumed that at the time t of engine operation the same effective work $L_{e1}$is generated in each cylinder, the degree of excellence ($\varepsilon_{Dn(ob)}$) can be expressed by the same relation as the excellence degree ($\varepsilon_{Ln(ob)}$) of energy conversion into effective work (L_e) by the given engine (16). This follows from that $\sum_{i=1}^{n} t_{(j)k} = t$. Therefore it can be accepted that in this second case the excellence degree ($\varepsilon_{Dn(ob)}$) of operation of a given piston internal combustion engine is equivalent to the excellence degree ($\varepsilon_{Ln(ob)}$) of energy conversion into effective work (L_e).

If these analyses include the indicated work L_i we can determine the factor (degree) of dissipation of engine operation caused by energy lost to overcome the mechanical resistances. The abovementioned dissipation degree of engine operation could be defined as:

$$\xi_{Dn(ob)} = \frac{\sum_{k=1}^{m}\sum_{j=1}^{n} L_{e(j)k} t_{(j)k}}{\sum_{k=1}^{m}\sum_{j=1}^{n} L_{i(j)k} t_{(j)k}} \quad (12)$$

If there can be accepted that during the time t of engine operation the event occurs that: L_i = idem and L_e = idem, then the dissipation degree of engine operation is equal to its mechanical efficiency [1].

3. Remarks and conclusions

Operation of an internal combustion engine was interpreted as delivery of the required energy at the defined time, which can be expressed in the form of a physical quantity with the unit of measurement called *the joule-second.*

While considering the energy related properties of internal combustion engines, not only their work should be analyzed but also their operation. Beside the work itself, the analysis of operation takes into account also the time of its performance.

The proposed method can be applied for defining the theoretical operation as standard which enables comparison of the real operation of diesel engines with different degree of wear. The theoretical work needed for calculating the value of this operation was determined with regards to the modified theoretical Sabathe cycles, to which the closest are real cycles of high-speed diesel engines. The modification of these cycles consisted in taking additionally into account the heat transfer in accordance with the isobaric or isothermal process.

Similar considerations can be conducted for medium- and low-speed engines by taking into account the modified Diesel cycles [1] including additionally the heat transfer in accordance with the isobaric or isothermal process.

A deterministic method was presented for evaluating the diesel engine operation, but this method can also be applied to evaluate operation of a petrol engine whose real cycles are close to the Otto cycle modified in a similar way.

A separate issue is development of a method for evaluating the operation of internal combustion engines in the stochastic approach. In this case the considerations should include that the processes of energy conversion during engine operation are of stochastic nature.

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