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Analysis of pre-heated fuel combustion and heat-emission dynamics in a diesel engine

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Analysis of pre-heated fuel combustion and heat-emission dynamics in a diesel engine

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Abstract. The article explores the feasibility of diesel fuel pre-heating. The research goal was to obtain and analyze the performance diagrams of a diesel engine fed with pre-heated fuel. The engine was tested in two modes: at rated RPMs and at maximum torque. To process the diagrams the authors used technique developed by the Central Diesel Research Institute (CDRI). The diesel engine's heat emission curves were obtained. The authors concluded that fuel pre-heating shortened the initial phase of the combustion process and moderated the loads, thus making it possible to boost a diesel engine's mean effective pressure.

1. Introduction

Nowadays, the diesel engine is the primary power source used in tractor-manufacturing industry. The diesel engine's characteristics are determined by the law of heat input and the nature of combustion process [1-4, 5, 23]. With the fuel injection pump (FIP) diesel engine heat input as well as heat emission are determined by the injection characteristics. This explains the limitations for boosting the diesel engine's mean effective pressure, as the increase in the cycle's fuel supply shifts the combustion process beyond the top dead center (TDC). [11-13]. Currently, one of the most promising ways to boost the diesel engine's mean effective pressure is to shorten the ignition delay period (IDP). By now various ways to shorten the IDP have been researched. Among such ways there is the use of ignition plugs, glow plugs, use of heat-resistant inserts, ceramic coating of the combustion chamber walls, fuel charge turbulization, use of heaters, various fuel additives, alternative fuels, and the combination of the above-mentioned measures [6, 14, 16, 17]. The most promising of them the authors consider fuel preheating (heating diesel fuel prior to its injection into the engine cylinders) [2-4, 14, 19]. It is a well-established fact that for optimal performance of a diesel engine the charge's temperature at the end of the compression cycle should be about 623 K, as well as high degree of fuel dispersion. At the same time the diameter of a fuel drop should not exceed 40 mkm, and the conditions should minimize heat loss of the air charge while the injected fuel fumes are heated, vaporized, and over-heated in the CC [1-4, 18, 21-23].When injected the fuel drops are satisfactorily spread throughout the complete CC volume. However, due to low fuel concentration in the air-fuel mix, the transition from pre-burning oxidation processes to self-accelerating reactions takes too long. While the heat input from outermost regions of the air charge to fuel jets is somewhat complicated [2, 20]. Hence the IDP value. To eliminate all the above-mentioned negative effects it is necessary to minimize the volume of accumulated fuel fumes in the diesel engine's CC within the period from fuel injection to its self-ignition. In modern fuel-feed systems this issue is solved by dividing the injection process into two stages: the preliminary and main ones.

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2. Research objectives

The objective of this research was to study the processes that make it possible to shorten the IDP through the increase of fuel jets' energy by pre-heating the fuel. Another task was to improve start properties of a diesel engine. Thus, the following tasks were set: to study the influence of fuel preheating on IDP, the explosiveness of the combustion process, speed of active heat emission, average cycle temperature, and start properties of the diesel engine as a whole.

3. Materials and methods

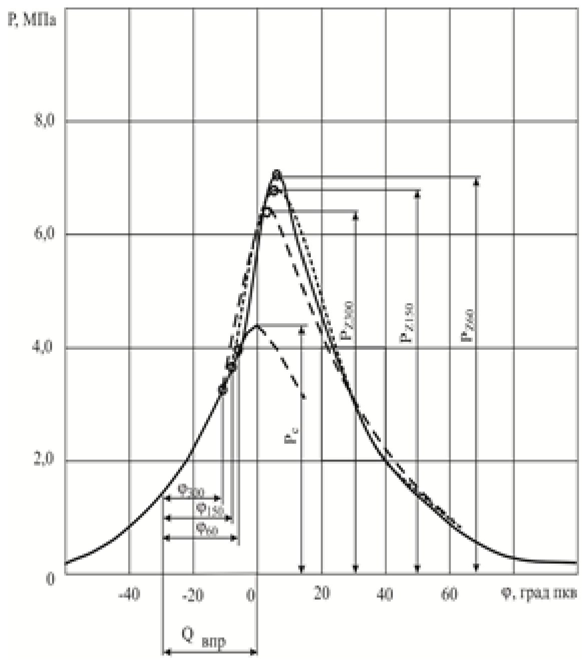
Researchers of the Vyatka State University (Russia) in cooperation with State Agrarian and Engineering University in Podilya (Ukraine) studied the effects of fuel preheating on the operation of 2Ch 10.5/12.0 (D-120) diesel engine. Generally, the study was performed within the framework of GOST 18509-88 requirements. The authors used grade L diesel fuel as per GOST 305-82. The diesel engine mounted on the testing bench is shown in Figure 1.

Figure 1. The 2Ch 10.5/12.0 diesel engine mounted on the testing bench**.**

The authors resorted to the indicator diagram technique to study the combustion process in a pre-heated fuel diesel engine in two operational modes: the rated one at RPM of $n=2000$ min^{-1} and the maximum torque mode at RPM of $n=1400$ min^{-1}. The indicator diagrams were drawn at the fuel injection advance angle of $\theta inj=30^0$ and constant mean effective pressure values in every operational mode. The indicator diagram data were processed using the CDRI developed technique [14]. The start of the serial produced diesel engine (at $\varepsilon=16.5$) was performed with CT-212 starter motor at $n=230…240$ min^{-1} RPM. The time required to achieve stable RPMs and the RPM values themselves were recorded.

4. Results and discussion

The analysis of the indicator diagrams demonstrated that the increase in fuel temperature resulted in the decrease of φ_i angle, corresponding to the ignition delay period (Figure 2) [7, 10]. Thus, at RPM of the diesel engine $n=2000$ min^{-1} and no fuel pre-heating the angle was $\varphi_{60}=25.7$ degrees, however, when the diesel fuel was heated to 150ºC and 300ºC the angle was $\varphi_{150}=23.2$ degrees and $\varphi_{300}=20.5$ degrees respectively (Figure 2, a). When the diesel engine operated in the maximum torque mode, then the IDP angle value also went down: $\varphi_{60}=22.7$ degrees, $\varphi_{150}=20.5$ degrees, and $\varphi_{300}=18.1$ degrees respectively (Figure 2, b). It was possible to suggest that the decrease of the φi angle, corresponding to the IDP, explained shortening of the thermo-chemical combustion reaction's induction time and lessening of the fuel amount injected during the IDP. As a result the explosiveness of combustion was moderated [1-4, 22, 23]. When the fuel was pre-heated, some drop in a cycle maximum pressure was observed Pz (Figure 2). Thus, at RPM equal to n = 2000 min^{-1} the cycle maximum pressure was Pz_{60}=6.955 MPa, Pz_{150}=6.683 MPa and Pz_{300}=6.391 MPa respectively (Figure 2, a).



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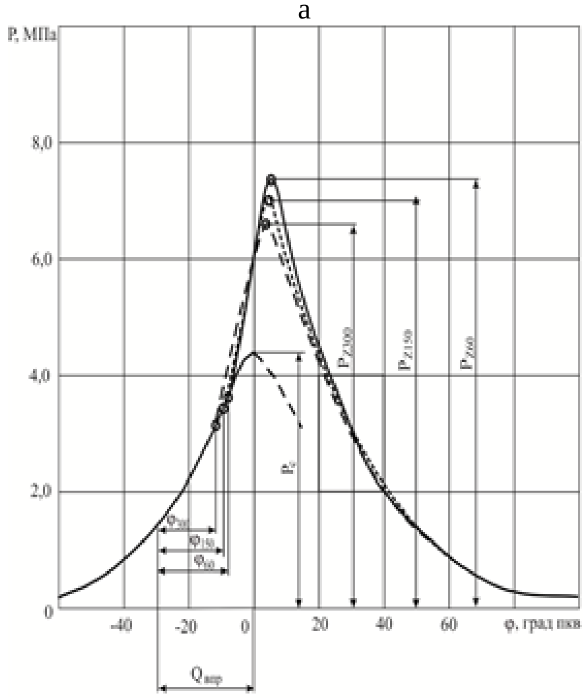
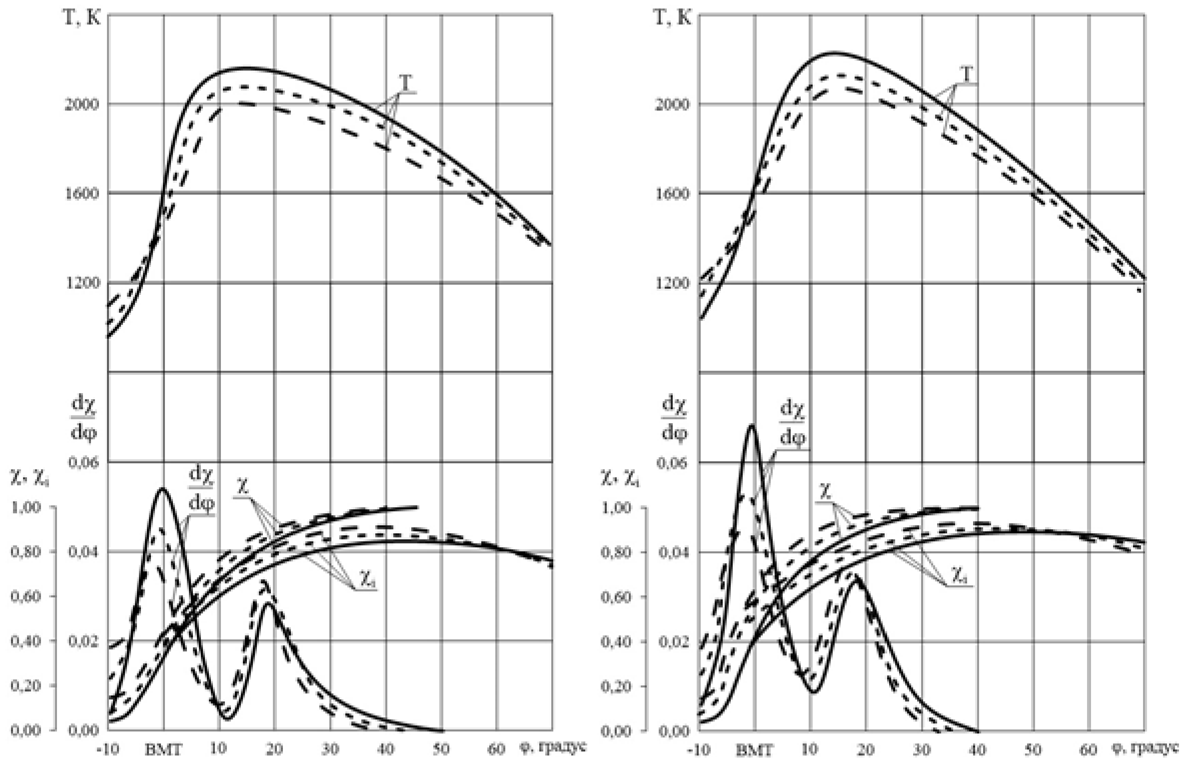


b

Figure 2. Indicator diagrams of 2Ch 10.5/12.0 diesel engine at: a – n=2000 min-1, b – n=1400 min-1

diesel fuel pre-heated to 60°C;
diesel fuel pre-heated to 150°C;
diesel fuel pre-heated to 300°C;

At RPM equal to n=1400 min^{-1} those values were Pz_{60}=7.369 MPa, Pz_{150}=6.964 MPa and Pz_{300}=6.614 MPa respectively (Figure 2, b). The drop in the cycle maximum pressure Pz was explained by the smaller amount of fuel injected into the cylinder of the diesel engine and eventually evaporated during the IDP. The analysis of the indicator diagrams using the CDRI technique proved that the diesel engine, when fed pre-heated fuel, demonstrated certain changes in its heat emission characteristics (Figure 3) [9].



a b

Figure 3. Graphs of heat emission dynamics $d\chi/d\varphi$, of average gases temperature in a cylinder T, of heat emission χ and active heat emission χ_i in relation to the diesel engine's crankshaft rotation angle φ at: a – n=2000 min^{-1}; b – n=1400 min^{-1}

——— diesel fuel pre-heated to 60°C;
– – – – diesel fuel pre-heated to 150°C;
— — - diesel fuel pre-heated to 300°C;

Thus at RPM n=2000 min^{-1} and no fuel pre-heating the maximum average gases temperature in the cylinder was recorded at $T_{max,60}$=2184 K, when the fuel was heated to 150°C and 300°C, the temperatures recorded were $T_{max,150}$=2092 K and $T_{max,300}$=2003 K respectively. At the same time, the maximum temperature values corresponded to $\varphi_{60}=14^0$ of the crankshaft rotation (CSR), $\varphi_{150}=12.5^0$ CSR and $\varphi_{300}=11^0$ CSR, however, by the end of the combustion process at $\varphi=60\ldots70^0$ CSR, the values were practically equal (Figure 3, a). The increase of the average cycle temperature could be explained by the following. One could suggest that when the fuel was pre-heated, the fuel-air temperature gradient along the jet axis diminished. Thus, fuel pre-heating could simultaneously increase total heat content of air/fuel mix at the end of the compression stroke [2]. The drop of the average maximum cycle temperature with its peak shifting towards TDC was determined by lower heat emission speed in the kinetic phase and its peak's shift in the same direction [9]. Comparison of the heat emission curve χ and active heat emission curve χ_i in the engine's rated operational mode at RPM of n=2000 min_{-1} revealed the fact that, when the fuel was pre-heated, the combustion started earlier. So, at the TDC the recorded values were χ_{i60}=0.32, χ_{i150}=0.39 and χ_{i300}=0.44. The heat emission process ended practically at once at φ=42…46^0 CSR angle (Figure 3, a). Growth of heat emission values as well as those of active heat generation, when the diesel fuel was preheated, could be explained by the shortening of thermo-chemical combustion reaction's induction time due to faster achievement of the fuel's self-ignition threshold during the IDP [15]. Once the diesel fuel was pre-heated, the maximum heat generation rate $d\chi/d\varphi$ in the kinetic phase of the combustion process was recorded at $(d\chi/d\varphi)_{max60}$=0.053, $(d\chi/d\varphi)_{max150}$=0.046, $(d\chi/d\varphi)_{max300}$=0.037, while in the diffuse phase it was $(d\chi/d\varphi)_{max60}$=0.029, $(d\chi/d\varphi)_{max150}$=0.031, $(d\chi/d\varphi)_{max300}$=0.033 respectively. At the same time, the maximum heat generation rate in the kinetic phase corresponded to φ_{60}=1 , φ_{150}=2 and φ_{300}=4 prior the TDC, while in the diffuse phase it measured φ_{60}=18 , φ_{150}=17 and φ_{300}=16.5, once the TDC was passed. The heat emission rate droped to zero practically at once at φ=42…46^0 CSR angle (Figure 3, a). With the diesel fuel pre-heated, the reduction of the heat emission rate in the kinetic phase along with shift of the rate's maximum value regarding the CSR was determined by the increase of fuel drops' initial temperature and the subsequent shortening of the ignition delay period. Moreover, the authors observed a drop in the pressure increase rate depending on the engine's crankshaft rotation angle. Another recorded fact was thermal destruction of fuel molecules with the formation of unsaturated hydrocarbons resulting in the rise of pre-combustion reactions' speeds, that subsequently gave start to yellow combustion flame [2, 3, 13, 20]. With the diesel fuel pre-heated, the increase of the heat emission rate in the diffuse phase along with the shift of the rate's maximum value regarding the CSR was determined by the increase of fuel drops' initial temperature and the subsequent shortening of the ignition delay period. Once the diesel engine was run in the maximum torque mode at n=1400 min^{-1}, no pre-heating, the average maximum gases temperature in the cylinder was recorded $T_{max,60}$=2242 K, $T_{max,150}$=2132 K and $T_{max,300}$=2074 K respectively. At the same time the maximum temperature values corresponded to φ=14^0 CSR and by the end of the combustion φ=60…70^0 CSR, the values were practically equal (Figure 3, b). Analysis of the heat emission curve χ and active heat generation curve χ_i demonstrated, that, when the diesel fuel was pre-heated, the combustion started earlier.. So, at the TDC the recorded values were χ_{i60}=0.40, χ_{i150}=0.51 and χ_{i300}=0.62. The heat emission process ended practically at once at φ=32…40^0 CSR angle (Figure 3, b). Once the diesel fuel was pre-heated, the maximum heat generation rate $d\chi/d\varphi$ in the kinetic phase of the combustion process went down. Thus, the authors recorded the following data at fuel temperature 60^0 C $(d\chi/d\varphi)_{max60}$=0.068, and, when the fuel was pre-heated $(d\chi/d\varphi)_{max150}$=0.052, $(d\chi/d\varphi)_{max300}$=0.044. In the diffuse phase it was $(d\chi/d\varphi)_{max60}$=0.034, $(d\chi/d\varphi)_{max150}$=0.035 and $(d\chi/d\varphi)_{max300}$=0.036. At the same time, the maximum heat generation rate in the kinetic phase corresponded to φ_{60}=1.5, φ_{150}=2.5 and φ_{300}=3 prior the TDC, while in the diffuse phase it measured φ_{60}=18 , φ_{150}=17 and φ_{300}=15.5 once the TDC was passed. The heat emission rate dropped to zero practically at once at φ=32…40 once the TDC was passed (Figure 3, b). Therefore, the authors concluded that such changes in the combustion characteristics were to be expected for the maximum torque mode as well. Certain changes in the values of heat emission and in the timing of their reaching the maximum values were determined by a drop in the engine's RPM. The tests unambiguously established direct connection and interdependence between the combustion and heat emission characteristics of the processes occurring in the cylinders of a diesel engine and the temperature of the pre-heated diesel fuel [7-10]. The start characteristics were monitored and recorded to check on the operability of the diesel engine when it was fed pre-heated fuel (Figure 4).

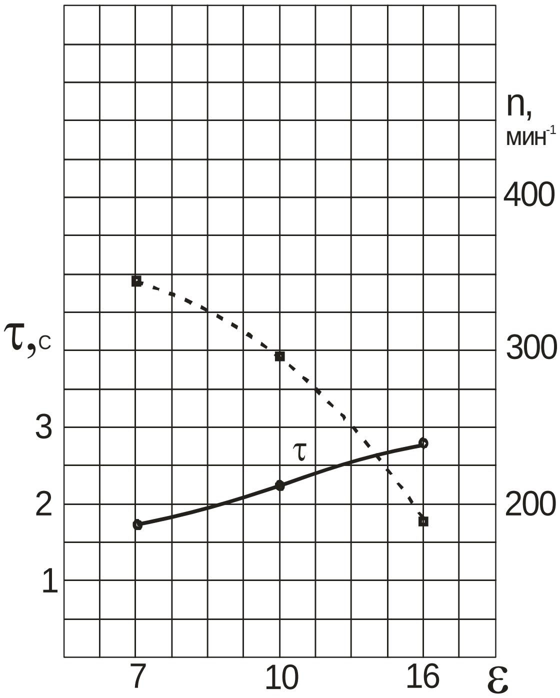


Figure 4. Start characteristics of 2Ch 10.5/12.0 diesel engine

As the data in Figure 4 demonstrate, the diesel engine fed pre-heated fuel started up easier than a serial production one. The authors believe that the most obvious cause was the increase of start RPM due to much lower resistance momentum.

5. Conclusion

1. Fuel pre-heating (thermal boost) makes the ignition delay period shorter and moderates the explosiveness of the combustion process.
2. Fuel pre-heating (thermal boost) lowers the speed of active heat generation.
3. Lowering the cycle average temperature, shortening the IDP, and moderating the explosiveness make it possible to boost a diese engine's average effective pressure.
4. Fuel pre-heating improves a diesel engine's start characteristics and facilitates the operation of starter motors.

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