A Study of the Characteristics of Electric Fuel Pumps of Automobile Engines

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Abstract. The article considers theoretical and experimental research of the fuel system of motor-and-tractor engines: the change in the current consumption of an electric fuel pump (EFP) from the degree of contamination $\varepsilon$ of series elements in the system and leakage in the injection unit of the EFP. The environmental friendliness and efficiency during operation of mobile energy resources is put first. According to some studies, currently, there are 43.5 millions of passenger cars in Russia, 29.2\% of which do not comply with EURO-2 toxicity standards. Among light commercial vehicles, 42.9\% do not comply with EURO-2 toxicity standards. Among trucks, 62.9\% of vehicles neither comply with EURO-2 toxicity standards. The electric fuel pump combines electronic and hydraulic elements. According to the statistics of failures, most of them (up to 35\%) fall at the electric motor. The main factors affecting failures of EFPs are: increased dustiness and humidity, water ingress into fuel, violation of maintenance intervals, etc.

1. Introduction
Currently, the environmental friendliness during operation of mobile energy means (MEM) is put first [1]. According to some studies, currently, there are 43.5 millions of passenger cars in Russia, 29.2\% of which do not comply with EURO-2 toxicity standards. At the same time, 16.4\% of the car fleet meet EURO-5 and higher standards. As of the beginning of this year, there were 4.1 millions of cars in the segment of light commercial vehicles, 42.9\% of which do not comply with EURO-2 toxicity standards, but only 3.1\% of the car fleet meet EURO-5 standard [2]. There are 3.8 millions of registered trucks, 62.9\% of which neither comply with EURO-2 toxicity standards, and only 4.4\% of the fleet meet EURO-5 and higher standards.

Modern fuel supply systems for motor-and-tractor equipment are complex hydraulic, mechanical and electronic systems [3, 4, 5]. The electric fuel pump combines electronic and hydraulic elements [6]. According to the statistics of failures, most of them (up to 35\%) fall at the electric motor [7, 8]. The
The main factors affecting failures of EFPs are: increased dustiness and humidity, water ingress into fuel, violation of maintenance intervals, etc. [9, 10]. The basis for maintaining the efficiency of the fuel supply system and the EFP in particular is test diagnostics. Taking this into consideration: the purpose of the research is to ensure the efficiency of electric fuel pumps for motor- and tractor engines through the use of the technologies for test diagnostics of their technical condition.

2. Theoretical Research

The entire fuel system has various series and parallel hydraulic resistances, for example, the passage area changes on the coarse and fine filter depending on the degree of clogging of the filters [5], the fuel supply line, as well as leakages in the EFP injection unit [8]. It follows from the energy balance that the total pressure loss is equal to the sum of the pressure losses in all the sections connected in series [11].

The fuel supply process was divided into several sections (A, B, C) allowing us to study the operation of all the elements of the power supply system: 1. Section (A) – the fuel movement from the tank to the injection unit of the EFP; 2. Section (B) - the fuel movement from the injection unit of the EFP to the fuel filter; 3. Section (C) - the fuel movement from the fuel filter to the fuel rail. Taking this into consideration, we will write:

$$\sum \Delta P_A + \Delta P_B + \Delta P_C = \sum P$$  \hspace{1cm} (1)

where $\Delta P_A$, $\Delta P_B$, $\Delta P_C$ are the pressure drops in the sections A, B and C, Pa, respectively.

Any changes in the structural parameters (resistance, leakage in the fuel system) will lead to changes in the parameters of the electric fuel pump: current $I$, A, and supply voltage $U$, V. These parameters are indirect parameters of the structural ones: pressure in the fuel system $P$, kPa, and fuel supply $Q$, l/h [8, 12]. The dependence should be considered in the form of an equation of the energy balance of the EFP current source ETN ($E_{del}$) with the energy of the fluid movement in the fuel supply line ($E_{trans}$):

Let us consider the energy balance of EFP, J:

$$E_{del} = E_{trans}$$  \hspace{1cm} (2)

where $E_{del}$ is the energy delivered to the EFP, J; $E_{trans}$ is the energy transmitted to the fuel supply line, J.

Let us present the left and the right sides in an expanded form:

$$I \cdot U \cdot t = \frac{U^2}{R} t + \frac{\Delta P}{\rho \cdot g} t + \mu \cdot S_{tot} \left( \frac{2 \cdot \Delta P^3}{\rho} \right)$$  \hspace{1cm} (3)

where $I$ is the current consumption of the EFP, A; $U$ is the supply voltage of EFP, V; $t$ is the pump operation time, sec; $R$ is the resistance of the EFP, Ohm; $\Delta P$ is the pressure drop at the section, kPa; $\mu$ is the fuel consumption ratio; $S_{tot}$ is the total passage area of the fuel supply line, which depends on the type of malfunction (clogging of the series elements or leakage in the injection unit of the EFP), m$^2$; $\rho$ is the density, kg/m$^3$; $g$ is the acceleration of gravity, m/s$^2$.

The total passage area of the fuel supply line when the series elements of the fuel system are contaminated is determined by the formula, m$^2$:

$$\mu \cdot S_{tot} = \mu \cdot S_1 + \mu \cdot S_2$$  \hspace{1cm} (4)

where $S_1$ is the passage area of the first clogged element, m$^2$; $S_2$ is the passage area of the second clogged element, m$^2$.

The total passage area of the fuel supply line in case of leakages in the EFP is determined by the formula, m$^2$:

$$\frac{1}{\mu \cdot S_{tot}} = \frac{1}{\mu \cdot S_1} + \frac{1}{\mu \cdot S_2}$$  \hspace{1cm} (5)

where $S_1$ is the passage area of the fuel supply line from the pressure side, m$^2$; $S_2$ is the passage area of the leakages, m$^2$. 


Let us equate the left and the right sides of equation (2); reducing by the operation time \( t \) in formula (3), we will express the current consumption of the EFP \( I \) from it, \( \Lambda \):

\[
I = \frac{U^2 + \Delta P}{R \cdot \rho \cdot S} + \mu \cdot \frac{S_{tot}}{U} \cdot \frac{2 \cdot \Delta P^3}{\rho}
\]

Thus, we established a theoretical dependence of the current consumption of the EFP on the electrical parameters of the drive motor \((U, R)\) and the technical condition of the main EFP elements \((\mu \cdot S_{tot}, \Delta P)\).

Let us consider the equation of the dependence of the EFP power consumption for hydraulic losses on the electrical parameters of the drive motor and the technical condition of the main EFP elements [13, 14, 15]:

\[
N_{hl} = I_{EFP} \cdot U_{EFP} - N_{el, losses}^{EFP} - \mu \cdot S_c \cdot \frac{2 \cdot \Delta P_{FS}}{\rho_f}
\]

where \( I_{EFP} \) is the pump’s current consumption, \( \Lambda \); \( U_{EFP} \) is the pump’s voltage consumption, \( \text{V} \); \( N_{el, losses}^{EFP} \) is the power of losses in the EFP electrical circuits, \( \text{W} \); \( N_{hyd, losses}^{EFP} \) is the power of hydraulic losses, \( \text{W} \); \( \Delta P_{FS} \) is the pressure drop in the fuel supply system, \( \text{kPa} \); \( \mu \) is the fuel consumption ratio, 0.8; \( S_c \) is the clearance area in the fuel supply system, or between the EFP housing and rollers, \( \text{m}^2 \); \( \rho_f \) is the fuel density, \( \text{kg/m}^3 \).

Substituting the values of the studied gasoline feed pump into equation (7), we obtained the dependencies of the power consumption of the EFP for hydraulic losses on the electrical parameters of the drive motor and the technical condition of the main EFP elements (Figure 1 (a, b) and Figure 2 (a, b))

**Figure 1.** Power consumption for hydraulic losses due to an increase in the area of fuel leakages inside the gasoline pump through radial and end clearences:

- a) \( S_c = 0.0000001539 \text{ m}^2 \); \( I = \text{const} \); b) \( S_c = 0.00000113 \text{ m}^2 \); \( I = \text{const} \).
Figure 2. Power consumption for hydraulic losses when the clearance area of the flow passage of the fuel supply line is reduced:

a) \( S_C = 0.00003847 \text{ m}^2; I = \text{const} \); b) \( S_C = 0.00000001539 \text{ m}^2; I = \text{const} \).

Thus, with an increase in the clearance area between the EFP housing and rollers in Figure 1 (a, b) \( S_C = 0.0000001539 \text{ m}^2 \) to \( 0.0000113 \text{ m}^2 \) the power consumption of the EFP is 2-4 times decreased, which is associated with hydraulic losses, namely \( N_{hl} = 28.64-36.14 \text{ W} \) to 7.07-19.44 W. Due to large clearances between the EFP rollers and housing, the pump body loses traction, the fuel is weakly injected into the line and returns to the inlet cavity [7].

Due to a decrease in the clearance area of the flow passage of the fuel supply line in Figure 2 (a, b) \( S_C = 0.00003847 \text{ m}^2 \) to \( 0.00000001539 \text{ m}^2 \), the power consumption of the EFP is 2-2.5 times increased, which is associated with hydraulic losses, namely with \( N_{hl} = 11.3-28.8 \text{ W} \) to 28.71-64.96 W [18, 19]. Due to the increase in the fuel supply line resistance, which is equal to clogging of the fuel filters and the fuel wire, the fuel poorly enters the fuel line.

3. The Results of Experimental Research

This research enables to control the technical condition of the fuel supply system elements - clogging of the fuel filters and the fuel supply line and wear of the EFP injection unit. In case of an abnormal operation of the fuel pump, leakage in its injection unit, contamination of the series elements of the fuel system, the necessary fuel supply to the engine injectors is not ensured [9], therefore, the stability of its operation [13, 14] is violated. Besides, the operation of the EFP in these conditions is accompanied by overheating and, ultimately, seizure, as a result of a severe contamination on the fuel induction through the coarse filter.

We carried out experimental research and a subsequent data analysis simulating failures in the fuel system. The simulation results are presented in Figs. 3, 4, 5.

When analyzing the data in Figure 3, it has been established that with a decrease in the diameter of the fuel supply line section of elements contaminated in series (for example, clogging of the fine fuel filter, the fuel supply line), the current consumption level increases. The research was carried out at a decrease in the supply voltage of the EFP in the range from 12.5 to 6.5 V.

An increase in the current consumption of the EFP is connected with an increase in the hydraulic resistance in the fuel system, for this reason the EFP rotor rotates under a considerably larger load, which results in the absorption of more energy.

Moreover, it is clear from Figure 3 that a significant increase in the current rate is observed from an equivalent section of 1 mm. The larger the supply voltage of the EFP, the more the current flows in its windings.
Let us analyze the data presented in Figure 4.

When analyzing the data in Figure 4, it has been established that with an increase in the diameter of leakages in the EFP pump body, the current consumption noticeably decreases. Due to the presence of clearances and leaks in the EFP injection unit, the fuel does not flow into the pumping cavity of the pump, as a result of which the rotor rotates freely, the consumed energy decreases with an increase in the equivalent leakage diameter.

Figure 4. Regularities of changes in the current rate $I$, A when simulating leakages $y$, % of the EFP injection unit.

Figure 5 shows the dependence of the change in the current consumption of the EFP at simultaneous leakages ($y$, %) and contamination in the fuel system $\varepsilon$. 

Figure 3. Regularities of changes in the current rate $I$, A when simulating clogging of fuel elements $D_{\text{ser}}$, mm (equivalent section diameter).
Figure 5. Regularities of changes in the current rate \( I, \) A at simultaneous leakages \( y, \% \) in the EFP injection unit and contamination of series elements of the fuel system \( \varepsilon. \)

An analysis of Figure 5 shows that the current consumption increased to the maximum of 4.2 A with an increase in the contamination \( \varepsilon \) to 0.96, and decreased to 2.2 A with an increase in leakage to 50%.

4. Conclusions

In the experimental part, we studied the dependence of the current consumption of the EFP on the electrical parameters of the drive motor \((U, R)\) and the technical condition of the main EFP elements \((\mu, S_{tot}, \Delta P)\). Due to the research, we obtained graphical dependencies of the current rate on:

1) contamination of series elements of the fuel system \( \varepsilon \), for example, fuel filters, fuel supply line;
2) fuel leakage through the EFP injection unit \( y, \% \);
3) simultaneous action of the contamination and leakage. The research has shown that with an increase in the contamination of the fuel system (Figure 3), the current consumption increases, moreover, it doubles to 6 A if the fuel supply line is almost completely blocked. In case of increasing leakages (Figure 4), the current rate decreased to the minimum value of 1.3 A at the maximum leakage of 58%. In case of a simultaneous action of the contamination and leakage (Figure 5), the indicators change as follows: the current consumption rises to the maximum value of 4.2 A with an increase in the contamination \( \varepsilon \) to 0.96, and decreases to 2.2 A with an increase in leakages to 50%.

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