Improving the performance of tractor diesel engines by optimizing the fuel supply characteristics

A K Apazhev, Y A Shekikhachev, V I Batyrov, A L Bolotokov and L Z Shekhacheva

Kabardino-Balkarian state agricultural university named after V.M. Kokov, 1v Lenin Ave., Nalchik, Kabardino-Balkarian Republic, 360030, Russia

1 E-mail: shek-fmep@mail.ru

Abstract. Diesel engines to the greatest extent satisfy the tendencies that take place in the engine building: increased power indicators, reduced specific fuel consumption and toxicity of exhaust gases. It is possible to realize the indicated advantages of diesel engines only if the parameters that characterize the fuel supply are ensured and maintained. The nature of the fuel supply predetermines the indicators that characterize the quality of the workflow in a diesel engine. As you know, during the operation of a diesel engine, there are significant differences between the real characteristics of the fuel supply to the optimum. These differences arise due to the fact that the technical condition of the elements of the high pressure fuel system (HPF) changes. Establishing the optimal parameters that characterize the fuel supply during the operation of the fuel equipment (FE) is a rather difficult task, which is caused by the interconnectedness and interdependence of these parameters. It is especially necessary to take into account that while optimizing some fuel supply parameters, others often deteriorate. In order to ensure a high-quality fuel combustion process, the fuel system of a diesel engine is faced with the task of ensuring guaranteed injection of a metered cyclic fuel supply (CFS), taking into account the specified phases and injection characteristics, which will have a beneficial effect on the fuel combustion process in any operating modes of the diesel engine. Thus, with a change in the technical characteristics of the HPF during operation, the characteristics of the injection also change. When studying the influence of the HPF parameters on the fuel supply characteristics, the change in the injection characteristics is often not taken into account, which is explained by the complexity and laboriousness of these studies. Considering the above, the optimization of the characteristics of diesel engines fuel supply is an urgent problem.

1. Introduction
The process of optimizing the parameters of fuel supply and indicators of the working process of diesel engines is carried out by multifactorial mathematical modelling [1-4].

During optimization, the technique of multifactor mathematical modelling based on the method of nodal points was used. Polynomial models allow, in a variant calculation, to set the CFS at a given level, that is, to simulate the process of operation of the HPF.

A multivariate mathematical model taking into account the nodal point method can be written as follows:
\[ Y = \frac{1}{(Y_0)^n} \prod_{i=1}^{n} f(X_i), \]  

where \( Y \) is the fuel supply parameter; \( Y_0 \) is parameter of fuel supply at the nodal point; \( n \) is the number of factors; \( f(X_i) \) is one-factor dependence.

2. Research results

The hydrodynamic calculation of the fuel supply made it possible to single out the factors that determine the characteristics of the injection process and the quality indicators that characterize the course of the working process in a diesel engine: cycle feed \( (g_c) \), injection pressure \( (P_b) \), injection lag angle \( (\phi_p) \), injection duration \( (\phi) \). It was also found that the identity of the hydraulic characteristics is determined mainly by the clearances in the plunger pair \( (\delta_p) \) and along the unloading shoulder of the discharge valve \( (\delta_k) \), the effective flow area of the high pressure fuel line \( (\mu_p f_p) \), and the effective flow area of the injector nozzle \( (\mu_f f_T) \).

It is known that the injection characteristic \( (X B) \) and the quality of fuel atomization are determined by the cycle supply, pressure and duration of fuel injection [5-11].

Figure 1 shows a diagram of a directed graph that characterizes the developed multivariate mathematical models that take into account the influence of the selected factors.

![Figure 1. Scheme of a directed graph.](image)

Based on expression (1) and the adopted directed graph, we get:

\[ g_c = \frac{1}{(g_{c_a})^3} (\delta_p) g_c (\delta_k) g_c (\mu_f f_T) g_c (\mu_p f_p) g_c; \]  
\[ \phi_p = \frac{1}{(\phi_{p_a})^3} (\delta_p) \phi_p (\delta_k) \phi_p (\mu_f f_T) \phi_p (\mu_p f_p) \phi_p; \]  
\[ P_b = \frac{1}{(P_{b_a})^3} (\delta_p) P_b (\delta_k) P_b (\mu_f f_T) P_b (\mu_p f_p) P_b; \]  

(2)  
(3)  
(4)
\[ \varphi_Z = \frac{1}{(\varphi_{Z_0})^3} (\delta_P \varphi_Z (\delta_K \varphi_Z (\mu_T \varphi_T) \varphi_Z (\mu_P \varphi_P) \varphi_Z), \]  

(5)

where \( g_{C_0}, \varphi_{C_0}, P_{B_0}, \varphi_{Z_0} \) — fuel delivery parameters at the nodal point;

\( (\delta_P)g_C, (\delta_K)g_C, (\mu_T \varphi_T)g_C, (\mu_P \varphi_P)g_C, (\delta_P)\varphi_P, (\delta_K)\varphi_P, (\mu_T \varphi_T)\varphi_P, (\mu_P \varphi_P)\varphi_P, \)

\( (\delta_P)P_B, (\delta_K)P_B, (\mu_T \varphi_T)P_B, (\mu_P \varphi_P)P_B, (\delta_P)\varphi_Z, (\delta_K)\varphi_Z, (\mu_T \varphi_T)\varphi_Z, (\mu_P \varphi_P)\varphi_Z \) — functions of factors influencing the value of the CFS, duration, pressure and lag angle of fuel injection.

The approximation of one-factor dependences of the parameters of the fuel supply on the indicators that determine the technical condition of the HPF was made using the following equations:

\[ \varphi_p = 8,514 + 0.0869\delta_p, \]

\[ \varphi_z = 10,223 + 0.0000345e^{0.971\delta_p}, \]

\[ g_C = 77,405 - 0.531\delta_p \]

\[ P_B = 24,979 - 0.535\delta_p \]

\[ \varphi_p = 11,882 - 0.284\delta_k \]

\[ \varphi_z = 10,284 + 10.56e^{0.6025\delta_k} \]

\[ g_C = 70,607 + 0.307\delta_k \]

\[ P_B = 19,205 + 0.258\delta_k \]

\[ \varphi_p = 12,582 - 3,786\mu_T \varphi_T \]

\[ \varphi_z = \text{const} \]

\[ g_C = 71,959 + 2,607\mu_T \varphi_T \]

\[ P_B = 33,293 - 122,143\mu_T \varphi_T \]

\[ \varphi_p = 12,098 - 6,964\mu_p \varphi_P \\
\varphi_z = 10,139 + 692,552e^{-2.702\mu_p \varphi_P} \\
g_C = -10,582,544 + 1065(1-e^{-26.447\mu_p \varphi_P}) \\
P_B = 29,629 - 17,429\mu_p \varphi_P \]

(6)

(7)

(8)

(9)

By jointly solving equations (6-9) and (2-5), the following mathematical models were obtained (for UTN-5):

\[ g_C = \frac{1}{(75)^3} (77,405 - 0.531\delta_p)(70,607 + 0.375\delta_k)(71,959 + \\
+ 2,607\mu_T \varphi_T)(-10,582,544 + 1065(1-e^{-26.447\mu_p \varphi_P})); \]

\[ \varphi_p = \frac{1}{(9)} (8,514 + 0.0869\delta_p)(11,862 - 0.284\delta_k)(12,582 - \\
- 3,786\mu_T \varphi_T)(12,098 - 6,964\mu_p \varphi_P); \]

(10)

(11)
\[
\begin{align*}
P_B &= \frac{1}{(22)^3}(24,979 - 0.535\delta_p)(19.205 + 0.258\delta_c) \\
&\times (33,293582 - 122,143\mu_t f_t)(29,629 - 17,429\mu_p f_p); \\
\varphi_Z &= \frac{1}{(10.5)^3}(10.223 + 0.00000345e^{0.975\delta_c})(10.284 + \\
&10.56e^{0.602\delta_c})(10.5)(10,139 + 692,552e^{-22.702\mu_p f_p}),(13)
\end{align*}
\]

Calculations show that with an increase \( \mu_p f_p \) from 0.33 to 0.6 mm², the cyclic fuel supply increases by 2.0 mm³ / cycle (2.7%). CFS grows to a critical value \( \mu_p f_p \) and further growth does not significantly affect its value. The critical value \( \mu_p f_p \) is determined by the ratio \( g_c \) and \( \mu_p f_p \). Taking this into account, \( \mu_p f_p \) the bench nozzle for the investigated FE is equal to 0.45±0.02 mm², and \( \mu_p f_p = 0.95±0.05 \) mm². It should be noted that in this case, the change in the characteristics of the fuel supply \( \{g_c, \varphi_p, P_B, \varphi_Z\} \) with the change \( \mu_p f_p \) and \( \mu_t f_t \) will be the smallest.

An increase in the clearance along the unloading shoulder of the discharge valve from 4.0 to 10 microns leads to an increase in the CFS by 3.0 mm³ / cycle (4%). However, an increase in CFS from an increase \( \delta_c \) is not equivalent to an increase in CFS from an increase \( \mu_p f_p \) due to an increase in injection pressure by 11.1% (in the first case) and a decrease by 8.18% (in the second case). Accordingly, there is a decrease in the injection duration \( \varphi_p \) by 1.8...° (by 20%) and by 1...° (by 9%). When selecting injectors and fuel lines according to such a criterion as throughput, these circumstances are usually not taken into account, as a result of which there is unevenness in \( \varphi_p \) and \( P_B \) with the identity of the values of the CFS for the HPF sections and the FE kits. Ultimately, the workflow is not identical in different cylinders of a diesel engine.

Using the obtained multifactorial mathematical models of the fuel supply parameters (10 ... 13), it is possible to substantiate the parameters of bench injectors and the fuel-conducting system, to establish the values of the HPF elements, which will provide a uniform CFS taking into account \( \varphi_p, P_B, \varphi_Z \).

As a result of optimization, the objective functions are obtained in the form of a regression equation:

\[
Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3, \quad (14)
\]

where \( Y \) is the indicator under study; \( X_1, X_2, X_3 \) are the factors; \( B_0, B_1, B_2, B_3 \) are the regression coefficients.

For various performance indicators of a diesel engine, equations (14) will be written as:

- indicator coefficient of performance:
  \[
  \eta_i = 0.593 + 0.000438\varphi_Z - 0.00263\varphi_p - 2.226q_c; \quad (15)
  \]

- indicator specific fuel consumption:
  \[
  q_i = 114.89 - 0.223\varphi_Z + 1.34\varphi_p + 1116.76q_c; \quad (16)
  \]

- indicator power:
\[ N_i = 8.33 + 0.019\varphi_Z - 0.12\varphi_p + 216.92q_c; \]  

- maximum gas pressure:
\[ P_Z = 3.078 + 0.0116\varphi_Z - 0.0428\varphi_p + 37.988q_c; \]

- the rigidity of the diesel engine:
\[ \Delta P = \frac{0.227 + 0.0198\varphi_Z - 0.000285\varphi_p + 8.032q_c}{\Delta \alpha}; \]

- average indicator pressure of the working cycle:
\[ P_i = 0.386 + 0.00813\varphi_Z - 0.00556\varphi_p + 9.939q_c; \]

- maximum gas temperature:
\[ T_Z = 1413.208 + 6.531\varphi_Z - 22.844\varphi_p + 111417.683q_c. \]

The indicator coefficient of performance of a diesel engine \( \eta_i \) is an integral criterion of the efficiency of heat release, which depends on the parameters of fuel supply. Taking this into account, this indicator is adopted as an optimization criterion.

Using equations (15-21), the indicator indicators of the diesel engine 4CH11 / 12.5 were calculated. Calculations have shown that the value \( \eta_i \) is significantly influenced by the magnitude and duration of the fuel supply, which together with the value of the angle of the beginning of fuel injection determine the qualitative indicators of heat release. With an increase in CFS from 0.05 to 0.065 g / cycle, there is a decrease \( \eta_i \) from 0.438 to 0.400, i.e., by 0.038 (by 8.68%). With an increase \( \varphi_p \) from 20 to 28...° there is a decrease \( \eta_i \) from 0.400 to 0.382, i.e., by 0.018 (by 4.5%). With a deviation \( \varphi_p \) from the initial value 26...° by ±4.0...° a decrease in the influence on \( \eta_i \) was found. At \( g_c = 0.05 \) g / cycle and \( \varphi_p = 20...° \) the deviation \( \eta_i \) turned out to be 0.001 ... 0.002 (0.25 ... 0.50%), and at \( g_c = 0.068 \) g / cycle and \( \varphi_p = 20...° - 0.001 (0.25\%). \) In the case when the injection duration and \( \varphi_p \) simultaneously increase, a slight change \( \eta_i \) is set (0.002 or 0.5%).

The difference between the values \( \eta_i \), established using the proposed models and by calculation for the 4Ch11 / 12.5 diesel engine was 0.5%, which confirms the adequacy of the developed models.

The search for the extremum of the objective function \( \eta_i = f(\varphi_p,\varphi_Z,\varphi_c) \) showed that the value of the extremum \( \eta_i = 0.440 \) takes place at \( \varphi_Z = 24.96...°, \varphi_p = 20...°, g_c = 0.0507 \) g / cycle. Therefore, these values can be considered optimal for a diesel engine 4CH11 / 12.5. In this case, the indicator indicators of the specified diesel engine are: \( N_i = 17.41 \) kW, \( g_c = 192.8 \) g / kWh, \( P_Z = 0.8 \) MPa.

3. Conclusion
Using the obtained multifactor mathematical models of fuel supply parameters, it is possible to substantiate the parameters of bench injectors and fuel lines, to establish the values of the HPF elements, which will provide a uniform CFS taking into account \( \varphi_p, P_Z, \varphi_c \).

The research results show that fuel delivery parameters are mainly determined by the technical condition of the injector nozzle and delivery valve, as well as injection pressure and cyclic fuel supply.

References
[1] Shekikhachev Yu A, Batyrov V I, Balkarov R A, Shekikhacheva L Z and Gubzhokov Kh L 2019 Research of operating modes of diesel engines of tractors in real operating conditions Machinery and Equipment for Rural Area 4(262) 14-9 DOI: 10.33267 / 2072-9642-2019 -4-
Shekihachev Yu A, Batyrov V I, Kardanov Kh B, Chechenov M M and Shekihacheva L Z 2019 Improving the reliability of injector nozzles for automotive diesel engines Scientific Life 14 (6) 929-37 DOI: 10.35679 / 1991-9476-2019-14-6-929-937

Kobozev A K, Shvetsov I I, Koichev V S, Gazizov I I and Bakholdin N V 2018 Detection and ways of troubleshooting - a reserve for deeper knowledge of the designs of tractors and cars Improvement of Scientific and Methodological Work at the University (Stavropol: Stavropol SAU) 278-82

Kurasov V S, Dragulenko V V and Sidorenko S M 2013 Theory of Internal Combustion Engines (Krasnodar: Kuban SAU)

Koichev V S, Kobozev A K, Shvetsov I I, Gritsai D I and Gerasimov E V 2017 Biofuel mixtures: perspective motor fuel Research Journal of Pharmaceutical, Biological and Chemical Sciences 8(5) 642-6

Coichev V and Mosikyan K 2016 Influence of combustion chamber design for power and fuel efficiency of gasoline engines running on natural GAS Bulletin of the National Agrarian University of Armenia 3 44-6

Kobozev A K, Shvetsov I I, Koychev V C 2016 Method of checking plunger pairs Proc. Sci.and Methodological Conf. on Topical Issues of Engineering Education (Stavropol: Stavropol SAU) pp 47-51

Koichev V S, Mosikyan K A and Barseghyan M S 2017 Features of assessing the operational reliability of the brake system of a car Proc. of the Int. Sci. and Practical Conf. on Problems of Scientific and Technological Progress in the Agro-Industrial Complex (Stavropol: Stavropol SAU) pp 278-82

Apazhev A K, Shekikhachev Y A, Batyrov V I, Balkarov R A, Kardanov Kh B, Gubzhokov Kh L and Bolotokov A L 2019 Vegetal fuel as environmentally safe alternative energy source for Diesel engines IOP Conference Series: Materials Science and Engineering 663(1) 012049

Kobozev A K, Shvetsov I I and Koiachev VC 2016 Methods for checking the installation of high-pressure fuel pumps on diesel engines Proc. Sci. and Methodological Conf. on Topical Issues of Engineering Education (Stavropol: Stavropol SAU) pp 51-6

Kurasov V S, Pleshakov V N, Samurganov E E and Ponomarev AV 2016 On the method of studying the movement and operation of machines, their energy balance, taking into account the law of changing the kinetic energy of a mechanical system and acting forces Works of the Kuban State Agrarian University 58 315-8