Розроблено робочий процес для двигунів з іскровим запалюванням і безпосереднім впорскуванням палива, що забезпечує організацію розшарованого збідненого паливоповітряного заряду на часткових навантаженнях та потужносного складу паливоповітряної суміші на підвищених навантаженнях.

Проведена модернізація конструкції двотактного двигуна з іскровим запалюванням шляхом установки системи безпосереднього впорскування палива, розміщення форсунки в стінці циліндра і зміни форми камери згоряння.

Розроблено методику проведення регулювальних характеристик за складом паливоповітряної суміші в циліндрі двотактного двигуна з іскровим запалюванням. Особливістю методики є реєстрація параметрів і показників двигуна при постійній цикловій подачі палива та регулюванні повітря на впуску. Запропонована методика дозволяє точніше регулювати склад паливоповітряної суміші завдяки більш точному дозуванню повітря, ніж циклової подачі палива.

Проведено експериментальні дослідження і побудовано регулювальні характеристики за складом паливоповітряної суміші в циліндрі двотактного двигуна з розробленим робочим процесом.

Побудовано навантажувальні характеристики (n=3000 хв$^{-1}$) раціонального регулювання за граничною економічністю та максимальною потужністю на базі даних регулювальних характеристик за складом паливоповітряної суміші.

Встановлено, що за навантажувальною характеристикою раціонального регулювання економічного складу паливоповітряної суміші в циліндрі двигуна ($\lambda_{цил.\ ек}$) змінюється від 1,31 до 1,94, а мінімальна витрата палива становить $g_{e\ min}$=259 г/(кВт·год).

За навантажувальною характеристикою раціонального регулювання потужносного складу паливоповітряної суміші в циліндрі двигуна ($\lambda_{цил.\ п}$) змінюється від 1,31 до 1,7, а витрата палива на часткових навантаженнях становить g_e=270 г/(кВт·год).

Характеристики за витратою повітря в залежності від циклової подачі палива можуть бути використані для зміни складу паливоповітряної суміші при автоматичному регулюванні навантаження двигуна

Ключові слова: двигунів з іскровим запалюванням, робочий процес, внутрішнє сумішоутворення, паливоповітряна суміш

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DETERMINING THE CHARACTERISTICS FOR THE RATIONAL ADJUSTING OF AN FUEL-AIR MIXTURE COMPOSITION IN A TWO-STROKE ENGINE WITH INTERNAL MIXTURE FORMATION

V. Korohodskyi
Doctor of Technical Sciences, Associate Professor
Department of Internal Combustion Engines*
E-mail: korohodskiy@ukr.net

S. Kryshtopa
Doctor of Technical Sciences, Professor
Department of Automobile Transport
Ivano-Frankivsk National Technical University of Oil and Gas
Karpatska str., 15, Ivano-Frankivsk, Ukraine, 76019

V. Migal
Doctor of Technical Sciences, Professor**

A. Rogovyi
Doctor of Technical Sciences, Associate Professor
Department of Theoretical Mechanics and Hydraulics*

A. Polivyanchuk
Doctor of Technical Sciences, Professor
Department of Urban Environmental Engineering
O. M. Beketov National University of Urban Economy in Kharkiv
Marshala Bazhanova str., 17, Kharkiv, Ukraine, 61002

G. Slyn'ko
Doctor of Technical Sciences, Professor
Department of Internal Combustion Engines
Zaporizhzhia Polytechnic National University
Zhukovskoho str., 64, Zaporizhzhia, Ukraine, 69063

V. Manoylo
PhD, Associate Professor**

O. Vasylenko
PhD, Senior Lecturer
Department of Heat Engineering, Heat Engines and Energy Management
Ukrainian State University of Railway Transport
Feuerbacha sq., 7, Kharkiv Ukraine, 61050

O. Osetrov
PhD, Associate Professor
Department of Internal Combustion Engines
National Technical University "Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
*Kharkiv National Automobile and Highway University
Yaroslava Mudroho str., 25, Kharkiv, Ukraine, 61002
**Department of Tractors and Cars
Kharkiv Petro Vasylenko National Technical University of Agriculture
Alchevskyh str., 44, Kharkiv, Ukraine, 61002

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1. Introduction

Global energy consumption between 2018 and 2050 will increase by almost 50 % and reach on average 911 quadrillion British thermal units (BTUs). The share of industrial energy production will decrease from 40 % in 2018 to 35 % in 2050, mainly due to faster growth in the transport sector [1]. Energy consumption for passenger transportation accounts for most growth of energy consumption for transportation. Growth of energy consumption in member-countries of the Economic Cooperation and Development Organization (ECDO) is expected to reach almost half that in countries outside the ECDO in the period from 2018 to 2050.

International energy forecast conducted in 2019 shows that world consumption of refined oil and other liquid fuels will increase by more than 20 % until 2050, however, their share will decrease from 94 to 82 % as the use of alternative energy sources increases [2]. The world transport sector will account for 59 % of total liquid fuel (fuel oil, diesel fuel, motor petrol, and aviation fuel) consumption in 2050 which is approximately the same as in 2018 [3].

Motor petrol including biofuel additives such as ethanol will remain in 2050 the main fuel for vehicles accounting for 32 % of global energy consumption in the transport sector [4].

During the forecast period until 2050, many world regions including countries that are not members of the ECDO, Europe and Eurasia, Middle East and Africa will mainly use small-tonnage vehicles with internal combustion engines (ICE) that run on fuels of oil origin. These regions continue to use mainly spark-ignition engines (SIE) and diesel engines for many reasons, such as cost, infrastructure, climatic and geographic [5].

It should be noted that there remains a global trend of improving SIE performance by improving its operation. Improvement of SIE operation efficiency due to a proper organization of internal mixture formation contributes to the continuation of their use as main car drives for the next 130 years [6].

The tendency to use an SIE and an electric motor in a hybrid car drive is explained by the general combination of their improved technical, economic, and environmental indicators [7] and a more reasonable cost compared to diesel engines [8].

To obtain the best efficiency of using hybrid drives in cars, it is necessary to rationally adjust by electronic means both the engine itself [9, 10] and its mutual operation with a power electric battery [11]. At the same time, the level of emission of not only harmful substances from exhaust gases into the atmosphere [12] and soil [13] but also from the products of complete combustion (CO_2) [14] is the main criterion for optimal adjustment.

However, relatively low efficiency and sticking to increasingly stricter regulatory requirements concerning the toxicity of exhaust gases (EG) is the common problem of SIE use. This is especially true for two-stroke SIE with external mixture formation whose level of efficiency does not exceed 23 % [15].

This problem can be solved by improving organization and rational adjustment of the spark-ignition engine operating process to ensure complete and efficient fuel combustion in all operating modes [16].

Therefore, the study line related to determining characteristics of rational adjustment of the fuel-air mixture (FAM) composition depending on the operating mode of a two-stroke spark-ignition engine with internal mixture formation is relevant.

2. Literature review and problem statement

The transition from external mixture formation to internal one in two-stroke SIE makes it possible to solve the problem of high fuel consumption and emission of harmful substances from exhaust gases. Elimination of fuel losses during purging through the use of direct fuel injection (DFI) into the cylinder after closing gas distribution elements reduces fuel consumption by up to 30 %. At the same time, harmful emissions from exhaust gases are reduced by more than 50 % [17]. However, FAM homogenization in the entire over-piston space and in the zone of ignition plug electrodes confines the limit of its effective leaning, which determines the lower FAM ignition limit.

The efficiency of the operating process of a two-stroke spark-ignition engine with DFI depends on the mutual influence of the processes of gas exchange, mixture formation, combustion, and exhaust gas recirculation which must be taken into account when organizing this process.

In comparison with a four-stroke engine in a hybrid car, the use of a two-stroke spark-ignition engine with DFI has made it possible to increase torque by up to 25 % and reduce specific fuel consumption by 10 % [18]. The technical and economical performance of the engine was improved due to additional feed and adjustment of the incoming air at the inlet. At the same time, the organization of the operating process with a relatively enriched FAM composition reduces the potential for additional reduction of specific effective fuel consumption.

Results of the studies conducted for optimizing processes of FAM self-ignition under compression by adjusting boost in a petrol engine with DFI operating in a two-stroke cycle are presented in [19]. The complexity of creating conditions and parameters for FAM self-ignition and the required accuracy of ignition moment when the engine operating modes change is inferior to spark ignition.

Improvement of the gas exchange processes in a two-stroke spark-ignition engine with direct-flow purging enables better cleaning of cylinders from exhaust gas but the processes of interaction of air and fuel particles were not taken into account in [20].

The use of heating in the nozzle for direct injection of petrol in a spark-ignition engine makes it possible to intensify the processes of fuel evaporation during the injection. Results obtained in the studies on the effect of heating a multi-nozzle injector on the fuel stream structure, dispersity of droplets and formation of petrol vapors during boiling are presented in [21]. However, the problems associated with the multistage injection of heated cycle fuel feed have not been solved.

The use of a mixture of petrol and ethanol in an SIE operating in the two-stroke cycle exceeds technical, economic, and environmental indicators obtained in the four-stroke cycle operation [22]. However, the organization of combustion of a stoichiometric and enriched air-fuel mixture contributes to an increase in fuel consumption.

Results of three-dimensional modeling of the process of combustion of a homogeneous, stratified lean and stratified enriched FAM compositions in a spark-ignition engine are presented in [23]. Rational relations between the intensity of pressure increase in the cylinder and average effective pressure were obtained. However, the problems associated with the change in intensity of feeding a fresh charge to the combustion zone and the removal of combustion products from it have not been solved.

The use of DFI and exhaust gas recirculation is one of the promising ways to reduce fuel consumption and emissions of harmful substances from exhaust gases in a two-stroke SIE [24, 25]. However, the issues connected with the change of the amount of recirculated exhaust gas relate to a specific method of organizing the operating process and cannot be fully extended to other operating processes that differ from it.

The use of a pre-chamber with an installed ignition plug makes it possible to efficiently burn lean FAM [26]. However, when the load is increased and the mixture is enriched, cleaning of the pre-chamber from combustion products worsens and maximum power is limited.

Noteworthy is an analytical study on the organization of the operating process in a two-stroke spark-ignition engine with DFI [27]. Computational studies have contributed to the optimization of gas exchange and mixture formation processes. An increase in compression ratio ε to 16, use of exhaust gas recirculation up to 20 % and organization of a stratified fuel-air charge (SFAC) at λ=2 in the cylinder have made it possible to determine the value of effective efficiency at a level of 47.2 %. However, it is not clear from the presented description which experimental data of the new operating process were used to optimize the Viebe combustion model. Also, the level of mechanical losses of the engine is not clear from the article matter. There are unresolved issues related to the formation of the volume of the fuel-air mixture symmetrical about the cylinder axis and uniform feed of air from the periphery of the over-piston space to the combustion zone. This is caused by the asymmetric surface of the combustion chamber in the cylinder head and asymmetric distribution of fuel jets relative to the cylinder axis which reduces the efficiency of fuel combustion and violates uniformity of heat emission to the surrounding walls.

Directed coordination of internal mixture formation processes along their entire length is the necessary condition for organizing an effective SIE operating process during DFI. This applies both to the organization of a homogeneous FAM distributed in the entire over-piston volume and FAM in the SFAC.

The rational combination of conditions for the organization of internal mixture formation determines the efficiency of the combustion processes, the engine economy, and the reduction of harmful substances contained in the exhaust gas. The main conditions include FAC composition at the time of ignition and subsequent combustion in the flame front, the intensity of air feed to the combustion zone, temperature, pressure, and physicochemical properties of the fuel.

When forming a homogeneous FAM, fuel is injected directly into the cylinder during the intake stroke when the intake valve is opened. This enables obtaining a homogeneous FAM composition at high rates of the fresh charge flow moving through the valve slot with time enough to mix the fuel particles with air.

The presented method of internal mixture formation has an advantage of much simpler and easier implementation.

In this case, DFI through the intake valve open for fuel injection into the intake manifold enables an increase in the specific power of the engine by increasing feed of fresh charge to its work space.

Reduction of the inlet resistance (air throttle is fully open) reduces pump losses, thereby reducing fuel consumption by up to 10 %. Lowering the temperature of the working medium during fuel injection makes it possible to increase the compression ratio ε by 1.5–2 units.

Representatives of the spark-ignition engine with DFI and organization of a homogeneous FAM: *Opel 2.2-DIRECT ECOTEC* with the power of 114 kW [28,29], *Audi/VW 2.0 TFSI* with supercharging and maximum power N_e=147 kW [30]. Also, a 12-cylinder *BMW* engine with *VALVETRONIC* valve adjusting system [31] and *V62GR-FSE* engine having N_e=228 kW with a *Lexus D4-S* dual fuel injection system [32] belong to this group.

The disadvantage of the operating process with internal mixture formation during the formation of homogeneous FAM combustion consists of limitation of increase in compression ratio ε and excess-air factor λ which brings about limitation of the potential reduction in fuel consumption.

To ensure the combustion of lean FAM composition, a *BPI-Verfahren (Bowl Pre-chamber Ignition)* operating process with DFI was developed. Fuel is injected into a cup-shaped combustion chamber in the piston and ignited by the ignition plug located in the combustion chamber space when the piston reaches the top dead center (TDC). The fuel-air mixture is enriched by means of DFI into the combustion chamber, and less than 5 % of the total amount of fuel is injected at the compression stroke.

The duration of fuel injection at the compression stroke and air-to-fuel ratio in the combustion chamber are adjusted by an electronic adjusting unit [33]. After ignition and flaming of FAM in the combustion chamber, the flame front spreads over the entire volume of the main combustion chamber intensively burning all fuel.

Studies of the processes occurring in SFAC combustion using the *BPI* operating process have shown a reduction in fuel consumption g_e of up to 3 % compared with the combustion of a lean FAM distributed in the over-piston space [34].

Analysis of the thermodynamic cycles taking place in internal combustion engines with external mixture formation and fuel injection to the intake valve and those taking place with internal mixture formation and DFI into the cylinder has shown that the level of thermal efficiency for an engine with internal mixture formation is higher due to a decrease in the amount of heat radiation in the exhaust process [35, 36].

Application of *E-TEC* DFI technology (*Direct Injection with stratified low RPM combustion mode*) to a two-stroke boat SIE (*Evinrude 250 H.O. E-TEC G2*) has significantly improved technical, economic, and environmental performance [37]. Based on internal tests of the *BRP* (*Bombardier Recreational Products*) *Corporation,* it was found that up to 20 % increase in torque and up to 15 % reduction in fuel consumption are provided in 200 to 300 h.p. engines. The amount of total harmful emissions of ($CO+CH+NO_x$) from exhaust gas is 51 ppm which is less than that provided by the world competitive manufacturers of four-stroke boat engines of comparable power (*Mercury OPTI 250 PROXS, Yamaha 250 SHO*).

Two-stroke 0.6 l engine *Rotax 600 H.O. E–TEC* is mounted on a *Ski-Doo* snowmobile. CO content in the exhaust gas in no-load mode is 80 % less than that observed in most four-stroke SIE of comparable power [38].

When organizing the operating process with DFI *E-TEC* technology in partial load modes, conditions are created in the engine cylinder that provide FAC stratification. However, at the time of ignition, ignited fuel jet passes between electrodes of the ignition plug in a form of fuel droplets that did not completely evaporate, thereby enriching the FAM. Stratification of FAC with enriched FAM composition reduces the potential for expanding the limit of effective leaning, which ultimately limits the reduction of fuel consumption and emissions of harmful substances with exhaust gases.

Theoretically, internal mixture formation provides the greatest efficiency in the course of combustion processes. This is due to low heat loss, absence of fuel particles on walls of the over-piston space as well as wide possibilities for adjusting the moment of fuel injection start and ignition spark formation. However, the implementation of effective internal mixture formation seems to be a rather complicated problem [39, 40].

It is necessary to use a high-pressure fuel injection system since mixture formation occurs in a very short time. The requirement of reliable formation and accurate positioning of the FAM cloud having a proper composition as well as the problem of synchronizing this process with the sparking moment add complexity as well.

At the same time, excess air in a lean FAM theoretically makes it possible to efficiently burn fuel and have a low content of harmful substances in the exhaust gas. However, in reality, as practical studies have shown, in order to reduce fuel consumption by creating a stratified lean FAC (SLFAC) and expand limits of effective FAM leaning, a series of conditions should be provided. The main conditions include rational cleaning of the cylinder from combustion products and its effective filling with a fresh charge during gas exchange which will create conditions for subsequent processes of mixture formation and combustion.

To obtain high technical, economic, and environmental indicators, it is advisable first of all to develop an operating process that includes a productive gas exchange with exhaust gas recirculation and quality and directed internal mixture formation ensuring complete and efficient fuel combustion.

Further, taking into account the peculiarities of organizing the operating process and the nature of change in the engine operating modes, it is necessary to determine rational FAM composition. In modes of partial loading, to ensure maximum efficiency, it is necessary to effectively deplete FAC in the engine cylinder. Under the modes of high loading and given the need to ensure maximum power, it is necessary to enrich the FAC effectively in the entire over-piston space.

Resolving these interrelated problems is the determining direction of the studies.

3. The aim and objectives of the study

The study objective is to obtain a minimum fuel consumption by a two-stroke spark-ignition engine with DFI at partial loads and maximum power at high loads.

To achieve this objective, it is necessary to solve the following tasks:

– develop an operating process and modernize the design of a two-stroke spark-ignition engine for implementation of internal mixture formation ensuring the formation of SLFAC in modes of partial loads and power FAM composition throughout entire over-piston space in modes of high loads;

– develop a procedure for constructing adjusting engine characteristics for FAM composition with constant cycle fuel feed;

– conduct experimental studies and construct adjustment characteristics for FAM composition in a cylinder of a two-stroke spark-ignition engine with DFI;

– based on adjusting characteristics in terms of FAM composition in the engine cylinder, construct load characteristics of rational adjustment taking into account maximum economy and power.

4. Features of organizing the operating process for the spark-ignition engine with internal mixture formation

To reduce fuel consumption in an internal combustion engine, it is advisable to raise the excess-air factor in the engine cylinder (λ_{cyl}).

Formation of a SLFAC by turbulizing FAM and intensive air feed to the combustion zone is a promising direction in the development of the operating processes that ensure the effective operation of a spark-ignition engine with increased values of λ_{cyl}.

The organization of the operating process with SLFAC makes it possible to reduce the number of products of incomplete combustion and emissions of harmful substances from exhaust gases.

Along with the reduction of emissions of carbon monoxide CO, unburnt hydrocarbons C_mH_n, nitrogen oxides NO_x from exhaust gases, a decrease in fuel consumption determines a decrease in emission of complete combustion product, i. e. carbon dioxide CO_2 into the atmosphere.

When SLFAC is burnt, a certain volume of FAM is formed at the time of ignition near the ignition plug electrodes and air on the periphery, near the walls of the over-piston space. Such directed stratified placement of FAM and air in the engine cylinder makes it possible not only to efficiently burn all fuel but also to create conditions for reducing heat loss to the walls.

The decrease in heat loss to the walls is due to the formation of air interlayer between the hot zone of flame and the relatively cold walls of the over-piston space. The interlayer of air determines a decrease in intensity of thermal radiation coming from the flame to the wall, serves as an insulator for the heat flux increasing the thermal resistance of heat transfer due to lower thermal diffusivity.

The reduction of heat loss to the walls increases the efficiency of the internal combustion engine.

Ideally, optimal conditions for ignition and combustion of SLFAC are created at FAM composition with $\lambda \approx 1$ throughout the volume of a homogeneous, well-mixed FAM which ensures efficient and complete fuel combustion.

However, in reality, because of the stochastic nature of the working medium flow and due to DFI, rich and lean FAM zones are formed in the over-piston space during the piston movement. These zones can be formed both between electrodes of the ignition plug and throughout the FAM volume.

Excessive leaning or enrichment of FAM in the interelectrode gap affects stabilization of formation of the primary flame zone during ignition which subsequently determines the intensity of course of the subsequent main combustion period.

Inhomogeneous composition of FAM in the interelectrode gap and in the zones of the FAM volume along the path of flame front propagation contributes to the creation of various conditions during combustion processes in subsequent engine operation cycles. A change in conditions during the combustion process leads to non-identical changes in pressure in the over-piston space at the combustion-expansion stroke.

In addition, the efficiency of fuel combustion and formation of products of incomplete combustion (CO and C_mH_n) in the afterburning section are affected by FAM composition when the flame front reaches final FAM volumes remote from the ignition plug electrodes.

At the boundary between the FAM and air, a zone of lean FAM is formed in which the intensity of the combustion processes is reduced to a minimum. Combustion stops when leaning gets significant and a part of unburned fuel joins the exhaust gas in a form of CO and C_mH_n. In this case, excess oxygen and high temperature contribute to the formation of harmful nitrogen oxides NO_x.

The directionality of the fuel jet and accuracy of fuel dosage in the case of DFI in accordance with the direction of movement of the air charge in the over-piston space contribute to a decrease in the volume of the lean FAM zone.

Organization of the operating process with SLFAC and compression ignition in a two-stroke engine is possible, but the use of petrol with its relatively low cetane number as compared to diesel fuel worsens the self-ignition processes.

The use of diesel fuel makes it possible to intensify the processes of self-ignition, however, leaning of the fuel-air mixture reduces the reliability of its ignition and limits the range of load changes. An increase in power by increasing the volume of lean vaporous fuel-air mixture is limited by a relatively short time of mixture formation processes with direct fuel injection. This determines the formation of an inhomogeneous composition of the fuel-air mixture. At the same time, an increase in power due to an increase in the volume of lean fuel-air mixture surrounded by air is complicated by variable intensity and direction of movement of the fresh charge, parameters of the mixture and the necessary moment of its ignition.

The use of an adjustable gas turbine boost in a two-stroke diesel engine and the use of exhaust gas recirculation enables the creation of conditions for a more accurate ignition moment and extends the range of load increase. However, in modes of minimum and medium loads, due to a decrease in exhaust gas parameters and turbocompressor efficiency, it is preferable to use a drive compressor and with a further increase in power, it is advisable to add a gas turbine boost.

Therefore, the complexity of the organization of the operating process with SLFAC and compression ignition in a two-stroke engine in the transition modes and a limited range of power adjustment exclude mass production of engines of this type.

Considering the above features, in order to implement the operating process with SLFAC, an operating process has been developed for a spark-ignition engine in which the relationship between the gas exchange processes, mixture formationand combustion is compounded [41].

The use of DFI and provision of volume-film mixture formation make it possible to organize the operating process of the engine with SLFAC in modes of partial loads and the enriched composition of FAM homogeneous in entire over-piston volume in modes of maximum loads.

To implement the operating process, the design of a two-stroke spark-ignition engine was modernized by installing a DFI system. Placement of the fuel nozzle in the cylinder wall and formation of the combustion chamber configuration in the cylinder head contribute to obtaining of a stratified and homogeneous FAM composition in the over-piston space of the internal combustion engine depending on the engine operating modes.

Coordination of interaction of injected fuel particles with air charge flows before FAM ignition at the compression stroke [42] is ensured by the fuel jet structure and during the course of combustion phases, it is organized due to the design features of the piston bottom and the inner surface of the combustion chamber in the cylinder head.

At the same time, intensification of the processes of FAM preparation before ignition and feed of air to the combustion zone and in the afterburning phase is also mainly due to the shape of the piston bottom and the inner surface of the combustion chamber in the cylinder head [41].

The use of direct pneumatic injection of petrol in two-stroke SIE by *Orbital Engine* (passenger car *GM-Holden Garnira*) and *Aprilia* (*Aprilia SR50 Ditech* scooter) makes it possible to organize the operating process with SLFAC. However, the use of a compressor for the direct feed of a lean vaporous FAM to the engine cylinder increases power consumption for its drive which predetermines an increase in fuel consumption. Therefore, the complexity of the design and, consequently, worsening of reliability and an increase in cost were among the main causes of discontinuing the engine production and transfer of *Aprilia* engines to the *3V Tech FI* petrol injection system. Application of *3V Tech FI* injection technology does not make it possible to organize an operating process with SLFAC, which limits the potentials of reducing fuel consumption and emissions of harmful substances with exhaust gases.

Application of the developed operating process with SLFAC on two-stroke SIE will ensure the application of not pneumatic but hydraulic direct injection system. The reduction of power loss on the compressor drive will further reduce fuel consumption and emissions of harmful substances with exhaust gases.

Moreover, in comparison, the level of NO_x in exhaust gases of the spark-ignition engine during combustion of the homogeneous stoichiometric composition of FAM in the entire over-piston space is superior in the organization of SLFAC combustion [43].

To reliably comply with current standards on exhaust gas toxicity in the modes of high loads, a three-component catalytic neutralizer can be used to oxidize CO, C_mH_n and reduce NO_x. The use of an additional neutralizer of accumulative type during engine operation on a lean FAM will enable the reduction of remaining toxic substances to harmless components [44].

5. The procedure of constructing adjusting characteristics of a two-stroke engine according to FAM composition at a constant cycle fuel feed

Adjusting characteristics make it possible to determine rational values of adjustable parameters of the engine under other conditions, for example, the amount of air entering the inlet at a constant cyclic fuel feed and crankshaft speed for modes of load characteristics. This makes it possible to form a rational economical composition of FAM in the cylinder ($\lambda_{cyl.\,ec}$) providing minimum specific effective consumption of fuel (g_e) or power FAM composition ($\lambda_{cyl.\,pow}$) providing maximum power.

To get high performance of the spark-ignition engine with DFI under partial and increased loads at a constant speed of crankshaft rotation, a procedure has been developed for constructing adjusting FAM composition.

The design features of the NVR-1 mechanical fuel pump with a cup-type plunger seal for DFI provide a relatively coarse adjustment of cycle fuel feed. Therefore, it is advisable to remove adjustment characteristics for the FAM composition in the engine operating modes with a constant cycle feed of fuel and a change in the amount of air at the inlet.

Cycle fuel feed is set on the NVR-1 fuel pump by changing the position of the eccentric which regulates the amount of injected fuel when a two-stroke engine is running with a crankshaft speed and, accordingly, the pump camshaft.

Fresh charge incoming the cylinder is adjusted at a fixed position of the eccentric in the steady-state of engine operation and constant cyclic fuel feed is adjusted by changing the position of the air throttle at the inlet. The composition of FAM in the engine cylinder is adjusted in this way.

Subsequently, the engine speed is adjusted by changing the load on the engine. In each subsequent adjustment mode, torque value is recorded according to the dynamometer head of the brake device of the experimental bench in a fixed position of the fuel feed eccentric and a constant position of the air throttle. After that, mass fuel flow rate, volumetric airflow rate, vacuum level at the inlet downstream the air throttle, inlet air temperature and exhaust gas temperature at the engine cylinder outlet, the temperature of an internal surface of the combustion chamber located in the cylinder head are measured.

Values of an excess-air factor in the cylinder (λ_{cyl}) of a two-stroke SIE are calculated according to the dependence:

$$\lambda_{cyl} = \frac{G_a}{B_{cycle} \cdot M_0} \cdot (1 - \upsilon), \qquad (1)$$

where G_a is the mass of fresh charge, that is, air entering the engine inlet, kg; B_{cycle} is the cyclic feed of fuel in the engine cylinder, kg; M_0 is the mass of air theoretically necessary for complete fuel combustion in the engine cylinder, kg;

$$\upsilon = \frac{G_{leak}}{G_a}$$

is the factor of fresh charge leakage during cylinder purging. This factor takes into account the ratio of the mass of fresh charge leaked from the cylinder during purging ($G_{leak} = G_a - G_{Beyl}$, where G_{Beyl} is the mass of fresh charge in the cylinder remaining after the gas exchange is completed) to the mass of fresh charge at the engine inlet (G_a).

The factor υ of fresh charge leakage when purging the cylinder can be determined by oxygen (O_2) content in the exhaust gas in the exhaust system of the working engine. To do this, an enriched composition of FAM at the inlet should be provided (total excess-air factor λ_Σ<1) and it is assumed that oxygen is completely used during combustion. Then the exhaust gases in the exhaust system will contain O_2 in a concentration corresponding to leakage of a fresh charge when the cylinder is purged.

During experimental studies, O_2 content in the exhaust gas was determined by analyzing the exhaust gas samples taken from the exhaust system of the engine with a CT 300.02 gas analyzer. [45]. Determination of the number of gas components by means of a device used for petrol engines corresponded to Class 1 of accuracy. The gas analyzer allowed us to measure the concentration of the following gases: O_2, CO, CO_2, and C_mH_n.

Parameters and calculation of the tested engine indicators were recorded in the course of experimental studies according to existing standards [46].

It should be noted that determination of adjustment characteristics for the FAM composition in the engine cylinder at continuous cyclic fuel feed and a changing amount of incoming air at the inlet is preferable as well when using electrically controlled DFI systems and air feed systems. It is explained by the fact that for complete combustion of a unit mass of petrol, it is necessary about 15 times more mass of air which is practically possible to dose more accurately. Moreover, the accuracy of dosing fuel feed is limited by design features and hydrodynamic characteristics of the fuel equipment depending on the magnitude of the cycle fuel feed.

6. Experimental adjusting characteristics for FAM composition in a cylinder of a two-stroke spark-ignition engine with DFI

Experimental studies were conducted in the laboratory at the Department of Internal Combustion Engines, the National Technical University "Kharkiv Polytechnic Institute" (Ukraine).

A motorized bench based on the *Schenk* hydraulic brake with maximum rotor speed n=10^4 rpm was used for experimental studies. It is equipped with an electric motor for dummy running and starting the engine. To ensure specified engine operating conditions, the stand contains a system for feeding water to the hydraulic brake and its draining, engine fuel and air feed system and a gas exhaust system.

The experimental stand and its measuring complex make it possible to study engine operating processes in accordance with the requirements of ISO 3046-3:2006.

Atmospheric pressure B_a was measured using an aneroid barometer MD-49-2 with an error no more than ±7.846 Pa in a temperature range from −10 °C to +50 °C. Taking the pressure of 101.3 kPa for the normalized value, the relative error is 0.008 %.

Torque moment M_t (N·m) of the engine was calculated according to the well-known formula where the brake load P_b (N) was determined by the dynamometer scale (in the range from 1/6 to 1/4 of the scale) with a standard error not more than ±0.2 %.

The rotational speed of the engine crankshaft (n=3,000 rpm) was measured using an F-5041 digital frequency meter-chronometer with an error of ±0.1 %.

The relative error in determining effective power was ±0.3 %.

The total error in measuring hourly fuel consumption was 0.34 % and specific effective fuel consumption was 0.64 %.

The flow rate of air incoming the engine was measured by means of an RG-100 rotary gas meter. Error in measuring airflow was determined as a sum of errors introduced by the gas meter and frequency meter-chronometer F-5041 and amounted to 1.04 %.

The total relative error in measuring the intake air temperature when using V7-16A universal digital voltmeter and the TSP-0879-01 platinum resistance thermometer was ±0.93 %. The relative error in measuring the temperature of exhaust gas and surface of the combustion chamber using A-565 digital device and a chromel-alumel thermocouple was ±0.88 % in the temperature range 100–800 °C.

Inlet depression ΔP_s was measured with a standard pressure gauge of accuracy class 0.4. The total error of depression measurement at the intake was ±1.01 %.

Required accuracy in determining angles of the fuel injection start φ_{inj} and ignition advance θ_{ign} was achieved by controlling these values with a special diagnostic device DTA-1 and an electronic stroboscope LS-911. The maximum permissible measurement error did not exceed 0.5.

Thus, all parameters of the engine measured and calculated during the experiment were determined with the required accuracy.

A modernized 1D 8.7/8.2 two-stroke spark-ignition engine with a two-channel crank-chamber purging was used in experimental studies. It had symmetrical phases of gas distribution: the start of gas blowoff at 102° crank angle degree (° CA) after TDC, the start of purging at 123° CA after TDC. The engine was equipped with an air-cooling system and a DFI system based on the NVR-1 fuel pump for implementing the operating process with SLFAC.

A symmetrical hemispherical combustion chamber was installed in the engine cylinder head to provide a geometric compression ratio ε=16.3. The area of the displacer around the combustion chamber neck was 71 % of the piston bottom area. A fuel nozzle with a valve atomizer was installed in the cylinder wall opposite the outlet port to form a fuel stream with the peripheral distribution of fuel particles. The nozzle atomizer axis was directed to electrodes of the ignition plug mounted in the upper part of the combustion chamber in alignment with the cylinder.

Since the zone of main engine operating modes was in the range n=2,000–3,000 rpm and the engine was intended to function as a drive for electric generator and pneumatic or hydraulic supercharger [47] in a combined power unit with a pneumatic motor, studies were carried out at crankshaft speed n=3,000 rpm.

The engine worked in all modes at a constant ignition dwell angle θ_{ign}=10° CA before the top dead center (TDC) and a constant moment of fuel injection start ϕ_{inj}=224° CA after TDC. Preliminary experimental studies defined these data obtained at n=3000 rpm as rational adjustment parameters.

In the zone of minimum loads (mode **A**), experimental studies on the adjustment characteristic were carried out to determine economical FAM composition in the engine cylinder ($\lambda_{cyl.ec}$) at n=3,000 rpm in order to obtain minimum specific effective fuel consumption $g_{e\,\min}$. With a fixed cycle fuel feed (B_{cycle}=6 mg/cycle) and open-air throttle, in the modes of adjusting characteristic, inlet depression decreases (ΔP_s) and intake of fresh charge, air, (G_a) to the engine increases (Fig. 1).

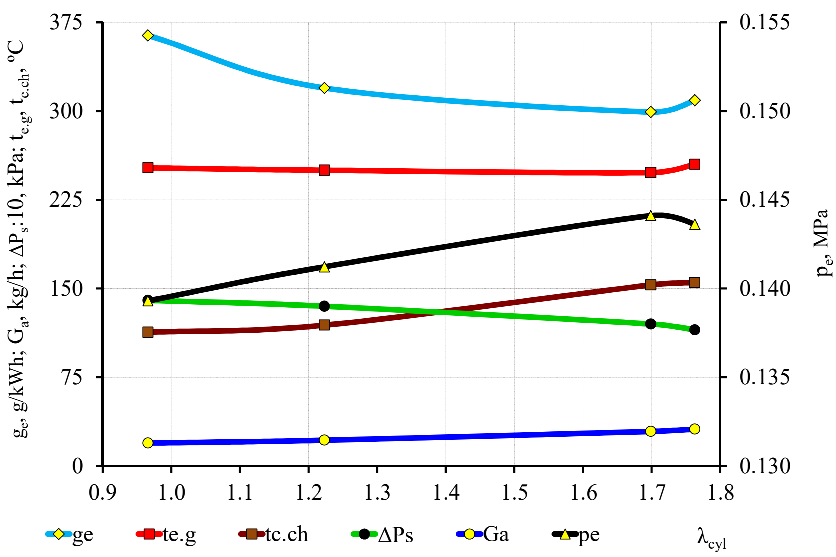

Fig. 1. Adjustment characteristic. Mode **A**

A decrease in depression ΔP_s at the inlet from 14 to 12 kPa contributes to an increase in the air entering the engine G_a from 19.34 to 29.19 kg/h and an increase in the effective power N_e from 3.19 to 3.32 kW. The increased effective power corresponds to the mean effective pressure p_e=0.144 MPa at which minimum specific effective fuel consumption $g_{e\,\min}$ is 299 g/kWh.

The value of the excess-air factor in the cylinder is at a level of the limit of effective leaning and is combined with the power composition of FAM (λ_{cyl}=$\lambda_{cyl.\,ec.}$=$\lambda_{cyl.\,pow}$=1.7). In this case, the temperature of the combustion chamber surface $t_{c.ch.}$ increases from 113 to 153 °C and the temperature of exhaust gases decrease from 252 to 248 °C. Further opening of the air throttle to ΔP_s=11.5 kPa contributes to an increase in air G_B incoming the engine to 31.151 kg/h and the excess-air factor in the cylinder λ_{cyl} to 1.76 but also leads to a decrease in effective power to N_e=3.31 kW and increase in specific effective fuel consumption g_e up to 309 g/kWh) which is consistent with an increase in temperature of exhaust gas to $t_{e.g.}$=255 °C and surface of the combustion chamber to $t_{c.ch.}$=155 °C.

With an increase in the cycle fuel feed to B_{cycle}==7.6 mg/cycle, the studies were carried out according to the adjustment characteristic in mode **B** (Fig. 2).

When the air throttle is opened, inlet depression ΔP_s decreases from 10.75 to 6.5 kPa which contributes to an increase in airflow rate G_a from 33.33 to 45.01 kg/h. In this case, in the partial adjustment mode (ΔP_s=9.5 kPa and G_B=37.59 kg/h), effective power increases from initial value N_e=4.58 kW (p_e=0.196 MPa) to $N_{e\,\max}$=5.23 kW (p_e=0.216 MPa). The value of λ_{cyl} also increases from λ_{cyl}=1.31 to λ_{cyl}=$\lambda_{cyl.\,pow}$=1.46 which corresponds to the power composition of FAM in the engine cylinder. Fuel consumption g_e is reduced to 275 g/kWh.

At this section of the adjusting characteristic, the combustion chamber surface temperature $t_{c.ch.}$ rises from 151 to 160 °C and the exhaust gas temperature first rises from 268 to 286 °C (p_e=0.214 MPa) and then decreases to 275 °C (p_e=0.216 MPa).

With a further increase in airflow rate G_a at the inlet, effective engine power N_e decreases. With an increase in G_a to 40.14 kg/h (p_e=0.192 MPa), the temperature of the combustion chamber decreases to $t_{c.ch.}$=155 °C. The exhaust gas temperature in this mode decreases to $t_{e.g.}$=263 °C and the factor of excess-air in the cylinder reaches λ_{cyl}=$\lambda_{cyl.ec}$=1.94 which corresponds to economical composition of FAM and minimum specific effective fuel consumption $g_{e\,\min}$=259 g/kWh.

A subsequent increase in the intake airflow to the maximum value (G_a=45.01 kg/h) leads to a decrease in efficiency of the combustion process which is characterized by an increase in the exhaust gas temperature ($t_{e.g.}$=265 °C) and temperature of the combustion chamber surface ($t_{c.ch.}$=165 °C), a decrease in effective power to N_e=4.45 kW (p_e=0.1873 MPa) and an increase in fuel consumption to g_e=289 g/kWh.

With an increase in G_a at a fixed cycle feed of fuel, B_{cycle}=7.6 mg/cycle, values of the factor of excess-air in the cylinder increase from λ_{cyl}=1.31 to the power composition of the FAM $\lambda_{cyl.\,pow}$=1.46 corresponding to the value of maximum effective power of the engine $N_{e\,\max}$=5.23 kW.

With a fixed setting of eccentric position at the NVR-1 mechanical fuel pump, which regulates the value of the cycle fuel feed (B_{cycle}), further experimental studies were carried out using adjustment characteristic in mode **B** at B_{cycle}=9.4 mg/cycle (Fig. 3).

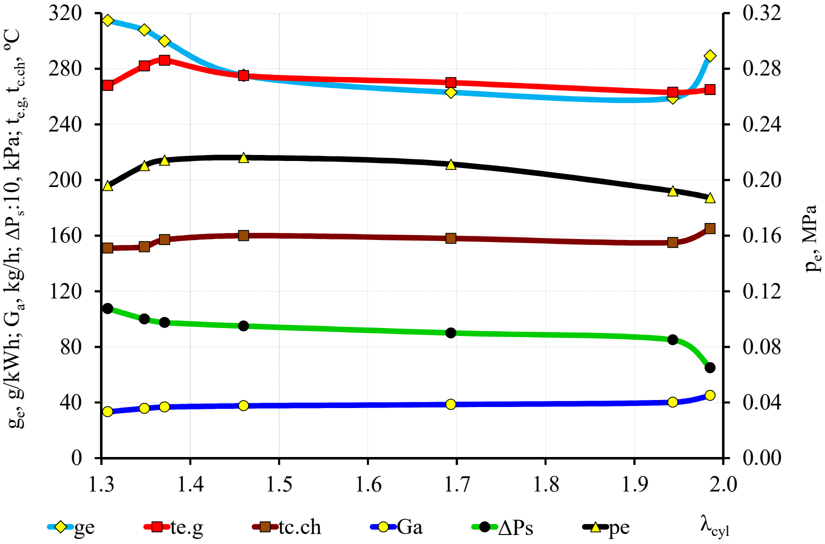

Fig. 2. Adjustment characteristic. Mode **B**

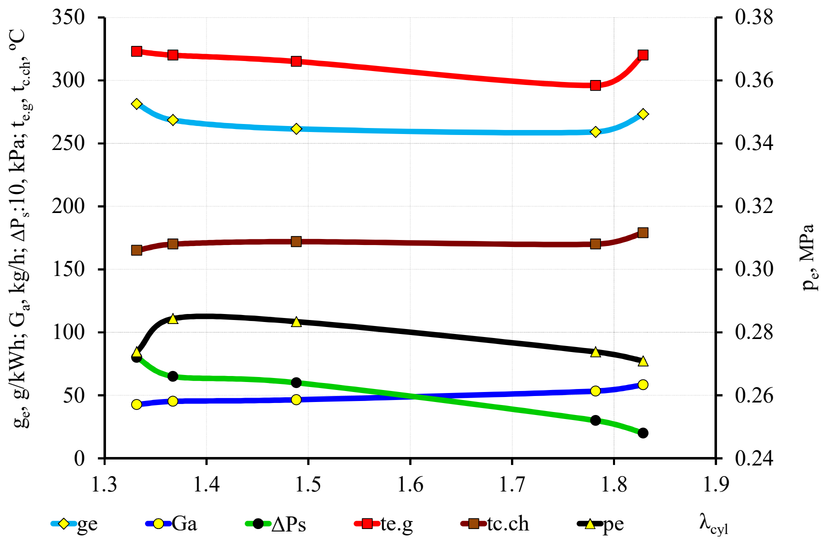

Fig. 3. Adjustment characteristic. Mode **C**

Opening of the air throttle in mode **B** of the adjusting characteristic for the FAM composition helps to reduce depression at the inlet ΔP_s from 8 to 2 kPa, increase airflow rate G_a from 42.57 to 58.39 kg/h and leaning of the FAM from λ_{cyl}=1.33 to λ_{cyl}=1.83.

In the partial mode of the adjusting characteristic corresponding to ΔP_s=6.5 kPa and G_a=45.25 kg/h, the engine develops a maximum effective power of $N_{e\ max}$=6.76 kW (p_e=0.288 MPa) with power composition of FAM $\lambda_{cyl.\ pow}$ =1.36 (Fig. 6). In this case, specific effective fuel consumption decreases to g_e=268 g/kWh which is consistent with a decrease in the exhaust gas temperature to $t_{e.g.}$=320 °C and an increase in the temperature of the combustion chamber surface to $t_{c.ch.}$=170 °C.

In the subsequent characteristic modes, the opening of the air throttle to ΔP_s=3 kPa contributes to an increase in airflow rate up to G_a=53.37 kg/h and ensuring minimum specific effective fuel consumption $g_{e\ min}$=259 g/kWh with a value of the effective FAM leaning limit $\lambda_{cyl.ec}$=1.78 (p_e=0.274 MPa). In this case, the exhaust gas temperature decreased to $t_{e.g.}$=296 °C and the temperature of the combustion chamber surface remained at the same level ($t_{c.ch}$=170 °C).

In subsequent adjustment characteristic mode at ΔP_s=2 kPa and G_a=58.39 kg/h, further leaning of FAM in the engine cylinder to λ_{cyl}=1.83 contributes to worsening of the combustion process as evidenced by an increase in the exhaust gas temperature to $t_{e.g.}$=320 °C, a decrease in power to N_e=6.28 kW (p_e=0.271 MPa) and an increase in fuel consumption to g_e=273 g/kWh with an increase in temperature of the combustion chamber to $t_{c.ch}$=179 °C.

With an increase in the cycle fuel feed to B_{cycle}=11 mg/cycle, the studies were carried out according to the adjustment characteristic for the FAM composition in mode **D** (Fig. 4).

In modes **D** of the adjustment characteristic for FAM composition with a fixed cycle fuel feed, opening of the air throttle makes an easier reduction of depression ΔP_s behind it in the range from 6.5 to 0.25 kPa, increases airflow rate G_A from 44.28 to 62.04 kg/h and provides leaning of FAM composition λ_{cyl} from 1.18 to 1.72.

In partial modes of the adjusting characteristic, with a decrease in depression ΔP_s behind the air throttle in a range from 6.5 to 4.5 kPa, airflow rate G_a increases from the minimum value of 44.28 to 54.86 kg/h.

The resulting increased airflow rate G_a corresponds to the power composition of the FAM $\lambda_{cyl.pow}$=1.36 (p_e=0.331 MPa) in the engine cylinder at maximum power $N_{e\ max}$=7.8 kW.

At the same time, with a 7.3 % increase in power, fuel consumption decreases from g_e=280 g/kWh at p_e=0.307 MPa to g_e=273 g/kWh at p_e=0.331 MPa and the exhaust gas temperature $t_{e.g.}$ decreases from 362 to 354 °C with an increase in the combustion chamber temperature $t_{c.ch}$ from 170 to 177 °C.

A further decrease in depression at the inlet to ΔP_s=0.5 kPa and an increase in airflow rate to G_a=60.81 kg/h leads to a decrease in engine power to N_e=7.51 kW and provides minimum fuel consumption $g_{e\ min}$=259 g/kWh at a value of the economical effective leaning limit of FAM $\lambda_{cyl.\ ec}$=1.66 (at p_e=0.322 MPa) and a decrease in temperature of the exhaust gas to $t_{e.g.}$=318 °C and the combustion chamber to $t_{c.ch.}$=190 °C.

A subsequent decrease in depression to ΔP_s=0.25 kPa and an increase in airflow rate to G_a=62.04 kg/h contribute to an increase in λ_{cyl} to 1.72 and a decrease in engine power to N_e=7.13 kW (at p_e=0.318 MPa), an increase in fuel consumption g_e up to 269 g/kWh with increasing temperature of the exhaust gas to $t_{e.g.}$=345 °C and of the combustion chamber surface to $t_{c.ch}$=191 °C.

Nature of the change in the values of fuel consumption g_e depending on FAM composition in the engine cylinder λ_{cyl} in modes **A, B, C, D** of adjustment characteristics (Fig. 1–4) is consistent with the known data reported by researchers of operating processes of SIE with FAM stratification [48–50].

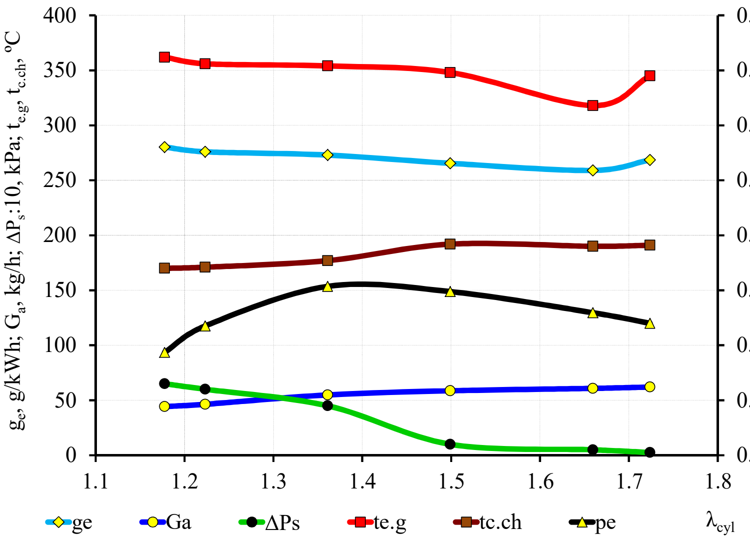

Fig. 4. Adjustment characteristic. Mode **D**

7. Construction of load characteristics of rational adjusting taking into account maximum economy and power

Based on the adjusting characteristics (modes **A**, **B**, **C**, **D**) in terms of the composition of the FAM in the cylinder λ_{cyl} at a fixed cycle fuel feed (B_{cycle}=6, 7.6, 9.4, 11 mg/cycle) and a constant crankshaft speed n=3000 rpm (Fig. 1–4), a load characteristic of rational adjustment of the economy of a two-stroke spark-ignition engine 1D 8.7/8.2 at DFI and organization of the operating process with SLFAC (Fig. 5) was constructed.

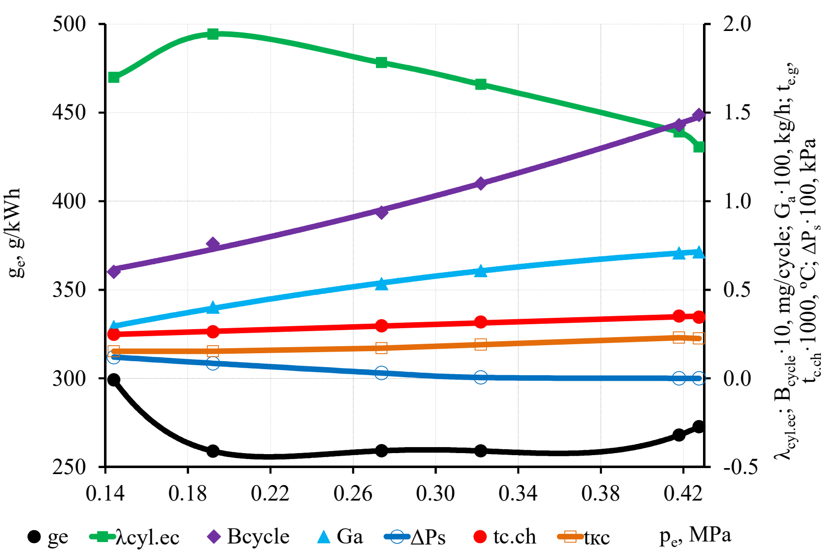

Fig. 5. Load characteristic of rational adjusting in terms of maximum economy

Using the load characteristic of rational adjustment of the economy at n=3,000 rpm, it is possible to assess the influence of the level of effective FAM leaning limit corresponding to the economical composition of SLFAC in the engine cylinder ($\lambda_{cyl.\,ec}$) on the values of maximum engine economy in a form of minimum value of the specific effective fuel consumption g_e.

The economical FAM composition presented in a form of the excess-air factor in the cylinder (λ_{cyl}=$\lambda_{cyl.\,ec}$), inlet air flow rate (G_a), exhaust gas temperature ($t_{e.g}$) and inlet depression (ΔP_s) correspond to the economical mode of engine operation with a minimum value of g_e.

With an increase from the minimum load, p_e=0.144 MPa to p_e=0.192 MPa, excess-air factor corresponding to the economical composition of SLFAC in the cylinder ($\lambda_{cyl.\,ec}$) of the engine increased from 1.7 to 1.94. In this case, the g_e value decreased from 299 g/kWh to the minimum value $g_{e\,\min}$=259 g/kWh (Fig. 5).

In the zone of partial loads (p_e=0.144÷0.322 MPa), when the stratified lean fuel-air charge is formed and the load gets increased, air throttle opens resulting in a decrease in depression ΔP_s from 12 to 0.5 kPa and an increase in the amount of fresh charge G_a delivered to the engine from 29.19 up to 60.81 kg/h.

With an increase in load and power, the composition of FAM was enriched to $\lambda_{cyl.\,ec.}$=1.66 but the minimum fuel consumption values were almost at the same level: $g_{e\,\min}$=259 g/kWh.

With an increase in load above p_e=0.322 MPa, the air throttle remained fully open (ΔP_s=0) and power was raised in a qualitative way: FAM composition was enriched by increasing cycle fuel feed. Enrichment of FAM to $\lambda_{cyl.ec}$=1.39 contributed to an increase in load to p_e=0.418 MPa and fuel consumption to g_e=268 g/kWh.

In the zone of increased loads (p_e=0.418÷0.428 MPa) where a homogeneous FAM is formed in the entire over-piston space without FAC stratification, adjustment characteristics in terms of FAM composition were not recorded because the air throttle was fully open (ΔP_s=0) in these engine operating modes.

When the load was increased to p_e=0.428 MPa by increasing the cycle fuel feed up to B_{cycle}=14.87 mg/cycle, amount of fresh charge entering the engine increased to G_a=71.36 kg/h and the excess-air factor in the cylinder ($\lambda_{cyl.\,ec}$) decreased to 1.31 which lead to an increase in fuel consumption to g_e=273 g/kWh.

In terms of the load characteristic of rational adjustment with taking into account the maximum economy of the engine at n=3,000 rpm, exhaust gas temperature increased from 248 to 345 °C when the load increased from p_e=0.144 to p_e=0.428 MPa. The temperature of the combustion chamber surface was $t_{c.ch}$ 225 °C at the maximum load.

Based on the adjustment characteristics in terms of FAM composition in the cylinder λ_{cyl} (Fig. 1–4) and taking into account the power composition of FAM $\lambda_{cyl.pow}$, load characteristic (n=3,000 rpm) of rational adjustment in terms of maximum power was built. The two-stroke spark-ignition engine 1D 8.7/8.2 worked with internal mixture formation and organization of the operating process with FAC stratification at partial loads and a homogeneous FAM composition in the entire over-piston space (Fig. 6).

Influence of power composition of FAM in the cylinder ($\lambda_{cyl.pow}$) in the formation of a stratified and homogeneous FAC on the engine efficiency in terms of specific effective fuel consumption g_e was estimated in modes of the load characteristic of rational adjustment in terms of maximum power.

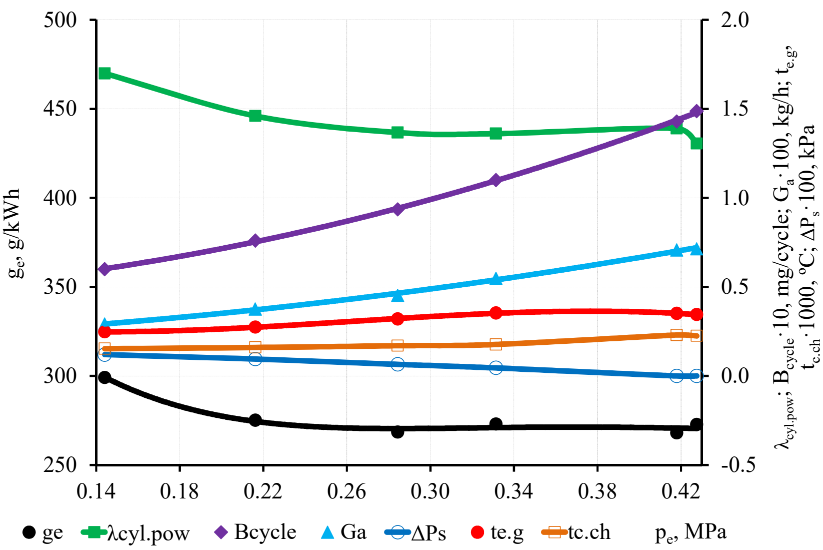

Fig. 6. Load characteristic of rational adjustment in terms of maximum power

The rational power composition of FAM ($\lambda_{cyl.pow}$) in the modes of adjustment characteristics (Fig. 1–4) at a fixed cycle fuel feed B_{cycle} was determined by enriching the FAM and reducing the amount of incoming air (G_a) at the engine inlet when closing the air throttle and increasing depression at the inlet (ΔP_s) until the maximum value of the effective power (N_e) or average effective pressure (p_e) was reached.

Excessive enrichment of FAM leads to an unacceptable decrease in power, an unjustified increase in fuel consumption and greater emission of harmful substances from exhaust gases, at least in a form of carbon monoxide CO.

It can be seen from the presented load characteristic of rational adjustment of maximum power that with an increase in load from minimum value p_e=0.144 MPa to p_e=0.284 MPa when the air throttle was opened to obtain depression at inlet ΔP_s=6.5 kPa, the amount of air G_a incoming to the engine increased from 29.19 up to 45.25 kg/h (Fig. 6).

The value of the optimal power composition of the FAM in the engine cylinder represented as the excess-air factor ($\lambda_{cyl.pow}$) decreased from 1.7 to 1.37. Specific effective fuel consumption g_e in this load range was reduced from 299 to 268 g/kWh.

With a further increase in load to p_e=0.418 MPa which corresponds to complete opening of the air throttle (ΔP_s=0), amount of air entering the engine to G_a=70.74 kg/h and a cycle fuel feed to B_{cycle}=14.29 mg/cycle, the excess-air factor changed insignificantly ($\lambda_{cyl.pow}$=1.37÷1.39). Fuel consumption g_e in this load range remained virtually unchanged and averaged 270 g/kWh (Fig. 6).

In the zone of increased loads (p_e=0.418÷0.428 MPa), values of exhaust gas temperature ($t_{e.g}$) and combustion chamber surface temperature ($t_{c.ch}$), amount of air at the inlet (G_a), cycle fuel feed (B_{cycle}), excess-air factor in the cylinder (λ_{cyl}) and, accordingly, specific effective fuel consumption (g_e) were the same in terms of the load characteristics of rational adjustment of maximum power (Fig. 6) and economy (Fig. 5).

As a result, a decrease in fuel consumption (g_e) was found when using the load characteristic of rational adjustment in terms of the maximum economy compared to the load characteristic of rational adjustment in terms of maximum power. Fuel consumption g_e was cut to 7.5 % at minimum loads (p_e=0.144÷0.192 MPa), 5.82 % in the partial load zone (p_e=0.192÷0.26 MPa) and by an average of 4.1 % in the medium-load zone (p_e=0.26÷0.38 MPa).

An increase in engine economy was consistent with a decrease in exhaust gas temperature in the zone of partial and medium loads by an average of 7 % at almost the same combustion chamber surface temperatures (Fig. 5, 6).

An increase in fuel consumption and exhaust gas temperature in terms of the load characteristic of rational adjustment of maximum power with respect to the characteristic of rational adjustment of maximum economy is connected with a decrease in the excess-air factor (λ_{cyl}) and, accordingly, an increase in the mass of FAC per unit surface area of the over-piston space.

8. Discussion of the results obtained in studying the characteristics of rational adjustment of FAM composition on a two-stroke engine with internal mixture formation

Based on the established prospects of using internal mixture formation taking into account peculiarities of its application to a two-stroke spark-ignition engine, an operating process with SLFAC was developed to obtain high technical, economic and environmental indicators [41]. Modernization of design of a two-stroke spark-ignition engine and the installation of the DFI system have ensured the implementation of the operating process with SLFAC and the engine operation in modes of partial loads with an excess air coefficient in the cylinder λ_{cyl}>1.

Use of the procedure of recording the adjustment characteristics of a two-stroke engine in terms of FAM composition in the cylinder (λ_{cyl}) (1) at a constant cycle fuel feed and adjustment of air intake has made it possible to more accurately determine economic and power compositions of FAM. This is connected to that, for example, there is about 15 times more air than fuel in the stoichiometric composition of FAM and the NVR-1 mechanical fuel pump provides a relatively rough dosage of the cycle fuel feed because of its design features.

Recording of adjustment characteristics in terms of FAM composition has made it possible to determine values of the economical ($\lambda_{cyl.ec}$) and power ($\lambda_{cyl.pow}$) composition of FAM (Fig. 1–4) in the studied engine operation modes at n=3,000 rpm. The economical composition of FAM ($\lambda_{cyl.ec}$) corresponded to the minimum specific effective fuel consumption ($g_{e\ \min}$) and the power composition of FAM ($\lambda_{cyl.ec}$) corresponded to the maximum value of average effective pressure (p_e).

Using the data of economical ($\lambda_{cyl.ec}$) and power ($\lambda_{cyl.pow}$) composition of the adjustment characteristics of the FAM (Fig. 1–4), load characteristics (n=3,000 rpm) with minimum fuel consumption (Fig. 5) and maximum power were constructed (Fig. 6).

Development and implementation of the operating process with SLFAC on a spark-ignition engine have made it possible to solve the problem of formation (at the time of ignition and subsequent combustion) of a qualitatively mixed lean composition of FAM surrounded with relatively clean air. The lean quality composition of FAM was ensured by evaporation of a part of the cycle fuel feed from the surface of the combustion chamber with directed intensive air movement above it. In the course of the combustion process, lean FAM was supplied towards the flame front which has made it possible to intensify the combustion process and reduce its time. Based on experimental studies with a 1D 8.7/8.2 two-stroke spark-ignition engine, it was found that combustion duration with SLFAC formation decreased on average by 40 % compared to the external mixture formation (carburetor feed system) and by 36 % compared to organization of the operating process with stratification of enriched FAM composition [51, 52].

The main advantages of the studies can be attributed to the fact that they demonstrated the possibility of reducing fuel consumption through the organization of the operating process with SLFAC which ensured efficient combustion of lean FAM composition (Fig. 5). A relatively simple procedure of determining rational FAM composition in the engine cylinder has made it possible to establish with sufficient accuracy the range of effective FAM leaning.

Similar studies were carried out to solve a problem associated with improving the economy of a spark-ignition engine during DFI due to FAM leaning in a stratified FAC [50]. In this study, the effect of fuel injection at the intake stroke and double injection at the compression stroke on the quality of FAM formation and combustion characteristics was considered. Organization of the operating process makes it possible to adjust FAM composition by the intensification of the processes of stepwise injection of the cycle fuel feed, however, it does not provide an increase in the speed of combustion of lean FAM composition which reduces its efficiency. A detailed analysis of the mixture formation and combustion processes using high-speed filming was made and 3-D modeling of hydrodynamic processes in the engine cylinder was used in the KIVA software package. However, the strategies used in the studies did not allow the authors to increase the speed of the lean FAM combustion and fully ensure the expansion of the limits of effective FAM leaning.

For effective application of the study results in practice and analytical studies, it is necessary to take into account all design features and adjustment parameters of the modernized 1D 8.7/8.2 two-stroke engine and the NVR-1 DFI mechanical system.

Obtaining similar or improved technical and economic indicators with spark-ignition engines and engines of different designs is possible using features of the organization of the operating process with SLFAC [41]. The main conditions that determine the effective organization of the operating process with SLFAC include:

– formation of a lean FAM volume symmetrical to the cylinder axis with relatively clean air near the walls of the over-piston space;

– ensuring the quality composition of the entire volume of lean FAM in the area of the ignition plug electrodes at the time of ignition;

– ensuring FAM temperature at the time of ignition close to the temperature of self-ignition but not exceeding it;

– providing almost diffusive combustion with an intensive feed of air into the combustion zone and simultaneous removal of combustion products from it.

Further expansion of the limits of effective leaning of the air-fuel mixture can be achieved through adjusting exhaust gas recirculation and the use of fuel with a higher-octane number.

9. Conclusions

1. An operating process has been developed for spark-injection engines with internal mixture formation by analyzing well-known operating processes and considering improved processes of gas exchange, mixture formation, and combustion. The operating process makes it possible to efficiently burn SLFAC in modes of partial loads and a homogeneous power composition of FAM in the entire over-piston space in modes of high loads.

Taking into account features of the organization of the operating process, the design of the two-stroke spark-ignition engine 1D 8.7/8.2 was modernized. A DFI system was installed on the engine, a fuel nozzle was mounted in the cylinder wall and a hemispherical symmetric combustion chamber installed in the cylinder head was used.

2. Taking into account peculiarities of the NVR-1 mechanical fuel equipment with a cup-type seal of the plunger and air to fuel ratio in FAM≈15:1, a procedure has been developed for adjusting the composition of FAM in the cylinder of a two-stroke spark-ignition engine with DFI. The procedure makes it possible to record engine parameters and indicators at a constant cycle fuel feed and adjustment of the incoming fresh charge at the inlet by changing the position of the air throttle in modes of the load characteristic.

3. Based on the results of experimental studies, adjustment characteristics were constructed in terms of FAM composition in the cylinder of the 1D 8.7/8.2 two-stroke spark-ignition engine with DFI in modes of load characteristic at n=3,000 rpm.

The range of values of rational economical FAM composition was determined $\lambda_{cyl.ec}$=1.66÷1.94 which corresponded to the limit of its effective leaning and provided a minimum specific effective fuel consumption $g_{e\ \min}$ in the range from 259 to 299 g/kWh.

The range of values of rational power composition of FAM was determined $\lambda_{cyl.pow}$=1.37÷1.7 which characterizes the limit of its effective enrichment and makes it possible to obtain maximum effective pressure p_e in the range from 0.144 to 0.331 MPa.

4. Based on the values of maximum economical and power FAM compositions of the adjustment characteristics, load characteristics of rational adjustment that provide minimum fuel consumption and maximum power were constructed at n=3,000 rpm.

In modes of the load characteristic of rational adjustment of maximum economy, the composition of FAM in the cylinder ($\lambda_{cyl.ec}$) of the engine varies from 1.31 to 1.94. The value of minimum specific effective fuel consumption is $g_{e\ \min}$=259 g/kWh at p_e=0.192÷0.38 MPa.

In the modes of load characteristic of rational adjustment of maximum power, the value of FAM composition in the cylinder ($\lambda_{cyl.pow}$) of the engine is in the range from 1.31 to 1.7. Fuel consumption is g_e=270 g/kWh in the partial load range (p_e=0.26÷0.43 MPa) which is on average 4.1 % higher compared to the rational adjustment of economic efficiency.

References

1. International Energy Outlook 2019 with projections to 2050. U.S. (2019). Energy Information Administration. Available at: https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf
2. Panchuk, M., Kryshtopa, S., Panchuk, A., Kryshtopa, L., Dolishnii, B., Mandryk, I., Sladkowski, A. (2019). Perspectives for developing and using the torrefaction technology in Ukraine. International Journal of Energy for a Clean Environment, 20 (2), 113–134. doi: https://doi.org/10.1615/interjenercleanenv.2019026643
3. World Energy Outlook 2019 (2019). International Energy Agency, 810.
4. Panchuk, M., Kryshtopa, S., Shlapak, L., Kryshtopa, L., Panchuk, A., Yarovyi, V., Sładkowski, A. (2018). Main trends of biofuels production in Ukraine. Transport Problems, 12 (4), 15–26. doi: https://doi.org/10.20858/tp.2017.12.4.2
5. Kryshtopa, S., Kryshtopa, L., Melnyk, V., Dolishnii, B., Prunko, I., Demianchuk, Y. (2017). Experimental research on diesel engine working on a mixture of diesel fuel and fusel oils. Transport Problems, 12 (2), 53–63. doi: https://doi.org/10.20858/tp.2017.12.2.6
6. Liu, W. (2017). Energy Management Strategies for Hybrid Electric Vehicles. Hybrid Electric Vehicle System Modeling and Control, 243–287. doi: https://doi.org/10.1002/9781119278924.ch6
7. Polivyanchuk, A., Ahieiev, M., Kagramanian, A., Baranovskis, A., Samarin, O. (2020). Features of Environmental Diagnostics of Heat Motors and Boiler Plants by Information Methods. Lecture Notes in Intelligent Transportation and Infrastructure, 360–367. doi: https://doi.org/10.1007/978-3-030-39688-6_45
8. Kryshtopa, S., Panchuk, M., Kozak, F., Dolishnii, B., Mykytii, I., Skalatska, O. (2018). Fuel economy raising of alternative fuel converted diesel engines. Eastern-European Journal of Enterprise Technologies, 4 (8 (94)), 6–13. doi: https://doi.org/10.15587/1729-4061.2018.139358
9. Dumenko, P., Kravchenko, S., Prokhorenko, A., Talanin, D. (2019). Formation and Study of Static and Dynamic Characteristics of Electronically Controlled Diesel Engine. Latvian Journal of Physics and Technical Sciences, 56 (2), 12–23. doi: https://doi.org/10.2478/lpts-2019-0009
10. Prohorenko, A., Dumenko, P. (2018). Software Algorithm Synthesis for Diesel Electronic Control Unit. Latvian Journal of Physics and Technical Sciences, 55 (3), 16–26. doi: https://doi.org/10.2478/lpts-2018-0017
11. Nüesch, T., Elbert, P., Flankl, M., Onder, C., Guzzella, L. (2014). Convex Optimization for the Energy Management of Hybrid Electric Vehicles Considering Engine Start and Gearshift Costs. Energies, 7 (2), 834–856. doi: https://doi.org/10.3390/en7020834
12. Polivyanchuk, A., Gritsuk, I., Skuridina, E. (2019). Improving the accuracy of the gravimetric method for control particulate matter in diesel exhaust. New Stages of Development of Modern Science in Ukraine and EU Countries. doi: https://doi.org/10.30525/978-9934-588-15-0-59
13. Kryshtopa, S., Melnyk, V., Dolishnii, B., Korohodskyi, V., Prunko, I., Kryshtopa, L. et. al. (2019). Improvement of the model of forecasting heavy metals of exhaust gases of motor vehicles in the soil. Eastern-European Journal of Enterprise Technologies, 4 (10 (100)), 44–51. doi: https://doi.org/10.15587/1729-4061.2019.175892
14. Arena, F., Mezzana, L. (2014). The Automotive CO2 Emissions Challenge. 2020 Regulatory Scenario for Passenger Cars. Arthur D. Little. Available at: https://www.adlittle.com/sites/default/files/viewpoints/ADL_AMG_2014_Automotive_CO2_Emissions_Challenge.pdf
15. Meyer, S., Kölmel, A., Gegg, T., Trattner, A., Grassberger, H., Schögl, O. et. al. (2015). Advantages and challenges of lean operation of two-stroke engines for hand-held power tools. 15. Internationales Stuttgarter Symposium, 247–261. doi: https://doi.org/10.1007/978-3-658-08844-6_17
16. Kryshtopa, S., Panchuk, M., Dolishnii, B., Kryshtopa, L., Hnyp, M., Skalatska, O. (2018). Research into emissions of nitrogen oxides when converting the diesel engines to alternative fuels. Eastern-European Journal of Enterprise Technologies, 1 (10 (91)), 16–22. doi: https://doi.org/10.15587/1729-4061.2018.124045
17. Marouf Wani, M., Mursaleen, M., Parvez, S. (2013). Investigations on a Two Stroke Cycle Spark Ignition Engine Using Gasoline Direct Injection. Energy and Power, 2 (7), 116–122. doi: https://doi.org/10.5923/j.ep.20120207.01
18. Mattarelli, E., Rinaldini, C. A. (2015). Two-Stroke Gasoline Engines for Small-Medium Passenger Cars. SAE Technical Paper Series. doi: https://doi.org/10.4271/2015-01-1284
19. Zhang, Y., Zhao, H. (2014). Optimisation of boosting strategy for controlled auto-ignition combustion in a four-valve camless gasoline direct injection engine running in two-stroke cycle. International Journal of Engine Research, 15 (7), 850–861. doi: https://doi.org/10.1177/1468087413519991

20. Wang, X., Ma, J., Zhao, H. (2017). Analysis of scavenge port designs and exhaust valve profiles on the in-cylinder flow and scavenging performance in a two-stroke boosted uniflow scavenged direct injection gasoline engine. International Journal of Engine Research, 19 (5), 509–527. doi: https://doi.org/10.1177/1468087417724977
21. Zhang, G., Xu, M., Zhang, Y., Hung, D. L. S. (2012). Characteristics of Flash Boiling Fuel Sprays from Three Types of Injector for Spark Ignition Direct Injection (SIDI) Engines. Proceedings of the FISITA 2012 World Automotive Congress, 443–454. doi: https://doi.org/10.1007/978-3-642-33841-0_33
22. Zhang, Y., Zhao, H., Ojapah, M., Cairns, A. (2013). CAI combustion of gasoline and its mixture with ethanol in a 2-stroke poppet valve DI gasoline engine. Fuel, 109, 661–668. doi: https://doi.org/10.1016/j.fuel.2013.03.002
23. Wang, X., Zhao, H., Xie, H. (2016). Effect of dilution strategies and direct injection ratios on stratified flame ignition (SFI) hybrid combustion in a PFI/DI gasoline engine. Applied Energy, 165, 801–814. doi: https://doi.org/10.1016/j.apenergy.2015.12.116
24. Mahmoudzadeh Andwari, A., Pesyridis, A., Esfahanian, V., Said, M. (2019). Combustion and Emission Enhancement of a Spark Ignition Two-Stroke Cycle Engine Utilizing Internal and External Exhaust Gas Recirculation Approach at Low-Load Operation. Energies, 12 (4), 609. doi: https://doi.org/10.3390/en12040609
25. Andwari, A. M., Abdul Aziz, A., Muhamad Said, M. F., Esfahanian, V. et. al. (2017). Effect of internal and external EGR on cyclic variability and emissions of a spark ignition two-stroke cycle gasoline engine. Journal of mechanical engineering and sciences, 11 (4), 3004–3014. doi: https://doi.org/10.15282/jmes.11.4.2017.4.0270
26. Gombosuren, N., Yoshifumi, O., Hiroyuki, A. (2020). A Charge Possibility of an Unfueled Prechamber and Its Fluctuating Phenomenon for the Spark Ignited Engine. Energies, 13 (2), 303. doi: https://doi.org/10.3390/en13020303
27. Wang, X., Zhao, H. (2019). A High-Efficiency Two-Stroke Engine Concept: The Boosted Uniflow Scavenged Direct-Injection Gasoline (BUSDIG) Engine with Air Hybrid Operation. Engineering, 5 (3), 535–547. doi: https://doi.org/10.1016/j.eng.2019.03.008
28. Schnittger, W., Königstein, A., Pritze, S., Pöpperl, M., Rothenberger, P., Samstag, M. (2003). 2.2 Direct Ecotec. MTZ Worldwide, 64 (12), 2–7. doi: https://doi.org/10.1007/bf03227635
29. Voss, E., Schmittger, W., Königstein, A., Scholten, I., Pöpperl, M., Pritze, St., Rothenberger, P., Samstag, M. (2003). 2,2 l ECOTEC DIRECT – Der neue Vollaluminiummotor mit Benzindirekteinspritzung für den Opel Signum. 24. Internationales Wiener Motorensymposium.
30. Krebs, R., Böhme, J., Dornhöfer, R., Wurms, R., Friedmann, K., Helbig, J., Hatz, W. (2004). Der neue Audi 2,0T FSI Motor Der erste direkteinspritzende Turbo Ottomotor bei Audi. 25. Wiener Motorensymposium. Available at: https://www.tib.eu/en/search/id/dkf%3A0409DKF189515/Der-neue-Audi-2-0T-FSI-Motor-Der-erste-direkteinspritzende/
31. Jägerbauer, E., Fröhlich, K., Fischer, H. (2003). Der neue 6,0-l-Zwölfzylindermotor von BMW. MTZ - Motortechnische Zeitschrift, 64 (7-8), 546–555. doi: https://doi.org/10.1007/bf03227108
32. Tsuji, N., Sugiyama, M., Abe, S. (2006). Der neue 3.5L V6 Benzinmotor mit dem innovativen stöchiometrischen Direkteinspritzsystem D-4S. 27. Internationales Wiener Motorensymposium.
33. Kettner, M., Fischer, J., Nauwerck, A., Spicher, U., Velji, A., Kuhnert, D., Latsch, R. (2003). Ein neues Brennverfahren mit Mehrfacheinspritzung für Ottomotoren mit Direkteinspritzung. 9. Tagung: Der Arbeitsprozess des Verbrennungsmotors. Available at: http://www.sfb606.kit.edu/index.pl/Haupt_Menu_Forschungsprogramm_M08/projekte/c3/Veroeffentlichung/Sept2003_BPi.pdf
34. Kettner, M., Fischer, J., Nauwerck, A., Tribulowski, J., Spicher, U., Velji, A. et. al. (2004). The BPI Flame Jet Concept to Improve the Inflammation of Lean Burn Mixtures in Spark Ignited Engines. SAE Technical Paper Series. doi: https://doi.org/10.4271/2004-01-0035
35. Herden, W., Vogel, M. (2002). Visionen idealer strahlgeführter BDE-Brennverfahren. Dieselund Benzindirekteinspritzung. Essen: Expert-Verlag.
36. Kemmler, R., Frommelt, A., Kaiser, T., Schaupp, U., Schommers, J., Waltner, A. (2002). Thermodynamischer Vergleich ottomotorischer Brennverfahren unter dem Fokus minimalen Kraftstoffverbrauchs. 11. Aachener Kolloquium Fahrzeug- und Motorentechnik.
37. Specifications engines Evinrude® E-TEC® G2™ 200 HO, 225 HP, 225 HO, 250 HP, 250 HO, 300 HP. Fuel inductions: E-TEC Direct Injection with stratified low RPM combustion mode / Bombardier Recreational Products Inc. 2003-2015. Available at: http://www.evinrude.com/en-US/engines/e-tec-g2/200-ho-300-hp.html#tab=0
38. Technical Details ROTAX 600 E-TEC. Available at: https://www.rotax.com/en/products/rotax-powertrains/details/rotax-600-ho-e-tec.html
39. Arcoumanis, C., Kamimoto, T. (Eds.) (2009). Flow and Combustion in Reciprocating Engines. Springer. doi: https://doi.org/10.1007/978-3-540-68901-0
40. Schumann, F., Sarikoc, F., Buri, S., Kubach, H., Spicher, U. (2012). Potential of spray-guided gasoline direct injection for reduction of fuel consumption and simultaneous compliance with stricter emissions regulations. International Journal of Engine Research, 14 (1), 80–91. doi: https://doi.org/10.1177/1468087412451695

41. Korogodskyj, V. A., Kyrylyuk, I. O., Lomov, S. G. (2007). Pat. No. WO2009044225A1. A Method of Mixing in a Combustion Chamber of an Internal Combustion Engine and a Spark-Ignition Direct-Injection Stratified Fuel-Air Charge Internal Combustion Engine. No. PCT/IB 2007/004105; declareted: 03.10.2007; published: 09.04.2009. Available at: https://patentimages.storage.googleapis.com/71/bb/f0/2d600f599211e0/WO2009044225A1.pdf
42. Korohodskyi, V., Khandrymailov, A., Stetsenko, O. (2016). Dependence of the coefficients of residual gases on the type of mixture formation and the shape of a combustion chamber. Eastern-European Journal of Enterprise Technologies, 1 (5 (79)), 4–12. doi: https://doi.org/10.15587/1729-4061.2016.59789
43. Reif, K. (Ed.) (2015). Ottomotor-Management im Überblick. Springer. doi: https://doi.org/10.1007/978-3-658-09524-6
44. Pesiridis, A. (Ed.) (2014). Automotive Exhaust Emissions and Energy Recovery. En-vironmental, Science, Engineering and Technology. N.Y.: Nova Science Publ. Inc., 293. Available at: https://novapublishers.com/shop/automotive-exhaust-emissions-and-energy-recovery/
45. Korohodskyi, V. A., Vasylenko, O. V., Tsykra, S. A., Oboznyi, S. V. (2010). Eksperymentalne vyznachennia koefitsienta vytoku robochoho tila pry produvtsi tsylindra u dvotaktnomu dvyhuni z iskrovym zapaliuvanniam. Zbirnyk naukovykh prats UkrDAZT, 112, 203–208.
46. Martyr, A., Plint, M. (2012). Engine Testing: The Design, Building, Modification and Use of Powertrain Test Facilities. Butterworth-Heinemann, 600. doi: https://doi.org/10.1016/c2010-0-66322-x
47. Rogovyi, A. (2018). Energy performances of the vortex chamber supercharger. Energy, 163, 52–60. doi: https://doi.org/10.1016/j.energy.2018.08.075
48. Van Basshuysen, R., Schäfer, F. (Eds.) (2017). Handbuch Verbrennungsmotor. Grundlagen, Komponenten, Systeme, Perspektiven. Springer. doi: https://doi.org/10.1007/978-3-658-10902-8
49. Reif, K. (Ed.) (2015). Gasoline Engine Management Systems and Components. Springer. doi: https://doi.org/10.1007/978-3-658-03964-6
50. Song, J., Kim, T., Jang, J., Park, S. (2015). Effects of the injection strategy on the mixture formation and combustion characteristics in a DISI (direct injection spark ignition) optical engine. Energy, 93, 1758–1768. doi: https://doi.org/10.1016/j.energy.2015.10.058
51. Korogodskiy, V. A., Vasilenko, O. V. (2007). The defenition of combustion parameters under indicator diagrams of a two-stroke engine with the carburettor and direct fuel ingection. Visnyk Kharkivskoho natsionalnoho avtomobilno-dorozhnoho universytetu, 37, 60–67. Available at: https://cyberleninka.ru/article/n/opredelenie-pokazateley-sgoraniya-po-indikatornym-diagrammam-dvuhtaktnogo-dvigatelya-s-karbyuratorom-i-neposredstvennym-vpryskom
52. Korohodskiy, V. A., Stetsenko, O. N., Tkachenko, E. A. (2015). The influence stratification of fuel and air charge on combustionindicators two-stroke engines with spark ignition. Zbirnyk naukovykh prats UkrDUZT, 154, 142–148. Available at: http://webcache.googleusercontent.com/search?q=cache:aE7Jtb7Nqr4J:irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe%3FC21COM%3D2%26I21DBN%3DUJRN%26P21DBN%3DUJRN%26IMAGE_FILE_DOWNLOAD%3D1%26Image_file_name%3DPDF/Znpudazt_2015_154_25.pdf+&cd=2&hl=ru&ct=clnk&gl=ua