2. Basic characteristics of the analysed cycles

The open, theoretical cycle, presented in the Figure 1, has been assumed as the model of the processes proceeding in the SI engine with early inlet valve closing (EIVC). The open cycle takes into consideration a charge exchange process.

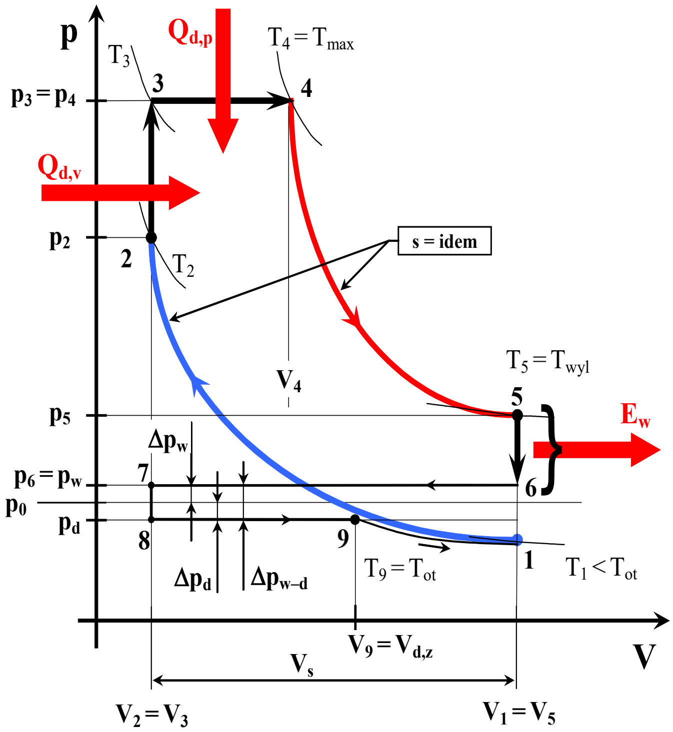

Fig. 1. The open, theoretical cycle of the system with early inlet valve closing (EIVC)

The volume V_9 ($V_{d,z}$) of a cylinder, at which an inlet valve closure occurs during filling stroke, is the control parameter of the engine load. The volume $V_{d,z}$ can be expressed in relation to the minimum volume of the cylinder:

$$\varepsilon_d = \frac{V_{d,z}}{V_2}, \qquad 1 < \varepsilon_d \le \varepsilon \tag{1}$$

The open, theoretical cycle of a combustion engine with early exhaust valve closing (EEVC) is presented in the Figure 2. The EEVC system enables, among other things, realization of an internal exhaust gas recirculation. EGR ratio α_r is defined by formula [9, 10]:

$$\alpha_r = \frac{m_{sr}}{m_1}, \qquad 0 \le \alpha_r < 1, \tag{2}$$

where: m_{sr} – mass of a recirculated exhaust gas, m_1 – total mass of a charge.

The volume V_7 ($V_{w,z}$) of a cylinder, at which an exhaust valve closing occurring is the control parameter of the engine load. 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:

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

$V_{d,o}$ is the volume of a cylinder at the moment of an intake valve opening. Therefore, this is start of the filling process (point 9).

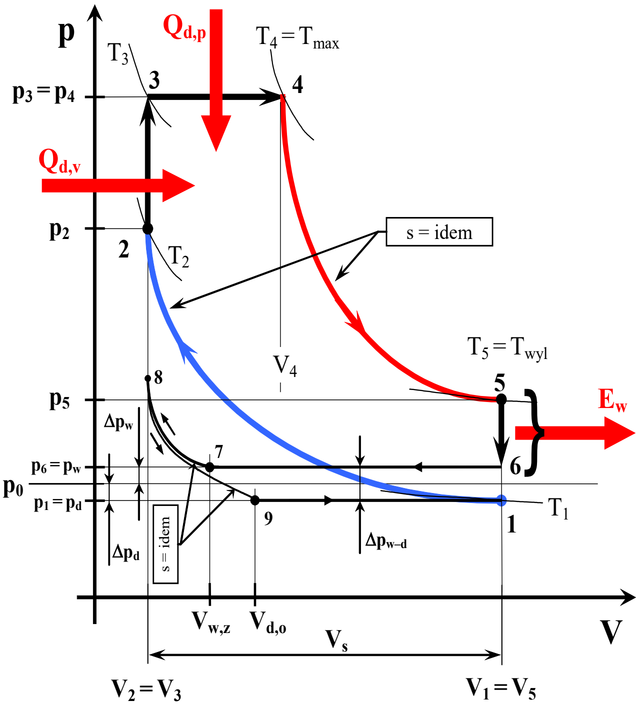

Fig. 2. Open, ideal cycle of the system with early exhaust valve closing (EEVC)

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” (the Figure 2).

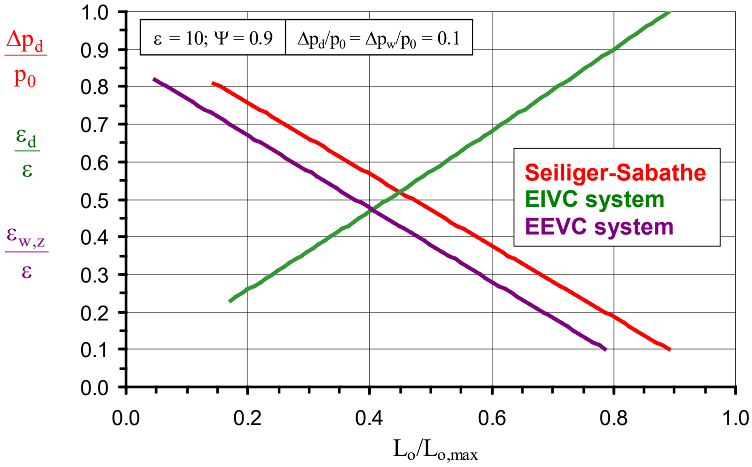

Fig. 3. Comparison of the control parameters of the analysed systems

The relative values of the control parameters (in relation to the total compression ratio ε) depending on the cycle work are presented in the Figure 3. Near-linear interdependence between the control parameters and the cycle work is favourable in respect of load governing.

3. Fuel dose

The fuel dose m_p depends on an engine load. 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 $\lambda = \text{idem}$. Then, the fuel mass m_p depending on the load control parameter for EIVC amounts to [21]:

$$m_p = m_{p,0}\left(1-\frac{\Delta p_d}{p_0}\right)\frac{\varepsilon_d}{\varepsilon} \tag{4}$$

and for EEVC [19]:

$$m_p = m_{p,0}\left(1-\frac{\Delta p_d}{p_0}\right)\frac{\varepsilon-\varepsilon_{w,z}\left(\frac{p_0+\Delta p_w}{p_0-\Delta p_d}\right)^{\frac{1}{\kappa}}}{\varepsilon-1}, \tag{5}$$

where $m_{p,0}$ is the fuel dose for the maximal mass of the fresh charge that is delivered into a cylinder. Therefore, a change of the engine load is achieved by the change of the fuel dose m_p and the compression ratios ε_d or $\varepsilon_{w,z}$ are the principal control parameters of the engine load.

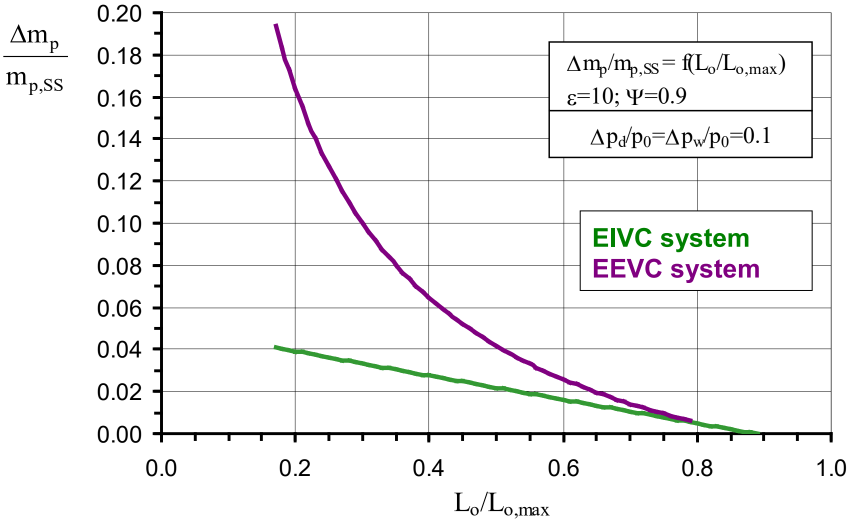

Fig. 4. Relative reduction of the fuel dose for the EIVC and EEVC systems compared with classic throttle governing system (Seiliger-Sabathe cycle)

Relative reduction of the fuel dose $\Delta m_p/m_{p,SS}$ for the EIVC and EEVC, in comparison with the system with the classic, throttle governing (the open Seiliger-Sabathe cycle) is illustrated in the Figure 4. Decrease of the fuel dose has been found in the whole load range. Using the EIVC results in the fuel economy of up to about 4% for the lowest value of the engine load. For EEVC 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.

4. Charge exchange work

The charge exchange work L_w of the cycles can be expressed as the sum of the component useful works. 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. For EIVC it is expressed as [21]:

$$\frac{L_w}{p_1 V_1} = -\frac{\frac{\Delta p_w}{p_0}(\varepsilon-1)+\frac{\Delta p_d}{p_0}(\varepsilon_d-1)}{\varepsilon\left(1-\frac{\Delta p_d}{p_0}\right)}\left(\frac{\varepsilon}{\varepsilon_d}\right)^{\kappa}, \tag{6}$$

and for EEVC [19]:

$$\frac{L_w}{p_1 V_1} = -\left(1+\frac{\Delta p_{w-d}}{p_1}\right)\left(1-\frac{\varepsilon_{w,z}}{\varepsilon}\right)+\frac{\varepsilon_{d,o}}{(\kappa-1)\varepsilon}\left[\left(\frac{\varepsilon_{d,o}}{\varepsilon_{w,z}}\right)^{(\kappa-1)}-1\right]+\left(1-\frac{\varepsilon_{d,o}}{\varepsilon}\right). \tag{7}$$

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

$$\mu = \frac{|L_w|}{L_o}, \tag{8}$$

as a ratio of the charge exchange work L_w 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 inlet or exhaust valve closing. Therefore, for comparison, characteristics of the specific charge exchange work L_w and the relative charge exchange work μ for the EIVC, EEVC and the Seiliger-Sabathe cycle are together presented in the Figures 5 and 6 respectively. These works for EIVC and EEVC are much smaller in the entire load range except for full load.

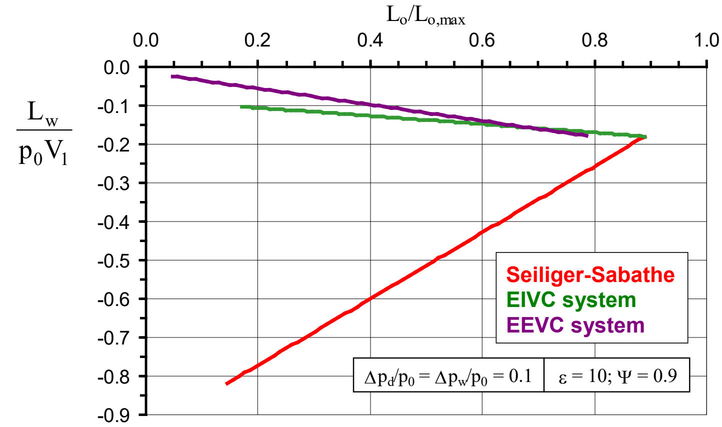

Fig. 5. Comparison of the charge exchange works for the EIVC, EEVC and Seiliger-Sabathe cycle

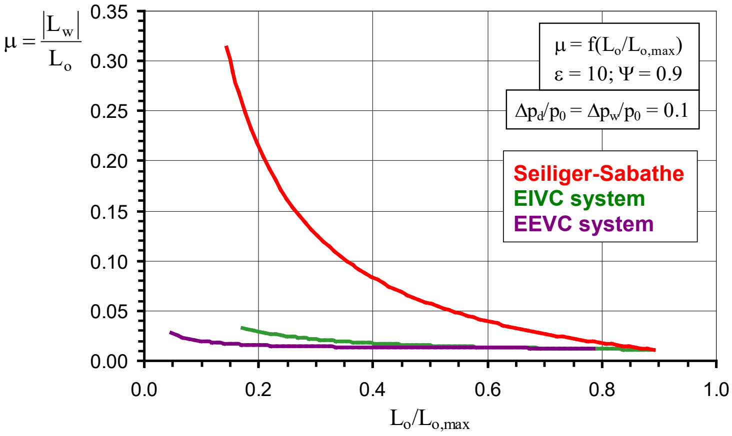

Fig. 6. Comparison of the relative charge exchange works μ for the EIVC, EEVC and Seiliger-Sabathe cycle

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

Magnitude of the charge exchange work for EIVC and EEVC reduces when the engine load decreases. This is especially advantageous characteristic feature of the analysed systems. 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 the intake system.

For the EIVC and EEVC, the courses of the relative charge exchange works μ are also formed favourably (the Figure 6). Their values do not exceed 3% in the whole range of the engine load. The reverse, unfavorable situation is observed for Seiliger-Sabathe cycle – the absolute value of the charge exchange work significantly increases with a decrease of the load and the value of the relative charge exchange work exceeds 30%.

5. Energy efficiency of the cycles

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

$$\eta_o = \frac{L_o}{Q_d}. \tag{9}$$

The efficiency η_o is significant parameter, which enables assessment of the cycle in the energy aspect. Comparison of the cycle energy efficiencies for the analysed systems and for the open Seiliger-Sabathe cycle depending on the cycle works is presented in the Figure 7.

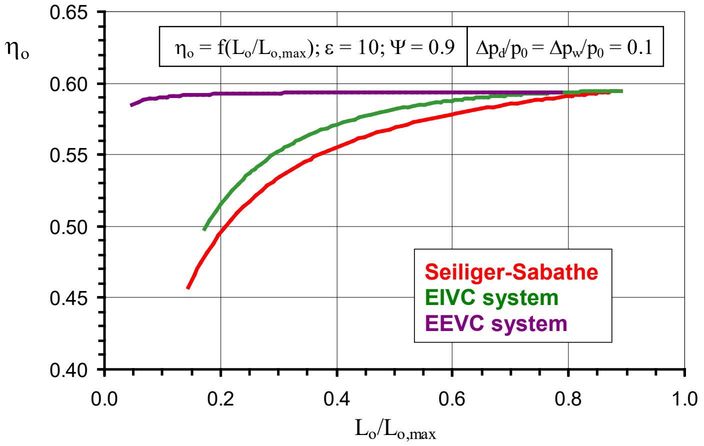

Fig. 7. Comparison of cycle efficiencies η_o for the EIVC, EEVC and Seiligera-Sabathe'a cycle

The energy efficiency of the EIVC cycle is higher by 2 percentage points than the efficiency of the open Seiliger-Sabathe cycle almost in the entire load range. However, the cycle efficiency η_o for EEVC is considerably higher (about 10 percentage points) than the efficiency of the Seiliger-Sabathe cycle particularly within the range of low loads. Increase of a cycle efficiency η_o leads directly to increase of an effective energy efficiency of an engine.

6. Parameters of the internal exhaust gas recirculation for EEVC

The principal parameter characterizing internal EGR process is the ratio of recirculation α_r – definition (2). This ratio can be expressed depending on the control parameter $\varepsilon_{w,z}$ of the load [19]:

$$\alpha_r = \frac{1+\frac{\Delta p_w}{p_0}}{1-\frac{\Delta p_d}{p_0}} \frac{\varepsilon_{w,z}}{\varepsilon} \frac{\varphi^{-\kappa}}{\gamma} \frac{M_{sr}}{M_1}, \tag{10}$$

where φ and γ are load parameters [16]. The EGR ratio α_r for the EEVC system is presented in the Figures 8.

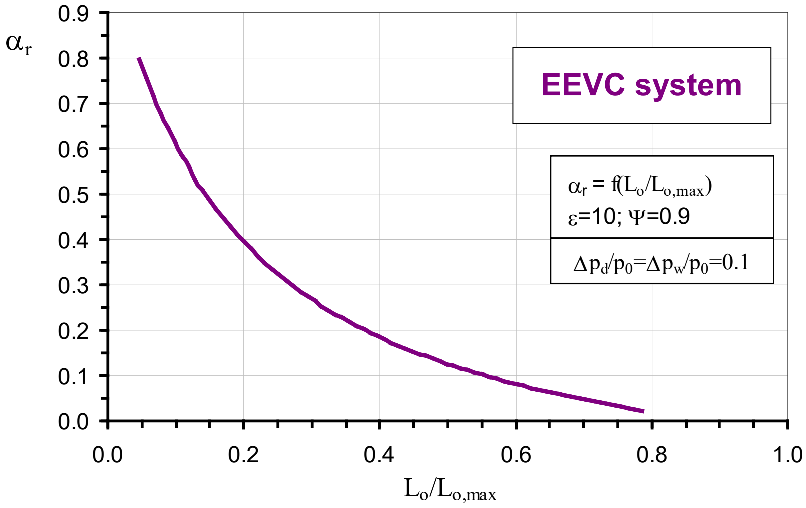

Fig. 8. Ratio of exhaust gas recirculation α_r for the EEVC system versus cycle work

The values of the EGR ratio α_r (up to 80%) within the range of the lowest 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 can be determined only experimentally.

7. Conclusion

Presented systems with early inlet valve closing (EIVC) and early exhaust valve closing (EEVC) are two of several possibilities of application of the fully independent valve control [11, 15, 16, 17, 18, 20]. 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 increase of the internal and effective works, which results in increase of the engine effective efficiency. The charge exchange work for EIVC and EEVC is about 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 is reduced when the engine load decreases that is especially advantageous characteristic feature of both the EIVC and EEVC. At all conditions except full load, effective energy efficiency for EIVC and EEVC is higher than for the Seiliger-Sabathe cycle. The consequence of increased efficiency is reduction of fuel consumption.

There is also additional ecological aspect of the EEVC application. The system provides an internal exhaust gas recirculation that leads to temperature and NO_x emission decrease.

Both system offers a high level of variability of the valve lift curves. 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.

Acknowledgements

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