Modeling of Single Cylinder Compression Ignition Engine by Using GT-Power Software and Performance Analysis

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Abstract

The combustion characteristics, performance, and emission analysis of a single cylinder compression ignition engine are investigated in this paper using GT-Power software. For result analysis four cases of engine rotation are considered here in this study such as 2400,3000,3600,4000 RPM. Inlet and outlet conditions are assumed to be same for modelling. The input values of pressure and temperature at inlet conditions have been assumed as output values from the turbocharger because this engine model is designed as a turbocharger-less model. Fuel mass injection, start of injection, start of combustion, injection timing, combustion duration, and mass fraction burned in premixed and diffusion combustion had taken as a fixed value. Different sub-models such as inlet environment, intake runner, intake port, inlet valve, fuel injection, cylinder, crank train, outlet environment, exhaust valve, port and runner are connected together for analysis. Some parameters are taken from GT-suite template library. After modelling simulation run for 10 cylces and the results obtained are, if the rpm goes on increasing the cylinder pressure, cumulative heat release rate, engine torque, Brake power, brake mean effective pressure, concentration of NOx in ppm increases and hydrogen concentration and CO concentration in ppm decreases.

Keywords
Compression Ignition Engine, Combustion, Performance, GT-Power and Brake Power.

1. Introduction
Diesel engine is also known as compression ignition engine (CI Engine) has wide application in the automobile, agricultural, industrial and transportation sectors due to its suitable properties such as reliability, low cost, high thermal efficiency, no need of spark plug to start the ignition of the fuel, no require throttle control to supply air to engine, load control is possible by varying fuel injection, high density of fuel gives more energy per gallon, no pumping losses, heterogeneous combustion in diesel engine provide lean air fuel ratio etc. Emission of harmful gases is the major challenge in diesel engine due to this researcher try to find alternate fuel Springer (2022).

Diesel fuel in CI Engines is useful due to ignition take place without the spark. Because of the higher efficiency of CI Engines compare to SI Engines makes them desirable to use in transportation even though increased prices. Combustion of diesel fuel in CI Engine emits some harmful gases such as, (HC) hydrocarbons, (PM) particulate matter, (NO_x) nitrogen oxides, and (CO) carbon monoxide which affect the environmental pollution. Out of these emissions black smoke and (NO_x) oxides of nitrogen are harmful and disgusting. Worldwide research is going on to reduce the (NO_x) oxides of nitrogen and smoke exhaust emissions from Diesel (CI) Engine. Reduction in both emissions concurrently is become difficult Springer (2020).

Because of their superior efficiency, Diesel (CI) engines are generally used in high load capacity vehicles used for transportation. Zero, quasi, multi-zone, as well as multi-dimensional models these are the four types of engine cycle simulation models Gudimetla.(2019). Zero-dimensional simulation model is having capacity to predict engine performance accurately; but the prediction of emissions not reliably. Due to their improved accuracy, multi-dimensional models have recently become more popular in combustion engine simulations Gudimetla. (2018). However, one difficulty with these models is that they require precise experimental data and a lot of computing power to solve Gudimetla. (2019). In this study one (1D)-dimensional model was selected for engine modelling and cycle simulation due to some limitations of the multi and zero-dimensional model. GT-power is working as best tool for prediction and calibration of engine emissions, combustions and performances. GT-power is capable of predicting both the transient and steady state behavior of the engine various system. Single-valued, crank-angle, or time-resolved quantities are the outputs. The software includes a post-processing tool for analyzing and plotting the various data Gudimetla. (2019).

In this study, the one thermodynamic model for a single (one)-cylinder four-stroke diesel (CI) engine running on commercially available diesel fuel was created using commercial GT-power software. A thorough investigation was conducted with the goal of characterizing and optimizing the various performance and combustion parameters for the purpose of the engine. The main objective of this paper is to investigate the effect of engine RPM variation on the engine performance, combustion and emission characteristics.

Problem statement is modeling of single cylinder compression ignition engine by using GT-Power software and performance analysis for further research work and validation of model with experimental data.

1.1 Objectives

The main objectives of this paper are as follows-

1) To design single cylinder compression ignition model on GT-Power software.
2) To run this model for different cases such as engine speed variation.
3) To validate the simulation results along with experimentation results.
4) To do the analysis of the design model for performance, emissions and combustion characteristics.

2. Literature Review

Gudimetla.(2019) was developed a model on GT-Power software for performance and combustion characteristics of diesel engine. They performed simulation and run at engine speed 800rpm to 2500rpm. The injection timing varied from 15^0 crank angle bTDC to 15^0 crank angle aTDC. They were changed compression ratio from 13 to 25. They found optimum engine performance at engine speed 1700rpm and compression ratio 20 and injection timing 10^0 crank angle bTDC. Wagh and Chougule (2019) was modeled internal combustion engine model on the GT-Power software for further research work. They developed this model for their student in laboratory for analysis of valve lift optimization, performance analysis, thermal analysis and engine noise analysis. They developed this model for test rig of diesel engine available in their laboratory. Galal (2002) was modeled single cylinder diesel engine mode for performance analysis by using GT-SUITE 6.2 software. They found out the performance results by analytical and simulation method. They developed 407cc engine model and concluded that brake power and indicated power is highest at 3000rpm.

3. Methods

The methods for modeling for result analysis used in this paper are first one is simulation on GT-Power software and experimentation on engine test rig available in the laboratory. The modeling was done on a Four-stroke diesel engine with a diameter of 83 mm, a stroke of 84 mm, connecting rod length 141mm , top dead centre clearance height 0.5mm and a compression ratio of 16.5.

4. Data Collection

4.1 Engine input data for modeling

Some other input parameters used as an input listed in the following Table 1. **[Source-GT Suite library, Experimental setup available in Lab]**

Table 1. Input parameters provided to run the simulations

Engine Parameters	Units	Values
Type of Engine		4-stroke
Load /Speed Specification		Speed
Speed of the Engine	RPM	[RPM]
Engine Friction Object (FMEP)	bar	Friction
Cycle Start (CA at IVC)		-95
Bore(B)	mm	83
Stroke(S)	mm	84
Length of Connecting Rod	mm	141
Compression Ratio(r_c)		16.5
Clearance Height at TDC	mm	0.5
Inlet Conditions		
Pressure (Absolute)	bar	2.4
Temperature	K	350
Composition		Air
Outlet Conditions		
Pressure (Absolute)	bar	2.4
Temperature	K	350
Composition		Air
Injected Mass	mg	80
Injection Timing	deg	-5
Fluid Object		diesel2-combust
Injected Fluid Temperature	K	300
Vaporized Fluid Fraction		0
Diameter of Nozzle Hole	mm	0.3
Number of Nozzle Holes		6
Temperature of Head	K	550
Temperature of Piston	K	590
Temperature of Cylinder	K	450
Ignition Delay	CAD	3
Premixed Fraction		0.07
Tail Fraction		0.01
Premixed Duration	CAD	2
Main Duration	CAD	35
Tail Duration	CAD	40

4.2 Used Governing Equations

The conservation of momentum, continuity, and energy equations were solved by using this model. A one-dimensional model was created using the various equations; the whole system was divided into number of small volumes in the developed model. A volume is marked to each flow split, and each pipe is divided into one or more small volumes. The volumes are connected by different boundaries. Following three equations are the basic equations for modeling. In these equations, first equation represents continuity equation, second equation represents as an energy equation and third equation represent as a momentum equation Nabi Rasul gudimetla. (2019)

$$\frac{dm}{dt} = \sum_{boundaries} \dot{m} \quad (1)$$

$$\frac{d(me)}{dt} = -p\frac{dV}{dt} + \sum(\dot{m}H) - h\,As\,(Tfluid - TWall) \quad (2)$$

$$\frac{d\dot{m}}{dt} = \frac{dpA + \sum_{boundaries}(\dot{m}u) \ -4Cf\frac{\rho u|u|\,dxA}{2D} - Kp(\frac{1}{2}\rho u|u|)A}{dx} \quad (3)$$

The injector's delivery rate can be calculated using Equation (4) Nabi Rasul gudimetla. (2019)

$$\dot{m}_{Delivery} = \eta_V \rho_{ref} N V_D (\frac{F}{A}) \frac{6}{(n)(pulse\ width)} \quad (4)$$

The Woschni's equation (5) was used to calculate convective heat transfer.

$$h_c = \frac{K_1 P^{0.8} W^{0.8}}{B^{0.2} T K_2} \quad (5)$$

The Wiebe function (6) was used to calculate combustion burn rate which is considered as function of (CA) crank angle Nabi Rasul gudimetla. (2019)

$$Combustion\ (\theta) = (CE)[1 - e^{(-WC)(\theta - SOC)^{(E+1)}}] \quad (6)$$

Equation (7) was used to calculate the specified thermal efficiency Nabi Rasul gudimetla. (2019)

$$\eta_i = \frac{Pi}{\dot{m}f \times lower\ heating\ value} \quad (7)$$

Equation (8) was used to calculate the $IMEP = \frac{Ib}{Displacement\ volume}$ (8)

Specific fuel consumption (Indicated) (ISFC) was calculated by using Equation (9)

$$ISFC = \frac{\dot{m}f}{Pi} \quad (9)$$

The FMEP was calculated using equation (10) Nabi Rasul gudimetla. (2019)

$$FMEP = 0.4 + (0.005*Pmax) + (0.09*Speed\ mp) + (0.009*Speed^2 mp) \quad (10)$$

In the same way, the performance parameters such as brake mean effective pressure (BMEP), thermal efficiency and specific fuel consumption (BSFC) are computed in the following equations applying brake power and torque. The model was built around a four-stroke, diesel engine (CI) with a diameter of 83 mm and a stroke of 84 mm and a compression ratio of 16.5:1. Engine cylinder, Inlet environment, injection nozzle, intake valve, runner, outlet environment, exhaust valve, intake, and exhaust port, engine were the major components of the model. Pipes are used to simulate the intake and exhaust ports of engine cylinders geometrically Nabi. (2019) Fuel qualities in both the vapour and liquid phases are required by the model. The GT-Power template fuel library contains the fuel attributes (Figure 1 and figure 2).

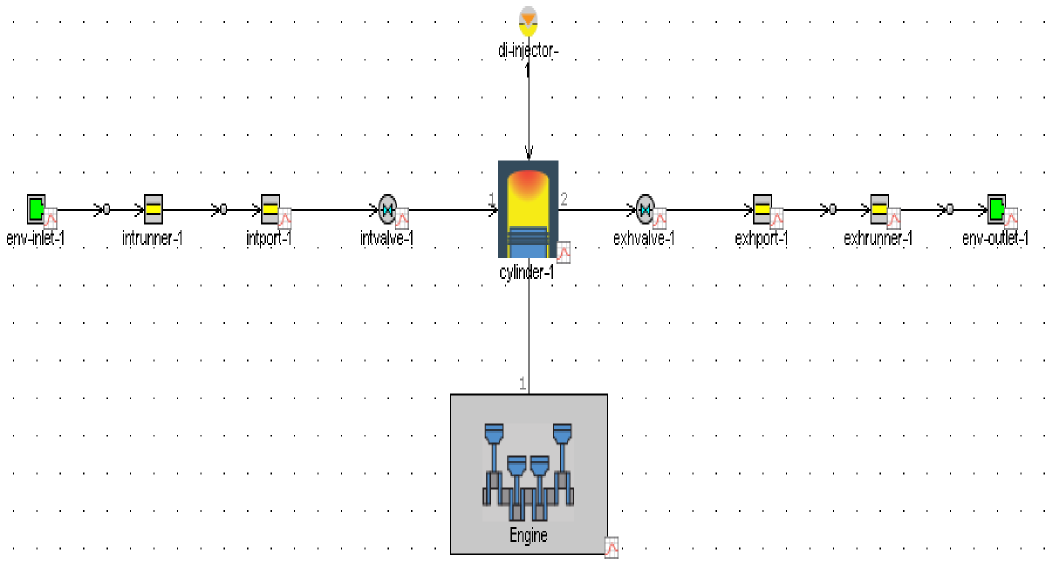


Figure 1. Single cylinder CI engine simulation model prepared on GT-Power

Figure 1. Shows simulation model prepared by using GT-power software and it consists of different sub models such as environment inlet, inlet runner, inlet port, inlet valve, cylinder, diesel injector, exhaust valve, exhaust port, exhaust runner and environment outlet.

5. Results and Discussion

5.1 Numerical Results

Below Table 2 shows the numerical results obtained from the simulation and experimentation performed on single cylinder compression ignition engine. The results for case 1 validation are given in the Table 2. The values of brake power, brake torque, brake efficiency and BSFC are given in the Table 2 at 2400RPM. After validation of results for case 1 simulation was continued for other cases.

Table 2. Simulation and experimentation results for different cases

Simulation Data					
CASE	RPM	Brake Torque [N-m]	Brake Power [kW]	Brake Efficiency [%]	BSFC [g/kW-h]
1	2400	78.1	19.6	28.5	293.5
2	3000	79.2	24.9	28.9	289.4
3	3600	80.8	30.5	29.5	283.7
4	4200	82.4	36.2	30.1	278.3
Experimental Data					
1	2400	78	16.78	28.83	294.02

5.2 Graphical Results

5.2.1. Engine performance, combustion, and emission factors are all affected by engine speed.

Engine speed has an effect on engine combustion, as seen in Figure 2(a). Cylinder pressure increases as engine speed increases. Figure 2(b) shows experimental P-Theta diagram for different loading conditions on engine with constant engine speed. From figure it is observed that pressure increases along with increased load on the engine at constant engine speed. Validation of simulation engine model was completed after comparing the engine simulation and experimentation results. Maximum cylinder pressure at 2400 rpm is around 130 bar from simulation results and 120 bar in experimentation results. There was an error of 10bar found in simulation results means 7.6% error.

Validation was completed for case 1 single reading at 2400rpm engine speed and further simulation continued for other cases.

5.3 Proposed Improvements

To reduce the error in the results some improvement necessary while defining the input parameters. Also experimental results must be accurate for the considering as an input value. For better result turbocharger and compressor sub models can add in the model. GT-Power software has that much ability.

5.4 Validation

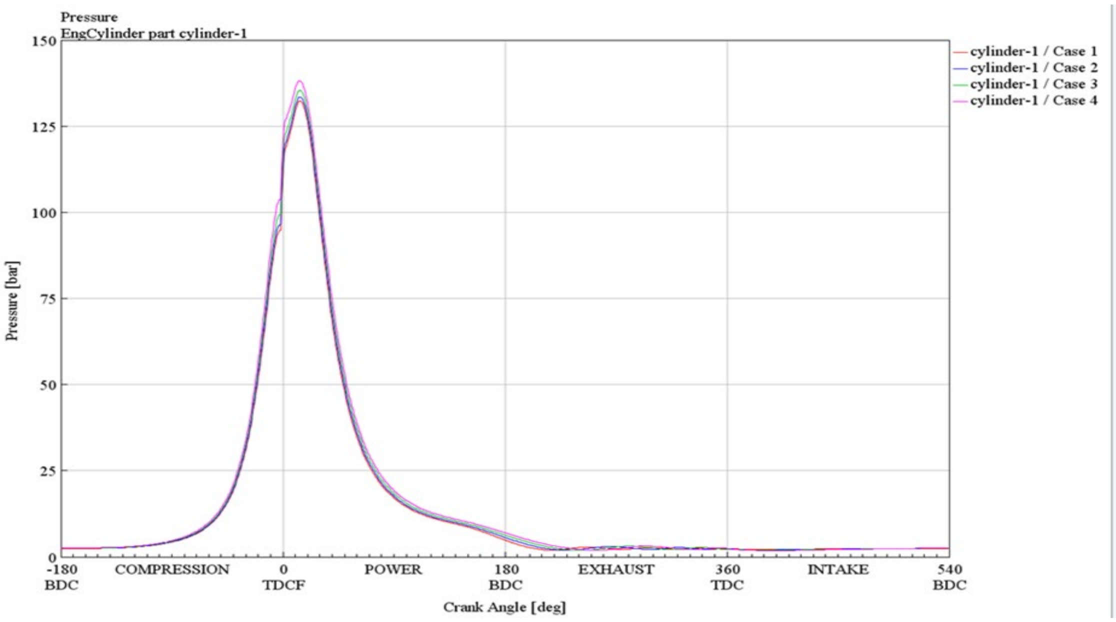


Figure 2a. Pressure –crank angle (p- Theta) diagram from simulation results

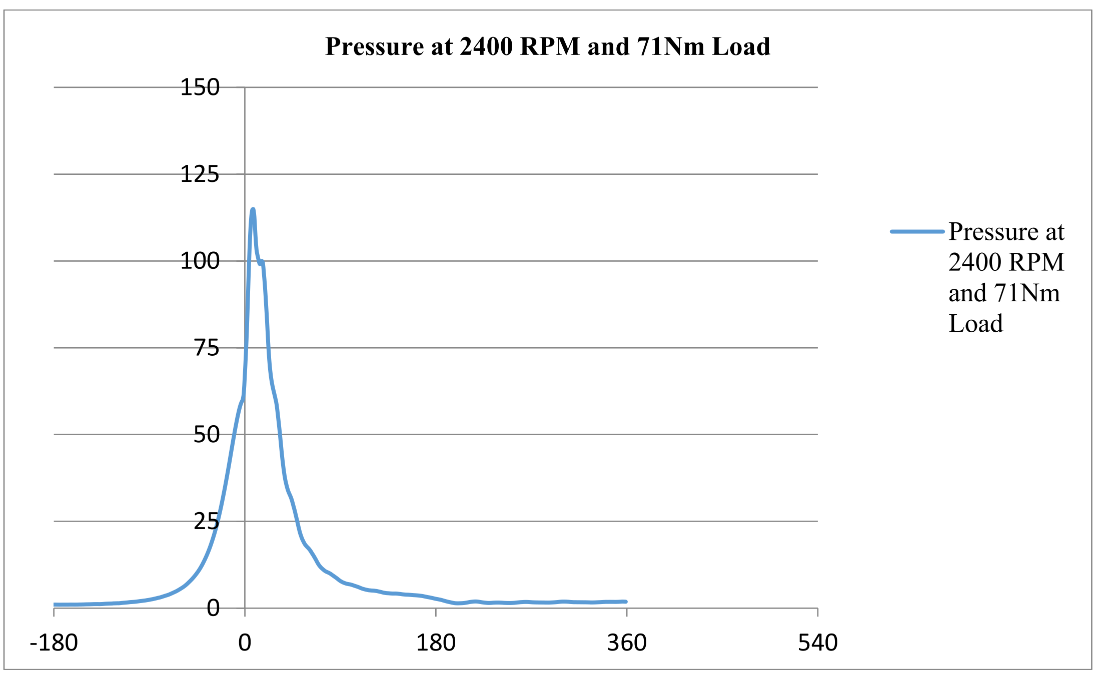


Figure 2b. Pressure (Bar) –crank angle (p- Theta) in degree diagram from experimentation result.

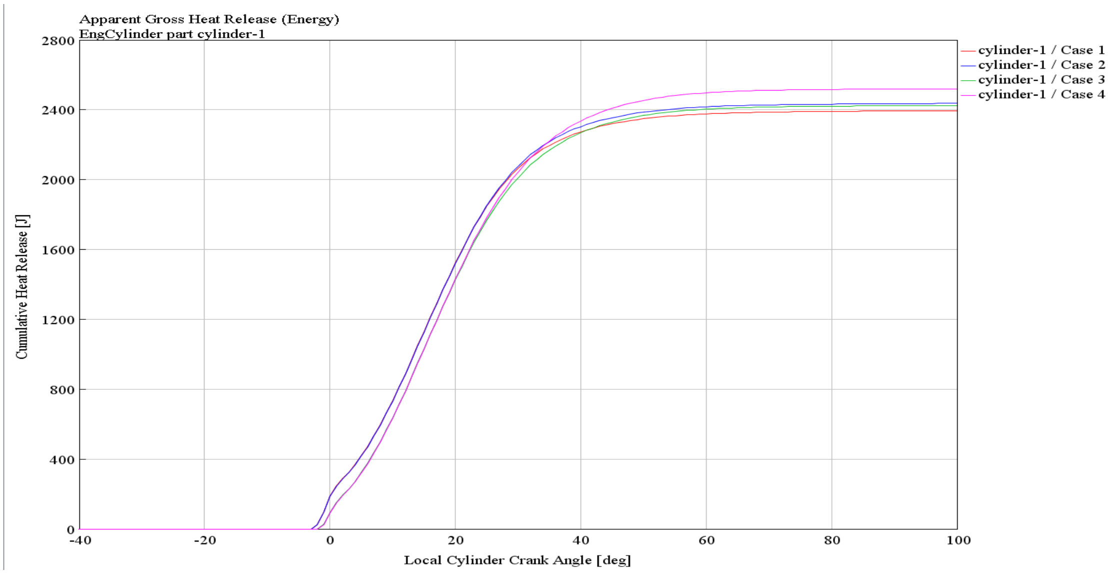


Figure 3. Cumulative heat release in (J) –crank angle (p- Theta) diagram

The cumulative heat release rate increases with engine speed, as seen in Figure 3.The heat release rate in the premixed combustion phase is highest at low speed, whereas the heat release rate in the diffusion combustion phase is lowest at low speed and highest at high speed, as illustrated in figure 4.Case 1 has a cumulative heat release rate of roughly 2355 (J) based on modeling results and 2139.74 (J) based on experimental data.

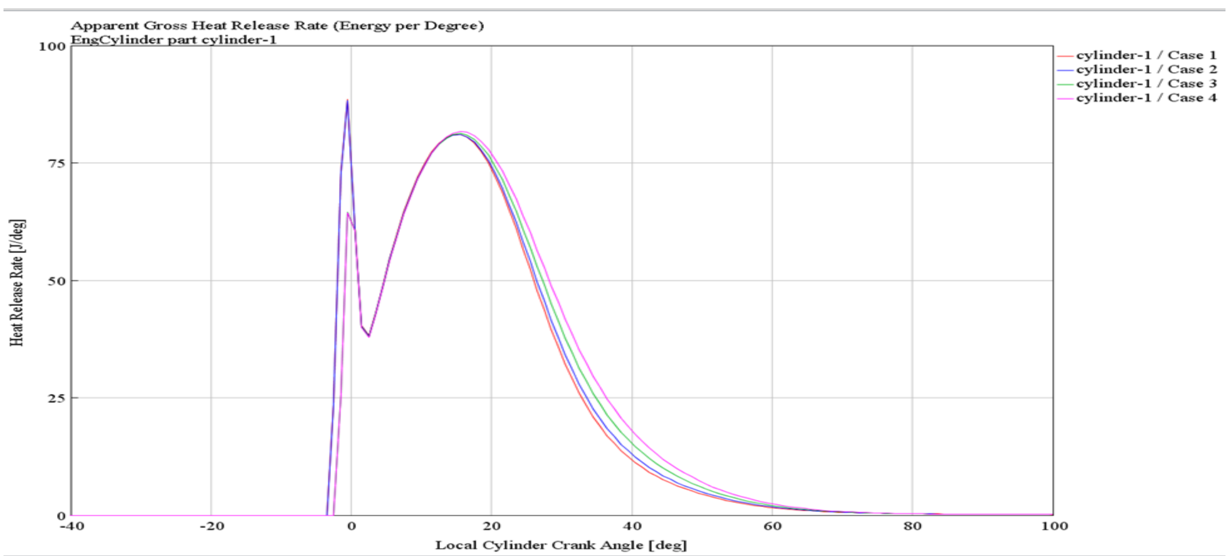
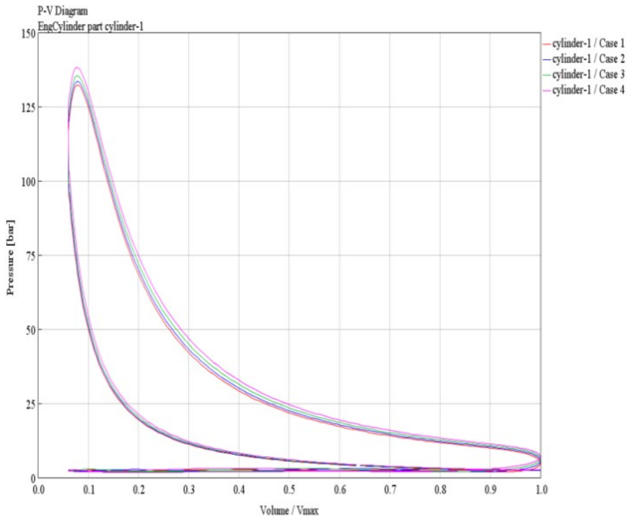


Figure 4. Heat release in (J) –crank angle (p- Theta) diagram

Figure 4 shows heat release rate diagram in joule per degree crank angle for four cases, from the simulation result value of heat release rate in premixed combustion is around 89 J/deg and value from experimental result is 95 J/ deg. GT-power software takes input values for the heat release rate in the form of fuel mass burn fraction in the premixed and diffusion combustion phase. So input given to the combustion model will give the correct results accordingly.

Figure 5 and 6 shows the P-V and T-S diagram for single cylinder compression ignition engine obtained from the simulation. From these figures (1-6), it is observed that cycle pressure and temperature increases with the engine speed.



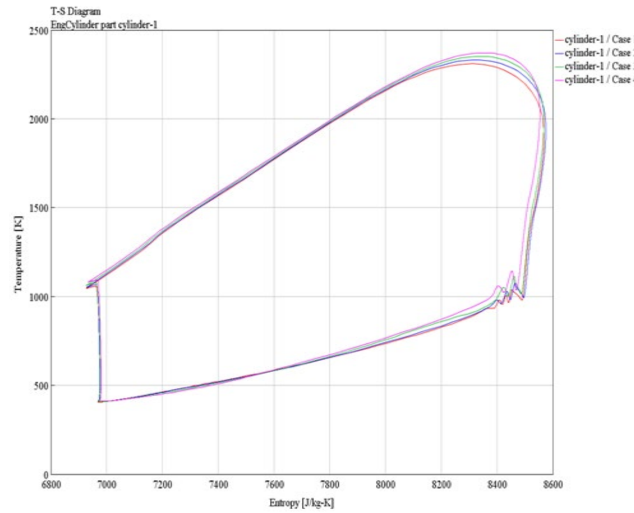


Figure 5. Pressure-Volume diagram Figure 6. Temperature (k)-Entropy (J/kg-K) diagram

Figure 7 shows that the mass burning rate in (mg/deg) with respect to crank angle (deg) did not change significantly as engine speed increased. Input values given to the combustion model in the simulation from experimental results were burning fuel mass fraction must exact values because it will affect the burn rate.

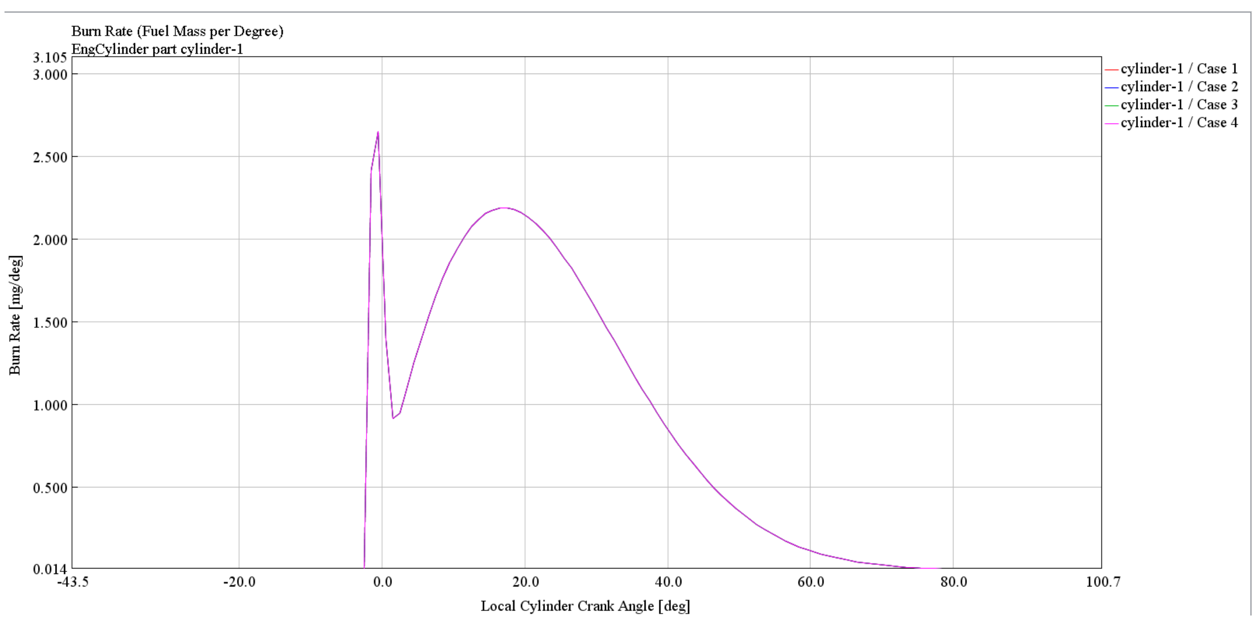


Figure 7. Mass burn rate (mg/deg)-crank angle (deg)

Figure 8 Shows the Logarithmic pressure verses volume diagram for different engine speed. From Figure 8 it is found that pressure and volume increases along with the engine speed.

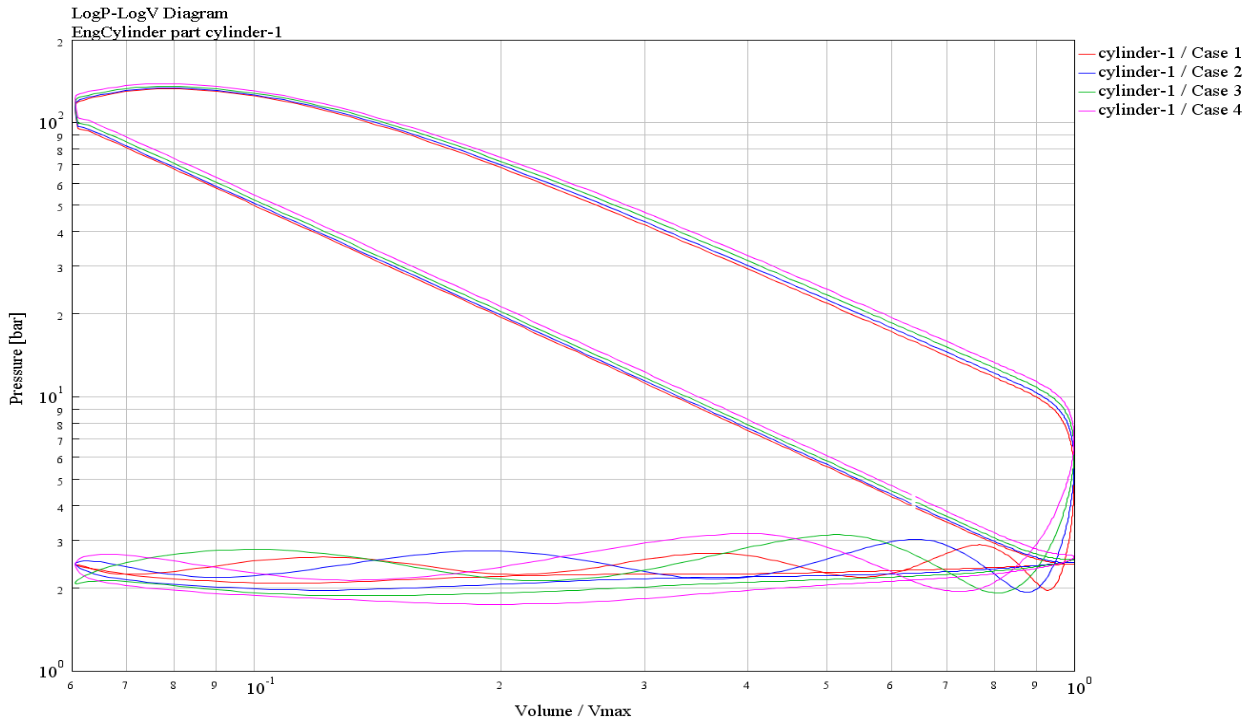


Figure 8. Log Pressure-Log Volume

Figure 9. Shows the indicated torque in Nm vs the crank angle in degrees (cylinder pressure only). The indicated torque is highest at case 4 according to the graph. It means that torque grows as engine speed increases; the higher the engine speed, the greater the torque.

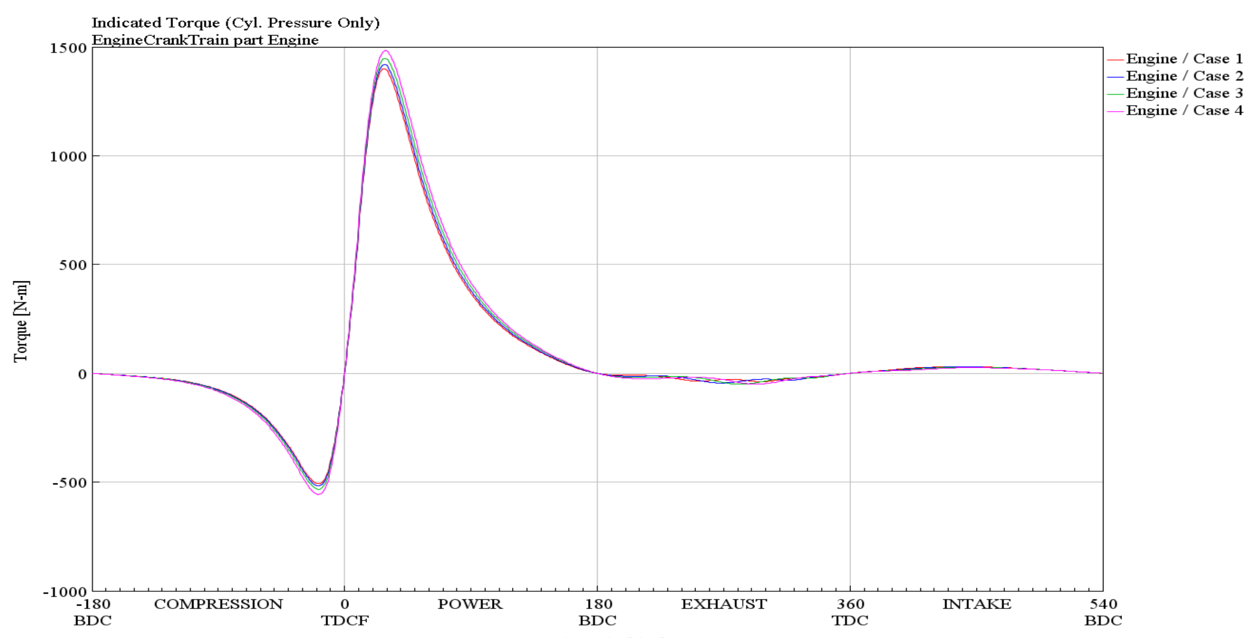
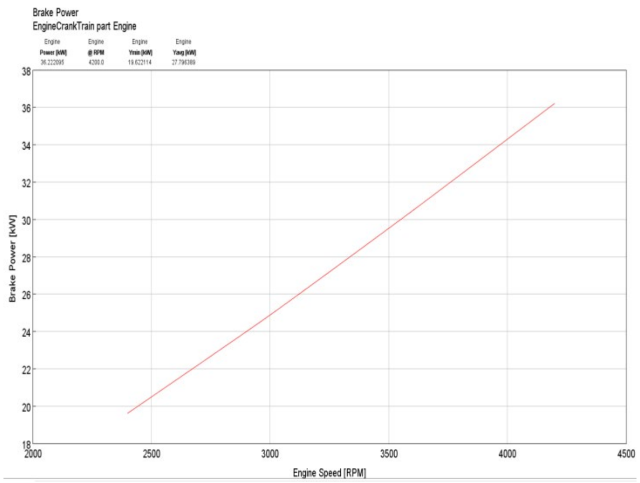


Figure 9. Indicated torque (Nm) - Crank angle in degrees

Brake power, Brake torque and brake mean effective pressure increases with respect to engine speed as indicate in Figure 10, Figure 11 and Figure 12 respectively. Because engine speed is directly proportional to the brake power and brake torque.



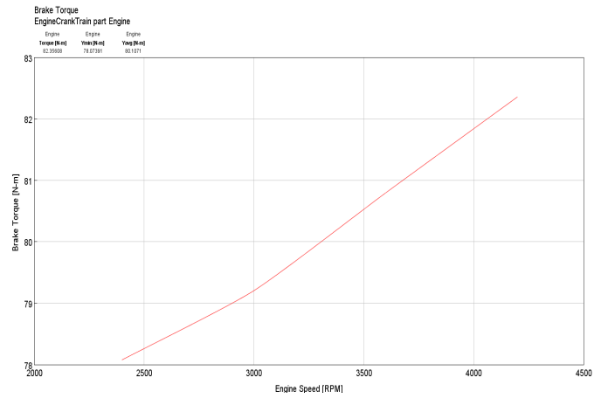


Figure 10. Brake power (KW) vs Engine speed [RPM]   Figure 11. Brake torque vs. Engine speed [RPM]

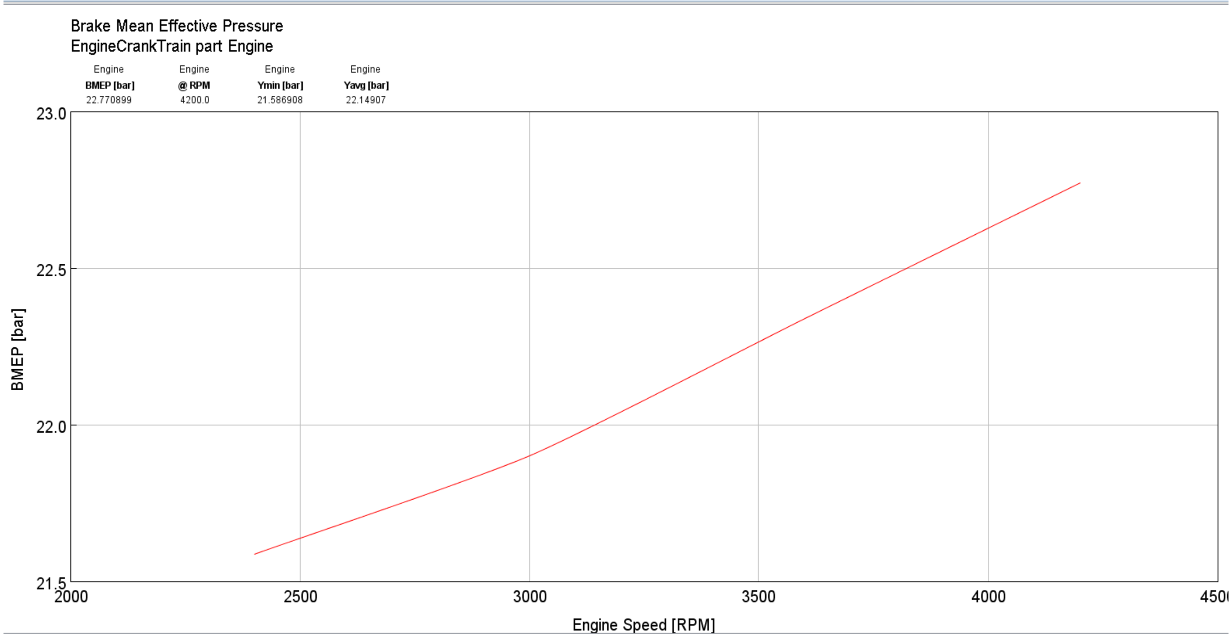


Figure 12. Brake mean effective pressure (Bar) vs. Engine speed (RPM)

Brake specific fuel consumption (g/KW-h), CO Concentration and Hydrocarbon concentration in PPM reduces with increase in engine (RPM) or speed as shown in Figure 13, Figure 14 and Figure 15 respectively. CO emissions from the diesel engine due to incomplete combustion of fuel inside the cylinder. This happens due to insufficient air supplied to the fuel combustion.

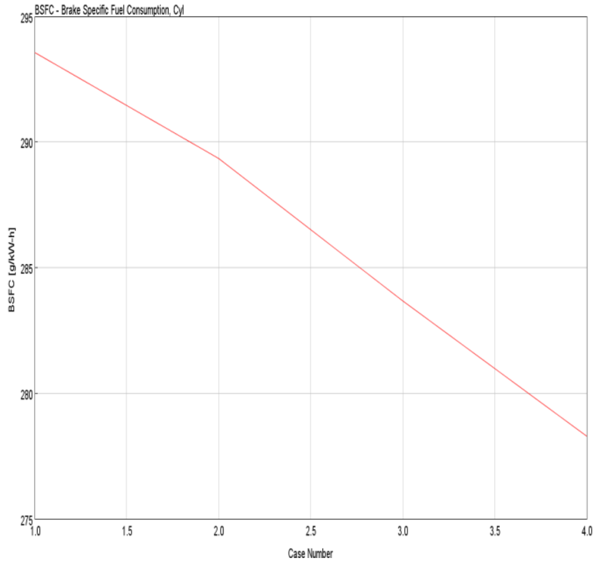


Figure 13. BSFC- Engine speed [RPM]

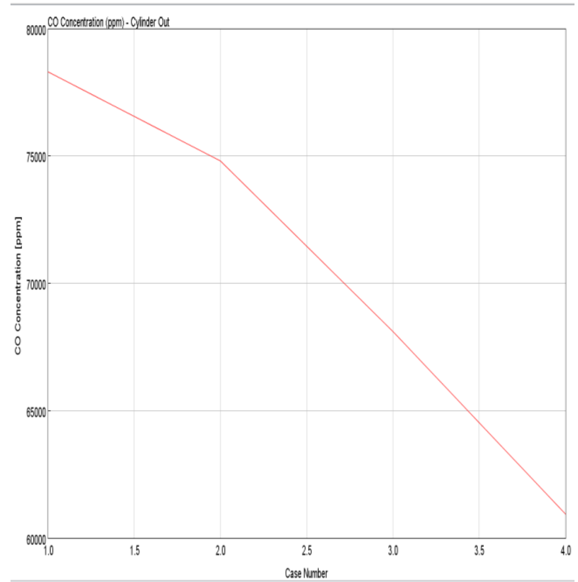


Figure 14. CO Concentration in ppm- Engine speed [RPM]

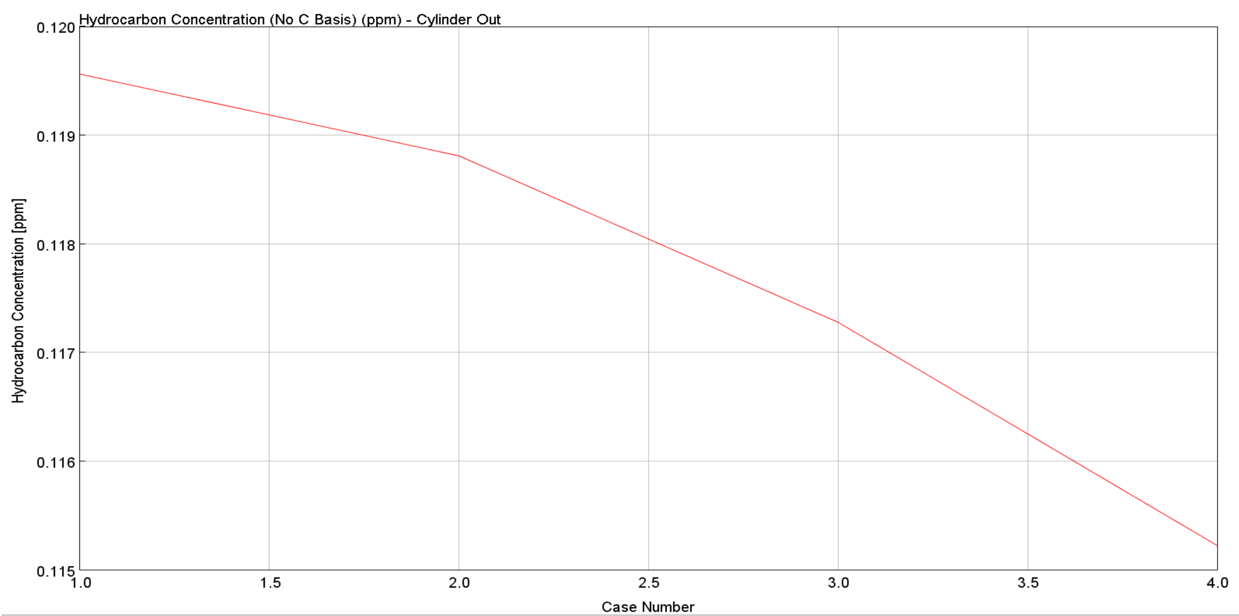


Figure 15. HC Concentration in ppm- Engine speed [RPM]

Figure 15. Shows the reduction of HC concentration along with increased engine speed this was happen due to complete combustion of fuel inside the engine. In diesel engine maximum HC concentration emits at low load and low engine rpm due to incomplete combustion of the fuel inside the cylinder. At low load and rpm engine run at lean air –fuel mixing conditions due to this required oxygen is not getting for combustion of total fuel.

6. Conclusion

GT-Power software is a powerful simulation tool for combustion, performance, and emission analysis, according to the findings of this study. The engine's performance is observed to be low at low speeds and vice versa. In comparison to a high-speed engine, low-speed emissions were higher. Effects of injection timing, fuel injection mass, premixed and diffusion fuel mixing fraction can be observed by using this software. The perfect inputs given in the simulation will lead to perfect results. This single cylinder CI Engine model is validated for further research on utilization of alcoholic fuel in CI engine. After research observed that the validated model will suitable for future research.

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