Model for Predicting the Performance and Exhaust Gas Emissions of a Diesel Engine Fuelled by Diesel and Biodiesel B20. Simulation and Validation

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Abstract. The increasing demand, price, and depletion of conventional Diesel fuel prompted extensive worldwide research into alternative energy sources for internal combustion engines. Among all the alternative fuel types, Biodiesel is considered a suitable fuel, and the most promising one for Diesel engines. This paper focuses on compression ignition engine fueled Diesel and Biodiesel B20. A model is proposed to providing realistic estimates of the engine performance, combustion characteristics and exhaust gas emissions for various engine speeds (1400 rpm, 2000 rpm, and 2400 rpm) at full load. Simulation results obtained by using the AVL BOOST v2013.2 code are presented. These results are validated against experimental data.

Keywords: Biodiesel, diesel engine, performance, emissions.

1 Introduction

Presently, there has been a global increase in investigations concerning the application of alternative fuels for daily use, such as Biodiesel and its blends as a fuel in Diesel engine. This universal search for alternative fuel is connected to the fact that the world population continues to grow and the limited amount of petroleum fuels begin to diminish, it may not be possible to provide the amount of energy demanded by the world by only using petroleum fuels to convert energy. Moreover, there is an awareness of the global concern regarding air pollution caused by the extensive use of petroleum fuels in internal combustion engines. Biodiesel was found to possess similar physical properties to those of Diesel fuel, and can be used in Diesel engines either directly or mixed with Diesel fuel, without any change of the original adjustments of the engine were prepared by the manufacture [1].

Biodiesel has some advantages which make it an acceptable fuel substitute to Diesel fuel in the future, such as renewable energy, lower sulfur and aromatics contents, safe to handle and store, better lubrication, improved biodegradability and decreased

International Congress of Automotive and Transport Engineering, CONAT 2016
Transilvania University of Brasov, 2016
ISSN 2069-0401

toxicity [2, 3]. In addition, Biodiesel has a higher cetane number compared to Diesel fuel, whose influence results in a shorter ignition delay time and then improved fuel combustion [4]. On the other hand, the higher viscosity of Biodiesel can be twice that of Diesel depending on the feedstock, and production significantly suppresses Biodiesel's fuel flow, fuel spray evaporation, and atomization process, which led to an increase in the combustion duration and resulted in slower burning [5, 6]. During the last decade, many researchers attempted to produce accurate models to predict engine performance and exhaust emissions with different types of software.

Perhaps one of the most useful aspects of engine modeling is that the simulation allows the user to imagine different scenarios, being able to see on a computer screen the temporal variations of pressure, volume and gas flow rate that take place during the engine cycle. Today, Diesel engines occupy a prominent role in current power generation, transportation sector and in most passenger cars due to the fact that the Diesel engine is considered more efficient and durable than the gasoline engine. Many methods have been tried and are in use to reduce pollutant emissions from Diesel engines. The one solution to reduce pollutants is the use Biodiesel and adopting some modifications to the combustion process [7, 8]. Numerical simulations of the Diesel engine can be used to understand its combustion characteristics, formulated exhaust gas emissions, and engine performance behavior, and these simulations can reduce the costs and effort.

Racovitza et al. [9] have investigated, by numerical and experimental study, the performance and emission characteristics of Biodiesel B20 at different starts of fuel injection (-7 degree (standard) and down to -44 degree) at 2400 rpm engine speed and 60% engine loads. These results indicated that the engine performance and efficiency of the tested engine maintain their reference values (SOI -7) a slight increase of BSFC when B20 is used; they explained that this behavior is due to a lower heating value and higher density of Biodiesel B20 compared to that of Diesel fuel.

Harch et al [10] developed an engine combustion model (which involves fuel atomization, burning velocity, combustion duration, temperature, and pressure) for a Diesel engine fuelled with second generation Biodiesel blends (B5 and B10) by using computational fluid dynamics (CFD) software and AVL Fire. The simulation results revealed that B10 provides better performance and efficiency, and significantly reduced engine emissions, while the B5 blend provides slightly improved performance and efficiency, and moderately reduced emissions compared to petroleum Diesel.

The purpose of this study is to present a model of a tested direct injection Diesel engine in order to simulate engine performance and exhaust gas emissions by using simulation tools called AVL Boost. The outcome of this modeling work is validated against experimental data.

2 Experimental Infrastructure

A four-cylinder, four-stroke, naturally-aspirated, water-cooled, direct injection tractor Diesel engine coupled to an eddy-current dynamometer equipped with a load controller was used in this study. The basic engine specifications are shown in Table 1. The fuel injector has five 0.24 mm diameter holes with an opening pressure of 330 bars. Two AVL GM 12 D pressure transducers with sensitivity 15.76pC/bar were used to measure the in cylinder pressure and one AVL QL21D pressure transducer with sensitivity 2.5pC/bar and maximum measuring range of 3000 bar was used to measure high pressure line values. For the purpose of analyzing the regulated gasses produce by the diesel engine, a Horiba Mexa 7170 D Gas Analyzer was used. Figure 1 illustrates the schematic diagram for the engine instrumentation [11]. The test bed operating using multiple fuels has been adapted for the purpose of the present work, allowing the engine to be alternatively fueled with tested fuels, i.e. Diesel and Biodiesel B20. The engine was initially fuelled with Diesel fuel until it achieved engine operation stability. All tests were done with Diesel fuel in order to provide the baseline data and then the fuel was switched to Biodiesel B20. Before stopping the test engine after each test with Biodiesel fuel, the engine was switched back to Diesel fuel operation until all the Biodiesel based blend was purged from the fuel lines, injection pump, and injector, to avoid clogging. The performance and emissions of the engine were monitored and registered at engine speed (1400 rpm, 2000 rpm and 2400 rpm), full load, and the injection timing was experimentally determined for all engine operating conditions based on the injector needle lift curve. In-cylinder pressure data were averaged over 200 consecutive engine cycles. The large number of cycles was to cancel out the random noise. The performance and emissions results were acquired from the average of three stable and continuously measured values.

Table 1. Engine specifications used in the test.

Tractor Diesel engine	4 stroke, vertical cylinder Diesel
No. of cylinder	4 in line
Bore x stroke (mm)	102 x 115
Displacement (cm^3)	3759
Combustion system	Direct injection (DI)
Maximum torque (Nm) @1400rpm	228
Max Rated output(kW) @2400rpm	50
Compression ratio	17.6

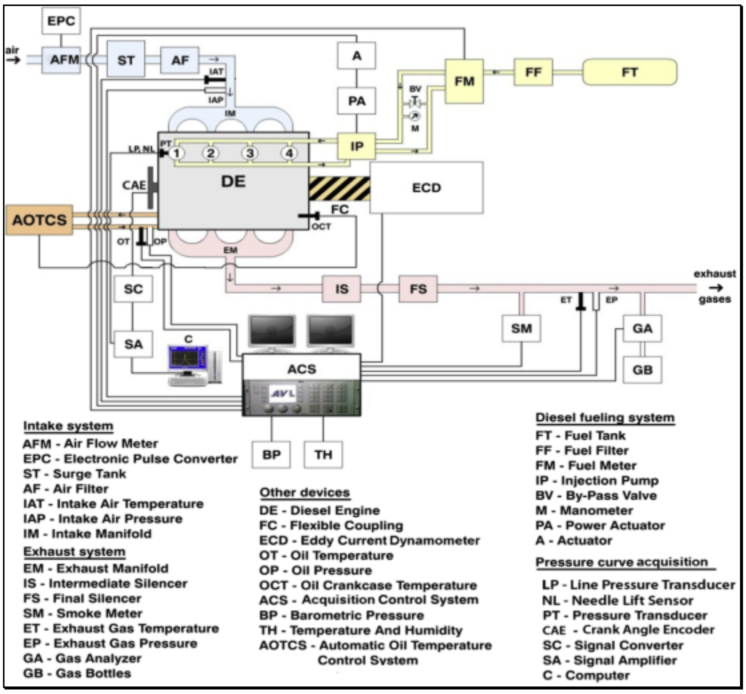

Fig. 1. Schematic diagram of the engine setup

3 Simulation Procedures

In the present work, the simulation model was created using the AVL BOOST simulation program in order to develop an analysis regarding engine operation and performances under the AVL- MCC combustion model and the Woschni 1990 heat transfer model. The chemical and physical properties of Diesel fuel are provided by the AVL Boost program, whereas for Biodiesel B20 they have been implemented to the program by the authors of this paper. This represents one of the main contributions of the added by the authors of the paper. The engine calibration parameters and cylinder processes' simulation were described by using code v2013.2 (AVL BOOST Theory and AVL BOOST Users Guide). Hence, the engine components, such as the intake and exhaust manifolds, the cylinders geometry, the air filter, the system boundaries, the catalyst were implemented in the Boost interface based on the real values which were taken from the engine used in this study, that have been modeled in [11]. All the components were chosen are linked together by pipes as shown Figure 2.

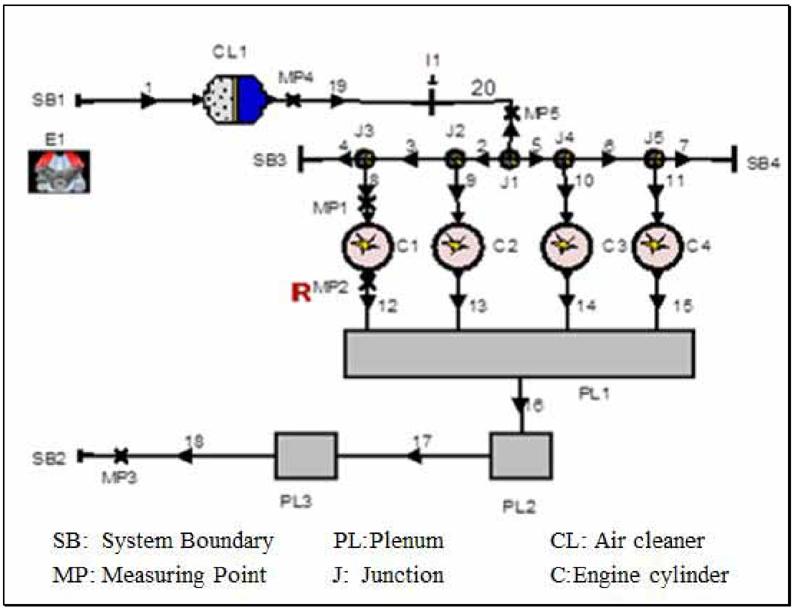

Fig. 2. Schematic of the engine symbolic model (AVL BOOST Theory and AVL BOOST Users Guide)

The Start and the rate of fuel injection, mass flow rate of air and fuel were experimentally measured and implemented in the AVL BOOST program for every specified engine speed and test fuels at full load. A group of parameters related to performance, combustion and emissions was changed in this visual manner, in order to fit the output experimental data with the simulation results. Hence, many runs of the program were repeated for the accurate determination of the combustion model's parameters. The calibration parameter values were chosen considering the AVL- MCC combustion model and the Woschni 1990 heat transfer model for which the operating data on injection and combustion characteristics would provide acceptable relative errors. These parameter values are listed in table 2 for Diesel and Biodiesel B20 fuels at full load and variety speeds.

Table 2. Calibration parameter values for diesel and biodiesel B20

Parameter	Diesel(D), Biodiesel (B20) at full load					
	1400 rpm		2000 rpm		2400 rpm	
	D	B20	D	B20	D	B20
Number of injector holes (-)	5					
Hole diameter (mm)	0.24					
Discharge coefficient(DisC) (-)	0.7					
Rail pressure (RaiP) (bar)	350					

Injection delay calibration factor (IgnDel) (-)	0.45	0.30	0.72	0.30	0.72	0.43
Combustion parameter (ComPar) (-)	1.3	1.18	1.32	1.25	1.38	1.50
Turbulence parameter (TurPar)(-)	1					
Dissipation parameter (DisPar)(-)	1.2	1.2	1	1	1	0.8
Premixed combustion parameter (PremixPar) (-)	0.5	0.18	0.21	1.2	0.23	1.2
NOx kinetic multiplier (NO KM) (-)	1.79	1.7	1.62	1.57	1.62	1.6
NOx post processing multiplier (NO PM)(-)	0.21	0.195	0.16	0.16	0.160	0.30
CO kinetic multiplier (COKM) (-)	0.026	0.0169	0.028	0.01	0.03	0.02
EGR parameter (EGRPar) (-)	1					
Evaporation Parameter (EvaPar) (-)	0.70353					

Computer output (effective power, effective torque, BSFC, cylinder pressure, cylinder temperature, NOx, CO, cylinder temperature, the rate of heat release etc.) is traditionally provided in the form of numbers, and analysis graphs are normally created after the computation process. The outcome of this modeling work was validated against the experimental data as discussed in Section 2.

4 Results and discussion

A simulation model was built in AVL Boost to investigate the effect of Biodiesel B20 fuel on engine performance and exhaust gas emission. The results were divided in two groups: first group compares the numerical results with the experimental results to test the usefulness of the model. The second group presents the effect of Biodiesel B20 on the brake specific fuel consumption, Nitrogen oxide (NOx), cylinder temperature and rate of heat release. All data were taken at different engine speeds (1400 rpm, 2000 rpm, and 2400rpm), at full applied loads and fuel supplies of pure Diesel and B20.

4.1 Cylinder pressure

The variations of cylinder pressure in respect to the crank angle, experimental and simulation for Diesel and Biodiesel B20 at varied engine speeds and full load operation are given in Figures (3- 5). Good agreement between the pressure traces, experimental and simulation, for all engines speeds and test fuels , has been observed. The relative variation between the experimental and numerical in maximum cylinder pressure for Diesel fuel at engine speeds of 1400 rpm, 2000 rpm and 2400 rpm were

0.61 %, 1.75% and 1.108 % respectively, whereas for Biodiesel B20 they were 2.51 %, 3.1%, and 2.61%, respectively.

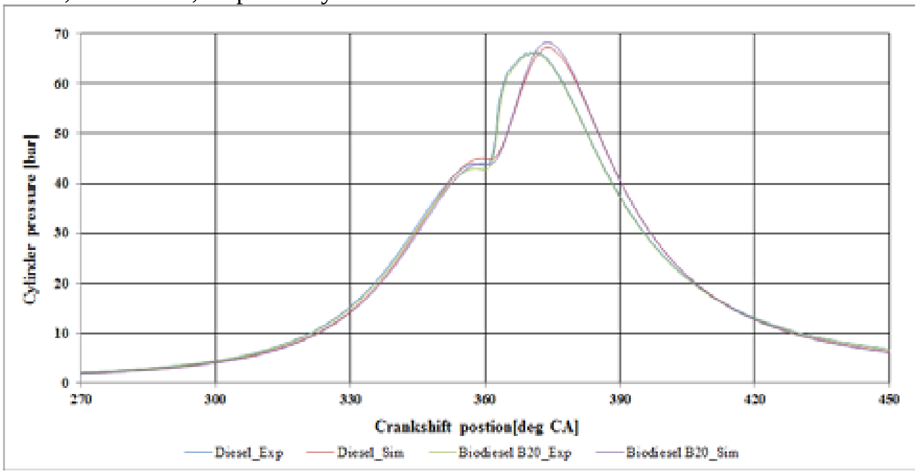

Fig. 3. Comparison between experimental and simulation pressure traces for full load, 1400 rpm speed.

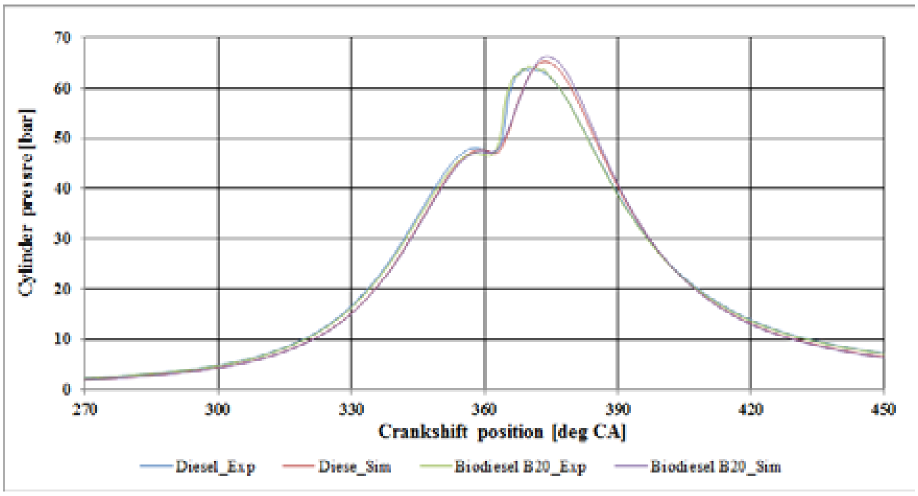

Fig. 4. Comparison between experimental and simulation pressure traces for full load, 2000 rpm speed.

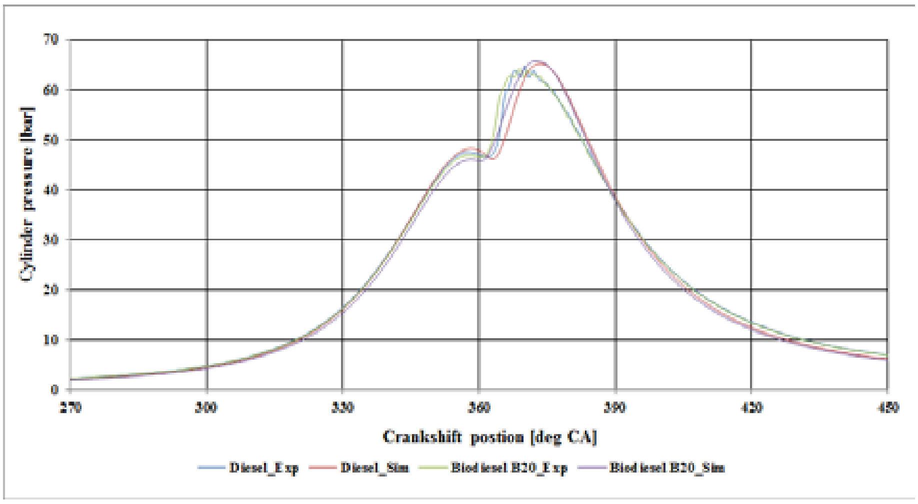

Fig. 5. Comparison between experimental and simulation pressure traces for full load, 2400 rpm speed.

4.2 Engine performance

The engine performance, efficiency indicators and exhaust gas emissions at engine speeds (1400 rpm, 2000 rpm, and 2400 rpm) with full load for Diesel and B20 fuels, simulation results with relative variations concerning the experimental result are presented in Table 3. The oxygen content 10-12% of Biodiesel B20 with higher cetane number contributed in improved the combustion process resulting in a reduction in CO emission. Moreover, Biodiesel B20 has higher density and lower heating value than Diesel fuel resulting in increased fuel consumption to produce the same output power. The brake thermal efficiency (BTE) was decreased with B20 compared to Diesel fuel. Overall operation conditions; Biodiesel B20 produced lower effective power (P_e) and effective torque (T_e). Hence, it is concluded that the simulation model carried out using the AVL Boost program has a wide scope for any microanalysis of combustion characteristics, engine performance and exhaust gas emissions. The results of the present models are in good agreement with the experimental results.

Table 3. Comparison between simulation and experimental results at (1400, 2000, 2400 rpm) and full load for Diesel and Biodiesel B20

					kWh]				h]		]	
												1400 rpm
	Num	Exp	N um	Ex p	Nu m	Exp	Nu m	Ex p	Nu m	E xp	Nu m	E xp
Di- esel	22 1.5	22 4.2	32. 5	32. 87	239. 29	236. 38	35.9 9	36. 43	1048.49	94 4	839 4.	8 66
St. dev	1.208%		1.125%		-1.269%		1.208%		3.097%		-3.070%	
B20	21 8.1	21 6.4	32. 17	31. 73	250. 96	254. 96	33.8	33. 3	1060	10 17	642	6 39
St. dev	-0.785%		-1.386%		1.568%		-1.519%		-4.228%		-0.469%	
												2000 rpm
	Nu m	Ex p	N um	Ex p	Nu m	Exp	Nu m	Ex p	Nu m	E xp	Nu m	E xp
Di- esel	202.8	20 4.7	42. 5	42.88	249. 53	247. 2	34.5 2	34. 84	697. 78	73 9	363	4 46
St. dev	0.493%		0.886%		-0.942		0.918%		5.57%		-4.310%	
B20	20 4.7	20 3.9	42. 86	42. 7	252. 95	253. 80	34.46	34. 34	755	78 9	358	3 88
St. dev	-0.392%		-0.375%		0.337%		-0.332%		4.309%		7.732%	
												2400 rpm
	Nu m	Ex p	N um	Ex p	Nu m	Exp	Nu m	Ex p	Nu m	E xp	Nu m	Exp
Di- esel	19 0. 38	188. 5	47. 9	47. 37	252.45	255.014	34.1 1	33. 77	624.91	64 0	470	6 12
St. dev	-0.997%		-1.119%		1.005%		-1.007%		2.357%		-3.070	
B20	188.9	186.3	47.47	46.83	257.89	261. 798	34.619	34. 188	713	727	550	5 39
St. dev	-1.395		-1.367%		1.493%		-1.261%		1.926%		-2.041%	

4.3 Brake Specific Fuel Consumption (BSFC)

The variation of brake specific fuel consumption (BSFC) with respect to engine speeds, at full load when fueled with pure Diesel and B20, predicted by the experimental and simulation model is given in Figure 6. From this figure, it can be observed that the BSFC is lower at low engine speeds and increases slightly by increasing the engine speed for the both tested fuel. The BSFC was higher with Biodiesel B20 than

Diesel fuel overall operation conditions. The explanation of this increase in BSFC is due to the fact that Biodiesel has lower calorific value and higher density than Diesel fuel resulting in increased fuel consumption to produce the same engine output. This increasing in BSFC for Biodiesel is in agreement with existing literature [12, 1]. The simulation results related to BSFC are in accordance with the experimental dada and similar curve trends can be observed.

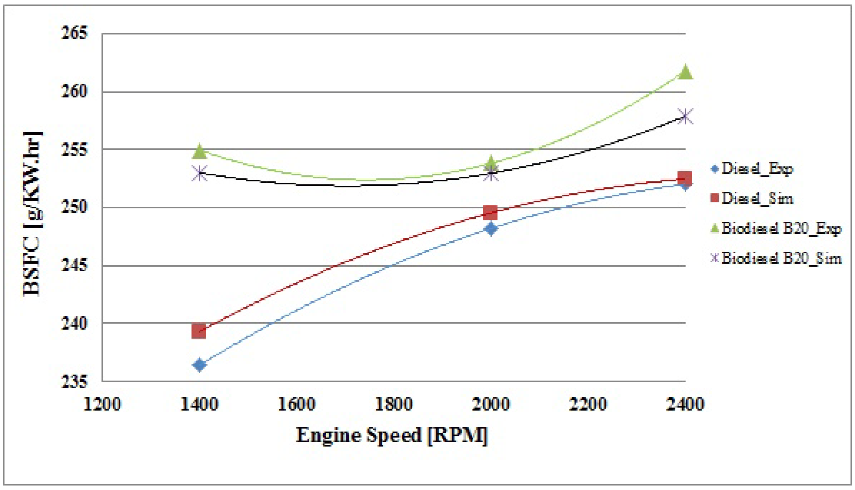

Fig. 6. Brake specific fuel consumption vs. engine speed at full load

4.4 Nitrogen Oxides (NOx)

The production of NOx emissions is influenced by the in-cylinder temperature, availability of oxygen (O_2) and residence time. Figure 7 presents the variation of nitrogen oxides (NOx) with respect to engine speeds when fuelled with Diesel and Biodiesel B20 at full load. Overall operation conditions, the Biodiesel B20 produced higher NOx emissions compared to Diesel fuel. The NOx emissions increased by 1.12%, 7.578% and 12.354% at engine speeds of 1400 rpm, 2000 rpm, and 2400 rpm respectively, over Diesel fuel. This may be due to decreased radiation heat transfer due to lower soot concentration and highest oxygen content of Biodiesel can be associated with higher post flame temperature, explaining higher NOx emission. Relative to the experimental, the simulation results were in good agreement and similar curve trends can be observed.

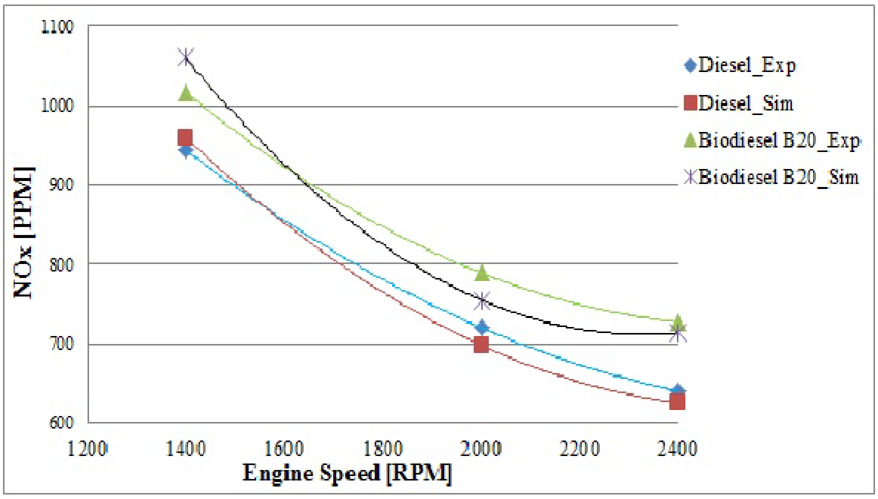

Fig. 7. Nitrogen Oxides (NOx) vs. engine speed at full load

4.5 Cylinder Temperature

The variation of cylinder temperature respect to the crank angle at engine speed 2400 rpm, 2000 rpm and 1400 rpm under full load operation for Diesel and B20 shown in figure 8. Biodiesel B20 produced higher temperature overall operation conditions compared to Diesel fuel. The higher cetane number of the B20 fuel and present the oxygen during the combustion resulting in a complete combustion, this may be the main explanations for the increase in the cylinder temperature.

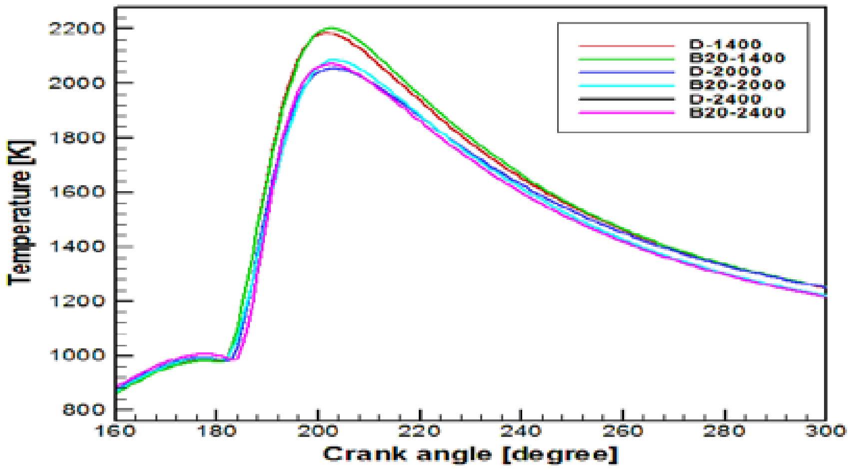

Fig. 8. Temperature as a function of crank angle during combustion

4.6 Rate heat release

Figure 9 compares the apparent rates of heat release for Diesel and Biodiesel B20 at the engine speed of 2400 rpm, 2000 rpm and 1400 rpm at full engine load predicted by the simulation model. At lower engine speed the rate of heat release pattern is similar for Diesel and Biodiesel B20, while at higher engine speed Biodiesel B20 has lower rate of heat release during the mixing controlled combustion. This is probably due to the fact that Biodiesel B20 has lower volatility and higher viscosity. However, figure 9 reveals that the Biodiesel B20 produces lower rate of heat release for all engine speeds and this may be attributed to the fact that Biodiesel B20 has lower heating value compared to Diesel fuel.

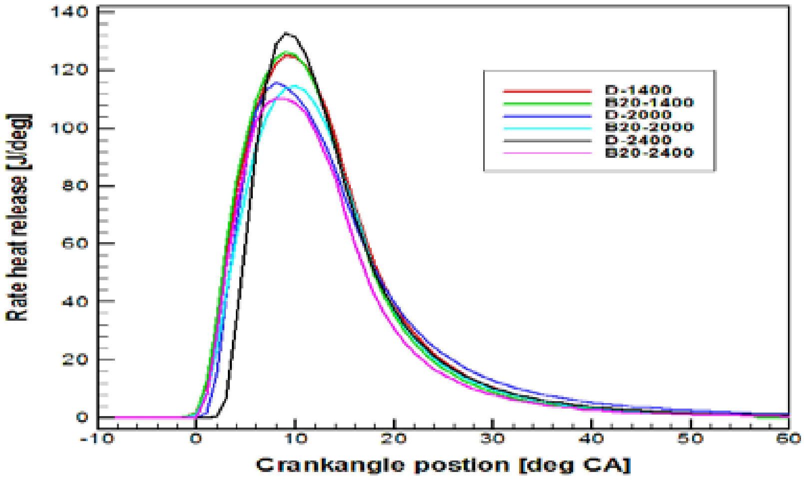

Fig. 9. Rate Heat release as a function of crank angle during combustion

5 Conclusion

A comprehensive simulation model created using AVL Boost was developed to predict the combustion characteristics, engine performance, and exhaust gas emission. The simulation results were validated against experimental results. Four cylinders, four strokes, naturally- aspirated and direct injection Diesel engine was used in this study. The results were collected at different engine speeds (1400 rpm, 2000 rpm, and 2400 rpm and full load conditions fueled with pure Diesel and Biodiesel B20. This model predicted the engine performance characteristics and exhaust gas emissions, and it was found that the model has been successful in correctly predicting the trend for effective torque, effective power, brake thermal efficiency, BSFC, and NOx emissions. The rate of heat release is found lower for B20 due to lower heating value. The BSFC was found to be higher for B20 at all engine speeds when compared to that of Diesel fuel, due to the fact that Biodiesel has a lower heating value and higher density than that of Diesel. A slight increase in NOx emissions was observed when using Biodiesel B20 fuel.

Acknowledgements

The authors of this paper acknowledge the AVL Advanced Simulation Technologies team for the significant support they have offered in performing the simulation part of this work. One of author (Mohanad ALDHAIDHAWI) thanks the Iraqi government for financial support.

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