Influence of oxygen-enrichment air intake and bioethanol–gasoline blends on exhaust emissions and fuel consumption of gasoline engine

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Abstract

Among human activities, motor vehicles play the most important role in air pollution. Air pollution has negative impacts on people and on the environment. In this paper the effect of oxygen-enriched air (20.8%, 21.8%, 22.8%, 23.8% and 24.8%) and different bioethanol-gasoline blends (zero, 5%, 10%, 15%, 20% and 25%) in different engine speeds (1000 rpm, 2000 rpm and 3000 rpm) on the amount of pollutants, particles, and fuel consumption were studied. To do so, a four-cylinder, four-stroke gasoline engine with Siemens fueling system was used. The results showed that when oxygen percentage in the inlet increased from 20.8% to 24.8%, the average amount of UHC, CO, fuel consumption and the number of fine and coarse particles decreased 126.75%, 11.25%, 17.02%, 77.37% and 243.25%, respectively, while the amount of CO2 and NOX increased 5.36% and 113.27%, respectively. Also the results showed that when bioethanol percentage in the mixture increased from zero to 25%, the average amount of UHC, CO2, CO and the number of fine and coarse particles decreased 104.53%, 3.45%, 34.57%, 41.42% and 96.09%, respectively, while the amount of NOX and fuel consumption increased 163.41% and 15.75%, respectively.

Keywords*: air pollution, bioethanol, fuel consumption, oxygen-enriched air, particulate matter, gasoline engine*

1. Introduction

Nowadays, air pollution is one of the most important concerns in developed countries. The pollutants emitted from motor vehicles play the most important role in air pollution [1]. Transits of vehicles have a significant share in emissions and particles and in release of toxic species such as benzene and several polycyclic aromatic hydrocarbons and metals [2]. The excessive use of fossil fuels has led to environmental impacts such as greenhouse effect, acid rain, the hole in Ozone layer, and climate changes [3]. Combustion process in internal combustion engines not only produces pollutants but also emits particles. Internal-combustion engines have the biggest share in the emission of particles. In terms of size, particles present in environment are divided into the following categories: thoracic particles (particles with aerodynamic diameter of less than 10 microns - PM10), fine particles (particles with aerodynamic diameter of less than 2.5 microns – PM2.5), coarse particles (particles with aerodynamic diameter between 2.5 and 10 microns – PM10-2.5), and ultrafine particles (particles with aerodynamic diameter of less than 0.1 micron) [4]. Particles penetrate into lung and respiratory system and give rise to cardiac and respiratory diseases such as Asthma and lung cancer. Fine particles are much more dangerous than coarse particles. Almost 3% of mortality caused by heart diseases and 5% of mortality caused by lung cancer in the world has been attributed to particles [5].

Internal combustion engines have a large share in production of suspended particles in urban areas. These particles occur due to incomplete combustion in internal combustion engines. Most of the particles during the combustion process become oxidized, while the remaining amounts of compressed particles are removed. These particles have a complex compounds that called soot and the most of organic particles are volatile. The chemical nature of the particles is depended on the combination of fuel and combustion conditions. Diesel engines Particles mainly are became compressed Primary carbon particles that are absorbed on volatile organic substances. While gasoline particles are made of organic materials [6]. The formation of particulate matter in diesel engine depended to working conditions [7].

Mass production of suspended particles in diesel engines is more than gasoline engines, so environmental laws and regulations are insists to reduce the diesel particulate [8]. In the same conditions, the average size of particle emissions from gasoline engines is less than suspended particles of diesel engines [2]. So that, in comparison with the same diesel engine Number Size Distribution the gasoline engine, gasoline engines produces smaller number of particles [7]. By considering the product of particles number produced by gasoline engines in number of vehicles in urban areas, gasoline-powered vehicles, are known a major source of particulate matter, especially fine particles in heavily populated urban areas. According to reports the World Health Organization, the effect of superfine particles and coarse particles are more dangerous [5]. Recently, European Commission has paid special attention to number-Mass of particles polluting gasoline engines. So that, European Commission is approved the laws that limit the number of particle emissions from diesel engines. The commission introduced critical limit 6 × 1011 particles/km for direct injection gasoline engines that manufactured after September 2017 and the commission introduced critical limit 6 × 1012 particles/km for engines that have Euro 6 standard in September 2014 [8].

In the process of combustion, thermal energy is achieved when all the fuel is completely burned. Providing Fuel combustion process in the combustion chamber is easy for perform process of combustion, but provide enough oxygen seems difficult for burn the fuel. So the amount of oxygen in the combustion chamber is main factor in determining the power of an engine. (Not amount of fuel). Therefore, research on the application of the method used to increase the oxygen in the air, so that need to at least take the necessary oxygen for complete combustion without the need for qualitative and quantitative changes in the smoke ducts satisfy is essential [9].

Combustion with higher oxygen percentage is an efficient method to reduce the pollutants emitted from internal-combustion engines. In this method, the air entering the engine has higher oxygen concentration and consequently lower nitrogen volume. Among the advantages of this method is the reduction of environmental impacts, including reduction of particles and improvement of engine efficiency. The use of additional oxygen in engine air results in higher thermal output, so less fuel is consumed to obtain the same amount of energy [10].

With the rapid development of industries and growth of population, more fossil fuel is needed [11]. As fossil fuels constitute a major part of today's energy resources, there is much concern about shortage of energy due to limited resources or due to political reasons [12]. In addition to efficiently designing engines to save fuel consumption, we need to search for alternative resources to all or part of the fuel currently being used. Therefore, we have to reduce demand for and dependence on fossil fuels [1]. In recent years, there has been a tendency to alternative fuels, particularly alcoholic fuels, due to increased energy consumption, shortage of crude oil resources, increased price of crude oil, and air pollution caused by transportation [13, 14]. Furthermore, the addition of MTBE to lead-free gasoline pollutes underground waters and threatens people's health [11], so it should be replaced with an alternative. Among various alcohols, ethanol is the most suitable fuel to internal combustion engines [13]. Ethanol is obtained from renewable resources such as sugar cane, barley, corn, and different agricultural wastes [15]. It has many advantages over gasoline, including higher octane number, good anti-knock properties, good thermal output, better engine output, higher ignition speed, and reduction of CO and UHC pollutants [16, 13, 11]. Ethanol is used in internal-combustion engines in pure form or in combination with gasoline. The use of ethanol in engine entails some changes in engine design and fuel system. However, if a low percentage of ethanol is used in combination with gasoline, modification of engine design would not be needed [13]. Ethanol is currently being used as an alternative to all or part of gasoline in many countries [17].

Pola and Sekar [18] studied the effect of additional oxygen on engine performance and on pollutants emitted from diesel engine of a locomotive. They concluded that when oxygen concentration of engine air, fuel supply rate, and injection time were optimal, the use of higher oxygen percentage reduced the amount of NOx by 15-20% and particles by 60%.Prez and Boehman [19] conducted a research on the effect of additional oxygen in air on engine performance. The results showed that when oxygen increased, brake fuel consumption decreased by 40% thanks to enhancement of fuel conversion efficiency.

A research has been made on the effect of higher oxygen percentage in engine air on the performance and the amount of pollutants of a diesel engine with rapeseed oil. The results indicated that when air oxygen increased, delayed combustion and premixing time reduced, while the pressure and peak temperature of the cylinder increased. When oxygen percentage increased, particles, CO and hydrocarbon decreased significantly, while NOx increased [20]. A research has been made on the effect of additional oxygen and diesel water and fuel emulsion on the performance and the amount of pollutants of diesel engine equipped with turbocharge. The results indicated that additional oxygen reduced brake fuel, delayed combustion, and pressure inside the cylinder, while the addition of water to fuel had a reverse effect. The simultaneous effect of higher oxygen in engine air and water in fuel denotes the reduction of NOX and PM pollutants [21]. Li and coworkers [9] made a study on the effects of oxygen-rich air combustion on a small gasoline engine with carburetor fuel supply system. They found out that as oxygen of the air entering the engine increased, combustion temperature and the pressure inside the cylinder increased. Their results also showed that air containing 24% oxygen increases the pressure inside cylinder by 15%.

A research has been made on combustion with higher oxygen percentage for starting combustion carburetor engine. The results indicated that when oxygen concentration in the air entering the engine increased, CO and UHC pollutants decreased but NOx increased [22].

A research has been made on the effect of oxygen-rich air on performance and the amount of pollutants in a four-stroke, combustion engine with multi point fuel injection system. Oxygen with various mass flows (5, 10 and 15 l/min) was mixed with the air entering the engine and different speeds (1000 rpm, 1500 rpm and 2000 rpm) in various loads (20, 40, 60 and 80 N/m) was used. The results revealed that brake fuel consumption decreased by 15% and CO and HC pollutants reduced by 20-30%, but NOx and CO2 increased [23]. Also many researches focused on the effect of higher oxygen percentage in air on particles emitted from diesel engine. The results showed that increased oxygen percentage in the air entering the engine resulted in reduction of particles [24-27].

Koç and coworkers [1] replaced single-cylinder gasoline engine fuel with a combination of lead-free gasoline and bioethanol and studied its effect on the performance and amount of pollutants of the engine. In their study, rotational speed of the engine increased from 1,500 rpm to 5,000 rpm. The results showed that the new fuel increased engine torque, reduced fuel consumption, and decreased CO, NOx and UHC.

Srinivasan and Saravanan [28] studied combustive specifications of combustion engine with bioethanol compounds and oxygen-rich fuels. The results indicated that fuel compounds mildly increased UHC and O2, significantly reduced CO2 and NOx, and slightly reduced CO.

A research has been made on the performance parameters and the amount of pollutants in a two-stroke gasoline engine with gasoline-ethanol fuel in different speeds and loads. Ethanol-gasoline ratios of 5%, 10% and 15% were used in speeds of 2,500 rpm, 3,000 rpm, 3,500 rpm, and 4,500 rpm. The results indicated that when ethanol increased, cleaning efficiency and delivery ratio improved but fuel conversion efficiency and brake power reduced. Also, UHC, CO, CO2 and NOx decreased significantly [17]. A research has been carried out on a four-cylinder, direct-injection diesel engine with density ratio of 19, working in the ratios of 6.1%, 12.2%, 18.2% and 24.2% bioethanol in two speeds of 1,800 rpm and 2,400 rpm. The results in both engine speeds indicated that when bioethanol percentage increased, the amount of particles decreased in terms of both size and mass. Also, the number and mass of particles in speed of 2,400 rpm was more than in speed of 1,800 rpm [29]. A research has been made on fumigation effect of ethanol on pollutant gases and particles in a four-cylinder engine (Ford 2701C). In fumigation technique, ethanol enters air manifold inlet in steam form. This was done using injector, pump, pressure regulator, heater for steaming ethanol, fuel tank, and separate pipes. The results indicated that when steamed ethanol was added to inlet manifold, the amount of NOx and PM2.5 decreased, while the amount of particles and UHC and CO pollutants increased. The addition of steamed ethanol to air reduced the amount of air entering the engine, thereby increasing the amount of UHC and CO and reducing NOx. The reduction of PM2.5 pollutant is due to tendency of ethanol to reduce soot because of higher ratio of hydrogen-carbon. In addition, ethanol does not contain aromatic compounds [30]. A research has been made on particles emitted from a single-cylinder diesel engine working with diesel, biodiesel and biodiesel-ethanol compound. The results showed that the use of biodiesel reduced particles. The reduction of particles was more when a combination of biodiesel and 20% ethanol [31]. A research has been made on the effect of turbocharge of emitted gases on the amount of nano scale particles in a gasoline-burning, direct-injection engine in three speeds and four loads. The results indicated that the amount of particles decreased in low loads and increased in high loads [32]. Zhao and coworkers [33] studied the effect of different ratios of hydrogen (2%, 5% and 10%) on the amount of particles and performance in a direct-injection combustion engine. Their results indicated that when hydrogen percentage increased, sustainability and speed of combustion process improved and the amount of particles decreased. When 10% hydrogen was applied, there was more than 95% reduction in the number or mass of particles.

The foregoing studies reveal that air pollution and particles produced by internal-combustion engines take disastrous impacts on people and on the environment. Although compression ignition engines have the biggest share in the emission of particles, combustion engines, Pride Car in particular, are most widely used in transportation system of Iran and emit a considerable amount of particles. Therefore, it is necessary to study the particles emitted by such cars. Besides, by reducing the consumption of fossil fuels, the amount of pollutants and particles can be considerably reduced. To achieve this goal, researchers have replaced some part of gasoline with renewable fuels such as bioethanol and have used certain methods such as combustion with oxygen-rich air. A review of the past studies reveals that so far no research has been made on the concurrent effect of combustion with oxygen-rich air and different ratios of bioethanol-gasoline in gasoline-burning engines. In this research, we aim to study combustion with oxygen-enrichment air and different bioethanol-gasoline ratios as an efficient method for reducing pollutant gases, particles and fuel consumption in Pride gasoline-burning engine.

2. Materials and Methods

The tests were carried out on pollution and biofuel application laboratory at biosystem mechanics engineering department of Razi University of Kermanshah in summer 2014. Figure 1 illustrates the general schema of test instruments.

Tests were performed in a 1323 cm3, four cylinder arranged in-line, four stroke, direct-injection, water-cooled, 9.7:1 compression ratio, spark-ignition engine pride (Saba) M13NI with Siemens fueling system (Figure 1. (g)); the maximum torque was 103.3 N.m at 2800 rpm and the maximum engine power was 62.5 hp at 5500 rpm.

Basic gasoline (mixture of plate formit and light gasoline) was procured from Kermanshah Oil Refinery and absolute bioethanol with purity degree of 99.6% from Jahan Alkol Teb Company of Arak. By combining bioethanol and basic gasoline, fuels were prepared with ratios of zero, 5%, 10%, 15%, 20% and 25% bioethanol. To carry out the tests, mixtures were prepared with different bioethanol percentages and kept in 4-liter containers. Before performing the tests relating to each type of fuel, 4-liter tank of engine was fully discharged and, after ensuring it is empty, filled with another fuel.

The mixtures of air and different oxygen percentages were prepared using oxygen tank, oxygen manometer, air compressor, gas mixing chamber, voluminous air bag, and automotive test analyzer (see Figure 1). To achieve the appropriate mixture of air and oxygen, a gas mixing chamber was used which has been designed by Rameshbabu and coworkers [34] and completed by Momen [35]. The gas mixing chamber has the capacity of 6750 cc and consists of 20 cells with walls being 3 mm thick, made of Perspex plates, two bars with diameters of 5 mm, an input and an output. After entering each cell, air and oxygen passed through two small holes each with diameter of 2 mm and then entered the next cell. Thanks to spiral movement of gas mixture in the cells, air and oxygen were fully mixed.

To store the mixture of air and oxygen, a nylon bag with capacity of 478 liters with two inlet and outlet valves was used. Air and oxygen entered the mixing chamber through a three-way connection. The mixture prepared in mixing chamber entered nylon bag through a hosing and was relaxed and stored there. Before arrival of the mixture to the bag, a three-way connection was used to measure the amount of oxygen by an automotive test analyzer. At the place where the mixture entered the engine, a bigger pipe was used to help the smooth flow of air-oxygen mixture into engine and air filter.

The gases emitted from the engine was analyzed using Airrex gas tester, model HG-550, made in Korea. To measure the particles, LIGHTHOUSE’s particle counter was used, model 3016-IAQ, made in USA. The particle counter measured the number of particles with diameters of 0.3, 0.5, 1, 3, 5 and 10 micron by sucking them in specified time and volume. The counter was placed 50 cm distant from exhaust. The number of particles was measured within a period of 30 seconds in the volume of 2 liters. In the analysis, the particles were divided into two groups of fine particles (particles with diameter of 0.3, 0.5 and 1 micron) and coarse particles (particles with diameter of 3, 5 and 10 micron). Injection and fuel pump pressure were 2.4 and 5 bar, respectively [36] so another fuel system parallel to the main fuel system was used. For this reason, a separate fuel system, four scaled cylinders made by Lab Glass Technical Company with volume of 10 ml and accuracy of 0.2 ml, cylinder chamber, and two inlet and outlet valves was used for measuring fuel consumption (see figure 2).

In the test, inlet and out let valves opened for 30 seconds and the consumption was measured by reading the fuel gathered in cylinders. The tests were carried out once the engine reached a stable condition (10-15 minutes after starting). After performing each test, the engine worked for several minutes so as to adapt to the conditions of the next test. In this research the effect of different oxygen percentages present in the air entering the engine, bioethanol-gasoline mixture and engine speed on pollutants, particles and fuel consumption were investigated. Air-oxygen mixtures were prepared with the ratios of 20.8% (environment), 21.8%, 22.8%, 23.8% and 24.8%. Also bioethanol-gasoline mixtures were prepared with the ratios of zero, 5%, 10%, 15%, 20% and 25%. The engine was tested in three speeds of 1,000 rpm, 2,000 rpm and 3,000 rpm. The tests were carried out in load-free mode. Each test was repeated three times and their average was calculated. Fuel consumption, unburned hydrocarbon (UHC), carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), and fine and coarse particles were measured.

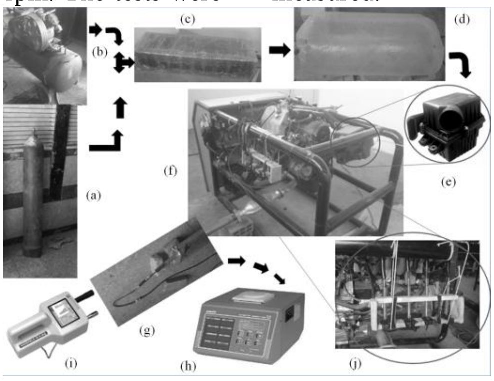

Fig.1 A schematic diagram of the experiment set-up: (a) Oxygen tank, (b) Air compressor, (c) Gas mixing chamber, (d) Voluminous air bag, (e) Air filter, (f) Spark-ignition engine, (g) exhaust, (h) Automotive emission analyzer, (i) Particle counter, (j) fuel consumption measurement system

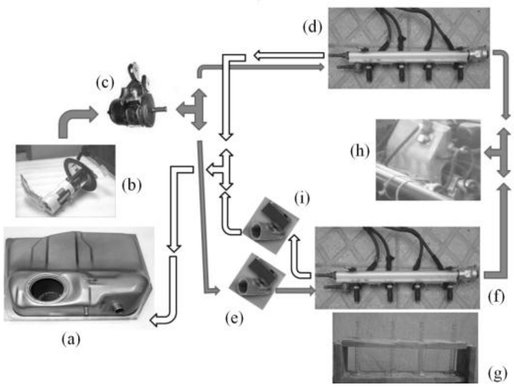

Fig.2 Fuel consumption measurement system: (a) fuel tank (b) gasoline pump (c) power pressure filter (d) main engine injector (e) inlet valve (f) fuel consumption measurement injector (g) scaled cylinders and cylinder chamber(h) air manifold (i) outlet valve

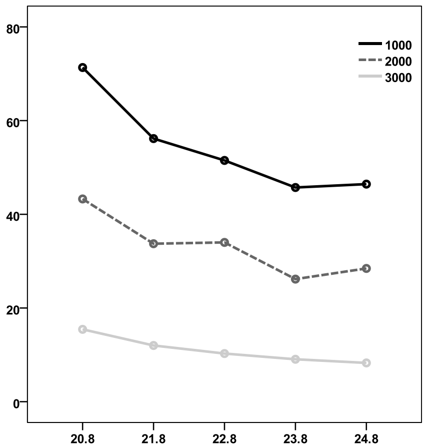

Fig 3. Effect of percent of oxygen in the air and engine speed on UHC

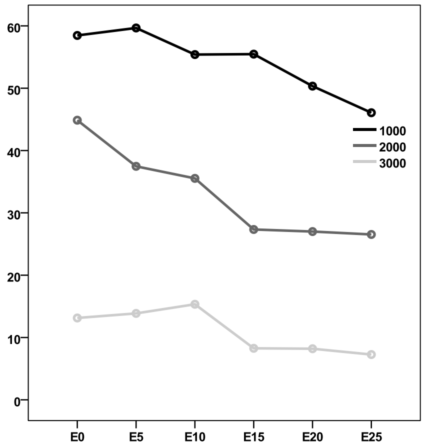

Fig 4. Effect of percent of bioethanol in the mixture and engine speed on UHC

Results and Discussion

Unburned Hydrocarbons

Hydrocarbon (HC) is an organic compound consisting of hydrogen and carbon. Unburned hydrocarbons are hydrocarbons remained after the burning of oil materials in engine [17]. The emission of unburned hydrocarbons from engine is caused by three mechanisms: A) incomplete combustion or misfiring which occurs in air-poor conditions or where fuel-air mixture contains the great deal of burned gas (exhaust gas) or nitrogen for extending combustion flame at combustion chamber; B) Flame Quenching effect which occurs in the vicinity of combustion chamber [11], so that some amount of fuel-air mixture is trapped in the gaps of grooves and consequently no frame reaches it. Also, some areas in combustion chamber might have very weak flame and low combustion temperature [17]; C) Deposits or oil membrane which stick to and absorbed by fuel. Unburned hydrocarbon may also be caused by the shape of engine, fuel structure, combustion temperature, available oxygen and duration of combustions process [37].

The figure 3 shows that as oxygen concentration in air increases, the amount of UHC in the gas exiting the engine decreases. This is because the existence of higher oxygen in combustion chamber increases UHC gas oxidation [20]. The additional oxygen improves combustion process by improving the flame, increasing the temperature inside cylinder, and increasing oxidation of hydrocarbons deposited in cylinder gaps. Furthermore, reduction of delayed combustion (faster combustion) resulting from additional oxygen prevents the unwanted arrival of fuel to cylinder walls [27]. The additional oxygen in the air entering the engine increases equivalence ratio [16], so that combustion takes place under stoichiometry conditions with the mixture of air and thin fuel. In such condition, the amount of UHC pollutant decreases thanks to the presence of sufficient oxygen for oxidation of unburned hydrocarbons [11]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, the amount of UHC decreased by 27.64%, 35.79%, 60.67% and 56.37% respectively compared with oxygen percentage of 20.8%.

Thefigure 4 shows that as bioethanol percentage in the mixture increases, UHC pollutant decreases. Thanks to the existence of an oxygen atom in its structure, ethanol is a hydrogen fuel and consequently has a higher air-fuel ratio. The ethanol added to gasoline increases the volume output, as the result of which full combustion occurs and flame temperature and cylinder pressure increases [13]. Compared with gasoline, ethanol produces a faster flame. Faster flame reduces combustion duration and increases combustion temperature. Higher combustion temperature helps full combustion [37]. Furthermore, ethanol prevents the development of porous deposits thanks to the absence of lead in its chemical structure. In addition, molecules of ethanol are polar and are not easily absorbed by non-polar molecules of lubricator oil, so the increase of ethanol reduces UHC pollutant [11]. Compared with E0 mixture, the amount of UHC decreased by 4.92%, 9.60%, 27.89%, 36.16% and 45.83% respectively in the mixtures of E5, E10, E15, E20 and E25.

Increase of engine speed was followed by reduction of UHC (see figures 3 and 4). When engine speed increased, combustion temperature and exhaust smoke increased, which caused UHC oxidation. As the result, UHC concentration in the gas exiting the engine decreased [38], so the amount of oxygen in the mixture increased and consequently hydrocarbon decreased due to increased exhaust temperature [39]. When the oxygen percentage in the intake rises from 20.8% to 24.8%, the concentration of UHC reduces from 77 ppm to 47 ppm in 1000 rpm engine speed, 75 ppm to 22 ppm in 2000 rpm engine speed, 32 ppm to 12 ppm in 3000 rpm engine speed. In higher speeds of engine, the addition of ethanol reduced UHC thanks to improvement of air-fuel mixing process. Improvement of mixing process helps the full combustion and reduces the amount of UHC [1]. When the bioethanol percentage in the blend rises from zero to 25%, the concentration of UHC reduces from 84.67 ppm to 51.67 ppm in 1000 rpm engine speed, 59.67 ppm to 23 ppm in 2000 rpm engine speed, 21.33 ppm to 6.33 ppm in 3000 rpm engine speed.

Carbon dioxide

Carbon dioxide pollutant is constituted through combustion of carbon-containing fuel around or above stoichiometry conditions. Studies show that CO_2 is a greenhouse gas and warms the earth planet [10]. As with other fuels, ethanol produces some amount of CO_2 when burning. However, CO_2 gas resulted from burning of ethanol changes into organic tissues during the growth of plant. Being a plant resource, ethanol has the lowest cycle of greenhouse gases. Therefore, CO_2 gas emitted from the burned ethanol does not increase greenhouse gases because it is obtained from renewable carbon resources [3]. Higher CO2 percentage in exhaust indicates higher oxidation of fuel in the fixed speed of engine, higher temperature for conversion of power, and better combustion, because a more amount of fuel is changed into CO2 rather than CO production as the result of combustion process [40].

As it shown in figure 5, when oxygen increases in the air entering the engine, CO2 pollutant increases. Increase of oxygen in the air converts CO into CO2 through oxidation [40]. As air oxygen increases, the engine works with a poorer mixture. In such condition, combustion process occurs more completely and the amount of CO2 increases [16]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, the amount of CO2 increased by 0.76%, 1.45%, 2.13% and 2.53% respectively compared with oxygen percentage of 20.8%.

As it shown in figure 6 when bioethanol percentage of the fuel increases, carbon dioxide decreases. When there is additional bioethanol in gasoline, the amount of carbon dioxide decreases thanks to fast evaporation, better mixing of air and fuel and, consequently, better combustion [39]. Compared with E0 mixture, the amount of CO2 decreased by 0.64%, 1.03%, 0.86% and 1.90% respectively in the mixtures of E5, E10, E15, E20 and E25.

As the figures 5 and 6 has shown, when engine speed increases, the amount of CO2 increases. When this happens, the reaction of CO oxidation to CO2 accelerates due to higher oxygen concentration in the air entering the engine. This also increases CO2 concentration [40]. When the oxygen percentage in the intake rises from 20.8% to 24.8%, the concentration of CO2 reduces from 12.32% to 12.84% in 1000 rpm engine speed, 12.46% to 13.21% in 2000 rpm engine speed, 12.57% to 13.29% in 3000 rpm engine speed. When the bioethanol percentage in the blend rises from zero to 25%, the concentration of CO2 reduces from 12.37% to 11.80% in 1000 rpm engine speed, 12.57% to 12.28% in 2000 rpm engine speed, 12.60% to 12.20% in 3000 rpm engine speed.

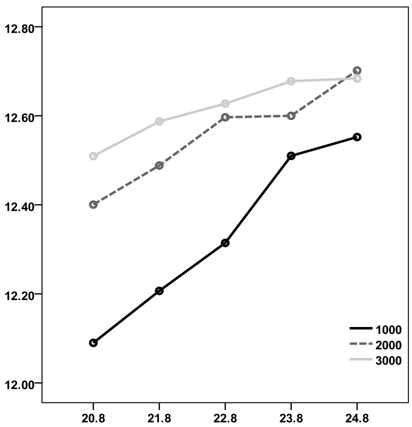

Fig5.Effect of percent of oxygen in the air and engine speed on CO2 [redacted]

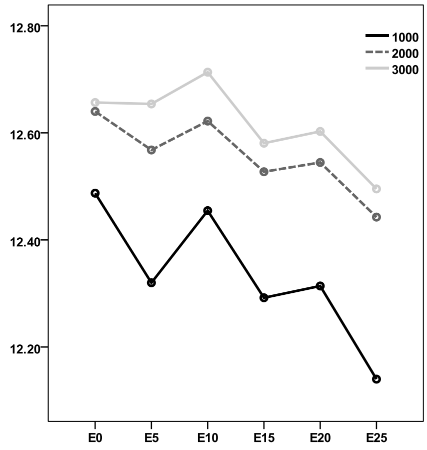

Fig 6.Effect of percent of bioethanol in the mixture and engine speed on CO_2

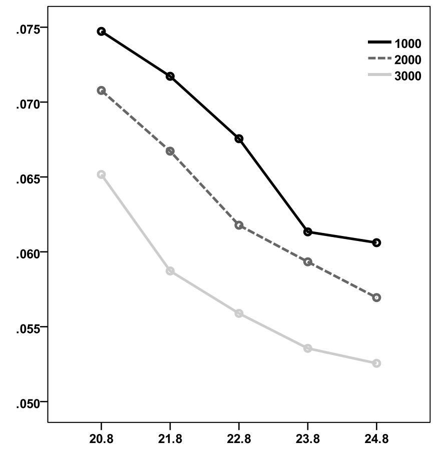

Fig 7. Effect of percent of oxygen in the air and engine speed on CO

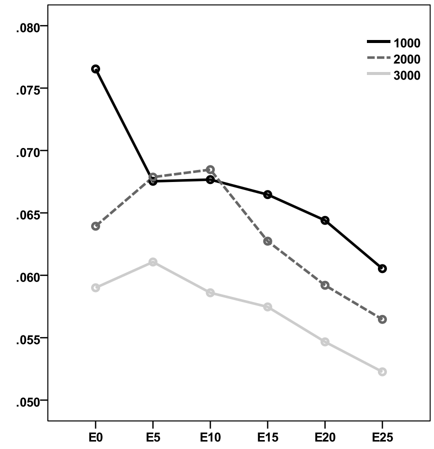

Fig 8. Effect of percent of bioethanol in the mixture and engine speed on CO

Carbon Monoxide

CO pollutant is a product of incomplete combustion due to insufficient air in air-fuel mixture or insufficient time for combustion to be completed [1]. CO is highly dependent on stoichiometry air-fuel ratio. Combustion of rich fuels necessarily produces CO pollutant, which linearly increases with deviation from stoichiometry ratio [14]. Carbon-hydrogen ratio of fuel is another factor in CO formation [41]. CO concentration decreases as oxygen percentage of the air entering the engine decreases (see figure 7). With the increase of oxygen concentration in the air entering the engine, the interval between two combustion decreases and the efficiency improves [42]. Besides, the enhancement of combustion efficiency resulting from additional oxygen increases the temperature. When temperature increases, chemical reaction and CO oxidation accelerates and the amount of CO decreases [43]. The use of higher oxygen percentages results in thermal analysis of CO and its conversion into CO2 in high temperatures [40]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, the amount of CO decreased by 6.85%, 13.74%, 20.92% and 23.84% respectively compared with oxygen percentage of 20.8%.

As it has shown in the figure 8, the amount of CO decreases when bioethanol percentage increases. Thanks to additional oxygen present in ethanol, the amount of CO reduces. This is considered as oxygen premixing effect which results in a more complete combustion. Generally, when engine works in rich conditions, the gases emitting from the engine contain a great deal of CO pollutant because there is not sufficient oxygen for converting all carbon atoms into CO2. Therefore, the most important factor in CO formation is equivalence ratio of to fuel [11]. When ethanol percentage increases, this ratio gets close to 1, as the result of which a more complete combustion occurs and flame temperature increases due to becoming close to stoichiometry conditions. In addition, ethanol has lower carbon than gasoline [13]. Due to the said reasons, increase of ethanol percentage would reduce CO amount. Compared with E0 mixture, the amount of CO decreased by 1.53%, 2.43%, 6.86%, 11.89% and 17.84% respectively in the mixtures of E5, E10, E15, E20 and E25. When engine speed increases, the temperature inside the cylinder and outlet manifold temperature increase due to more cycles. This leads to post reaction of carbon monoxide in the gases exiting the engine with higher temperature. This increases the oxidation of carbon monoxide and converts it into carbon dioxide. As the result, less carbon monoxide will be produced. When the oxygen percentage in the intake rises from 20.8% to 24.8%, the concentration of CO reduces from 0.075% to 0.071%in 1000 rpm engine speed, 0.070% to 0.061% in 2000 rpm engine speed, 0.065% to 0.057% in 3000 rpm engine speed. When the bioethanol percentage in the blend rises from zero to 25%, the concentration of CO2 reduces from 0.097% to 0.067% in 1000 rpm engine speed, 0.074% to 0.056% in 2000 rpm engine speed, 0.072% to 0.058% in 3000 rpm engine speed.

Nitrogen Oxides

The formation of nitrogen oxide stems from the nitrogen present in fuel, presence of additional oxygen, high burning temperature, and duration of stay in reaction area [42]. High combustion temperature and reaction of nitrogen to oxygen may produce NOx. This mechanism is called Extended Zeldovich thermal NO mechanism [44]. Three mechanisms have been accepted for NOx production: A) Thermal NOx, which is produced due to temperature increase as the result of reaction of oxygen to nitrogen; B) Prompt NOx, which is produced as the result of fast reaction between nitrogen, oxygen and hydrocarbon. Production of prompt NOx is the most important mechanism in low temperature processes; C) Fuel NOx, which is formed by direct oxidation of organic nitrogen-containing compounds in fuel. In combustion process, post-flame temperature and oxygen concentration play a role in NO formation. Therefore, NOx increases as air oxygen increases [40]. The more fuel-air equivalence ratio becomes close to stoichiometry ratio, the more the amount of NOX [42].

As it has shown in the figure 9, combustion with higher oxygen results in more NOx. Increase of oxygen in the air entering the engine leads to increase of NO and, consequently, NOx. NO pollutant is formed in both thermal and prompt modes [27]. With respect to NO, it could be said that the addition of oxygen increases air-fuel ratio [18]. This causes equivalence ratio to become close to 1. Consequently, combustion occurs in stoichiometry conditions and flame temperature increases [16]. With the increase of flame temperature, temperature inside cylinder increases. This improves combustion process and extends the scope of flame. In addition, this reduces delayed combustion and increases the pressure peak in cylinder. As the result, the temperature inside the cylinder increases. With respect to prompt NO, increase of oxygen results in increase of pre-combustion reactions and free radicals. Therefore, NOx increases as oxygen rises [27]. On the other hand, in each engine cycle, the number of oxygen molecules increases as oxygen concentration rises, while the number of nitrogen molecules and combustion temperature does not change considerably. Therefore, it could be said that increase of NOx is not basically due to the rise of engine temperature but is due to the higher number of oxygen molecules in each engine cycle [45]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, the amount of NOx increased by 25.45%, 50.75%, 73.31% and 97.59% respectively compared with oxygen percentage of 20.8%.

As the figure 10 shows, the amount of NOx increases as bioethanol percentage in gasoline-bioethanol mixture rises. Several mechanisms contribute to the formation of NOx in ethanol. First, oxygen present in fuel increases NOx formation. Second, alcohol's cooling effect reduces combustion temperature and consequently decreases NOx. Third, due to higher octane number of alcohol, combustion temperature rises in the premixed mixture. The effect of octane number and oxygen present in alcohol on increase of cylinder temperature is more than the effect of evaporation effect on the reduction of temperature. Therefore, concentration of nitrogen oxide pollutant increases as alcohol rises [33]. Compared with E0 mixture, the amount of NOx increased by 48.52%, 91.08%, 113.52%, 171.57% and 207.16% respectively in the mixtures of E5, E10, E15, E20 and E25. An important factor in the formation of nitrogen oxides is temperature increase which increases NOx concentration as engine speed rises.

When the oxygen percentage in the intake rises from 20.8% to 24.8%, the concentration of NOX reduces from 156 ppm to 634 ppm in 1000 rpm engine speed, 325 ppm to 612 ppm in 2000 rpm engine speed, 440 ppm to 720 ppm in 3000 rpm engine speed. When the bioethanol percentage in the blend rises from zero to 25%, the concentration of NOX reduces from 211 ppm to 515 ppm in 1000 rpm engine speed, 250 ppm to 589.33 ppm in 2000 rpm engine speed, 263.33 ppm to 803.67 ppm in 3000 rpm engine speed.

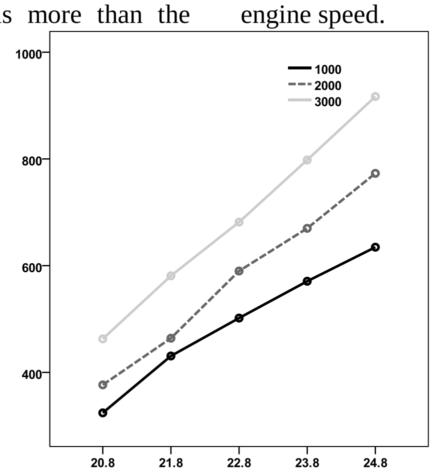

Fig 9. Effect of percent of oxygen in the air and engine speed on NOx

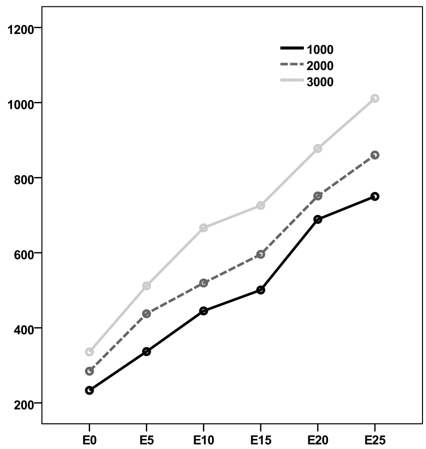

Fig 10.Effect of percent of bioethanol in the mixture and engine speed on NOX

Fuel Consumption

Fuel consumption is a function of thermal value of fuel, ignition time, air-fuel ratio, load, and engine speed [41]. As oxygen concentration in the air entering the engine increases, the ratio of oxygen to fuel rises [18] (see figure 11). Higher air-fuel ratio reduces fuel consumption [41]. On the other hand, the amount of energy generated by fuel increases as oxygen concentration rises, as the result of which fuel consumption decreases [26]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, fuel consumption decreased by 3.56%, 6.12%, 7.91% and 15.11% respectively compared with oxygen percentage of 20.8%.

The more thermal value of fuel and air-fuel ratio, the less fuel consumption will be [41]. Theoretical air-fuel ratio of gasoline is 1.6 times that of ethanol [16]. On the other hand, the added ethanol reduces thermal value of ethanol-gasoline compound. Therefore, where gasoline-ethanol compound is used instead of gasoline, more fuel is needed to achieve the same amount of power [13] (see figure 12). Also, density of bioethanol is more than gasoline, which increases fuel consumption because higher density of the mixture increases the consumed mass of fuel mixture [46]. Compared with E0 mixture, the amount of fuel consumption increased by 4.81%, 5.28%, 8.46%, 11.00% and 13.31% respectively in the mixtures of E5, E10, E15, E20 and E25.

When engine speed rises, fuel consumption increases due to more work cycles in a specific time period and higher frictional power of engine in high speeds of engine (41, 42). When the oxygen percentage in the intake rises from 20.8% to 24.8%, the concentration of fuel consumption reduces from 0.253 ml/s to 0.231 ml/sin 1000 rpm engine speed, 0.4 ml/s to 0.324 ml/s in 2000 rpm engine speed, 0.569 ml/s to 0.486 ml/s in 3000 rpm engine speed. When the bioethanol percentage in the blend rises from zero to 25%, the concentration of fuel consumption reduces from 0.24 ml/s to 0.3 ml/s in 1000 rpm engine speed, 0.46 ml/s to 0.51 ml/s in 2000 rpm engine speed, 0.59 ml/s to 0.69 ml/s ppm in 3000 rpm engine speed.

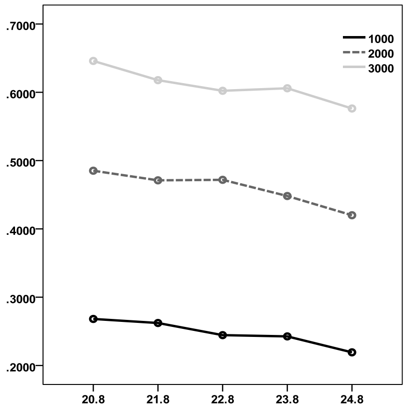

Fig 11. Effect of percent of oxygen in the air and engine speed on fuel consumption

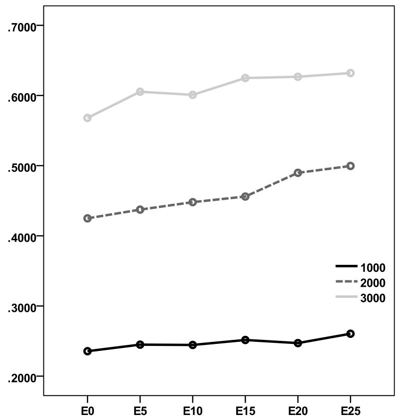

Fig 12. Effect of percent of bioethanol in the mixture and engine speed on fuel consumption

Fuel Consumption

Fuel consumption is a function of thermal value of fuel, ignition time, air-fuel ratio, load, and engine speed [41]. As oxygen concentration in the air entering the engine increases, the ratio of oxygen to fuel rises [18] (see figure 11). Higher air-fuel ratio reduces fuel consumption [41]. On the other hand, the amount of energy generated by fuel increases as oxygen concentration rises, as the result of which fuel consumption decreases [26]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, fuel consumption decreased by 3.56%, 6.12%, 7.91% and 15.11% respectively compared with oxygen percentage of 20.8%.

The more thermal value of fuel and air-fuel ratio, the less fuel consumption will be [41]. Theoretical air-fuel ratio of gasoline is 1.6 times that of ethanol [16]. On the other hand, the added ethanol reduces thermal value of ethanol-gasoline compound. Therefore, where gasoline-ethanol compound is used instead of gasoline, more fuel is needed to achieve the same amount of power [13] (see figure 12). Also, density of bioethanol is more than gasoline, which increases fuel consumption because higher density of the mixture increases the consumed mass of fuel mixture [46]. Compared with E0 mixture, the amount of fuel consumption increased by 4.81%, 5.28%, 8.46%, 11.00% and 13.31% respectively in the mixtures of E5, E10, E15, E20 and E25.

When engine speed rises, fuel consumption increases due to more work cycles in a specific time period and higher frictional power of engine in high speeds of engine (41, 42). When the oxygen percentage in the intake rises from 20.8% to 24.8%, the concentration of fuel consumption reduces from 0.253 ml/s to 0.231 ml/sin 1000 rpm engine speed, 0.4 ml/s to 0.324 ml/s in 2000 rpm engine speed, 0.569 ml/s to 0.486 ml/s in 3000 rpm engine speed. When the bioethanol percentage in the blend rises from zero to 25%, the concentration of fuel consumption reduces from 0.24 ml/s to 0.3 ml/s in 1000 rpm engine speed, 0.46 ml/s to 0.51 ml/s in 2000 rpm engine speed, 0.59 ml/s to 0.69 ml/s ppm in 3000 rpm engine speed.

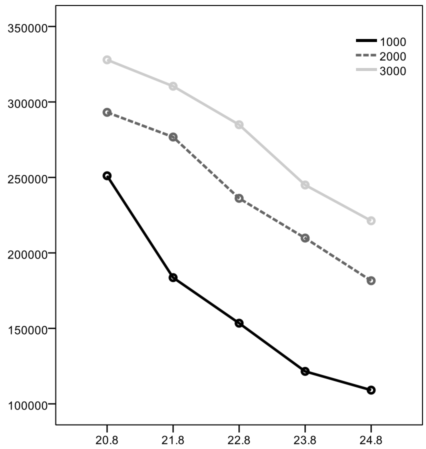

Fig 13. Effect of percent of oxygen in the air and engine speed on fine particles number

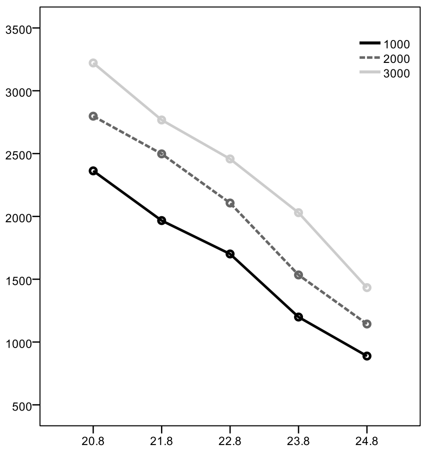

Fig 14. Effect of percent of oxygen in the air and engine speed on coarse particles number

Particles

Soot or particles are formed when there is not sufficient air for reaction of all carbon atoms present in fuel or when combustion process occurs in a rich area of fuel [26]. In the areas with rich fuel-air ratio, unburned fuel changes from gas state into solid cores [14]. When getting big enough, polycyclic aromatic hydrocarbons form the initial cores of soot and particles [33]. Researchers have found that formation of soot and particles is highly associated with stoichiometry, temperature, pressure and mixture [21]. The reduction of particles is attributed to higher oxygen percentage in fuel, reduced air-fuel stoichiometry ratio, and reduced aromatic content [31]. As it shown in figures 13 and 14 when oxygen percentage intake enhanced, the number of fine and coarse particles decreased. The major effect of oxygen on the formation of soot is the increased ratio of oxygen to fuel [21] which increases temperature inside cylinder during combustion process, increases oxidation of soot, and prevents soot formation [18]. The increased oxygen completes combustion process even in the flames with rich fuel (near fuel injection point) and prevents the formation of particles by oxidation of soot [27]. Another effect of oxygen is the reduction of delayed combustion, i.e. higher burning speed and shorter combustion period [21]. This increases the duration of particles stay in high temperature. As the result, soot oxidation rises and the amount of soot and particles decreases [27]. With oxygen percentages of 21.8%, 22.8%, 23.8% and 24.8%, the amount of fine particles decreased by 13.14%, 29.30%, 51.32% and 70.34% respectively compared with oxygen percentage of 20.8% also the amount of coarse particles decreased by 15.90%, 33.79%, 75.99% and 141.89%, respectively.

One of the sources of particles is the soot formed during combustion. Fuels with higher carbon-hydrogen mass ratio produce more soot compared with fuels with lower ratio [10]. Therefore, when bioethanol ratio increases in the mixture, less soot is formed and the amount of particles decreases.

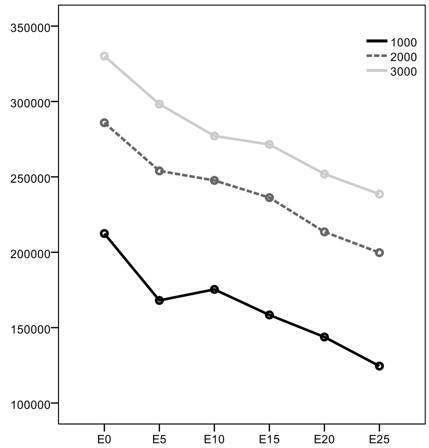

Fig 15. Effect of percent of bioethanol in the mixture on fine particles number

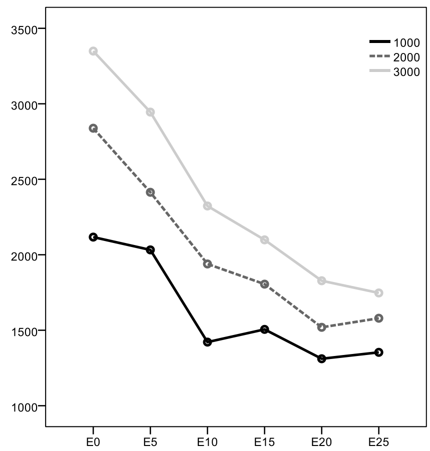

Fig16. Effect of percent of bioethanol in the mixture on coarse particles number

As it shown in figures 15 and 16 Compared with E0 mixture, the amount of fine particles decreased by 15.02%, 18.32%, 24.37%, 35.97% and 47.19% respectively in the mixtures of E5, E10, E15, E20 and E25 also the amount of coarse particles decreased by 12.36%, 46.11%, 53.50%, 78.27% and 77.43%, respectively. Chen and coworkers reported that the use of bioethanol in fuel reduces soot formation due to the presence of oxygen in fuel molecules [47]. The oxygen present in fuel reduces the probability of formation of rich areas and improves oxidation of soot cores [37]. Song and coworkers reached the same conclusion. They reported that higher oxygen percentage in air and the use of oxygen-rich fuels such as bioethanol reduces soot formation and consequently decreases the amount of particles [24]. Oxygen compounds in fuel reduce the formation of primary cores of soot and decrease the amount of carbon. Free radicals resulting from the fuel oxygen prevent the growth of aromatic cycle and soot formation and improve carbon oxidation [14].

When engine speed increases, temperature rises and particles oxidize. However, the number of particles increases due to the increased cycles. When the oxygen percentage in the intake rises from 20.8% to 24.8%, the number of fine and coarse particles reduces from 279217 to 117332 and 2325 to 666, respectively in 1000 rpm engine speed, 291595 to 176784 and 3009 to 922, respectively in 2000 rpm engine speed, 307852 to 201272 and 3326 to 934, respectively in 3000 rpm engine speed. When the bioethanol percentage in the blend rises from zero to 25%, the number of fine and coarse particles reduces from 304340 to 163318 and 3147 to 1839, respectively in 1000 rpm engine speed, 325968 to 265349 and 4142 to 2061, respectively in 2000 rpm engine speed, 380736 to 286256 and 4739 to 2234, respectively in 3000 rpm engine speed.

Conclusion

In this research, the effects of combustion with higher oxygen percentage and gasoline-ethanol fuel compounds in different engine speeds on the amount of pollutants and fuel consumption in Pride gasoline engine were studied. The general results are as follows:

1. When bioethanol percentage in fuel mixture increases, the amount of unburned hydrocarbon, carbon monoxide, carbon dioxide, and fine and coarse particles decreases, the amount of nitrogen oxide increases, and fuel consumption rises.

2. When oxygen percentage in the air entering the engine increases, the amount of unburned hydrocarbon, carbon monoxide, and fine and coarse particles decreases, the amount of carbon dioxide and nitrogen oxide rises, and fuel consumption decreases.

3. Considering the significant reduction of particles, unburned hydrocarbons and carbon monoxide, concurrent use of bioethanol-gasoline mixture and oxygen-rich air is an efficient method to reduce pollutants and particles. The increased fuel consumption resulting from the use of bioethanol-gasoline mixture can be compensated by oxygen-rich air.

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