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Efficiency Evaluation of Using Water-Fuel Emulsion as Fuel for Automobiles

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Abstract: Road transport is the main consumer of petroleum fuel as well as a source of toxic substances. Therefore, reducing fuel consumption and emissions of harmful substances in road transport is one of the most important problems facing modern engine construction. One of the ways to solve this problem is through the use of mixed fuels, including water-fuel emulsions. Water-fuel emulsion is a promising alternative fuel that could fulfill such requests in that it can improve the combustion efficiency of internal combustion engines and reduce harmful exhaust emissions, especially nitrogen oxide (NOx) and particulate matter (PM). Up to now, there have been many studies on water-fuel emulsions, especially on performance, emissions and micro-explosion phenomena. Using water-fuel emulsion as fuel for ships worldwide was studied and applied to the 80-ies of the last century, but using it for automobiles is still limited by the emulsion stability and economic difficulties to calibrate engine parameters for a new fuel. This article provides an overview of the mechanism and performance operating cycle of internal combustion engines using water-fuel emulsions and the efficiency, economy, and environmental friendliness of this fuel type for automobiles. Hence, conclusions are drawn about the possibility and effectiveness of using emulsions as fuel for automobiles, especially under conditions in Vietnam.

Keywords: water-fuel emulsion, water-diesel, fuel consumption, power, efficiency, economy, exhaust emissions.

1. Introduction

Internal combustion engines (ICE), including gasoline and diesel engines, are used as the primary source of propulsion in mobile vehicles, including automobiles. For mobile vehicles, such as automobiles and cars, fuel costs account for about 70% of the total investment cost throughout the engine's working cycle [1]. Therefore, in automobile operations, saving fuel is always an urgent issue.

Currently, there are many research options for using cheaper alternative fuels for vehicles such as natural gas [2], liquefied petroleum gas [3], biodiesel [4],[5], alcohol [5],[6], dimethyl ether [7]-[9], and hydrogen [10],[11]. However, using petroleum fuels (gasoline, diesel) for vehicles usually takes several decades but will continue to be the main focus.

The use of water in the working process of ICEs using petroleum fuels began almost simultaneously with their appearance. Back in 1864, Hugon supplied water to the combustible mixture to improve the performance of Lenoir's engine [12]. In the 1930s, water injection began to be used in high-speed engines to increase the compression ratio (prevent detonation combustion), increase the ICE's power, and reduce engine parts' temperature. Based on [13]-[22] several methods have been developed for supplying water to engine cylinders (Fig 1). It is possible to supply water to the engine cylinders in the liquid phase or the form of steam. The supply of water vapor to ICEs can be implemented in power plants with a heat recovery circuit (exhaust gas heat, cooling water, lubricating oil) removed from the engine and used to heat water and evaporate it. For high-speed vehicle engines, it is preferable to supply water to the combustion chamber in the liquid phase. The following methods have found the most significant practical application: (1) Injecting water directly into the cylinders using water-fuel emulsion as fuel, and (2) supplying water into intake pipelines (manifolds).

The mixture made up of water and fuel is called an emulsion. There are two emulsions: "water in fuel" and "fuel in water". In practice, the first emulsion type, called "water-fuel emulsion" (WFE), is mainly used, in which water accounts for about 10 ÷ 40% of the mixture volume and is broken down to micro or nano size [23]. Using emulsion as fuel for vehicles can be done by two methods: the first is to use a pre-made emulsion, and the second is to use an emulsion created directly on the automobiles.

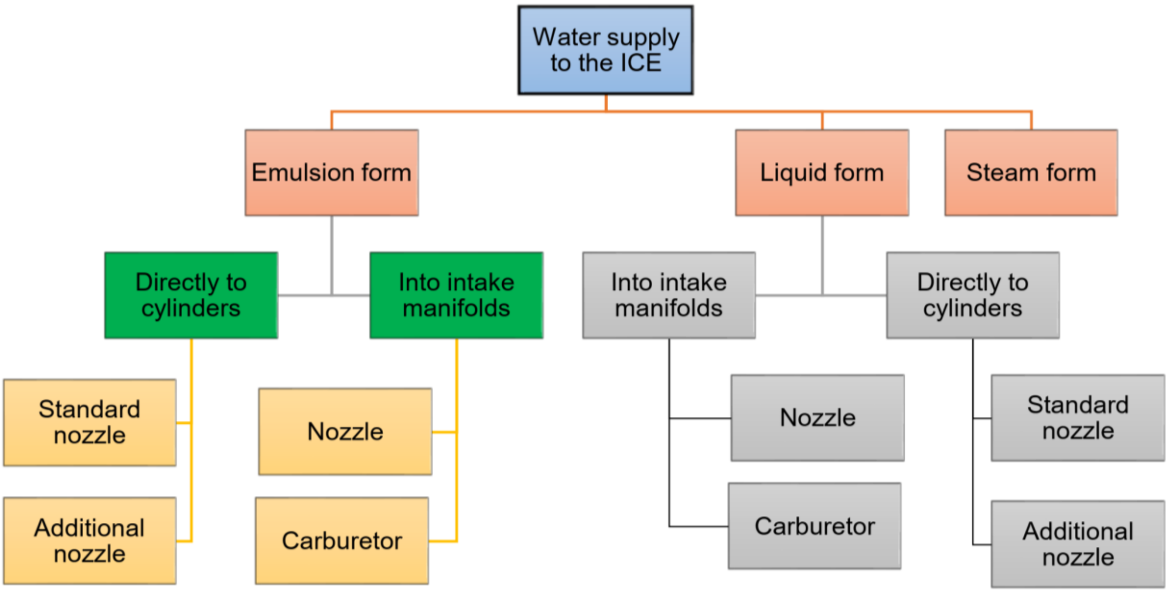


Fig 1. Methods for supplying water to engine cylinders

Experience using emulsion as fuel for ships has been researched and applied worldwide since the 80s of the last century [13],[23]-26]. However, its use in automobiles still needs to be improved due to some exploitation problems with techniques and technology, especially under conditions in Vietnam. First, due to the complexity of creating emulsions, their stability, and the inability to maintain long-term emulsion quality when using pre-made emulsions, the complexity of using under cold conditions, low-temperature conditions, expensive water-in-fuel mixing equipment, as well as the complexity of adjusting the ratio between water and fuel to obtain an emulsion mixture with optimal composition for different working conditions of the engine. Second, some practical and theoretical issues in studying the influence of water on the working process in engines have yet to be thoroughly researched.

Using water as a fuel component affects the engine's power and economy. On the one hand, the loss of part of the heat to drying and evaporation of water leads to a decrease in the above parameters. On the other hand, due to the formation of active radicals when creating a mixture in the engine cylinder and the "micro-explosion" phenomenon of nano-sized water particles, it increases the speed of chain reactions, increasing the turbulence of the engine mixture so the fuel burns more completely [27]-29]. The mechanism of the "micro-explosion" phenomenon is represented in Fig 2 [29]. The cooling effect of water also improves the quality of air intake into the cylinder, reducing thermal-mechanical stress on engine combustion chamber parts, improving anti-knock properties of gasoline, reducing NOx and CO emissions concentrations; it increases power, fuel economy, engine longevity, and automobile mileage [30].

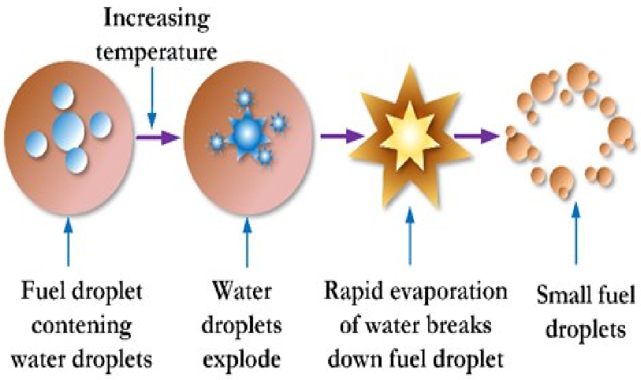


Fig 2. The mechanism of the micro-explosion phenomenon

In recent years, interest in water use in the form of WFEs increased, opening up broader prospects than using water only as a depressive medium. This method of improving ICE performance is implemented in gasoline and diesel engines. In both cases, in most operating modes, the processes of mixture formation and combustion are improved, the emission of nitrogen oxides is reduced, and the thermal stress of engine parts is significantly reduced. At the same time, when water is supplied to the cylinders of a gasoline engine, a deterioration in some of its indicators is observed in some cases. In particular, in partial load modes, excessive cooling of the working mixture due to the evaporation of water leads to insufficient homogenization of the mixture, deterioration in the quality of the work process, and an increase in the duration of vehicle acceleration. The best results are obtained by supplying water to diesel engines' cylinders, ensuring high-quality mixture formation, and the smokiness of exhaust gases is noticeably reduced.

Thus, supplying a certain amount of water to the combustion chamber is one of the effective methods for improving the economic and environmental performance of diesel engines. Currently, water supply to the cylinders is widely used in marine diesel engines. Injecting WFE into the combustion chamber of these engines makes it possible to solve the problems of increasing the operational fuel efficiency of a ship's power plant, improving its environmental performance, reducing thermal stress, and using viscous fuels. Research is being conducted on using WFE in diesel locomotives and stationary diesel engines. The increased interest in supplying water to the cylinders of high-speed diesel engines for automotive use is due to the possibility of a noticeable improvement in the toxicity of their exhaust gases [31]-33].

The article presents an overview of the history of using emulsions as fuel, analyzes the basis of working cycle theory using emulsions as fuel, and explores some results using emulsion. From there, conclusions are drawn about the possibility and effectiveness of using emulsions as fuel for cars, especially under climatic conditions in Vietnam.

2. Brief history of the using emulsions as fuel

In 1920-1921, two-compartment carburetors were installed on many British buses. One compartment is for the fuel supply, and the other is for the water supply [12]. In the 1930s, water was of interest to aeronautical technicians. In some studies, the use of water not only improves anti-knock properties but also reduces aviation engine heat load. In the Soviet Union, experiments were conducted on test benches as well as on the road when spraying water into the intake manifold of car engines ZIS-150 and ZIS-151, as well as the bus ZIS-155, here instead of using indexed gasoline 66 octane is equal to 56 octane gasoline [34].

During World War II, water injection was used on fighter aircraft and bombers produced in the Soviet Union, Germany, and the United States. For example, water injection was applied to the V12 engine installed on the B-29 bomber [34]. This research direction was implemented for the first time at NASA. Then, based on the research, Rolls Royce successfully manufactured an aviation engine with water injection applications.

Engine enhancement by water injection (or water-alcohol mixture) was commonly used during World War II by American (Pratt & Whitney) and German (Daimler Benz and BMW) engine manufacturers. Water is added to the fuel-air mixture, and the entire mixture is injected into engine cylinders. Due to contact with the hot surface of the piston and cylinder wall, water quickly turns into steam, creating favorable conditions for the combustion process. Cooling the fuel-air mixture increases the amount of mixture injected and improves fuel combustion efficiency.

The French automobile manufacturing group "Renault" has been applying water injection to fuel since 1977 (water injection) on racing automobiles. In 1983, during the World Automobile Championship “Formula-1” “Renault” installed a 12-liter water tank, an electric pump, and a pressure regulator, which increased engine power up to 440 kW. In 1986, the power of this engine was increased to 640 kW. In 1983, the Italian company “Ferrari" also applied water injection, which used a mixture of alcohol and water. Then, the German automobile company “Porsche” also applied water injection to "Formula-1" automobiles to increase engine power [34]. In the early 1980s, on racing motorcycles from Harley-Davidson, Suzuki, BMW, Honda, and Kawasaki, water injection was applied to reduce the heat load on the engine because the heat load on racing motorcycles was very high, if water is not sprayed, the motorcycles often stop working [35]. After that, the water injection method was no longer used because the world's fuel exploitation increased significantly, and fuel prices decreased significantly.

Domestically, since 2009, several scientists from the Department of Science and Technology of Ho Chi Minh City have initially researched. In early 2011, the Department of Science and Technology of Ho Chi Minh City announced that they had successfully tested equipment production to create emulsions from mixtures. Combining diesel fuel and water used for engines helps save fuel and reduce environmental pollution emissions [35]. Researchers continue to perfect the design to be applied to Ho Chi Minh City buses.

3. Analysis of the theoretical basis of using emulsions as fuel

At Cooling the engine cylinders with water increases the engine's power and efficiency. The cooling effect depends on the heat of vaporization and evaporation conditions of the fuel. The heat of vaporization of water is 2260 kJ/kg, while that of alcohol is 860 kJ/kg, and that of gasoline is 315 - 350 kJ/kg [29]. Therefore, if using alcohol entirely or a mixture of alcohol with gasoline or fuel with water, it means the alternative fuel has a higher heat of vaporization than gasoline, requiring less oxygen to burn, improving cooling efficiency. Water reduces not only the temperature of engine parts but also the temperature of the fuel-water mixture.

Water injection affects combustion chemical reactions, thereby reducing the fuel combustion temperature. The result is reduced nitrogen oxide and carbon concentrations in the exhaust gas. When using emulsion as fuel, the disadvantage is that the HC concentration in the exhaust gas increases. In some mining cases, the engine works unstable when the car moves at low speed. It is related to the uneven distribution of water to the engine cylinders.

Along with experimental studies related to water use in engines, many studies clarify the role of steam in the combustion process. When water participates in the combustion process, it affects the fire spread speed and enhances the conversion of CO into CO_2. It is pronounced when the water concentration is 7 - 9% [37]-[39]. As the water concentration continues to increase, the process speed decreases because of the decrease in combustion temperature.

To analyze more clearly, build a theoretical basis to calculate the working cycle thermal efficiency of diesel engines with the following assumptions:

- The evaporation of water in the emulsion takes place instantaneously at the end of the isovolumic heating process;

- The water vapor concentration in the working medium is small (less than 1%) and does not affect the working cycle parameters.

On that basis, the ideal working cycle of a diesel engine is shown in Fig 3. The formulas below consider the working cycle of 1 kg of working fluid.

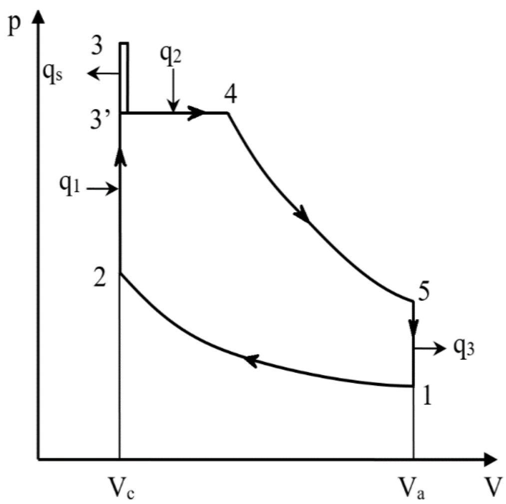


Fig 3. Ideal working cycle of a diesel engine using emulsion as fuel. 1-2: adiabatic compression; 2-3': isovolumetric heat supply; 3'-3: isovolumic heat release; 3-4: isobaric heat supply; 4-5: adiabatic expansion; 5-1: isovolumic heat release; q_1, q_2 are isovolumetric and isobaric specific heat, kJ/kg, respectively; q_3, q_s are the amount of specific heat released isovolumically and released by evaporation, kJ/kg, respectively; V_c, V_a - combustion chamber volume and total volume.

Thermal efficiency of the working cycle is determined as follows:

$$\eta_t = \frac{q_1 - (i_3 - i_w) m_w \frac{1}{L_a} + L_{wp} + q_2 - q_3}{q_1 + q_2} \quad (1)$$

Where i_3 is the enthalpy of water vapor at point 3, kJ/kg; i_w is the enthalpy of water injected into the engine cylinder, kJ/kg; m_w is the mass of water in the emulsion, kg/kg; $L_a = \alpha L_0$ is the actual mass of air needed to burn 1 kg of fuel, kg/kg; α is the excess air coefficients; L_0 is the theoretical air mass to burn 1 kg of fuel, kg/kg; L_{wp} is theoretical work done by steam after 1 work cycle, kJ/kg.

The theoretical work done by steam after 1 working cycle is determined as follows:

$$L_{wp} = (i_3 - i_5) m_w \frac{1}{L_a} \quad (2)$$

where i_5 is the enthalpy of the gas mixture in the cylinder at point 5, kJ/kg.

From (1) and (2) we have:

$$\eta_t = 1 - \frac{q_3 + (i_5 - i_w) m_w \frac{1}{L_a}}{q_1 + q_2} \quad (3)$$

The equation (3) is used to determine η_t at the rated working mode of engine when using traditional diesel fuel ($m_w = 0$) and WFE ($m_w \neq 0$). From (3), we see that η_t decreases as m_w increases. Therefore, it is not possible to use the theory of engine working cycle to analyze the efficiency of using water as a fuel component, but we need to use combustion models to determine the burning velocity and heat release rate of the medium.

Due to the presence of free radicals, chemical reaction speeds occur faster, so the combustion delay time when using emulsion as fuel is reduced compared to traditional diesel. The burning velocity is determined according to the two-component formula of I.I. Vibe [39], in which the dynamic combustion and diffusion combustion characteristics parameters, when applied to emulsion fuels, need to be determined experimentally.

4. Analysis of some results of using emulsion as fuel

Below is an overview of some research results on the effectiveness of using emulsion as fuel for diesel engines.

Many studies have shown that NOx emissions can be reduced by using WFE [41]-43]. Various studies have found that NOx is reduced by 50%. By [44] a reduction of up to 25% in NOx emissions when using large water droplets in an emulsion. [43] observed up to 20% reduction when using 20% water emulsion diesel fuel. In addition, there is a strong relationship between the increase in the amount of water. The percentage reduction in NOx emissions has also been reported. Many researchers agree that the reduction in NOx emissions is directly related to the increase in the share of water. This drop in temperature occurs due to the loss of latent heat. They are caused by the evaporation of water in the emulsion. According to [45], the endothermic reaction occurs due to the transition of water to steam, which reduces the temperature of the combustion zone. This reduces NOx formation in the combustion chamber. In addition, [46] explain the drop in combustion temperature by the effect of heat removal. The contained water absorbs heat from combustion. Consequently, the combustion temperature of the gas inside the cylinder is reduced, which limits the formation of NOx.

Several studies have been carried out abroad on single-cylinder units and full-size diesel engines such as Cummins VTA-1710-C and GMC-12-149T. It has been shown that adding water to diesel fuel by up to 25% by weight slightly reduces the smoke of exhaust gases and the emission of nitrogen oxides. The Doxford Engine company has established that when water is supplied to a low-speed diesel engine from 0 to 20%, with increasing engine load, it is necessary to increase its concentration in the WFE to increase the adequate performance of the ICE itself. The use of WFE for diesel engines operating in conditions with limited air exchange (underground mines, greenhouse farms, factory floors, etc.) is of particular relevance. It has been established that when WFE is supplied to a diesel engine with 5–10% water by weight to the fuel, it is possible to simultaneously reduce emissions of nitrogen oxides NOx, carbon monoxide CO, and exhaust smoke [47]-49].

According to [47], a test to evaluate the effectiveness of using low water emulsion on IAMZ-238L diesel engines compared to traditional diesel fuel. The emulsion composition includes 79% conventional diesel fuel L-0.2-40 GOST 305-82, 20% water, and 1% PAV-AMDM-0.8 (oil-soluble additive). The test was conducted under the same conditions to compare the toxic components of the exhaust gases. The results of testing the engine when working with traditional diesel fuel and emulsion with the above composition are shown in Fig 4. Accordingly, CO is reduced by an average of 28%, NOx is reduced by an average of 35%.

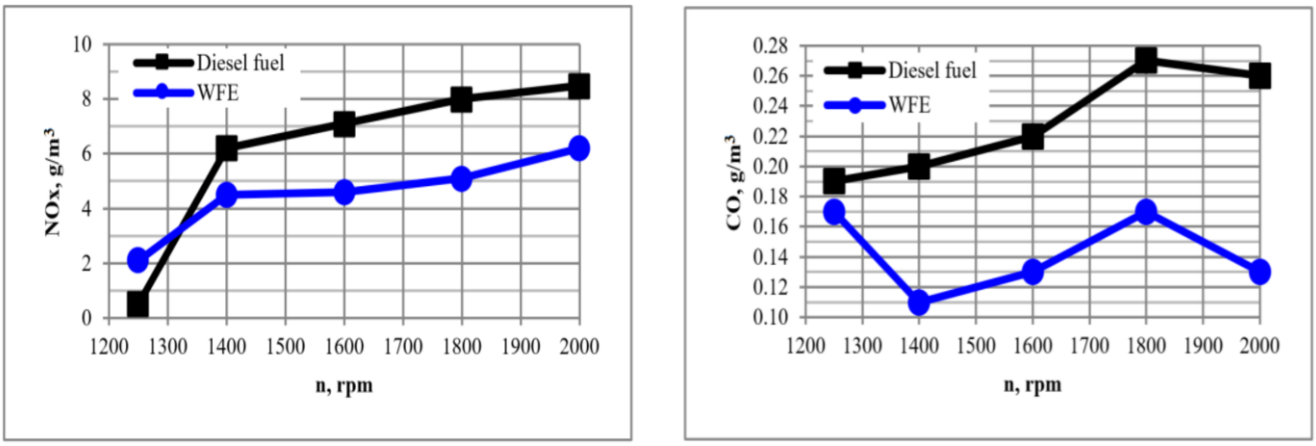
At the Saint Petersburg Academy of Military Logistics and Transport, KAMAZ-740 engines were tested using emulsion as fuel. Test results demonstrate that the optimal water concentration in the emulsion to ensure minimal toxic emissions and improve fuel economy and engine power is within the limit of 10 ÷ 20%. The concentration of toxic substances in the exhaust gas is reduced, with CO 17 ÷ 18%, NOx 40 ÷ 70%, and black smoke concentration 3 ÷ 4 times or 35 ÷ 50% according to [47].

In research [35], a device to create emulsions directly on a car was successfully designed and manufactured. Basic technical specifications of the emulsifying device directly on the vehicle: water content in the emulsion 5 ÷ 30%; water particle size in emulsion 5 ÷ 10 μm; maximum power required for the device is less than 100W; required power in working mode 50W; automatic working mode; working environment temperature -30 to +50°C; barrel size 2 ÷ 40 liters; maximum weight (excluding water) 10 kg. The device is installed on the engine according to the diagram in Fig 5.

Positions on Fig 5:

Original fuel system equipment: 1 – fuel tank; 2 – fuel flow sensor; 3 – low pressure pump; 4 – pipe; 5 – pressure regulating device; 6 – fuel return line; 7 – high pressure pump; 8 – high pressure pipeline; 9 nozzles.

Equipment for emulsifying water supply system: 10 – water tanks; 11 – water pump; 12 – pump capacity adjustment device; 13 – water pressure sensor; 14, 17 – mouth; 15 – solenoid valve; 16 – water return line to the tank; 18 – electric water heater; 19 – water level sensor; 20 – water temperature sensor; 21 – controller.



(a) (b)

Fig 4. The dependence of NOx (a) and CO (b) on engines speeds

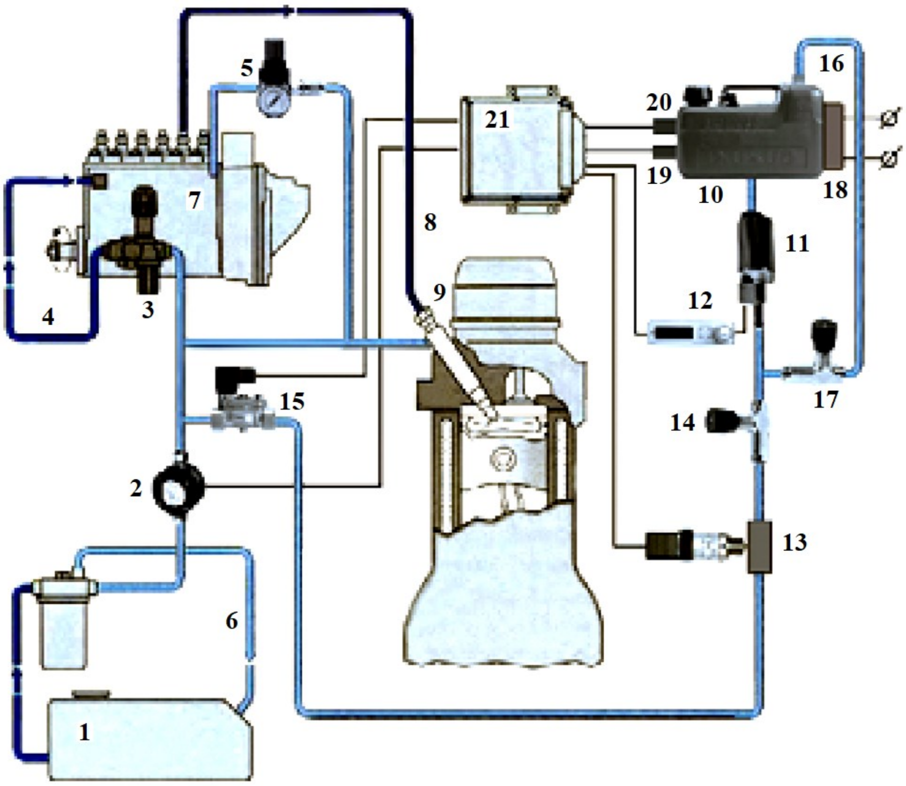


Fig 5. Diagram of engine fuel system using automatic emulsifying device

The emulsifying device can be installed directly on the vehicle and on KAMAZ, MAZ, and BELAZ cars, reducing fuel consumption by up to 10% [35]. It reduces soot formation in engine cylinders, reduces black smoke and the concentration of toxic substances in exhaust without the need to install expensive exhaust neutralizers, prevents deposits on spray holes and exhaust valves, and has high reliability and simplicity in exploitation.

According to [50], the company "OKBM" of the Russian Federation, has produced the IM-70 device (Fig 6 and Fig 7) for trucks and buses equipped with engines with a capacity of up to 500 HP. The IM-70 device has a capacity of 100 kg of fuel-water emulsion per hour, a mass of 5 kg, and a size of 200x180x150 mm; effective when used in reducing fuel consumption by 8 ÷ 15% (when maintaining engine capacity), reduce toxic emissions of NOx by 40 ÷ 60%, CO2 by 30 ÷ 50%, CO by 30 ÷ 60%; equipment lifespan 15 years.

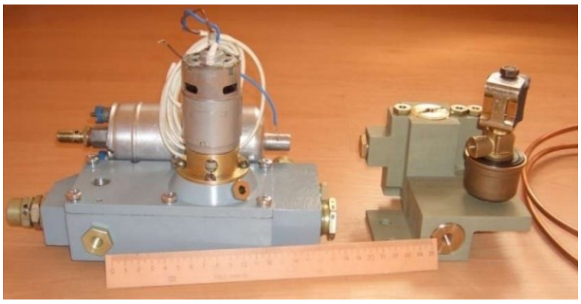


Fig 6. The IM-70 device

Fig 7. Installation of IM-70 device in the bus engine

Ho Chi Minh City Department of Science and Technology, New Equipment Design and Manufacturing Center (NEPTECH), in collaboration with Viet-Nga New Technology Company Limited, introduced new emulsion fuel creation technology that can save up to 15% of fuel. According to [35], this technology was developed by OKBM Company. The system line includes a pump, ultrasonic vibration activator, spray mixer, automatic dosing system, and function control. The system has a unique part to mix water and fuel in a prescribed ratio. When the fuel-water mixture passes through a platinum catalyst surface, the water will be softened and pulverized by the vibration activation system to a size of 100 ÷ 300 nm (nano size). At this size, water can no longer recombine with each other but combines with fuel to create an emulsion. Test results of an emulsion containing 15% water show that the engine operates at the highest capacity, the content of toxic emissions such as CO is reduced by 30% ÷ 60%, and NOx is reduced by 30% ÷ 40%. In particular, the device is compact and can be installed directly on vehicles, ships, or boilers. Currently, there are many types of equipment corresponding to different operating capacities, such as IM70 (used for cars), IS1000 (used for ships), and MIP101 (used for boilers).

Thus, emulsion is used as an alternative fuel for diesel engines. Studies on the effectiveness of using emulsion as fuel for diesel engines have been conducted relatively diversely. On the other hand, the optimal composition of the emulsion, that is, the water concentration and the degree of its impact on the valuable and environmental parameters of the engine, are different between studies. Most authors confirm that the optimal water concentration is 10 ÷ 20%. Other authors confirm the optimal water concentration is up to 50%. The difference in assessing the optimal concentration of water in the emulsion depends not only on the type of engine and type of fuel used but also on the engine working mode.

5. Conclusions

Water cannot wholly replace gasoline, kerosene, and diesel fuel, but using water as a fuel component has been practiced since the beginning of the 19th century. Water can be mixed with fuel into a finished emulsion, injected directly into the engine cylinder, or sprayed into the engine intake manifold as an intake air additive. The water content of the emulsion in research papers is indicated differently from 5% to 30%; this content depends on the type of engine, the fuel used, and the vehicle's operating mode.

Using an emulsion as fuel reduces the engine temperature and the temperature of the air-fuel mixture while maintaining engine power characteristics, improving the anti-knock properties of gasoline. Using emulsion as fuel reduces the concentration of pollutants in the exhaust gases of car engines, improving the environmental situation in cities and residential areas; NOx has decreased by an average of 35%, CO by 28%, and PM by 10%.

Methods and equipment for applying emulsions directly to cars have been developed. However, studies of the interaction of water with the working process in internal combustion engines still require careful theoretical and experimental analysis. Vietnam has a tropical climate, so using emulsions in high ambient temperatures will not lead to water freezing. Therefore, the use of emulsions for cars in Vietnam is one of the areas in need of improvement.

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