Determining of optimum composition of water-fuel mixture for a spark-ignition internal combustion engine with electronic control

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Abstract. The relevance of the study is stipulated by the necessity for determining of optimum composition of water-fuel mixture (WFM) for a spark-ignition internal combustion engine with electronic control. The objective of the study is the determining of the optimum composition of water-fuel mixture (WFM) during the operation of a VAZ-21114 engine which allows for the best quantitative performance specifications. For this purpose, an experimental test fixture was developed, consisting of a KI-2139 electrical brake bench with a pendulum arm machine and an "AVTOTEST-02.03" 5-component gas analyzer, with equipment for bench testing in accordance with the requirements of GOST 14846-81 "Automotive engines. Bench test methods". As a result, for the first time, optimum quantitative WFM composition was obtained for operation of VAZ-21114 spark-ignition engine with electronic control providing for the best quantitative performance specifications. The analysis of the obtained data demonstrates lowering of the concentration of toxic exhaust gas (EG) components of the engine, specific effective ($g_e$) and hourly ($G_m$) fuel consumption rate, as well as the EG temperature ($T_{eg}$) during its operation by the external rpm vs. load curve within the utilization range of WFM with 0 to 12% water content. At water content growth in the WFM from 12 to 20%, a growth of carbon monoxide (CO) and unburnt hydrocarbons ($CH$) in the EG is observed, as well as a growth of $g_e$ and $G_m$. The minimum quantitative values of the parameters CO, CH, NOx, $g_e$, and $G_m$ were: 6.0 and 1.65% of CO at water content in WFM of 10 and 13%, respectively; 173 and 142.5 ppm of CH at 10% water content in WFM; 113 and 215 ppm of NO, and $T_{eg}$ 650 and 730 K at up to 20% water content in WFM; $g_e$ 330 and 303 g/kWh at 12.5 and 11.5% water content in WFM, respectively, $G_m$ 6.5 kg/h at 11.5% water content in WFM. The maximum quantitative value of the effective engine power $N_e$ of 44.2 kW was obtained with WFM with 20% water content. The obtained results demonstrate that, for the operation of a spark-ignition type VAZ-21114 engine with electronic control, the WFM should contain 9…12% water as an optimum providing for achievement of the best quantitative performance values.

1. Introduction

For the time being, the world practice offers no single method allowing for simultaneous improvement of both the performance and the environmental friendliness of internal combustion engines. The improvement of these specifications is advisable to get started along with the solving of the exhaustion problem of conventional fuel sources. Using of non-conventional fuels in their natural forms leads to a
number of drawbacks, such as: lowering of environmental friendliness, energetic and economic performance, sophistication engine design concepts, variance of physical and chemical fuel properties and reluctance of the fuel and energy branch to produce new fuel types. In this connection, the use of fuel mixtures consisting of conventional fuels and different non-petroleum additives is a matter of vital importance.

Fuel mixtures are used both in diesel and in spark-ignition internal combustion engines [1]. The studies of water-fuel mixtures (WFM) (emulsions) are carried out in two directions: 1) individual water supply to the combustion chamber prior to the fuel ignition; 2) timely preparation of the water-fuel emulsion [1-24]. Emulsions are thermodynamically unstable of two or more mutually immiscible liquids, which are stabilized kinetically with the absorption film [2]. As emulsion stabilizers surfactants can be used (SAS) [3]. Mechanical agitation is the most frequently used method of emulsion preparation [4].

Use of WFM in emulsion form in internal combustion engines leads to the emission of the total nitrogen oxides \( \text{(NO}_x \text{)} \). This fact is stipulated by high specific heat capacity and specific heat of evaporation of about 2256 kJ/kg [5]. The cooling effect of a thermodynamic system occurring as a result of water injection into the combustion chamber improves the mixture build-up and combustion on the fuel injection step, minimizing the ignition delay and influencing the chemical reactions generating soot [6-10]. The addition of water to the fuel also reduces the maximum combustion temperature which, in its turn, decreases the build-up of thermal \( \text{NO}_x \) [5, 11]. Using of emulsions to reduce \( \text{NO}_x \) emission has been studied for quite a prolonged time. The conclusions based on the result of studies [12, 13] in which three different methods of \( \text{NO}_x \) emission reductions were evaluated, such as: recirculation of exhaust gases, water injection and WFM use by means of a multi-zone imitation models demonstrate that the use of emulsions is optimal from the point of view of decreasing the toxicity of the exhaust gases and and the fuel consumption rate.

As a result of the conducted experimental studies of three different water contents in the water-gasoline emulsions 5%, 10% and 15%, respectively, during test runs of the vehicle at 90 km/h, a reduced concentration of \( \text{NO}_x \) by 35.0% was measured, compared with pure gasoline [14]. Paper [15] also notes the mutual dependency of the thermal build-up efficiency of \( \text{NO}_x \) while using emulsified fuel.

The basic reduction method of \( \text{NO}_x \) emissions is using water-based fuel additives [16, 17]. This method allows for a reduction of the maximum temperature in the combustion chamber [17]. The results of [18] demonstrate that water-gasoline emulsions feature anti-knock properties. The results of studies [19] demonstrate that using of a water-gasoline emulsion scores no direct fuel savings. At optimum water content of 20%, the efficiency in most operation modes is almost the same the same as with pure gasoline. Emulsions with water contents of up to 40% cannot be used in contemporary engines without their re-designing. At equal values of the air excess coefficient, the concentration of \( \text{CO} \) in the exhaust gases does not depend on the water content, the concentration if \( \text{NO}_x \) goes back by appr. 1.3% per each additional percent of water; the \( \text{CH} \) contents rises in certain operation modes several-fold.

The results of studies [20, 21] of water-gasoline mixture supply to the intake manifold demonstrate a reduced rate of combustion, a shorter ignition delay, as well as a shortening of the combustion process phases [22-24].

Studies of WFM with water contents 5, 10 and 15% in a 4-stroke engine with 125 cm³ displacement, with injector, spark ignition and electronic control at crankshaft rpm rate \( n = \) 2000 – 7000 rpm, at completely open gasoline throttle, in idle run demonstrate lower carbon monoxide \( (\text{CO}) \) and nitrogen oxides \( (\text{NO}_x) \) concentrations on water content growth in the emulsion [13, 22]. The content values of the unburnt hydrocarbons \( (\text{CH}) \) were growing with the growth of the water content, stipulated by the combustion chamber cooling [17, 22]. At 5 and 10% water content in WFM, higher torques and improved fuel consumption rates were observed. However, at 15% water content in the emulsion, reduced torques, uncreased fuel consumption rates and EG temperatures were registered, due to a slower combustion process rate [5].
The results of the experimental studies of engine fueling with water-gasoline emulsion with 5, 10 and 15% water content, in a one-cylinder 4-stroke spark-ignition engine with 376 cm³ displacement show that CO, NOx, and CH contents in the EG went back with the growth of the water content in the fuel, whereas the power with 5 to 15% water content grew from 3.8 to 14% [23, 24].

The analysis of the results of the studies makes it evident that the search for optimum WFM composition at which optimum quantitative performance specifications of spark-ignition engines with electronic control can be provided for is, for the time being, a promising initiative.

2. Research objectives
The objective of the present study is to determine an optimum WFM composition for VAZ-21114 spark-ignition engine with electronic control system ensuring the best quantitative specifications of the environmental friendliness.

3. Methods and materials
The device under test is a 4-stroke spark-ignition VAZ-21114 engine with sequential multi-point fuel injection, modified by integration of a WFM feed system. The bench testing method corresponds to GOST 17.2.2.02–86, GOST 17.2.2.05–86.

The experimental test fixture consisted of a KI-2139 electrical braking bench with a pendulum arm machine, an engine feed system adapted for WFM supply and measurement instruments. The equipment included into the experimental test fixture was compliant with GOST 14846–81 "Automotive engines. Bench test methods".

The coolant temperature was maintained within the range from 93 to 95°C by means of a closed-circuit cooling system with forced circulation. The lubrication system of the engine was standard. The motor oil pressure measurement in the lubrication system of the engine was carried out by means of an MT type pressure gauge with 1.0 MPa scale range and A accuracy class.

The diagram and the general appearance of the experimental test fixture, see Figure 1. The test fixture consists of a gasoline fuel tank (1), a water cylinder (2), a gasoline pump (3), a measurement cylinder (4) for water flow rate measurement, filters (5), (6) for gasoline and water filtering, a fuel pressure regulator (7), a mixer (8) for WFM mixing, a scale (9) for gasoline quantity measurement, a gasoline tank (10) for fuel feed system flushing, a load simulation device (11) for brake torque generation, an electronic engine controller (EEC) (12), a laptop PC (13) with software for real-time parameter monitoring of the electronic engine control system (EECS), an "AVTOTEST-02.03" 5-channel gas analyzer (14), an exhaust gas temperature sensor (EGTS) (15), a 16 UKT-38SchCh EGTS transmitter.

Figure 1. Experimental test fixture: a) diagram; b) general appearance: 1 – fuel tank; 2 – water cylinder; 3 – gasoline pump; 4 – measurement cylinder; 5, 6 – filters; 7 – fuel pressure regulator; 8 – WFM mixer; 9 – scale; 10 – flush gasoline tank; 11 – brake device for load simulation; 12 – electronic engine controller (EEC); 13 – laptop PC; 14 – "AVTOTEST-02.03" 5-channel gas analyzer; 15 – exhaust gas temperature sensor; 16 – EGTS transmitter.
The experimental tests were carried out in terms of the external speed (at \( n = 4000 \text{ rpm} \)) and load (at \( n = 2000 \text{ rpm} \) and \( N_e = 20 \text{ kW} \)) curves. During the tests, the influence of different WFM compositions on the environmental friendliness specifications of VAZ-21114 engine.

During the tests, the rotation frequency of the crankshaft (CS) of the engines, the torque, the effective power, the hourly and the specific water and gasoline consumption, as well as the hourly air consumption. To determine the contents of carbon monoxide (CO), unburnt hydrocarbons (CH) and the total nitrogen oxides (NOx), samples of EG were taken.

J5 On-line Tuner Software installed in the laptop PC connected to the diagnostic interface of the EECS (OBD-II) allowed for on-line measurement of the engine's CS rpm, of the air mass flow, of the coolant temperature and throttle valve position. Based on standard methods set forth in GOST 17.2.2.02–86, GOST 17.2.2.05–86, a calculation of the basic parameters, such as torque, effective engine power, as well as specific fuel and water consumption rates was carried out. The measurement of the consumed water quantity was volumetric. The concentration of toxic EG components was measured with an "AVTOTEST-02.03" 5-channel gas analyzer. The total nitrogen oxides concentration was determined by a 3NF/F Nitric Oxide CITIcel electrochemical cell.

During the test, EG temperature was measured in the exhaust manifold. For this purpose, a DTPK 135-0314.250 thermocouple cpl. with a UKT 38-Sch4-TP transmitter. After conducted experimental tests, content dependencies of CO (\%), CH (ppm), NOx (ppm) in EG and EG temperature on the fuel mixture composition fed to the engine.

During the experiment, simultaneous recording of all monitored parameters was carried out, which, in its turn, could ensure the trustworthiness of the obtained data. In accordance with the methods set forth in GOST 17.2.2.02–86, GOST 17.2.2.05–86, the limit error value of single measurements and the maximum possible statistical error of the mean absolute error in multiple measurements were determined.

4. Result and discussion

As a result of the studies, dependencies of the quantitative concentrations of toxic components of EG of the spark-ignition engine with a control system were obtained with WFM with 0 to 20% water content during operation by the external rpm (\( n = 4000 \text{ rpm} \)) and in the load mode (\( n = 3000 \text{ rpm} \) and \( N_e = 20 \text{ kW} \)).

Figure 2 shows the dependencies of the influence of WFM composition on the performance parameters of VAZ-21114 engine at operation by the external rpm curve (at \( n = 4000 \text{ rpm} \)).

The analysis of the obtained dependencies has shown that along with the growth of the water content in WFM from 0 to 20%, the effective engine power (\( N_e \)) also grows from 42 to 44.2 kW.

The influence of the use of different WFM compositions on CO and content CH in the EG of the engine, as well as on the specific effective fuel consumption \( g_e \) is unambiguous. The increase of the water content in WFM from 0 to 13% was leading to the reduction of CO concentration in OF from 8.5 to 6.0%, whereas the subsequent growth of the water content in the WFM from 13 to 20%, was leading, on the contrary, to increased concentrations of CO in the EG from 6.0 to 6.9%. A reason for that could be improved combustion efficiency due to the turbulization of the mixture during water vaporization in the WFM and to the action of the active radicals \( H \) and \( OH \) [5-11]. In general, at all studied WFM compositions, the concentration of CO in the EG was lowered, however, at the growth of the water content in the WFM beyond 13%, the growth of the CO concentration was observed, due to the lower combustion efficiency [5].

The minimum CH concentration in the EG of 173 ppm was observed at water content in the WFM equal to 10%. The reduction of the water content from 10 to 0% increased the CH content up to 214 ppm, whereas the increase of the water content from 10 to 20% lead to an increase of CH concentration from 173 to 203 ppm. It can be explained by complete combustion due to better mixing during water evaporation [17, 22]. However, if the water \( \alpha \) content in WFM is increased beyond 10%, the water considerably cools down the wall layers of the working mixture inside the ICE cylinder making the combustion less effective [22].
The increasing of the water content in WFM from 0 to 12.5% has lead to a reduction of the specific effective fuel consumption \(g_e\) from 363 to 330 g/kWh. The increasing of the water content in WFM s 12.5 to 20% has lead to a growth of the specific effective fuel consumption \(g_e\) from 330 to 348 g/kWh. This fact can be explained by a slower combustion process [5, 23, 24].

The reduction of NO\(_x\) concentration in the EG, as well as of the EG temperature \(T_{eg}\) occurred within the entire range of the water content in the WFM.

The biggest reduction of NO\(_x\) emission from 138 to 113 ppm was observed at the increase of the water content in the WFM from 0 to 20% of the total weight of the fuel. The EG temperature was also going down from 740 to 650 K at the increase of the water content in the WFM from 0 to 20%. It occurred due to the lower temperature of the operation cycle stipulated by the cooling of the work charge by the water contained in the WFM [5, 6].

The influence of the variance of WFM composition on CO and CH contents in the engine's EG, as well as on the specific effective \(g_e\) and the hourly \(G_m\) fuel consumption rates is unambiguous. The diagram makes it obvious that, along with the growth of the water content in the WFM from 0 to 10%, the CO concentration went down from 3.46 to 1.65%, and the CH concentration went down from 186.7 to 142.5 ppm. Along with the further growth of the the water content from 10 to 20%, the CO concentration grew from 1.65 to 3.02%, and the CH concentration grew from 142.5 to 184 ppm.

The minimum specific effective \(g_e = 303\) g/kWh an the hourly \(G_m = 6\) kg/h fuel consumption rates are achieved using WFM with 11.5% water content. The reduction of the water content in the WFM from 11.5 down to 0% and the increase of the water content from 11.5 up to 20% were leading to the
increase of \( g_e \) values up to 338 and 320 g/kWh, and to the increase of \( G_m \) values up to 6.75 and 6.41 kg/h, respectively.

Observed was also the reduction of \( NO_x \) concentration in the EG, as well as of the EG temperature \( T_{\text{eg}} \) within the entire range of the water content in the WFM.

\( NO_x \) concentration reduction in the EG from 270 down to 215 ppm and EG temperature reduction from 810 down to 730 K were observed after the increase of the water content in the WFM from 0 to 20%.

Based on the analysis of the obtained data, it is getting obvious that \( CO \) and \( CH \) contents in the EG get better with WFM water content of 9…12%, whereas at further increase of the water percentage they begin to worsen, again. It can be explained, that up to the optimum point of the function, each of the parameters under test is influenced positively by the addition of water, due to the intensification of the turbulization of the mixture in the ICE cylinder, the intensification of the chemical reaction rates and the more effective fuel combustion [5-11, 17, 22-24]. However, having passed the optimum peak, that is, the minimum of the function for \( CO \) and \( CH \) values, the further increasing of the water content in the mixture begins to produce a negative impact mainly due to the unwanted heat dissipation and the decreased combustion rate and efficiency [25-28]. The \( NO_x \) content, on the contrary, goes down rather intensively within the whole water content range 0…20%, since the build-up of the nitrogen oxides is mostly stimulated by high cycle temperatures which get lower with the growth of the water content in WFM [28-30].

5. Conclusions

1. As a result, for the first time, optimum quantitative WFM composition was obtained for operation of VAZ-21114 spark-ignition engine with electronic control providing for the best quantitative performance specifications.

2. The lowest quantitative values of \( CO \), \( CH \) concentrations in the EG, of the specific effective \( g_e \) and hourly \( G_m \) fuel consumption during the engine operation by the speed and the load curve were: 6.0 and 1.65% of \( CO \), at 10 and 13% of water in the WFM, respectively; 173 and 142.5 ppm of \( CH \) at 10% of water in the WFM, 330 and 303 g/kWh \( g_e \) at 12.5 and 11.5% of water in the WFM, respectively; 6.5 kg/h \( G_m \) at 11.5% of water in the WFM, respectively.

3. The minimum quantitative values of \( NO_x \) concentration and \( T_{\text{eg}} \) during the engine operation by the speed vs. load curve were: 113 and 215 ppm of \( NO_x \), and 650 and 730 K \( T_{\text{eg}} \), respectively, at BTC do 20% of water in the WFM.

4. The maximum quantitative value \( N_e = 44.2 \) kW was obtained during the motor operation by the speed curve at 20% of water in the WFM.

5. The obtained results demonstrate that, for the operation of a spark-ignition type VAZ-21114 engine with electronic control, the WTM should contain 9…12% water as an optimum providing for achievement of the best quantitative performance values.

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