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Methodological Foundations of Training Agricultural Engineers for the Implementation of Alternative Fuels: From Combustion Theory to Thermal Efficiency

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ABSTRACT

The article reveals the conceptual foundations of forming the professional profile of a modern agricultural engineer in the context of the global transformation of the agricultural energy sector. The authors substantiate the necessity of transitioning from a traditional educational model to an innovative methodology, where fundamental knowledge of combustion theory serves as the basis for achieving maximum thermal efficiency of technical systems. The publication provides a detailed analysis of the cause-and-effect chain between the physicochemical specifics of alternative energy sources and the dynamics of in-cylinder processes. It considers a methodological approach that enables future specialists to master the tools for adapting engines to operate on oxygenated fuel compositions through mathematical modeling and experimental research. Particular attention is paid to the algorithmization of practical training in laboratories. The authors describe the logic of a student's actions during bench tests as a process of consistently seeking a compromise between power, fuel economy, and environmental safety. The article proves that an engineer's "green" competence is formed not as an abstract ideology, but as the ability to manage the emission of toxic components through the precise adjustment of fuel supply parameters. The methodological novelty of the work lies in the proposed structure of educational modules, where theoretical content is integrated into practice-oriented case studies. The conditions for creating an interactive educational environment are described, which require specific material and technical equipment to visualize complex thermodynamic phenomena. In conclusion, the authors emphasize that the proposed methodology allows for the training of personnel capable not only of operating multi-fuel systems but also of initiating the implementation of renewable energy at the level of agricultural enterprises.

KEYWORDS

agricultural engineering education, alternative fuels, teaching methodology, combustion theory, thermal efficiency, bench tests, environmental competence, case-study technologies.

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Методологічні засади підготовки агроінженерів до впровадження альтернативних палив: від теорії згорання до теплотехнічної ефективності

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СТАТТЯ

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АНОТАЦІЯ

У статті розкриваються концептуальні засади формування професійного профілю сучасного агроінженера в умовах глобальної трансформації енергетичного сектору сільського господарства. Авторами обґрунтовано необхідність переходу від традиційної моделі навчання до інноваційної методики, де фундаментальні знання з теорії згорання стають базисом для досягнення максимальної теплотехнічної ефективності технічних систем. В публікації детально проаналізовано причинно-наслідковий ланцюг між фізико-хімічною специфікою альтернативних енергоносіїв та динамікою внутрішньоциліндрових процесів. Розглядається методологічний підхід, який дозволяє майбутньому фахівцю через математичне моделювання та експериментальні дослідження опанувати інструментарій адаптації двигунів до роботи на оксигенатних паливних композиціях. Особлива увага приділяється алгоритмізації практичної підготовки у лабораторіях. Автори описують логіку дій здобувача освіти під час стендових випробувань як процес послідовного пошуку компромісу між потужністю, паливною економічністю та екологічною безпекою. У статті доведено, що «зелена» компетенція інженера формується не як абстрактна ідеологія, а як здатність керувати емісією токсичних компонентів через точне налаштування параметрів паливоподачі. Методична новизна роботи полягає у запропонованій структурі навчальних модулів, де теоретичний контент інтегрований у практико-орієнтовані кейси. Описано умови створення інтерактивного освітнього середовища, що потребує специфічного матеріально-технічного забезпечення для візуалізації складних термодинамічних явищ. У підсумку автори наголошують на тому, що запропонована методологія дозволяє готувати кадри, здатні не лише експлуатувати мультипаливні системи, а й виступати ініціаторами впровадження відновлюваної енергетики на рівні аграрних підприємств.

КЛЮЧОВІ СЛОВА

агроінженерна освіта, альтернативні палива, методика викладання, теорія згорання, теплотехнічна ефективність, стендові випробування, екологічна компетентність, кейс-технології.

1. Introduction

The current state of global energy and the aggravation of environmental challenges dictate new rules of the game for the agricultural sector, which is traditionally one of the largest consumers of fossil fuels. In the context of rapidly rising prices for petroleum products and a shortage of traditional energy carriers, the transition to renewable energy sources, in particular to various types of biofuels and oxygenate mixtures, is of strategic importance. However, the introduction of alternative energy carriers into the machine and tractor fleet is not just a matter of logistics or replacing the fluid in the tank. This is a complex engineering challenge that requires a rethinking of the fundamental principles of internal combustion engines. Under such circumstances, the role of the agricultural engineer is transformed: he is no longer just a maintenance specialist and must become an expert in the field of energy efficiency, able to adapt complex technical systems to the changing characteristics of fuels.

The relevance of this problem is enhanced by the fact that most of the existing educational programs are focused on the study of the operating cycles of engines designed for reference diesel fuel. This creates a significant cognitive gap in training: future specialists have a good understanding of the mechanics of the nodes, but often feel helpless in the face of thermodynamic anomalies that arise when using biodiesel, alcohol mixtures, or esters. The physical and chemical differences of these fuels – different viscosities, excellent calorific values, and specific heat-release kinetics – require the engineer to predict changes in the spontaneous ignition delay period and adjust injection phases. Without such skills, the introduction of “green” technologies leads to premature wear and tear of equipment, a drop in power and leveling of the environmental effect, which discredits the very idea of alternative energy in the eyes of farmers.

The scientific and practical value of the proposed methodology lies in the creation of an interactive educational environment that simulates real production scenarios. The use of case methods, such as independent adaptation of farm equipment to biofuels of its own production, allows students to feel responsible for the decisions made. As a result, this provides training of specialists who are able to act as architects of energy independence of agricultural enterprises, combining technical literacy with the principles of sustainable development.

2. Literature Review

In particular, V. Piljavsky et al. [18] thoroughly describe the characteristics of oxygenate-based fuels, which are key to understanding combustion processes. The issues of raw material potential of Ukraine are considered in detail by M. Kyzym et al. [11], emphasizing the relevance of the transition to domestic resources.

The studies of V. Melnyk and M. Hnyp [14] on mixtures of diesel fuel and soybean oil, as well as the work of A. Yakovlieva et al. [23] on camelina oil esters, create the necessary basis for the study of viscosity and density of biocomponents. Practical aspects of the use of additives to improve fuel characteristics are highlighted in the work of N. Domantsevych [3]. The problems of fuel quality in the Ukrainian market and its impact on the operation of engines, which is critical for agricultural engineering, are covered in the articles by O. Sibilyeva [21] and B. Mitkov et al. [16].

The mathematical basis and methods for determining the efficiency of engines on alternative mixtures are presented in the work of I. Gritsuk et al. [6], which offer improved methods for determining fuel consumption. Modeling of these processes for road transport is also the object of research by R. Kolodnytska [9].

The environmental component that forms the “green” competence of an engineer is revealed in the work of A. Marchenko et al. [13], where the relationship of internal combustion engines with the environment is analyzed. The ecological and economic advantages of such production are emphasized by A. Doronin [4], and fuel processing technologies are analyzed by I. Sinkevich and O. Mardupenko [22]. In turn, L. Mertensson [15] and D. Shevchenko [19] provide an overview of best practices for using alternatives for large-scale and mobile equipment.

The transformation of the educational process in the context of informatization is the subject of research by N. Dotsenko [5] and V. Havrysh et al. [7]. The authors emphasize the importance of digital technologies for acquiring professional competencies. T. Lychova [12] and A. Shostachuk [20] focus on the need to restructure engineering education and search for new forms of formation of professional skills of bachelors in agricultural engineering.

A special place in the methodological arsenal is occupied by the case method, the advantages and disadvantages of which are considered by P. Petrychenko [17], and the practical effectiveness as a teaching tool is confirmed by K. Chabanova [2]. The issue of diagnosing equipment in the conditions of enterprises, which is an integral part of practical training, is covered in the work of V. Kashkanov and R. Zhomiruk [8].

Thus, the available scientific and methodological developments create a proper foundation for the synthesis of technical knowledge about alternative fuels with innovative teaching methods, which is the main task of this article.

3. Problem Statement

However, the methodological component of engineering personnel training, which would integrate this knowledge into a holistic system of professional action, remains fragmentary. There is an urgent need to create such a teaching methodology, where the theory of combustion is not an abstract discipline, but acts as a living tool for achieving thermal efficiency. The student must learn to see complex molecular transformations from the fuel consumption figures, understand the role of intramolecular oxygen in oxidation processes and be able to mathematically justify the need to change the fuel supply parameters for each specific type of mixture.

The purpose of this article is to develop and substantiate the methodological foundations for the training of agricultural engineers, which would be based on a deep synthesis of theoretical knowledge and experimental skills. We propose the concept of "end-to-end research", where the training begins with the analysis of the fuel microstructure, goes through the stage of mathematical modeling of work processes and ends with the practical optimization of the engine on the test bench. This approach allows students to form not only professional, but also "green" competence – a conscious ability to minimize environmental risks through engineering excellence.

4. Methods and Materials

The study is based on an axiological approach, which considers the transition to alternative fuels not just as a technical necessity, but as a value in the context of sustainable development and energy independence of the agricultural sector. The methodology is based on the principle of unity of theory and practice, where deep knowledge of thermodynamic processes becomes a tool for solving real operational problems.

The training of an agricultural engineer is revealed through the prism of system analysis. The object of research here is not a separate discipline, but a holistic model of a specialist who is able to work in the system "man – machine – alternative fuel – environment". This means that the methodology is not limited only to the description of the engine, but covers the entire cycle of energy transformation: from the chemical composition of fuel (bioethanol, biodiesel) to the thermal efficiency of its combustion.

The methodological core of the article was interdisciplinary integration. On the one hand, the methodology of physicochemical analysis is used to understand how changes in the molecular structure of fuel affect the speed of flame propagation.

The methodology also includes a comparative and deductive analysis. The study is carried out from general to specific: first, the general laws of combustion of hydrocarbons are analyzed, and then, through deduction, specific conditions of operation of the engine on mixed fuels are deduced. An important element was the criterion approach, when the effectiveness of the preparation is evaluated by the ability of the future engineer to minimize heat loss and harmful emissions during the operation of a real object.

5. Results and Discussion

The fundamental basis of the methodology for training engineers in the agricultural sector is the understanding that any change in the component composition of the fuel leads to the transformation of the thermodynamic cycle of the engine. A comparative analysis of traditional diesel fuel of petroleum origin, methyl esters of fatty acids (biodiesel) and alcohol compounds reveals a number of critical differences that determine the thermal efficiency of power plants.

A key determinant of alternative fuels lies in their molecular structure. Unlike petroleum diesel, which consists mainly of a mixture of hydrocarbons, biodiesel and alcohols belong to the class of oxygenates – fuels containing bound oxygen. In biodiesel, the oxygen content reaches 11%, and in ethanol – more than 34% [19].

From a methodological point of view, it is important to focus the attention of students of a modern university on the "energy paradox": the presence of oxygen contributes to the completeness and quality of combustion (which reduces CO and soot emissions), but it also causes a decrease in the heat of combustion. Since oxygen is already in a chemical bond, it does not participate in the exothermic reaction as an external oxidizer, which leads to a drop in the calorific value of biodiesel by about 10–12% compared to its oil counterpart, and ethanol – almost twice. For an agricultural engineer, this means the need to adjust the volume of injected fuel to achieve an identical power [23].

The next aspect that requires descriptive analysis is viscosity and temperature characteristics. Biodiesel is characterized by significantly higher kinematic viscosity and density. In real operating conditions of agricultural machinery, this leads to an increase in the diameter of the droplets when spraying fuel with an injector. Larger droplets have higher kinetic energy and are able to penetrate deeper into the combustion chamber, but they evaporate more quickly [14].

Alcohol compounds have the opposite tendency – their low viscosity and high volatility contribute to the rapid formation of the fuel-air mixture, but low lubricating properties create a risk of premature wear of precision parts of fuel equipment [1]. The training of specialists should include the analysis of these risks through the prism of the reliability of technical systems.

A special place in the comparative analysis should belong to the cetane number (a criterion that characterizes the flammability of diesel fuels). Biodiesel usually demonstrates a higher ability to spontaneously ignite compared to mineral fuels. This causes a shorter ignition delay period, which ensures a smooth increase in pressure in the cylinder and reduces dynamic loads on the parts of the crank mechanism [21].

On the other hand, alcohol mixtures have an extremely low cetane number, which makes their spontaneous combustion in the diesel cycle problematic. In the educational process, this should serve as a basis for studying methods of initiating combustion: the use of promoter additives, dual fuel systems, or increasing the compression ratio.

A separate methodological block in the educational process in the training of agricultural engineers should be the study of the physical and chemical stability of mixtures. Mixtures are subject to phase stratification at low temperatures or when moisture enters. A modern specialist in agricultural engineering should be aware that alternative fuels are a "living" system that requires special storage and preparation conditions, including the use of depressor additives and emulsifiers to ensure the homogeneity of the mixture [15].

Thus, a detailed description of physical and chemical properties allows you to move from an abstract study of fuel to a practical prediction of the thermal efficiency of a power plant, which is the ultimate goal of the methodology for training a modern engineer.

The process of professional training in the context of working with alternative fuels is based on the transformation of the student from a user of equipment to a researcher of energy processes. At the center of such an educational model is the ability of a specialist to interpret physical and chemical transformations in the engine cylinder as a controlled technological process.

At the stage of theoretical training, the emphasis shifts from a simple statement of the fact of ignition to the analysis of cause-and-effect relationships. The future engineer learns to understand that the use of oxygenates radically changes the "biological clock" of the engine. When working with biodiesel, the student analyzes the effect of reducing the preparatory period: due to the high cetane number, the fuel begins to burn almost instantly after appearing in the chamber [18].

In the educational context, this becomes the basis for the study of mechanical reliability: a lower delay means a smooth increase in pressure, which should be interpreted as a way to extend the life of the crank mechanism parts. In contrast, the consideration of alcohol impurities teaches the specialist to predict the opposite effect – the "delay" of ignition due to intense evaporation, which requires the engineer to be able to compensate for this failure with parametric settings of the system.

The educational model should require the specialist to clearly differentiate how the fuel behaves in different stages of combustion. The study of the rapid (kinetic) combustion of oxygenates allows us to understand the phenomenon of "internal oxidation". When the future agricultural engineer analyzes the diffusion stage, where air oxygen usually does not have time to get into the center of the fuel flare, he discovers the main advantage of alternative fuel: oxygenate "helps" itself to burn completely [3].

This forms ecological thinking in the student not as an abstract concept, but as a result of a controlled chemical reaction. He realizes that the clean exhaust of the equipment is a consequence of the fact that oxygen was present in the molecular structure of the fuel he chose even before the injection.

The final element of preparation is the formation of the ability to see the entire cycle holistically. The training is aimed at ensuring that the specialist can recognize the risks associated with the transition to alternative energy carriers. Since oxygenates have a lower energy density, a modern agricultural engineer must understand that in order to maintain power, the volume of fuel in the cylinder increases, and this can lead to an expansion of the afterburning phase.

From the point of view of professional competence, this means the ability to calculate the heat balance. The student learns to simulate the situation: if the combustion phase shifts too far from the top dead center, the energy will not turn into useful work, but will be used to overheat the exhaust tract. This approach teaches the future specialist not only to observe the operation of the engine, but to act as a "conductor" of heat flows, adapting the technical system to the complex energy parameters of alternative fuels.

The mathematical justification for the training of agricultural engineers is based on the ability to transform the chemical composition of fuel into specific energy indicators. In the educational process, this transition is considered through two key vectors: energy density and oxygen balance.

The calculations are based on the principle of additivity, when the total calorific value of the mixture is determined as the weighted average value of its components. Because alternative impurities (oxygenates) have lower carbon and hydrogen content compared to petroleum diesel, their lower calorific value reduces the overall energy yield per unit mass of fuel.

For a future specialist, this means a transition from quantitative fuel measurement to energy measurement. The student must master the method of calculating the "energy deficit" of biofuels, which usually ranges from 10% to 35%. Understanding this indicator allows us to justify the need to increase the injection volume to preserve engine torque, which is critical for performing heavy field work [9].

The second aspect of the mathematical basis is the calculation of the theoretically required amount of air. Here, agricultural engineers discover mathematical confirmation of the superiority of oxygenates: since the fuel already contains part of the oxygen in its structure, it requires less outside air to completely oxidize.

From a methodological point of view, this radically changes the approach to engine regulation. If traditional fuel requires about 14.3 kg of air per 1 kg of fuel, then for alcohol mixtures, this value can be half as much. Mathematical analysis shows that when using alternative fuels, the coefficient of excess air increases automatically [6].

The final stage of the analysis is the assessment of the calorific value of the working mixture in the cylinder itself. It is important to teach the future agricultural engineer to see that although alternative fuels are less energy-intensive, they allow you to "fit" more fuel molecules into the same cylinder volume due to less air demand. As a result, the overall heat output of the cycle remains stable. Such a mathematical conclusion forms a specialist's confidence in the technical feasibility of switching to "green" fuels, supported by accurate calculations of the thermodynamic balance.

At the final stage, the methodology of practical training of agricultural engineers on the introduction of alternative fuels should be based on the algorithm of a direct comparative experiment. This allows students to implement theoretical calculations through visualized data of thermal efficiency. The test process usually begins with the basic calibration of the power plant on standard diesel fuel. The applicant records the "reference response" of the engine: power, torque and specific energy consumption. This forms the future specialist's skills in working with control and measuring equipment and understanding of the standard parameters of a serviceable unit [8].

The next step is to dynamically monitor the change in the state of the system during the transition to oxygenates. The student has the opportunity to independently change the fuel composition and bring the engine to a stable thermal regime. The main analysis tool here is an electronic pressure indicator, which allows you to see in real time how the chemical nature of the fuel changes the "architecture" of combustion: from the moment of ignition to the end of the afterburning phase.

The key point of training is experimental optimization. The student does not just record the power drop due to the low calorific value of the alternative fuel, but actively intervenes in the settings, for example, changes the injection advance angle. The goal is to find such a moment of heat release at which the mechanical work of the expansion of gases will be maximum [10]. It teaches the engineer how to manage energy efficiency, not just observe it.

The algorithm ends with an analytical synthesis. The applicant compares the obtained characteristics and builds an energy balance. The result is the understanding that energy losses in fuel can be partially or fully compensated by the accuracy of engineering settings. This approach forms professional readiness for the introduction of "green" technologies, based on objective data from bench tests. As a fundamental part of the "green" thinking of a modern specialist, the environmental component of the educational process should be provided in the training of a modern agricultural engineer. In the context of the introduction of alternative fuels, exhaust gas toxicity analysis becomes a tool for assessing the quality of the work process in the cylinder. The student must learn to interpret the composition of exhaust gases as a "diagnosis" of the efficiency of engine settings [4].

The main aspect that future agricultural engineers are investigating is a significant reduction in smoke (soot) and carbon monoxide emissions when working on biofuels. The presence of intramolecular oxygen in oxygenates allows the fuel to burn out even in those zones of the combustion chamber where the access of atmospheric air is limited. In the educational process, this demonstrates the advantage of "green" technologies: the student has the opportunity to make sure that the use of renewable energy sources allows the equipment to be operated in enriched modes without harming the environment.

Particular attention should be paid to the critical analysis of nitrogen oxide emissions. Since oxygenates contribute to the intense release of heat, the temperature in the combustion chamber may increase, which leads to the undesirable formation of nitrogen oxides. For the agricultural engineer, this becomes a professional challenge: he must learn to balance between high thermal efficiency and environmental safety, applying gas recirculation methods or correction of injection angles [13].

The training methodology should include the use of gas analyzers during bench tests, which allows students to build a holistic picture:

– the student compares the "carbon footprint" of petroleum, diesel and biofuels, taking into account the closed cycle of carbon circulation in nature;

– the future agricultural engineer learns to justify that although alternative fuels may be more expensive in cost, their implementation reduces environmental risks and the cost of gas treatment systems.

This approach transforms environmental knowledge from theoretical postulates into practical tools for an engineer. A university graduate begins to perceive toxicity not as an external factor, but as a controllable parameter that directly depends on their professional skills in setting up thermal engineering systems.

The design of the educational process in the training of future agricultural engineers should be based on the logic of a gradual transition from microscopic chemical processes to macroscopic indicators of machine units. At the same time, the theoretical foundation should become a tool for ensuring practical energy efficiency management.

At the initial stage, attention should be focused on the thermochemical foundations of energy conversion. The descriptive and theoretical components dominate here, covering about two-thirds of the study time. The specialist should study in detail the mechanisms of oxidation of hydrocarbons and the specifics of oxygenates. It is important that at this stage the student does not just memorize formulas, but learns to see the energy potential of the fuel through its elementary composition [11]. The practical part of this block is reduced to analytical calculations of calorific value, which prepares the basis for understanding the future "energy deficit" of alternative mixtures.

The next stage of preparation should be devoted to thermodynamics and intra-cylinder processes. Here the distribution of hours becomes parity: theory and practice are combined in the format of research modeling. Applicants study the physics of combustion phases, analyzing how the viscosity and density of biofuels change the geometry of the fuel flare. The main methodological technique is to work with virtual indicator diagrams, where a specialist can experiment with pressure and temperature parameters, without risking the integrity of real equipment. This forms the ability to predict – a key quality of a modern engineer.

At the final stage of training, the main emphasis should be on working in laboratories with bench equipment. The student personally optimizes the real engine: he varies the injection angles, monitors the toxicity of gases and builds curves of thermal efficiency.

Such a distribution of the educational load – from in-depth theory at the start to almost complete practical autonomy – can ensure the transformation of knowledge into stable professional competence. The general balance of time (approximately 40% of theory and 60% of practice) allows you to train an agricultural engineer who not only knows about the existence of alternative fuels, but also owns methods of their effective adaptation to complex technical systems of agricultural production.

An important stage in the transition from academic accumulation of knowledge to imitation of real professional activities of agricultural engineers is the introduction of case methods into the educational process. This allows the student to find himself in a situation where he has to make a responsible decision in the conditions of multifactorial analysis, which is typical for modern agricultural production [12].

In the educational process, the case method is implemented through the consideration of specific production tasks, where the technical parameters of the engine are inextricably linked with the economy and ecology. For example, students are offered a scenario: "Transfer of the tractor fleet of the farm to mixed biodiesel fuel of its own production".

Within this case, the student must go through three stages of analysis:

1) diagnostic – assessment of the technical condition of the available equipment and its compatibility with methyl esters (analysis of sealing materials, the condition of fuel equipment);

2) technological – calculation of the necessary adjustments (change in the injection advance angle, installation of additional separators and heating systems);

3) energy – forecasting changes in thermal efficiency and fuel consumption, taking into account the lower calorific value of the mixture.

The descriptive model of the case method allows you to move away from formal problem solving to problem discussion [2]. Students are divided into groups (for example, "engineers", "environmentalists", "economists"), where each party must justify the feasibility of introducing alternative fuels.

For "engineers", the challenge is to compensate for the loss of power and ensure the stability of the combustion phases. For "environmentalists", the priority is to minimize emissions of nitrogen oxides, which often occur with intensive combustion of oxygenates. It is important for "economists" to assess the payback of equipment modernization.

The case method forms the so-called "project reflection" in the future agricultural engineer [17]. He begins to perceive the theory of combustion and thermal efficiency not as abstract sections of a textbook, but as tools for solving a real crisis or optimizing a business.

This technique educates a specialist capable of critical thinking: he realizes that the introduction of alternative fuels is not just an energy substitute, but a complex engineering strategy that requires the integration of fundamental knowledge and practical experience.

An important foundation on which the theory of combustion is transformed into the practical competence of an agricultural engineer during training is the material and technical base of a modern university. The organization of a modern educational and research space requires a move away from static visual aids to the creation of an interactive test site that allows simulating real operating conditions of equipment on alternative fuels [20].

The main element of material support for the process of studying the characteristics of alternative fuels should be a training bench equipped with a system for quick replacement of fuel compositions. This equipment will allow students not only to observe the operation of the engine, but to conduct comparative tests of petroleum diesel and different types of oxygenates (biodiesel, alcohol mixtures) in identical load modes [5]. The stand should be aggregated with common models of autotractor engines, which provides a connection between the training and the real machine and tractor fleet of the agricultural sector.

To reveal the internal processes of energy conversion, the laboratory of a modern university should be equipped with electronic induction means, which includes:

– high-precision pressure sensors in the cylinder and fuel line, allowing you to visualize combustion phases on the monitor screen;

– fuel flow meters of increased accuracy, capable of recording small changes in the flow rate of energy carriers with different densities;

– multi-component gas analyzers and smoke meters that transform the environmental aspect from a theoretical concept into digital data on the composition of exhaust gases.

Since alternative fuels have specific physical and chemical properties, the necessary minimum are devices for operational analysis of fuel quality:

– viscometers and hydrometers to control the viscosity and density of mixtures, which is critical in the study of mixture formation processes;

– equipment for diagnostics of fuel equipment, which allows students to study the effect of alternative fuels on the condition of precision parts.

An important component of an effective educational process is software for mathematical modeling of thermodynamic processes. This will allow conducting virtual experiments before the start of real tests, comparing theoretical calculations of thermal efficiency with the actual data obtained at the stand [7].

Such comprehensive support turns the laboratory from a place of passive study of the structure into a center of engineering analysis. Students will have the opportunity to go all the way: from the preparation of the fuel mixture and the analysis of its properties to the optimization of the engine duty cycle based on the experimental data obtained.

It should also be emphasized that the transition to multi-fuel systems in agricultural engineering is associated with several technical and operational barriers, which become central objects of research in the process of training specialists. Training should be aimed at ensuring that the future engineer perceives these difficulties not as obstacles, but as tasks that require a comprehensive thermal engineering solution.

The main difficulty is the instability of the physical and chemical properties of different types of fuel. When switching from oil diesel to biofuels or alcohol mixtures, there is a problem of a mismatch of injection characteristics. Due to the higher viscosity of biodiesel, the load on the fuel pump increases, and a change in the ignition delay period leads to a violation of the combustion phases [16].

During the training, students should acquire skills in developing adaptation algorithms that allow the engine to “recognize” the type of fuel by indirect indicators and instantly change the supply parameters to maintain thermal efficiency.

In addition, multi-fuel systems face the chemical aggressiveness of alternative components. Ethanol and methyl esters of fatty acids are able to dissolve rubber seals and cause corrosion of non-ferrous metals in the fuel line. The tendency of biofuels to oxidation during long-term storage can lead to the formation of deposits in the injectors [14]. Therefore, the methodology for training agricultural engineers should provide for the study of modern composite materials and fluororubbers resistant to aggressive environments. An important component of the educational process should also be the mastery of technologies for the use of antioxidants and stabilizing additives that ensure the homogeneity of fuel and the purity of fuel equipment.

It should be noted that the transition to multi-fuel modes is quite often accompanied by a drop in energy efficiency and an increase in emissions of nitrogen oxides due to the higher intensity of combustion of oxygenates [22]. Therefore, students should master the method of thermal balancing of the engine. The use of exhaust gas recirculation systems and two-stage injection allows you to level the temperature peaks in the cylinder. Thus, the future engineer learns to create “flexible” energy systems, where environmental safety is not sacrificed to power. End-to-end process: from materials science to digital combustion control. This approach prepares an agricultural engineer to work in conditions of real energy uncertainty, where the ability to quickly adapt equipment becomes his main professional advantage.

6. Conclusions

In modern conditions of the development of the fuel and energy complex, understanding the physical and chemical features of oxygenates (the presence of bound oxygen, changes in viscosity and cetane number) is critical for the correct prediction of engine operation. Comparative analysis shows that the lower calorific value of alternative fuels requires the skills of mathematical modeling of the energy balance from an agricultural engineer to compensate for the “energy deficit” of the mixture.

The teaching methodology turns the student into a researcher who, through the analysis of indicator diagrams and heat release characteristics, learns to optimize the phases of combustion. The transition to multi-fuel systems requires from the engineer not only knowledge of mechanics, but also the ability to adapt the injection parameters to the specifics of the kinetics of combustion of alternative compounds.

The assessment of the toxicity of exhaust gases in the educational process ceases to be a formal measurement, turning into a tool for diagnosing the completeness of combustion. The use of oxygenates allows the future engineer to practically implement the concept of "green" energy, minimizing soot and carbon monoxide emissions, provided that the temperature regime of the cycle is properly managed.

Effective structuring of training modules with an emphasis on practical activities and the implementation of case methods allows you to simulate real production challenges. Solving cases regarding the transfer of the fleet of equipment to biofuels of its own production forms a systematic vision for students, where technical solutions are consistent with the economic feasibility and available material and technical support of laboratories.

A debatable analysis of the difficulties of the transition to multifuel (corrosive aggressiveness, instability of mixtures, changes in the spontaneous ignition delay) indicates the need to train personnel capable of working with intelligent engine adaptation algorithms.

Thus, the proposed methodology provides training of a new generation of agricultural engineer who has the tools for the effective operation of equipment on alternative energy carriers, contributing to energy independence and environmental sustainability of the agricultural sector.

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