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INFLUENCE OF MULTIPHASE FUEL INJECTION ON THE TECHNICAL AND ECONOMIC INDICATORS OF A TRANSPORTATION DIESEL ENGINE

Purpose. Selection of parameters of multiphase fuel injection using mechanical fuel pumps for engines of ground transport vehicles and estimated impact of parameters of the fuel injection process on the technical and economic indicators of a forced transport diesel engine.

Methodology. Scientific research is based on the use of comparative numerical experiment methods. Modern numerical methods are used to model the process of diesel fuel injection, the processes of mixture formation and combustion, with the assessment of the load on the parts of the crank-and-connecting mechanism (CCM) from the gas pressure forces. Based on the results of the calculations, a compromise option is chosen that provides acceptable fuel economy, the minimum rate of pressure increase during fuel combustion, and the minimum load on the CCM parts.

Findings. It was established that when using multiphase fuel injection in a diesel engine of type 6Ch15/15, it is possible to reduce the rate of pressure increase during combustion by almost 1.8 times and to reduce the maximum force from the action of gas ticks on the piston by 16.3 %. In the future, this enables to create reserves to increase the level of engine forcing and improve its performance.

Originality. The research made it possible to study the influence of multiphase fuel injection on the stiffness of the combustion process and technical and economic indicators of a highly forced diesel engine. The obtained results allow formulating recommendations for choosing a multiphase fuel injection strategy (the number of injections, their duration and the amount of fuel for each injection).

Practical value. Changing the conditions of mixture formation and combustion made it possible to reduce the rigidity of the working process of a highly forced diesel engine, reduce the load on the parts of the crank-and-connecting mechanism from gas pressure forces, and improve the operational performance of the internal combustion engine.

Keywords: *diesel engine, fuel injection, cyclic supply, rate of pressure increase during combustion, work process*

Introduction. An increase in the level of boosting of modern diesel engines, especially transport engines that operate with a significant share of transient processes of unloading - loading, requires a comprehensive analysis of the injection, mixture formation, and combustion processes to improve their technical and economic performance [1, 2].

The inevitable increase in the maximum combustion pressure with the liter capacity of a diesel engine increasing is the main factor limiting the level of boost [3, 4].

The use of the concept of multiphase fuel injection allows one to effectively influence the processes of mixture formation and combustion and reduce the rate of pressure growth during combustion [5, 6]. As a result, this leads to a decrease in the rigidity of the combustion process and a reduction in the load on the parts of the crank mechanism [7, 8].

The choice of rational values of the number of fuel injections, injection advance angles, volume of pilot and main dose of diesel fuel is a promising area of research to improve the technical and economic performance of diesel engines, especially with the increase in their level of boost [9, 10].

Literature review. Improvements in the design of fuel equipment for modern diesel engines allow up to 9 fuel injections per cycle (Common Rail systems) [11, 12]. At the same time, it is possible to reduce the rigidity of the working process, reduce the noise and vibration level of the engine, improve its environmental performance (primarily to reduce exhaust smoke and nitrogen oxide emissions) while ensuring high fuel efficiency [13, 14].

The strategy of multiphase fuel injection implemented by the MTU company on its diesel engines is shown in the form of graphs in Table 1 [15].

The injection rate determines when and how much fuel is injected into the cylinder [15]. In order to reduce emissions and fuel consumption, the MTU fuel injection system development strategy divides the fuel injection sequence into three distinct phases (Table 1). The injection start time, duration and amplitude are determined according to the engine performance map.

The main injection phase supplies fuel to provide engine power output. The pre-injection phase initiates pre-combustion to provide controlled fuel combustion during the main injection phase. This reduces nitrogen oxide emissions as the harsh combustion prevents high peak temperatures and stresses on crank components. The next phase, after the main injection phase, reduces emissions of solid particles. This improves the process of mixing fuel and air during the late combustion phase to increase the temperature in the combustion chamber, which also contributes to soot oxidation [15, 16].

According to the multiphase fuel injection strategy proposed by the authors of works [17, 18], when using two-phase injection, there is already a significant effect on changing the characteristics of heat generation and the rate of increase in combustion pressure (Table 2).

As can be seen from the above results, the implementation of the fuel pre-injection strategy can be successfully applied to reduce the rate of increase in combustion pressure (Table 2).

The study by the authors of [17, 18] found that the supply of a pilot dose of fuel can reduce the rate of increase in combustion pressure by 43 %. When using this strategy, it is necessary to reduce the injection time to ensure identical engine power. Double fuel pre-injection is more effective (reducing the rate of increase in combustion pressure by up to 61.5 %).

The main disadvantage of Common Rail systems is the complexity of the design, high cost of components and the presence of an electronic control unit with a significant number of sensors.

Table 1

The strategy of multiphase fuel injection implemented by MTU

Fuel injection sequence	Pre-injection	Main injection	Post injection
Binding to TDC	before TDC	after TDC	

Table 2

Changes in the characteristics of heat release and the rate of increase in combustion pressure at multiphase fuel injection

Parameter	Fuel injection mode	
	Without pre-injection	With pre-injection
Characteristics of heat emission	Two peaks (before and after TDC)	One peak (near TDC)
Change in pressure growth rate	0.62 MPa/deg. of c.r.	0.38 MPa/deg. of c.r.

The development and use of modern electromagnetic interference generation systems and other devices can negatively affect the performance of electronic control units of internal combustion engines [19, 20].

In the case of high-powered diesel engines of special-purpose land transport vehicles, such shortcomings do not allow the effective use of Common Rail systems for such engines.

In the case of high-powered diesel engines of special-purpose land transport vehicles, such shortcomings do not allow the effective use of Common Rail systems for such engines.

Therefore, for diesel engines of land transport vehicles, it is necessary to create multiphase fuel injection systems that are resistant to external electromagnetic and detonation effects.

One of the ways to ensure efficient and reliable operation of a diesel engine of a land transport vehicle is to use multiphase fuel injection systems without electronic control [21]. Such systems, despite their shortcomings, make it possible to reduce the rigidity of the work process with an increase in the level of boost and to operate in extremely difficult (extreme) conditions that are typical for land transport vehicles.

Unsolved aspects of the problem. As can be seen from the results of the literature review, the development of a strategy for multiphase fuel injection using mechanical plunger-type fuel pumps and the selection of rational injection process parameters that will ensure efficient and trouble-free operation of the diesel engine in extreme conditions is an extremely important scientific and practical task.

The purpose of the article. The aim of the study is to select the parameters of multiphase fuel injection using mechanical plunger-type fuel pumps for engines of land transport vehicles and to calculate the influence of fuel injection process parameters on the technical and economic performance of a forced transport diesel engine.

To achieve this goal, the following tasks were solved in the study:

- to conduct a literature review on modern methods for reducing the rigidity of the combustion process by improving the fuel injection process;
- to select the parameters of the fuel supply process to ensure multi-stage fuel injection using mechanical plunger-type fuel pumps;
- using calculation methods to evaluate the influence of the main factors (number of fuel injections, injection advance angles, volume of pilot and main dose of diesel fuel) on the parameters of the operating process of a forced diesel engine when operating at rated power;
- to evaluate the impact of multiphase fuel injection on the technical and economic performance of a diesel engine;
- to develop scientific and practical recommendations for the selection of rational fuel supply parameters that will ensure efficient and reliable operation of the diesel engine with increasing level of boost.

The objects of study are the processes of injection, mixture formation and combustion in the cylinder of 6Ch 15/15 transport engine operating at rated power with $N_e = 223$ kW at the crankshaft speed of $n = 2{,}600\ \text{min}^{-1.}$

The investigated engine has a Hesselman combustion chamber with the implementation of a volumetric method of mixture formation and a centrally located nozzle; the sprayer has 7 nozzle holes.

Description of the research methodology. Brief technical characteristics of the 6Ch 15/15 diesel engine are given in Table 3.

The modeling of ICE work processes in the presented work was carried out according to the methodology developed at the ICE of KHNADU.

This methodology involves:

- preparation of initial data for mathematical modeling (design and operating parameters ICE);
- selection and justification of the model of sprayed fuel plume development;
- selection and justification of the model of air charge movement in the combustion chamber;
- interaction of the atomized fuel plume with the air charge in the combustion chamber;
- interaction of the atomized fuel plume with the combustion chamber wall;
- modeling the process of mixture formation;
- modeling the fuel combustion process.

The basic equations of the mathematical models are given below.

The work considers the zonal excess air coefficient, i.e., the division of the plume into separate zones during injection.

In this case, the criteria are used to assess the course of the mixture formation process α_M, α_V.

The indicator α_M is the ratio of the amount of fuel air used for combustion at the analyzed moment of the combustion process to the amount of air required for the combustion of fuel vapors present at this moment in the CC

$$\alpha_{M_i} = \frac{G_{B\_C}}{V_{B\_N}},$$

where

$$G_{B\_C} = (x_i - x_{i-1}) B_c \cdot L_0;$$

$$G_{B\_N} = (\sigma_i - x_{i-1}) B_c \cdot L_0.$$

The indicator α_M takes into account the impact of injection and evaporation processes, the nature of fuel and air flow, the impact of the CC wall on evaporation, chemical kinetics, heat exchange, etc., and is used to assess the quality of the mixture process. The indicator α_V is the ratio of the total volume of fuel flares and their carried away vapors to the volume of the CC at each moment of time.

Table 3

Brief technical characteristics of the diesel engine 6Ch 15/15

No.	Parameter	Units change	Value
1	Rated power, N_e	kW	223
2	Rotation frequency corresponding to the rated power mode, n	min^{-1}	2,600
3	Cylinder diameter, D	mm	150
4	Piston stroke, S	mm	150
5	Degree of compression, ε	–	15.8
6	The order of operation of the cylinders	–	1l-1r-2l-2r-3l-3r
7	Working volume	l	15.9
8	Overall dimensions ($L \times W \times H$)	mm	791 × 1,150 × 748

$$\alpha_V = \frac{\sum_{n=1}^{i=x} V_{fi}}{V_c}.$$

It is assumed that the trajectory of an equivalent droplet is given in the parametric form

$$\bar{r}(t) = \left\{ \begin{array}{l} x = x(t) \\ y = y(t) \\ z = z(t) \end{array} \right\},$$

where $x(t)$ is the coordinate of the equivalent droplet along X-axis; $y(t)$ is the coordinate of the equivalent droplet along the Y-axis; $z(t)$ is the coordinate of the equivalent droplet along the Z-axis.

The notation of vectors in the fuel plume is shown in Fig. 1.

For the arc of length ℓ, shown in Fig. 4, we can write

$$\ell(t) = \int_0^t \left|\bar{r}(t)\right| dt;$$

$$\left|\bar{r}(t)\right| = \sqrt{[x'(t)]^2 + [y'(t)]^2 + [z'(t)]}.$$

Accordingly

$$\bar{\rho}(t) = \ell(t) \cdot \mathrm{tg}\alpha.$$

Then the equation of the surface of the torch can be described by

$$\bar{R}(t) = \bar{r}(t) + \bar{\rho}(t)(\bar{n}\cos\psi + \bar{\beta}\sin\psi); \quad 0 \le \psi \le 2\pi,$$

where α is the half angle at the top of the fuel flare; ψ is the angle of change of the vector $\bar{\rho}(t)$ in the normal plane; $\bar{n}$ is the normal vector; β is the binormal vector; $R(t)$ is the vector describing the surface of the fuel flare.

The normal and binormal vectors for each section under consideration are located in a plane perpendicular to the tangent drawn to the arc ℓ and serve to orient the vector $\rho(t)$.

The combustion process (due to the very short duration of fuel combustion in a diesel engine) was described by the following relationship

$$\mathrm{CH}_n + \frac{\alpha_s}{\varphi} \cdot (\mathrm{O}_2 + 3.78\mathrm{N}_2) \rightarrow \mathrm{CO}_2 + $$
$$+ \frac{n}{2} \cdot \mathrm{H}_2\mathrm{O} + \alpha_s \left(\frac{1}{\varphi} - 1 \right) \cdot \mathrm{O}_2 + \frac{3.78\alpha_s}{\varphi} \cdot \mathrm{N}_2.$$

The force of gas pressure on the piston was calculated according to the following relationship, kN

$$P_g = (p_c - p_0) \cdot F_p \cdot 10^3,$$

where p_c is the current pressure in the cylinder; p_0 is the atmospheric pressure; F_p is the piston area.

Presentation of the main material and scientific results. In the presented work, taking into account the design features of the fuel equipment of the 6Ch 15/15 diesel engine, the possibility of implementing multiphase injection in the following form (supply of a pilot dose of fuel and the base dose) was considered. A series of comparative calculations (18 variants) was carried out for different volumes of the pilot and main fuel doses, injection advance angles, and injection durations (Table 4).

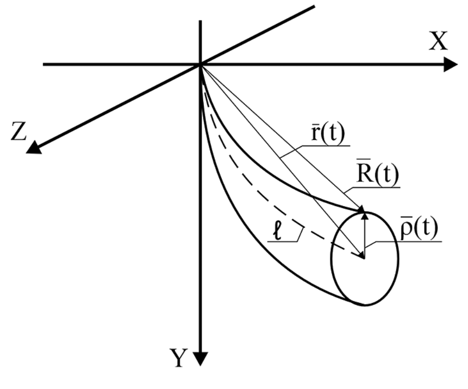


Fig. 1. Designation of vectors in a fuel plume

The best results were obtained for the calculation variant when the pilot dose (20 % of the main dose) is supplied at 20 degrees of c.r. to TDC, and the duration of the main dose is (15 degrees of c.r., of them – 10 degrees of c.r. – after TDC).

The results of the comparative computational study to determine the effect of multiphase fuel injection on the technical and economic performance of the 6Ch 15/15 diesel engine are as follows.

The change in pressure in the engine cylinder for the standard and upgraded (multiphase injection) variants is shown in Fig. 2.

As can be seen from the results shown in Fig. 2 for the design variant without fuel pre-injection (Fig. 2, *a*), the maximum combustion pressure reaches 7.99 MPa, at angle 4 degrees of c.r. – after TDC. For the variant with a pilot fuel dose (Fig. 2, *b*), a decrease in the maximum combustion pressure to 6.68 MPa at angle 7 degrees of c.r. – after TDC, which indicates a decrease in the rigidity of the combustion process.

The change in the average cylinder temperature for the standard and upgraded variants is shown in Fig. 3.

As can be seen from the results shown in Fig. 3 for the design variant without preliminary fuel injection (Fig. 3, *a*), the maximum cycle temperature reaches 1,790 K, at an angle of 27 degrees of c.r. – after TDC. For the variant with a pilot fuel dose (Fig. 3, *b*), a decrease in the maximum temperature to 1,743 K at angle 20 degrees of c.r. – after TDC, which indicates a decrease in the rigidity of the combustion process.

The change in the rate of heat release in the engine cylinder for the standard and upgraded variants is shown in Fig. 4.

As can be seen from the results shown in Fig. 4 for the design variant without preliminary fuel injection (Fig. 4, *a*), the heat release rate reaches values of 0.0455 1/deg. At the same time, the bulk of the heat is released to the TDC. For the variant with the pilot fuel dose (Fig. 4, *b*), a change in the nature of the heat release rate is observed (the maximum heat release rate decreases and approaches the TDC), which also indicates a decrease in the rigidity of the combustion process.

The results of the comparative computational study are summarized in Table 5.

As can be seen from the results shown in Table 5, the use of multiphase fuel injection allows one, almost without reducing the effective power, to improve the operating conditions of a forced diesel engine.

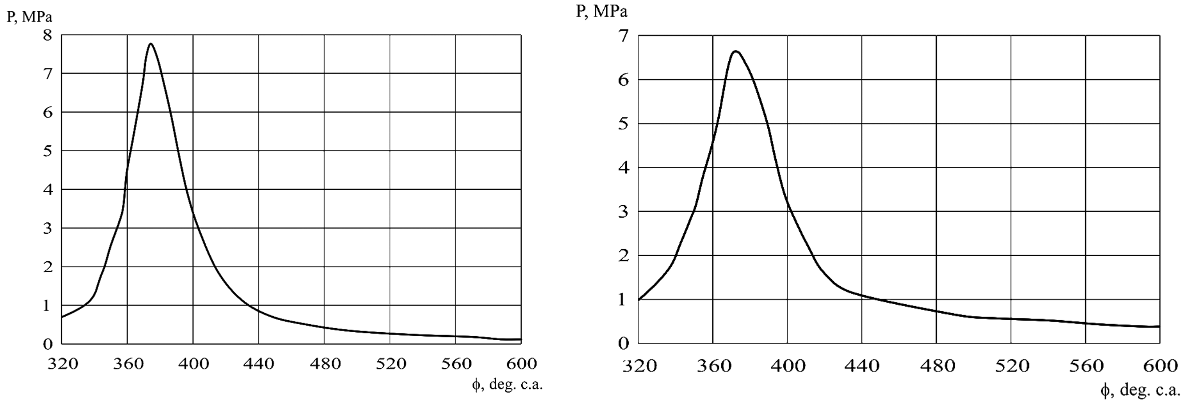
The upgraded version shows an increase in specific effective fuel consumption by 1.5 % and, accordingly, a decrease in effective efficiency by 1.5 %.

Table 4

Main parameters of the fuel injection process

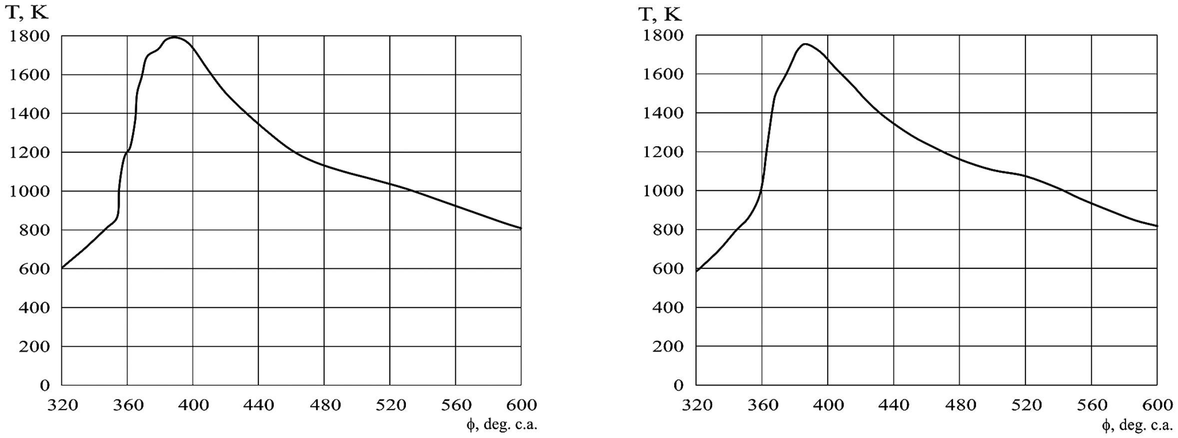
No.	Volume of the pilot dose, %	The angle of advance of the pilot dose injection, deg. of c.r. to TDC	The angle of advance of the main dose injection, deg. of c.r. to TDC
1	20	50	27
2	15	45	23
3	10	40	23
.....	.....	.....	.....
15	20	20	23
16	20	20	11
17	20	20	7
18*	20	20	5

* the best calculated variant.



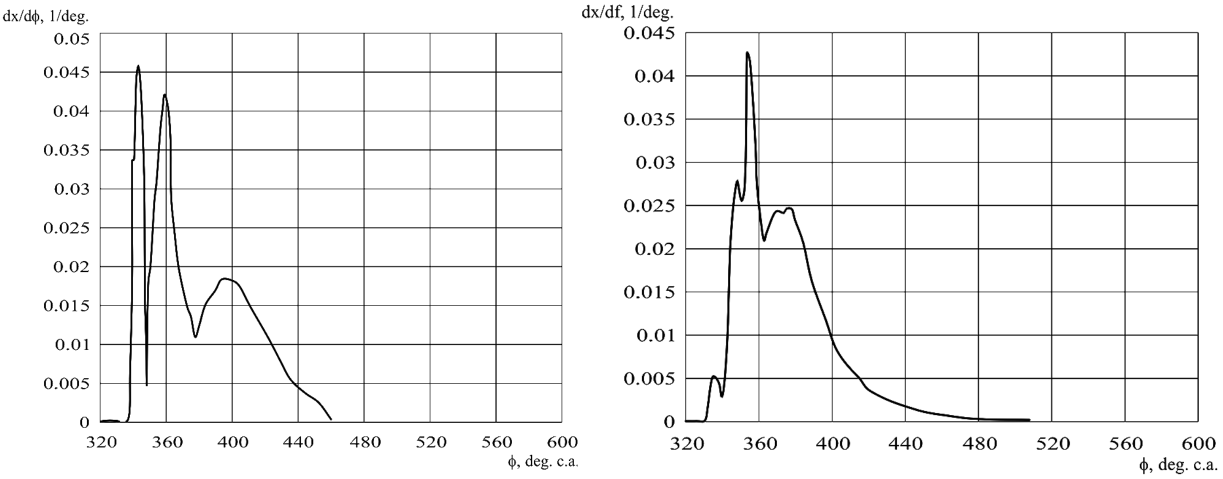
a *b*

Fig. 2. Changes in engine cylinder pressure for the standard (a) and upgraded (b) versions



a *b*

Fig. 3. Changes in the average temperature in the engine cylinder for the standard (a) and upgraded (b) variants



a *b*

Fig. 4. Changes in the rate of heat generation in the engine cylinder for the standard (a) and upgraded (b) variants

This is due to the peculiarities of the processes of mixture formation and combustion when using multiphase fuel injection. These effects can be compensated for by increasing the pilot fuel injection rate (the fuel system needs to be upgraded), optimizing the mixture and combustion processes, and reducing heat loss to the combustion chamber walls.

The upgraded version has a 16.3 % reduction in maximum combustion pressure, which is explained by the peculiarities of the main fuel injection (injection continues after the top dead center (TDC) with a pull 10 degrees of c.r. At the same time, there is also an increase in the angle of maximum pressure from 4 to 7 degrees of c.r. – after TDC.

This reduction in the maximum combustion pressure and increase in the maximum pressure angle has a positive effect on reducing the load on the crank mechanism parts (primarily on the crankshaft bearings).

Table 5

Summarized results of the comparative design study

Parameter	Units change	Basic	Upgraded
Power, N_e	kW	223	221.5
Specific effective fuel consumption, g_e	kg/kW · h	0.26	0.264
Effective efficiency, h_e	%	32.5	32
Maximum combustion pressure, P_z	MPa	7.99	6.68
Maximum cycle temperature, T_z	K	1,790	1,743
Maximum pressure angle, f_z	deg. of c.r. – after TDC	4	7
Maximum pressure growth rate, dp/df_i	MPa/deg	0.33	0.184
Maximum force from the action of gas pressure on the piston, F_p	kN	143.05	119.65

As a result, the use of a multiphase fuel injection strategy for the upgraded version has reduced the rate of increase in combustion pressure by almost 1.8 times and reduced the maximum force from the action of gas pressure on the piston by 16.3 %.

This makes it possible to further obtain reserves to increase the boost level of the 6Ch 15/15 engine and improve its performance.

Conclusions. The aim of the work has been achieved. The effect of multiphase fuel injection using mechanical plunger-type fuel pumps for engines of land transport vehicles was investigated and the influence of fuel injection process parameters on the technical and economic performance of a forced transport diesel engine was calculated.

A literature review on modern methods for reducing the rigidity of the combustion process by applying a multiphase fuel injection strategy, which is expected to have a significant effect on changing the characteristics of heat generation and the rate of increase in combustion pressure, has been carried out.

On the basis of the review, the characteristics and limits of rational parameters of the fuel supply process for the implementation of multistage fuel injection using mechanical plunger-type fuel pumps are selected.

The study, with the help of the used computational model at operation at rated power, established:

- the influence of the number of fuel injections (for mechanical plunger-type fuel pumps, it is advisable to use two injections);
- when studying the injection advance angles of the pilot dose in the range from 25 to 70 degrees of c.r. – to TDC – the best results were obtained for the design variant with an injection advance angle of 20 degrees of c.r. – to TDC;
- the effect of the volume of the pilot fuel dose on the parameters of the working process of a forced diesel engine when operating at rated power (variants from 5 to 30 % of the main dose were studied – it is advisable to use a pilot dose of 20 %).

The influence of multiphase fuel injection on the technical and economic performance of a diesel engine has been evaluated (according to the results obtained for the best design variant, it was possible to reduce the rate of increase in combustion pressure by almost 1.8 times with a slight deterioration in fuel efficiency (within 1.5 %).

According to the results of the comparative computational study, to ensure the efficient operation of a forced diesel engine of type 6Ch 15/15 with an increase in the level of boost, it is recommended to use multistage fuel injection with a pilot dose within 20 % of the main dose and an injection advance angle of – 20 degrees of c.r. – to TDC.

It is also necessary to improve the design of cylinder-piston group parts to ensure efficient operation ICE with an increase in the level of boost [22, 23] and to develop new approaches to the analysis of complex heat and mass transfer processes in power equipment using modern numerical methods [24].

In the further work, the authors plan to conduct a comparative experimental study on a test bench with the 6Ch 15/15 engine to verify the approach proposed in this paper and improve the fuel supply process of the investigated engine with an increase in the level of boost.

References.

1. Timoshevsky, B.G., Tkach, M.R., & Shalapko, D.O. (2016). Improved performance characteristics of diesel engines with additional water. *Water transport*, (2), 24-28.

2. Liu, Z., Yuan, X., Tia, J., Han, Y., Li, R., & Gao, G. (2018). Investigation of Sectional-Stage Loading Strategies on a Two-Stage Turbocharged Heavy-Duty Diesel Engine under Transient Operation with EGR. *Energies*, *11*(1), 69. MDPI AG. https://doi.org/10.3390/en11010069.

3. Mata, C., Rojas-Reinoso, V., & Soriano, J.A. (2023). Experimental determination and modelling of fuel rate of injection: A review. *Fuel*, *343*, 1-21. https://doi.org/10.1080/23311916.2020.1724848.

4. Nabi, M.N., Rasul, M.G., Arefin, M.A., Akram, M.W., Islam, M.T., & Chowdhury, M.W. (2021). Investigation of major factors that cause diesel NO_x formation and assessment of energy and exergy parameters using e-diesel blends. *Fuel*, *292*, 120298. https://doi.org/10.1016/j.fuel.2021.120298.

5. Wang, Z., Wyszynski, M.L., Xu, H., Abdullah, N.R., & Piaszyk, J. (2015). Fuel injection and combustion study by the combination of mass flow rate and heat release rate with single and multiple injection strategies. *Fuel Processing Technology*, *132*, 118-132. https://doi.org/10.1016/j.fuproc.2014.11.024.

6. Djamari, D.W., Idris, M., Paristiawan, P.A., Abbas, M.M., Samuel, O.D., Soudagar, M.E.M., ..., & Veza, I. (2022). Diesel Spray: Development of Spray in Diesel Engine. *Sustainability*, *14*(23), 15902. MDPI AG. https://doi.org/10.3390/su142315902.

7. Xu, L., Xue-Song, B., Ming, J., Yong, Q., Xinqi, Q., & Xingcai, L. (2018). Experimental and modeling study of liquid fuel injection and combustion in diesel engines with a common rail injection system. *Applied Energy*, *230*, 287-304. https://doi.org/10.1016/j.apenergy.2018.08.104.

8. Nguyen, T.Q., Le, H., & Dunin, A.Y. (2023). Influences of injector geometry parameters on fuel injection characteristics and parameters of a diesel engine. *Transport and Communications Science Journal*, *74*, 530-543. https://doi.org/10.47869/tcsj.74.4.12.

9. Wang, G., Yu, W., Yu, Z., & Li, X. (2022). Study on Characteristics Optimization of Combustion and Fuel Injection of Marine Diesel Engine. *Atmosphere*, *13*(8), 1301. https://doi.org/10.3390/atmos13081301.

10. Ahmed, M.B., & Mekonen, M.W. (2022). Effects of Injector Nozzle Number of Holes and Fuel Injection Pressures on the Diesel Engine Characteristics Operated with Waste Cooking Oil Biodiesel Blends. *Fuels, 3*(2), 275-294. https://doi.org/10.3390/fuels3020017.

11. Mata, C., Rojas-Reinoso, V., & Soriano, J.A. (2023). Experimental determination and modelling of fuel rate of injection: A review. *Fuel*, *343,* 127895. https://doi.org/10.1016/j.fuel.2023.127895.

12. Sujesh, G., & Ramesh, S. (2018). Modeling and control of diesel engines: A systematic review. *Alexandria Engineering Journal*, *57*(4), 4033-4048. https://doi.org/10.1016/j.aej.2018.02.011.

13. Zhao, W., Yan, J., Gao, S., Lee, T.H., & Li, X. (2022). The combustion and emission characteristics of a common-rail diesel engine fueled with diesel, propanol, and pentanol blends under low intake pressures. *Fuel*, *307*, 121692. https://doi.org/10.1016/j.fuel.2021.121692.

14. Emiroğlu, A.O. (2019). Effect of fuel injection pressure on the characteristics of single cylinder diesel engine powered by butanol-diesel blend. *Fuel*, *256*, 115928. https://doi.org/10.1016/j.fuel.2019.115928.

15. Zwehl, D. (2014). *Electronic engine management: Key technology for intelligent engine control*. Retrieved from https://www.mtu-solutions.com/content/dam/mtu/download/technical-articles/3100661_MTU_General_WhitePaper_EngineManagement_2014.pdf/_jcr_content/renditions/original./3100661_MTU_General_WhitePaper_EngineManagement_2014.pdf.

16. Kech, J., Willmann, M., Gorse, P., & Boog, M. (2011). *MTU White Paper Fuel Injection*. Retrieved from www.mtu-online.com.

17. Punov, P., & Evtimov, T. (2015). Combustion optimization in a modern diesel engine by means of pre-injection strategy. *SCIENTIFIC PROCEEDINGS XXIII INTERNATIONAL SCIENTIFIC-TECHNICAL CONFERENCE "trans & MOTAUTO '15"*, (pp. 88-91). ISSN 1310-3946.

18. Jaipuria, A., & Lakshminarayanan, P.A. (2022). Prediction of the Rate of Heat Release of Mixing-Controlled Combustion in a Common-Rail Engine with Pilot and Post Injections. In: Modelling Diesel Combustion. *Mechanical Engineering Series*. Springer, Singapore. https://doi.org/10.1007/978-981-16-6742-8_10.

19. Liu, J., Yu, M., Yu, Z., & Nicolosi, V. (2023). Design and advanced manufacturing of electromagnetic interference shielding materials. *Materials Today*, *66*, 245-272. https://doi.org/10.1016/j.mattod.2023.03.022.

20. Gao, G. Q., Lu, M., & Yang, Z. P. (2013). Electromagnetic interference analysis of magnetic resistance sensors inside a projectile under complex electromagnetic environments. *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/418/1/012082.

21. Prokhorenko, A. O., Kravchenko, S. S., & Sweetsky, E. I. (2022). The method of organizing two-stage fuel injection into a diesel cylinder using hydromechanical fuel equipment. *Internal combustion engines*, (2), 25-32. https://doi.org/10.20998/0419-8719.2022.2.04.

22. Wróblewski, P. (2023). The Theory of the Surface Wettability Angle in the Formation of an Oil Film in Internal Combustion Piston Engines. *Materials*, *16*(11), 4092. https://doi.org/10.3390/ma16114092.

23. Wróblewski, P. (2023). Reduction of friction energy in a piston combustion engine for hydrophobic and hydrophilic multilayer nanocoatings surrounded by soot. *Energy*, *271,* 126974. https://doi.org/10.1016/j.energy.2023.126974.

24. Rogovyi, A., Korohodskyi, V., Khovanskyi, S., Hrechka, I., & Medvediev, Y. (2021). Optimal design of vortex chamber pump. *Journal of Physics: Conference Series, 1741*(1), 2021. https://doi.org/10.1088/1742-6596/1741/1/012018.

Вплив багатофазного впорскування палива на техніко-економічні показники транспортного дизельного двигуна

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Мета. Вибір параметрів багатофазного впорскування палива з використанням механічних паливних насосів плунжерного типу для двигунів наземних транспортних машин і розрахункова оцінка впливу параметрів процесу впорскування палива на техніко-економічні показники форсованого транспортного дизельного двигуна.

Методика. Наукове дослідження засноване на використанні методів порівняльного чисельного експерименту. Сучасні чисельні методи використовуються для моделювання процесу впорскування дизельного палива, процесів сумішоутворення та згоряння, з оцінкою навантаження на деталі кривошипно-шатунного механізму від сил тиску газів.

Результати. Установлено, що при використанні багатофазного впорскування палива у дизельному двигуні типу 6Ч 15/15 вдається зменшити швидкість зростання тиску при згорянні майже у 1,8 рази та знизити максимальне зусилля від дії тику газів на поршень на 16,3 %. У подальшому це дає змогу створити резерви для збільшення рівня форсування двигуна та поліпшити його експлуатаційні показники.

Наукова новизна. Дослідження дозволило вивчити вплив багатофазного впорскування палива на жорсткість процесу згоряння й техніко-економічні показники високо форсованого дизельного двигуна. Отримані результати дозволили сформувати рекомендації з вибору стратегії багатофазного впорскування палива (кількість упорскувань, їх тривалість і обсяг палива за кожне упорскування).

Практична значимість. Зміна умов сумішоутворення та згоряння дозволила знизити жорсткість робочого процесу високо форсованого дизельного двигуна, зменшити навантаження на деталі кривошипно-шатунного механізму від сил тиску газів і поліпшити експлуатаційні показників ДВЗ.

Ключові слова: *дизельний двигун, упорскування палива, циклова подача, швидкість зростання тиску при згорянні, робочий процес*

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