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Zbigniew ŻMUDKA
Stefan POSTRZEDNIK

Combustion Engines
Polish Scientific Society of Combustion Engines

Comparative analysis of theoretical cycles of independent valve control systems of the SI engine

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The objects of the study were theoretical cycles of the load control systems and charge exchange process in the naturally aspirated SI engine, including classic, quantitative throttling control (Seiliger-Sabathe open cycle); a system with late inlet valve closing LIVC (the Atkinson-Miller open cycle); a system with early inlet valve closing EIVC; a system with early exhaust valve closing EEVC, enabling internal exhaust gas recirculation; system of fully independent valve control FIVC. The aim of using camless independent valve control algorithms is to eliminate the throttle as an control valve for load and filling control of the SI engine, while retaining quantitative load control. The research aims to select the camless valve control algorithm most beneficial in terms of energy (the highest effective efficiency) and economy (the lowest fuel consumption).

Key words: *spark ignition engine, thermodynamic cycle, charge exchange, energy efficiency, camless valve control*

1. Introduction – variable valve timing systems

In spark-ignition engines, quantitative load control is used by throttling the airflow reaching the engine. Currently, this is most often implemented by a throttle valve installed in the inlet system.

SI engines sometimes use unusual load control solutions that can regulate the engine load without using the throttle. At the turn of the 1950s and 1960s, the first patents were issued for solutions allowing to change the valve lift in internal combustion engines. The first mass-produced engine equipped with a system allowing the valve lift to be changed (or, more precisely, the disconnection of 2 of the 4 valves per cylinder at a speed 9500 rpm) was the REV (Revolution-Modulated Valve Control) system used in 1983 on the Honda CBR400RR motorcycle. In 1989, the REV system evolved into the VTEC (Variable Valve Timing and Lift Electronic Control) system, which allowed switching between two cam profiles on the camshaft. In 1992, Mitsubishi used a similar system called MIVEC (Mitsubishi Innovative Valve timing and lift Electronic Control system). At the turn of the century, more companies started to use variable valve timing (e.g. Nissan and Toyota) [6].

With advances in technology, the first solutions appeared to allow load regulation in SI engines by controlling the operation of the valve train, eliminating a throttle in the inlet system. The best known solutions are presented below.

In 2001, BMW introduced the Valvetronic system, which allows for step-less adjustment of lift and valve opening time. The solution used by BMW has an additional electromechanically operated lever between the camshaft and the rocker arm which allows adjustment of the inlet valve lift [1]. A very similar solution was used by Nissan (system VVAL – Variable Valve Event and Lift) and Toyota (Valvematic system) in 2007 [18]. A more advanced solution emerged in 2009. Fiat has developed an electro-hydraulic valve control system called MultiAir (UniAir). This solution eliminates one of the camshafts and the throttle. The inlet valves are electro-hydraulically operated and the exhaust valves are conventionally operated. This system allows the inlet valves to be opened and closed at any time and even opened several times during the suction stroke [2, 5, 7, 14]. Fiat for the first time on the Alfa Romeo MiTo has used engine with electro-hydraulic inlet valve control with "UniAir" ("Multiair") technology.

Advanced work is also being done on mechanisms where the opening and closing of valves is done by electromagnetic actuators [4, 9, 12, 17]. The latest solution is a system being developed by Freevalve AB. This technology, still in the prototype phase, eliminates camshafts and throttle valves using hydraulic and pneumatic actuators. [13].

Data presented in the literature [3, 15] demonstrate the potential for significant improvements in engine performance and fuel consumption reduction (by 20%) in the part-load range through the use of camless valve control systems. Maximum engine torque can increase by 10% and torque in the part-load range can increase by up to approximately 50%. Fuel savings in this engine operating range can be up to 20% [16].

Also noteworthy is the development of camless valve control systems for marine engines. At the beginning of the 21st century, MAN B&W launched two-stroke, low-speed, electronically controlled marine Diesel engines without a camshaft. They were marked as ME. The 7S50ME-C engine was the first ME engine. Its official presentation took place on 19.02.2003 in Denmark [10, 11].

The ME engine refers to the smart engine concept, using an electronic system to control a hydraulically driven exhaust valve, a hydraulically driven fuel injection system and an integrated engine control process. The energy to actuate both systems comes from the engine-driven hydraulic system that distributes oil at a pressure of 200 bar through a common line.

An important feature of the ME engines is the ability to optimise exhaust valve timing and fuel dosage. The main advantages of ME series engines with an electronic control system are as follows:

- – liquidation of the camshaft and its drive as well as other mechanical components
- – electronic control of exhaust valve opening time and fuel injection time, which leads to lower fuel consumption and better engine performance
- – very low minimum engine speed, which has a decisive influence on the ship's maneuverability
- – more favorable emission characteristics, lower NO_x emission and lower engine smoke at all loads.

In the development of Polish designs, the HCP D55 type engine is an example of a daring innovation solution. In the period 1961–1971, 17 engines of this type with a total of 123 cylinders were produced. [10, 11]. In the 1970s, based on this engine, the HCP plants also carried out construction and research work in the field of electronic control of marine diesel engines.

Reducing the charge exchange work, especially at partial loads, may be a design measure leading to an increase in the effective efficiency of the SI engine. This can be achieved by introducing modifications to the regulation and control systems of the charge exchange process, the essence of which is the use of independent valve control.

The objects of the study were theoretical cycles of the load control systems and charge exchange process realization of the SI engine, including:

1) classic, quantitative throttling control, using a throttle valve (Seiliger-Sabathe open cycle) [19, 21]
2) late inlet valve closing LIVC (the Atkinson-Miller open cycle) [19]
3) early inlet valve closing EIVC [19]
4) early exhaust valve closing EEVC, enabling internal EGR [20]
5) fully independent valve control FIVC that enables internal EGR and precise control of the fuel rate (general variant, which is a combination of variants 3 and 4, i.e. the systems EIVC and EEVC) [20].

In the analysis carried out, the classic control system (1) was the reference for all the other (2 to 5) studied systems for the charge exchange, using independent valve control.

This approach to the analysis was due, among other things, to the fact that the objective of independent valve control is elimination of the throttle as a load and fill control valve for the SI engine, while retaining quantitative load control. In the proposed independent valve control systems, the throttle's role in regulating the load and filling of the engine is covered by the valves controlling the entire load exchange process. The role of the intake valves is to match the amount of fresh charge delivered to the cylinder to the engine load. The task of the exhaust valves, on the other hand, is the controlled implementation of internal EGR. Eliminating the throttle through the use of independent valve control leads to a decrease in charge exchange work, an increase in the internal work of the engine and effective work, and consequently to an increase in the effective energy efficiency of the engine.

The aim of the research is an analytical study of systems of independent control of inlet and exhaust valve movement. Then, the selection of the camless valve control algorithm most beneficial in terms of energy (highest effective efficiency) and economy (lowest fuel consumption). Taking into account both aspects mentioned above, the most advantageous is the algorithm for variant 1 of the FIVC system, which has been evidenced in the following chapters.

2. Theoretical cycles of independent valve control systems – basic characteristics

2.1. System with late inlet valve closing LIVC

The theoretical Atkinson-Miller open cycle presented in Fig. 1 provides a model for the LIVC system [19].

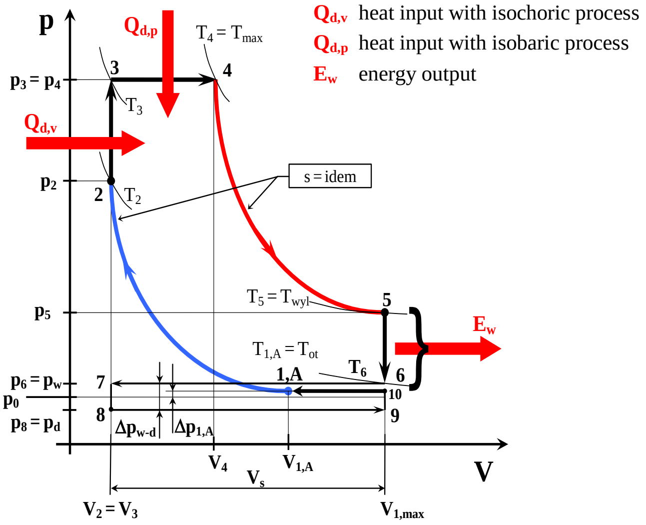

Fig. 1. System with late inlet valve closing – the open, theoretical Atkinson-Miller cycle [19]

The inlet valve closes at the volume $V_{1,A}$ and this is a load regulation parameter. This parameter can also be expressed in a relative (dimensionless) way as:

$$\varepsilon_A = \frac{V_{1,A}}{V_2}, \qquad 1 < \varepsilon_A \le \varepsilon \tag{1}$$

which can be called the isentropic compression ratio.

2.2. System with early inlet valve closing EIVC

The theoretical cycle for the EIVC system is that shown in Fig. 2 [19].

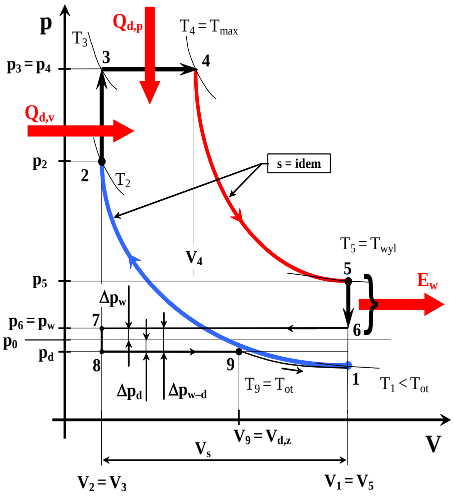

Fig. 2. The open, theoretical cycle of the system with early inlet valve closing [19]

In this case, the volume V_9 ($V_{d,z}$) of the cylinder (the moment of closing the intake valve) is a load control parameter. This parameter ε_d can also be expressed in dimensionless terms as defined by:

$$\varepsilon_d = \frac{V_{d,z}}{V_2}, \qquad 1 < \varepsilon_d \le \varepsilon \tag{2}$$

It should be mentioned here, that he expansion of gases from point “9” to point “1” leads to a lowering of temperature and as a result, to a higher specific volume of the charge.

2.3. System with early exhaust valve closing EEVC

The theoretical cycle SI engine for the EEVC is shown in Fig. 3 [20]. The load (filling) control parameter is the volume $V_{w,z}$ (V_7) of the cylinder at which the exhaust valve closes. At the same time, it is a parameter that regulates the mass of the recirculated exhaust gas m_{sr} and thus the value of the EGR rate α_r. The volume $V_{w,z}$ can be related to the minimum volume V_2 of the cylinder, thus defining the compression ratio $\varepsilon_{w,z}$ 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 rate of the recirculated exhaust gas is also defined:

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

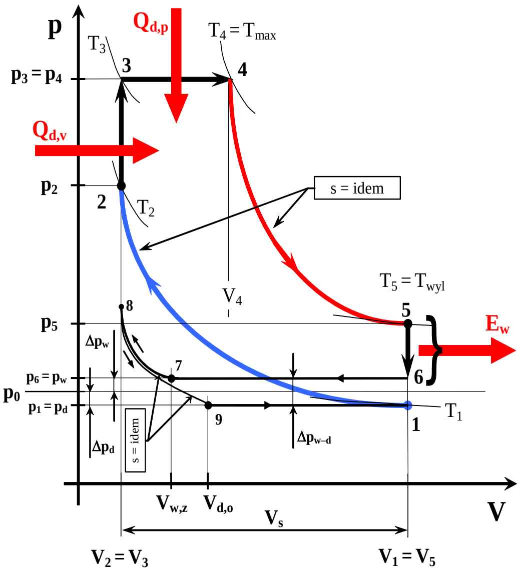

Fig. 3. Open, theoretical cycle of the system EEVC [20]

The relation between the expansion ratio $\varepsilon_{d,o}$ and compression ratio $\varepsilon_{w,z}$ of the recirculated exhaust gas is expressed by the formula:

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

where: p_0 – ambient pressure, Δp_d – pressure drop in inlet system, Δp_w – pressure drop in exhaust system.

It is noteworthy that the system under consideration enables, among other things, the realization of internal EGR. The EGR rate α_r is defined as:

$$\alpha_r = \frac{m_{sr}}{m_1}, \qquad 0 \le \alpha_r < 1 \tag{6}$$

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

In addition, multiplicity of the exhaust gas recirculation α_k is defined as:

$$\alpha_k = \frac{m_{sr}}{m_m}, \qquad \alpha_k > 0 \tag{7}$$

where: m_m – mass of the fresh charge.

2.4. System of fully independent valve control FIVC

The fully independent valve control system is an algorithm that combines the procedures for independent control of the inlet and exhaust valves. FIVC is achieved by combining the EIVC system [19] with the EEVC system [20]. The theoretical cycle for FIVC is presented in Fig. 4. [20].

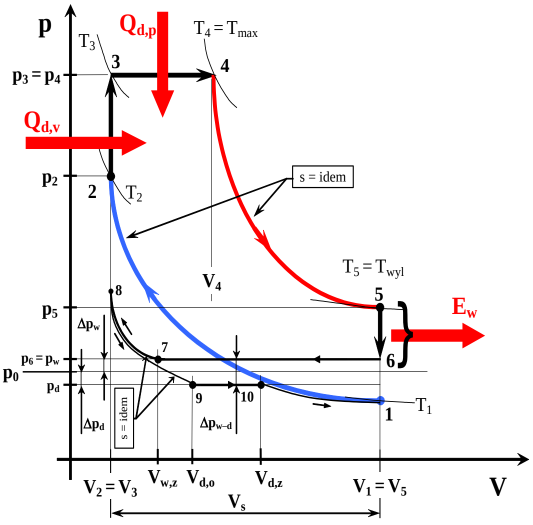

Fig. 4. Open, theoretical cycle for the system of fully independent valve control [20]

The FIVC system is implemented using two control parameters:

- $\varepsilon_{d,z}$ (2) relative cylinder volume when the intake valve is fully closed
- $\varepsilon_{w,z}$ (4) compression ratio of the recirculated exhaust gas.

3. Comparative analysis of the effectiveness of using the tested independent valve control systems

As part of the joint consideration of the studied control procedures for the internal combustion engine valves, a comparative analysis of the effectiveness of the use of the proposed systems was carried out based on the following quantities:

- load control parameters
- dose of fuel m_p
- total energy Q_d supplied to the cycle
- work of the cycle W_o

- charge exchange work W_w and relative charge exchange work μ
- theoretical open cycle efficiency η_o
- parameters of the internal EGR: α_r – recirculation rate and α_k – recirculation multiplicity (for EEVC and FIVC).

The analysis carried out assumes an excess air ratio (λ) of 1 for all systems tested, over the entire load range, including part loads, as the test object is a spark-ignition engine.

The course of the above-mentioned parameters, separately for each of the tested systems, has been presented in previous publications: LIVC in [19], EIVC in [19], EEVC in [20], FIVC in [20]. In this publication, to evaluate the effectiveness and benefits of the proposed independent valve control systems, a comparative analysis of the selected, listed above, key parameters has been carried out. In the conducted analysis, the classic throttling load control (Seiliger-Sabathe open cycle) was the reference for all other tested systems.

The values of control parameters for the tested systems, depending on the work of the cycles are compared in Fig. 5. In this figure and all others, the work of the cycles W_o is related to the maximum work $W_{o,max}$ of the theoretical Seiliger-Sabathe cycle. This approach allows to compare the tested systems with each other, and thus to assess the effectiveness and benefits of their use.

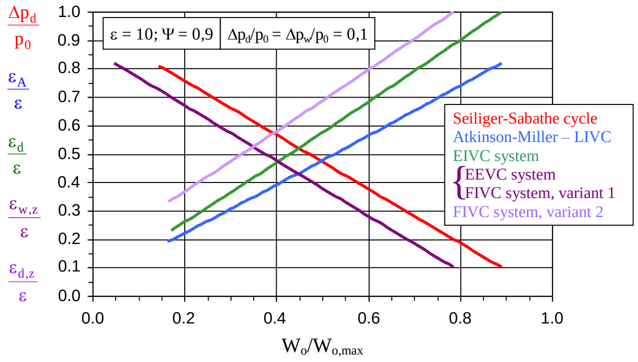

Fig. 5. Comparison of the control parameters for the analysed independent valve control systems versus work of the cycles

From the list of control parameters (Fig. 5), it can be seen that specified values of cycle work can be achieved by implementing each of the systems. This situation is observed in a wide load range. It should be emphasised that the dependence of the control parameters on circuit operation is linear for all systems, which is beneficial for regulatory reasons.

Figure 6 shows a comparison of the relative reduction of fuel doses $\Delta m_p/m_{p,SS}$ for the tested systems, in relation to the system with classic throttling control (Seiliger-Sabathe cycle).

Using each of the tested systems of independent valve control, a decrease in the fuel dose is observed in the entire range of the cycle work. Fuel consumption reduction is particularly significant in the low load range and amounts up to 4% for the EIVC system, up to 8% for variant 2 and up to 19% for variant 1 of the FIVC system. A fuel dose saving of 19% is achieved for a relative work of the cycle $W_o/W_{o,max}$ of approximately 0.18. Achieving such a reduction in fuel consumption in variant 1 may therefore not be possible due to too high value of the recirculation rate (α_r = 0.35) at this cycle work. However, a reduction in fuel consumption in the order of 15% is realistic, as it is achieved with recirculation rates that are acceptable in operation [20].

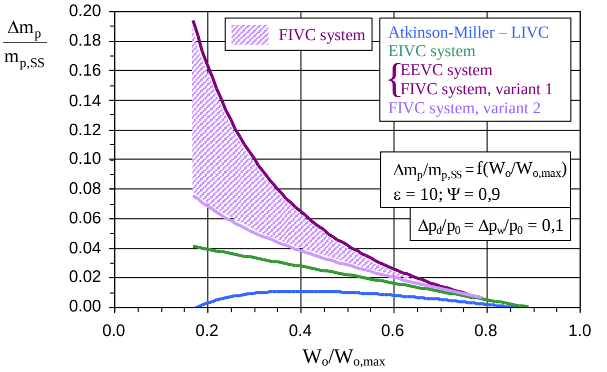

Fig. 6. Comparison of the relative reduction of the fuel doses $\Delta m_p/m_{p,SS}$ for the analysed independent valve control systems compared with the classic throttle governing system, versus work of the cycles

The observed benefits in terms of fuel consumption reduction result primarily from the fact that the charge exchange work is reduced. The charge exchange work $W_w/(p_0V_1)$ (in dimensionless terms) for the tested systems of independent valve control, depending on the achieved work of the cycles is compared in Fig. 7. Figure 8, on the other hand, shows a comparison of the index μ of relative charge exchange work, which is defined as:

$$\mu = \frac{|W_w|}{W_o} \tag{8}$$

where: W_w – charge exchange work, W_o – cycle work.

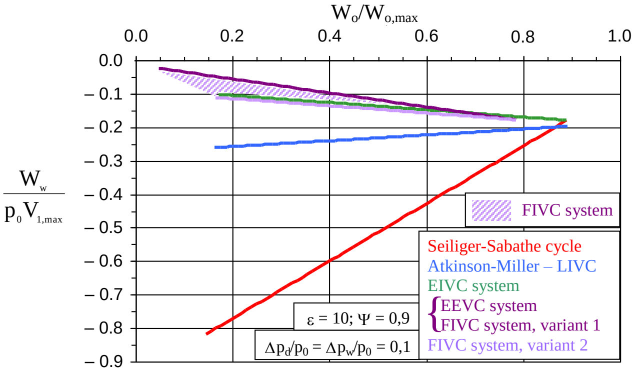

Fig. 7. Comparison of the charge exchange works $W_w/(p_0V_1)$ for the analysed independent valve control systems versus work of cycles

The works W_w of the charge exchange, as to the absolute value, for all systems of independent valve control is much smaller than the work of the charge exchange for the classic throttling control. The differences in works of charge exchange in favor of independent valve control systems are the greater, the lower the load (Fig. 7). The reduction in charge exchange work in systems of the independent valve control is primarily due to the elimination of the throttle as a load control valve for the SI engine, while retaining quantitative load control.

An advantageous feature of the EIVC, EEVC and FIVC systems is that the absolute value of the charge exchange work reduces as the value of the cycle work decreases (Fig. 7). The reverse, unfavorable situation is observed for the classical throttling control and the LIVC system, in which the absolute value of the charge exchange work increases with the decrease of the load. This increase is particularly large for the open S-S theoretical cycle and is the effect of closing the throttle, and thus increasing the resistance to the flow of fresh charge in the inlet system.

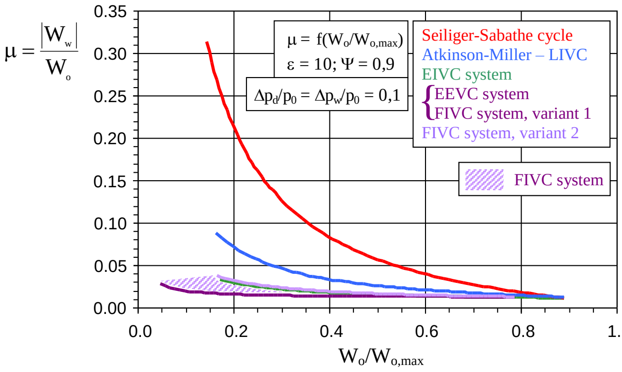

Fig. 8. Comparison of the relative charge exchange works μ for the analysed independent valve control systems versus work of the cycles

For all the tested systems of independent valve control, the relation of charge exchange work W_w to the cycle work W_o is also favorable, compared to this relation for the classical system. The parameter characterising this relationship is the index μ of the relative work of charge exchange. For the classic throttling control of load, the index μ reaches very high values, even over 30% in the range of small loads (Fig. 8.). For all variants of independent valve control, the index μ is below 10%, in the whole range of cycles work. The system of fully independent valve control, also in this case, proved to be the most beneficial, as the index μ is below 4%. Such low values for the relative work of charge exchange are precisely the result of eliminating the throttle valve from the inlet system.

From an energy point of view, the key parameter of the cycle is its efficiency, defined as follows:

$$\eta_o = \frac{W_o}{Q_d} \tag{9}$$

where: W_o – cycle work, Q_d – total energy fed into a cycle.

The efficiency η_o of the cycles for the studied charge exchange systems, depending on the cycle work achieved, is compared in Fig. 9.

The cycle efficiencies η_o of all investigated independent valve control systems are higher than the theoretical Seiliger-Sabathe cycle efficiency. The highest efficiencies are achieved by the cycle for variant 1 full independent valve control. In the low load range, the cycle efficiency η_o of variant 1 of the FIVC system is approximately 0.13 higher than the efficiency of the cycle for classic throttle control (Fig. 9). For this variant 1, a flat course of the cycle efficiency η_o is characteristic and advantageous, in the entire range of the achieved cycle work. Thus, this variant is the most suitable for controlling the load of the SI engine.

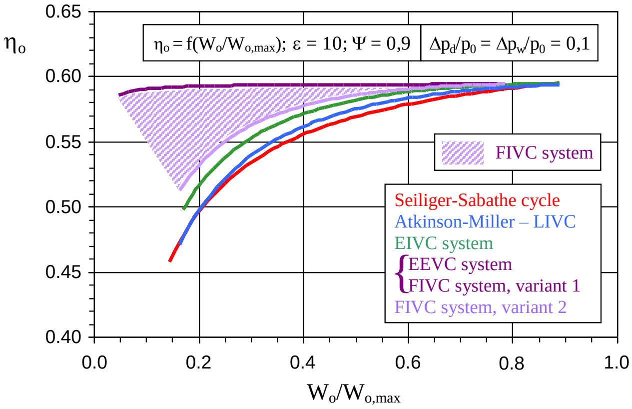

Fig. 9. Comparison of efficiencies η_o of the cycles for the analysed independent valve control systems, versus work of the cycles

4. Conclusion

Four independent valve control systems for the SI engine, presented in Chapter 3, were analysed. The reference for the evaluation of the efficiency of work acquisition, as a result of the use of independent valve control systems, is the S-S theoretical cycle, which is a model of the processes occurring in an SI engine with classic load control using a throttle.

For each system tested (except the LIVC cycle), a decrease in fuel consumption (fuel dose) is observed, with a particularly large decrease in the low load range (Fig. 6). It has been shown that the greatest (up to 15%) fuel consumption savings can be achieved using variant 1 of the FIVC system. Experimental studies of engines equipped with electromagnetic valve control systems, presented in publications, show fuel consumption savings from 7% to 19% [3, 4, 9, 12].

The charge exchange work for all proposed systems is considerably lower, especially for partial loads, than the charge exchange work for classic throttle control. For variant 1 of the FIVC system, at the smallest loads ($W_o/W_{o.max} < 0.2$), the charge exchange work is over 8 times lower than the charge exchange work for the S-S theoretical cycle. The nature of changes in the work of charge exchange is also particularly advantageous (except for the LIVC), as it, in terms of the absolute value, decreases with the decrease in the work of the cycle. The result of this desirable situation is a significant reduction in the relative work of charge exchange. For the FIVC and EEVC systems, the value of the index of the relative charge exchange work is less than 4% over the entire engine operating field. The above-mentioned beneficial effects of independent valve control systems can be best expressed by the energy efficiency of the cycles. The highest energy efficiency is achieved by the fully independent valve control system. Therefore, this variant is the most advantageous in terms of engine load regulation.

It should be emphasised that in FIVC and EEVC systems, the maximum temperature during combustion is lowered by internal EGR, with a consequent reduction in nitrogen oxide emissions. However, the main benefits investigated are related to the reduction in charge exchange work as a result of the elimination of the throttle.

Acknowledgments

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Nomenclature

EEVC	early exhaust valve closing
EIVC	early inlet valve closing
E_w	energy output
FIVC	fully independent valve control
LIVC	late inlet valve closing
m	mass
m_p	fuel dose
MIVEC	Mitsubishi innovative valve timing and lift electronic control system
p	pressure
p_d	pressure in an inlet system,
p_w	pressure in the exhaust system
Q	heat
$Q_{d,p}$	heat input with isobaric process
$Q_{d,v}$	heat input with isochoric process
REV	revolution-modulated valve control
s	entropy
SI	spark ignition
V	volume
V_s	cylinder displacement
VTEC	variable valve timing & lift electronic control
VVAL	variable valve event and lift
W	work
W_o	cycle work
W_w	charge exchange work
α_k	multiplicity of exhaust gas recirculation
α_r	exhaust gas recirculation rate
ε	compression ratio
ε_A	isentropic compression ratio for LIVC
ε_d	load control parameter for EIVC
$\varepsilon_{d,o}$	expansion rate of a recirculated exhaust gas
$\varepsilon_{w,z}$	compression ratio of a recirculated exhaust gas
η_o	cycle energy efficiency
μ	relative charge exchange work
Ψ	heat distribution number

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Prof. Zbigniew Żmudka, DSc., DEng. – Faculty of Energy and Environmental Engineering, Silesian University of Technology, Poland.

e-mail: *zbigniew.zmudka@polsl.pl*

Prof. Stefan Postrzednik, DSc., DEng. – Faculty of Energy and Environmental Engineering, Silesian University of Technology, Poland.

e-mail: *stefan.postrzednik@polsl.pl*