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Investigation of the effects of civil aviation fuel Jet A1 blends on diesel engine performance and emission characteristics

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Study on use of aviation fuels in the internal combustion engines in road vehicles has been conducted for a long time. After the JP-8 is accepted as a single fuel on land and in the air (single fuel concept) by the North Atlantic Treaty Organization (NATO), the majority of these studies have focused on JP-8. For this reason, there is hardly any study on using the Jet A1, which is structurally very similar to the JP-8, in the internal combustion engine. However, in obligatory cases such as in periods of war, using the Jet A1 in the same way as the JP-8 in internal combustion engines may be required. In cold climates especially, the Jet A1 may gain strategic importance due to its very low freezing point. In this study, both the effects of the diesel and Jet A1 blends on engine performance and exhaust emissions in both the single cylinder, and the direct injection diesel engine have been examined. As a result, it has been determined that use of Jet A1 reduces engine torque to 5.85% and increases the specific fuel consumption to 8.77%. In addition, while there is an increase in smoke and carbon monoxide (CO) emissions 82% and 71.9%, respectively, there is a decrease in nitrogen oxide (NO_x) emissions by 29%. In conclusion, there is no positive effect in using the Jet A1 in the diesel engine except for the reduction of NO_x emission and the decrease of the freezing point.

Keywords: Jet A1, Aviation fuel, Diesel engine, Emission, Engine performance

The process in the development of aviation fuels has continued for many years. Many studies have been conducted on aviation fuels in order to reduce costs, ease supplies, reduce the dependence on foreign oil supplies, and ensure reliability in military applications. For this purpose, using non-petroleum based energy sources such as coal; natural gas and biomass energy as aviation fuel have been investigated[1].

Jet engines are powered by kerosene, which consists of complex hydrocarbon mixtures with a boiling point of 145-300°C. Jet fuels have a similar petroleum fraction to diesel and fuel oil. The most common aviation fuel for military engines is jet propulsion fuel 8 (JP-8), and for the civil aviation jet engines is Jet A1[2].

In 1988, NATO made a joint decision to use a single fuel in military aircraft and all land motor vehicles and equipment[3]. This idea is called a single fuel concept (SFC). The main purposes of this decision are elimination of the logistical problems in case of war and ensuring the more effective use of the NATO pipeline in peacetime. JP-8 military jet fuel, which is very similar to civil aviation fuel Jet A1, was chosen as the single fuel[3,4]. Diesel and JP-5 showed similar fuel consumption, with diesel consumption increasing at high engine loads. Ternary blends showed similar behavior. The blends with lower biodiesel content showed lower volumetric fuel consumption. Fuel sulfur content has an undesirable effect on smoke opacity[5].

The rapid development of today's modern diesel engines has enabled the use of diesel engines in general aviation vehicles. Diesel engine-powered aircrafts are reliable because of known fuel properties, low fuel consumption and high thermal efficiency relative to the gasoline engine. The main drawbacks of a diesel-engined aircraft are weight, cost, and appropriate fuel supply and fuel injection for a convenient diesel engine combustion characteristic. The fuel to be used in an aviation diesel engine is expected to have a good low temperature performance, sufficient lubrication properties, and an acceptable level of cetane number[6].

The selection of the JP-8 as a single fuel on land and air vehicles by NATO began the investigations related to using the JP-8 on diesel engine rather than diesel fuel. The diesel engines that had a mechanical distributor type

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pump or unit type pump fuel injection system ran successfully with the JP-8[7-10]. In the use of JP-8, it was determined that the engine torque decreases and the fuel consumption increases dependant on the low density of the JP-8. When exhaust emissions were analysed it was seen that the JP-8 has the potential to reduce smoke emission[11]. The overwhelming advantage of the use of fatty acid methyl esters (biodiesel) seems to be the independent use of raw materials used for their production, and the addition of biodiesel in JP-8 fuel lowers the emissions of PM[12].

JP-8 is approximately 99.8% kerosene by weight, and is a complex mixture of higher-order hydrocarbons, including alkanes, cyclo-alkanes, and aromatic molecules[12]. Jet A1 primarily differs from JP-8 in that its specification ASTM D1655 does not specify the requirement for the three additives that are required in JP-8. JP-8 contains three mandatory additives: a fuel system icing inhibitor, a corrosion inhibitor, and a static dissipater additive[9,13-15].

In the United States, JP-1, JP-2, and JP-3 were unsuccessful attempts in regard to balancing the conflicting requirements of volatility, freezing point and availability cost. A wide-cutnaphtha/kerosenemixture called JP-4 in the United States (MIL-F-5624 in 1950) and a kerosene fuel with a -50 °C freeze point (DERD-2494 in England and Jet A-1 in ASTM D-1655 in the United States) emerged in the late 1940s and early 1950s. This freeze point determined through a significant research effort. ASTM D-1655 also specified Jet A with a -40 °C freeze point. The Jet A-1 freeze point was changed to -47 °C in the late 1970s in order to increase availability. Additionally, Jet A does not normally contain a static dissipater additive, while Jet A1 often requires this additive[16-18].

Diesel engine performance, combustion efficiency and emissions are simply related to the engine design, running parameters and fuel properties. These parameters are important for the optimization of the engine performance, and for reducing emissions[19]. Various investigations clearly reported that the cetane number affects exhaust emissions. The ignition delay period is reduced by increasing the cetane number, and this gives an opportunity for the stable running of the engine[20-22]. The ASTM specification for Jet-A, ASTM D1655, has no minimum cetane rating because it is not necessary for a turbine engine. The low cetane number of the Jet A1 may cause problems in the use of the Jet A1 in the diesel engine. However, the problem may be resolved by using fuel additives that increase the cetane number. It is known that the cetane number of biodiesel is high[23,24]. This means the Jet A1 and biodiesel blends can be used as an alternative to diesel fuel. The low lubrication property, which is the other problem with the Jet A1, may be improved by fuel additives or biodiesel blends.

Although a lot of research related to the use of JP-8 in the diesel engine has been conducted, so far to date there is no study regarding using Jet A1 in a diesel engine. Indeed, JP-8 and Jet A1 have quite similar basic properties. Jet A1, which is used in civil aviation, may be used in both military vehicles and diesel-engined aircrafts if necessary. The low freezing point of the Jet A1 may provide an advantage in cold climates for military purposes or in diesel-engined aircraft.

The aim of this study is to carry out performance and emission testing on a four-stroke, a single-cylinder direct injection engine fuelled with a petroleum-based diesel, and a mixture of aviation fuel Jet A1. The emissions data includes rates of smoke, CO, and NO_x. This experimental study gives us the opportunity to compare diesel fuel and diesel fuel mixtures with aviation fuel Jet A1.

Materials and Methods

Test fuels

Engine performance and emission tests were carried out with five different fuels. Diesel and Jet A1 commercial aviation fuel blends were used in the experiments. Table 1 shows the volumetric percentages and abbreviations of the fuels used in the experiments. Some properties of the test fuels are given in Tables 2 and 3. The fuel properties

Table 1—The volumetric percentages of fuel used in the experimen

Abbreviation	Percentages of fuel
J0	100% Diesel
J5	95% Diesel + 5 % Jet A1
J10	90% Diesel + 10 % Jet A1
J25	75% Diesel + 25 % Jet A1
J50	50% Diesel + 50 % Jet A1

Table 2—Properties of test fuels

Fuel	Diesel	JetA-1	Method
Density (g/cm^3, 15°C)	0.8372	0.775	ASTM D 1298
Viscosity (cSt)	2.8(40°C)	3.87(-20°C)	ASTM D 445
Freezing point (°C)	-5	-47	ASTM D 2386
Flash point (°C)	73	38	ASTM D 93
Lower heat value (kcal/kg)	10450	10200	ASTM D 2015
Cetane number	54	42	ASTM D 976

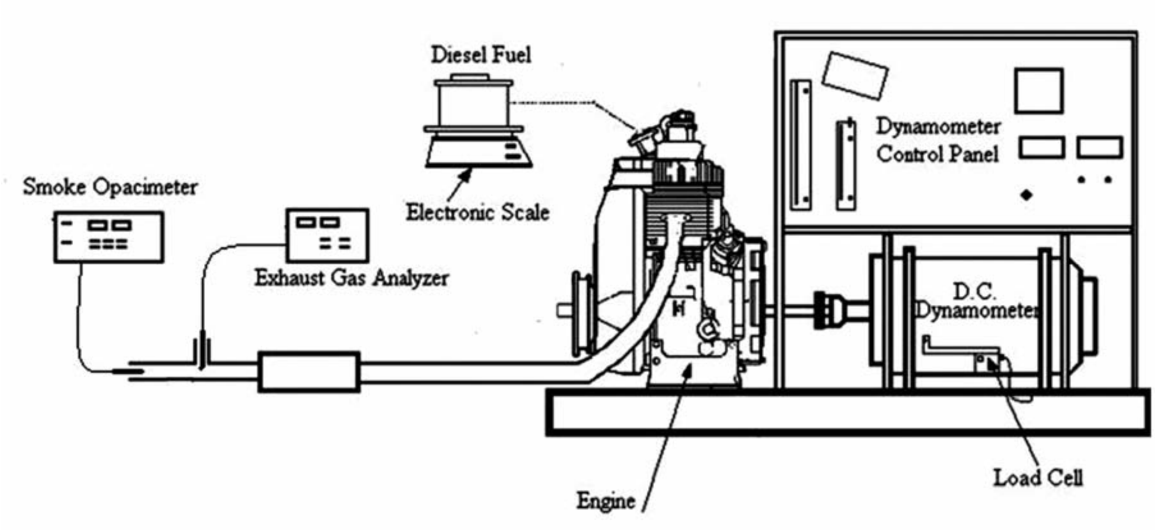

Fig. 1—Schematical view of the experimental set-up

Table 3—Properties of fuel blends

Blend	Density 15°C (g/cm^3)	Viscosity 40°C (cSt)	Freezing point (°C)	Flash point (°C)
J5	0.8319	2.29	-4	40
J10	0.8302	2.207	-4	43
J25	0.8247	1.975	-6	52
J50	0.8161	1.676	-10	58

Table 4—Technical specifications of the test engine

Engine type	4-Stroke DI diesel
Cylinder number	1
Cylinder x stroke (mm)	86x68
Cylinder volume (cm^3)	395
Compression ratio	18/1
Maximum torque	2200 d/dak'da 19,6 Nm
Inj. pressure (bar)	180
Inj. advance	24^{o}

were determined at the Turkey Petroleum Refineries Co. (TUPRAS) laboratories, and the JP-8 fuel was provided by TUPRAS. The freezing point of the Jet A1 is determined as 47^{o}C. As seen in Table 3, the freezing points of the blends decrease with the increase of the Jet A1 proportion. This may provide an advantage in cold running conditions. On the other hand, the densities of the blends decrease with Jet A1. This property may cause performance loss.

Experimental set-up

Experiments were carried out in full load conditions with six different engine speeds in a single cylinder direct injection diesel engine. The technical specifications of the test engine are given in Table 4. The schematic diagram of engine is shown in Fig. 1.

Table 5—VLT 2600 S opacimeter technical features

Parameter	Measuring range	Accuracy
Exhaust smoke density	0-99%	0.01
k smoke factor (1/m)	0-10	0.01
Engine speed	0-9999 1/min	1/min

Table 6—Technical features of the Testo 350 XL emission measuring device

Combustion products	Measuring range	Accuracy
Oxygen (O_2)	0-25% vol	+/- 0.2 mv
Carbon monoxide (CO)	0-10000 ppm	5 ppm (0-99 ppm)
Carbon dioxide (CO_2)	0-50% vol	± 0.3% vol +1% mv (0-25% vol)
Hydrocarbon (HC)	0.01-4%	< 400 ppm (100-4000 ppm)
Nitrogen oxide (NO_x)	0-3000 ppm	5 ppm (0-99 ppm)

The engine speed was controlled constantly by a 10 kW DC dynamometer Cussons P8160. The engine load was measured with a strain gauge load cell. A magnetic sensor that was on the dynamometer shaft was used for the engine speed measurement. To measure the fuel consumption, a sensitive electronic scale and a chronometer was used.

To measure the smoke VLT 2600 S opacimeter was used and a Testo 350 XL gas analyser was used for emission measurement. The technical features of both devices are given Tables 5 and 6, respectively. The ambient air temperature, relative humidity and atmospheric pressure were almost constant during the tests.

To prove the accuracy of the experiments, uncertainty analysis is needed. Holman[25] described an uncertainty analysis method to determine experimental uncertainties. We calculated the uncertainties for computed values such as fuel consumption, engine movement and engine power with the following equation.

$$\Delta R = \left[\left(\frac{\partial R}{\partial x_1} \Delta x_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \Delta x_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} \Delta x_n \right)^2 \right]^{0.5} \quad \ldots (1)$$

This equation ΔR defines the uncertainty of the measurement. x_n and Δx_n define the independent variables of the function and uncertainty. The calculated uncertainty values are given in Table 7.

Table 7—Uncertainty values of measured data

	Measuring range	Accuracy	Uncertainty (%)
Fuel consumption (g)	0-8000	∓0.1 g	∓ 0.3
Enginemoment (Nm)	0-50Nm	∓ 0.25 %	∓ 0.12
Engine power (kW)	0-10 kW	∓ 0.21 %	∓ 0.13

Results and Discussion

As a result of the experiments carried out in full load condition, both engine performance and exhaust emissions curves were obtained.

Engine performance

Figure 2 shows the variation of engine torque with the engine speed. The maximum engine torque was measured as 18.85 Nm at 2250 1/min with J0 fuel. It was noted that additional Jet A1 to diesel fuel reduced the engine torque. According to the J0 fuel the engine torque decreased by 1.71%, 2.99%, 4.73% and 5.85% by using the J5, J10, J25 and J50 fuel blends, respectively. Table 2 shows that the lower heating value of the Jet A1 fuel is lower than the diesel fuel. The decrease in engine torque may be resulted from the lower calorific value of the Jet A1 fuel. In addition the density of the Jet A1 fuel is lower than the diesel fuel. As the increasing rate of Jet A1 in the blend, the blend density decreases. Even if the same amount of fuel is injected in the cylinder, lower density of the blend causes the lower energy capacity. In this case the engine toque may be reduced.

Specific fuel consumption is the ratio between mass flow by density of fuel and effective power[25]. Figure 3 shows the variations of the specific fuel consumptions with engine speed for five different blends. The lowest specific fuel consumption curve was obtained with J0 fuel. The lowest value of the specific fuel consumption was recorded as 354.9 g/kWh. As the JetA-1 fuel ratio increases in the mixture, the BSFC value decreased. When the J5, J10, J25 and J50 fuel blends were used, the specific fuel consumptions of the engine increased 2.55%, 3.93%, 6.41% and 8.77% respectively. The specific fuel consumption depends on the fuel properties such as fuel density and the lower heating value[27]. The reason for the increase in the specific fuel consumption may be the lower heating value of the Jet A1. Regarding specific fuel consumption, more fuel mass flow rate is required to provide the same engine output due to the lower density and lower energy content of Jet A1, and this results in higher specific fuel consumption.

Exhaust emissions

NO_x emission variations in the engine speed are shown in Fig. 4. As the engine speed increased, NO_x

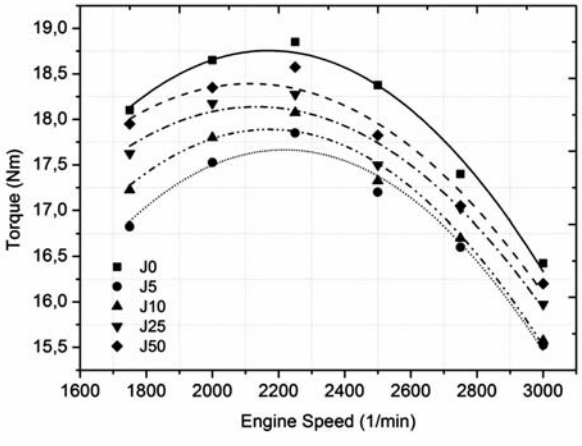

Fig. 2—Engine torque variations by engine speed

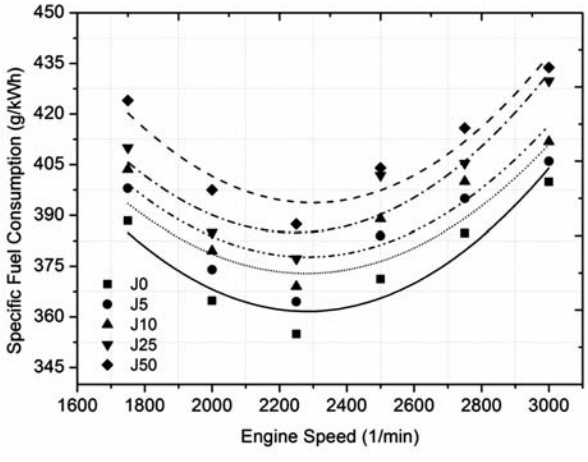

Fig. 3—Specific fuel consumption variations by engine speed

emissions decreased with all blend types. Due to the improvement in volumetric efficiency until a certain engine speed and acceleration of the gases in the cylinder at high engine speeds, the mixture formation improves and the ignition delay period becomes shorter. Because of the decreasing reaction duration due to the rising engine speed in each engine cycle, the duration which the hot gases remain in the cylinder decreases. This leads to decreasing NO_x emissions in high rpm values[28,29]. The highest NO_x emissions are seen in J0 fuel. Jet A1 usage leads to decrease in NO_x emissions. NO_x emissions are related to the combustion temperature in the engine cylinder. For the blends, the effect of lower heating value and higher latent heat of evaporation could reduce the combustion temperature and for this reason reduce the NO_x emissions. Due to rising homogenous pre-mixture, the equivalence ratio of fuel reduces and the inner cylinder temperature also decreases. Because of this, NO_x emissions decrease[30-33]. The cetane number of Jet A1 aviation fuel is less than diesel fuel. Thus, due to the decreasing cetane, the ignition delaying duration strings out while the Jet A1 share in the mixture rises. This condition leads to an air-fuel mixture occurrence before combustion starts and because of this the homogenous combustion period in the normal combustion process strings out. NO_x emissions may reduce due to a decreasing diffusion combustion period. Compared with use of the J0 fuel the NO_x emissions decreased 12.25%, 21.32%, 27.52% and 29% with use of J5, J10, J25 and J50 fuel blends, respectively. Another factor for the decrease in NO_x emissions may be the lower heating value of the Jet A1 fuel.

Smoke formation begins in areas where the air and the fuel injected in the cylinder do not mix when the inlet temperature of the cylinder reaches a certain value at the diffusion combustion phase. In other words, as a result of incomplete combustion, the smoke emission is seen[24,34,35]. Figure 5 shows the smoke emissions variations with the engine speed. The least smoke was measured with J0 fuel. The smoke emissions increased with Jet A1 fuel. With use of the J5, J10, J25 and J50 fuel blends, the smoke emissions increased on average by 45%, 65%, 74% and 82%, respectively. Smoke formation occurs largely at the diffusion combustion phase, so reducing the diffusion combustion phase duration may reduce the smoke formation. It is expected that prolonging the ignition delay period increases the premixed combustion phase due to the low cetane number of the Jet A1, and as a result of this, the smoke formation decreases. However, in the experiments, the smoke formation increased in opposite to this case. This proves there is another factor triggering the smoke formation. The chemical formula of the Jet A1 differs in various references[36,37]. TUPRAS states that the Jet A1 occurs from the complex hydrocarbons mixtures between C_9 and C_{16}[38]. The reason for the increase in smoke emissions by using Jet A1 may be from a high proportion of carbon in the Jet A1 fuel.

The CO emissions variations with the engine speed are seen in Fig. 6. While the engine speed increased, the CO emissions decreased. As the engine speed increases, the turbulence ratio increases in the cylinder and the combustion improves. In this case the CO emissions may decrease[39]. It was seen that the lowest CO emissions were obtained with J0 fuel, and the use of Jet A1 increased the CO emissions. When J5, J10, J25 and J50 fuel blends were used, CO emissions increased on average by 20.3%, 40.2%,

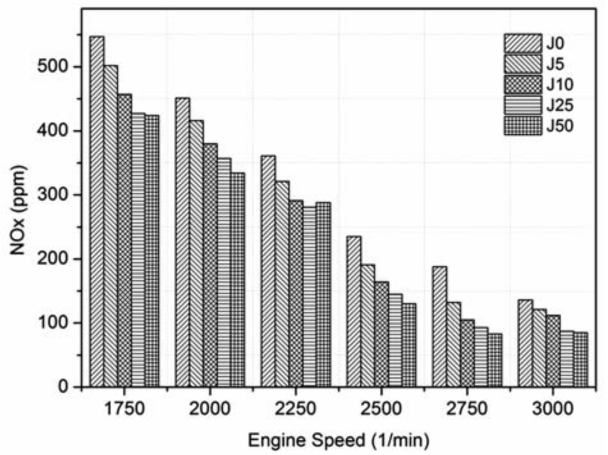

Fig. 4—NO_x emissions variations by engine speed

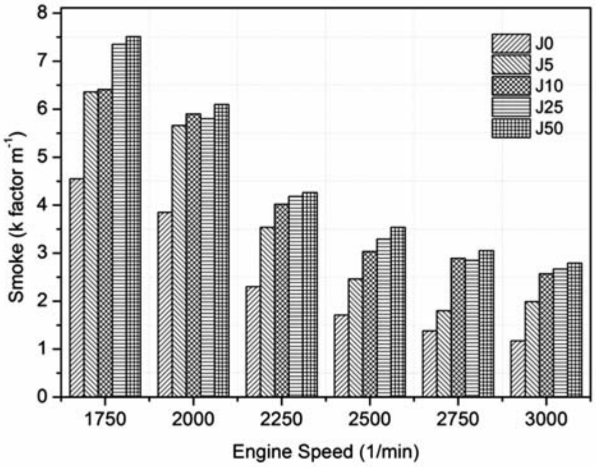

Fig. 5—Smoke emissions variations by engine speed

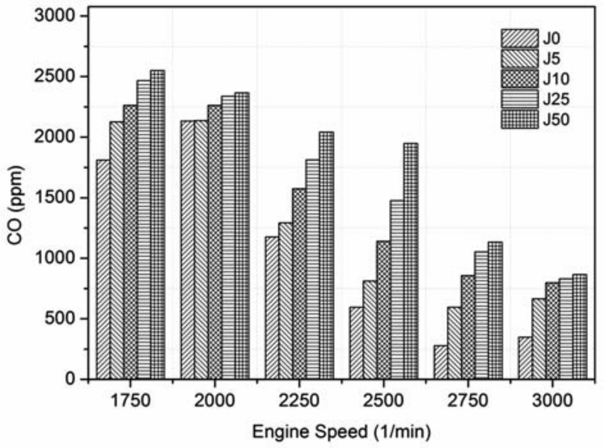

Fig. 6—CO emissions variations by engine speed

57.3% and 71.9%, respectively. In diesel engines the CO emission formation largely originated from oxygen deficiency[24,40]. The use of fuels which have high carbon content such as Jet A1 in a normally aspirated engine may increase the CO emissions.

Conclusions

In this study, diesel and Jet A1 fuel blends were tested in a single cylinder direct injection diesel engine at full load condition. As a result of the experiments engine torque, specific fuel consumption, NO_x, smoke and CO emissions were examined.

The engine performance dropped and the specific fuel consumption increased with the use of Jet A1. When J50 (50% diesel + 50% Jet A1) was tested, it was determined that the engine torque decreased by 5.85%, and the specific fuel consumption increased to 8.77%. While using the Jet A1, the aviation fuel increased the smoke and CO emission, but reduced the NO_x emissions. The NO_x emissions decreased by 29% with the use of the J50 fuel blend. However, on average there was a significant increase in the CO and smoke emissions; up to 71.9% and 82%, respectively.

As a result, it was determined that use of Jet A1 fuel in the diesel engine did not create a positive effect, except for reducing the freezing point of the fuel and NO_x emission. It is evident that in order to make the Jet A1 suitable for use in internal combustion diesel engines, its cetane level should be increased. However, in obligatory cases, Jet A1 may be used in internal combustion engines with JP-8 aviation fuel. It may be advantageous that the freezing point of the fuel is reduced.

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