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Experimental and Computational Optimization of Cold-Start Performance in 4DTNA Series Diesel Engines Under Variable Environmental Conditions

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ABSTRACT

This study aimed to optimize the cold-start performance of 4DTNA series diesel engines at low ambient temperatures through experimental testing and computational modelling. A total of 77 valid cold-start experiments were conducted using a specially designed test bench and processed with the Approximation_LSM software to develop a six-factor second-degree polynomial regression model. Key independent variables included fuel supply, fuel injection advance angle, equivalent cold-start temperature, crankshaft speed, glow plug preheating time, and glow plug tip temperature. The results indicated that optimal adjustment of fuel cycle parameters and glow plug heating significantly reduced cold-start time and exhaust smoke emissions. Simulation of cold engine oil resistance using an external inertial load proved accurate without requiring climate chambers. The validated regression model can be integrated into electronic control unit (ECU) algorithms for adaptive parameter adjustment, improving engine reliability and environmental performance in harsh conditions. Future work should assess the effects of alternative fuels and additives.

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1. INTRODUCTION

In the operating conditions of diesel engines, it is important to ensure reliable start-up in various climatic conditions, especially at low temperatures. The quality of diesel start-up significantly deteriorates at low temperatures, which is conditioned upon several factors: increased viscosity of engine oil, deterioration of fuel combustion conditions due to its low evaporation rate and lower values of pressure and temperature in the cylinder achieved by compression at an equivalent speed, and deterioration of the energy properties of the starting battery [1]. One of the key tasks for improving engine efficiency is to optimise the parameters of the fuel supply and start-up system, which allows improving the starting characteristics and reducing the smoke content of exhaust gases. Some researchers [2] considered the effect of low temperature and increased torque resistance of the crankshaft of an automobile diesel engine on fuel consumption. The paper uses the common least squares method for processing experimental data and constructing regression dependencies in the form of quadratic polynomials.

Despite significant advances in improving the design of diesel engines and exhaust cleaning systems, the problems associated with starting engines in difficult environmental conditions remain relevant. The study of engine starting capacity requires a comprehensive approach that combines experimental methods with mathematical modelling. This allows investigating the interaction of key factors that affect the start-up process, and finding optimal settings to ensure reliable start-up under various conditions.

The problem of starting characteristics of diesel engines in low-temperature conditions is relevant in the field under study, since it directly affects the environmental performance and efficiency of engines. Some reports [3] investigated the optimization of fuel supply system parameters, emphasising that this significantly affected the reduction of pollutant emissions during cold start-up. Their results indicated the possibility of improving the environmental performance of diesel engines by improving the starting characteristics. Some researchers [4] focused on the effect of temperature on diesel engine performance, which allowed the development of recommendations for improving start-up in difficult conditions. They argued that adapting the engine to changing temperature conditions was crucial to ensure reliable operation. The use of new fuel atomization technologies significantly increased start-up efficiency at low temperatures [5]. Their research demonstrated how innovative approaches can improve the performance of diesel engines. Reducing the volume of air supplied to the engine can significantly reduce the smoke content of the exhaust, especially during start-up [6]. This aspect was important for the implementation of environmental regulations. Other researchers [7] analyzed the effect of humidity on starting characteristics, emphasising the need to adapt the control system in conditions of high humidity. This study pointed to a link between atmospheric conditions and launch efficiency.

Some researchers [8] drew attention to the choice of diesel engine oil, emphasising its importance in winter, which directly affected the lubricating properties. Their findings demonstrated how proper oil selection can improve engine starting performance. Other researchers [9] investigated the integration of electronic control systems that helped to optimise the start-up process depending on the ambient temperature. They argued that such systems could significantly improve the reliability and efficiency of diesel engines. Other reports [10] highlighted the efficiency of using new materials to manufacture launch system components, which had a positive impact on their reliability. This study pointed out the importance of manufacturing innovation to improve engine performance. Other researchers [11] considered algorithms that allowed predicting engine starting characteristics in various climatic conditions. Their research has provided valuable information for optimising the performance of diesel engines at variable temperatures. Other researchers [12] emphasised the importance of modelling start-up processes, which allowed studying in detail the impact of various factors on their effectiveness. This research contributed to the development of more accurate methods for analysing the starting characteristics of diesel engines. Despite numerous studies, there are still gaps that require further investigation, in particular, optimising the integration of all factors affecting starting characteristics, and creating a comprehensive model for predicting engine behaviour in difficult start-up conditions.

The purpose of the study was to improve the process of starting diesel engines of the 4DTNA series at low temperatures by reducing the time to achieve start-up while optimising energy consumption and reducing the number of emissions of harmful substances with exhaust gases during start-up by experimental and computational research and analysis of the regression model of the start-up time parameter. The research objectives are in the following:

(i) To develop a methodology for conducting a multi-factor experimental cold start study, design and create a research physical model for implementing the study according to the developed methodology.
(ii) To prepare a laboratory stand and fully implement the multi-factor experimental research plan.
(iii) To investigate the influence of each control factor on the effectiveness of the selected rationalization parameters.

2. METHODS

In terms of the volume of existing traffic, cargo and passenger cars, minivans, and minibuses have a significant share in the total use of all types of transport. Therefore, the choice of a 2-litre 4-cylinder diesel engine of the 4DTNA series developed by the Kharkiv Machine Building Design Bureau as an object of research is quite acceptable, considering the simultaneous interest in diesel engines in the 6-cylinder version [13].

The test stand created for starting tests of this diesel engine was placed in the laboratory of Kharkiv National Automobile and Highway University. Since the process of starting a diesel engine is complex, the choice of independent parameters that affect its starting capacity was substantiated (**Figure 1**).

Figure 1. Engine compartment of the MA33 research vehicle with 4DTNA1 diesel engine.

The original brands of Ukrainian automobile 4-cylinder diesel engines of the 4DTNA series are diesel 4DTNA1 with a two-valve cylinder head and diesel 4DTNA2 with a four-valve cylinder head. The main technical characteristics of the 4DTNA1 and 4DTNA2 diesels are obtained from the draft technical specification for the development project "Creation of a subcompact automobile diesel engine with a capacity of 150-175 HP dual-use".

As shown in **Table 1**, the more boosted 4DTNA2 diesel engine has an explained lower compression ratio, which is reduced from 18.5 to a promising 17-17.5 units. It was this compression ratio that was recreated by the experimental physical model, which was designed based on a 4DTNA vortex-chamber diesel engine.

Table 1. Comparative characteristics of 4DTNA1 and 4DTNA2 diesel engines.

Parameter	Diesel brand	
	4DTNA1	**4DTNA2**
Designation	4DTNA-1 8.8/8.2	4DTNA-2 8.8/8.2
Number of cylinders	4	4
Cylinder location	Inline	Inline
Diesel displacement, cm3	2,988	2,988
Cylinder diameter, mm	88	88
Piston stroke, mm	82	82
S/D ratio	0.93	0.93
Compression ratio	18.5	17.5
Combustion chamber	Undivided, open	Undivided, open
Fuel supply system	Direct action of the NRM type	Common Rail type
Method of filling cylinders with air	Turbocharged, adjustable	Turbocharged, adjustable
Method for increasing the fill factor	Supercharged air cooler	Supercharged air cooler
Number of valves per cylinder	2	4
Number and layout of camshafts	One, top location	One, top location
Rated power, kW (HP)	73.5 (100)	84.6 (115)
HP speed at Rated Power, 4ac-1	4,200	4,200
Maximum torque, N·m	191	245
Speed of rotation of HP at maximum torque, min-1	2,000-2,300	1,800-2,100
Idling speed, min-1	Min. 800; Max. 4,500	Min. 600; Max. 4,500
Minimum specific fuel consumption g/(kW·h) (g/(HP·h))	230 (170)	210 (150)
Environmental level (without diesel particulate filter and urea injection)	Euro-4	Euro-4

The diagram of the specified test bench at Kharkiv National Automobile and Highway University, Ukraine, intended for starting tests of the physical model "Slobozhansky Diesel", is shown in **Figure 2**, and the general view of the components of this stand is shown in **Figures 3 and 4**. The scientific and technical approach to creating an effective starting system for diesel engines is based on experimental tests of the physical model of the engine, following the mathematical plan of the experimental study.

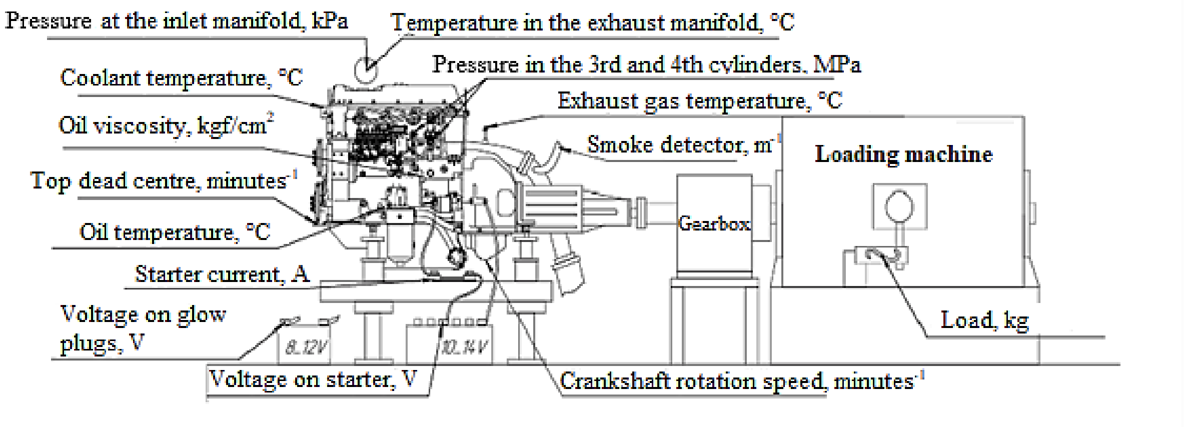


Figure 2. Physical model measurement scheme for studying the starting characteristics of the 4DTNA Ukrainian automobile diesel engine.

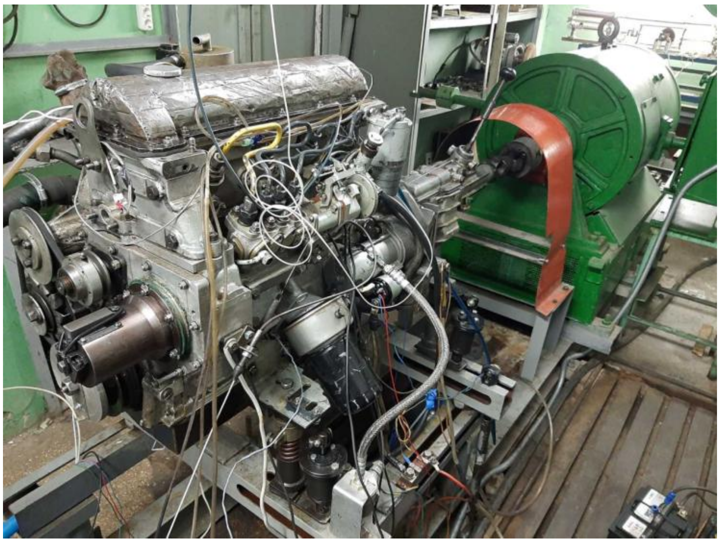


Figure 3. Laboratory stand at the Kharkiv National Automobile and Highway University for starting tests of the 4DTNA diesel engine.

Figure 4. The control panel of the Kharkiv National Automobile and Highway University laboratory stands for starting tests of the 4DTNA diesel engine.

To process the results of the experimental study, the Approximation_LSM software was used, which helped to obtain a polynomial dependence of the cold start time on the specified six independent parameters. Statistical evaluation of the results was performed to confirm the adequacy of the obtained polynomial dependence following the Fischer criterion. As a result of the analysis of the obtained polynomial dependence of the cold start time of an automobile diesel engine, the fuel supply parameters were optimised, in particular, the fuel supply in the cycle and the injection advance angle. Optimisation was carried out in terms of ambient temperature, preheating time, glow plug temperature, and crankshaft torque. The following equations were used in the study (see equations (1-3)):

$$f(x_i) = a_{(z=z_0)} + \sum_{i=1}^{n} a_{(z=z+1)} x_i + \left[\sum_{i=1}^{n} \sum_{j=1}^{n} a_{(z=z+1)} x_i x_j\right] + \left\{\sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{l=1}^{n} a_{(z=z+1)} x_i x_j x_l\right\} \quad (1)$$

where $f(x_i)$ is the response function, the parameter that will be used to optimise the process; a is the weight coefficient of the independent factor, a member of the polynomial; z is the order number of the member of the polynomial ($z_0 = 1$); xi is the independent factor (i=1 n n); n is the number of independent factors.

$$\begin{aligned}\tau_{start} &= a0 + a1Q_C + a2\theta_{FIAT} + a3t_{CS.eqv} + a4n_{SS} + a5t_{g.p} + a6\tau_{g.p} + \\ &+\left[a11{Q_C}^2 + a22{\theta_{FIAT}}^2 + a33{t_{CS.eqv}}^2 + a44{n_{SS}}^2 + a55{t_{g.p}}^2 + a66{\tau_{g.p}}^2\right] + \\ &+[a12Q_C\theta_{FIAT} + a13Q_Ct_{CS.eqv} + a14Q_Cn_{SS} + a15Q_Ct_{g.p} + a16Q_C\tau_{g.p} + \\ &+a23\theta_{FIAT}t_{CS.eqv} + a24\theta_{FIAT}n_{SS} + a25\theta_{FIAT}t_{g.p} + a26\theta_{FIAT}\tau_{g.p} + \\ &+a34t_{CS.eqv}n_{SS} + a35t_{CS.eqv}t_{g.p} + a36t_{CS.eqv}\tau_{g.p} + \\ &+a45n_{SS}t_{g.p} + a46n_{SS}\tau_{g.p} + a56t_{g.p}\tau_{g.p}\} \quad (2)\end{aligned}$$

where τ_{start} is the cold start time of the diesel engine; Q_C is the fuel supply; θ_{FIAT} is the fuel injection advance angle; $t_{CS.eqv}$ is the equivalent cold start temperature; n_{SS} is the crankshaft scroll speed; $t_{g.p}$ is the glow plug preheating time; $\tau_{g.p}$ is the heating temperature of the glow plug tip; (a0, a1, …, a66) are the coefficients of the polynomial that determine the effect of the corresponding variables on the cold start time (equation (3)).

$$F = \frac{S_{adeq^2}}{S_{exp^2}}, \quad (3)$$

where F is the Fischer's criterion; Sadeq2 is the variance of adequacy of the regression model; Sexp2=0.516 s2 is the variance of the experimental estimate of the measured cold start time parameter obtained from three repeated experiments with the values of factors in the middle of the range of variation (degrees of freedom for estimating variance of 2).

This determined how well the model describes the experimental data, confirming its statistical significance.

3. RESULTS AND DISCUSSION

Passenger cars, minivans, and minibuses play an important role in the country's transport system, as they account for a significant share of the total volume of traffic by all modes of transport. These vehicles provide not only passenger transportation but also perform important functions of cargo delivery, which makes them indispensable in the modern economic environment [16].

As shown in **Table 1**, the 4DTNA diesel engine is equipped with a basic fuel system of the hydropneumomechanical type. Control of the fuel cycle supply and fuel injection angle/time (FIAT) is carried out using an original hydro-mechanical control system, the sensitive element of which is a high fuel pressure regulator. The change in FIAT geometry depending on the speed of rotation of the crankshaft is shown in **Figure 5**.

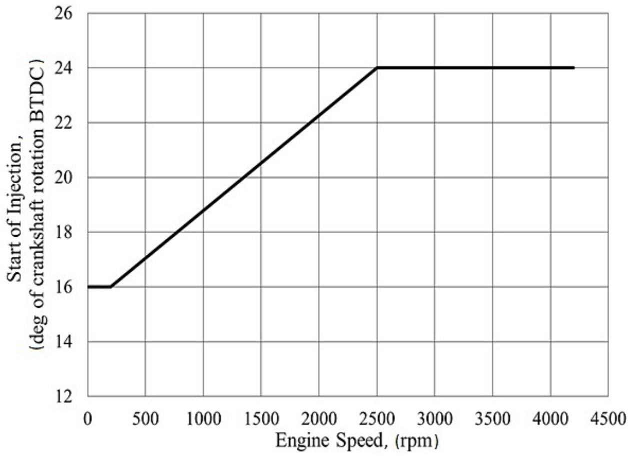


Figure 5. Characteristics of fuel injection advance time depending on the speed of rotation of the crankshaft.

The high fuel pressure adjustment angle determines the constant angle value in the horizontal section on the right side in **Figure 2**. However, the introduction of such a characteristic into the existing design cannot be considered as an optimisation of fuel supply parameters during start-up, since this was conditioned by the capabilities of the fuel system and the state of knowledge about the need for rationalisation at that time [17-19]. Increase fuel supply during the cold start of the 4DTNA diesel engine to Qc=40...45 mm^3/cycle is achieved by forcibly moving the maximum fuel supply stop, which also does not meet modern process optimisation requirements. A physical model has been developed for experimental studies of the starting characteristics of all 4DTNA series engines, capable of increasing the power of these engines to 90 kW [20]. At the same time, the condition for creating such a model was the possibility of studying the mechanism of preheating the air in the combustion chamber (τg.p, s) using a glow plug before starting, while the engine is running in the cylinder. All previous studies have focused on determining the lowest heating temperature of the glow plug tip (tg.p,°C), which is necessary for the catalyst ignition of the fuel.

These two factors allowed choosing the original 4DTNA diesel engine with a vortex chamber for mixture formation as the basis for the physical model. The use of a vortex chamber allowed reducing the compression ratio from 18.5 to a promising 17-17.5 units and providing optimal conditions for maximising the temperature of the air charge around the tip of the glow plug (**Figure 6**). It is worth noting that creating a calculated model of fuel ignition near the glow plug, considering the heating temperature of the tip and the time of pre-activation of the glow plug, is quite a difficult task. In addition, it is only possible to speculate how the temperature in the combustion chamber at the end of the compression stroke during a cold start attempt will change as the crankshaft speed changes, considering the preheating from the glow plug [21]. It is also necessary to consider the well-known truth that this parameter changes in each local cavity of the combustion chamber volume. The characteristics of such heating in the local cavity around the nozzle jets before attempting to start the 4DTNA diesel engine are shown in **Figure 7**. In the case of a particular physical model, the temperature continues to rise steadily until almost the 45th second of heating.

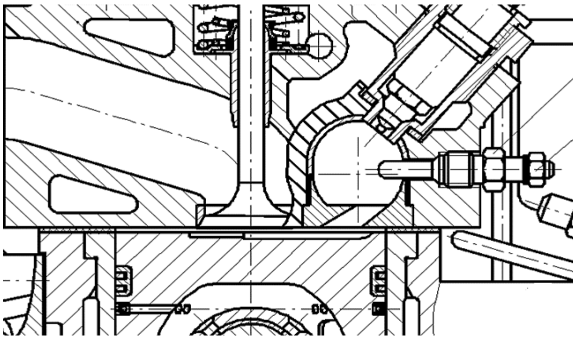


Figure 6. 4DTNA diesel engine combustion chamber with vortex chamber.

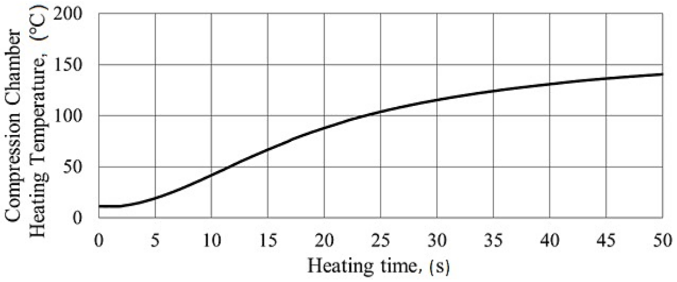


Figure 7. Time-dependent pre-heating of the air in the vortex chamber by a glow plug (piston at the TDC, thermocouple at the nozzle).

An additional advantage of the created physical model is the presence of a special experimental mechanism that allows adjusting the fuel injection advance angle within 28 degrees of rotation of the crankshaft for each start-up without the need to disassemble the high-pressure pump drive unit. An important element of the scientific and technical approach to solving the problem of the cold start of automobile diesel engines is the unique representation of engine torque resistance as an equivalent load due to the influence of low ambient temperature on any engine oil. The difficulty of solving this problem, due to the lack of access to special climate chambers, was to change the load on the crankshaft through the kinematically connected shaft of the rotary machine through the gearbox.

The other three parameters, among the most influential on launch speed and quality, are well known and do not require additional comments. This is the speed of rotation of the crankshaft by the starter (nSS, rpm), fuel cycle supply (Qc, mm^3/cycle), and setting the fuel injection advance time (θ, also denoted as θFIAT, degrees of the crankshaft to TDC).” Meanwhile, the maximum fuel cycle supply was limited by environmental requirements, namely the maximum exhaust smoke of 67% and was Qc=36 mm^3/cycle [22]. The physical parameters recorded during the experimental study are shown in **Table 2**.

Table 2. Physical parameters measured during the experimental study.

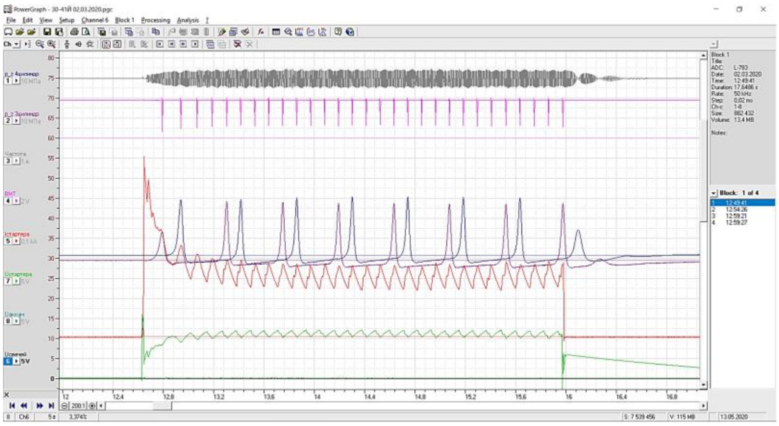
Parameter	Designation	Units	Sensor used
Position of the crankshaft when the piston is in TDC	TTDC	s	Optical position sensor
Crankshaft speed	nCrSh	rpm	Inductive crankshaft position sensor (speed sensor)
Time	τg.p	s	DOSTMANN mechanical stopwatch
Ambient temperature	t0	°C	Liquid thermometer
Coolant temperature	tcoolant	°C	Chromel-Kopel thermocouple
Engine oil temperature	toil	°C	Chromel-Kopel thermocouple
Pressure in the lubrication system	poil	kgf/cm^2	EDMU-6 pressure gauge

Table 2 (continue). Physical parameters measured during the experimental study.

Parameter	Designation	Units	Sensor used
Diesel cylinder pressure	pcyl	MPa	AVL 8QP505cs piezometric pressure sensor
Ambient pressure	p0	mmHg	MD-49-2 laboratory barometer
Battery voltage	UBat	B	ADC channel L-Card L-783
Starter terminal voltage	Ustart	B	ADC channel L-Card L-783
Starter current	Istart	A	Current shunt 0.75 Ohms 500 a

During the measurement of physical quantities and subsequent data processing, the total error of each measuring channel did not exceed 0.5%, which corresponds to the class of laboratory devices. The total error of the measuring line did not exceed 1%. Electrical signals from the sensors were recorded using a multi-channel analogue-to-digital converter, L-Card L-783, and their processing and reproduction were carried out on a personal computer using PowerGraph 3.3 software. For further processing, pre-calibrated measuring channels of current in the starter winding circuit, voltage at its terminals, and crankshaft speed are simultaneously recorded. The PowerGraph working window is shown in **Figure 8**.

The need to prepare three controlled variable parameters that affect the cold start of a diesel engine, and conduct a complex experimental and computational study, led to the next stage of using the method of planning a mathematical experiment in engine research. In particular, this is the selection and justification of a mathematical plan for a 3-factor experiment aimed at studying the starting characteristics of a diesel engine, and the development and practical use of specialized software (namely Approximation_LSM). The Approximation_LSM program implements an algorithm for generating full power polynomials of degree 1 to 3.



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Date: 02.03.2020
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Ch-s: 1-8
Size: 882 432
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1 12:49:41
2 12:54:26
3 12:59:21
4 12:59:27

8 | Ch6 | 5 s | 3,374% | S: 7 539 456 | V: 115 MB | 13.05.2020

Figure 8. PowerGraph 3.3 working window.

Examples of variations in the three selected during the application of the Box-Wilson central composite design [23] demonstrate the distribution of each factor and its effect on cold start time over the entire study range. It is important to note that during the experiment, the parameter of the equivalent cold start temperature was calculated depending on the non-linearly dependent controlled torque resistance factor of the crankshaft, and on environmental conditions. Thus, with a uniform orthogonal variation of the influence factor on the resistance of the crankshaft torque, the dependent factor of the equivalent cold start temperature, which is of practical importance and will be used to implement the automatic start control algorithm, differs from the orthogonal one. Curves approximating specific factors constructed according to the regression model are given with constant values for the other 3 factors under study, which are on their average values of variation (**Figures 9-11**).

With fixed values of other factors (FIAT 19 degrees TDC, cold start temperature 2.7°C, crankshaft rotation speed 250 rpm, glow plug temperature 1,150 K, and preheating time 34.5 s), an increase in fuel supply leads to a reduction in start-up time. This indicates the importance of properly adjusting the fuel supply to achieve optimal starting performance.

At average values of other factors (fuel supply 32 mm^3/cycle, cold start temperature 2.7°C, rotation speed 250 rpm, glow plug temperature 1,150 K, and preheating time 34.5 s). The change in FIAT significantly affects the start time and has an extreme in the studied range, which allows optimization for this parameter. An optimal injection angle can improve fuel combustion, which reduces the time required to start the engine.

With the same average values of other factors (fuel supply 32 mm^3/cycle, FIAT 19 degrees TDC, rotation speed 250 rpm, glow plug temperature 1,150 K, and preheating time 34.5 s), an increase in the equivalent cold start temperature has a positive effect on the engine start time. This highlights the importance of properly heating the combustion chamber to improve starting performance.

In general, the starting characteristics of a diesel engine depend on a number of factors, including fuel supply, injection advance angle, and equivalent cold start temperature. Optimising these parameters can significantly reduce the cold start time, which is critical for reliable engine operation at low temperatures. In particular, proper adjustment of the fuel supply system and proper heating of the glow plugs can ensure a successful cold start even in adverse weather conditions.

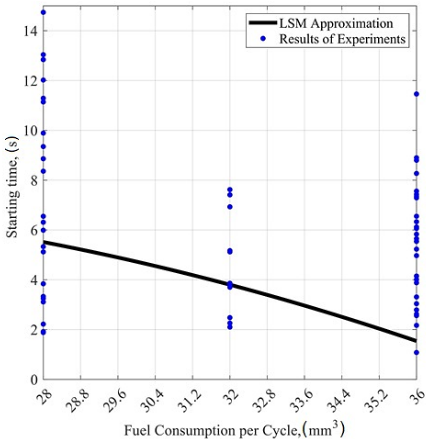

Figure 9. Distribution of experimental data showing the dependence of the start-up time on the fuel supply.

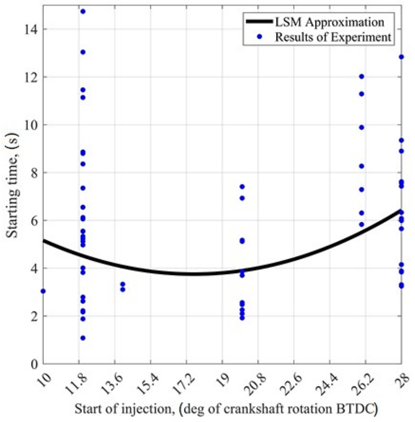

Figure 10. Distribution of experimental data showing the dependence of the start-up time on FIAT.

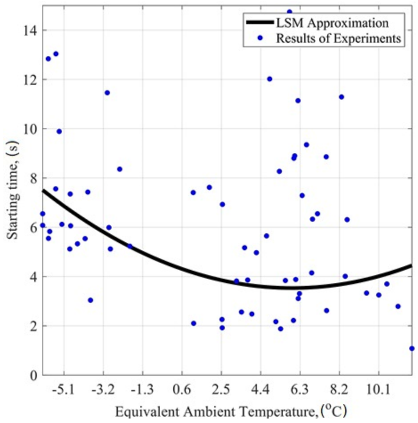

Figure 11. Distribution of experimental data showing the dependence of the start-up time on the equivalent cold-start temperature.

One of the regression equations obtained as a result of the described study for parameters that characterise starting qualities is equation (2), namely, the equation for determining the cold start time of a 4DTNA series diesel engine. The coefficients of this equation, obtained as a result of processing experimental data using the least squares method, are shown in **Table 3**.

A sample from the complete table of processed experimental data, demonstrated by the example of changes in three of the six independent factors under study, which are shown in **Figures 12-14**, is presented in **Table 4**. The values of unspecified factors remain constant throughout the sample and correspond to a certain level of variation of factors with permissible deviations: crankshaft speed – 300 rpm; glow plug temperature – 1,150 K; preheating time of the combustion chamber by the glow plug – 35 s.

Table 3. Regression equation coefficients for cold start time.

Coefficient designation	Weight	Value	Coefficient designation	Weight	Value
a0	-	8.64213385620053	a13	Qc×tcs.eqv	- 0.0001550542
a1	Qs	0.0881961007	a14	Qc×nss	0.0001376772
a2	θFIAT	0.0015378285	a15	Qc×tg.p	0.0000193700
a3	tCS.eqv	0.0501085778	a16	Qc×τg.p	0.0002543227
a4	nSS	-0.0516115511	a23	θFIAT×tcs.eqv	0.0002327235
a5	tg.p	0.0002681549	a24	θFIAT×nss	- 0.0000613459
a6	τg.p	-0.1477722727	a25	θFIAT×tg.p	0.0000075254
a11	Qc2	-0.0026051274	a26	θFIAT×τg.p	- 0.0002136671
a22	θFIAT2	0.0002303053	a34	tcs.eqv×nss	- 0.0003758781
a33	tCS.eqv2	0.0024535528	a35	tcs.eqv×tp.g	- 0.0000209378
a44	nSS2	0.0000770706	a36	tcs.eqv×τg.p	0.0008041888
a55	tg.p2	-0.0000007588	a45	nss×tg.p	0.0000010131
a66	τg.p2	0.0011915563	a46	nss×τg.p	0.0001719398
a12	Qc×θFIAT	0.0000181846	a56	tg.p×τg.p	0.0000109898

Variance of the adequacy of the regression model: Sadeq2=2.30 s2 (degrees of freedom of variance – 49); mean square deviation of the regression model: σ=1.517 s. Statistical evaluation of the adequacy of the obtained square polynomial and the quality of the description of experimental data of the physical start-up process was performed using the Fischer criterion (equation (4)).

$$F = \frac{2.3}{0.516} = 4.46. \qquad (4)$$

Based on the ratio of the residual variance (or adequacy) of the model to the experimental estimate of the measured cold start time parameter with the specified degrees of freedom, the resulting model corresponds to the significance level α=0.05. Thus, a mathematical description of the model for the cold start time (Qc, θFIAT, tCS.eqv, nSS, tg.p, τg.p) is considered adequate.

Analysis of **Figures 12-14**, which show the cold start time of a diesel engine as a function of fuel supply, fuel injection advance angle, and crankshaft speed, allows drawing several important conclusions.

Table 4. Sampling of processed experimental data and estimation of regression model deviations.

Variable factors*			**Start-up time parameter (experiment and calculation)**		**Estimation of deviations of calculated values**	
Cyclic fuel supply (mm^3/cycle)	FIAT, (deg. to TDC)	Equivalent temperature (oC)	Start-up time, (s) [Experiment result]	Start-up time, (s) [LSM Approx result]	Absolute deviation [(Exp.) – (LSM)], (s)	Relative deviation [(EXP.) – (LSM)] (Exp.) (%)
36	28	6.09	3.88	4.58	-0.70	-18.10
28	12	7.14	6.55	6.64	-0.09	-1.44
36	12	-5.85	5.55	5.97	-0.42	-7.60
28	28	10.10	3.25	3.46	-0.21	-6.34
36	28	6.27	3.31	3.76	-0.45	-13.68
28	12	5.98	2.22	2.54	-0.32	-14.31

Note: * is the three unspecified parameters that have constant values: (i) crankshaft scroll frequency, ncr.ang=300 min-1; (ii) heating temperature of the glow plug tip, tg.p.=1,150 K; (iii) glow plug warm-up time, τg.p.=35 s.

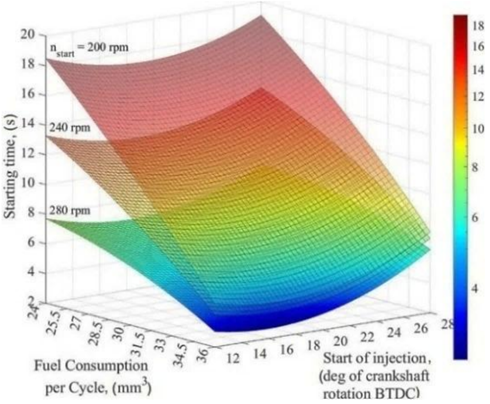

Figure 12. Cold start time as a function of fuel supply, fuel injection advance angle, and crankshaft speed. Note: ambient temperature of -16°C; glow plug temperature of 1,250 K; glow plug preheating time of 30 s.

At an ambient temperature of -16°C, the cold start time increases significantly. A higher fuel supply can reduce the start-up time, but it is necessary to maintain a balance to avoid excessive enrichment, with the development of a significant amount of soot in the exhaust gases. The optimal injection advance angle significantly affects the starting process, as the correct angle adjustment improves fuel-air mixing, resulting in better combustion. Increasing the speed of the crankshaft also helps to reduce the cold start time, emphasising the importance of adequate operation of the starter power supply system.

When the temperature rises to -8°C, the cold start time decreases compared to -16°C, which indicates an improvement in combustion conditions. Optimal fuel supply and injection advance values help to reduce the start-up time, while maintaining the ability to vary the feed rate for best results.

At 0°C, the cold start time is significantly reduced, which indicates that the engine is operating in more favourable conditions, which improves its starting characteristics. As in the previous cases, proper adjustment of the fuel supply and advance angle remains critical to ensure optimal engine performance.

In general, as the ambient temperature increases, the starting characteristics of the 4DTNA diesel engine improve. Optimising the fuel cycle parameters, injection advance angle, and crankshaft speed is critical to ensuring a reliable cold start in various temperature conditions. The presence of glow plugs (1,250 K, 30 s) has a positive effect on the start-up process, especially in low temperature conditions. This analysis highlights the importance of an experimental approach to optimising the starting characteristics of a diesel engine depending on environmental conditions. By measuring the crankshaft speed for a 4-stroke diesel engine every two revolutions (one engine duty cycle), the ECU firmware program can instantly select the optimal nozzle adjustment parameters (fuel supply and injection advance angle) during the diesel engine start-up process. This choice is based on the type of fuel used and the heating efficiency of the glow plug. The preheating time of the glow plug is determined solely by its characteristic time of reaching the operating temperature.

The results of an experimental study of the starting characteristics of a 4DTNA series diesel engine confirmed the significant influence of the selected independent parameters on the cold start time. It turned out that optimization of factors such as crankshaft speed, cyclic fuel supply, and injection advance angle provided a noticeable reduction in engine start-up time at low temperatures. These results show that careful selection of start-up system parameters can significantly improve the performance of automotive diesel engines, especially in cold weather.

This issue was also investigated by previous reports [24], and the results confirmed that independent parameters such as ambient temperature, fuel viscosity, and battery condition significantly affect the start-up time of a diesel engine. At low temperatures, the fuel becomes denser, which makes it difficult to burn. Insufficient battery power can delay the ignition process, especially during a cold start. Optimization of the start-up system can include the use of preheaters for fuel and air, which allows reaching the operating temperature faster [25]. It is also important to improve the efficiency of the starter and improve the thermal insulation of the engine. Innovative materials and electronic control systems can reduce energy loss during start-up, reducing start-up time. It is worth noting that the use of fuel additives can also help improve the cold start of a diesel engine, reducing the freezing point of fuel and improving its combustion [26-28]. In addition, modern engine control systems can automatically adapt to different temperature conditions, optimising the fuel and air supply. This allows reducing the load on the starting system and increasing the reliability of the engine in conditions of difficult start-up.

The analysis also showed that the temperature conditions of the external environment are critical for the start-up process. When the ambient temperature dropped to 6°C or lower, the cold start time increased significantly, which indicates the need for special measures to improve the starting characteristics. The study, which considered the effect of equivalent temperature due to external inertial load on the crankshaft, allowed simulating the effect of increased viscosity of cold oil, but did not consider changes in fuel characteristics and additional convection heat loss. In this study, in the absence of the possibility of using a climate chamber, the specified parameters are considered significantly less influential at the cold start temperatures considered, but their consideration is an important prospect for further research, especially with lower cold start temperatures.

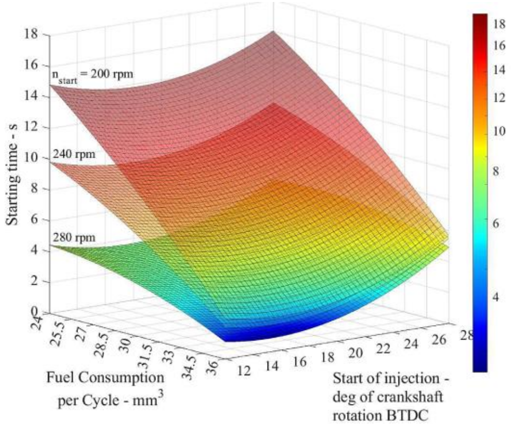

Figure 13. Cold start time as a function of fuel supply, fuel injection advance angle, and crankshaft speed. Note: ambient temperature of -8°C; glow plug temperature of 1,250 K; glow plug preheating time of 30 s.

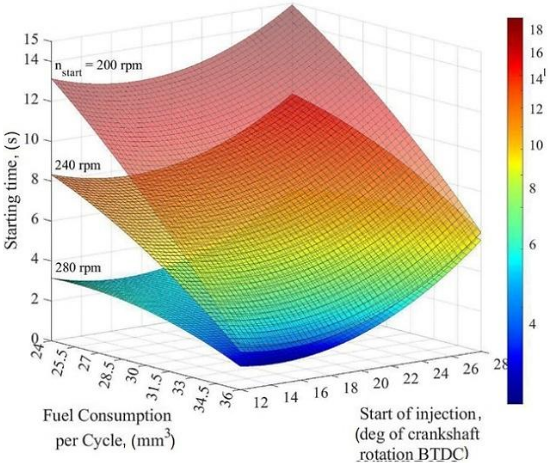

Figure 14. Cold start time as a function of fuel supply, fuel injection advance angle, and crankshaft speed. Note: ambient temperature of 0°C; glow plug temperature of 1,250 K; glow plug preheating time of 30 s.

At low temperatures, fuel in diesel engines becomes more viscous, making it difficult to feed and burn [29]. This leads to an increase in the start-up time and may require additional measures, such as fuel heating. High temperatures can also negatively affect starting, causing engine components to overheat and reducing the efficiency of the starting system. Accurate modelling of start-up conditions allows predicting engine behaviour at different temperatures and considering changes in fuel viscosity and other parameters [29]. This helps engineers to optimise the design of the launch system and reduce the risk of a failed launch. Based on modelling, it is also possible to determine the optimal settings for different climatic zones, which increases the reliability of diesel engines. These results support the above study, as they show that ambient temperature is indeed a key factor affecting the start of diesel engines. Modelling of start-up conditions allows taking these changes into consideration, providing optimization of the start-up algorithm for different climatic conditions [30]. Thus, the use of such methods helps to improve the efficiency and reliability of engines in conditions of difficult start-up.

In addition, the results of the study confirmed that appropriate preparation and adjustment of the launch system parameters and the development of a rational start-up control algorithm play a crucial role in ensuring a successful cold start. This highlights the importance of monitoring the environmental parameters and system status, in particular the battery status, before starting and adaptive adjustment of the start-up system parameters during the start-up process to improve the reliability of the start-up in difficult start-up conditions.

It is necessary to emphasise the previous study [31], which also found that reducing the warm-up time of the air in the combustion chamber allows reaching the temperature required for auto-ignition of the fuel faster. Using advanced glow plugs and an exhaust gas recirculation system can help to reduce this time. Optimization of the warm-up process helps to start the engine more efficiently and reduces emissions of harmful substances. In turn, the glow plug temperature directly affects the rate of heating of air in the combustion chamber and the engine start process itself [32]. If the glow plug temperature is not high enough, the engine may be difficult to start or not start at all in cold conditions. On the contrary, the optimally selected glow plug temperature ensures a stable and fast start-up, even at low temperatures [33, 34]. These data correspond to the theses given in the previous section, as they confirm the importance of optimising the operation of the starting system to ensure efficient start-up of diesel engines. Like the influence of ambient temperature, the glow plug temperature is a key factor in determining the speed and reliability of the start-up. Improving these parameters reduces the load on the engine, increasing its performance in conditions of difficult start-up.

The next important aspect was to present the polynomial dependence of the cold start time on six independent factors as an adequate regression start model for optimizing it. The use of the Approximation_LSM software allowed forming the necessary multivariate regression model and conducting its further analysis. The results obtained in this study can be used to develop efficient control algorithms for electronic control units, which will significantly improve the starting characteristics to improve the performance of the target 4DTNA1 diesel engine.

Some researchers [35] also conducted a study that confirmed that polynomial models can accurately describe the dependence of cold start time on various parameters, such as temperature, pressure, and battery status. The use of such models helps to predict the engine start time under various conditions, which makes it easier to optimise it. This allows engineers to develop more efficient launch systems that consider multiple impact factors. Diesel engine software allows automating the processes of monitoring engine start-up and operation in real-time. It can adapt start-up parameters depending on current conditions, such as temperature or fuel condition [36]. Based on such technologies, it is possible to increase engine efficiency and reduce fuel consumption.

In the course of this study, it was confirmed that the representation of complex dynamic processes in diesel engines, in particular the start-up process, in the form of regression models obtained by experimental calculation, helps to create a theoretical basis for predicting real physical processes and implement rational management of this dynamic process. In addition, the use of an automatic start-up control system based on an electronic control unit and appropriate electro-mechanical actuators to control the parameters of the start-up system provides flexibility and adaptability in setting up the system, increasing the performance of the diesel engine as a whole [37].

It should also be noted that the conducted research has certain limitations. It was implemented on a specific diesel engine model, which may limit the possibility of generalising the results obtained to other types of engines. Thus, in order to achieve greater versatility, future research should focus on studying the impact of these parameters on different diesel engine models, which will allow identifying common patterns and developing more effective solutions to improve starting performance.

Diesel engines are more efficient than gasoline engines, but their performance is associated with higher emissions of harmful substances such as nitrogen oxides and soot particles. In addition, diesel engines are more difficult to start in cold weather due to the properties of diesel fuel and higher requirements for the start-up system as a whole. These restrictions pose challenges to environmental compliance and reliable operation in harsh environments. Further research is needed to reduce emissions and improve the environmental efficiency of diesel engines, especially in connection with tougher environmental standards [38]. Innovations in the field of launch systems are also needed to improve launch reliability in different climatic conditions. Continuous development of technologies will help maintain the competitiveness of diesel engines in the market, considering modern requirements for efficiency and environmental friendliness. When analysing the results of the study, it is clear that the limitations of diesel engines can be partially solved by introducing the latest technologies and optimising their work processes. Research points to the need to improve launch systems and reduce harmful emissions, which are key factors for improving their environmental and technical efficiency. Continuous work in this area will preserve the importance of diesel engines, highlighting their ability to meet the requirements of modern environmental and operational needs.

The conclusions drawn based on the conducted study indicate the prospects for further research of the starting characteristics of diesel engines. Additional research may focus on the impact of different fuel types, technological innovations in control systems, and providing start-up conditions that can improve engine performance. The application of the results obtained in the automotive industry can significantly affect the reduction of emissions of harmful substances during start-up, which, in turn, will contribute to improving the environmental situation in cities.

4. CONCLUSION

Considering the complexity of the process of starting an automobile diesel engine, the choice of independent parameters that affect its starting capacity was substantiated. To investigate these parameters, which determine the diesel engine starting process, an experimental setup was developed based on a Ukrainian diesel engine of the 4DTNA series, located at the laboratory of Kharkiv National Automobile and Highway University. Using this setup and the experimental design method, the engine start process was investigated. As part of the study, 77 valid cold starts were performed with varying independent parameters within the specified limits. A special feature of considering the cold start temperature was the use of equivalent temperature values when changing the external load on the diesel engine, considering the type of engine oil used.

In particular, the study examined the effect of a complex of independent variable parameters on the cold start time of an automobile diesel engine. Among them: rotation of the crankshaft in the range from 200 to 300 rpm, fuel supply in the range from 28 to 36 mm^3/cycle, the injection advance angle in the range from 12 to 28 degrees to TDC, the preheating time of the air in the combustion chamber by the glow plug in the range from 25 to 45 seconds, the heating temperature of the tip of the glow plug in the range from 950 to 1,350 K, and the equivalent cold start temperature in the range from -6 to 12°C.

The results of the experimental study were processed to obtain a polynomial dependence of the cold start time on the specified six independent parameters using the author-developed software Approximation_LSM. A statistical assessment was carried out, which confirmed the adequacy of the obtained polynomial dependence of the diesel cold start time according to the Fischer criterion. Using this polynomial dependence, the parameter of the start-up time was investigated and optimised depending on the value of the fuel cycle parameters, the injection advance angle, the ambient temperature, and the heating time and temperature of glow plugs.

Optimised fuel supply parameters during the start-up of an automobile diesel engine reduce the start-up time depending on the specific operating conditions. The defined polynomial dependence and the proposed graphical dependences of the start-up time can be implemented in the control algorithms of microcontrollers of electronic control units of modern automobile engines. In future studies, it is necessary to further investigate the effect of different types of fuel and their additives on the starting characteristics of diesel engines at low temperatures.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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