Modernization of the fuel supply system in the internal combustion engine by electronic control of the ring valve

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Abstract. The research was carried out in order to develop a method for skipping fuel supplies (turning off individual piston strokes) at low frequencies of crankshaft rotations and at partial engine operating modes with direct-acting fuel supply systems to increase fuel efficiency. The developed method is easily implement using a ring-type discharge valve with electronic control. A valve made in the form of a split elastic ring and installed in a high-pressure line above the plunger pair controls the fuel supply. An electromagnet, located in the cavity of the annular valve, controls the valve, using an electronic regulator, acting at the right moment according to the signals coming from the sensors of the engine crankshaft speed, the volume of incoming air and the position of the piston. The proposed direct-acting fuel supply system with an electronically controlled ring valve reliably ensures the speed and load characteristics of the engine by affecting the number of cyclic feeds. With a decrease in the load and speed of the engine crankshaft, the number of cyclic fuel supplies decreases due to a decrease in signals sent to the electromagnet winding and, as a result, the valve does not attract the fuel and misses the fuel supply. Reducing the unevenness of the fuel supply by the dynamic component that occurs when the supply is switch off is ensured by reducing the inertia of the regulator due to the electronic control of the ring valve. The developed mathematical model of a direct-acting fuel supply system with an annular discharge valve allows us to reveal the relationship of fuel supply parameters with the design dimensions of the split ring. Such direct-acting fuel supply system with an electronically controlled discharge valve allows, due to the skipping of working strokes in low-load and idle modes, redistributing the provided amount of fuel to the working cylinders, significantly reducing fuel consumption.

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1 Introduction

Agricultural production is one of the main sectors of the country's economy, which constantly needs to attract mobile energy resources to perform technological processes in crop production and animal husbandry. The most promising way to ensure the efficiency of the use of technical means in the agro-industrial complex is the modernization of the fuel supply system of the internal combustion engine [1].

Fuel supply systems of direct action of diesel engines have proven themselves well throughout the entire period of the long-term operation. Their wide distribution became possible thanks to the modified design of all elements of the system, unification, maintainability and unpretentiousness.

They work most effectively in modes close to nominal [2]. A study of tractor and combine diesels in operation has shown that most of the time in the balance is occupied by the work that requires only a partial load on the engine [3]. Similar results were shown by our earlier observations in conditions of a very high culture of equipment operation in the Berthold farm (Bavaria, Germany).

With a decrease in the load on the engine and the transition to low rotational speeds of its crankshaft and at idle, the efficiency of the fuel supply system deteriorates significantly due to a decrease in the value of the cyclic supply and an increase in its irregularities between sections and between cycles [4].

One of the options for preventing a decrease in the cyclic supply and the efficiency of diesel under partial loads is the method of turning off the cylinders [5]. This method proved itself when idling engines D-108, D-160 and D-180 of the Chelyabinsk Tractor Plant and A-01M of the Altai Engine Plant.

The positive effect of turning off the cylinders was obtained on the basis of the eight-cylinder engine of the Kamaz-740 car [6]. The disconnection of a part of the cylinders was carried out by connecting the high-pressure pump discharge line with the low-pressure line using a controlled electromagnetic valve in the fuel supply system.

Research is underway to analyse the turn-off of the cylinders of tractor and automobile diesels with simultaneous action on the valves of the gas distribution mechanism in partial load modes [7] to reduce losses on the piston pumping strokes in the suction and compression cycles. A reduction in the hourly fuel consumption of diesel up to 38% was found when some of the cylinders were switch off in low-load modes [8].

The company "MTU" (Germany) has modernized diesel engines 12V956TB, introducing the technology of sequential shutdown of cylinders [9].

Tula Technology [10] developed the method of disconnecting cylinders on an engine operating using a Miller cycle with an adjustable suction stroke through the control of the valve lift of the gas distribution mechanism. Studies have shown the possibility of reducing the engine fuel consumption by 23%.

The cylinder shut-off method is widely used on gasoline engines of passenger cars. Mercedes used the Active Cylinder Control (ACC) system to automatically turn off half of the cylinders on eight- and twelve-cylinder engines on its 500- and 600-series cars. The Multi-Displacement System (MDS) is used in Jeep, Dodge and Chrysler vehicles. General Motors has also implemented a Displacement on Demand (DoD) system in its cars. Honda has developed a Variable Cylinder Management (VCM) system. Since 2012, Volkswagen has been using a similar system called Active Cylinder Technology (ACT), but already in four-cylinder TSI engines with a volume of 1.4 litters. Audi also supplied its powerful V8 and V12 engines first, and then four-cylinder 1.4-liter engines with the COD (cylinder on demand) system.

The common disadvantages of the cylinder shutdown method on various engines are an increase in the required starting speed and the uneven rotation of their crankshaft.

The purpose of the scientific work is to study the method of skipping fuel supplies when operating a diesel engine under low loads with an electronically controlled ring valve and a mathematical description of its functioning.

2 Conditions, materials and methods of research

We have conducted research on the development of a method for skipping the fuel supply by alternating in all cylinders when operating a diesel engine with a partial load. This method will reduce the impact of the disadvantages of the cylinder shutdown method on the engine operation.

Preliminary calculations carried out for the D-240 four-cylinder tractor diesel engine showed that a consistent increase in the number of disconnected cylinders leads to an increase in the unevenness of rotation of its crankshaft and the conditional values of the starting revolutions. The calculation data are given in table 1.

From the data in the table, it can be seen that the values of δ are greater than the values of unevenness recommended for tractor diesels - 0.004...0.010, but slightly. To reduce δ to 0.01, it is necessary to start the engine when working using all cylinders or increase the moment of inertia of the flywheel.

Reducing the inertia of its mechanical regulator is essential for improving the quality of fuel supply. Electromechanical regulators with annular discharge valves, which can ensure the passage of fuel supplies, have shown themselves well in improving the quality of fuel supply in any modes [11].

The annular discharge valve is installed above the plunger pair of the high-pressure pump as shown in Figure 1.

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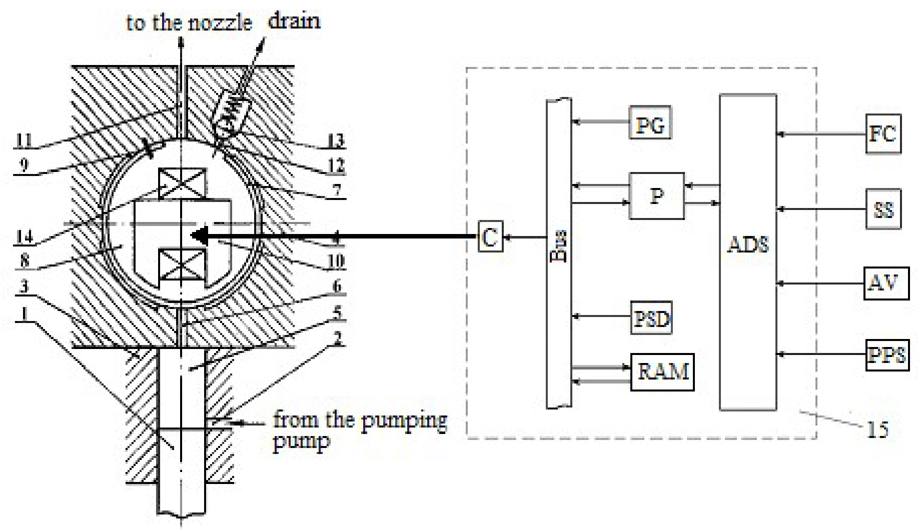

Fig. 1. Diagram of an electromechanical regulator with an annular discharge valve: 1 - plunger; 2, 6, 11, 12 - channels; 3 - sleeve; 4 - valve body; 5, 8 - cavities; 7 - split ring; 9 - pin; 10 - electromagnet; 13 - drain valve; 14 - electromagnet coil; 15 - electronic regulator; PSD - permanent storage device; PG - pulse generator; ADC - analog to digital converter; P – processor; RAM - random access memory; C – switchboard; PPS - piston position sensor; AV - incoming air volume sensor; SS - engine crankshaft speed sensor; FC - fuel supply control lever.

A split ring 7 is built into the valve body 1, fixed on one side with a pin 9. An electromagnet 10 with a coil 14 is installed in the valve cavity 8. The free side of the ring is capable of blocking the drain channel 12.

To supply fuel to the cylinder through the nozzle, the plunger 1 of the pump pumps fuel through the discharge valve by lifting the split ring 7, while the electromagnet 10 additionally attracts the ring, which covers the drain channel 12 with a free edge.

When the electromagnet is de-energized, the split ring is lower and the drain channel 12 opens. The high-pressure line connects to the drain and fuel injection into the cylinder stops. The residual fuel pressure in the high-pressure line is provided by the drain valve 13.

Thanks to the electronic regulator 15, the annular discharge valve can adjust the fuel injection advance angle and the feed duration (the value of the cyclic feed), determined by the moment and duration of the control pulse to the electromagnet.

The timely supply of a pulse to the electromagnet is provided in accordance with the data received from the sensors of the piston position, the volume of incoming air, the rotational speed of the engine crankshaft and the fuel supply control lever.

To skip the supply, when the plunger is injected with fuel, the control pulse is not applied to the electromagnet and the fuel is sent directly to the drain. The elasticity of the ring is calculated so that the height of its lifting and the movement of the free edge from the fuel pressure is not enough to close the drain channel 12.

Thus, an annular discharge valve with an electromagnet can regulate the operating modes of a diesel engine by passing fuel supplies depending on the load. When the load decreases, it is not the amount of cyclic feeds that decreases, but the number of missed feeds increases. In this case, the value of the cyclic feed will be equal to the nominal value. This will have a positive effect on the quality of fuel spraying, mixing and combustion. In this connection, it is expected to increase the efficiency of the engine.

3 Results of the study

A mathematical model of an electrically controlled fuel supply system with an annular discharge valve has been developed, taking into account the peculiarities of its operation, based on the use of the method of hydrodynamic calculation of existing direct-acting fuel supply systems.

The movement of fuel in the high-pressure nozzle was considered taking into account the pressure of waves coming towards at the speed of sound. The fuel flow rates in the injection and control channels were determined based on the continuity equation of the fluid flow.

To describe the ongoing process in a high-pressure pump, the equations of the volume of liquid (fuel) and the dynamic equilibrium of a ring-type discharge valve were used:

$$6 \cdot n_n \cdot \beta_a \cdot V_a \cdot \frac{dp_a}{d\phi} = \left(f_n \cdot s_p - \sigma_{iv} \cdot Q_o - \sigma_{vc} \cdot Q_1 - Q_3 - Q_4 \right). \quad (1)$$

$$6 \cdot n_n \cdot \beta_{vc} \cdot V_{vc} \cdot \frac{dp_s}{d\phi} = \left(\sigma_{vc} \cdot Q_1 - \sigma_{cc} \cdot Q_2 - f_{hp} \cdot s_{ci} \right) \cdot \sigma_2 \quad (2)$$

$$\frac{dV_{fv}}{d\phi} = -\left(\sigma_{vc} \cdot Q_1 - \sigma_{cc} \cdot Q_2 - f_{hp} \cdot s_{ci} \right) \cdot \frac{\sigma_3}{6 \cdot n_n}. \quad (3)$$

$$6 \cdot M_k \cdot n_n \frac{ds_{vc}}{d\phi} = \left(\left(f_i \left(p_a - p_s \right) + \right. \right.$$
$$\left. + f_i \cdot \rho_f \cdot s_p \left(s_p - s_{ci} \right) - p_{rp} \cdot b \cdot D - f_i \cdot p_s \cdot \sigma_c \right) \sigma_{vc}; \quad (5)$$

where p_a, p_s are the pressure of the supplied fuel in the cavities above the plunger and in the suction channel, Pa;

f_{cc}, f_i, f_{hp} are the cross–sectional areas of the control channels, injection and high pressure lines, mm^2;

s_p is the speed of the plunger, m/s;

s_{ci}, s_{cc}, s_{vc} are the fuel feed rates in the channels injection, control and in the valve cavity, m/s;

V_a, V_{vc}, V_{fv} are the volume in the cavities above the plunger, in the valve cavity and free volume, m^3;

ρ_f is the density of the supplied fuel, kg / m^3;

Q_0, Q_1, Q_2, Q_3, Q_4 are the fuel consumption in the system of equations in the intake channel, in the discharge channel, in the control channel, through the plunger gaps in the spool part and in the piston part, kg/s;

M_k is the weight of the ring with a cut, kg;

n_n and φ are the rotational speed (min^{-1}) and the angle of rotation (degree) of the cam shaft of the pump;

σ_{iw}, σ_{vc}, σ_{cc}, σ_2, σ_3, σ_c are the logical elements;

h_{rr} is the rise of the split ring, mm;

p_{rp} is the radial pressure of the ring, Pa;

b and D are the width and diameter of the ring, mm;

β_a, β_{vc} are the compressibility coefficient of fuel in the cavities above the plunger and in the valve cavity.

Formula (1) is the balance of the fuel volume in the cavity above the plunger. The following equations (2) and (3) are the balance of the fuel volume in the valve cavity. If there is no gap, the expression (2) is used for calculation, if there is a gap – (3).

The amount of fuel entering the cavity per unit of time with the ring valve raised in equation (2) is equal to the flow through the discharge channel, with the exception of fuel in the control channel and in the discharge pipe. When the control voltage is applied to the electromagnet, the step function is $\sigma_{cc} = 0$. Equation (3) (its left part) describes the volume changes (V_{fv}) per unit of time in the cavity (V_{vc}) of the ring. At the same time, the right part of this equation demonstrates an increase in the volume of fuel in the cavity of the V_{vc}, which leads to a decrease in the free volume of the V_{fv}.

The dynamic equilibrium of the annular discharge valve is described by formulas (4) and (5). In equation (4) the left part is the inertia force of the split valve ring, and the sum of the fuel pressure forces and the valve force in the right part.

The following logical elements were taken into account: with $p_a \geq p_{iw}$ $\sigma_{iw}=1$ was taken; with $p_a \leq p_{iw}$ $\sigma_{iw} = -1$ was taken; when the intake window was open, $\sigma_{iw} = 0$ was taken. When the ring was pressed against the body, $\sigma_c=1$ was taken; in other cases, $\sigma_c=0$; with $p_a \geq p_s$, $\sigma_{vc}=1$ was taken; with $p_a \leq p_s$, $\sigma_{vc} = -1$ was taken.

The order of use in the calculation of equations (2) and (3) is determined by the logical elements σ_2 and σ_3: so for $V_{vc} \geq 0$ and $p_{vc}=0$, $\sigma_2=0$ and $\sigma_3=1$ were taken; for $p_{vc}>0$ and $V_{vc}=0$ $\sigma_2=1$ and $\sigma_3=0$ were taken.

Injection pressure and fuel consumption are determined by the following expressions:

$$p_{\phi}^{1} = \frac{(\mu f)_p^2}{(\mu_s \cdot f_h)^2}(p_f - p_g) + p_g, \tag{6}$$

$$Q_n = \mu_p \cdot f_h \cdot \sqrt{\frac{2}{\rho_f}} \cdot \sqrt{p_n - p_g}, \tag{7}$$

where $(\mu f)_p$ is the effective section of the atomizer, mm^2;

μ_p, μ_s is the fuel consumption coefficients in the plunger sections and spray holes;

p_g is the gas pressure in the cylinder, Pa;

p_f is the fuel pressure in front of the needle cone, Pa;

f_h is the cross-sectional area of the spray holes, mm^2.

For the calculation, the fuel injection process was divided into a number of stages, from the beginning of the plunger movement and the lifting of the annular discharge valve to the landing of the nozzle needle cone on the locking belt (completion of injection).

Calculations carried out using these equations made it possible to clarify the design dimensions of the developed fuel supply system with an electronically controlled annular discharge valve, in particular, the parameters determining the stiffness of the ring and the volume of the valve cavity: diameter (D), width (b) and thickness (t) of the split ring.

The adequacy of the developed mathematical model was checked by comparing the calculated data with the experimental results. Previously, the design dimensions of the annular discharge valve were assumed to be equal to D=20 mm, b=10 mm, t= 0.5 mm. The rotational speed of the camshaft of the fuel injection pump with a dimension of 1TN-9X10 is assumed to be n_n = 600 min^{-1}, the pressure in the nozzle is P_0 = 1.0 MPa with full cyclic fuel supply with the FD-22 nozzle.

Table 2 shows the calculated (C) and experimental (E) fuel pressure values in the nozzle and the values of the cyclic fuel supply.

Table 1. Calculated and experimental pressure values in the nozzle fitting and cyclic fuel supply

Indicators		**Angle of rotation of the crankshaft, degree**								
		4	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
Pressure in the nozzle fitting, MPa	**C**	0	25	45	50	52	53	20	0	0
	E	0	23	46	48	50	54	18	0	0
Cyclic fuel consumption, g/cycle	**C**	0	4.2	6.2	6.3	6.3	6.4	6.5	3	0
	E	0	5.1	6.0	6.2	6.3	6.4	6.5	3.2	0

https://doi.org/10.1051/bioconf/20225200028

A comparative analysis of the calculated and experimental data revealed that the deviation is no more than 3%, which confirms the adequacy of the mathematical model.

Fig. 2 shows the results of a study of the main performance indicators of the D-240 diesel engine among the number of cylinders operating simultaneously, i.e. when one, two and three cylinders are switched off, respectively. Experiments have shown that when the cylinders are switched off, the unevenness between the fuel supply sections also changes.

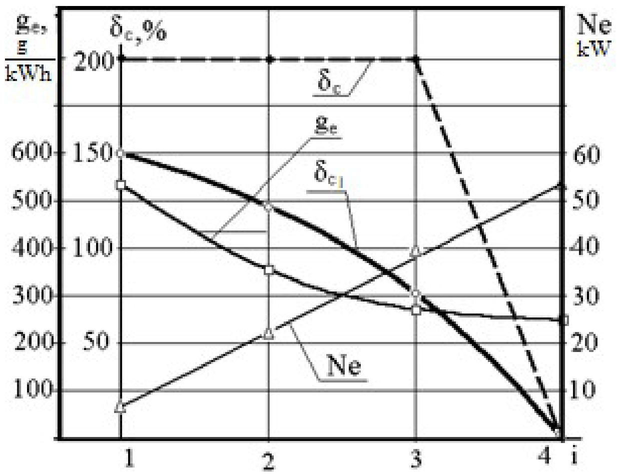

Fig. 2. Dependences of specific effective fuel consumption (g_e), power (N_e) and unevenness between sections (δ_c) of diesel D-240 on the number of working cylinders (i).

It is proven that the unevenness increases as the number of disconnected cylinders increases. The specific effective fuel consumption increases significantly and the effective power decreases (fig. 2).

Turning off the cylinders significantly affects the minimum-stable engine crankshaft speed. So when working using four cylinders, it was 750 min^{-1}, when using one – 700 min^{-1}.

Disconnecting one of the two cylinders of the D-21A engine with an effective power of N_e = 3 kW ensured a reduction in the specific fuel consumption from 700 to 420 g/kWh.

The calculated and experimental data obtained allow us to establish the possibility of regulating the engine crankshaft speed by passing fuel supplies depending on the load. For example, reducing the load by 1% makes it possible to skip every hundredth working stroke, by 10% – every tenth, by 20% – every fifth, etc. Such regulation makes it possible to inject the full fuel rate in each operating cycle, and therefore, as the load decreases, the specific fuel consumption will decrease, and the load characteristic itself will change smoothly.

Thus, turning off the cylinders, or even better, skipping the working strokes (fuel supply) as the load decreases are an effective way to increase the fuel efficiency of diesels.

4 Conclusion

The following conclusions can be made.

A direct-acting fuel supply system with an electronically controlled annular discharge valve ensures reliable regulation of the engine shaft rotation speed by passing fuel supplies while reducing the load.

The develop mathematical model of the fuel supply system with an electronically controlled ring valve allows you to establish the relationship and perform calculations of the design parameters of the fuel supply system (switching off the working strokes of the pistons) of the engine.

The effect of the proposed fuel supply system with an electronically controlled injection ring valve is manifested in an increase in the fuel efficiency of a diesel engine, especially in partial load and idle modes. So the diesel D-21A specific consumption decreased from 700 to 420 g/kW·h in the Ne = 3 kW mode.

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