Influence of Method of Adding Water to Combustible Mixture on Diesel Engine Performance

S N Devyanin¹, A V Bigaev¹, V A Markov²

¹ Russian State Agrarian University of Moscow Timiryazev Agricultural Academy, 49, Timiryazevskaya st., Moscow, 127550, Russia
² Bauman Moscow State Technical University, 5, 2-ya Baumanskaya st., Moscow, 105005, Russia

E-mail: vladimir.markov58@yandex.ru

Abstract. The supply of water to the cylinders of the diesel engine is one way to reduce the maximum temperature in the combustion zone of the fuel. A reduction of the maximum combustion temperature allows reducing the formation of nitrogen oxides and improving the environmental characteristics of the engine, which remains one of the urgent tasks at the present stage of their development. The methods of supplying water to the engine together with air at the inlet and with the fuel into the cylinder are well known. This article considers the influence of the way the water is supplied to the engine cylinders on its environmental characteristics. It presents the results of experimental studies on the internal combustion engine and analysis of the method of adding water on the engine performance from exhaust gas toxicity, operating efficiency and its thermal state. There are marked different effects on the motor performance of the method of adding water.

1. Introduction

The addition of water to the combustion chamber (CC) of diesel engines is an effective method of reducing the toxic emissions of exhaust gases [1-3]. Related to this, the problem of the choice of the method of supplying water to the cylinder arises. For this study, the two most common and rational ways of supply of water were chosen:
- through regular injectors with fuel;
- through a special system with air.

The supply of water with fuel is carried out in the form of a water-fuel emulsion (WFE) through a standard fuel injector with a high-pressure fuel pump (HPFP). This system works on WFE as well as with diesel fuel (DF) in the usual mode, except for the presence of a system for preparing emulsions.

The supply of water with air is carried out by means of a special system dosing out the amount of water due to the duration of the injection and injecting it into the engine's intake path through special electrically controlled injectors. The flow and opening frequency is controlled by an electronic system specially designed for this system. The injector injects water into the intake manifold synchronously with the gas exchange system until the inlet valve of each cylinder is opened. The angle of the beginning of the water supply is estimated relative to the bottom dead centre (BDC) of the engine crankshaft position, which is controlled and can have both positive and negative values.
2. Experimental Setup and Methodology. Research Results

The research was carried out on diesel engine D-120 with a rated power of 20 kW. The 125 kW brake stand contained indicators of engine speed and engine torque. For the indication of fuel consumption or WFE, the flow meter "DFM" was used. The water flow to the inlet was determined from the period of the nozzle opening by the "C1-117" oscilloscope. To measure the toxicity of the exhaust gas, a 5-component gas analyzer "Infracar 5M-2.02" was used. The amount of carbon black in the exhaust gas was measured with a Bosch chimer by filtration of a portion of exhaust gas through a filter paper of grade "F". The thermal state of the cylinder head was estimated by the thermocouple type "HK" of the factory design.

The results of the engine tests in the form of load characteristics at a rotation speed of 1800 rev/min with supply of water in the amount of 40% with WFE and with air at the inlet, as well as without supply of water, are shown in Fig. 1. As follows from the results obtained when water is supplied in the form of an emulsion, an increase in the effective efficiency of the engine is noted at high loads from 0.36 to 0.38 (Fig. 1a), but without additional adjustment of the injection pump, the maximum power decreases from 19 to 13.5 kW. This effect is explained by a decrease in the amount of fuel supplied in proportion to the water fraction in the water-fuel emulsion. When adding the same amount of water to the air, the engine power is not reduced, but the effective efficiency at low loads is reduced from 0.26 to 0.24.

![Figure 1. Dependence of toxic indicators and efficiency of the engine: a) - $\eta_e$ (Energy conversion efficiency) and CO (Carbon monoxide); b) - NOx (Nitrogen oxides) and CxHy (Hydrocarbons); - - - - - - - - - WFE; ················ - addition of water with air.](image)

More significant impact of the supply of water has a toxic effect. When water is supplied with air, carbon monoxide CO is higher by 0.01 ... 0.02% (Fig. 1a) than when working on DFs in the entire range of loads. When water is supplied from the WFE, the increase in CO is much higher and with a power of 13.5 kW - 0.06%, which is almost 2 times higher, and at low loads, CO emissions reach 0.16%, which exceeds the emissions by DF almost 5 times. This difference can be explained by a more significant decrease in the temperature in the fuel combustion zone when water is supplied from the WFE. A decrease in the temperature in the combustion zone leads to a decrease in the combustion rate and an increase in the products of incomplete combustion [4, 5, 6], which is confirmed by the presented experimental data.

The presented results showed an increase in carbon monoxide CO emissions with the addition of water, and this increase is stronger if water is supplied together with fuel in the form of WFE.

Hydrocarbon emissions are also products of incomplete combustion of fuel, and when they are supplied with water, their amount increases due to a decrease in the combustion temperature (Fig. 1b).
When water is supplied with air, at a section of 5 ... 12 kW, the concentration of $C_xH_y$ is 50 ppm and more when working on a diesel engine at 20 ppm. A further increase in power leads to a reduction in the difference to 8 ppm at a power of 19 kW.

When water is supplied from the WFE at a power of 5 ... 8 kW the concentration of hydrocarbons $C_xH_y$ is 43 ... 45 ppm, which is higher by 13 ... 15 ppm than when operating on a diesel engine. A further increase in power to 13.5 kW leads to a decrease in hydrocarbon concentrations of up to 38 ppm, and the excess of emissions compared to work on diesel fuel is reduced to 4 ppm, which is less than when supplying water with air by almost 20%. Such increase in hydrocarbon emissions when the water is supplied with air can be explained by the lower temperature of the air charge in the air zone of the cylinder, and slows the chemical reactions of oxidation in the near-wall zones of the combustion chamber.

Thus, the supply of water in each way leads to an increase in the concentration of hydrocarbons $C_xH_y$ in the exhaust gas; however, in contrast to CO, a larger increase is noted for the addition of water together with air. With an increase in the engine load, the value of the increase in the emissions of $C_xH_y$ decreases.

If the decrease in the combustion temperature adversely affects the products of incomplete combustion, then the effect on the formation of NOx oxides is the opposite (Fig. 1b). When water is supplied from the WFE, the emissions of nitrogen oxides are 3 ... 4 times less than when operating on the DF in the entire range with loads. So with a power of 4.5 kW, NOx emissions are 240 ppm instead of 1300 ppm, and with 13.5 kW loads - 1660 ppm instead of 3700 ppm. When supplying water with air, NOx emissions decrease not so much as when supplied with WFE. For example, with a power of 5 kW, a reduction from 1300 ppm to 800 ppm is observed, and with a power of 15.5 kW, nitrogen oxides are reduced from 4000 ppm to 2170 ppm, and the total drop is thus 1830 ppm. With a maximum power of 19 kW, nitrogen oxides are reduced compared to work on diesel from 3180 ppm to 1780 ppm. The tendency of a decrease in the concentration of nitrogen oxides is caused by the dependence of the intensity of their formation on the combustion temperature of the mixture [7, 8, 9]. The concentration of nitrogen oxides decreases due to a decrease in temperature and decreases more strongly where the temperature in the combustion zone of the fuel is lower.

Thus, in order to reduce NOx oxides, a greater effect will be achieved when water is added together with fuel in the form of WFE than when it is supplied with air.

As expected, soot emissions tend to increase with increasing load on the ICE (Fig. 2). At the same time, the difference in soot emissions between methods of supply of water is not significant. When water is supplied with air at low loads, soot emissions are reduced by 0.2 ... 0.3 points Bosch, and at high loads increases by 0.2 ... 0.3 points Bosch, reaching a value of 2.3 points Bosch. With the supply of water in the form of WFE a mixed trend within the measurement error. It is possible to observe an increase in soot emissions in the region of increased loads up to 1.3 points Bosch, at the same value of the load, the emission of soot when water is supplied with air is less and is 0.8 points Bosch, which is almost 1.5 times lower.

The evaluation of the thermal state of the combustion chamber parts was carried out according to the temperature of the head on the fire surface, measured by the thermocouples of each cylinder. The results of the measurements are shown in Fig. 2 in the form of relative values in comparison with work on DF.

At average values of engine power (11 ... 13 kW), supply of water with air in an amount of 40% of the fuel supplied leads to a decrease in the temperature of the fire surface of the head to 27%, and for small and high loads this decrease is somewhat smaller and is about 20%. When water is supplied from the WFE, the effect of reducing the thermal state of the head is smaller, and at low loads it is about 5%, and reaches 20% with a power of 12 ... 14 kW.
Figure 2. Relative temperature change of the diesel engine head ($T_w/T$) and emission of soot with exhaust gases (K) from the engine load;

- DF; - - - - - - WFE; ··············· - addition of water with air; $T_w$ - the temperature of the head in water supply; T - the temperature of the head without water.

Thus, a greater effect on reducing the thermal state of the cylinder head at small and medium engine loads is achieved when water is supplied together with air. At high loads, the effect is approximately the same and allows the temperature of the fire surface of the head to be reduced by approximately 20%.

3. Conclusion
The addition of water to the engine cylinders affects the emissions of toxic components and the thermal state of the cylinder head, and this effect depends on the way the water is supplied.

When 40% of the water is supplied from the amount of fuel into the cylinders of the diesel, the D-120 results in an increase in the emissions of incomplete combustion products (CO and C$_x$H$_y$), with CO emissions increasing more when supplying water from the WFE than when supplied with air. Emissions of hydrocarbons on the contrary increase more when water is supplied with air than with WFE. Emissions of nitrogen oxides are reduced and this decrease is stronger when water is supplied from the WFE than with air.

The thermal state of the combustion chamber parts decreases when water is supplied to the engine cylinders and this decrease is greater when supplied with air.

The addition of water from the WFE without additional adjustment of the injection pump leads to a reduction in the maximum power.

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