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Original Research Article

Investigation of combustion and emission in a DI diesel engine fueled with hydrogen-biodiesel blends

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ABSTRACT

The aim of this study was to determine the availability of canola oil methyl ester as an alternative fuel in diesel engines and by adding canola oil methyl ester and hydrogen to diesel fuel. This study was carried out experimentally and numerically. The engine was studied at 2000 rpm speed and full load. The analyzes carried out in the AVL-FIRE ESE Diesel part.

In-cylinder combustion and emission analyzes were examined experimentally by adding 10% (B10) and 20% (B20) of the canola oil methyl ester to the diesel (D100) fuel. Also, hydrogen fuel by the amount of 3% and 6% of the mass were added to diesel and biodiesel mixture fuels to eliminate some disadvantages of biodiesel fuels. The obtained findings in experimental and numerical studies were similar to each other. The similarity of these results was also validated by numerical studies using hydrogen.

The boundary conditions obtained in experimental studies were determined, and the effect of hydrogen fuel on temperature, in-cylinder pressure, spray distribution and CO formation were examined numerically. In the experimental studies conducted with D100, B10 and B20 fuels, the maximum pressures in-cylinder were measured as 87 bar, 88 bar and 89.09 bar respectively. In numerical results, these values were recorded as 90.02, 90 and 93.8 bar respectively. Addition of 3% and 6% hydrogen to these three different fuel mixtures increased in-cylinder pressures and temperatures. Also, in-cylinder droplet diameters with the addition of hydrogen decreased in all test fuels. This situation led to a reduction in CO emissions.

Keywords: Diesel Engine; Hydrogen; Canola oil methyl ester: CO emission; AVL Fire.

1. Introduction

The oil sector has an important place in the world. Oil and petroleum products; It meets energy needs in many areas such as transportation, industrial manufacturing and small scale consumption. Today, because of the increasing number of vehicles and global climate changes, the consumption of fossil fuels is one of the most controversial issues. Energy is supplied from petroleum products worldwide, especially for internal combustion engines used for transportation and energy production.

Diesel engines in the class of internal combustion engines; is advantageous in terms of high efficiency, power, better fuel economy and emissions. Diesel engines are used in many areas such as truck, tractor, earth mover and passenger vehicles, all marine vehicles, locomotives, stationary power machines and generators. For this reason, it is very important to improve the combustion efficiency of diesel engines and to reduce emissions.

Various studies have been carried out on the efficient use of fuel in engines and the reduction of pollutant emissions in exhaust gases. Researches on the structural properties of the engines and the engine fuels are concentrated in these studies.

Alternative fuels have highlighted issues such as the increase of combustion efficiency, energy shortage, measures taken to protect the environment due to emission values and lower fuel consumption [1]. In diesel engines have been the subject of research many alternative fuels such as Bio-diesel, Biogas, Hydrogen, compressed natural gas (CNG), Hydrogen enriched natural gas (HCNG), Ethanol and Liquefied Petroleum Gas (LPG).

Hydrogen is an alternative fuel that can be used as automobile fuel. Hydrogen; is an alternative to hydrocarbon based fuels producing hydrocarbon (HC) and carbon monoxide (CO) [2]. However, Specific oxides of nitrogen (NO_x) emissions increase due to increased combustion chamber temperature [3]. Hydrogen has some properties such as high flame speed and high thermal value [4]. Hydrogen is a renewable, highly efficient and clean fuel that has a great importance for the future of diesel engines [5]. The spontaneous ignition temperature of the hydrogen / air mixture is higher than for other fuels. Hydrogen is a clean fuel without carbon emissions. The combustion of hydrogen produces only water and some nitrogen oxides. It helps to reduce carbon dioxide (CO_2) emissions when used with fossil fuels. Hydrogen with these emission properties is the ideal fuel to meet the more stringent environmental controls associated with greenhouse gases and emissions [6]. Hydrogen has the ability to ignite in a large area long-term renewable and less polluting, non-toxic and odorless [7]. It is not possible to use hydrogen widely in vehicles in the near future due to the lack of hydrogen as a fuel substructure and lack of fuel supply stations [8]. In other respects, early ignition and early combustion occurs due to low ignition energy in the case of hydrogen-fueled engines. Also, water vapor in the hydrogen-air mixture causes a decrease in power as it reduces the combustion temperature. Furthermore, due to the low combustion rates in very poor mixtures, the contact of the new mixture with the combustion gases as a result of the increase in combustion time, hot particles from the engine oil can initiate the combustion before the desired. Therefore, it can be used with fuel types such as diesel and bio-diesel. Several studies have been conducted on the impact of the engine on performance and emissions.

Four-cylinder diesel engine is operated at full load and different speeds. 2.5%, 5% and 7.5% hydrogen are added inside diesel fuel. The torque, power, thermal efficiency, exhaust gas temperature and NO_x are increased with the increase of hydrogen fuel in the engine. HC, CO and O_2 emissions are decreased [9].

Another study is a review study on the use of hydrogen-CNG mixture (HCNG) in internal combustion engines. Hydrogen fuel has decreased HC and CO_2 emissions due to carbon deficiency compared to CNG fuel, while NO_x emissions have increased due to chamber temperature rise. Also, the speed of laminar flame has increased with hydrogen [10]. The increase in laminar flame velocity with the addition of different amounts of hydrogen into natural gas is more clearly indicated by an experimental setup. The experimental setup consists of a spherical combustion chamber coupled to a classical shadowgraph system [11]. In addition, the speed of flame propagation increases as hydrogen fuel is added into the CNG [12]. As a result of the reaction of CNG fuel with hydrogen fuel, the stability of combustion has increased [13].

HCNG fuel can be used with fossil fuels. Thus, the efficiency and emission values reduces. In any case, if the advance is well adjusted, the engine torque increases [14]. The effect of the compression ratio is emphasized on torque, brake specific fuel consumption and emission parameters in a single cylinder diesel engine tested at different HCNG ratios [15]. Generally, when hydrogen is added into CNG fuel in the diesel engine, it is observed to reduce HC, CO_2 and CO emissions due to the absence of carbon in the hydrogen [16]. Also, NOx emissions increases due to the increase in combustion chamber temperature as well as combustion chamber pressure. In addition, hydrogen fuel has increased flame speed and thermal efficiency and reduced combustion duration. Maximum cylinder pressure and maximum heat release increases. Bsfc (Brake-specific fuel consumption) parameter is also reduced have been determined in different studies [1, 16-20].

One of the alternative fuels whose research extends to this day is the fuel (biodiesel), which is obtained from vegetable or animal oil. Biodiesel fuel is a fuel that has a lower CO_2 emission and similar combustion characteristics as diesel fuel.

Many biodiesel fuels have been used to improve performance and emissions in diesel engines. Kumar and his friend, maduca longifolia oil (MO), ethanol, hydrogen and water injection fuels are operated in different ratios of single-cylinder diesel engine at 1500 rpm, 3.7 kW power and full load. Ethanol is showed a higher ignition delay than hydrogen fuel. It has been seen that engine performance improves when ethanol, hydrogen and MO fuels are used together [21]. In another study, Pomegranate seed oil biodiesel (POB), hydrogen and diesel fuels are used in different ratios. Adding POB fuel to the diesel fuel in the engine has a positive effect on the engine power and bsfc parameters. Engine performance and emissions are improved with the addition of hydrogen fuel to these fuels [22]. Serin et. al, tea seed oil biodiesel, hydrogen and diesel fuels are investigated the effect on engine performance and emissions by using different ratios in a single cylinder diesel engine. Biodiesel is showed a positive effect on engine performance and bsfc parameters. While biodiesel reduced CO emissions, it has increased CO_2 and NO_x emissions [23]. In a single cylinder diesel engine, Waste oil biodiesel (WOB), hydrogen and diesel fuels are tested no-load at 1500 rpm. The addition of WOB fuel reduces thermal efficiency. WOB fuel increases fuel consumption and CO_2 parameters. While thermal efficiency is increased by the addition of hydrogen fuel, fuel consumption, CO and CO_2 emissions are decreased [24]. Tamanu methyl ester (TME), ethanol, diesel and hydrogen fuel are used as fuel in a diesel engine. Hydrogen fuel is provided high NO_x emission and this NO_x value is reduced by using TME + Ethanol fuel mixture [25]. When jatropha oil is used as a biodiesel in a diesel engine, it is seen that the thermal efficiency increased, while the soot, HC and CO emissions are decreased [26].

Another fuel used in diesel engines as biodiesel fuel is rapeseed oil (canola oil) fuel. There are experimental studies on rapeseed oil, hydrogen and diesel fuels in the literature. Rapeseed oil, hydrogen and diesel fuel are tested with different mixing ratios in diesel engine. The effects of combustion characteristics, performance and emissions are investigated with different rates of hydrogen fuel has added to B20 (20% rapeseed oil and 80% diesel) fuel. Rapeseed oil fuel is reduced performance and efficiency while it is reduced other emissions without NO_x emissions. Also, the ignition delay of this fuel is shorter. It doesn't have a significant effect on B20 fuel on ignition delay of hydrogen fuel [27,28]. In another study, rapeseed methyl ester (RME) and diesel fuel are used as pilot fuel, natural gas and hydrogen fuel are used as main fuel in a diesel engine. Experiments are performed at different engine speeds. It is observed that the delay of the ignition is shortened by pilot spraying of rapeseed methyl ester fuel [29]. In addition, a better trade-off between HC and NO_x is attempted by pilot spraying of rapeseed methyl ester fuel [30]. Pilot fuel RME according to pilot fuel diesel, emission values are generally similar because of the physical and chemical properties [31]. It is determined that there is a better result in NO_x emissions in the medium power range as pilot fuel RME and diesel fuel and as main fuel hydrogen-diesel fuel [32]. In another experimental study, as pilot fuel RME and diesel fuel and as main fuel natural gas are used. The lower thermal efficiency of the RME fuel compared to diesel fuel is obtained [33]. RME fuel according to diesel fuel, CO_2, UHC and NO_x emissions are lower and thermal efficiency is higher in different speed and load conditions [34].

Increased canola oil methyl ester in diesel fuel due to incomplete combustion, this situation increased emissions of O_2 while reducing CO emissions in exhaust emissions. Also, exhaust gas temperature has decreased [35].

Many of the rapeseed-hydrogen fuel uses in the literature are related to the effects of engine performance and emissions. Also, in general studies, rapeseed oil is used by mixing with methyl ester. In the present study, the effects of different proportions of diesel, canola oil methyl ester and hydrogen fuels were investigated on combustion characteristics and emissions. Both experimental and modeling were performed with different fuel mixture ratios at 2000 rpm engine speed and full load. All features of the engine were constant kept except for the fuel ratio for fully understand the effect of used fuels on the combustion and emissions. The difference of this study from literature, chamber pressure and temperature, heat release, state of the fuel-air mixture inside the chamber, spraying process, particle formation, evaporation and temperature distribution of the fuel were examined by using the ESE-DIESEL part of the AVL-FIRE software in the model. After that, the experiments were carried out on diesel fuel, B10 (10% canola oil methyl ester 90% diesel) and B20 (10% canola oil methyl ester 90% diesel) fuels, and this results were compared with the model. The results obtained from the models and experiments were found to be close to each other. Then, the effects of hydrogen on combustion and emissions were investigated by adding 3% and 6% hydrogen to the diesel, B10 and B20 fuels in the model.

2. Material Method

2.1. Experimental study

The air-cooled, single-cylinder Antor 3LD 510 direct injection diesel engine was used as the test engine. In-cylinder pressure measurement of the engine was used in the Febris combustion analysis program. Combustion chamber pressure was measured by the Optrand brand optical fiber pressure sensor. After connecting the encoder and the pressure sensor to the single cylinder diesel engine, the data obtained was transferred to the computer instantly by way of the Febris interface. The engine was operated at full load and maximum torque. The engine test setup was given in Figure 1. The technical specifications of the engine were given in Table 1. Also, experimental test uncertainty analysis results were showed in Table 2.

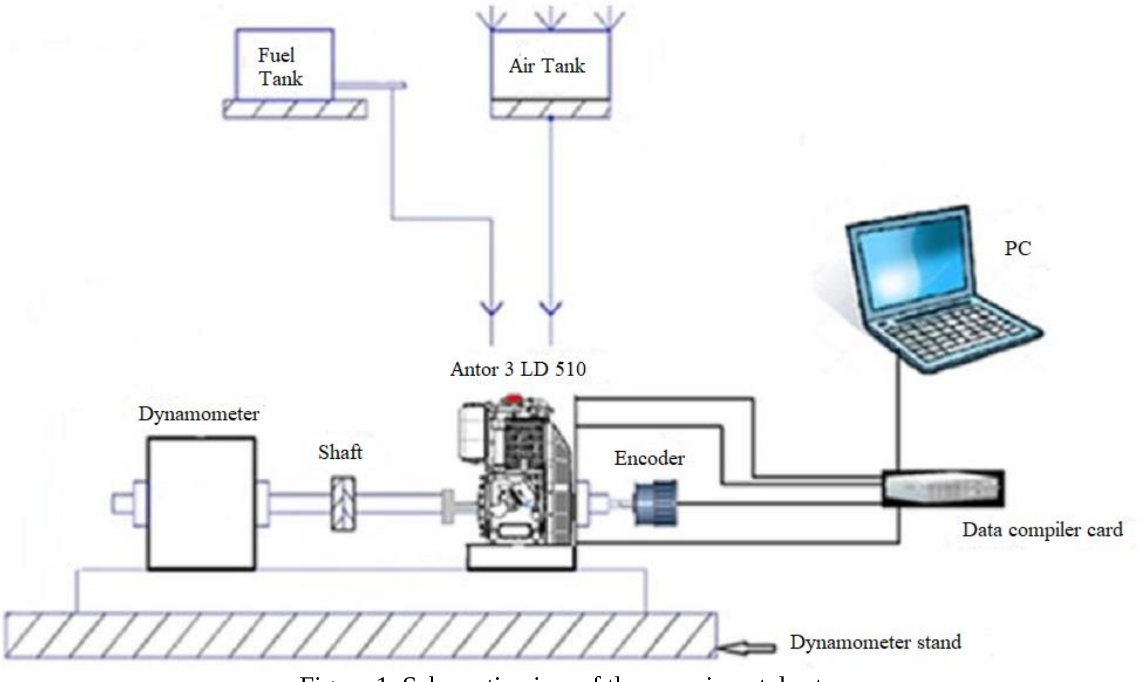


Figure 1. Schematic view of the experimental setup.

Table 1. Test engine specifications.

Specifications	Descriptions
Engine Type	4- stroke, direct injection diesel engine
Number of cylinders	1
Cylinder volume	510 cm^3
Bore x Stroke	85 x 90 (mm x mm)
Compression ratio	17.5:1
Maximum power	8.8@3000 (kW)
Maximum torque	32.8@1800 (Nm)
Injection angle	126°
Number of Nozzles	4

Table 2. Uncertainties of experimental measurement devices

Pressure Sensor	Encoder	Electric dynamometer
Optrand fiber optic	Cubler	Baturalp Tayland brand brake
Measuring range 0 -200 bar	Measuring range 0-12000 rpm	Maximum torque of 80 Nm
0,025 V/bar sensitivity	Encoder resolution 360x1^0 CA	%±0.02 Uncertainty
120 kHz natural frequency	Converts angle value to digital TTL signal	Torque sensor ± 10 VDC output
% ≤±0,5 accuracy	It can be supplied with 5V or 120 mA	Powered by 220 Volt voltage
Measurement in temperature range -40 and 360 °C	Measurement in temperature range -40 and 85 ^{0}C	Measurement in temperature range -10 and 60 ^{0}C

2.2. Numerical study

The analysis of fuels with different ratios was made by ESE-DIESEL part of the AVL-FIRE software. In this program were simulated parameters such as combustion temperature, viscosity, particle distribution, ignition delay, emission and engine performance values. All values of the single cylinder engine were taken in the conducted analysis. WAVE model was used as breakup model in the mode, k-zeta-f model was used as a turbulence model, Multi-Component as an evaporation model. Also ECFM-3Z model were used as a combustion model. Wall interaction model known as "Wall jet 10" was used for hydrogen, canola oil methyl ester and diesel fuels in the numerical study. The spray angle was defined as 126^0 in this analysis [36-39]. This model simulates separated of small droplets from the fuel particle. In the model, the spray wall interaction model was used to calculate the effect of non-atomizable or non-vaporized fuel on the combustion chamber walls of the sprayed fuel. On the other hand, this model could be used for EGR and spray type combustion models. Hydrocarbon based many fuels could be defined in the ECFM-3Z model. The extended Zeldovich model was used for NO emissions. As initial conditions, the temperature and pressure values were taken respectively 293 K and 1 Bar. The cylinder walls and cylinder head values were fixed in the boundary conditions and also the piston was selected as the moving boundary condition. On the other side, C2-13 Weber number model was performed depending on physical and dynamic parameters of sprayed and dispersed fuel in Wave fragmentation model. To investigate the mesh independency, it was considered containing a different number of cells. Though the resulting combustion parameters were identical for all cases, the case which contained approximately 50,000 cells had closest result compared to experimental results. The geometry of the combustion chamber was given in Figure 2. The input and boundary conditions were given in Table 3.

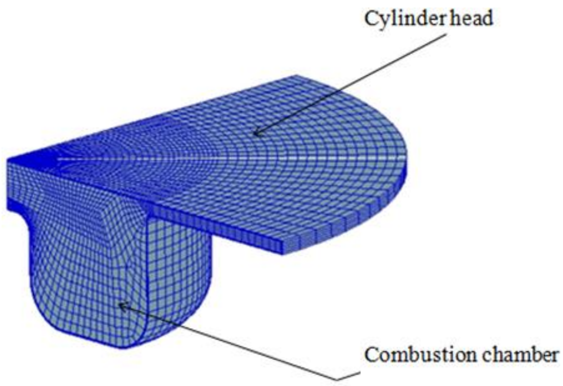


Figure 2. Combustion chamber geometry.

Table 3. Determined initial and boundary conditions.

Specifications	Descriptions
Engine speed	2000 (rpm)
Air inlet temperature	293.15 (K)
Air inlet pressure	1 (bar)
Fuel injection temperature	330.15 (K)
Cylinder head temperature	575.15 (K)
Cylinder wall temperature	475.15 (K)
Spraying range	-20-0 (KA)
Fuel consumption	1.9 (lt/h)

Test fuels consist of diesel, canola oil methyl ester and hydrogen fuels in the AVL-FIRE library. The engine torque was selected as 2000 rpm in the numerical study. Model had been created by keeping constant parameters such as engine volume, cylinder volume, compression ratio, injector angle and nozzle structures, exhaust and intake valve opening and closing advances. Fuel injection pressure is 200 bar both experimental and numerical. The effects of different fuel mixtures were investigated on combustion characteristics and emissions. Numerical studies were compared with experimental data in different fuel types. The properties of diesel-hydrogen and diesel-canola oil methyl ester fuels were given in Table 4.

3. RESULTS

The analysis of the combustion in the engine should be interpreted as an indicator of some parameters in-cylinder. The crankshaft angle measured by the encoder connected to the crankshaft was measured in the engine.

Table 4. Comparison of diesel fuel and hydrogen characteristics [40,41].

Properties	**Diesel**	**Hydrogen**	**Canola oil methyl ester**
Formula	n-$C_{13}H_{28}$	H_2	-
Auto ignition temperature (K)	530	858	-
Minimum ignition energy (MJ)	-	0.02	-
Flammability limits (volume % in Air)	0.7-5	4-75	-
Stoichiometric air–fuel ratio on mass basis	14.5	34.3	-
Molecular weight (g/mole)	100	2	-
Limits of flammability	-	0.1-7.1	-
Density at 160 ^{0}C and 1.01 bar (kg/m^3)	833-881	0,0838	881
Net heating value (Lower) (MJ/kg)	42.5	119.93	-
Flame velocity (cm/s)	30	265-325	-
Quenching gap in NTP Air (cm)	-	0.064	-
Diffusivity in Air (cm^2/s)	-	0.63	-
Octane number	30	130	-
Cetane number	40-55	-	45-59
Calculated cetane index distillation (%)	57.8	-	47.2-55
Boiling point (K)	436-672	20-27	-
Pour point (°C)	-6	-	-10.0
Freezing point (°C)	-	-	-12.9
Ester content (%)	-	-	99.6
Flash point (°C)	58	-	135.7
Viscosity at 15.5 °C, centipoise (mm^2/s)	2.6-4.1	-	4.44
Specific gravity	0.83	0.091	-

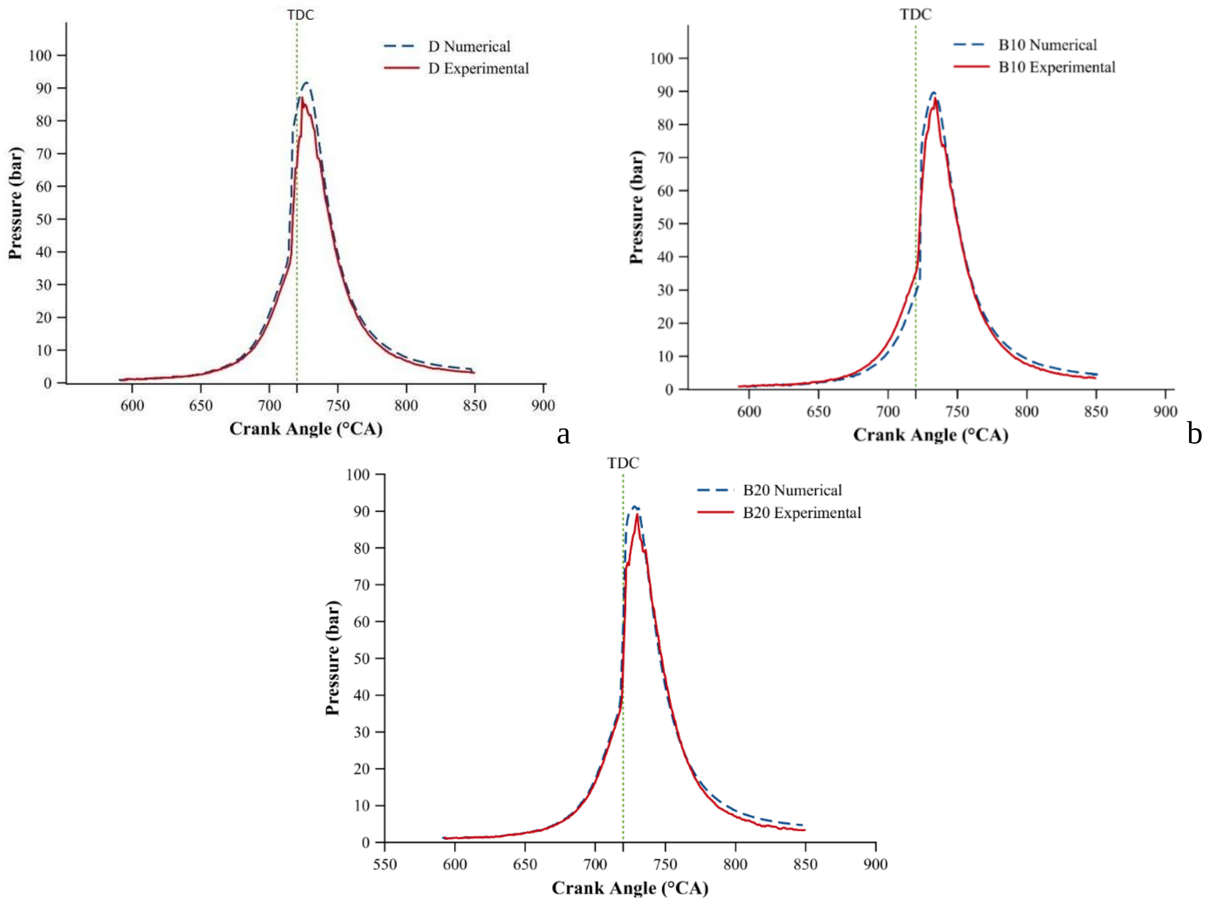


Figure 3. Experimental and numerical comparison of in-cylinder pressure changes of Diesel (a), B10 (b) and B20 (c) fuels.

In-cylinder pressure change measured by the optical sensor connected to this encoder was an important parameter used in the combustion analysis of the engine. The engine experiments performed in this study were modeled numerically in the AVL-Fire program. Thus, numerical and experimental results were presented comparatively, and the validity of the numerical model was emphasized. In the experiments, diesel fuel, B10 (10% canola oil methyl ester 90% diesel) and B20 (10% canola oil methyl ester 90% diesel) fuels were performed at 2000 rpm engine speed and full load. The in-cylinder pressure values of these fuels depending on the crank angle were compared both experimentally and numerically (Figure 3).

It is seen in all test fuels where the pressure values obtained from modeling with biodiesel fuel in AVL library and experiment were close to each other. In the experimental study, it was aimed to minimize the margin of error by making an average calculation of 200 cycles for all test fuels. When the B10 and B20 fuels were compared to diesel fuel, the maximum pressure values in-cylinder had slightly increased. There were different reasons for this increase. The first of these was that the biodiesel fuels have a higher density than diesel fuel. The biodiesel fuel injected from the injector may had increased the maximum pressure by spraying more fuel per unit volume. Another reason was the oxygen found in the chemical structure of biodiesel fuel. It could be said that the amount of oxygen is higher in the combustion chamber and the fuel breaks down more easily by increasing the temperature in-cylinder. This situation could be said to cause a slight increase in maximum pressures. As a matter of fact, these results also overlap with the combustion analysis performed in the AVL Fire program.

Increases in penetration depths due to the use of biodiesel fuels and the separation of the fuel into smaller particles performed a more homogenous distribution of the fuel in the combustion chamber. This was thought to be effective in increasing the maximum pressures in biodiesel blended fuels. The fact that the experimental results obtained with different fuels and the numerical results were similar to each other, the results obtained by the addition of hydrogen to test fuels were also validate in modeling.

By adding 3% and 6% hydrogen to fuels, the in-cylinder pressure changes depending on the crank angle were given numerically in Figure 4. Hydrogen compared to diesel and biodiesel fuels, the maximum pressures in the cylinder increased in all mixtures where hydrogen was added due to the high flame velocity and high thermal value.

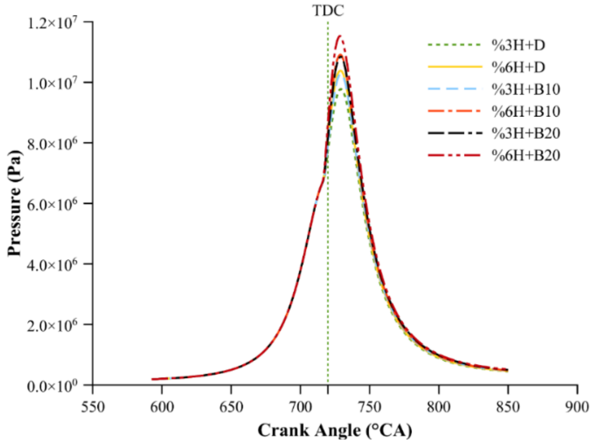


Figure 4. Pressure change in-cylinder by addition of hydrogen to fuels at different mixing ratios.

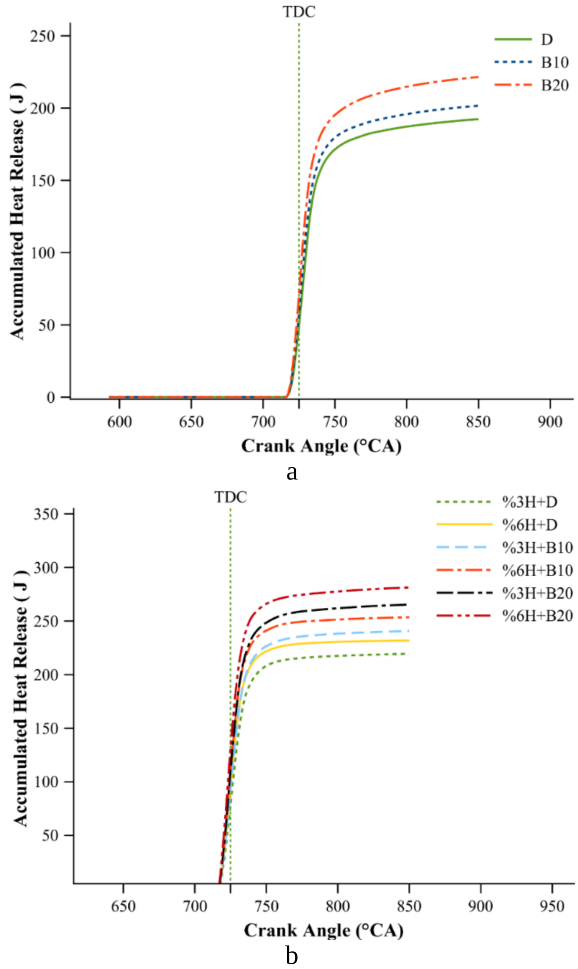


Figure 5. Change of accumulated heat release diesel and biodiesel fuel mixtures (a) and the addition of hydrogen to fuels (b).

In addition, the in-cylinder combustion behavior of hydrogen fuel and biodiesel fuels were examined. In particular, these two fuels had improved the combustion process, and oxygen in the structure of biodiesel fuels provides better combustion with hydrogen fuel and in Figure 5 was shown that the resulting heat release is increased. Accumulated heat release (AHR) rate provides information on combustion in engines. Accumulated heat release values increase in parallel with the increase in-cylinder pressure and temperature of biodiesel blended fuels. In particular, increased in ignition delay durations as a function of the cetane number of fuels had increased the maximum heat release, and in parallel to this, had increased at maximum in-cylinder temperatures. As a matter of fact, this situation was clearly seen in spray distribution and temperature graphs.

3.1. The formation of local CO

Hydrogen fuel has many advantages such as ignition limits in wide A / F ratios, absence of carbon components, high octane numbers, high thermal value compared to gasoline and diesel fuels. Its use as a double fuel is quite common due to this advantages. In diesel engine used by 10% and 20% canola oil methyl ester were mixed with diesel fuel. 3% and 6% hydrogen were added to eliminate some disadvantages of this fuel mixture. The dispersion and combustion process resulting from spraying the fuels into the combustion chamber were analyzed experimentally and numerically.

In numerical analysis; especially in-cylinder CO formation, spray distribution and temperature formation were investigated extensively for each model. CO is a kind of harmful emission caused by toxic and incomplete combustion. The formation of CO varies greatly depending on the air / fuel ratio. The CO emission formation was obtained for all test fuels at different crank angles in-cylinder. Combustion and emissions occurring were investigated before and after the 720 crank which is accepted as TDC in the engine. The CO formation in the combustion chambers was investigated at four different crank angles, 715^0,720^0,730^0 and 735^0. In the below figures were given the CO distribution in the combustion chambers of fuel mixtures D, B10, B20, D + 3% H, D + 6% H, B10 + 3% H, B10 + 6% H, B20 + 3% H and B20 + 6% H (Figure 6). When the figures were examined, the highest CO formation was obtained in the study using pure diesel fuel. It was thought that oxygen in the structure of canola oil methyl ester is a factor that improves combustion. As a result of the recovery of combustion, CO emissions had also decreased with the increase in the rate of biodiesel fuel. In particular, by adding hydrogen to diesel, B10 and B20 fuels have caused significant reductions in CO emissions (Figure 6). In addition, significant reductions in CO emissions were observed due to the lack of carbon in the structure of hydrogen. In particular, the lowest CO emission formation was observed in the B20 studies with hydrogen added. Another factor in the reduction of CO emissions was that hydrogen fuel had improved evaporation by increasing combustion temperatures in the combustion chamber. In addition, the high flame speed of hydrogen fuel compared to diesel and biodiesel fuels had led to better combustion of the fuel mixture. The homogeneous mixture of biodiesel fuels with air in the cylinder was another factor in the reduction of CO emissions. In all test fuels, local CO formation is lower at the angle of 5 degrees before the TDC (Figure 6). This situation could been seen more clearly in the spray distribution / temperature patterns of the fuel.

In all test fuels, in parallel with the increase in cylinder temperature and pressure, the evaporation of the fuel and the air-mixing rate were more clearly seen at the 720° crank angle. The combustion effect was quite high at 730° crank angle. In the process of initiation and continuation of combustion, CO formation is observed in a wider area by the end of the spraying at the 735° crank angle.

3.2. Spray distribution / temperature formation

In diesel engines, the penetration depth and spray formation in the combustion chambers are very important on the fuel / air mixture ratio. At the same time, the formation of in-cylinder temperature and the distribution of fuel particles give important information about combustion. In the following figures, the spray distribution-temperature distributions in the combustion chambers were given at different crank angles of the fuel mixtures D, B10, B20, D + 3% H, D + 6% H, B10 + 3% H, B10 + 6% H, B20 + 3% H and B20 + 6% H (Figure 7).

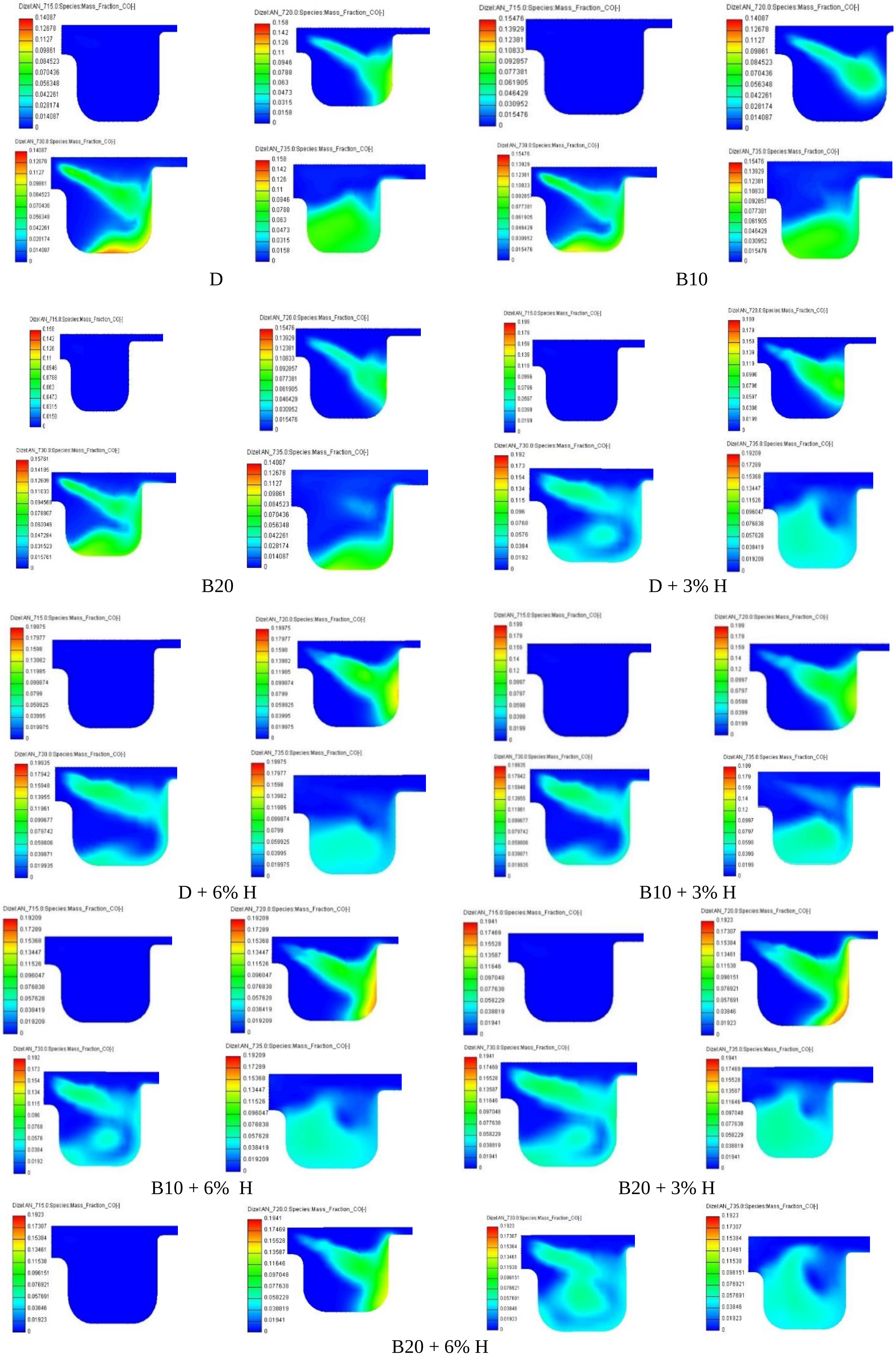


Figure 6. Investigation of the in-cylinder CO emission in different fuel mixtures.

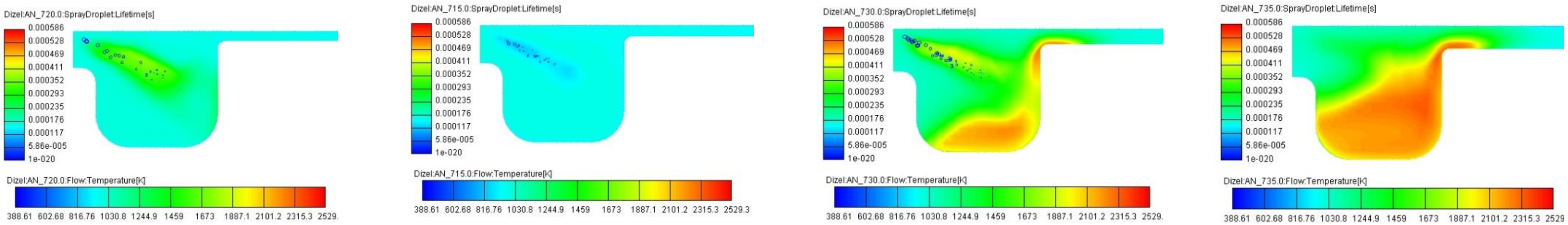
Especially the high viscosity and density of biodiesel fuels was a negative result in terms of combustion and emissions. However, when the engine was operating at 2000 rpm, the inclusion of oxygen in the structure of biodiesel fuel and the injection of excess fuel due to its density increased the in-cylinder combustion temperatures compared to the diesel fuel used. This effect of the temperature had improved the decomposition and penetration of the fuel into smaller particles by eliminating this negative situation caused by the fuel viscosity. In all the test studies, the dispersion of the flame in the combustion chamber was given with the end of spraying at the 731 crank angle. With the advancement of the crank angle, it had been observed that the fuels have broken down and continued to burn in the chamber pocket (Figure 7). The fuel particles that were plastered to the combustion chamber walls started to burn due to the temperature and caused the temperatures to increase in this region. At the first outlet of the injector, larger fuels were decomposed into small fuel particles together with in-cylinder temperatures and mixture formation. In particular, biodiesel blended fuels compared to diesel fuel had been observed that it had a longer carbon-hydrogen chemical chain structure, the excess oxygen and the decomposition of smaller fuel particles due to high temperatures. Also, B10 and B20 fuels had higher combustion temperatures than D fuel. In addition, the separation of B10 and B20 fuels into smaller particles increases the penetration of the spray . Reduction of the stress applied to the fuel surface by separating the fuel into small particles, it caused the fuel particles to continue to exist in the combustion chamber. Adding 3% and 6% hydrogen fuel to the D, B10 and B20 fuels have highly affected the particle distribution and temperature formation (Figure 7). For example, when the piston was at the TDC, the maximum temperatures obtained in the combustion chamber for D, B10 and B20 fuels were recorded as 2498 K, 2529 K and 2571 K respectively. Both the increase in the rate of biodiesel and the increase in the rate of additional hydrogen fuel had led to an increase in these temperatures. For example, when 3% and 6% hydrogen were added to the D fuel, the combustion temperatures were 2612 K and 2671 K, respectively. Similarly, when 3% and 6% hydrogen were added to the B10 fuel, the combustion temperatures were 2644 K and 2701 K respectively. When 3% and 6% hydrogen were added to the B20 fuel, the combustion temperatures were 2675 K and 2719 K respectively. Also, in Table 5 was showed the maximum spray sauter diameters (d32 m) of different fuels. These results confirm the above-mentioned sentences. The addition of hydrogen-biodiesel and diesel fuel caused a decrease in the maximum spray sauter diameter (d32 m).

Table 5. The maximum spray sauter diameter (d32 m) of different fuels

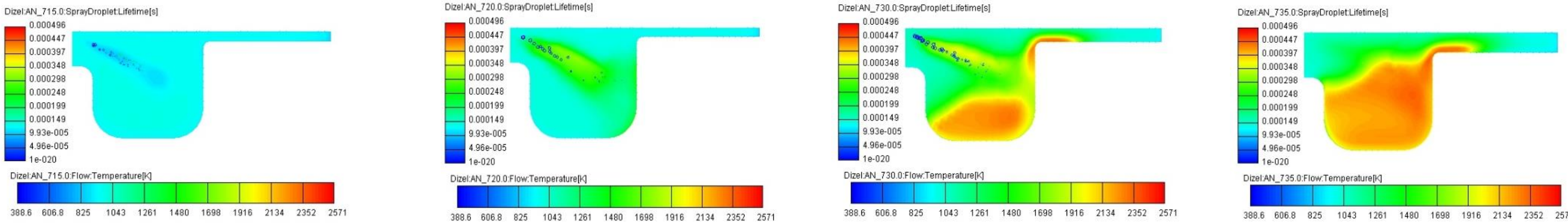
Fuel	The maksimum Spray Sauter Diameter (d32 m)
D	0.00015135
B10	0.00015096
B20	0.00015095
D + 3% H	0.00015068
D + 6% H	0.00014952
B10 + 3% H	0.00015068
B10 + 6% H	0.00015026
B20 + 3% H	0.00015078
B20 + 6% H	0.00015022

4. Conclusions

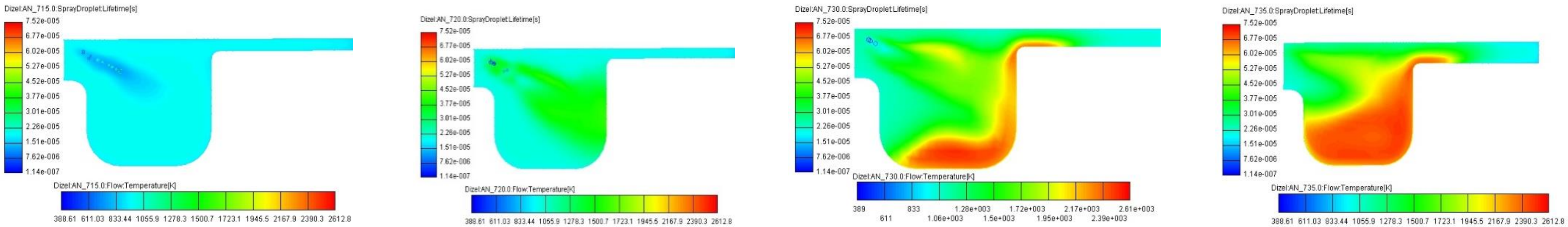
In this conducted study, D, B10 and B20 fuels were investigated experimentally and numerically in a direct injection diesel engine. The engine was operated at 2000 rpm with engine speed and full load. All other engineparameters were kept constant to understand the effect of fuels. In the experimental study, it was aimed to minimize the margin of error by making an average calculation of 200 cycles for all test fuels. In this study were examined parameters such as in-cylinder pressure change, accumulated heat release, the formation of local CO, spray distribution and temperature formation in different fuel mixtures and the change of temperature and the distribution of fuel particles in different fuel mixture. When the B10 and B20 fuels were compared to diesel fuel, the maximum pressure values in-cylinder had slightly increased. The reason of this could be said that the oxygen found in the chemical structure of biodiesel fuel and higher density than diesel fuel. Also, increases in penetration depths due to the use of biodiesel fuels and the separation of the fuel into smaller particles performed a more homogenous distribution of the fuel in the combustion chamber.



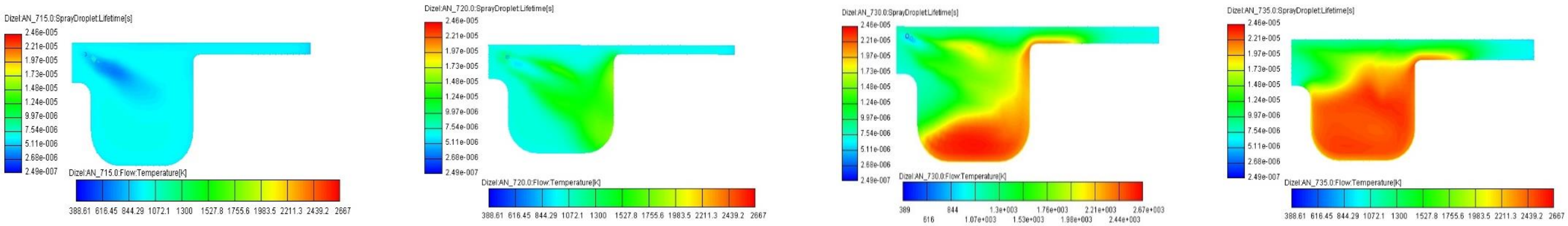
B10



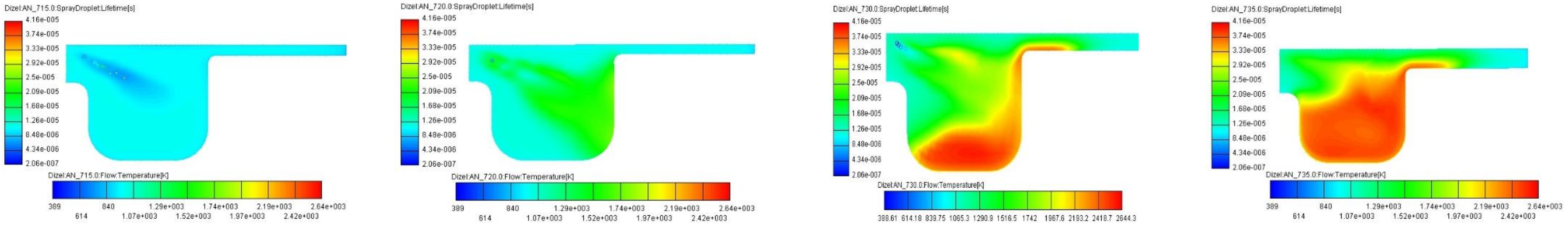
B20



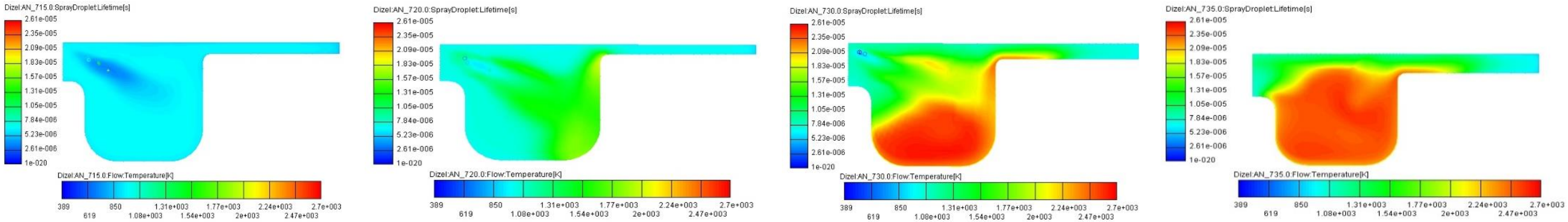
D + 3% H



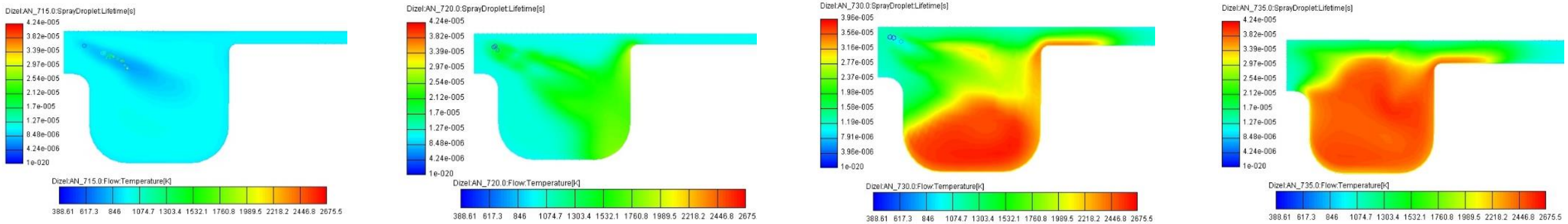
D + 6% H



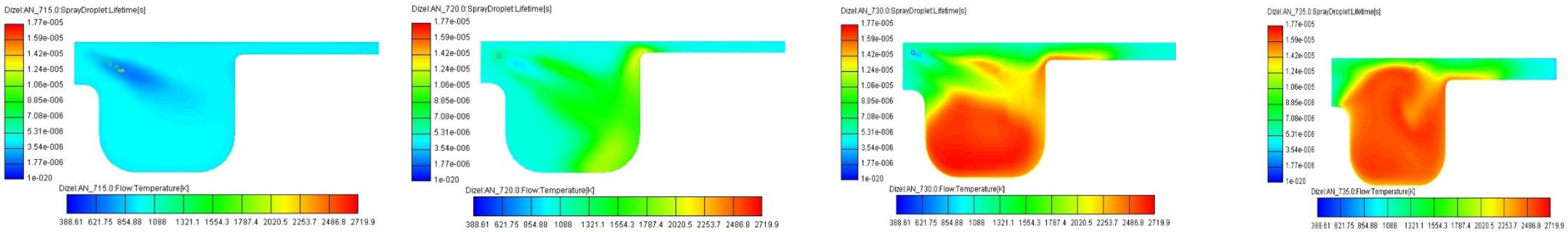
B10 + 3% H



B10 + 6% H



B20 + 3% H



B20 + 6% H

Figure 7. The formation of in-cylinder temperature and the distribution of spray droplet in different fuel mixture.

When the ratio of in-cylinder pressure and accumulated heat release were examined, it was seen that the experimental and numerical results were close to each other. This situation proved the accuracy of the results obtained from the numerical study. Then, the effect of hydrogen was investigated numerically by adding 3% and 6% hydrogen to D, B10 and B20 fuels. By adding of hydrogen fuel, the high flame speed of the fuel and the high heat value of the hydrogen fuel compared to diesel and biodiesel fuels, and it increased the in-cylinder maximum pressures in all the operations. Hydrogen and biodiesel fuels had improved the combustion process, and oxygen in the structure of biodiesel fuels provides better combustion with hydrogen fuel and this situation, accumulated heat release was increased. The maximum flame zone was obtained by using B20 + 6% H mixed fuel in the combustion chamber. Increasing the rate of hydrogen in biodiesel blended fuels was provided easier disintegration of the fuel and distribution within the combustion chamber. It was concluded that the addition of hydrogen to biodiesel fuels with low cetane numbers a factor that facilitates combustion.

Investigation of the thermal and chemical effects of the addition of hydrogen to may use in both diesel and biodiesel fuels may be the next study on engine parts.

Nomenclature

D : Diesel
H : Hydrogen
TDC : Top Dead Center
CA : Crank Angle
A/F : Air/Fuel
CFD : Computational Fluid Dynamic
CO : Carbon monoxide
HC : Hydrocarbon
O_2 : Oxygen
RME : Rapeseed Methyl Ester
AHR : Accumulated Heat Release

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