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CHARGE EXCHANGE CONTROL IN A SI ENGINE BY EARLY EXHAUST VALVE CLOSING

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Abstract

The paper tackles the problems connected with the charge exchange in internal combustion engines. The theoretical analysis of the charge exchange process in the SI engine has been presented. A system with independent, early exhaust valve closing has been analysed. The analysed system enables realization of an internal EGR and elimination of a throttling valve from an inlet system and reduce the charge exchange work, especially within the range of partial load. The decrease of the charge exchange work leads to an increase of the internal and effective works, which results in an increase of the effective efficiency of the spark ignition engine. The open, theoretical cycle has been assumed as a model of processes proceeding in an engine. The system has been analysed individually and comparatively with open Seiliger-Sabathe cycle. Benefits resulting from application of the system with early exhaust valve closing have been assessed on the basis of the selected parameters: a fuel dose, a cycle work, a relative charge exchange work and a cycle efficiency. The best results within decrease of fuel consumption and increase of cycle efficiency are obtained for low engine load. The main parameters characterizing the process of the internal exhaust gas recirculation were also determined. These are the ratio and the multiplicity of the exhaust gas recirculation.

Keywords: *spark-ignition engine, variable valve actuation, early exhaust valve closing, open theoretical cycle, charge exchange process, exhaust gas recirculation*

1. Introduction

A timing gear system is a mechanism which controls charge exchange process in an internal combustion engine. Whereas a throttle is a constructional element which is used to governing of the filling ratio in the spark ignition engine. The throttle causes increase of the charge exchange work especially for partial load of an engine that is connected with a method of the load control. Quantity governing with the aid of the throttle, installed in an intake system, is disadvantageous especially from thermodynamic point of view because throttling generates losses of exergy [9].

The use of the independent intake and exhaust valves actuation has been proposed in order to increase of the efficiency of the open, ideal cycle as well as effective efficiency and effective power of the spark-ignition engine [10, 13]. Theoretical research of the system with early exhaust valve closing (EEVC) has been carried out. This system enables elimination of the choke valve from an intake system of SI engine. The open Seiliger-Sabathe cycle [13] is the reference cycle for an assessment of advantages and effectiveness of work gaining in consequence of application of the early exhaust valve closing.

Many engine concerns persistently work on a fully variable valve control systems [3, 4, 7, 11]. Electromagnetic and electro-hydraulic valve actuation systems for a camless engine are the most advanced and promising [1, 2, 8, 12]. *FIAT* is mass-producing the first fully variable intake valve train, which is based on electro-hydraulic valve drive [5, 6]. The variable valve drive is one of the key technologies for fuel consumption reduction, low CO_2 emission and increase of the effective efficiency and torque especially in the lower speed range [5].

2. The system with early exhaust valve closing – EEVC

2.1. Basic characteristics of the cycle

The open, theoretical cycle of a combustion engine with early exhaust valve closing is presented in Fig. 1. The open cycle takes into consideration a charge exchange process.

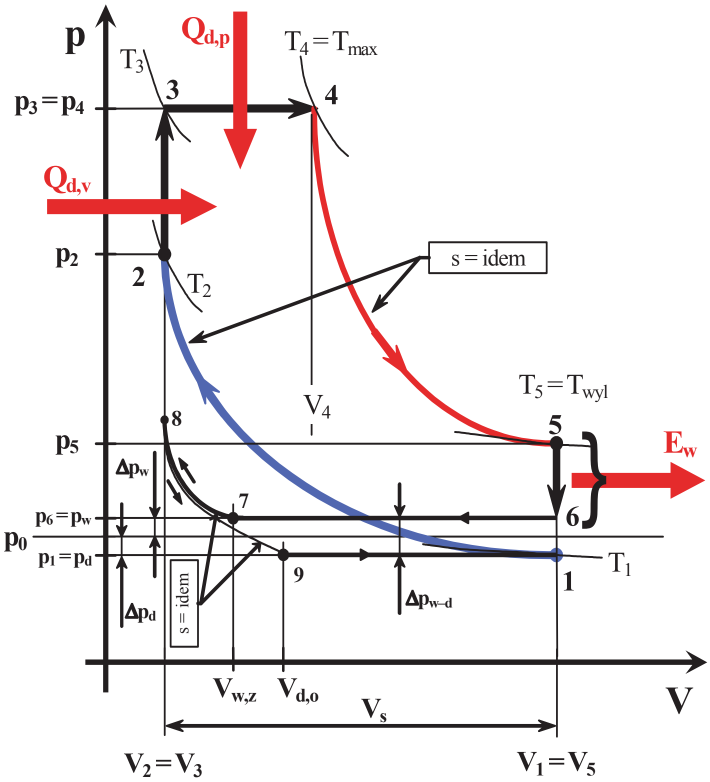

Fig. 1. Open, ideal cycle of the system with early exhaust valve closing (EEVC)

The EEVC system enables, among other things, realization of an internal exhaust gas recirculation. EGR ratio α_r is defined by formula [9, 10]:

$$\alpha_r = \frac{m_{sr}}{m_1}, \quad 0 \le \alpha_r < 1, \tag{1}$$

where m_{sr} is the mass of a recirculated exhaust gas, and m_1 is the total mass of a charge.

Additionally, multiplicity of the exhaust gas recirculation αk is defined as [10, 13]:

$$\alpha_k = \frac{m_{sr}}{m_m}, \quad \alpha_k > 0, \tag{2}$$

where m_m is the mass of the fresh charge.

The volume $V_{w,z}$ (V_7) of a cylinder, at which an exhaust valve closing occurring is the control parameter of load (the filling). Simultaneously, this is parameter adjusting the mass of the recirculated exhaust gas m_{sr} and EGR ratio α_r. The volume $V_{w,z}$ can be divided by the minimal cylinder volume V_2, defining the compression ratio of the recirculated exhaust gas:

$$\varepsilon_{w,z} = \frac{V_{w,z}}{V_2}, \qquad 1 \le \varepsilon_{w,z} < \varepsilon. \tag{3}$$

The expansion ratio of the recirculated exhaust gas is also defined:

$$\varepsilon_{d,o} = \frac{V_{d,o}}{V_2}, \tag{4}$$

where $V_{d,o}$ is the volume of a cylinder at the moment of an intake valve opening. So this is start of a filling process (point 9). Relation between the expansion ratio $\varepsilon_{d,o}$ and compression ratio $\varepsilon_{w,z}$ of the recirculated exhaust gas is expressed by the formula:

$$\varepsilon_{d,o} = \varepsilon_{w,z} \left(\frac{p_0 + \Delta p_w}{p_0 - \Delta p_d} \right)^{1/\kappa}. \tag{5}$$

The pressure drop Δp_w determines the flow resistance in a exhaust system and the pressure drop Δp_d determines the flow resistances in an intake system. In the cycle analysis, the assumptions were made that the filling process starts in the point “9” and finishes in the point „1” (Fig. 1) at the following parameters of the working medium:

– the volume: V_1,
– the pressure: $p_1 = p_0 - \Delta p_d$,
– the temperature: $T_0 < T_1 < T_9$,
– the mass: $m_1 = m_{sr} + m_m$.

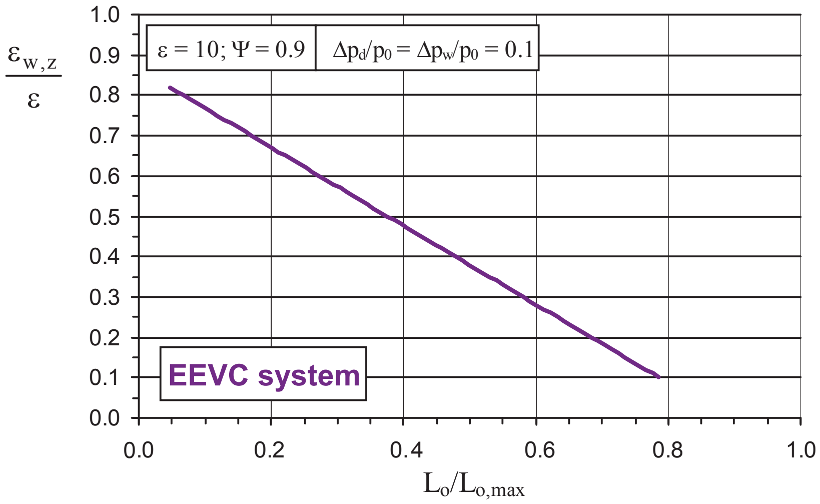

Fig. 2. Control parameter $\varepsilon_{wz}/\varepsilon$ of the EEVC cycle

The relative values of the control parameter $\varepsilon_{wz}/\varepsilon$ depending on the cycle work are presented in Fig. 2. Near-linear interdependence between the control parameter and the cycle work is favourable in respect of load governing.

2.2. Fuel dose

The fuel dose m_p depends on an engine load. The basic parameters influencing the fuel dose are the following:

$V_{w,z}$ – cylinder volume at the moment of the exhaust valve closing that is the compression ratio of the recirculated exhaust gas $\varepsilon_{w,z}$ (the control parameter),
$V_{d,o}$ – cylinder volume at the moment of the intake valve opening that is the expansion ratio of the recirculated exhaust gas $\varepsilon_{d,o}$,
T_0 – temperature of the fresh charge,
Δp_d – pressure drop in the exhaust system,
Δp_d – pressure drop in the inlet system,
λ – air excess number.

The flow resistances in the inlet and exhaust systems are taken into consideration and assumptions are made that the temperature of the fresh charge is equal to the ambient temperature T_0 and λ = idem. Then, the fuel mass m_p depending on the load control parameter $\varepsilon_{w,z}$ amounts to [10, 13]:

$$m_p = m_{p,0}\left(1 - \frac{\Delta p_d}{p_0}\right)\frac{\varepsilon - \varepsilon_{w,z}\left(\dfrac{p_0 + \Delta p_w}{p_0 - \Delta p_d}\right)^{1/\kappa}}{\varepsilon - 1}, \tag{6}$$

where $m_{p,0}$ is the fuel dose for the maximal mass of the fresh charge that is delivered into a cylinder when $\varepsilon_{w,z} = 1$. Therefore, a change of the engine load is achieved by the change of the fuel dose m_p and the compression ratio $\varepsilon_{w,z}$ of the recirculated exhaust gas is the principal control parameter of an engine load. The relative fuel dose $m_p/m_{p,0}$ depending on the cycle work for EEVC system is presented in Fig. 3.

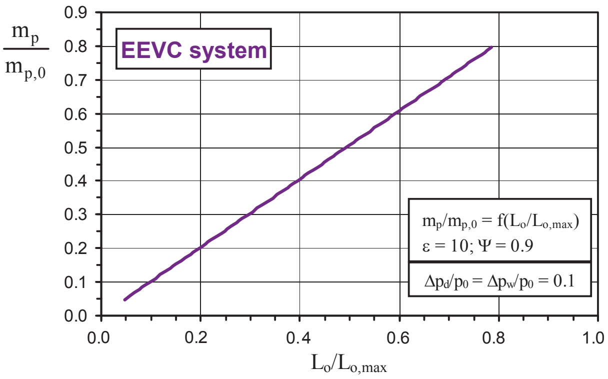

Fig. 3. Relative fuel dose of the EEVC system vs. relative cycle work

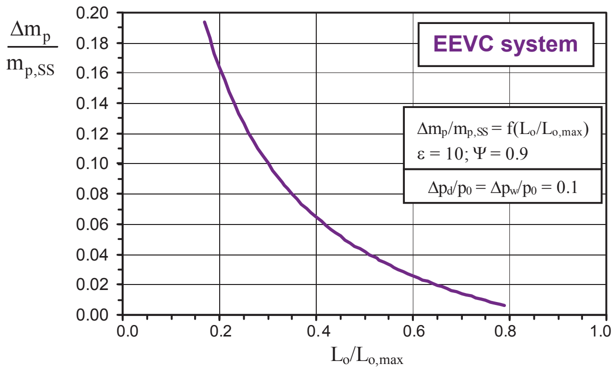

Fig. 4. Relative reduction of the fuel dose for the EEVC system compared with classic throttle governing system

Relative reduction of the fuel dose $\Delta m_p/m_{p,SS}$ for the EEVC system in comparison with the system with the classic, throttle governing (the open Seiliger-Sabathe cycle) is illustrated in Fig. 4. Decrease of the fuel dose has been found in the whole load range. Fuel economy reaches maximal value 19% at the low load and results first of all from considerable reduction of the charge exchange work at this operation range of an engine.

2.3. Charge exchange work

The charge exchange work L_w of the open cycle for EEVC system (the Fig. 1) can be expressed as the sum of the component useful works:

$$L_w = L_{u,6-7} + L_{u,7-8} + L_{u,8-9} + L_{u,9-1}. \tag{7}$$

The specific charge exchange work L_w in relation to (p_1V_1) is obtained inserting relations expressing the useful works of the individual processes to the formula (7):

$$\frac{L_w}{p_1 V_1} = -\left(1 + \frac{\Delta p_{w-d}}{p_1}\right)\left(1 - \frac{\varepsilon_{w,z}}{\varepsilon}\right) + \frac{\varepsilon_{d,o}}{(\kappa - 1)\varepsilon}\left[\left(\frac{\varepsilon_{d,o}}{\varepsilon_{w,z}}\right)^{(\kappa-1)} - 1\right] + \left(1 - \frac{\varepsilon_{d,o}}{\varepsilon}\right). \tag{8}$$

The index μ of the relative charge exchange work is calculated by definition:

$$\mu = \frac{|L_w|}{L_o}, \tag{9}$$

as a ratio of the charge exchange work (7) to the cycle work L_o.

The open, ideal Seiliger-Sabathe cycle with generally applied, classic throttle governing of an engine load, being a model of the internal processes proceeding in the typical SI engine, is the reference cycle for evaluation of benefits and the work effectiveness of an engine in consequence of use of the system with early exhaust valve closing. Therefore for comparison, characteristics of the specific charge exchange work L_w and the relative charge exchange work μ for the EEVC system and the open Seiliger-Sabathe cycle are together presented in Fig. 5 and 6, respectively.

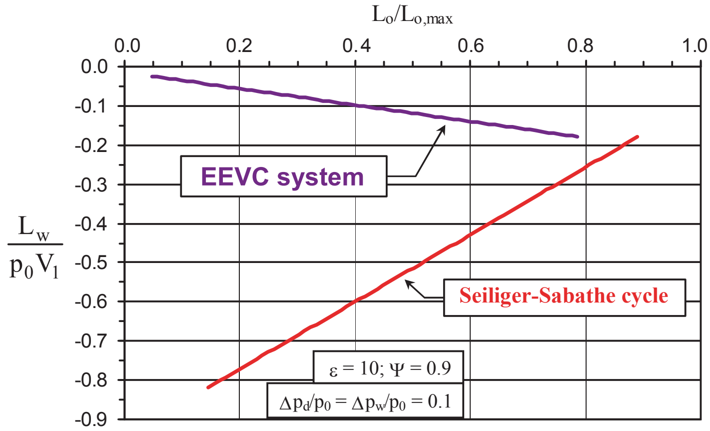

Fig. 5. Comparison of the charge exchange works for the EEVC system and Seiliger-Sabathe cycle

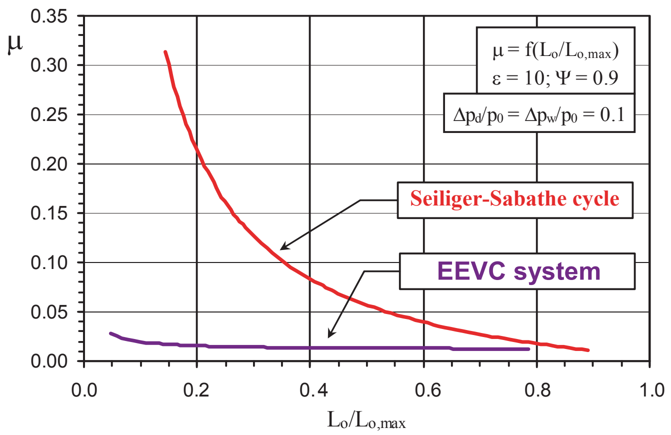

Fig. 6. Comparison of the relative charge exchange works μ for the EEVC system and Seiliger-Sabathe cycle

Absolute value of the charge exchange work L_w for EEVC system is considerably smaller than the charge exchange work for the classic throttle governing (Seiliger-Sabathe cycle) particularly within the range of low loads (Fig. 5). Reduction of this work for EEVC results first of all from removing a throttle from an intake system of the spark ignition engine, keeping quantitative control of a load.

Magnitude of the charge exchange work for EEVC system reduces when the cycle work (engine load) decreases. This is especially advantageous characteristic feature of the EEVC. Contrary, unfavourable situation is observed for the Seiliger-Sabathe cycle – considerable increase of the charge exchange work with decrease of load. This increase results from throttle backing and increase of flow resistance in an intake system.

For the EEVC system, the course of the relative charge exchange work μ is also formed favourably (Fig. 6). Its value do not exceeds 3% in the whole range of the cycle work (engine load).

2.4. Energy efficiency of the cycle

Efficiency of an ideal cycle is defined as a ratio of the cycle work L_o to the supplied heat Q_d:

$$\eta_o = \frac{L_o}{Q_d}, \tag{10}$$

which can also be formulated using the relative quantities:

$$\eta_o = \frac{L_o}{Q_d} = \frac{\dfrac{L_o}{p_1 V_1}}{\dfrac{Q_d}{p_1 V_1}} = \frac{\dfrac{L_o}{p_1 V_1}}{E}. \tag{11}$$

Next, inserting the energy-stoichiometric parameter E and the cycle work L_o [10, 13] to (11), the following formula is obtained:

$$\eta_o = \frac{\kappa - 1}{\varepsilon^{(\kappa-1)}[\gamma - 1 + \kappa\gamma(\varphi - 1)]}$$
$$\left\{ \begin{array}{l} -\dfrac{\varepsilon^{(\kappa-1)} - 1}{\kappa - 1} + \gamma(\varphi - 1)\varepsilon^{(\kappa-1)} + \dfrac{\gamma\varphi}{\kappa - 1}\left[\varepsilon^{(\kappa-1)} - \varphi^{(\kappa-1)}\right] - \left(1 + \dfrac{\Delta p_{w-d}}{p_1}\right)\left(1 - \dfrac{\varepsilon_{w,z}}{\varepsilon}\right) + \\ + \dfrac{\varepsilon_{d,o}}{(\kappa - 1)\varepsilon}\left[\left(\dfrac{\varepsilon_{d,o}}{\varepsilon_{w,z}}\right)^{(\kappa-1)} - 1\right] + \left(1 - \dfrac{\varepsilon_{d,o}}{\varepsilon}\right) \end{array} \right\}. \tag{12}$$

The efficiency η_o is significant parameter which enables assessment of the cycle in the energy aspect. Comparison of the cycle efficiencies for the system with early exhaust valve closing and the open Seiliger-Sabathe cycle depending on the cycle works is presented in Fig. 7.

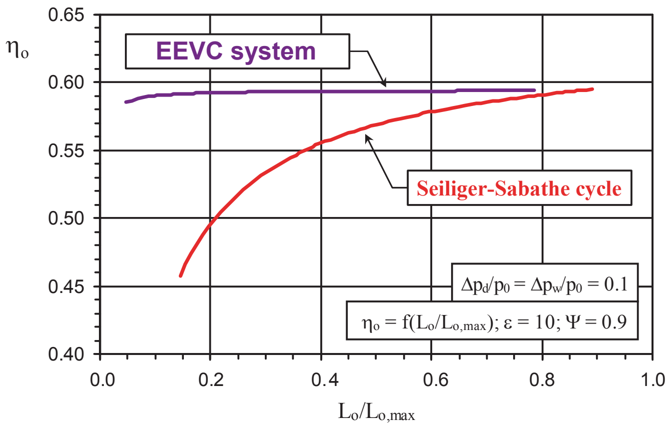

Fig. 7. Comparison of cycle efficiencies η_o for the EEVC system and Seiligera-Sabathe'a cycle

The cycle efficiency η_o for EEVC system is considerably higher than the efficiency of the open Seiliger-Sabathe cycle particularly within the range of low loads (Fig. 7). Increase of a cycle efficiency η_o leads directly to increase of an effective energy efficiency of an engine.

2.5. Parameters of an internal exhaust gas recirculation

The principal parameters characterizing internal EGR process are the following:

– ratio of the exhaust gas recirculation α_r – definition (1),
– multiplicity of the exhaust gas recirculation α_k – definition (2).

There is interdependence between the parameters α_r and α_k:

$$\alpha_r = \frac{\alpha_k}{1 + \alpha_k}. \tag{13}$$

Mentioned parameters can be expressed depending on the control parameter of load $\varepsilon_{w,z}$ [13]:

$$\alpha_r = \frac{1+\frac{\Delta p_w}{p_0}}{1-\frac{\Delta p_d}{p_0}} \frac{\varepsilon_{w,z}}{\varepsilon} \frac{\varphi^{-\kappa}}{\gamma} \frac{M_{sr}}{M_1}, \tag{14}$$

$$\alpha_k = \frac{1+\frac{\Delta p_w}{p_0}}{1-\frac{\Delta p_d}{p_0}} \frac{\varepsilon_{w,z}}{\varepsilon-\varepsilon_{d,o}} \frac{M_{sr}}{M_m} \cdot \frac{\frac{\varphi^{-\kappa}}{\gamma}}{1+\frac{p_w}{p_1}\frac{\varepsilon_{w,z}}{(\varepsilon-\varepsilon_{d,o})}\left[\left(\frac{\varepsilon_{w,z}}{\varepsilon_{d,o}}\right)^{(\kappa-1)}-\frac{\varphi^{-\kappa}}{\gamma}\right]}, \tag{15}$$

where φ and γ are the load parameters.

The EGR ratio α_r and the EGR multiplicity α_k for the EEVC system are presented in Fig. 8 and 9, respectively.

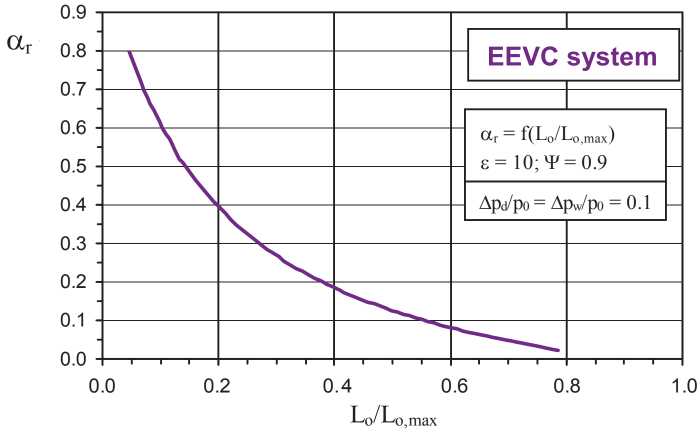

Fig. 8. Ratio of exhaust gas recirculation α_r for the EEVC system versus cycle work

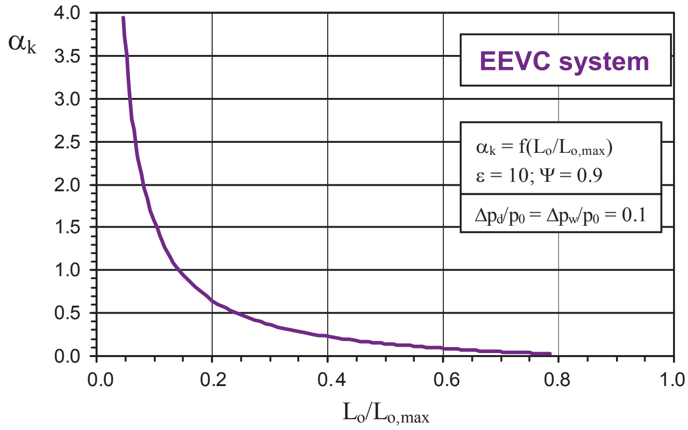

Fig. 9. Multiplicity of exhaust gas recirculation α_k for the EEVC system versus cycle work

The values of the EGR ratio α_r (up to 80%, the Figure 8) and the values of the EGR multiplicity α_k (up to 4, see Fig. 9) within the range of the lowest cycle work (engine load) are too high for the sake of reliability of an ignition and regularity of fuel combustion process. Thus, the EGR ratio must be decreased in this operation range of the real engine. Acceptable, maximal values of the EGR ratio and multiplicity can be determined only experimentally.

3. Conclusions

Presented system with early exhaust valve closing (EEVC) is one of several possibilities of application of the fully independent valve control [10, 13]. Generally, the use of the fully variable valve actuation systems to governing of engine load enables to eliminate a throttling valve from intake system of spark ignition engine and reduce the charge exchange work, especially within the range of partial load. The decrease of the charge exchange work leads to an increase of the internal and effective works, which results in an increase of the engine effective efficiency. The charge exchange work for EEVC system is eight times smaller than the charge exchange work for the classic throttle governing (Seiliger-Sabathe cycle) within the range of the lowest loads. This work reduces when the engine load decreases that is especially advantageous characteristic feature of the EEVC system. The system offers a high level of variability of the valve lift curves. There is also additional ecological aspect of the EEVC system application. The system provides an internal exhaust gas recirculation that leads to temperature and NO_x emission decrease.

The variability of valve trains is an important component of internal combustion engine technology of the future, and will assist in fulfilling strict current and future legal requirements regarding emissions and fuel consumption.

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