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

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Abstract

Internal combustion engines, used for driving of different cars, occur not only at the full load, but mostly at the part load. The relative load exchange work at the full (nominal) engine load is significant low. At the part load of the IC engine his 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. The load exchange work of IC engine essentially determines the effective engine efficiency.

It is directly connected with the quantitative regulation method common 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 independent actuating (steerage) procedures of the ICE inlet valves should assure 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. The idea presented in the paper leads to diminishing the charge exchange work of the IC engines. The mentioned above problem can be solved using presented in the paper a new concept of the reference cycle (called as eco-cycle) of IC engine.

***Keywords**: engine efficiency, charge exchange work, engine load, valve actuating, thermodynamic cycle*

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. Depend 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 significant low. The engine speed influences the real investigation results too. The new 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 independent actuating (steerage) procedures of the ICE inlet valves should assure 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.

2. Effective energy efficiency and relative charge exchange work of IC engine

The internal combustion engine at the normal (nominal) working state (Fig. 1) can be characterised by the following quantities and parameters:

$N_{e,0}$, *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).

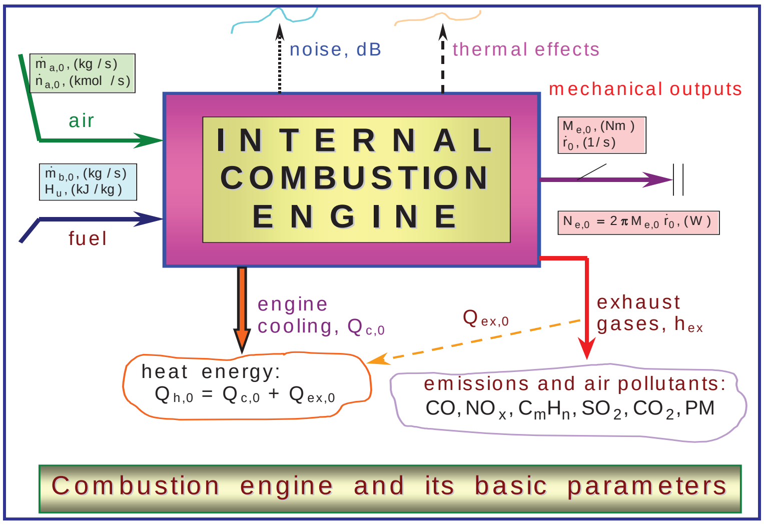

Fig. 1. Internal combustion engine as a complex energy object

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

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

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 an example engine shown in the Fig. 2) of its actual performance parameters:

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

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]:

$$b_e = \frac{\dot{m}_p}{N_e} , \text{ kg/kJ (or: g/kWh – Fig. 2)}, \qquad (3)$$

whereby:

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

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

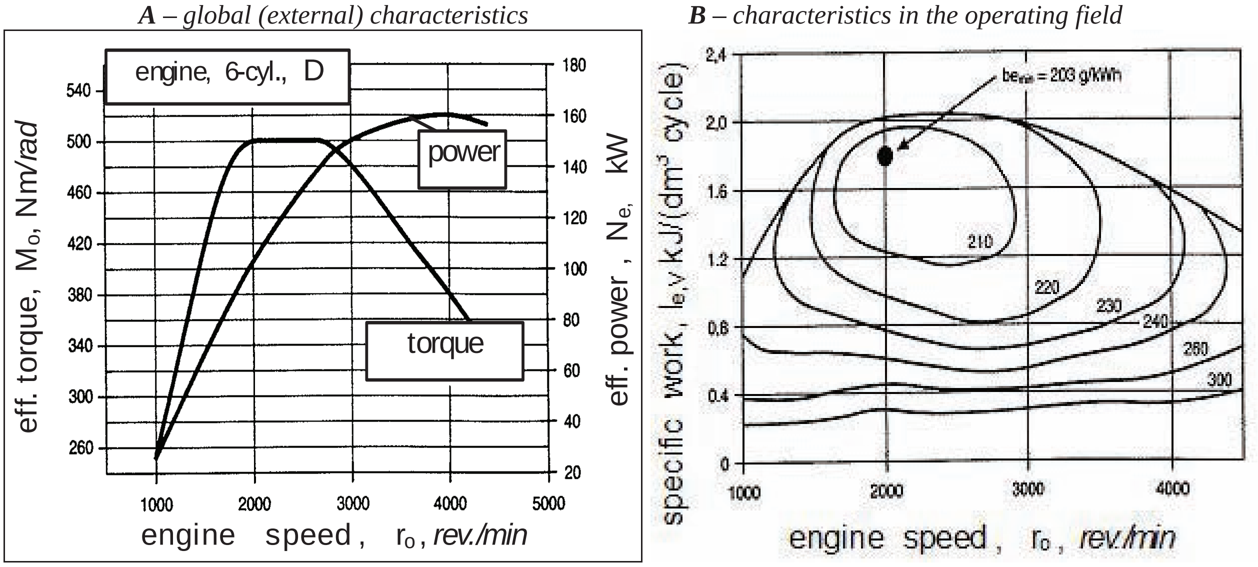

Fig. 2. Operating characteristics of the ICE

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 significant lower (the specific fuel consumption b_e – Eq. (4) – is adequate higher) as in the optimal (nominal field) stage of the performance parameters – Fig. 2. 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. 3).

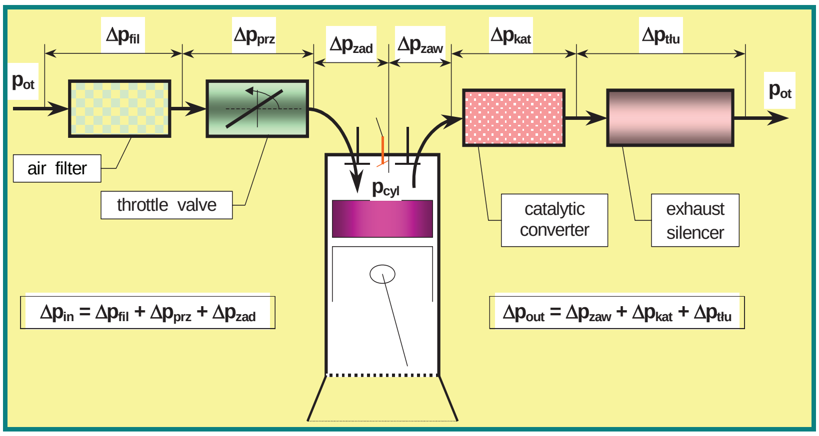

Fig. 3. Main elements of the charge exchange system (throttle valve for IC spark ignition engine)

The isenthalpic throttle causes pressure drops: Δp_{in}, Δp_{out} – shown in the Fig. 3, and next exergy losses δB occur in the inlet and outlet channels (mainly by using the quantitative engine regulation – shown in the Fig. 4). The mentioned exergy losses occurring by each (i - th) throttle element can be calculated using formula:

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

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

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*).

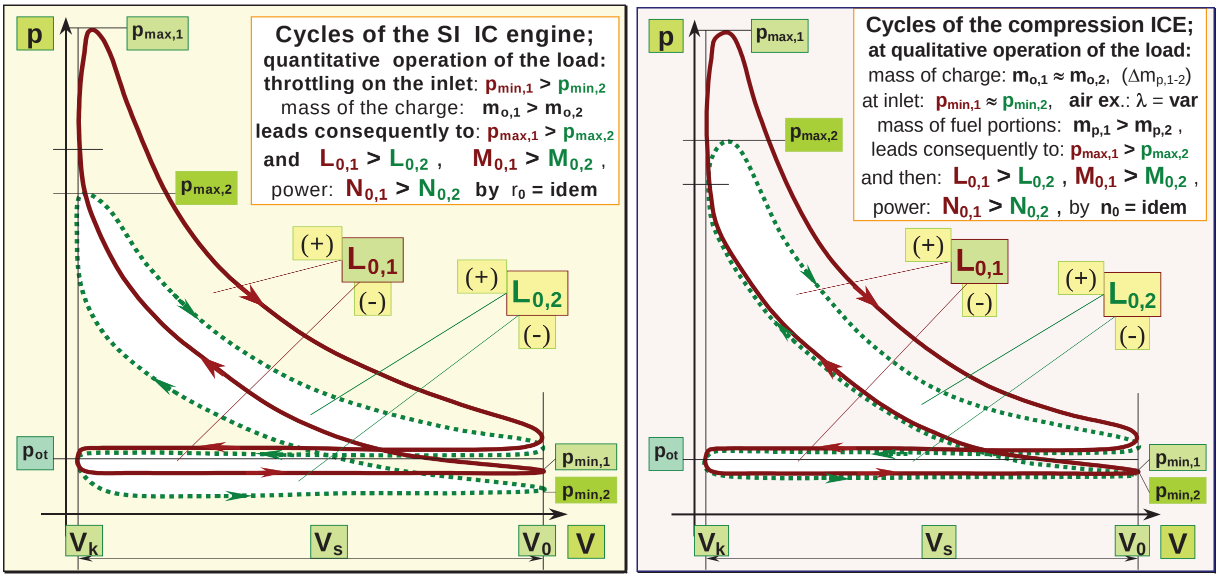

Fig. 4. Typical shapes of SI and CI – ICE cycles at different engine load

The spark ignition engines (SI, Fig. 4, 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. 4, 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 the 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:

$$|L_{in}| \approx \Delta p_{in}\, V_s\,, \qquad |L_{out}| \approx \Delta p_{out}\, V_s \quad \text{and than} \quad |L_{ew}| \approx (\Delta p_{in} + \Delta p_{out})\, V_s\ . \tag{7}$$

The mentioned problem was at this step 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, schematically shown in the Fig. 5), 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).

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 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].

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

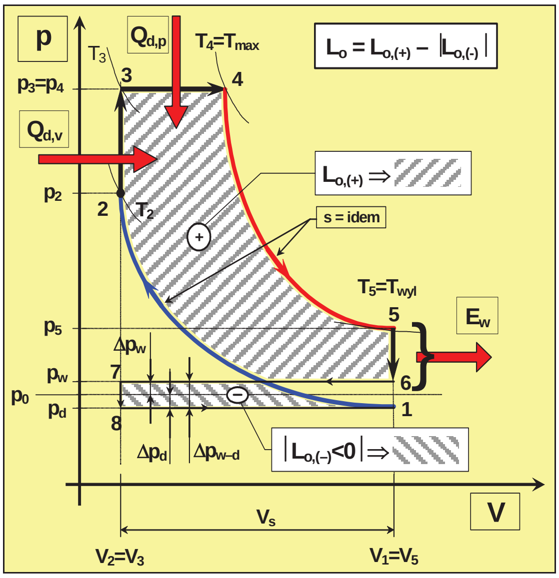

Fig. 5. Typical reference (Seiliger-Sabathe) cycle of IC engine accounting the charge exchange work

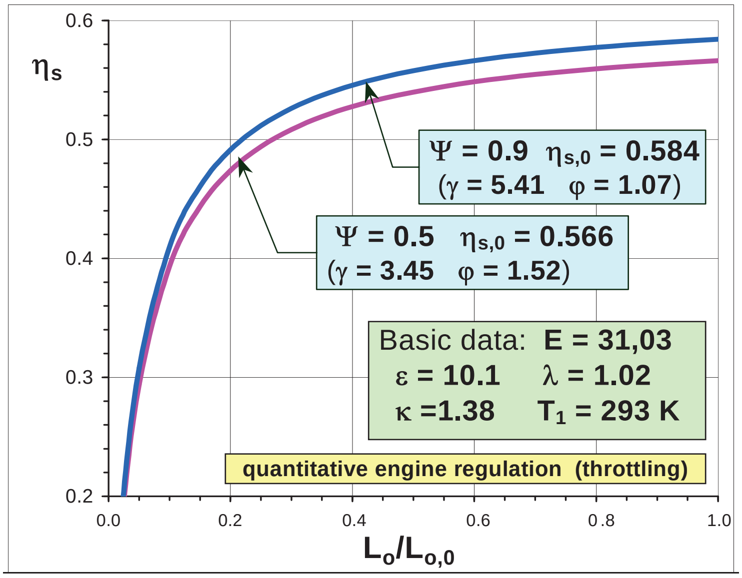

Fig. 6. Influence of the relative load on the engine energy efficiency

Using the scheme shown in the Fig. 5 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. 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. The speed of real engines influences the investigation results too. Results achieved by experimental investigations of many real engines are shown in the Fig. 7. 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.

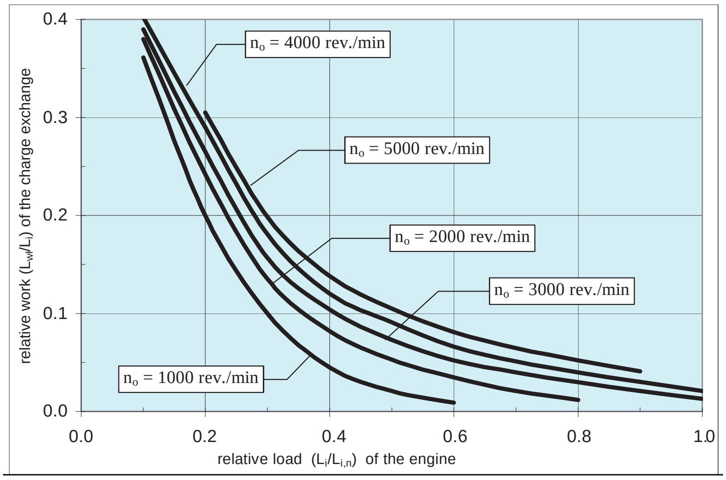

Fig. 7. Influence of load ratio on the relative exchange load work of the real IC engines

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

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

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:

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

whereby:

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

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 can not 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 (Fig. 8). The analysis can refer to both spark-ignition and compression-ignition engine because the ideal engine cycle is considered.

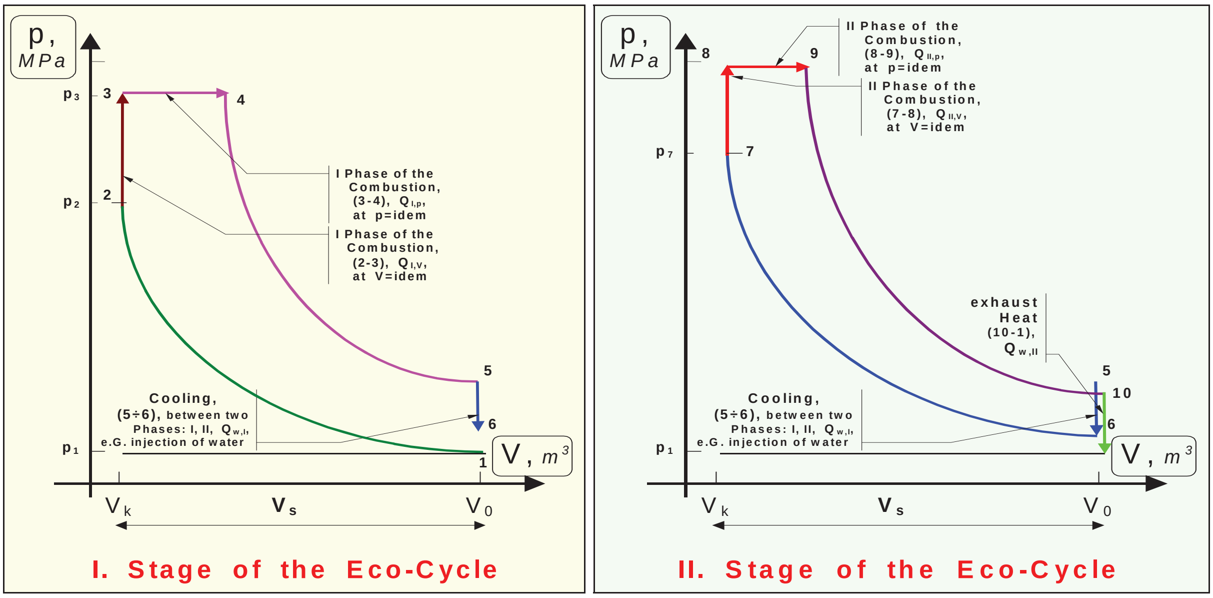

Fig. 8. Main components of the two stages of the elaborated eco-cycle

In the **I.** stage (illustrated in the Fig. 8, 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 full 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.

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, what 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 flu 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. 8, 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. 9.

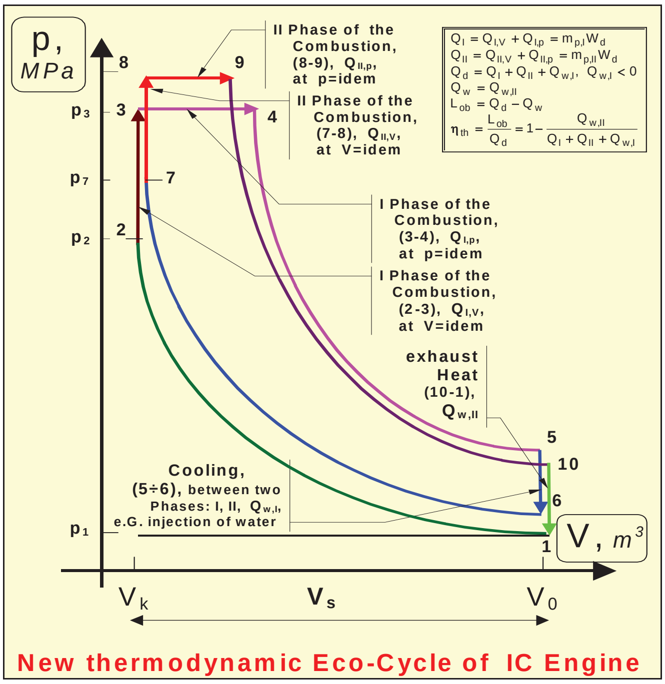

Fig. 9. Full composition of the thermodynamic reference eco-cycle

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 (Fig. 10), 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 $\lambda_{ef} \approx 1$. For this case the adequate values of the air excess (λ_1, λ_2), shown in fig. 11, can be calculated using below given relations.

For the two separate values (λ_1, λ_2) of air (oxygen) excess, the effective air excess $\lambda_{ef} = \lambda_0$ at the outflow of flu gases from engine reaches value:

$$\lambda_0 = \frac{\lambda_1 \; \lambda_2}{\lambda_1 + \lambda_2 - 1}, \qquad \lambda_0 \le \lambda_i, \qquad i = 1,\; 2. \tag{11}$$

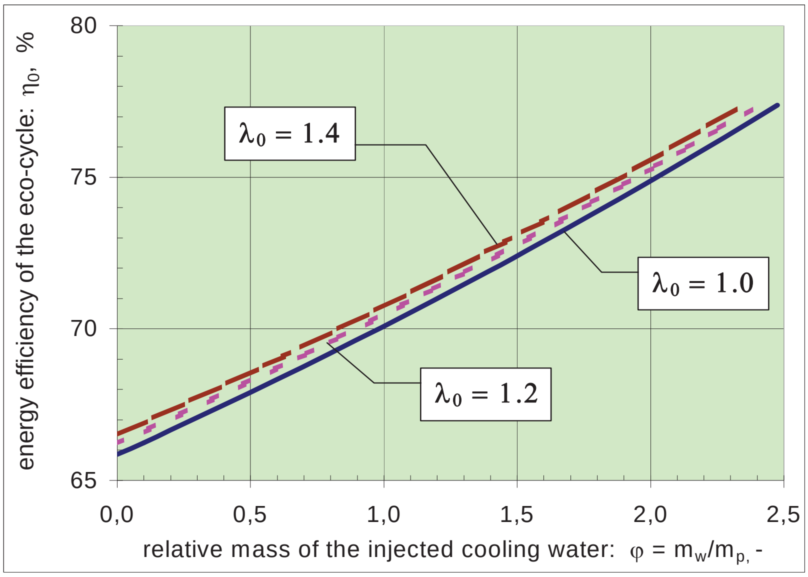

Fig. 10. Influence of the dimensionless parameters on the efficiency of the eco-engine

The achieved results show 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).

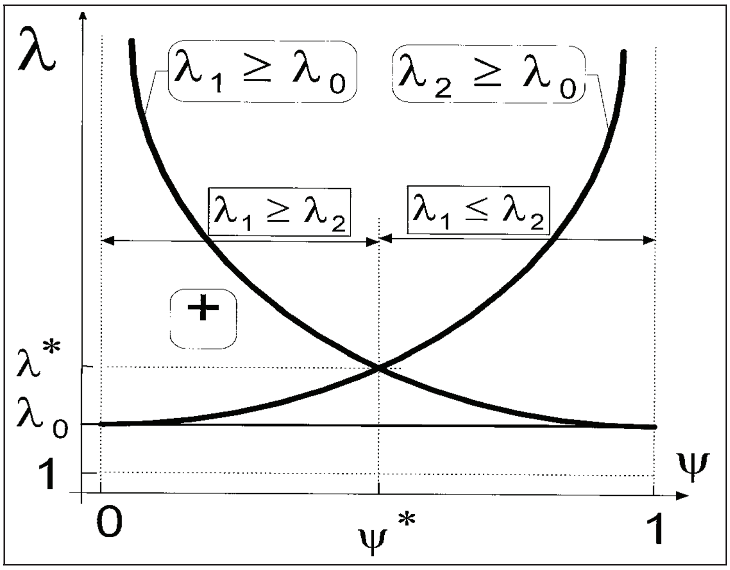

Fig. 11. Air excess ratio of each stage and for the whole thermodynamic cycle

The engine expansion effective work is performed twice within the cycle, but the exchange charge work only once; therefore the proposed thermodynamic eco-cycle of IC engine possesses features of the 3-stroke cycle. The proposed system (eco-cycle) leads to the diminishing of the toxic substance emission and simultaneously to improving of engine work efficiency - among other things - through abatement of the IC engine charge exchange work especially at its the part load; whereby the 3-way catalysts can be applied 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] (Fig. 12).

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.

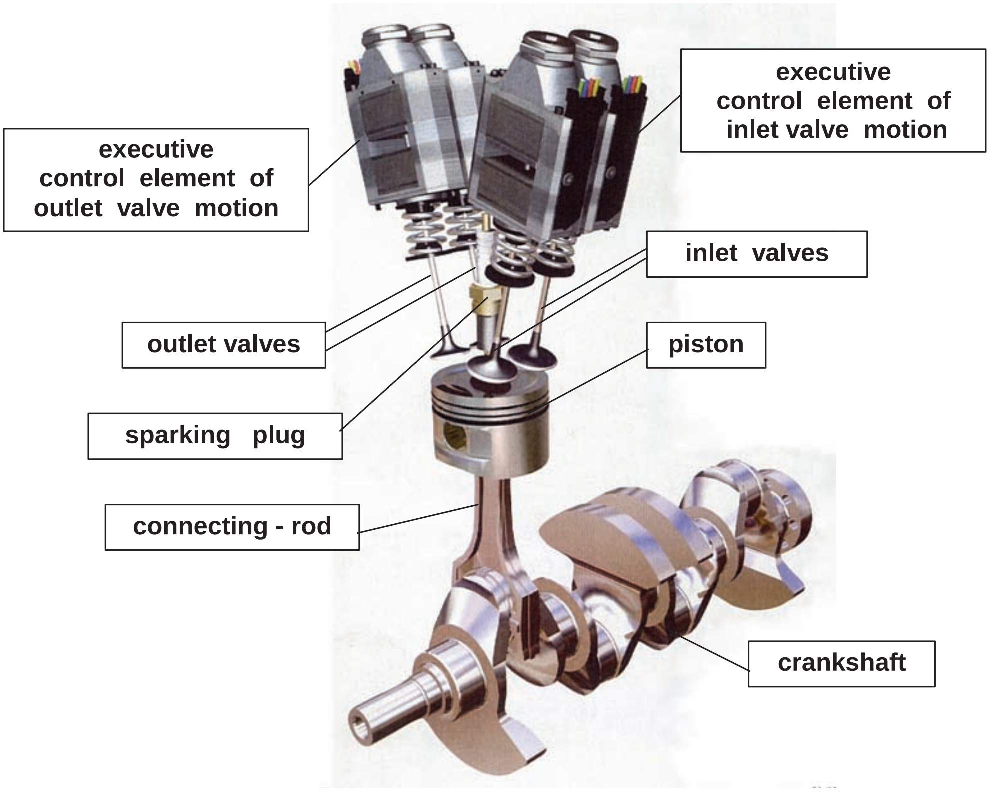

Fig. 12. Independent motion system of ICE valves

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 effective achieved. In this case the internal recirculation of flue gases, lean combustible mixture can be prepared and effective burned.

The known Atkinson cycle can be applied in this case as a thermodynamic reference cycle.

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 common 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 to improving of engine work efficiency – among other things – through abatement of the IC engine charge exchange work.

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