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## METHODS OF DIAGNOSING VEHICLE DIESEL INJECTORS

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**Abstract.** The results of the method, of diesel injector state estimation are presented. On the basis of the hydrodynamic accumulator of the fuel supply process, there were obtained recommendations on the selection of design and adjusting parameters of the stand for checking the injectors. The criteria for quantitative estimation of diesel engine injector estimation are determined.

**Key words:** diesel fuel system, fuel system, bench tests, diagnostics, mathematical model, injector, determining the state of the injector.

## МЕТОДИКА ДИАГНОСТИРОВАНИЯ ФОРСУНКИ ТРАНСПОРТНОГО ДИЗЕЛЯ

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**Аннотация.** Представлены результаты разработки методики диагностирования состояния дизельной тепловозной форсунки. На основании гидродинамического расчета процесса топливopодачи получены рекомендации по выбору конструктивных и регулировочных параметров стенда для проверки форсунок. Определены критерии количественной оценки состояния форсунки транспортного дизеля.

**Ключевые слова:** дизельная топливная система, математическая модель, стендовые испытания, определение состояния форсунки.

## МЕТОДИКА ДІАГНОСТУВАННЯ ФОРСУНКИ ТРАНСПОРТНОГО ДИЗЕЛЯ

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**Анотація.** Надано результати розробки методики діагностування стану дизельної форсунки. На підставі гідродинамічного розрахунку процесу подачі палива отримані рекомендації з вибору конструктивних і регулювальних параметрів стенда для перевірки форсунок. Визначено критерії кількісної оцінки стану форсунки транспортного дизеля.

**Ключові слова:** дизельна паливна система, математична модель, стендові випробування, форсунка.

### Introduction

Used nowadays diagnostics methods of state of split-type fuel system components, medium rotating diesel engines, exploiting in Ukraine, does not allow effectively carry out such works in service station conditions. Efficiency is meant a set of time and material parameters: duration and service cost, the opportunity of identifying and eliminating the causes of work deterioration.

The putting into operation of fuel systems with electronic control will require full hardware upgrades of fuel system areas. Demand for servicing of fuel equipment system can be obtained from foreign manufacturers or deliver components for maintenance to service centers located abroad.

Creating of own diagnostics methods is alternative and relevant. Probably the

methodology being developed, should meet the following requirements:

- state evaluation is conducted by the parameters that characterize the dynamic processes in the fuel equipment;
- criteria for the evaluation of fuel equipment used by the system should simplify the process of service.

Such conditions can be performed if modern computer algorithms and systems are used in the methodology.

### Analysis of publications

The vast amount of transport diesels in Ukraine has a split-type fuel equipment with hydro-mechanical closed injectors. [1] The use of such injectors is perspective because, at implementation of electronic control by fuel supply, task of cycle supply and injection characteristic may be performed by solenoid valve installed on the high pressure fuel pump [2]. In operation these injectors are characterised by change of these settings:

- injection start pressure;
- effective flow area of sprayer;
- diametrical precision clearance in a pair of needle – housing of spray;
- diameter of closing zone of needle;
- change of spray needle stroke.

Typically, even at full disassembly of injectors it is problematic to determine these parameters with a high accuracy. Currently estimation of these parameters is carried out by using of compression stands, method of use, technology and equipment of which have not changed over the decades.

The majority of methods are based on the use of these stands, equipped with pressure gauges or electronic interpreters of pressure signal in the fuel pipe near the injector. Application of these stands does not allow to reproduce conditions of fuel supply identical to regular. With this diagnosis it is almost not considered the dependence on structural and regulatory parameters of injector and injection dynamic parameters, it is impossible to quantify these parameters in connection with a large variety of injectors sizes.

### The aim and problem definition

The aim of this research is the creation of a new method of transport diesels injector diagnosing,

which will be based on the obtained dynamic characteristics, determined on the stand at injector testing. To achieve this goal it is necessary to solve the following problems:

1. To create a model of hydrodynamic processes on the stand and injector during diagnosis.
2. To determine the volume of hydrodynamic accumulator for each injector which participates in the research.
3. To search the dependence on characteristics of the impact of injector structural and adjustment parameters change.

### Methods of diagnosis

The proposed here method involves measuring of the three parameters that vary over time - pressure of fuel in system, the amount of injected fuel and the amount of fuel that bypasses a drain. Measurements are carried out under continuous fuel supply in the volume attached to the injector nipple. In this volume, the pressure level exceeds the injection start pressure, pre-determined tightening the injector spring, by 15–25 %. Versatility of method (the ability to check the injectors of different engines) is achieved by changing the amount of hydraulic accumulator.

At the department of maintenance and repair of rolling stock of Ukrainian State University of Railway Transport was established a stand (fig. 1). It is designed to check the state of medium-speed diesels injectors.



Fig. 1. Stand of verification of medium-speed diesels injectors state

The stand is equipped with radial, triplex plunger high pressure fuel pump that injects fuel into the accumulator, connected by the pipeline with the diagnosed injector nipple. State electronic system provides the processing, conversion and submission to display the signal

from the pressure sensor installed in the fuel accumulator. The stand provides the ability to determine the consumption of injected fuel, and drainage.

**Simulation of hydrodynamic processes**

The current state of development of special software allows carrying out the detailed modeling of hydrodynamic processes at diagnosing what was used earlier by designers and researchers of fuel equipment. For this purpose one can use such software as Amesim, AVL BOOST HYDSIM [3], GTFUEL. They allow the engineer to model and conduct appropriate settlement research.

The task that is solved in the hydrodynamic modeling processes as related to the definition

of parameters stand test injectors. In dealing with this part of the research it is necessary to determine the volume of fuel accumulator, length and diameter of fuel pipes that connect the fuel pump with the accumulator and the accumulator with injector nipple, fuel pump shaft rotation frequency. The necessity to ensure effective checking of injectors of different diesel engines (Д49, К6S310DR, Д80, etc.) complicates the task. Therefore it is necessary conducting the settlement research using adequate mathematical model.

In carrying out this research in an environment AVL BOOST HYD SIM [3] it was composed model of stand hydrodynamic system to test the injectors (fig. 2).

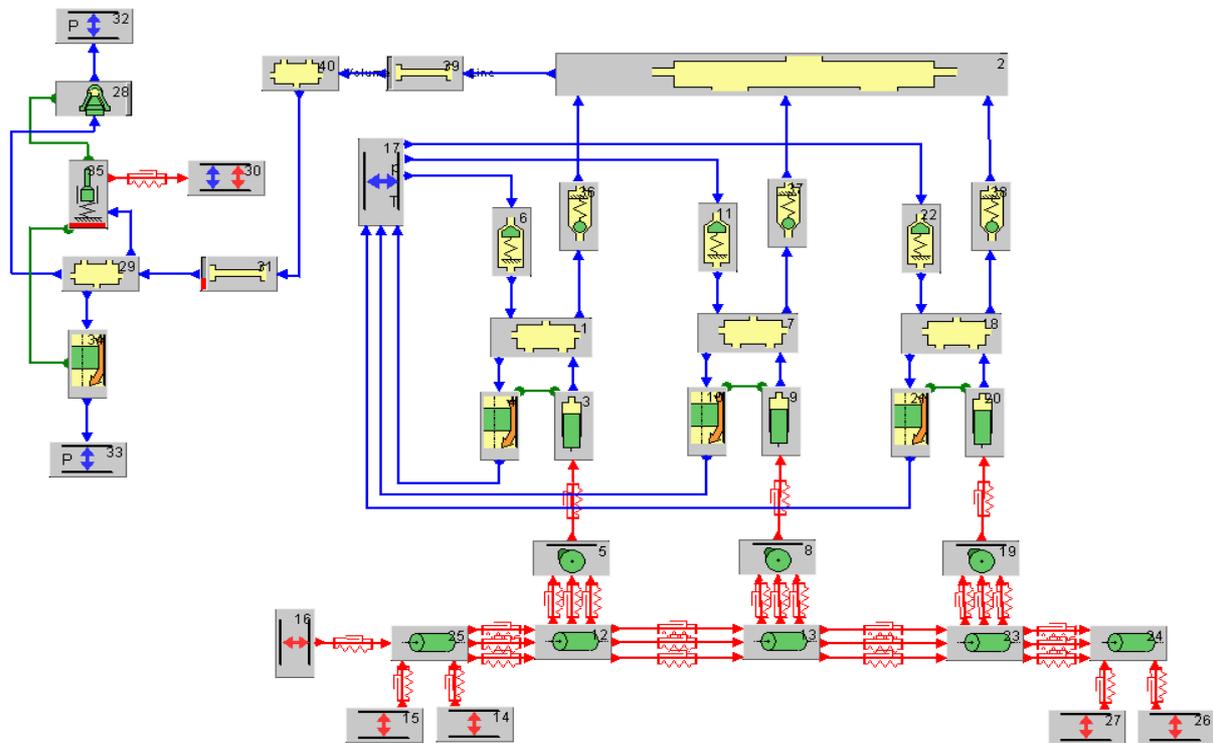


Fig. 2. Hydrodynamic model of processes on the stand in an environment AVL BOOST HYDSIM

The components of the model are the fuel pump of system Common Rail [2], which provides fuel injection to accumulator, connecting pipes and injector. The problem of leaks of fuel in pipelines and accumulator is solving on the basis of direct and reflected waves, by d'Alembert's method. In the simulation one focuses on the description of the processes occurring in the injector at the diagnostic by proposed method because the character of the injection in this case differs from the regular on the engine. A

simulation accuracy determines the effectiveness of the method itself.

**General provisions of model**

The problem of fuel leakage in the channel connecting the injector nipple and volume above the spray needle, is solved in submodel with concentrated parameters considering hydraulic friction. In submodel change in pressure is determined using the continuity equation

$$\frac{\partial p}{\partial t} = -\frac{\beta}{f} \cdot \frac{\partial Q}{\partial x}, \quad (1)$$

where  $f$  is cross sectional area of the channel;  $\beta$  is volumetric elasticity module, which takes into account fuel compressibility and deformation of the channel walls;  $Q$  is volumetric rate of fuel;  $t$  is time;  $x$  is longitudinal coordinate.

Qualitatively, the design of injector spray of hydrodynamic injection systems are identical. Features of this design are described in [1, 2].

Volumetric consumption of fuel passing through the sprayer is determined by the Bernoulli equation. Without significant loss of accuracy one can take immutability of consumption coefficients in specific sections. This assumption is justified if there is no reliable information about the value of these coefficients (eg, unknown dependence  $\mu$  on the value of needle rise). In this case, the equation is specified

$$Q_{inj} = \text{sign}(p_{in} - p_{out}) \times \mu_f \sqrt{\frac{2}{\rho} |p_{in} - p_{out}|}, \quad (2)$$

where

$$f = \sqrt{\frac{1}{\frac{1}{f_s^2} + \frac{1}{f_h^2}}}$$

$Q_{inj}$  is volumetric consumption;  $\mu_s$  and  $\mu_h$  are consumption coefficients for shutoff cone of spray and injector holes, respectively;  $f_s$  and  $f_h$  are passage sections areas for needle cone and injector holes, respectively;  $p_{in}$  and  $p_{out}$  are pressure in spray pocket and at the exit of injector holes, respectively;  $\rho$  is fuel density. To determine the consumption factor it is proposed to use experimental depending on the relative position of the spray needle [5].

In the spray model the limiting passage section is determined by the following equations:

$$\begin{aligned} \forall h \leq 0: f_p &= 0, \\ \forall h > 0: f_p &= \pi h \sin \frac{\alpha_r}{2} \times \\ &\times \left( d_c - h \sin \frac{\alpha_r}{2} \cos \frac{\alpha_r}{2} \right), \\ \forall f_p > f_c: f_p &= f_c = \frac{\pi d_c^2}{4} \end{aligned} \quad (3)$$

where  $h$  is movement of the needle;  $\alpha_r$  is cone angle;  $f_c$  and  $d_c$  are cross sectional area and diameter of the injector holes, respectively. If the area around the spray cone more the total area of injector holes,  $f_c$  is assigned to a section limiting (invariant of needle lifting).

The equation of needle motion of one spring injector has the form:

$$m_{pin} \frac{d^2 h}{dt^2} = P_a \cdot f_r'' + P_f \cdot f_r' - z_r \cdot (h_0 + h), \quad (4)$$

where  $m$  is weight of needle and injector parts which go with it;  $h$  is the needle rise;  $t$  is time;  $P_a$ ,  $P_f$  is fuel pressure in the well and in the pocket of spray;  $f_r'' = f_r' - f_r'$ ,  $f_r'$  is cross sectional area of the needle;  $f_r'$  is differential area of the needle;  $z_r$  is stiffness of injector spring;  $h_0$  is previous compression of injector spring.

#### The model of the fuel leaking process in the precision gap

The model of the fuel leaking process in the precision gap is based on the law of Hagen-Poiseuille [4], according to which taking laminar the flow passing through the annular gap of pair needle-spray without breaks. At the entrance to the annular gap, velocity profile is linear. The rate of fuel flow at the spray wall is zero, and at the needle wall corresponds to the speed of its movement. Fuel layer formed in precision gap provides significant force to shear of inner layers, so the fuel flow rate exceeds the speed of the needle movement to satisfy the principle of flow continuity.

Formed boundary layers impede the achievement of the maximum speed in the middle of the gap thickness. Velocity profile is parabolic and remains the same throughout the length of the precision gap (fig. 3).

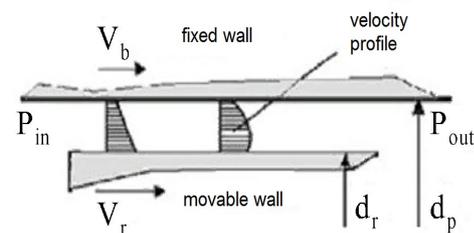


Fig. 3 Distribution of the flow in thin channel

For steady laminar flow through the annular gap, Navier-Stokes equation becomes

$$\frac{dp}{dx} = \mu \frac{d^2V}{dy^2}, \quad (5)$$

where  $x, y$  are movement coordinates;  $V$  is the rate of fuel in the  $x$  direction;  $p$  is pressure;  $\mu$  is dynamic viscosity ( $\mu = \nu\rho$ , where  $\nu$  is kinematic viscosity). Twice integrating equation (5) and after the reshuffle of the similar terms of an equation, we get fuel velocity profile as a function of  $y$

$$V(y) = \frac{1}{\mu} \frac{dp}{dx} \frac{dy^2}{2} + C_1 y + C_2. \quad (6)$$

Constants  $C_1$  and  $C_2$  can be calculated from the boundary conditions

$$\begin{aligned} V &= V_p, y = 0,5 + d_p, \\ V &= V_b, y = 0,5 + d_p. \end{aligned} \quad (7)$$

Substituting these boundary conditions to the equation (6), we get:

$$\begin{aligned} V(y) &= T_1 y^2 + \left\{ \frac{V_b - V_p}{R_b - R_p} - T_1 (R_b + R_p) \right\} \times \\ &\times y + V_b - \frac{V_b - V_p}{R_b - R_p} R_b + T_1 R_b R_p, \end{aligned} \quad (8)$$

where

$$T_1 = \frac{1}{2\mu} \frac{dp}{dx}.$$

In addition, assuming linear a pressure gradient along the length of the precision gap

$$\frac{dp}{dx} = \frac{P_{out} - P_{in}}{L}, \quad (9)$$

where  $L$  is the length of the gap.

Consumption through precision gap can be determined by the formula

$$Q = \int_{R_p}^{R_b} V(y) 2\pi y dy. \quad (10)$$

After substituting equations (3) and (4) in equation (8) and integrating, we obtain the dependence for calculating the leaks consumption

$$\begin{aligned} Q &= \frac{\pi}{\mu} \frac{P_{out} - P_{in}}{L} \times \\ &\times \left[ \frac{1}{4} (R_b^4 - R_p^4) - \frac{1}{3} (R_b + R_p) \right. \\ &\left. \left[ (R_b^3 - R_p^3) + \frac{1}{2} R_b R_p (R_b^2 - R_p^2) \right] \right. \\ &\left. + \pi (V_b - V_p) \times \right. \\ &\left. \times \left[ \frac{2}{3} \frac{R_b^3 - R_p^3}{R_b - R_p} - R_b (R_b + R_p) \right] \right. \\ &\left. + \pi \nu_b (R_b^2 - R_p^2) \right]. \end{aligned} \quad (11)$$

### Simulation results and recommendations for using the method of injector test

Presented in this article part of research allows to select the criteria for the evaluation of four selected parameters.

As a result of calculations injection characteristics were received and analyzed similar to those shown in fig. 4.

For operating range of change the precision gap  $\delta$  according to research data the consumption in drain is obvious dependence (table 1). A slight deviation  $\delta$  leads to increasing the drainage (16 mm<sup>3</sup> per micron of diametrical gap). Less informative is dependence on gap  $\delta$  and fixed one by fluctuations of the pressure in the hydraulic accumulator of injections frequency.

This dependence is nonlinear, but also is very informative for possible use for diagnosis. With the growing of gap  $\delta$  pressure recovery duration in the accumulator between injections increases. Only in the case of increasing the gap  $\delta$  to 0,02 mm or more value of fuel consumption by sprayer is falling.

To determine the possible change of force of the previous injector spring  $F_{sp}$  the most informative is the change in the amplitude of the pressure in accumulator  $\Delta P_{bat}$  and increasing with growth of this duration power of pressure restoration (table 2).

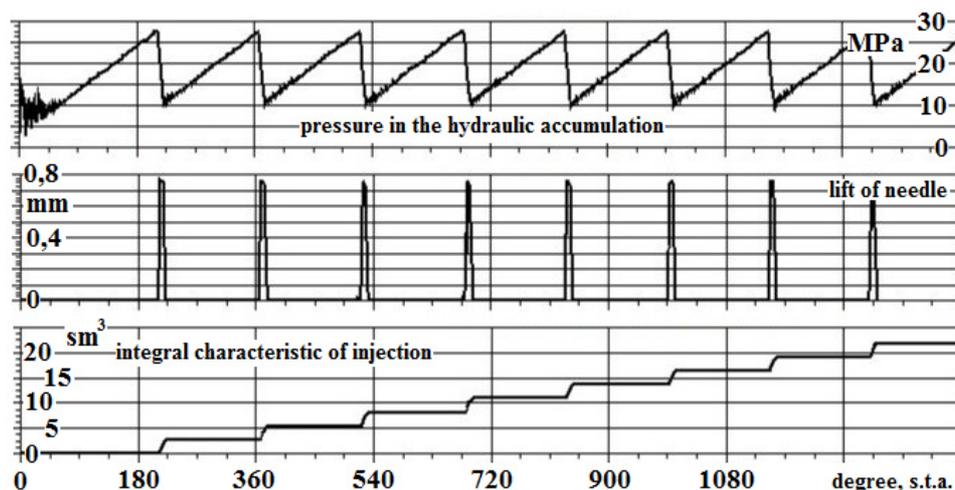


Fig. 4. Calculated characteristics of the fuel supply for injector of diesel engine Д 49 installed on the stand «SPC TRS A106.001»

Table 1 Dependence on diagnosed parameters and precision gap  $\delta$

$\delta$ , mm	Consumption in the drain for 5 s, mm <sup>3</sup>	$\Delta P_{bat}$ , MPa	Time for the 10th injection from time start, s	Consumption through sprayer for 5 s, cm <sup>3</sup>
0,006	19	230 – 120	3,86	20,5
0,008	50	230 – 120	3,875	20,5
0,01	88	230 – 120	3,877	20,5
0,02	750	230 – 120	4,0	18,7

Table 2 Dependence of parameters recorded by stand on consumption coefficient through sprayer

$F_{sp}$ , H	Consumption in the drain for 5 s, mm <sup>3</sup>	$\Delta P_{bat}$ , MPa	Time for the 10th injection from time start, s	Consumption through sprayer for 5 s, cm <sup>3</sup>
300	12	140 – 80	2,328	21
500	19	230 – 120	3,86	20,5
700	26	320 – 160	5,5	20

Research results of dependence of the parameters that are registered by stand, from passage intersection of spray are shown in (table 3).

There occurs an inverse dependence for injected fuel consumption. That also explains by the increase of the needle movement, and also by growth of spring force at compressing for bigger value with increasing of  $h$ .

Table 3 Dependence of the injector parameters on passage intersection of spray

$\mu$	Consumption in the drain for 5 s, mm <sup>3</sup>	$\Delta P_{bat}$ , MPa	Time for the 10th injection from time start, s	Consumption through sprayer for 5 s, cm <sup>3</sup>
0,5	19	230 – 120	4,0	19,5
0,6	19	230 – 120	3,92	20
0,7	19	230 – 120	3,86	20,5

Consumption change in the drain at increasing  $F_{sp}$  is secondary index associated with increasing of fuel pressure drop at the inlet and outlet of the

precision gap. Also informative is pressure reducing speed during the injection and nature of further increase of pressure. At the next com-

putational study the variable parameter is accepted consumption coefficient  $\mu$ , which can vary in the injector depending on coking of spray holes, mechanical damages. Changing of passing section for workable injector is reflected during the operation and consumption through sprayer respectively.

### Conclusions

The analysis of currently used methods of diagnosing of diesel injector showed the necessity for the creation of a new method based on getting the dynamic characteristics of injection. In the Ukrainian State Academy of Railway Transport was developed the stand for receiving and processing of dynamic characteristics in real time. The stand is equipped with radial triplex plunger high pressure fuel pump that pumps fuel into the accumulator connected with injector by pipeline. Electronic system of stand provides the processing, conversion and injection to display of signal from the pressure sensor installed in the fuel accumulator. There is the ability to determine the injected fuel consumption and drainage in the stand.

In developing of method of diagnosing the injector state in the environment AVL BOOST HYDSIM was made stand model of hydrodynamic system for injector test. At modeling the main focus was made on descriptions of the processes occurring in the injector during the verification by the proposed method, since the character of the injection in this case differs from the regular one on the engine.

As a result of computational study it was calculated for each injector the value of hydraulic accumulator volume, length and diameter of pipelines, shaft rotational speed of the fuel pump.

The obtained calculated characteristics of the fuel supply made it possible to identify regularities that connect the basic design and regulatory parameters of injector: the maximum movement of spray needleing; effective flow section of injector; force of the needle previous tightening; precision gap in a pair of needle-spray with a change in pressure in the accumulator, fuel

consumption in the drain and fuel passing through spray holes.

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