Determining the criteria and the degree of the stratification of the air-fuel charge in a cylinder of a spark-ignition engine during injecting fuel

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Abstract. In internal combustion engines with spark ignition and the direct fuel injection, the indicators are offered to evaluate the organization of the working process in the form of a criterion for the stratification of the air-fuel charge and the degree of stratification of the air-fuel mixture. Using the experimental data of a two-stroke engine with spark ignition and the direct injection of fuel with load characteristics, the values of the excess air coefficient in a cylinder and in the volume of the air-fuel mixture are determined. A comparative assessment of the suggested indicators in the organization of the workflow with the stratification of depleted fuel-air charge is presented. It has been defined that a more promising way of organizing the workflow to improve the fuel and economic performance of a spark ignition engine is organizing the fuel injection with the stratification of a depleted air-fuel charge.

1. Introduction
One of the promising areas for improving the technical, economic and environmental operation of spark ignition (SI) engines is the use of a power system for the direct fuel injection (DFI) into a cylinder. The formation of internal mixture contributes to the creation of conditions for the engine operation on depleted air-fuel mixtures (AFM). The air excess in the AFM allows to efficiently burn fuel with a low level of emissions of harmful substances with exhaust gases.

However, the features of organizing the working process in the internal mixture formation related to the shaping of a homogeneous or layered composition of the AFM depending on the engine operating conditions, affect the efficiency of the combustion processes and the fuel consumption respectively.

Therefore, to evaluate the effectiveness of the organization of internal mixture formation in SI engines, it is proposed to use indicators characterizing the features of the formation of the AFM composition by the head-end volume.
2. Determining the stratification of the air-fuel charge in a cylinder of an SI engine

For a qualitative assessment of the processes of internal mixture formation it is offered to use \( L \) criterion, which characterizes the stratification of the air-fuel charge (SAFC) in a cylinder of an SI engines during DFI [1].

\[
L = \frac{\lambda_{cyl} - \lambda_{e.f.f.}}{\lambda_{c.f.f.}} = \frac{\left(\lambda_{\Sigma} - \lambda_{\Sigma} \cdot \nu\right) - \lambda_{e.f.f.}}{\lambda_{c.f.f.}}. 
\]  

where \( \lambda_{e.f.f.} \) normalized air-fuel ratio (AFR / AFRstoichiometric) is the coefficient of excess air which takes into account the lower limit of the emission of the flame front in the petrol and air mixtures of SI engines; \( \lambda_{\Sigma} \) is the total coefficient of excess air (AFR / AFRstoichiometric); \( \lambda_{cyl} \) is the coefficient of excess air in an engine cylinder (AFR / AFRstoichiometric); \( \nu \) is the coefficient which takes into account the leakage of purge air or AFM from an engine cylinder.

The value of the coefficient \( \lambda_{e.f.f.} \) depends on the parameters (pressure and temperature) in an engine cylinder, the composition of the gasoline used [2] and the intensity of the oxidant supply to the combustion zone.

To estimate the lower limit of the emission of the flame front in petrol and air mixtures, to a first approximation \( \lambda_{e.f.f.} = 1.35 \) is used [2]. Values of \( \lambda_{e.f.f.} \) can be specified for a particular case after systematizing the statistical experimental data which takes into account the conditions and characteristics of the fuel used.

At the same time, the use of the stratification \( L \) criterion allows to evaluate the influence of the organization of internal mixture formation processes on the technical, economic and environmental operation of an SI engines and to characterize the excess of the lower limit of the flame front emission in the AFM.

For a qualitative assessment of the features of the working process organization during the internal mixture formation with SAFC in SI engines, it is suggested to use the SAFC degree indicator:

\[
\varepsilon_L = \frac{\lambda_{cyl}}{\lambda_{AFM}}, 
\]  

where \( \lambda_{cyl} \) is the coefficient of excess air in a cylinder:

\[
\lambda_{cyl} = \frac{M_{inc.ch}}{B_{cyl} \cdot M_0} \cdot (1 - \nu), 
\]  

where \( M_{inc.ch} \) is the mass of incoming charge, kg; \( B_{cyl} \) is the cyclic fuel supply, kg; \( M_0 \) is the mass of air theoretically necessary for the complete fuel combustion in an engine cylinder, kg; \( \nu \) is the leakage coefficient of purge air or AFM; \( \lambda_{AFM} \) is the average coefficient of excess air in the AFM volume at the moment of its ignition, corresponding to the ignition dwell angle \( \theta_{ign} \) when a spark discharge is applied to the electrodes of a spark plug:

\[
\lambda_{AFM} = \frac{M_{airAFM}}{B_{cyl} \cdot M_{air}}. 
\]  

where \( M_{airAFM} \) is the air mass in the AFM volume, kg; \( M_{air} \) is the air mass theoretically necessary for the complete fuel combustion in the AFM volume, kg.

3. Experimental methodology

At values of the SAFC power coefficient \( \varepsilon_L > 1 \) the composition of the AFM or AFM and air layers is distributed in the engine head-end volume, and at the values \( \lambda_{cyl} = \lambda_{AFM} \) and accordingly \( \varepsilon_L = 1 \) there is no SAFC, which is characterized by a uniform distribution of fuel particles over the entire head-end volume.

The AFM volume in the head-end volume at the DFI and due to feeding the AFM into a divided combustion chamber can be determined by its size taking into account the possible flow of a part of AFM into an engine cylinder. At DFI, the AFM volume can be determined in a semi-separated and non-separated combustion chamber, for example, as a result of experimental studies using high-speed
multi-channel video recording [3] or laser diagnostics [4] when registering any luminescent radiation in the ultraviolet wavelength range [5].

The obtained experimental images taken by a high-speed video camera synchronized with the laser radiation can also be used for the comparison in modeling the mixture formation processes and the SAFC combustion [6].

The AFM volume in a semi-separated and non-separated engine combustion chamber at the time of ignition can be determined by 3-D modeling [7].

To organise the conditions for the internal mixture formation in a two-stroke SI engines at DFI on the surface of a hemispherical combustion chamber with the off-centre exhaust port and a hemispherical symmetric combustion chamber [8], the AFM volume is formed inside the combustion chamber until the voltage is applied to the electrodes of a spark plug. Due to the fact that the air charge flows during the compression stroke are directed inside the combustion chamber [9], the AFM do not travel from the volume of the combustion chamber to an engine cylinder. For that reason, the $\lambda_{AFM}$ value at the moment of the AFM ignition is determined by the amount of the air $M_{air,AFM}$ that is in the volume of the hemisphere of the combustion chamber according to its design dimensions, the amount of injected fuel cycle supply $B_{cyl}$ and the values of the theoretical air mass $M_{0,AFM}$ required for the complete combustion of the fuel used.

4. Experimental data and results

On a two-stroke SI engines 1D 8.7 / 8.2 with DFI, two work processes are organized: with the separation of the air-fuel charge (SAFC) and the separation of the depleted air-fuel charge (SDAFC).

In general, the term SAFC should be understood as such an organization of the mixture formation process in which the different AFM concentration with the head-end volume or the air excess coefficient $\alpha$ is provided.

In the first workflow, the SAFC was organized with the formation of an enriched AFM spark plugs ($1.0 > \lambda > 0.8$) in the electrode zone and the air ($\lambda = \infty$) at the walls of the head-end volume.

The working process with SAFC is organized at DFI into an engine cylinder on the surface of a hemispherical combustion chamber, displaced to the exhaust port and the movement of the air charge inside the combustion chamber during the compression stroke (Figure 1) [8].

The peculiarity of the SAFC organization is that the direction and intensity of the movement of the air charge in the combustion chamber throat during the volume and film-type mixture formation does not allow to transfer fuel particles into the cylinder volume. As a result, at the time of the ignition a fuel-air charge is formed in layers in the head-end volume, in the volume of the hemisphere of the combustion chamber - AFM, and in the cylinder volume - the air.

By the amount of the air in the hemisphere of the combustion chamber, the cyclic supply of injected fuel, and the position of a piston in the cylinder at the moment of the AFM ignition, at a first approximation, the values of $\lambda_{AFM}$ at the load characteristic modes have been determined (Figure 2).

![Figure 1. Organization of the work process with SAFC.](image)

The values of the total coefficient of the excess air $\alpha_{E}$ are determined due to the experimental studies obtained on the basis of measuring the air output at the inlet and the mass fuel consumption by the load characteristic at $n=3000 \text{ min}^{-1}$.  

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The values of the excess air coefficient in a cylinder $\lambda_{cyl}$ are determined by the amount of air entering the cylinder, the air leakage during the purge of a cylinder and the cyclic supply of the fuel directly injected into the engine head-end volume.

With increasing the load from $b_{nep} = 0.15 \, MPa$ to $b_{nep} = 0.29 \, MPa$ and the opening of a choke valve, the AFM composition $\lambda_{AFM} = 1.21$, respectively the coefficients of the excess air in a cylinder $\lambda_{cyl} = 1.46$ and the total coefficient of the excess air $\lambda_{\Sigma} = 1.7$ are combined up to $\lambda_{AFM} = 1.35$, $\lambda_{cyl} = 1.64$, $\lambda_{\Sigma} = 2.03$.

In the second working process, the SDAFC is organized with the formation of a depleted AFM spark plug in the electrode area (1.5 $> \lambda$ $> 1.0$), and at the walls of the combustion chamber there was almost only the air ($\lambda = \infty$) at the value of the excess air coefficient in a cylinder $\lambda_{cyl} < 5$.

![Figure 2. Values of the coefficients of the excess air: the total coefficient ($\lambda_{\Sigma}$), in the cylinder ($\lambda_{cyl}$) and in the volume of the air-fuel mixture ($\lambda_{AFM}$) during the organization of the working process with SAFC during different load characteristic conditions at $n = 3000 \, min^{-1}$.](image)

The workflow with SDAFC is organized by installing a symmetrical hemispherical combustion chamber and using an outward-opening pintle-type nozzle that forms the peripheral distribution of fuel particles in the fuel jet (Figure 3).

A specific feature of the SDAFC organization is that the AFM is formed at the compression stroke during the fuel injection on the surface of a symmetrical hemispherical combustion chamber and the air movement from a cylinder into the combustion chamber volume, which is directed to the electrodes of a spark plug [8]. The nature of the “pressing” of the AFM volume from a cylinder from all sides by the air contributes to the organization of the layered distribution of AFM and the air in the head-end volume.

The organized directed layer-by-layer distribution of AFM and the air in the head-end volume at the time of ignition and the movement of air into the mixture volume contributes to the formation of a uniform AFM composition within the flammability range with the subsequent feeding of the air into the combustion zone.
To evaluate the AFM composition, the experimental data were used at the load characteristic conditions at $n = 3000 \text{ min}^{-1}$ and the functional features of an engine at the time of ignition.

For this purpose, the total values of the excess air coefficient ($\lambda_\Sigma$) are determined at the investigated operating modes of the 1D 8.7 / 8.2 two-stroke engine taking into account the incoming air quantity at the inlet and the cyclic fuel supply.

Based upon the defined values of the working fluid leakage during the gas exchange, the amount of the air in a cylinder after closing the units of the gas distribution is determined and, taking into account the cyclic fuel supply, the coefficient of the excess air in the engine cylinder ($\lambda_{clyl}$) is calculated. Considering that AFM are formed in the volume of the hemisphere of the combustion chamber so the amount of the air contained in it is defined with regard for its size and by the evaporated fuel amount, in a first approximation the coefficients of the excess air in the AFM ($\lambda_{AFM}$) are determined.

The results of certain values $\lambda_{AFM}$ during the load characteristic conditions at $n = 3000 \text{ min}^{-1}$ (Figure 4) show that when the load decreases from $b_{mep} = 0.428 \text{ MPa}$ to $b_{mep} = 0.192 \text{ MPa}$ the AFM composition $\lambda_{AFM} = 1.00$, respectively the coefficient of the excess air in a cylinder $\lambda_{cyl} = 1.31$ and the total coefficient of the excess air $\lambda_\Sigma = 1.74$ are depleted up to $\lambda_{AFM} = 1.49$, $\lambda_{cyl} = 1.94$, $\lambda_\Sigma = 2.30$.

With a further decrease to a minimum load ($b_{mep} = 0.144 \text{ MPa}$), the AFM composition is enriched up to $\lambda_{AFM} = 1.30$, $\lambda_{cyl} = 1.70$, $\lambda_\Sigma = 1.97$ (Figure 4).

The expansion of the AFM depletion limit during the SDAFC organization during the partial load conditions up to $\lambda_{AFM} = 1.49$ ($b_{mep} = 0.192 \text{ MPa}$) is contributed by the increased compression ratio $\varepsilon = 11.3$, the intensive AFM turbulization and the air supply to the combustion zone.

However, the increase in the content of combustion products in the working fluid and, accordingly the increase in the values of the coefficient of residual gases while reducing up to a minimum load ($b_{mep} = 0.144 \text{ MPa}$) and increasing up to a maximum load ($b_{mep} = 0.428 \text{ MPa}$) facilitate the AFM enrichment.

5. Analysis of the results according to the indicators of the stratification of the air-fuel charge in an SI engine cylinder

According to the experimental studies of a two-stroke SI engines 1D 8.7 / 8.2 with DFI and the SAFC organization considering the load characteristic ($n = 3000 \text{ min}^{-1}$), the maximum value of the SAFC criterion $L_{SAFC} = 0.212$ is determined by the formula (1) [1] taking into account the distribution limit of the flame front in petrol-air mixtures ($\lambda_{e.f.f} = 1.35$) and the coefficient of the excess air in a cylinder $\lambda_{cyl}$, which corresponds to the maximum SAFC at $b_{mep} = 0.29 \text{ MPa}$ (Figure 5).

With the decrease in load up to $b_{mep} = 0.15 \text{ MPa}$, the level of values $L_{SAFC}$ decreases up to 0.08, and with the increase up to the maximum loads in the range from $b_{mep} = 0.39 \text{ MPa}$ to $b_{mep} = 0.47 \text{ MPa}$, the $L$ level has negative values, which characterizes the SAFC absence. To ensure the increased pressure in an engine cylinder during the maximum load conditions, the fuel assembly composition is enriched (Figure 2), and the AFM volume tends to increase up to the size of the head-end volume, which is consistent with the results of $L_{SAFC}$ values obtained in the experimental studies (Figure 5).
Figure 4. Values of the coefficients of the excess air: the total coefficient ($\lambda_{\Sigma}$), in the cylinder ($\lambda_{cyl}$) and in the volume of the air-fuel mixture ($\lambda_{AFM}$) during the organization of the working process with SDAFC during different load characteristic conditions at $n = 3000\ min^{-1}$.

Figure 5. Values of the stratification of the air-fuel charge $L$ and the degree of stratification $\varepsilon_L$ when organizing the working process with SAFC and SDAFC according to the load characteristic conditions at $n = 3000\ min^{-1}$. 
The values of SAFC criterion $L_{SAFC}$ by the load characteristic ($n = 3000 \text{ min}^{-1}$) for the SDAFC working process and the increase in load from $b_{nmep} = 0.144 \text{ MPa}$ to $b_{nmep} = 0.192 \text{ MPa}$ increase from 0.26 to 0.44. With a further increase in load, the level of the stratification criterion decreases and $L_{SAFC} = 0$ is at $b_{nmep} = 0.42 \text{ MPa}$, which is characterized by the SAFC absence. In the load range over $b_{nmep} = 0.42 \text{ MPa}$, it corresponds to negative values of the stratification criterion and the SAFC absence (Figure 5).

The change in the $L_{SAFC}$ values is related to the nature and data of the change in the coefficient of the excess air in a cylinder ($\lambda_{cyl}$) and the value adopted in the first approximation ($\lambda_{e.f.} = 1.35$).

The level of the degree of the SAFC separation when organizing the work process with SDAFC ($\varepsilon_L = 1.3$) is higher than when organizing SAFC ($\varepsilon_L = 1.2$) (Figure 5), considering the higher values of $\lambda_{cyl}$ and $\lambda_{AFM}$ (Figure 2 and Figure 4). Due to the fact that an engine with large values of the SAFC degree ($\varepsilon_L$) has a higher indicator efficiency ($\eta_i$), it can be stated that increasing the $\varepsilon_L$ values contributes to a more rational organization of the working process for the efficient fuel combustion and improving the fuel and economic operation of SI engine. The degree of separation ($\varepsilon_L$) characterizes the perfection of the organization of the working process with SAFC in an SI engine.

### 6. Conclusion

The proposed criterion for the separation of the air-fuel charge ($L$) characterizes the presence of the separation of the air-fuel charge and allows a qualitative assessment of the influence of the internal mixture formation and combustion processes on the characteristics of an engine as a whole.

The proposed indicator of the degree of the separation of the air-fuel charge ($\varepsilon_L$) characterizes the perfection of the organization of the working process with the separation of the air-fuel charge in an SI engine.

It has been proved that a more promising way of organizing a workflow to increase the fuel and economic operation of an SI engine is to organize the internal mixture formation with the stratification of a depleted air-fuel charge.

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