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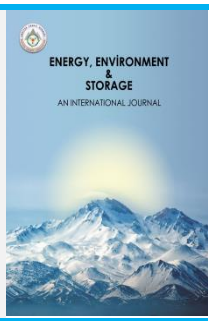

Experimental Investigation of the Effect of Acetone Additive to Diesel Fuel on Engine Performance and Exhaust Emissions at Partial Loads

Ahmet Duhan Coşkun [1], Volkan Sabri Kül [2*], Selahaddin Orhan Akansu [3]

[1*]*Erciyes University, Faculty of Engineering, Department of Mechanical Engineering, Kayseri, Turkey*
ahmetduhancoskunn@gmail.com, ORCID: 0000-0003-2529-4183

[2]*Erciyes University, Faculty of Engineering, Department of Mechanical Engineering, Kayseri, Turkey*
volkanskul@gmail.com, ORCID: 0000-0002-6412-6062

[3]*ErciyesUniversity, Faculty of Engineering, Department of Mechanical Engineering, Kayseri, Turkey*
akansu@erciyes.edu.tr, ORCID: 0000-0002-0085-7915

ABSTRACT. In this study, it is aimed to gain good characteristics that can directly affect daily life with more environmentally friendly, economical and performance fuels. For these purposes, acetone has been added to the fuel. Since acetone has a high vapor pressure, it is aimed to increase engine performance by taking advantage of its volatility. It is thought that emissions will also improve with increased engine performance. The experiments were carried out using a heavy-duty engine with a displacement of 11.670 cc. Engine performance and emission values were investigated at 100, 200 and 300 Nm partial loads and at 600 rpm constant engine speed by adding 5% and 10% acetone to diesel fuel. The results were compared with pure diesel fuel. Compared to the pure diesel fuel, the BTE value of A5D95 fuel was observed to be 3.28% and 2.60% better, respectively, under 100 and 200 Nm load, while the BTE value of A10D90 fuel was 0.23% and 0.05% worse. Compared to the pure diesel fuel, the BTE value of A5D95 fuel was observed to be 3.28% and 2.60% better, respectively, under 100 and 200 Nm load, while the BTE value of A10D90 fuel was 0.23% and 0.05% worse. Since there was an unexpected decrease in the BTE value of pure diesel under 300 Nm load, only A5D95 and A10D90 fuels were compared at this load. It was found that the BTE value of A5D95 fuel under 300 Nm load was 0.65% higher than A10D90 fuel. While 10% acetone additive A10D90 fuel could not have a positive effect on efficiency, it was determined that A5D95 fuel with 5% acetone additive was more efficient than other fuel types at all loads. When the emission rates of D100, A5D95 and A10D90 fuels are evaluated according to the power they produce under 100, 200 and 300 Nm loads, the CO emission rate of A5D95 fuel is less than that of pure diesel at other loads except 100 Nm load. However, the NO_x ratio was higher at all loads. These results support the higher efficiency of A5D95 fuel compared to pure diesel. Other results are discussed in detail in section 3.

Keywords: Diesel fuel, Acetone, Mixture, Emission, Performance

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1. INTRODUCTION

Energy consumption is a big part of our daily lives. With the increasing population, our energy needs are increasing day by day. The most commonly used source of energy consumption is fossil fuels. According to the 2020 data, fossil fuels are used at a rate of 79.3%. Petrol is the most consumed energy among fossil fuels. In 2020, oil was one of the most consumed energy sources in the world's primary energy consumption with 31.2 million % TEP. In Turkey, crude oil has been the most consumed energy source with 29 million % TEP in primary energy consumption. The transportation sector, where engines are used a lot, has a primary energy consumption of 23.42% across Turkey. Oil consumption has increased by 6% in the world and 44% in Turkey in the last decade [1]. Diesel engines are superior to petrol engines in terms of exhaust emission and engine performance [2]. Although diesel engines have lower exhaust emissions than other engines, they still emit large amounts of gases that are harmful to the atmosphere. In order to reduce the negative effects of diesel engines and to increase engine performance, additives are used for diesel fuels. While trying to achieve higher engine performance with these additives, it is also aimed to reduce exhaust emission values. Additives may have different chemical contents. In diesel fuels formed with a titanium mixture, the engine performance has not changed much, while the exhaust emission values have been reduced [3]. Addition of less than 15% dimethyl

*Corresponding author: volkanskul@gmail.com

ether to diesel fuel reduces specific fuel consumption, while high proportions of dimethyl ether mixture increases specific fuel consumption [4]. Another study 20% LPG was used as a fuel additive, certain improvements were observed in fuel consumption and emissions [5].

In this study, acetone (C3H6O, Dimethyl Ketone) with a purity rate of 99.5% was used as an additive. Acetone is used in the production of many chemicals in the industrial sector, as a paint thinner in the paint sector, as a nail polish remover in the cosmetics sector and in the production of cleaning materials. Acetone is an extremely flammable substance [6]. According to some, while this feature is dangerous, it has the opportunity to be used as a fuel additive thanks to its highly flammable feature. Thanks to this opportunity, it is aimed to decrease the exhaust emissions compared to pure diesel and to decrease the harmful gases released to the environment. In addition, the engine performance was also requested to increase. In the study, this opportunity was evaluated by mixing 5% and 10% acetone in the rate of pure diesel mass to diesel fuel. Engine performances and exhaust emissions were measured at 100 Nm, 200 Nm and 300 Nm in the engine with these mixtures set at constant speed. The information obtained was compared with the information obtained by going through the same experimental stages of pure diesel fuel.

2. MATERIALS AND METHODS

2.1 Experimental Setup

The test setup consists of fuel, engine, engine performance test system, emission measurement system and in-cylinder pressure measurement system. Before starting the work, the cables to the systems were checked. In order to obtain more accurate and precise results, the fuel in the engine was removed from the engine without pumping new fuel into the engine.

The BOSCH BEA060 model emission analyzer was used for exhaust emissions. The emission analyzer was directly connected to a screen and processed the emission values instantly. Instant performance information of the engine used in the experiment was obtained with the PCS Engine Test System. Another instrument used in the experiment is the PCB Piezotronics 113B22 branded piezoelectric sensor. The pressure inside the cylinder was measured with this sensor.

2.2 Fuels and Test Engine

Pure diesel (D100) and diesel-acetone mixture was used in the study. The acetone used in the experiment has 99.5% purity. The properties of acetone and diesel are given in **Table 1.** Precision scale were used to prepare the mixtures. Mixtures were formed by adding 5% and 10% acetone to each 1000 g of diesel fuel. The mixture with 5% acetone was named A5D05, and the mixture with 10% acetone was named A10D90.

Table 1 Acetone and Diesel Specifications

Specifications	Acetone (C_3H_6O)	Diesel
Boiling point	56.2 °C (1013 hPa)	-
Density	0.79 g/cm3 (20 °C)	820-845 kg/cm3
Explosion limit	2.6 - 12.8 %(V)	-
Flash point	-17.0 °C	55 °C
Auto-ignition Temperature	465 °C DIN 51794	186–230 °C
Higher Heating Value(HHV)	-	45.6 MJ/kg
Low heat Value (LHV)	29.6 MJ/Kg	42.7 MJ/kg
Melting Point	-94.0 °C	-
pH value	5 - 6(395 g/l, H_2O, 20 °C)	-
Vapor pressure	24.53 kPa (20 °C)	< 1 kPa (38°C)
Cetane Number	-	51
Viscosity	-	2.0- 4.5 mm^2 /s

The experiment was carried out on the test engine in Erciyes University Engines Laboratory. The features and visual of the test engine are given in **Fig.1** and **Table 2**, respectively.

Fig. 1. Test Engine

Table 2 Engine Specifications

Test engine	NİSSAN PE6H
Bore	133 mm
Stroke.	140 mm
Number of cylinders	6
Displaced volume	11670 cc
Max. Power	234 Hp
Max. Speed	2300 rpm
Max. Torque	724 Nm (at 2300 rpm&234hp)
Compression ratio	16.5
Injection timing	16 'BTDC
Nozzle opening pressure	200 kg/cm^2 (2850 psi)
Firing order	1-4-2-6-3-5
Valve clearance (COLD)	In. 0.4 mm, Exh. 0.4 mm

2.3 Methods

The experiments were carried out at a constant engine speed of 600 rpm, under a load of 100, 200, 300 Nm, respectively, using pure diesel, A5D95 and A10D90 fuels, respectively. Theoretically, the maximum torque value was calculated as 724 Nm according to the maximum torque and power value on the label value of the test engine. Experimentally, a maximum torque of 350 Nm has been reached at 600 rpm. The percentage values of 3 different torque values used in the experiments according to the maximum torque value at 600 rpm correspond to 29, 57 and 86% for 100, 200 and 300 Nm, respectively. A total of 9 sets of experiments were conducted. Before starting the experiments, the fuel in the engine was completely drained and this process was repeated when each fuel type was changed. In the experiments, fuel consumption was determined by measuring with precision balance. Fuel consumption measurements were recorded in 5-minute periods. In-cylinder pressure values were recorded separately for each load and each fuel type, thanks to a piezoelectric sensor. Engine performance data such as engine speed, load and exhaust temperature were taken from the engine performance measurement program screen. Exhaust emission values were obtained with Bosch BEA 60 emission analyzer. Recordings were taken in each experimental set.

Experiments were first started with pure diesel. Then, it was continued with A5D95 and A10D90 fuel type, respectively. The recorded values for each set of experiments were analyzed and the results were presented in section 3.

3. RESULTS, FIGURES AND TABLES

3.1 Engine Performance

Brake thermal efficiency (BTE) is a function of the braking power produced by an internal combustion engine and the thermal energy of the fuel entering the engine. Thus, it is calculated how much of the fuel energy entering the engine is converted into useful work.[7] In this study, BTE calculation was made using equation (1). In equation 1: Pb; Braking power, ṁf; fuel flow rate, LHV; the lower heating value of the fuel.

$$\eta_{th} = \frac{P_b}{\dot{m}f \text{ x LHV}} \quad (1)$$

The LHV values of the mixtures were calculated using Equation (2).

$$LHV_K = \frac{m_b x LHV_b + m_m x LHV_m}{m_b + m_m} \quad (2)$$

In equation 2: m_b; amount of first fuel, m_m; amount of second fuel, LHV_b; lower heat value of first fuel, LHV_m; the lower heat value of the second fuel.

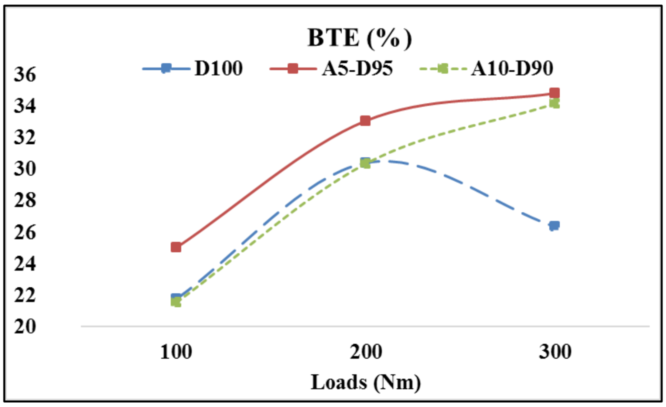

Fig. 2. Brake Thermal Efficiency (BTE)

Table 3 BTE values (%)

BTE	**100 Nm**	**200 Nm**	**300 Nm**
D100	21.77	30.43	26.37
A5-D95	25.04	33.10	34.85
A10-D90	21.54	30.38	34.20

The BTE values and graph obtained as a result of the experiments are shown in **Table 3** and **Fig.2**, respectively. A5D95 fuel has the highest BTE value at all loads. Although D100 and A10D90 had very close BTE values at 100 and 200 Nm loads, the BTE value of D100 fuel decreased sharply at 300 Nm load. Actually, this is not expected, it is thought that the reason for this may be measurement error.

Brake specific fuel consumption (BSFC) indicates how efficiently fuel is used in a power generating internal combustion engine [8]. It is the amount of fuel consumed per brake power produced. BSFC values were calculated using equation (3). In equation 3: Pb; Braking power, ṁf; represents the fuel flow rate.

$$bsfc = \frac{\dot{m}_f}{P_b} \quad (g/kW.h) \tag{3}$$

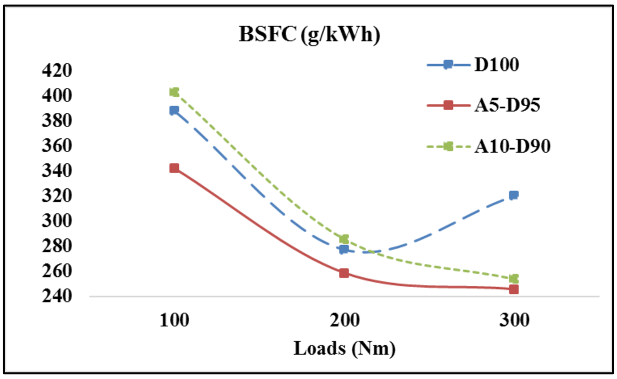

Fig. 3. Brake Specific Fuel Consumpsion (BSFC)

Table 4 BSFC values (g/kWh)

BSFC	100 Nm	200 Nm	300 Nm
D100	387,299	276,985	319,705
A5-D95	341,619	258,481	245,489
A10-D90	402,622	285,449	253,581

The BSFC value of the A5D95 fuel with the highest BTE value has the lowest value as expected. As with BTE values, BSFC values of D100 and A10D90 fuels were observed to be close under 100 and 200 Nm loads. D100 fuel has the highest BSFC value under 300 Nm load and therefore the lowest BTE value at 300 Nm load.

It is seen from the graphs and tables above that the BTE value of A5D95 fuel is 3.27, 2.67 and 8.48% higher than D100 fuel under 100, 200 and 300 Nm load, respectively. Likewise, A5D95 fuel is 3.5, 2.72 and 0.83% more efficient than A10D90 fuel.

In order to understand the reason for this, it would be useful to divide the graph of the in-cylinder pressure into phases as in **Fig. 4** and examine it. 1. Phase: After fuel is injected into the cylinder, the fuel does not ignite immediately, there is a delay period for the fuel to ignite. This process refers to the time from the moment of fuel injection to the start of combustion. The most important factor affecting the 1st phase is the ignition temperature of the fuel. The shorter the ignition delay, the better the combustion in the cylinder. 2. Phase: This phase starts at the moment of inconsistency of the in-cylinder pressure and lasts until the pressure spike. In this phase, with oxygen molecules that dissociate into atoms, hydrocarbons that dissociate into atoms form OH molecules and the combustion process begins. A significant amount of the heat generated at the beginning of combustion is used to evaporate the fuel injected into the cylinder. The decrease in in-cylinder pressure in this phase is due to the heat used to evaporate the fuel. Since evaporation takes place by taking heat, it uses some of the heat inside the cylinder and this causes a pressure drop. The evaporation property of the fuel is the most important factor affecting this phase. 3. Phase: It is the process in which all of the injected fuel participates in the combustion and an explosion occurs in the cylinder center. It is the region with the highest pressure and heat release. 4. Phase: This phase is the main combustion process of the fuel and is the process by which the combustion is converted into work. At the end of the phase, the maximum combustion temperature is reached and the pressure drops rapidly. The 5th and 6th phases are the fast pressure drop phase and the slow pressure drop phase, respectively [9].

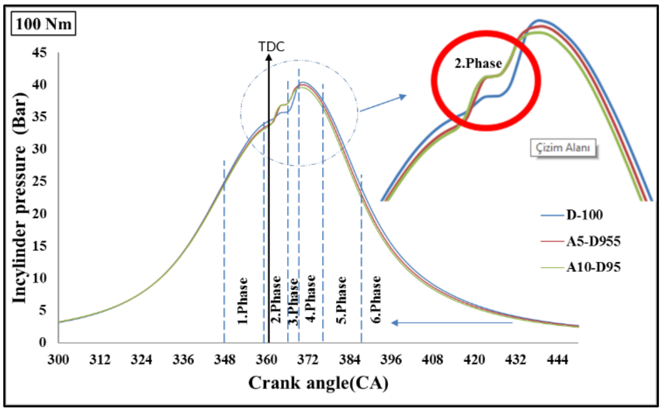

Fig. 4. Incylinder Pressure under 100 Nm load.

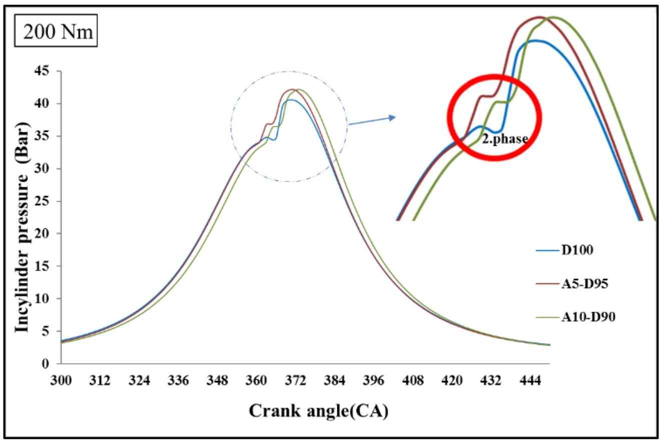

Fig. 5. Incylinder Pressure under 200 Nm load.

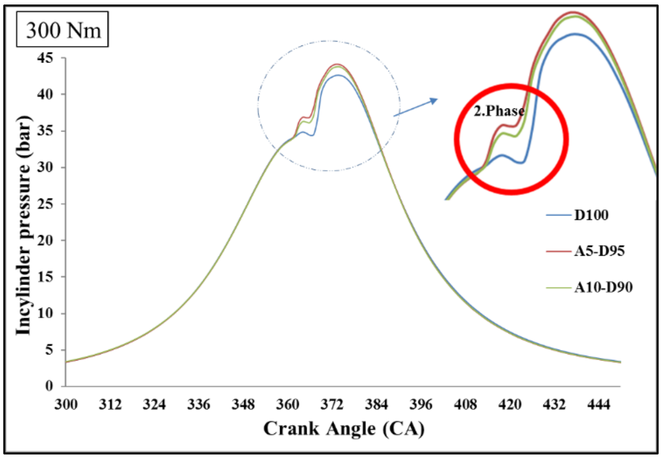

Fig. 6. Incylinder Pressure under 300 Nm load.

As seen in **Fig. 4, 5** and **6**, the highest pressure loss occurred in D100 (pure diesel) fuel in the 2nd phase region. Less pressure loss occurred in acetone-added fuels in the 2nd phase compared to D100 fuel. Acetone is more volatile than diesel because the vapor pressure of acetone (24.53 kPa (20 °C) [16]), is considerably higher than that of diesel (< 1 kPa (38°C) [17]). For this reason, fuels with acetone additives used less of the heat generated at the start of combustion in the 2nd phase during evaporation compared to D100 fuel. Since there is less heat loss in the same phase, the pressure loss of acetone added fuels was less than D100 fuel. This resulted in an increase in efficiency in fuel with 5% acetone additive.

Contrary to volatility, since the auto-ignition temperature of acetone is higher than diesel fuel, 10% acetone additive increased the auto-ignition temperature of the mixture compared to pure diesel and caused relatively delayed combustion. This explains why the efficiency of 10% acetone additive fuel is low compared to D100 fuel. As a result, while acetone additive in low proportions (%5) increased the efficiency thanks to the high volatility of acetone, 10% acetone additive delayed the combustion and adversely affected the efficiency as it increased the auto-ignition temperature of the mixture.

3.2 Exhaust Emissions and Temperature

In **Fig. 7**, the CO emission amounts per power are given. While the lowest CO emission at 100 Nm load belongs to D100 fuel, at high loads (100, 200 Nm) the lowest CO emission belongs to A5D95 fuel. The CO emission of A10D90 fuel is higher than other fuel types at all loads. Since slow oxidation occurs with the decrease in in-cylinder pressure and temperature, CO emission occurs. Incomplete combustion and incomplete combustion time are another factor that increases CO emissions [10]. In this study, in-cylinder pressure loss of fuel with 5% acetone additive in the second phase, especially at high loads (200, 300 Nm), is less than other fuels thanks to the high volatility of acetone. Thus, both in-cylinder pressure and temperature were preserved. For this reason, a better combustion occurred and CO emission was observed at lower values compared to other fuels. Since the auto-ignition temperature of acetone in 10% acetone added fuel is higher than diesel, it increased the auto-ignition temperature of the mixture. For this reason, the oxidation time was shorter than other fuels and late combustion occurred. This situation caused an increase in CO emissions in A10D90 fuel.

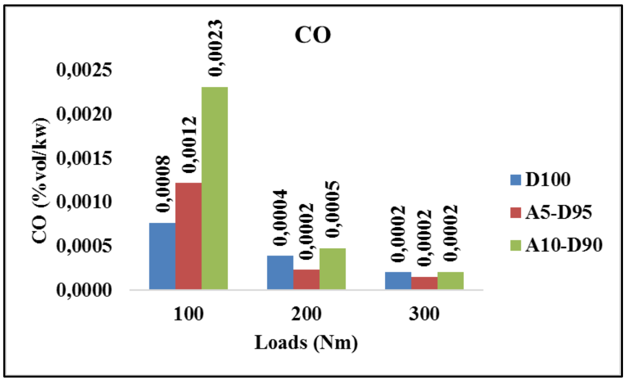

Fig. 7. CO Emission

Fig. 8 shows the CO_2 emission values. The lowest CO_2 emission at all loads belongs to A10D90 fuel. Especially at 100 and 200 Nm loads, the CO_2 emission rates of D100 and A5D95 fuels were observed to be very close to each other. Except for 300 Nm load, it is expected that CO_2 emissions will be low in A10D90 fuel, which has the lowest thermal efficiency at other loads. Because the CO molecules are expelled from the exhaust without being oxidized to CO_2. In complete combustion, all hydrocarbons are expected to turn into CO_2 and H_2O. When there is no complete combustion, CO molecules cannot be oxidized to CO_2 and CO_2 emission is seen as low [10, 11]. In this study, since 10% acetone additive increased the auto-ignition temperature of the mixture to a higher value than D100 fuel, there was a late combustion and the CO molecules were ejected from the exhaust before they could be oxidized to CO_2. Therefore, its seen that the CO_2 rate is low compared to other fuel types in A10D90 fuel.

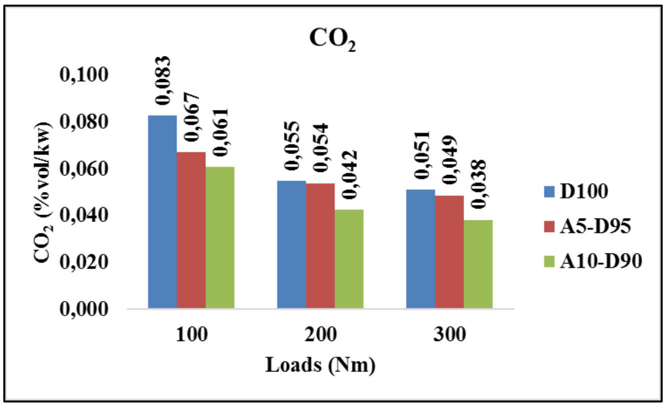

Fig. 8. CO_2 Emission

The combustion temperature in the cylinder and the length of the combustion period are the two most effective factors in the formation of NO_x emission [12-14]. Thanks to the high temperature, N_2 and O_2 molecules react by dissociating into their atons and NO_x emission occurs as a result of this reaction [13, 15]. NO_x emission values are given in **Fig.9**. In this study, the highest NO_x values occurred in A5D95 fuel. Although the exhaust temperature of the A10D90 fuel (**Fig. 10**) at 200 and 300 Nm loads was relatively higher than the A5D95 fuel, the amount of NO_x emission was quite low. The reason for this is delayed combustion due to the high spontaneous combustion temperature of the 10% acetone added fuel (A10D90) mixture and short burning time.

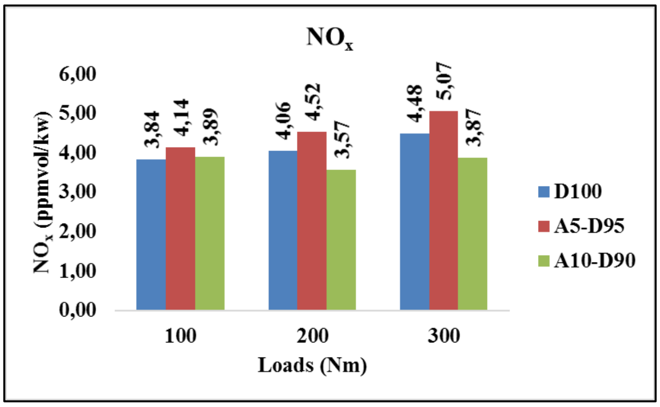

Fig. 9. NO_x Emission

It has been observed that the exhaust temperature of 5% acetone added (A5D95) fuel is higher than D100 (pure diesel) fuel. In other words, 5% acetone additive to pure diesel has an increasing effect on NO_x formation. Since there is the least heat and pressure loss in 5% acetone added fuel (2nd phase, **Fig. 4, 5 and 6**), it has a longer burning time than D100 fuel. For this reason, although the exhaust temperature of A5D95 fuel is lower than that of D100 fuel, the amount of NO_x has increased.

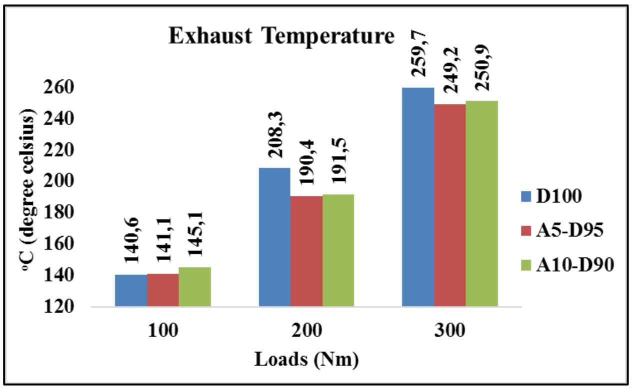

Fig. 10. Exhaust Temperature

4. CONCLUSION

Since the vapor pressure of acetone is higher than that of diesel, it is more volatile. Therefore, fuel with 5% acetone-added less heat and pressure loss at the beginning of combustion. In addition, the in-cylinder pressure graph of A5D95 fuel is better than other fuels. It has the highest pressure value especially at 200 and 300 Nm loads. For these reasons, it has been observed that the BTE value of 5% acetone added fuel is higher than other fuels. However, 10% acetone additive increased the auto-ignition temperature of the mixture due to the high auto-ignition temperature of acetone. Therefore, combustion was delayed compared to other fuels and efficiency loss occurred.

Since the efficiency of the fuel with 5% acetone additive is high, a better combustion has taken place compared to other fuels. This has contributed to the reduction of CO emissions. But it caused an increase in NO_x emission. In summary, while the 5% acetone additive had a positive effect on the yield, the 10% acetone additive had a negative effect on the yield. While the 5% acetone additive improved the efficiency, it worsened the NO_x emission, but improved the Co emission.

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