Regulating characteristics of a diesel engine working on natural gas

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Abstract. The article presents regulating characteristics of a diesel engine according to the fuel injection advance angle during the work of engine on a gas-diesel process. Currently, for many manufacturers the task of reducing production costs is a key priority. In agriculture the essential expenditure item is made up of costs for mobile power facilities fuel. One way to decrease these costs is to use alternative, cheaper fuels. Natural gas is one of them. Diesel is the most common type of engine in agriculture. Though a lot of research on converting diesel engines to natural gas have been carried out, the problem of transition of high performance diesel engines of low dimension to natural gas is still understudied. Diesel D-245.7 (4CHN11/12.5) was taken as the object for the research. The aim of study is converting diesel to a gas-diesel process. Carrying out bench tests with recording regulating characteristics according to the fuel injection advance angle was one of the research stages. As the result of the bench tests there have been established the parameters of the combustion process, heat release characteristics, and effective indicators at different fuel injection advance angles when working on diesel and gas-diesel process.

1. Introduction and aim of the research
One of the basic tasks of any manufacturer nowadays is cutting production costs. The considerable part of agricultural production cost is made up of machine-and-tractor fleet fuel expenditures. The solution to this problem can be found through using cheaper alternative fuel.

Natural gas is among perspective alternative fuels. Its advantages are evident. Natural gas has low cost (less than 50% of petrol or diesel fuel cost). This natural resource is in good supply in the country, gas pipeline system is widespread. There are some challenges with filling and storage of natural gas in auto and tractor facilities but these problems can be coped with.

In agriculture the types of machinery equipped with diesel engine as a source of power are most commonly used. Though a lot of research on converting diesel engines to natural gas have been carried out, the problem of transition of high performance diesel engines of low dimension is still understudied [1].

When converting diesel to work on natural gas (NG) some problems are to be solved. First of all, it should be noted that diesel cannot work only on natural gas without any structural changes. There are two ways for transition diesel engine to natural gas – the conversion of it into gas engine and gas-diesel engine. Conversion into gas-diesel is more reasonable. By this way of conversion there is no need to make significant changes in the design of a diesel [2].
2. Methods of research
At the Department of Heat engines, Automobiles and Tractors of the Vyatka State Agricultural Academy the studies on converting diesel engines to natural gas were carried out. Diesel D-245.7 (4CHN11/12.5) equipped with charging and aftercooling systems was taken as the object for the research. By carrying out the gas-diesel process with this engine natural gas is forced into the intake manifold before the turbocharger through gas mixing and metering unit, ignition charge of diesel fuel is admitted through standard fuel system [3].

3. Results and discussion
When converting diesel to natural gas the indication was carried out and indicator diagrams at different fuel injection advance angles (FIAA) were obtained [4].

In figure 1(a) there are combined indicator diagrams of a diesel process at FIAA $\Theta_{inj} = 7^\circ$, $9^\circ$, $11^\circ$ at nominal engine speed $n=2400 \text{ min}^{-1}$ (nominal speed mode) and mean effective pressure $p_e = 0.947 \text{ MPa}$. As the graphs show, by later injection of diesel fuel ($DF$) the maximum pressure of the cycle $p_{z\max}$ decreases and the whole combustion process is moved to expansion line. If at optimum value of FIAA ($\Theta_{inj} = 9^\circ$) the maximum value of gas pressure $p_{z\max} = 13.8 \text{ MPa}$ and is reached at the angle $\varphi_z = 6.5^\circ$ of crankshaft rotation after top dead center (TDC), at higher value $\Theta_{inj} = 11^\circ$ gas pressure in the cylinder rises to $p_{z\max} = 14.0 \text{ MPa}$ and is reached at angle $\varphi_z = 6.3^\circ$ degree of crankshaft rotation after TDC [5]. The points corresponding to the beginning of visible combustion at indicator diagrams recorded for DF injection advance angles $\Theta_{inj} = 7^\circ$, $9^\circ$, $11^\circ$ lie on compression curve at angle values $\varphi_c = 1.0^\circ$ of crankshaft rotation after TDC and $\varphi_c = 0^\circ$, $1.5^\circ$ of crankshaft rotation before TDC, respectively. The period of ignition delay is $\varphi_i = 8.0^\circ$, $9.0^\circ$, $9.5^\circ$, respectively [6].

**Figure 1.** Combined indicator diagrams at various FIAA at $n=2400 \text{ min}^{-1}$, $p_e = 0.947 \text{ MPa}$: (a) diesel process, (b) gas-diesel process.

In figure 1(b) there are combined indicator diagrams of a gas-diesel process at injection advance angle of ignition diesel fuel = $5^\circ$, $7^\circ$, $9^\circ$ at nominal engine speed $n=2400 \text{ min}^{-1}$ and mean effective pressure $p_e = 0.947 \text{ MPa}$. Similar to diesel working on DF, at later injection the maximum pressure of the cycle $p_{z\max}$ decreases. The specific feature of indicator diagrams at FIAA $\Theta_{inj, gd} = 5^\circ$ and $7^\circ$ is that after the TDC there is a small segment up to the point corresponding to the maximum combustion pressure $p_{z\max}$ where the current value of indicator pressure falls [7].
Thus, the pattern of change of gas pressure in indicator diagrams at transition from diesel to gas-diesel process is maintained. In all cases of increasing FIAA the value of the maximum combustion pressure $p_{z\text{ max}}$ rises and the point of reaching it moves to the left of the indicator diagram, closer to TDC [8].

In a diesel process at earlier FIAA due to low temperature, pressure, and insufficient turbulization in the cylinder there is a delay of spontaneous combustion of diesel fuel ignition charge. Simultaneously, the time of warming up and droplet evaporation increases. The formation of initial radical sightings of chemical reactions goes slowly. The period of ignition delay increases and in the conditions of continuing injection it leads to accumulation of a large amount of fuel in the cylinder. When temperature in the cylinder achieves its critical point, self-ignition occurs, all the fuel starts to burn quickly. The rate of pressure rise increases significantly, the greater part of fuel burns away before TDC. This results in increasing maximum pressure of the cycle $p_{z\text{ max}}$, the point of achieving maximum pressure moves to the left, closer to TDC, compression work rises, expansion work falls. Indicator parameters of the work process go down, loads on the cylinder-piston group increase [9].

During the work on a diesel process at later FIAA the fuel is injected into the air charge which is characterized by high values of pressure and temperature. Under these conditions the rate of the pre-flame reactions rises, though the ignition delay period decreases. However, the timing of the start of visible firing moves to the right of the indicator diagram due to late injection. The greater part of the fuel burns away after the piston passes TDC that leads to decrease in maximum pressure of the cycle $p_{z\text{ max}}$. A larger portion of heat released by burning is wasted in the cylinder walls for useless warming-up of the cooling system. Work output of the cycle decreases, fuel consumption rises [10].

In a gas-diesel process the fuel igniting mechanism has some specific features. The methane-air mixture inside the cylinder of the diesel cannot self-ignite in any way due to too low temperature at the end of the compression. In order to ignite it a small ignition charge of DF is used. Under the given conditions in the cylinder of a diesel DF self-ignites well and becomes a powerful source of igniting the methane-air mixture [11]. Thus, ignition of methane-air mixture is connected with spontaneous combustion of ignition charge of DF, not by temperature and pressure in the cylinder. As the ignition of methane-air mixture is connected with spontaneous combustion of ignition charge of DF, it may be concluded that the basic principles of changes in indicator diagram in a gas-diesel process are similar to a diesel one.

In figure 2 there are graphic charts of combustion process at different FIAA in nominal speed mode.

![Figure 2. Combustion process parameters at $n=2400$ min$^{-1}$, $p_e = 0.947$ MPa: —— diesel process, – – – gas-diesel process.](image-url)
Comparing the graphs of diesel process (work on DF) and gas-diesel processes (work on NG) it can be noted that combustion process parameters increase when the engine runs on NG in contrast with DF use. The maximum mean temperature of gases in the cylinder $T_{\text{max}}$ is significantly higher by NG using than with DF. At FIAA $\Theta_{\text{inj}} = 7^\circ$ when converting to NG the temperature $T_{\text{max}}$ rises from 1940 K to 2350 K, at $\Theta_{\text{inj}} = 9^\circ$ the temperature $T_{\text{max}}$ grows from 2020 K to 2420 K. The maximum combustion pressure $P_{z\text{max}}$ by using NG is higher. At $\Theta_{\text{inj}} = 7^\circ$ the pressure $P_{z\text{max}}$ grows from 13.0 MPa to 14.6 MPa. At $\Theta_{\text{inj}} = 9^\circ$ the pressure $P_{z\text{max}}$ grows from 13.8 MPa to 15.4 MPa. At $\Theta_{\text{inj}} = 7^\circ$ the pressure ratio $\lambda$ increases from 1.55 to 1.85 when converting to NG, at $\Theta_{\text{inj}} = 9^\circ$ the value of $\lambda$ increases from 1.60 to 1.92. The maximum pressure rise rate $(dp/d\phi)_{\text{max}}$ is significantly higher by NG using than with DF. At $\Theta_{\text{inj}} = 7^\circ$ when converting from DF to NG the $(dp/d\phi)_{\text{max}}$ value increases from 0.68 MPa/degree to 0.93 MPa/degree, at $\Theta_{\text{inj}} = 9^\circ$ the $(dp/d\phi)_{\text{max}}$ value increases from 0.78 MPa/degree to 1.08 MPa/degree. The value of ignition delay period $\phi_i$ at $\Theta_{\text{inj}} = 7$ degrees increases from 8 to 9.5 degrees of crankshaft rotation. At $\Theta_{\text{inj}} = 9^\circ$ when diesel works on NG and DF the angles $\phi_i$ are equal and this value is $\phi_i = 9.0$ degrees of crankshaft rotation [12].

Increase of pressure and temperature of gases in the cylinder in gas-diesel process can be explained by higher rate of natural gas burning. Volumetric mechanism of ignition predominates [13].

In figure 3 there are graphs of heat release characteristics at different FIAA in nominal speed mode.

Comparing work of a diesel on DF and NG it can be noted that values of heat release characteristics increase when the engine runs on NG in contrast with DF use. The crankshaft rotation angle corresponding to the timing of maximum temperature in the cylinder $\varphi_{T\text{max}}$ is larger when the engine runs on NG than with DF use. At $\Theta_{\text{inj}} = 7^\circ$ when converting from DF to NG the value of $\varphi_{T\text{max}}$ grows from 9.5 degrees of crankshaft rotation after TDC to 10.5 degrees of crankshaft rotation after TDC. At $\Theta_{\text{inj}} = 9$ degrees the value of $\varphi_{T\text{max}}$ increases from 8.0 degrees of crankshaft rotation after TDC to 9.5 degrees of crankshaft rotation after TDC. The value of active heat release, at the time of peak firing pressure in the cylinder $\chi_i P_{z\text{max}}$ is higher when the engine runs on NG. At $\Theta_{\text{inj}} = 7^\circ$ the value of $\chi_i P_{z\text{max}}$ grows from 0.59 to 0.71, at $\Theta_{\text{inj}} = 9^\circ$ the value of $\chi_i P_{z\text{max}}$ grows from 0.63 to 0.76. The value of active heat release, at the time of maximum temperature in the cylinder $\chi_i T_{\text{max}}$ is higher when the engine runs on NG. Thus, at $\Theta_{\text{inj}} = 7^\circ$ the value of $\chi_i T_{\text{max}}$ increases from 0.66 to 0.80, at $\Theta_{\text{inj}} = 9^\circ$ the value of $\chi_i T_{\text{max}}$ grows from 0.70 to 0.82. The value of maximum rate of relative heat release $(d\chi/d\phi)_{\text{max}}$ is also higher when engine works.
on NG that on DF. At $\Theta_{inj} = 7^\circ$ the value of $(d\chi/d\phi)_{\text{max}}$ grows from 0.14 to 0.155, at $\Theta_{inj} = 9^\circ$ the value of $(d\chi/d\phi)_{\text{max}}$ grows from 0.15 to 0.165.

When studying the values of the parameters it can be said that in a gas-diesel process the greater part of fuel is consumed at the initial phases of combustion process before the time of reaching maximum values of pressure and temperature in the cylinder [14].

As the result of the research, all the criteria considered, the final fuel injection advance angles have been chosen: for diesel process $\Theta_{inj_d} = 9^\circ$, for gas-diesel process $\Theta_{inj_{gd}} = 7^\circ$. Performance indicators for both processes are shown in comparison in table 1 [15].

Table 1. Performance indicators of D-245.7 diesel at optimal fuel injection advance angles (at nominal load).

| Operating mode | $\Theta_{inj}$ | $p_{\text{max}}$, MPa | $T_{\text{max}}$, K | $(dp/d\phi)_{\text{max}}$ |
|----------------|---------------|----------------------|-------------------|------------------|
| Diesel         | 9$^\circ$     | 13.8                 | 2020              | 0.78             |
| Gas-diesel     | 7$^\circ$     | 14.6                 | 2350              | 0.93             |

4. Conclusion

On basis of the material submitted, the following conclusions should be made:

- When diesel works on a gas-diesel process, the parameters of combustion process and heat release characteristics change as compared to the diesel one. Particularly, the maximum pressure, maximum temperature, and maximum pressure rise rate increase. However, the values of the parameters do not exceed the maximum allowed values specified by diesel manufacturer.
- Engine power specifications in a gas-diesel process remain the same as in a diesel one.
- Working on a gas-diesel process, it is necessary to decrease the diesel fuel injection advance angle in order to achieve minimal economical operation and reduce the “harshness” of the combustion process.

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