engine efficiency, charge exchange work, engine load,
valve actuating, thermodynamic cycle

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ACHIEVEMENT OF THE CHARGE EXCHANGE WORK DIMINISHING OF AN INTERNAL COMBUSTION ENGINE IN PART LOAD

Summary. Internal combustion engines, used for driving of different cars, occurs not only at full load, but mostly at the part load. The relative load exchange work at the full (nominal) engine load is significantly low. At the part load of the IC engine its energy efficiency η_e is significantly lower than in the optimal (nominal field) range of the performance parameters. One of the numerous reasons of this effect is regular growing of the relative load exchange work of the IC engine. It is directly connected with the quantitative regulation method commonly used in the IC engines. From the thermodynamic point of view - the main reason of this effect is the throttling process (causing exergy losses) occurring in the inlet and outlet channels. The known proposals for solving of this problem are based on applying of the fully electronic control of the motion of inlet, outlet valves and new reference cycles.

The idea presented in the paper leads to diminishing the charge exchange work of the IC engines. The problem can be solved using presented in the paper a new concept of the reference cycle (called as eco-cycle) of IC engine. The work of the engine basing on the eco-cycle occurs in two 3-stroke stages; the fresh air is delivered only once for both stages, but in range of each stage a new portion of fuel is burned. Normally the charge exchange occurs once during each engine cycle realized. Elaborated proposition bases on the elimination of chosen charge exchange processes and through this the dropping of the charge exchange work can be achieved.

UZYSKANIE ZMNIEJSZENIA PRACY WYMIANY ŁADUNKU PRZY CZĘŚCIOWYM OBCIĄŻENIU SILNIKA SPALINOWEGO

Streszczenie. Silniki spalinowe, stosowane jako jednostki napędowe samochodów, pracują nie tylko przy pełnym (nominalnym) obciążeniu, ale także (najczęściej) pod obciążeniem częściowym. Względna praca wymiany ładunku silnika przy jego pełnym obciążeniu jest stosunkowo niewielka. Przy obciążeniu częściowym energetyczna sprawność η_e silnika spalinowego jest znacznie niższa aniżeli przy jego pełnym (optymalnym) obciążeniu, co między innymi jest powiązane z wielkością pracy wymiany ładunku w układzie. Z termodynamicznego punktu widzenia przyczyną tych zmian jest proces dławienia (przepustnica, straty egzergii) głównie na dopływie do silnika, co jest efektem tzw. ilościowej regulacji silnika spalinowego. Przygotowywane są różne propozycje rozwiązań, prowadzące do efektywnego zmniejszenia pracy wymiany ładunku przy niskich obciążeniach silnika. Jednym z proponowanych prostszych rozwiązań w tym zakresie może być zastosowanie tzw. ekoobiegu, którego idea polega na zmniejszeniu liczby napełnień cylindra. Przedmiotem analizy są możliwości realizacyjne oraz uwarunkowania eksploatacyjne ekoobiegu silnika spalinowego.

Zasadniczym warunkiem branym pod uwagę, było kryterium sprawności energetycznej ekoobiegu w stosunku do sprawności istniejących obiegów klasycznych, a w szczególności stwierdzenie możliwości zwiększenia sprawności układu, głównie w zakresie obciążeń częściowych silnika spalinowego. Wskazano na sposób kontroli i dobór warunków spalania w układzie.

1. INTRODUCTION

Piston combustion engine belongs to the internal combustion heat machines, which periodically performs the work in frames of the realised thermodynamic cycle. Work of internal combustion engines, which are used as the driving source of different cars, occurs not only at the full load, but mostly at the part load [2, 5]. The basic criteria taken into account by assessment and exploitation of internal combustion engines are among other things:

a) emission of pollutants and other toxic substances,
b) efficiency of energy conversion processes,
c) reliability and correctness of the used system.

Diminishing of emission of toxic substances (components in the gaseous phase: CO, NO_x, C_mH_n, SO_y, and likewise solid particles: soot, condensed hydrocarbons) from combustion engines can be achieved by realisation of two groups of measures:

- primary (otherwise inside-engine),
- secondary (outside-engine: catalysts and filters).

The load exchange work of IC engine essentially determines the effective engine efficiency. At the part load of the IC engine the energy efficiency η_e is significantly lower than in the optimal (nominal field) range of the performance parameters. One of the numerous reasons of this state is regular growing of the relative load exchange work of the IC engine [1, 4].

The main reason of this effect is the throttling process (causing exergy losses) occurring in the inlet and outlet channels. It is directly connected with the quantitative regulation method common used in the IC engines. Depending on the engine load a different mass of the inlet fresh charge inlets into the cylinder (chamber), while the effective air (oxygen) excess is quasi invariable in whole range of the engine load.

Improving of engine operating parameters can be achieved through diminishing of the charge exchange work. The relative load exchange work at the full (nominal) engine load is significantly low. The load exchange work of IC engine essentially determines the effective engine efficiency. The engine speed influences the real investigation results of the charge exchange work too.

The newest proposal for solution of this problem is based on applying the fully electronic control of the motion (actuating) of inlet and outlet valves [2, 5]; a scheme of this system is shown in the Fig. 1.

The solutions of this problem are based on the fully independent control of the motion of inlet and outlet valves, whereby the optimal internal recirculation ratio of flue gases should be taken into account.

Typical ICE timing gear system with camshafts located in the engine head and the throttling valve can be eliminated. Applying of the adequate (for the actual IC engine load) timing of the inlet and outlet valves the diminishing of the charge exchange work can be effectively achieved. In this case the internal recirculation of flue gases, lean combustible mixture can be prepared and effectively burned.

A very important problem is elaborating of the steerage procedures, adequate for inlet and outlet valves.

The independent actuating (steerage) procedures of the ICE inlet valves should insure the adequate mass of the fresh charge, while procedures of the outlet valves are focused on the optimal exhaust gas recirculation rate, according to the engine load.

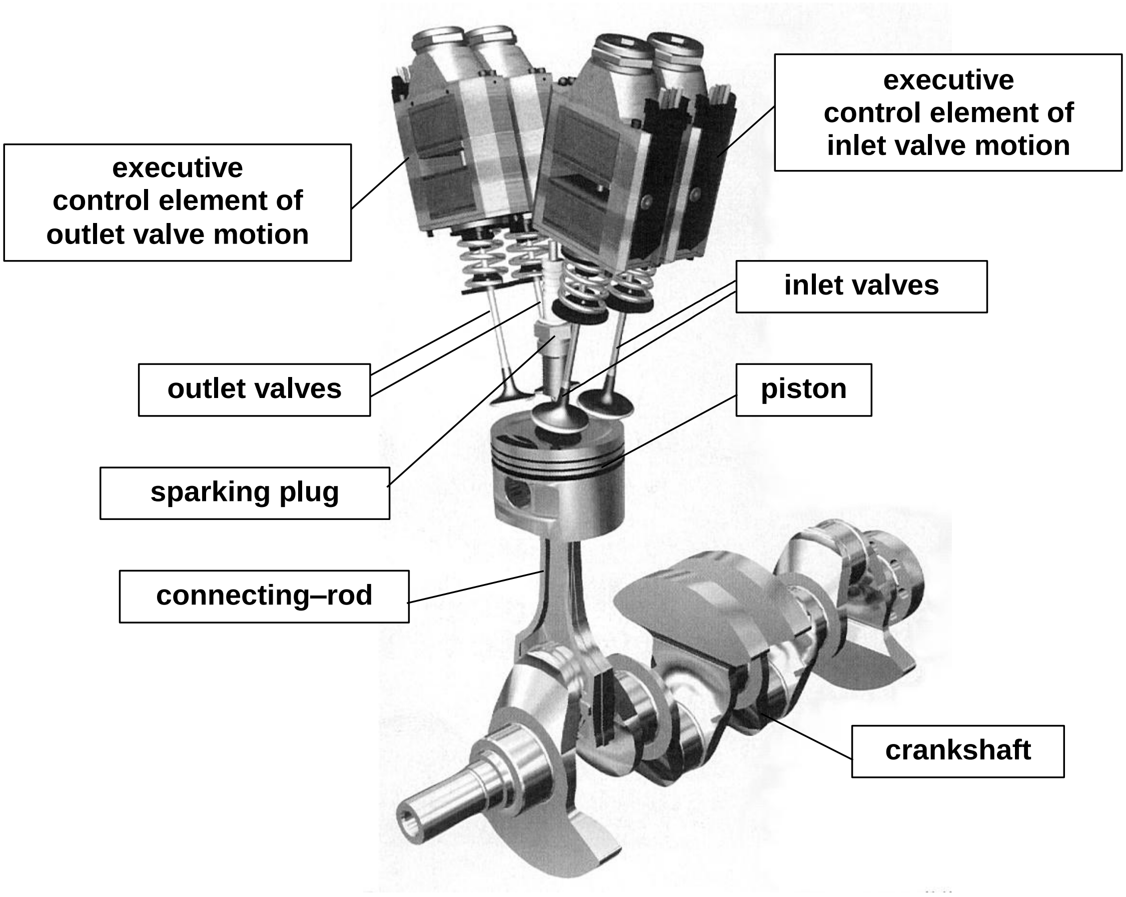

Fig. 1. Independent motion system of ICE valves
Rys. 1. Układ niezależnego sterowania ruchem zaworów silnika

2. EFFECTIVE ENERGY EFFICIENCY AND RELATIVE CHARGE EXCHANGE WORK OF IC ENGINE

Internal combustion engine should be treated as a complex energy object, shown in the Fig. 2.

At the normal (nominal) working state the internal combustion engine can be characterised by the following quantities and parameters (Fig. 2):

$N_{e,0}$, *kW*, – effective power output, $M_{e,0}$, *Nm/rad*, – effective torque,

$\dot{r}_0$, *1/s*, – engine speed, $\eta_{e,0}$, – effective efficiency,

$\dot{m}_{b,0}$, *kg/s*, – mass flux of the consumed fuel, b_e , *kg/kJ*, – specific fuel consumption,

$\dot{m}_{a,0}$, *kg/s*, – mass flux of the intake air (the molar flux $\dot{n}_{a,0}$, *kmol/s*, too).

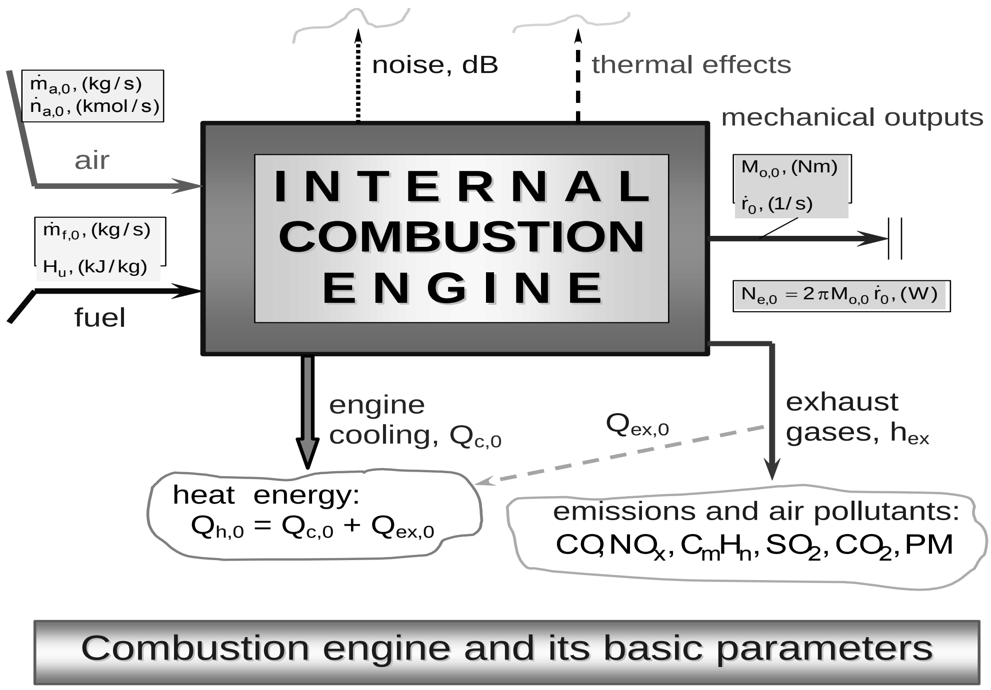

Fig. 2. Internal combustion engine as a complex energy object
Rys. 2. Silnik spalinowy jako złożony obiekt energetyczny

The effective energy efficiency of the working internal combustion engine is defined as [1, 5]:

$$\eta_{e,0} \overset{df}{=} \frac{N_{e,0}}{\dot{m}_{b,0} H_{u,b}} , \tag{1}$$

where: $H_{u,b}$, *kJ/kg,* – the lower calorific value of the supplied liquid fuel.

Effective energy efficiency η_e of the real IC engine should be treated as a function (for example engine shown in the Fig. 2, and its characteristics in the Fig. 3) of its actual performance parameters:

$$\eta_e = F(M_e,\ \dot{r}_o), \qquad \text{or:}\ \ \eta_e = F(N_e,\ \dot{r}_o) , \tag{2}$$

where: M_e, *Nm/rad* – effective actual torque.

Instead of effective energy efficiency η_e the specific fuel consumption b_e can be used [3]:

$$b_e = \frac{\dot{m}_p}{N_e} , \quad \text{kg/kJ} \quad \text{(or: g/kWh} \quad \text{– see Fig. 3)}, \tag{3}$$

whereby:

$$\eta_e\, b_e\, H_{u,p} = 1 . \tag{4}$$

Work of internal combustion engines, which are used as the driving source of cars, occurs not only at the full load, but mostly at the part load. In this range the energy efficiency η_e – Eq. (1), (3) – is significantly lower (the specific fuel consumption b_e – Eq. (4) – is adequately higher) as in the optimal (nominal field) stage of the performance parameters; so it can be observed in Fig. 3.

A – global (external) characteristics B – characteristics in the operating field

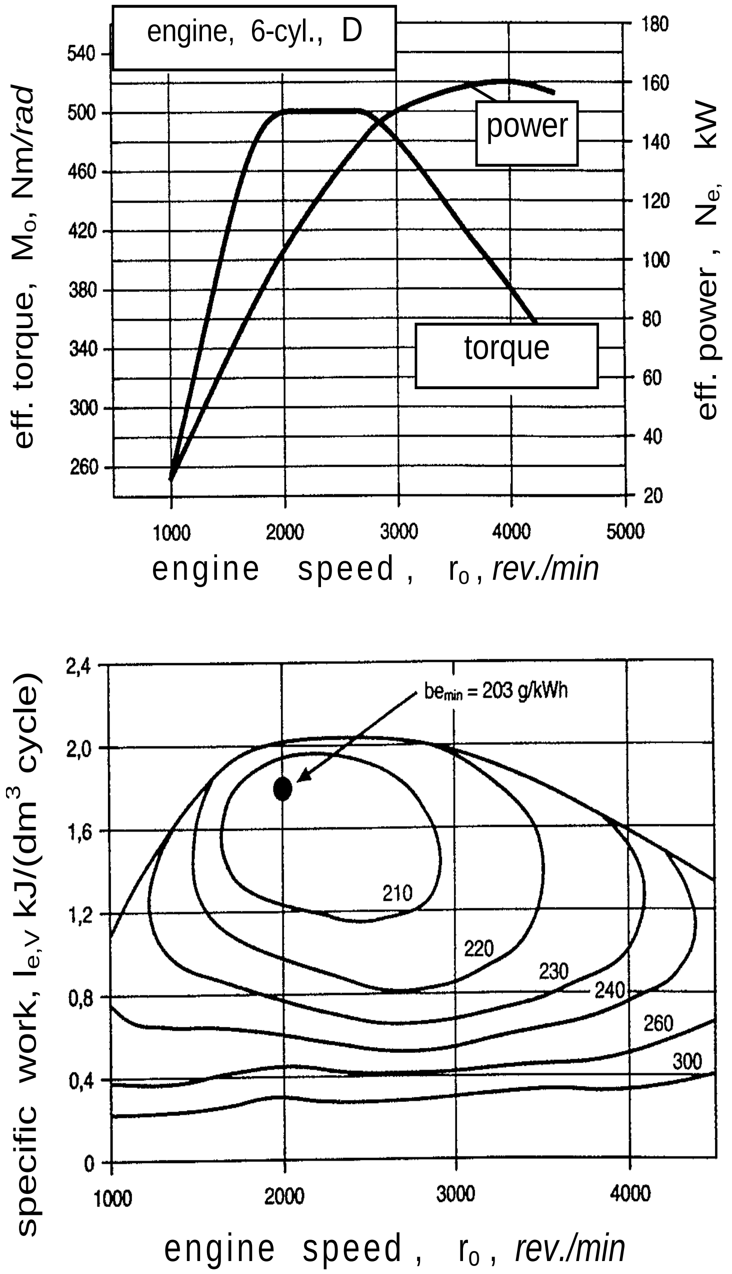

Fig. 3. Operating characteristics of the ICE
Rys. 3. Charakterystyki eksploatacyjne silnika spalinowego
(A – charakterystyka zewnętrzna, B – charakterystyka w polu pracy silnika)

The main reason of this effect is the throttling process occurring in the inlet and outlet channels (main element is the throttle valve and next occurring pressure drops: Δp_{in}, Δp_{out} – are shown in the Fig. 4).

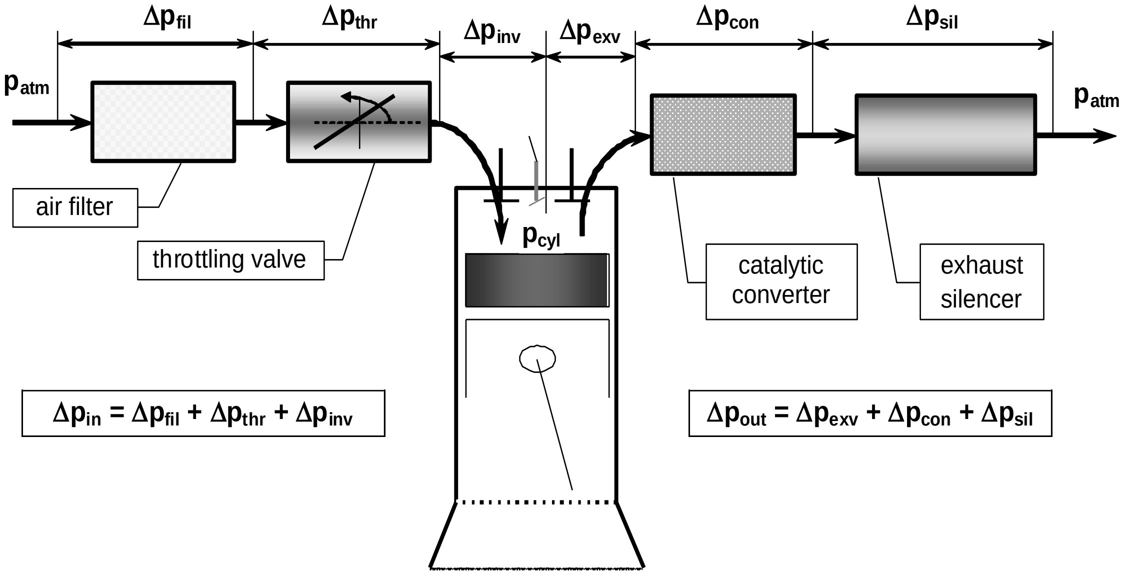

Fig. 4. Main elements of the charge exchange system (throttle valve for IC spark ignition engine)
Rys. 4. Podstawowe elementy układu wymiany ładunku (przepustnica dla silników ZI)

The isenthalpic throttle causes pressure drops: Δp_{in}, Δp_{out} – shown in the Fig. 4, and next energy losses δB occur in the inlet and outlet channels.

The mentioned energy losses occurring by each (i - th) throttle element can be calculated using formula:

$$\delta \dot{B}_i = \dot{m} R \ln\left(\frac{1}{1-\dfrac{\Delta p_i}{p_i}}\right), \qquad \text{for Ti = idem,} \tag{5}$$

where: Δp_i – the pressure drop of the i-th element, p_i – pressure at the inlet of i-th point.

Importance of flow exergy losses is high - mainly by using the quantitative engine regulation (at spark ignition, SI) – shown in Fig. 5.

The combustion process proceeds at the required value of the air excess ratio, calculated as:

$$\lambda_0 = \frac{\dot{m}_{a,0}\, z_{a,O_2}}{\dot{m}_{b,0}\, n'_{O_2,\min,b}\, M_a} = \frac{\dot{n}_{a,0}\, z_{a,O_2}}{\dot{m}_{b,0}\, n'_{O_2,\min,b}}, \tag{6}$$

where: $n'_{O_2,\min,b}$, *kmolO₂/kg b* - minimal specific oxygen demand of the liquid fuel, z_{a,O_2} - content of the oxygen in the ambient air (~ 0,21), M_a, *kg/kmol,* - molar mass of the filling air ($M_a \approx 29{,}1$ *kg/kmol*).

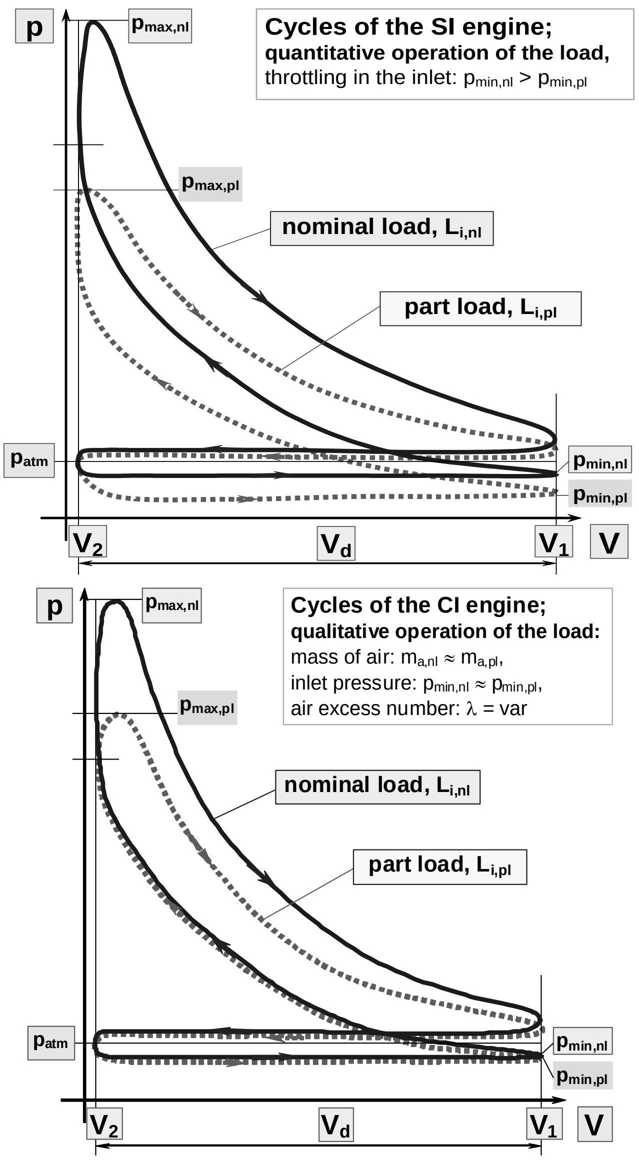

Fig. 5. Typical shapes of SI and CI – ICE cycles at different engine load
Rys. 5. Kształtowanie się obiegów silników ZI oraz ZS przy różnych ich obciążeniach

The spark ignition engines (SI, Fig. 5, left) are regulated using the quantitative method, it means that the global mass of the intake air (m_a = var), depending on the engine load, changes in a very wide range, whereby the air excess ratio $\lambda_0 \approx$ idem.

The compression ignition engines (CI, Fig. 5, right) are regulated using the qualitative method, the global air excess ratio λ_0, depending on the engine load normally changes in a very wide range (up to 8).

During the intake stroke the inlet air mass m_a is approximately the same ($m_a \approx$ idem), but the mass $m_{p,0}$ of the injected fuel changes ($m_{p,0}$ = var), depending on the engine load. Due to this the global air excess ratio λ_0 equals (1,1 – 1,2) at the full load, and adequately (7 - 8) at idle running. Progress of the burning causes mass changes of the fuel $m_p(t)$ and oxygen $n_{O2}(t)$.

Improving of engine operating parameters can be achieved through diminishing of the charge exchange work (a regular growing of the relative load exchange work is observed at the part load of the IC engine).

The charge exchange work can be calculated as:

$$\left| L_{in} \right| \approx \Delta p_{in} \, V_s \,, \qquad \left| L_{out} \right| \approx \Delta p_{out} \, V_s$$

and than . (7)

$$\left| L_{ew} \right| \approx (\Delta p_{in} + \Delta p_{out}) \, V_s$$

The mentioned problem was at this stage first theoretically for a thermodynamic IC engine reference theoretical cycle analysed.

As standard reference cycle of any IC engine is the ideal thermodynamic cycle, called as theoretical cycle (e.g. the Seiliger–Sabathe cycle, accounting to the charge exchange work, schematically shown in the Fig. 6), where supplying of the heat (Q_d) occurs in two phases: first ($Q_{d,v}$) isochoricly (2–3), second ($Q_{d,p}$) isobaricly (3–4). The heat output (Q_w) is realised once and isochoricly (5-6-1).

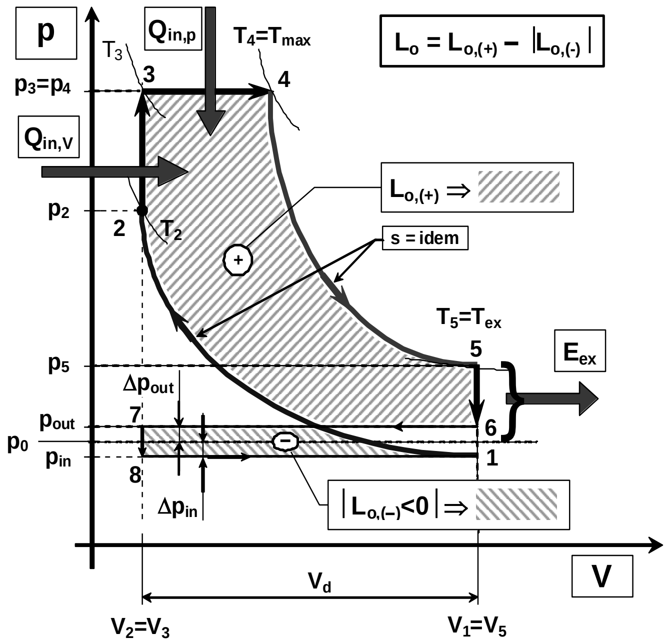

Fig. 6. Typical reference (Seiliger-Sabathe) cycle of IC engine accounting to the charge exchange work
Rys. 6. Typowy obieg porównawczy (Seiligera-Sabathe'a) silnika spalinowego wraz z pracą wymiany ładunku

Introduction of the isothermal phase (afterburning, by T = idem, e.g. Seiliger-Sabathe-Eichelberg cycle) is important too, because it refers to the maximal temperature (T_{max}) of the whole cycle, on which value depends on the possibility and rate of the formation of the nitrogen oxides NO_x, carbon monoxide CO, and the out-burning ratio of the injected fuel [6].

Using the scheme shown in the Fig. 6 and elaborated formulas it has been calculated that the relative load exchange work can significant influence the values of energy efficiency (up to 55% at the part load, e.g. idle run) of the SI IC engine.

On the base of the achieved [4, 6] theoretical results the systematic dropping of energy efficiency has been confirmed and for illustration the achieved approximate results are shown in the Fig. 7.

Next, on the base of the experimental results and using the elaborated formulas it has been calculated that the relative load exchange work can achieve value up to 40% at the part load (e.g. idle run) of the IC engine. Results achieved by experimental investigations of many real engines are shown in Fig. 8.

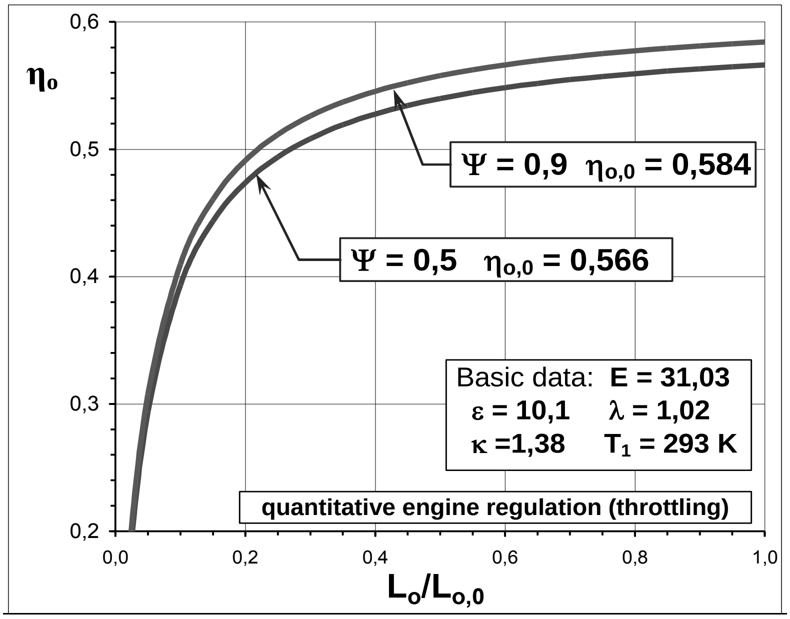

Fig. 7. Influence of the relative load on the energy efficiency (of the engine ideal cycle)
Rys. 7. Wpływ względnej pracy wymiany ładunku na sprawność energetyczną silnika (obieg idealny)

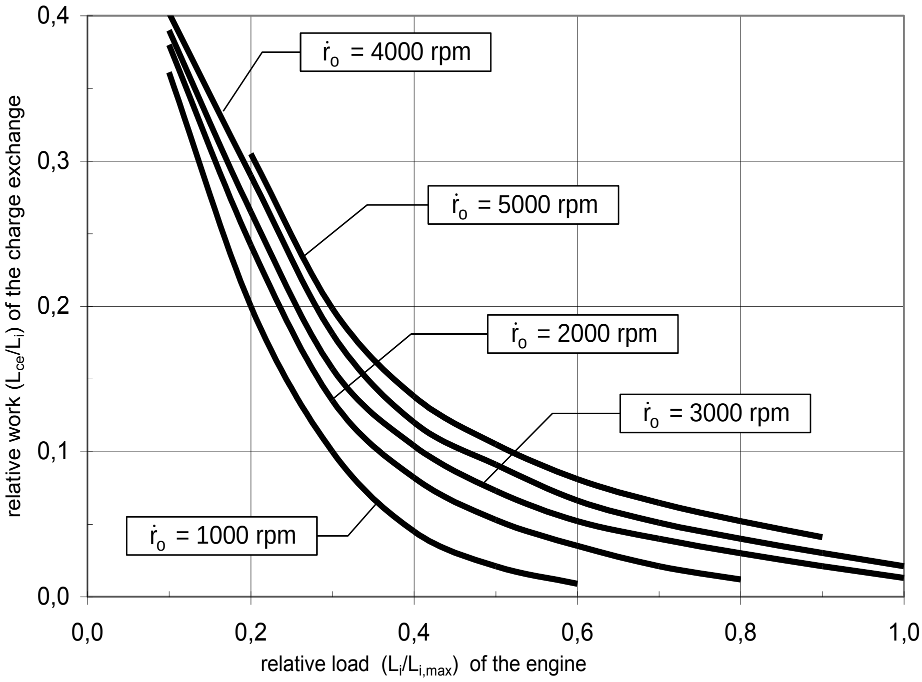

Fig. 8. Influence of load ratio on the relative exchange load work of the real IC engines
Rys. 8. Wpływ względnego obciążenia silnika na jego względną pracę wymiany ładunku

As consequence of the growth of the relative load exchange work is the regular and significant drop of the engine energy efficiency; from ca. 55% down to ca. 25% at the idle running. The main reason of this effect is the throttling process (mainly by the throttle valve, causing exergy losses given by Eq. (5)) occurring in the inlet and outlet channels. The speed of real engines influences the investigation results too.

Effective energy efficiency η_e of IC engine (Eq. (1)) depends on the energy efficiency η_0 of the reference thermodynamic cycle, expressed as:

$$\eta_0 = \frac{N_0}{\dot{m}_p \, H_{u,p}} \quad , \tag{8}$$

where N_0, *kW* is power output of the ideal engine working due to the reference ideal thermodynamic cycle,

For the coming analyse, important is the relation between mentioned two energy efficiencies:

$$\eta_e = \eta_0 \; \xi_i \; \xi_m \quad , \tag{9}$$

whereby:

$$\xi_i = \frac{N_i}{N_0} \; , \quad \xi_m = \frac{N_e}{N_i} \quad , \tag{10}$$

where: ξ_I - internal goodness rate of the engine, ξ_m - mechanical goodness rate of the IC engine.

Therefore improving the structure of the reference cycle (the energy efficiency η_0 should be achieved higher) leads (due to Eq. (9)) to reaching of better effective energy efficiency η_e of the real internal combustion engine.

The energy efficiency of each heat engine cannot be greater than thermal efficiency of the ideal engine working according to Carnot cycle.

The main idea presented in the paper leads to diminishing the charge exchange work of the IC engines. Normally the charge exchange occurs once during each engine cycle realized.

Elaborated proposition bases on the elimination of chosen charge exchange processes and through this the dropping of the charge exchange work can be achieved. The first step is introduction of only one charge exchange, but for two fuel injection, and ipso facto two work output stages.

3. DEVELOPED CONCEPT AND BASIC ELEMENTS OF THE ECO-CYCLE

Normally the charge exchange occurs once during each engine cycle realized. The idea shown and described below gives an alternative solution of the charge exchange work problem. Elaborated proposition bases on the elimination of chosen charge exchange processes and through this the dropping of the charge exchange work can be achieved. Below the functioning of the considered eco-cycle is discussed and main stages of this thermodynamic eco-cycle are in detail described (shown in Fig. 9). The analysis can refer to both spark-ignition and compression-ignition engine because the ideal engine cycle is considered.

In the **I.** stage (illustrated in the Fig. 9, left) the following steps are realised:

- filling of the engine cylinder (0-1) with the fresh air charge,
- compression (1-2) of the fresh charge (change of the cylinder volume: from V_0 to V_k),
- initial phase of the fuel injection and mixture combustion (energy release and heat output),
- first expansion (4-5) of the working medium (I stage of the work performance),
- isochoric (at the cylinder volume V_0) cooling (5-6) of the charge (e.g. by injection and vaporising of the liquid water), which results in the temperature and pressure dropping.

The first step is introduction of only one charge exchange, but for two fuel injection, and ipso facto two work output stages. During the first stage the engine cylinder is fully filled with the fresh charge (mostly with the air), and after this process the cylinder charge is compressed. At the end of the compression the first portion of the fuel is injected and first stage of combustion process occurs, and afterwards the whole charge expands and decompresses.

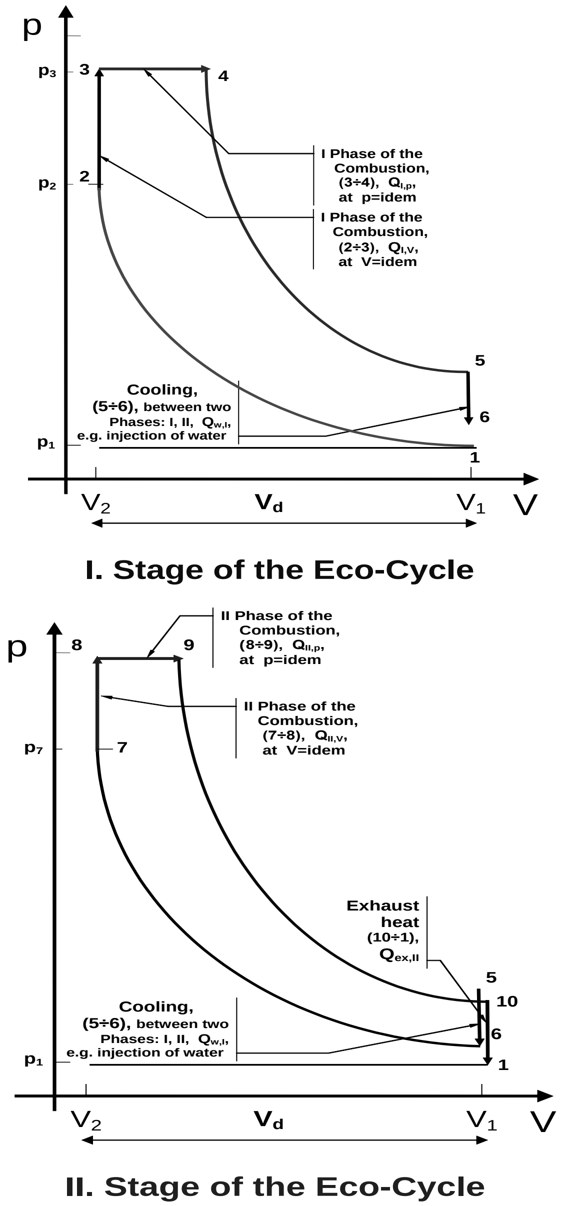

Fig. 9. Main components of the two stages of the elaborated eco-cycle
Rys. 9. Główne elementy dwóch etapów realizacji ekoobiegu

The second stage of the eco-cycle begins with the isochoric cooling of the charge. This effect can be achieved by injection of liquid water into the volume of hot part-combustion products in the cylinder; the injected water is heated and vaporises immediately, which results with the dropping of the charge temperature and pressure. The achieved new mixture is compressed again, and then after injection of the second portion of fuel, the second stage of combustion process occurs. The whole charge expands and decompresses, and next the open expansion and outflow of flue gases process. In the range of each stage a new portion of fuel is injected into the combustion chamber, so the combustion of the prepared combustion mixture, energy release and heat output take place in two stages too.

During the II. stage (shown in the Fig. 9, right) the following steps are realised:

- renewed compression (6-7) of the working medium (provided by change of the cylinder and charge volume: from V0 to Vk),

- second phase of the fuel injection and mixture combustion (energy release and heat output): approximately – isochoricly (7-8), and next – isobaricly (8-9),
- final expansion (9-10) of the combustion products (II stage of the work performance),
- open expansion and outflow of flu gases.

The second combustion stage (containing anew the isochoric and next isobaric phases) processes by nearly stoichiometric combustion conditions (the actual oxygen excess ratio equals one $\lambda_2 \geq \cong 1$), but also in the presence of significant amount of the inert substances (recirculating gases), what efficiently limits the excessive temperature rise in the combustion chamber, and through this diminishes the formation of the nitrogen oxides NO_x. In the second stage the reburning of earlier (in the first stage) unburned gaseous (hydrocarbons C_mH_n, carbon monoxide CO) and solid (soot) substances takes place. The elaborated thermodynamic cycle of ICE in the composed form is presented in the Fig. 10.

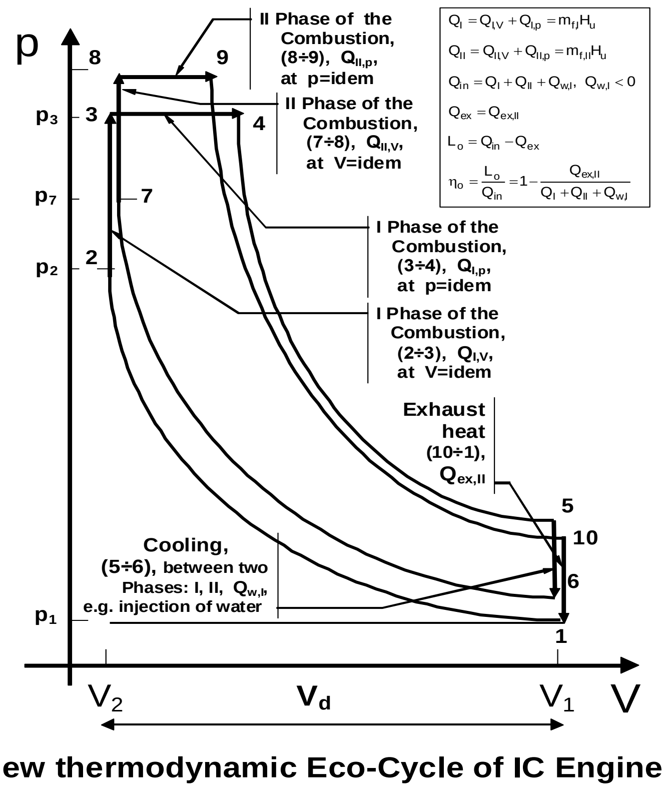

Fig. 10. Full composition of the thermodynamic reference eco-cycle
Rys. 10. Pełny obraz termodynamicznego ekoobiegu porównawczego

The characteristic feature of the proposed solution is among other things that it contains almost all ways of the diminishing of the toxic substance emission:

- combustion of the lean air-fuel mixtures,
- multistage injection of the fuel,
- recirculation of combustion flu gases,
- after-burning of combustible components,
- loading of additional water into the cylinder, appearing in the primary measures.

The first stage of combustion process (containing the isochoric and next isobaric phases) is signified through this, that is realised in the range of the lean combustion mixtures, it means at the high air (oxygen) excess $\lambda_1 > 1$. The recirculation of the flu gases is realised by keeping of the whole charge in the cylinder volume between both stages, and renewed compression at the beginning of the second stage of the eco-engine. Improving the structure of the reference thermodynamic cycle leads to reaching of better effective energy efficiency of the internal combustion engine (results shown in the Fig. 11), in the wide range of its operating parameters and especially at the part load.

The work of the engine basing on the eco-cycle occurs in two 3-stroke stages; the fresh air is delivered only once for both stages, but in range of each stage a new portion of fuel is burned.

The elaborated system is very important because in this case for engines with the combustion of lean fuel-air mixtures (air (oxygen) excess $\lambda_1 > 1$ in the stage) the 3-way catalysts can be applied, through this that the effective air excess (observed in the flu gases outflow from engine) can reach values of $\lambda_{ef} \approx 1$.

The achieved results shows that the fuel combustion for the whole eco-cycle can be performed at relatively low values of air excess $\lambda_{ef} \geq 1$, nevertheless locally in each stage the oxygen excess can be freely high (especially in the I stage, λ_1 of the process).

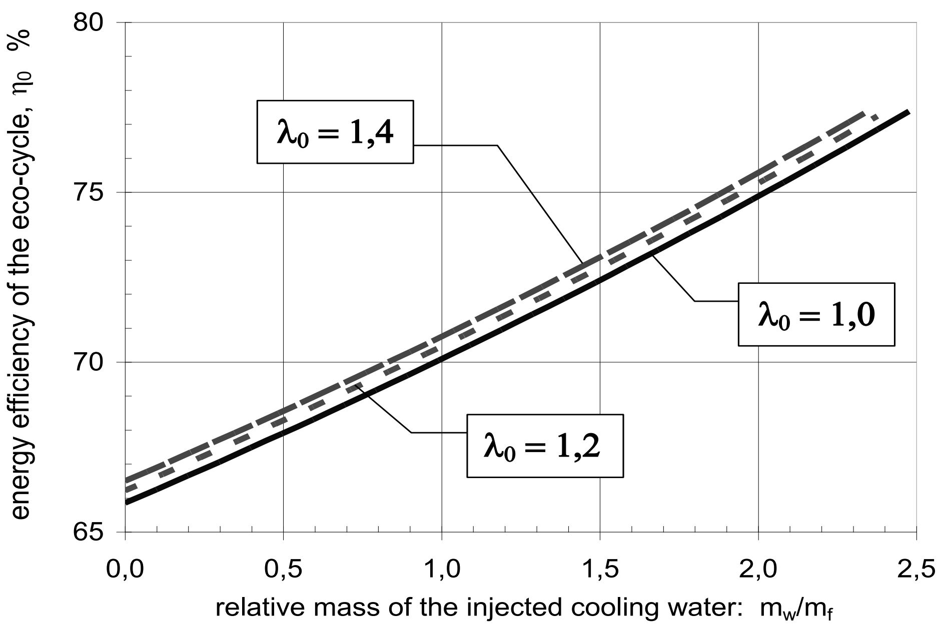

Fig. 11. Influence of the dimensionless parameters on the efficiency of the eco-engine
Rys. 11. Wpływ bezwymiarowych parametrów na sprawność ekoobiegu

4. CONCLUSIONS

Work of internal combustion engines, which are used as the driving source of cars, occurs not only at the full load, but mostly at the part load, when the energy efficiency η_e is significantly lower than in the optimal (nominal field) range of the performance parameters.

The load exchange work of IC engine essentially determines the effective engine efficiency. The main reason of this effect is the throttling process (causing exergy losses) occurring in the inlet and outlet channels. It is directly connected with the quantitative (different mass of the inlet fresh charge, while the effective air (oxygen) excess is quasi invariable for given load of the engine) regulation method commonly used in the IC engines. Improving of engine operating parameters can be achieved through diminishing of the charge exchange work. One of the numerous reasons of this state is regular growing of the relative load exchange work of the IC engine.

Consequence of the growing of the relative load exchange work is the regular and significant drop of the engine energy efficiency; from ca. 42% down to ca. 25%. Using the worked out formulas it has been calculated that the relative load exchange work can achieve value up to 55% at the part load (e.g. idle run) of the IC engine. The proposed system (called as eco-cycle) leads to the diminishing of the toxic substance emission and simultaneously at improving engine work efficiency – among other things – through abatement of the IC engine charge exchange work.

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