

DEVELOPMENT OF A TECHNICAL AND TECHNOLOGICAL SOLUTION FOR THE SUPPLY AND MIXING OF A FOUR-COMPONENT TWO-PHASE MIXTURE IN AN ENGINE COMBUSTION CHAMBER

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The article considers the issue of developing a technical and technological solution to ensure stable supply, dosing and effective mixing of a four-component two-phase mixture directly in the engine combustion chamber. The relevance of the study is due to the need to increase the completeness of fuel combustion, improve the energy and environmental performance of the engine, as well as ensure controlled formation of the fuel-air mixture under variable operating conditions. The functional structure of the component supply system is substantiated, the requirements for dosing, mixing and spraying elements are determined, as well as for coordinating the flow rates, pressure, temperature and phase state of the components. A basic scheme for forming a two-phase flow is proposed, which involves the phased introduction of the mixture components, preliminary dispersion of the liquid phase and subsequent intensification of mixing in the injection zone. Particular attention is paid to ensuring the homogeneity of the mixture, flame stability, reducing the size of the drops and increasing the rate of mass and heat transfer. The methodological basis of the work is the analysis of the mixture formation processes, structural and functional modeling of the system and evaluation of the main operating parameters. The influence of the design parameters of the mixing unit, the geometry of the channels, the ratio of components and feed modes on the quality of mixture formation is considered. An algorithm for controlling the supply of components depending on the load and thermal state of the engine is formed. The proposed solution creates the prerequisites for increasing the combustion efficiency of the four-component mixture, reducing the unevenness of its distribution in the combustion chamber and improving the engine performance. The results obtained can be used when designing and modernizing fuel systems of engines operating on multi-component alternative fuel compositions.

Keywords: four-component mixture, two-phase mixture, combustion chamber, engine, mixture formation, fuel supply, mixing of components, dispersion, fuel atomization, multicomponent fuel, fuel system, alternative fuel, combustion process, technical and technological solution.

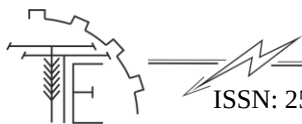
Eq. 3. Fig. 4. Ref. 10.

1. Statement of the problem

Modern trends in the development of internal combustion engines are associated with increasing their fuel efficiency, energy efficiency and environmental safety. One of the promising directions for achieving these indicators is the use of multicomponent fuel mixtures, which make it possible to combine the properties of traditional and alternative fuels and purposefully influence the processes of mixture formation and combustion. At the same time, the use of four-component two-phase mixtures complicates the organization of their supply to the combustion chamber, since the components can differ significantly in density, viscosity, volatility, evaporation temperature and other physicochemical characteristics [1].

Of particular importance is the provision of a stable ratio of components, their uniform distribution in the flow and the formation of a homogeneous mixture in composition under different engine operating modes. Uneven dosing and mixing of components can lead to stratification of the two-phase medium, the formation of droplets of different sizes, local over-enrichment or depletion of the mixture, deterioration of ignition conditions





and a decrease in the completeness of combustion. The consequence of this is an increase in specific fuel consumption, instability of the working process and increased emissions of harmful substances with exhaust gases.

Existing fuel supply systems are mainly oriented to work with single-component or two-component fuels and do not fully take into account the peculiarities of the formation of a four-component two-phase flow. This necessitates the development of a special technical and technological solution that will ensure controlled dosing of individual components, their preliminary mixing, and effective dispersion of the liquid phase and subsequent formation of a homogeneous combustible mixture directly in the feed zone to the combustion chamber [1, 2].

An important task in this case is to determine the rational design of the mixing and spraying units, the parameters of the feed channels, the pressure and temperature of the components, as well as the modes of their introduction into the general flow. It is necessary to ensure the coordinated operation of individual elements of the system with changes in load and engine speed, minimize the possibility of mixture stratification and create conditions for intensive mass and heat transfer in the combustion chamber.

2. Analysis of recent research and publications

The problem of organizing mixture formation in internal combustion engines is the subject of a significant number of domestic and foreign studies. It becomes especially relevant when switching from traditional motor fuels to alternative, mixed and multicomponent fuel compositions. The physicochemical properties of individual components of such fuels can differ significantly in density, viscosity, volatility, heat of vaporization and reactivity, which directly affects the processes of dosing, atomization, evaporation, mixing with air and subsequent combustion.

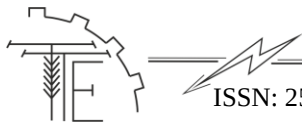
Among domestic researchers, a significant contribution to the development of theoretical and applied foundations of the use of alternative fuels in internal combustion engines was made by A. P. Marchenko, I. V. Parsadanov and O. P. Stokov. In their studies, the use of alternative fuels is considered as one of the promising areas for increasing the energy and environmental performance of diesel engines. The authors systematized the experience of using natural gas, fuels of plant origin, their mixtures, water-fuel emulsions and hydrogen-containing compositions. It is shown that the use of alternative fuels requires coordination of fuel supply parameters with the features of their physicochemical properties and the course of the combustion process [1].

Further development of this direction is traced in the works of S. S. Kravchenko, A. O. Prokhorenko and A. P. Kuzmenko, who studied the adaptation of a gasoline engine to work on mixed fuel with bioethanol. The authors found that a change in the concentration of bioethanol leads to a change in the heat of combustion and the stoichiometric ratio of the fuel-air mixture, and at increased concentrations of the biocomponent there is a need to adjust the fuel supply algorithms. As one of the approaches, the use of information from fuel composition sensors and the oxygen control system in the exhaust gases for adaptive control of the injection duration has been proposed [2]. This is of great importance for multicomponent systems, since it confirms the need not only for mechanical mixing of components, but also for coordinated control of their quantitative ratio depending on the engine operating mode.

The domestic scientific school has also developed approaches to assessing the fuel and environmental efficiency of engines, modeling the thermophysical properties of alternative fuels, and studying working processes when using mixed compositions. At the same time, most of the work is focused mainly on two-component fuel systems, in particular mixtures of traditional fuel with bioethanol, vegetable oils, biodiesel, water, or a gaseous component. Thus, domestic research has created a significant theoretical and experimental basis for the use of alternative fuels, but the issues of simultaneous metered supply and controlled mixing of four components with the formation of a two-phase medium remain insufficiently studied.

A much broader issue of the physics of a multicomponent fuel flare is presented in the works of foreign researchers. One of the leading areas is mathematical modeling of heating and evaporation of droplets. In the works of SS Sazhin, a comprehensive approach to the description of non-stationary heating, heat and mass transfer, and evaporation of fuel droplets has been formed. The author emphasizes that for multicomponent fuels, the use of a simplified single-component representation does not always provide sufficient accuracy, since the components have different volatility and can evaporate with different intensities [3]. Therefore, when forming a four-component mixture, it is necessary to take into account not only its initial composition, but also a possible change in the ratio of components during the heating process and the movement of droplets in the combustion chamber.

An important place among foreign studies is occupied by the works of Youngchul Ra and Rolf D. Reitz. In the model of evaporation of discrete multicomponent fuel flares proposed by them, each drop is



considered as a system consisting of several components with different evaporation characteristics. This approach made it possible to model the change in the composition of the liquid and vapor phases during the development of the fuel jet [4]. In subsequent studies, Y. Ra and RD Reitz extended this approach to modeling the combustion process of multicomponent fuels in internal combustion engines, linking the characteristics of evaporation with chemical kinetics and heat release [5].

Further development of the theory of multiphase injection is associated with the studies of RN Dahms and co-authors, who considered the features of the behavior of multicomponent fuels at high pressures and temperatures typical of modern combustion chambers. It was shown that under certain thermodynamic conditions the traditional idea of clearly separated liquid and gas phases may require clarification, and the nature of mixing significantly depends on the temperature, pressure and composition of the fuel [6]. This provision is especially important when developing a multicomponent two-phase medium supply system, since the parameters at the outlet of the atomizing device determine the subsequent mechanism of formation of the combustible mixture.

A comparative analysis of domestic and foreign research shows that Ukrainian scientific works are mainly focused on the practical adaptation of engines to alternative and mixed fuels, the assessment of their energy and environmental characteristics, and the improvement of fuel supply control systems, while foreign works pay significant attention to the fundamental modeling of multicomponent atomization, evaporation, phase transitions, and chemical kinetics of combustion.

At the same time, the analyzed studies do not sufficiently highlight a comprehensive technical and technological solution that would simultaneously provide separate dosing of the four components, their controlled combination, the formation of a stable two-phase structure, intensive mixing and subsequent feeding of the resulting mixture into the engine combustion chamber. Most of the known works separately study the composition of the fuel composition, spray characteristics, evaporation process or combustion patterns, while the relationship between the design parameters of the feed system and the process of forming a four-component two-phase mixture requires additional scientific justification.

3. Purpose of the study

The purpose of the research is to develop and scientifically substantiate a technical and technological solution for controlled feeding, dosing, mixing and formation of a four-component two-phase mixture in the engine combustion chamber, which ensures the stability of its composition, uniform distribution of components, the necessary dispersion of the liquid phase and increased efficiency of the mixture formation process.

4. Results and discussion

To assess the effectiveness of the proposed technical and technological solution, a computational study of the process of feeding and mixing a four-component two-phase mixture was conducted. The main parameters characterizing the operation of the system were the mixture feeding pressure P , the total area of the passage sections of the mixing unit A , and the mixture temperature T . The mixture homogeneity coefficient K was used as the main criterion for the effectiveness of the process, and the average diameter of the liquid phase droplets D_{32} and the uneven distribution of components were used as additional indicators δ .

The homogeneity coefficient characterizes the degree of equalization of local concentrations of components in the formed two-phase flow. An increase in its value indicates improved mixing conditions and the formation of a more homogeneous combustible mixture [7]. The uneven distribution of components was defined as:

$$\delta = 100 - K. \quad (1)$$

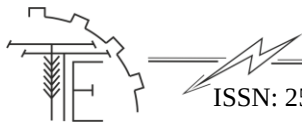
To describe the influence of the main factors on the quality of mixture formation, a calculated regression dependence was obtained:

$$K = 96,2 - 42(P - 0,45)^2 - 28(A - 1,20)^2 - 0,010(T - 60)^2 \quad (2)$$

where P is the supply pressure, MPa; A is the total area of the passage sections, mm²; T is the temperature of the mixture, °C.

The obtained dependence has a pronounced extreme character and indicates the existence of a rational combination of design and operating parameters of the supply system. The maximum calculated value of the uniformity coefficient is 96.2% at a supply pressure of 0.45 MPa, a total area of the passage sections of 1.20 mm² and a mixture temperature of about 60 °C.

Fig. 1 shows the dependence of the homogeneity coefficient of a four-component two-phase mixture on its supply pressure. Analysis of the obtained dependences shows that an increase in pressure from 0.20 to 0.45 MPa



contributes to an increase in the intensity of flow turbulence and improvement of mutual penetration of components. At a temperature of 60 °C, the homogeneity coefficient increases from approximately 93.6 to 96.2%.

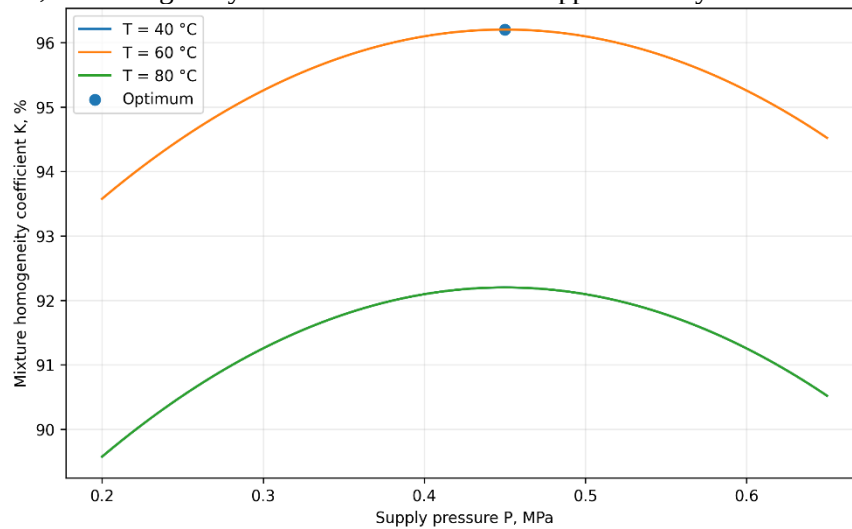


Fig. 1. Effect of supply pressure on mixing quality

Further increase in pressure above 0.45–0.50 MPa does not provide a significant improvement in the mixing process. Within the limits of the adopted model at (P=0.65) MPa the homogeneity coefficient decreases to approximately 94.5%. This confirms the expediency of choosing not the maximum, but the rational supply pressure. Excessive increase in flow rate potentially reduces the duration of the components in the pre-mixing zone and increases hydraulic losses [8].

An important indicator of the process of formation of a two-phase mixture is the dispersion of the liquid phase. The calculated dependence of the average diameter of the droplets on the operating parameters is taken as:

$$D_{\{32\}} = 58 - 42(P - 0,20) + 16(A - 1,20)^2 - 0,12(T - 60), \quad (3)$$

where D_{32} – average droplet diameter according to Sauter, μm .

As can be seen from Fig. 2, increasing the feed pressure contributes to more intensive destruction of the liquid phase and a decrease in the average droplet size. At a temperature of 60 °C, increasing the pressure from 0.20 to 0.45 MPa leads to a decrease in D_{32} from approximately 58 to 47.5 μm . At a pressure of 0.65 MPa, the calculated value is about 39.1 μm .

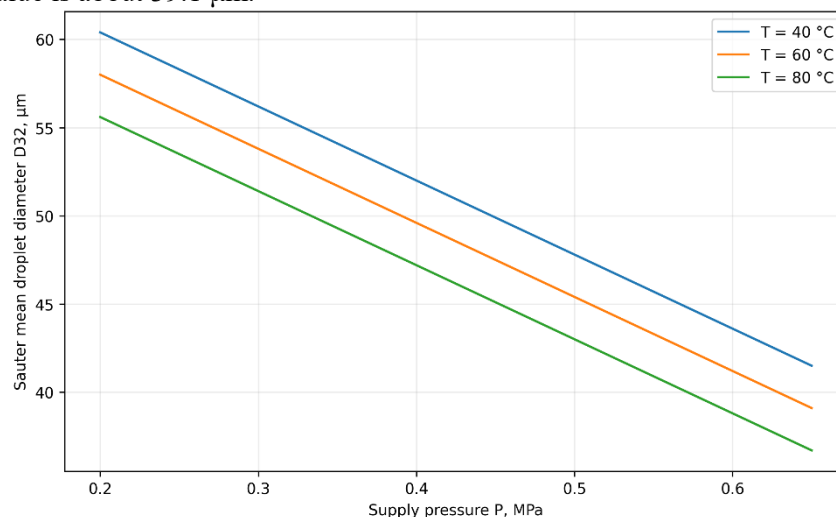
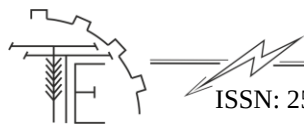


Fig. 2. Effect of supply pressure on liquid-phase dispersion

Reducing the droplet size increases the specific surface area of phase contact, which creates favorable conditions for intensification of heat and mass transfer and acceleration of evaporation of liquid components. At the same time, when choosing the working pressure, it is necessary to take into account not only the dispersion, but also the homogeneity of the mixture and the energy costs to ensure the required feed rate.



Temperature also significantly affects the formation of a two-phase medium. Increasing the temperature helps to reduce the viscosity of liquid components, improve their atomization and intensify evaporation. However, excessive heating can lead to premature evaporation of the most volatile components and change the ratio of liquid and gas phases even before the mixture enters the main zone of the combustion chamber [9]. Therefore, the calculated temperature level of about 60 °C can be considered as a rational range for the adopted modeling conditions.

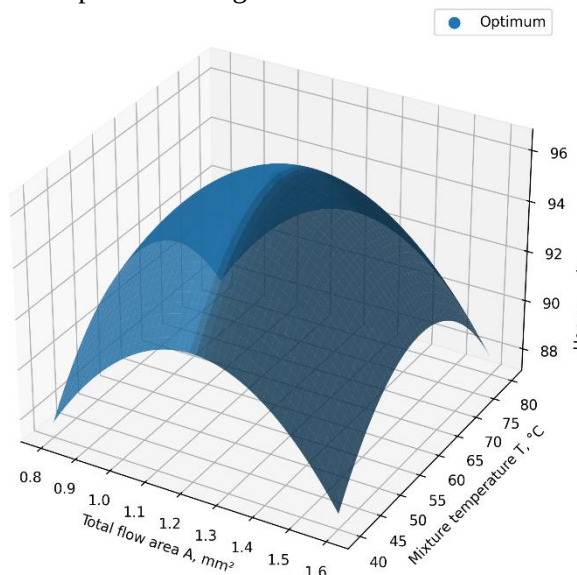


Fig. 3. Response surface of mixing quality

Fig. 3 shows the response surface, which characterizes the joint influence of the area of the passage sections of the mixing unit and temperature on the uniformity coefficient at a pressure of 0.45 MPa. The surface has a pronounced curvilinear shape with a maximum in the central region of the studied factor space. The optimal point corresponds to the values ($A=1.20$ mm² and ($T=60$) °C.

Reducing the area of the flow cross-sections from the optimal value increases the hydraulic resistance of the system and can create uneven supply of individual components. Excessive increase in area, on the contrary, reduces the flow rate and weakens the intensity of turbulent mixing [10]. Thus, the design parameter A must be coordinated with the supply pressure and system performance.

The results of modeling the mixture nonuniformity are shown in Fig. 4. In the rational parameter region, its minimum value is about 3.8%, which corresponds to a homogeneity coefficient of 96.2%. Deviation of pressure or temperature from the optimal region is accompanied by an increase in the nonuniformity of the distribution of components.

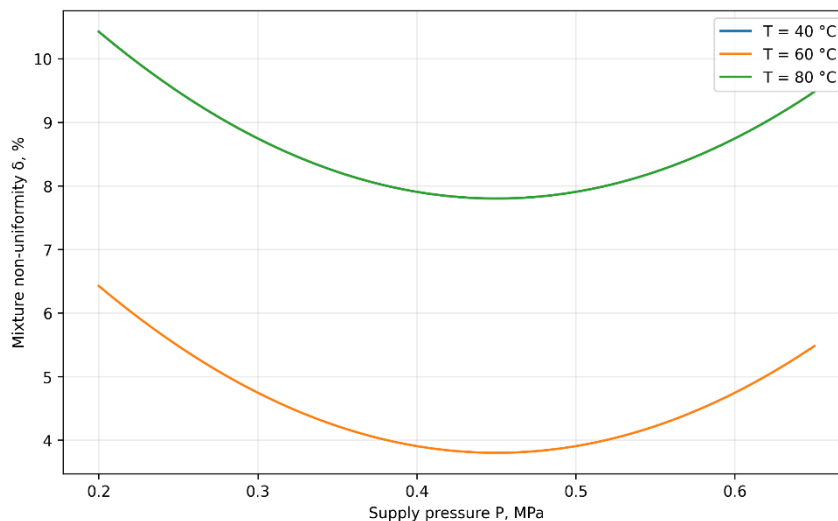
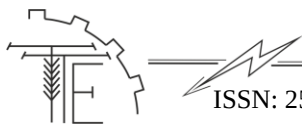


Fig. 4. Effect of supply conditions on mixture non-uniformity

A comprehensive analysis of the obtained dependencies allows us to identify the rational mode of operation of the proposed system: supply pressure – 0.45 MPa; total area of through-sections – 1.20 mm²; mixture temperature – 60 °C; homogeneity coefficient – 96.2%; uneven distribution of components – 3.8%.

The average droplet diameter D_{32} is about 47.5 microns.

The obtained results confirm the feasibility of stepwise formation of a four-component two-phase mixture with controlled dosage of components and intensive mixing in a specially designed mixing unit. Unlike systems in which the components are combined immediately before injection without controlling the flow



structure, the proposed approach allows simultaneously influencing the homogeneity of the mixture, the dispersion of the liquid phase and the stability of the ratio of its components.

5. Conclusions

As a result of the research, a technical and technological solution for feeding, dosing and mixing a four-component two-phase mixture in the engine combustion chamber has been developed and substantiated. The proposed approach is based on the phased introduction of components, their controlled combination, dispersion of the liquid phase and the formation of a homogeneous two-phase flow before entering the combustion zone.

It has been established that the efficiency of mixture formation is determined by the combined effect of the operating and design parameters of the system, among which the feed pressure, mixture temperature and the total area of the passage sections of the mixing unit are of the greatest importance. According to the results of the computational and modeling study, the area of rational parameters has been determined, which ensures maximum mixture homogeneity and a sufficient level of dispersion of the liquid phase.

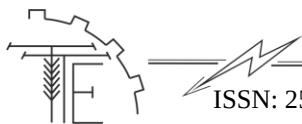
For the adopted modeling conditions, the most favorable combination of parameters corresponds to a supply pressure of 0.45 MPa, a mixture temperature of about 60 °C, and a total area of the passage sections of 1.20 mm². Under these conditions, the mixture homogeneity coefficient is about 96.2%, the uneven distribution of components is about 3.8%, and the average diameter of the liquid phase droplets D_{32} is about 47.5 μm.

It has been established that increasing the feed pressure to a rational level contributes to the intensification of turbulent mixing and a decrease in the average droplet size. At the same time, a further increase in pressure does not provide a proportional improvement in the homogeneity of the mixture and may be accompanied by an increase in hydraulic losses. The temperature factor also has a pronounced effect on the mixture formation process, since it determines the viscosity of liquid components, the intensity of their evaporation and the ratio of phases in the formed flow.

The constructed regression dependences and the response surface confirmed the presence of an extreme region within which the best combination of indicators of homogeneity, dispersion and stability of the two-phase mixture is ensured. This indicates the feasibility of comprehensive coordination of the design parameters of the mixing unit with the modes of component supply.

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РОЗРОБКА ТЕХНІКО-ТЕХНОЛОГІЧНОГО РІШЕННЯ ДЛЯ ПОДАЧІ ТА ЗМІШУВАННЯ ЧОТИРЬОХКОМПОНЕНТНОЇ ДВОФАЗНОЇ СУМІШІ В КАМЕРІ ЗГОРЯННЯ ДВИГУНА

У статті розглянуто питання розробки техніко-технологічного рішення для забезпечення стабільної подачі, дозування та ефективного змішування чотирьохкомпонентної двофазної суміші безпосередньо в камері згоряння двигуна. Актуальність дослідження зумовлена необхідністю підвищення повноти згоряння палива, покращення енергетичних та екологічних показників двигуна, а також забезпечення керованого формування паливоповітряної суміші за змінних режимів роботи. Обґрунтовано функціональну структуру системи подачі компонентів, визначено вимоги до дозувальних, змішувальних і розпилювальних елементів, а також до узгодження витрат, тиску, температури та фазового стану компонентів. Запропоновано принципову схему формування двофазного потоку, яка передбачає поетапне введення складових суміші, попереднє диспергування рідкої фази та подальшу інтенсифікацію змішування в зоні впорскування. Особливу увагу приділено забезпеченню однорідності суміші, стабільності факела, зменшенню розміру крапель і підвищенню швидкості масо- та теплообміну. Методичну основу роботи становлять аналіз процесів сумішоутворення, структурно-функціональне моделювання системи та оцінювання основних режимних параметрів. Розглянуто вплив конструктивних параметрів змішувального вузла, геометрії каналів, співвідношення компонентів та режимів подачі на якість сумішоутворення. Сформовано алгоритм керування подачею компонентів залежно від навантаження та теплового стану двигуна. Запропоноване рішення створює передумови для підвищення ефективності згоряння чотирьохкомпонентної суміші, зниження нерівномірності її розподілу в камері згоряння та покращення робочих характеристик двигуна. Отримані результати можуть бути використані під час проектування та модернізації паливних систем двигунів, що працюють на багатокомпонентних альтернативних паливних композиціях.

Ключові слова: чотирьохкомпонентна суміш, двофазна суміш, камера згоряння, двигун, сумішоутворення, подача палива, змішування компонентів, диспергування, розпилювання палива, багатокомпонентне паливо, паливна система, альтернативне паливо, процес згоряння, техніко-технологічне рішення.

Ф. 3. Рис. 4. Літ. 10.

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