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Studies on Performance and Emission Characteristics of Compression Ignition Engine using MATLAB® and Simulink® Simulation

Sumedh S. Soman[1] and Siddappa S. Bhusnoor[2]
[1] Undergraduate Student, Department of Mechanical Engineering, K.J. Somaiya College of Engineering, Somaiya Vidyavihar University, Mumbai-400077, India. Email: sumedh.soman@somaiya.edu
[2] Professor, Department of Mechanical Engineering, K.J. Somaiya College of Engineering, Somaiya Vidyavihar University, Mumbai-400077, India. Email: siddappabhusnoor@somaiya.edu

***Abstract*—Diesel engines have been widely used as power source of engineering machinery, automobile, and shipping equipment for its excellent drivability and thermal efficiency. At the same time, diesel engines are major contributors of various types of air pollutant emissions such as Carbon monoxide (CO), Oxides of Nitrogen (NOx), Particulate matter (PM), and other harmful compounds. With the increasing concern of environmental protection and more stringent government regulation on exhaust emissions, reduction in engine emissions becomes a major research task in engine development. Hence it is necessary to predict the performance and emission characteristics of diesel engine without conducting experiments to avoid cost of experimentation and delay in conduction and analysis of results. The focus of present study is modeling of performance and emission characteristics of Diesel engine at various engine speeds and loads, using modified versions of Simulink® pre built models. In this work a Simulink® model was created using Powertrain Blockset™ components, and the model was simulated for different simulation runtimes, ranging from 10 to 90 minutes. Three emission parameters and two performance parameters were evaluated against this model. Carbon monoxide, carbon dioxide and Hydrocarbons as emission parameters are plotted against engine speed keeping engine load constant, and vice versa. Power at crank and the exhaust mass flow rate were the two performance parameters plotted and evaluated. From the various plots and their trends, it was concluded that the trends closely resembled actual profile of the respective plots that are found in actual Diesel Engine Testing.**

***Index Terms*— Compression Ignition engine, modelling, Simulation, engine speed, engine load, Air fuel ratio, combustion efficiency, emissions, mass flow rates.**

I. INTRODUCTION

With the advent of advanced Hardware-in-Loop simulation techniques, it is possible to analyze the performance of Internal Combustion Engines without conducting actual performance test. Emission modelling has gained prominence due to adverse effect of pollutant on health and environment.
Primary emissions of a CI engine include CO, NOx, Hydrocarbons. In Compression ignition engines, there is a tendency to run on leaner mixtures, thus it sees relatively lower carbon monoxide emissions.[1] Hydrocarbons are produced when there is not sufficient air for the combustion of the fuel and some portion of the fuel-air

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mixture remains unburned. Hydrocarbon emissions can also be an effective measurement of the engine combustion efficiency.

Actual Engine testing process is is a time consuming and expensive, hence Mathematical modeling with Hardware-in-Loop simulation has emerged as a substitute for testing and of development process, Simulation predicts accurate results with lesser computational time, and the flexibility to change various parameters. MATLAB® and Simulink® are extremely popular softwares which allow implementation of Hardware-in-Loop simulation for simulating internal combustion engines with required ancillaries.

Among the various approaches A CFD (Computational Fluid Dynamics) code can be built to analyze performance and emission parameters for mathematical modelling of IC engine. Yongmo Kim, Heoet al., [2,3,4,5]. Su, Yin et al., [5] created a MATLAB® script to model all the governing equations of the engine and extract the results. In Simulink®, 'blocks' simulating the desired mechanical system can be used for accurate modeling results, which is the focus of the present work due to not necessity of exact geometry of the engine. Also a variety of emission and performance parameters can be calculated accurately, with less computational time as compared to other methods.

II. Materials and Methods

Methodology followed to achieve the focus of the study is twofold; initially from literature study engine operating parameters and the engine conditions are fixed up in the model. In the second stage a Simulink® model was created using Powertrain Blockset™ components for different simulation runtimes, wherein a compression ignition engine along with the requisite ancillaries have been modelled on Simulink® (Version R2020a). Details of the Materials and methods used in this study are explained in below sub sections.

A. Introduction to Simulink

Simulink® is a MATLAB® based graphical programming environment for modeling, simulating and analyzing multi domain dynamical systems. The primary interface of Simulink is a graphical block diagramming tool, containing a vast number of libraries for varied applications such as Mechanical engineering, electrical systems, data science, aeronautics etc. Powertrain Blockset™ (introduced in 2016) components were utilized for this application [6]. Variables used in this model are shown in Table I, whereas variables used in control block are shown in Table II.

TABLE I. VARIABLES USED IN CI ENGINE CONTROL BLOCK

Sr. No	*Symbol*	Parameter with units
1	$\dot{m}_{fuel}$	Fuel mass flow, g/s
2	$m_{fuel,inj}$	Fuel mass per injection
3	Cp_s	Crankshaft revolutions per power stroke, rev/stroke
4	N_{cyl}	Number of engine cylinders
5	N	Engine speed, rpm
6	Q_{fuel}	Volumetric fuel flow
7	Sg_{fuel}	Specific gravity of fuel
8	T_{exh}	Engine exhaust temperature
9	h_{exh}	Exhaust manifold inlet-specific enthalpy
10	Cp_{exh}	Exhaust gas specific heat
11	$\dot{m}_{intk}$	Intake air mass flow rate
12	$\dot{m}_{fuel}$	Fuel mass flow rate
13	$\dot{m}_{exh}$	Exhaust mass flow rate
14	$Y_{in,fuel}$	Intake fuel mass fraction
15	$y_{exh,i}$	Exhaust mass fraction for i = CO2, CO, HC, NOx, air, burned gas
16	$\dot{m}_{exh,i}$	Exhaust mass flow rate for i = CO2, CO, HC, NOx, air, burned gas
17	T_{brake}	Engine brake torque
18	$y_{exh,air}$	Exhaust air mass fraction
19	$y_{exh,b}$	Exhaust air burned mass fraction
20	F	Injected Fuel mass

TABLE II. VARIABLES USED IN CONTROL VOLUME

Sr. No	Symbol	Parameter with units
1	Q_1	Heat flow from the internal gas to a specified wall depth
2	$Q_{1,conv}$	Heat flow convection from the internal gas to the internal wall
3	$Q_{1,cond}$	Conduction heat transfer rate
4	Q_2	Heat transfer rate
5	$Q_{2,cond}$	Heat flow conduction from the external middle portion of the wall to the external wall
6	h_{int}	Internal convection heat transfer coefficient
7	x_{int}	Internal mass flow rate breakpoints
8	A_{int_conv}	Internal flow convection area
9	T_{int_gas}	Temperature of the gas inside the chamber
10	T_{w_int}	Temperature of the inside wall of the chamber
11	A_{int_cond}	Internal conduction area
12	A_{ext_conv}	External convection area
13	T_{w_ext}	Temperature of the external wall of the chamber
14	k_{ext}	External wall thermal conductivity
15	A_{ext_cond}	External conduction area
16	D_{ext_cond}	External wall thickness
17	T_{mass}	Temperature of the thermal mass
18	m_{wall}	Thermal mass

B. Model Description

The entire model was split up into two subsystems. One subsystem contains the CI engine block which simulates the diesel engine along with ancillaries. The second subsystem consists of the CI Controller block, which based on the torque demand and speed value, computes the injection pulse width and start of injection timing. The CI engine block was programmed to run based on the simple torque lookup approach, wherein the block uses a torque-speed lookup table, and emission mass fraction tables along with physical properties of the fuel to analyze emission and performance parameters. To simulate the intake and exhaust manifolds, Control volume blocks were implemented. External wall convection heat transfer model was implemented to analyse heat transfer across the wall to the surroundings.

The CI Controller, block implements a compression-ignition (CI) Controller with air flow, torque, exhaust gas recirculation (EGR), exhaust back-pressure, and exhaust gas temperature estimation. The block uses the commanded torque and measured engine speed to determine injector pulse width, Fuel injection timing, variable geometry turbocharger rack position and EGR valve open. Based on the commanded engine torque (Load) and the required engine speed, the controller calculates the Injector pulse-width, and fuel injection timing. Further, based on these commands, the controller block estimates the air mass flow, torque, exhaust gas back pressure and temperature.

C. Engine Performance Parameters

The fuel volumetric flow rate can be expressed as;

$$Q_{fuel} = \dot{m}_{fuel} / Sg_{fuel} \qquad (1)$$

Air Fuel ratio can be expressed as;

$$AFR = \dot{m}_{air} / \dot{m}_{fuel} \qquad (2)$$

Intake heat flow is expressed as the product of the intake air mass flow and Intake port specific enthalpy

$$\dot{m}_{intk}h_{intk} \qquad (3)$$

Power at the crankshaft is calculated as:

$$-T_{brake}\omega \qquad (4)$$

Heat transfer rate from the exhaust manifold to the surroundings can be expressed as

$$Q_1=Q_{1,conv}=Q_{1,cond} \qquad (5)$$

$$Q_{1,conv}=h_{int}(x_{int})\bullet A_{int\_conv}\bullet(T_{int\_gas}-T_{w\_int}) \qquad (6)$$

$$Q_{2,cond} = k_{ext}(A_{ext\_cond}/D_{ext\_cond})(T_{mass} - T_{w,ext}) \qquad (7)$$

$$dT_{mass}/dt = (Q_1\text{-}Q_2)/(cp_{wall}m_{wall}) \qquad (8)$$

The control volume blocks, employed as inlet and exhaust manifolds (figure 1) to determine the interior convection heat transfer coefficient using a lookup table.

D. Emission Parameters of the Engine

Engine- exhaust emissions are determined by using scope blocks. The emissions calculated are Carbon dioxide and monoxide, and hydrocarbons. Specific enthalpy of exhaust gas is determined by:

$$h_{exh}= C_{p,exh}T_{exh} \qquad (9)$$

Emission mass fractions are a function of the engine torque and speed, and can be expressed as: -

$$y_{exh,i}=f_{i\_frac}(T_{brake},N) \qquad (10)$$

Mass flow rate of each individual species are a product of the mass fraction of the species and the mass flow rate of the exhaust, which can be expressed as-

$$\dot{m}_{exh,i}=\dot{m}_{exh}y_{exh,I} \qquad (11)$$

Exhaust gas mass flow rate can be expressed as:

$$\dot{m}_{exh}=\dot{m}_{intake}+\dot{m}_{fuel} \qquad (12)$$

The burned gas mass fraction is calculated by the following equation:

$$y_{exh,b}=max[(1-y_{exh,air}-y_{exh,HC}),0] \quad (13)$$

E. Model Line diagram

Model line diagram describes the basic block-layout of the model. The engine subsystem has been shown, wherein the CI engine block and the other ancillaries have been connected. Two control volume systems replicate the intake and exhaust manifolds respectively.

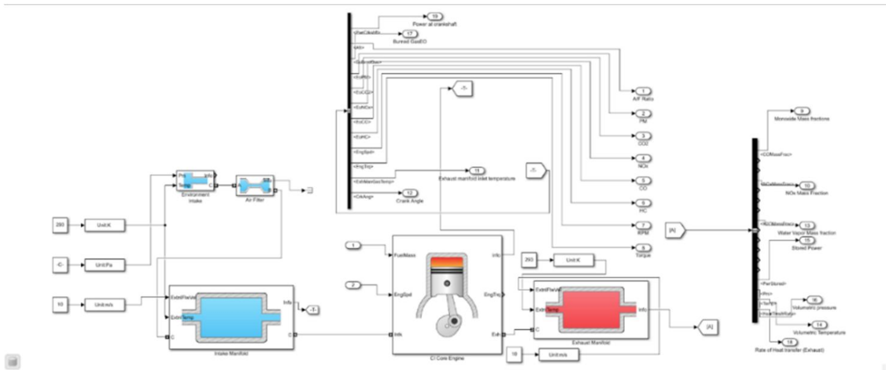

Figure 1: CI engine model line diagram using Simulink®. The blue and red blocks represent the inlet and exhaust manifold, connected to the 'CI Core engine', which is responsible for simulating the compression ignition engine. Other components used are for signal logging.

F. Simulink® model simulation details

In the first stage, Engine testing was done using the Compression Ignition engine model at constant torque by varying the engine speed from 1000 to 6000 rpm in a step of 1000 rpm. Various engine performance and emission parameters are recorded. In the second stage, Engine testing was done using the Compression ignition engine model at constant speed by varying the engine torque from No load to 280 Nm in a step of 20Nm. various engine performance and emission parameters are recorded. The results of both tests are discussed in next section. To reduce the time required for computation, a MATLAB® script was created, wherein the computer was programmed to run multiple simulations simultaneously, employing multiple Central Processing Unit (CPU) cores, using the Parallel Computing Toolbox™ in MATLAB®. The results are discussed in the next section.

III. Result and Discussion

To analyze the performance and emission parameters of the CI engine the "compression ignition engine model", built on Simulink was run to simulate an engine load and speed test. Data was logged using 'Scope' blocks. Engine performance and emission parameters are discussed in detail in below subsections.

A. Engine Emission Parameters

Engine emissions parameters measured are Hydrocarbons, CO_2 and CO, which is discussed in below paragraph.

1. Influence of Engine Speed and load on Emission of CO_2

Figure 2 and Figure 3 shows the variation in the CO_2 emission rate at engine speed and load test respectively.
It is observed that the CO_2 mass flow rate increases with the engine speed, at a constant load of 100 Nm and 200 Nm. However, it is observed that the slope of the graph decreases as the speed increases due to decrease in air-fuel ratio with an increase in engine speed. This causes the combustion efficiency to decrease, leading to a lesser mass fraction of CO_2 in the exhaust gases. However, due to the mass flow rate of the exhaust increasing, an increase in the CO_2 mass flow rate is observed.
Engine load test shows that the mass flow rate is having exponentially increasing trend. As the torque demand increases the air-fuel ratio becomes more fuel-rich, consequently resulting in an increase in CO_2 mass flow rates due to the increase in rate of injection.

2. Impact of engine speed and load on emission of HC

The effect of engine load and speed on HC emissions are shown in Figure 4 and Figure 5 respectively. Hydrocarbon content in the exhaust increases with a decrease in combustion efficiency. Since the exhaust mass flow rate increases with increase in the engine speed, the hydrocarbon mass flow rate also increases. However,

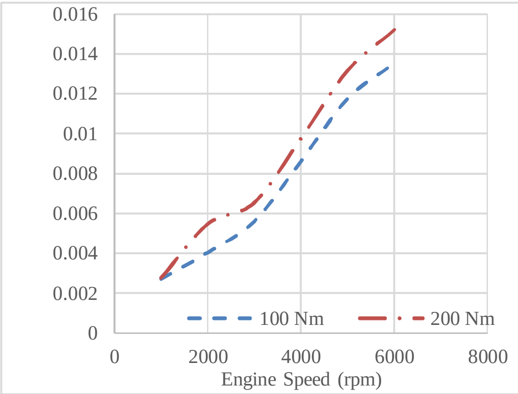

Figure 2: Variation of CO_2 mass flow rate with respect to speed

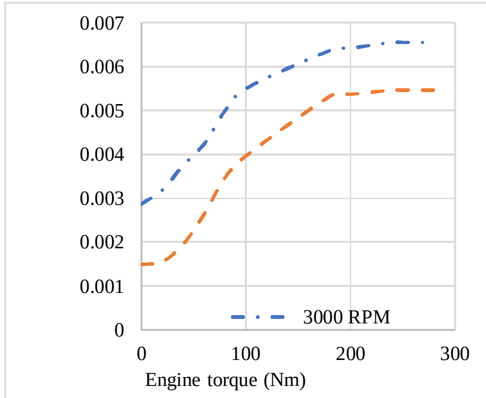

Figure 3: Variation of CO_2 mass flow rate with respect to load

the mass fraction of hydrocarbons decreases when the combustion efficiency is high i.e., the air fuel ratio is lean enough for the complete combustion of the fuel to take place.

However, a noticeable reduction is observed at a particular engine speed, after which the combustion efficiency worsens, and an increase in the mass flow rate is observed. This phenomenon is more pronounced when the simulation model is run at a higher commanded torque value of 200 Nm. Consequently, the combustion efficiency at any engine speed for given engine torque command remains high, and the HC mass flow rate increment can be largely attributed to an increase in the mass flow rate of the exhaust, due to increasing engine speed. [8]. When the HC mass flow rate is plotted with respect to engine torque demand, an increasing trend can be seen, due to the air-fuel mixture becoming more fuel rich, leading to a decline in combustion efficiency. The increase in the exhaust mass flow rate further contributes to an increase in the mass flow rate of hydrocarbons, leading to an exponential increase in HC mass flow rates.[9].

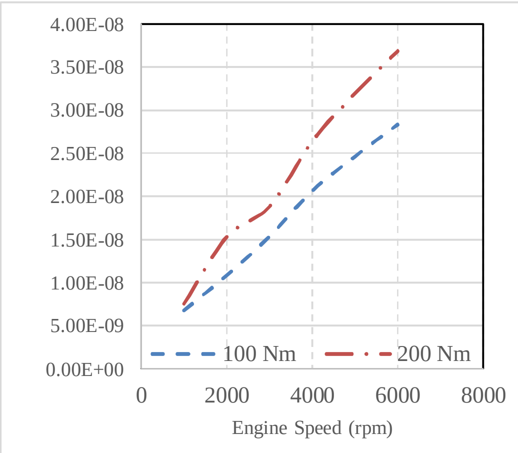

Figure 4: Impact of varying engine speed on HC Mass flow

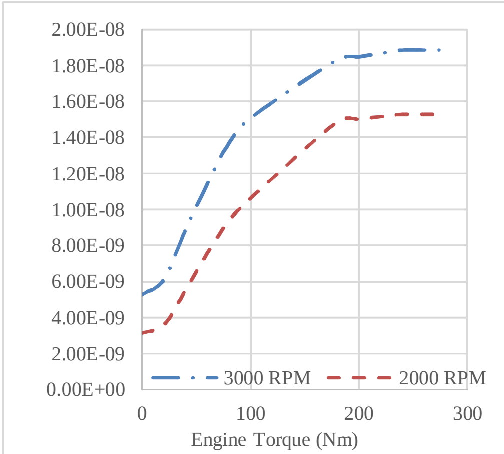

Figure 5: Impact of varying engine load on HC Mass flow rate

3. Effect of Engine Speed and Load on Emission of Carbon monoxide.

Figure 6 and Figure 7 shows the effect of engine speed and load on emission of Carbon monoxide. Combustion efficiency and air-fuel ratio is very closely linked to CO mass flow rates. Incomplete combustion of fuel results in CO production. As with all other emissions, it is seen that the mass flow rates of CO show an increasing trend with engine speed, but the slope of the graph is not linear. At both load values, there is a point of minima on the graph, at which there is maximum combustion efficiency. This is due to the air fuel ratio becoming more fuel-rich, leading to excess fuel. Consequently, this phenomenon is the cause for an exponential increase in the mass flow rate.[10]

The graph of CO mass flow rate versus load also shows an increasing trend in CO mass flow rate with an increase in engine torque since the fuel-air mixture becomes more fuel-rich because of increase in the rate of injection [7]. The CO mass flow rate at 2000 RPM is initially lesser, then subsequently higher than the mass flow rate of CO at 3000 RPM. This is due to the commanded engine torque values approach the engine torque value corresponding to the given engine speed on the engine torque-speed curve, which is where the combustion efficiency is highest.

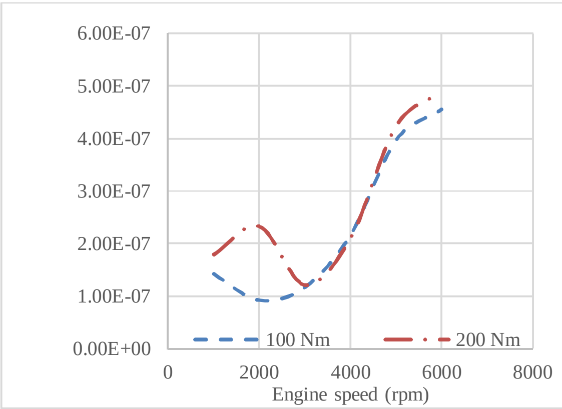

Figure 6: Variation of CO mass flow rate with engine speed

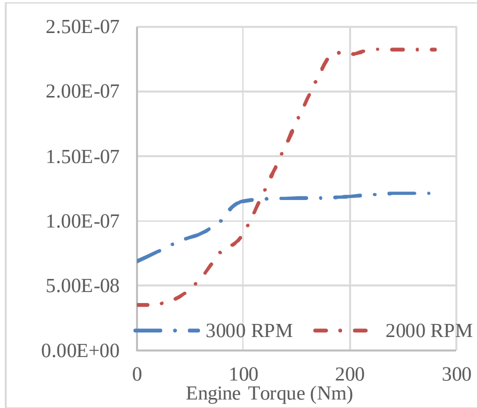

Figure 7: Variation of CO mass flow rate with torque

B. Engine performance parameters

Effect of engine operating conditions on engine performance parameters are analyzed at various engine conditions and results are discussed in below paragraphs.

1. Influence of engine speed and load on the Engine out power

Figure 8 and Figure 9 shows the effect of speed and load on the power generated at the engine crank.

The engine torque demand is constant in this particular simulation run; variation of brake torque in this plot is negligible. The increase in power is directly related to the rise in the engine speeds. This leads to a linearly increasing trend. When the power at the crank is plotted against commanded engine load, an increase in power corresponding to an increase in torque demand is observed. The variation here is that the engine torque command values are being varied while the engine speed is being kept fixed. This leads to the power at crank to have a stepwise increase, as the torque demand on the engine is incremented.

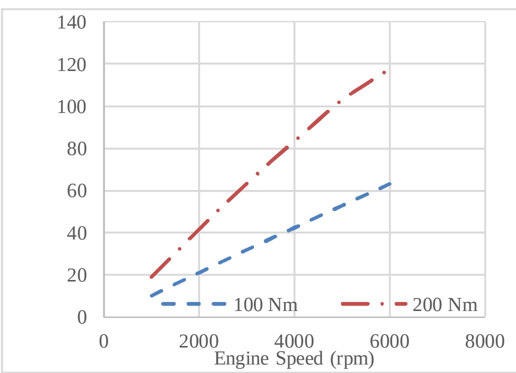

Figure 8: Variation of power at crank with respect to speed

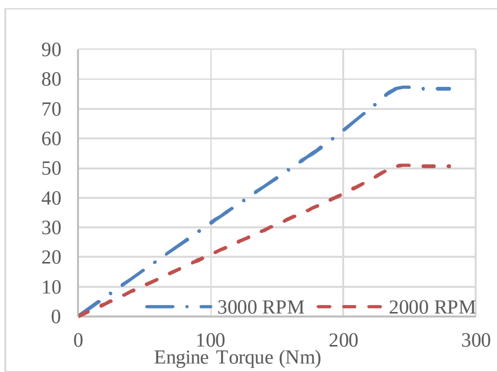

Figure 9: Variation of power at crank with respect to load

2. Influence of varying engine load on exhaust mass flow rate and Influence of varying engine speeds on exhaust mass flow rates

In Figure 10, the graph plots the variation of the exhaust gas mass flow with respect to variation in engine load, at 2 different engine speeds. Figure 11 details the variation of the exhaust gas mass flow with respect to variation in engine speed.

Increase in load on the engine causes increase in the rate of injection. Since the engine speed remains constant, the mass flow rate of air does not vary. However, due to the increase in load, the mass flow rate of fuel increases, thus resulting in an increase of the exhaust mass flow rate. In the given graph the exhaust mass flow rate has been plotted as a function of engine speed, at two values of commanded engine torque. Since the intake mass flow rate increases with an increase in the engine speed, following the continuity equation for fluids, the exhaust gas mass flow rate also increases. The plot has an almost linearly increasing trend, caused by linear increase in the intake mass flow rate. Since the fuel mass flow rate at higher torque demands on the engine is higher than that at low speeds, the mass flow rate of exhaust at a higher commanded engine torque value remains higher as compared to the flow rate at a lower torque demand placed on the engine.

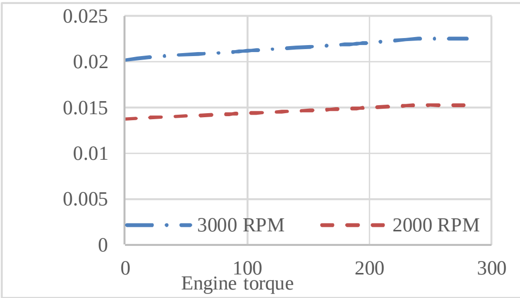

Figure 10: Exhaust mass flow plotted against load

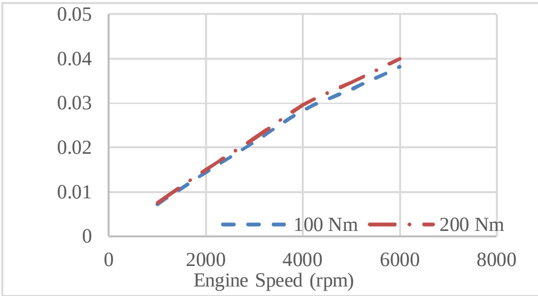

Figure 11: Exhaust mass flow plotted against speed

IV. Conclusion

Performance and Emission characteristics of the Diesel engine at simulated engine conditions are analyzed using Simulink®. A summary of modeling analysis drawn on the basis of present work are summarized here.

1. In all the simulation runs at load test (keeping the engine speeds constant), the focus was on the combustion efficiency and the air-fuel ratio. When the engine load value reached the maximum allowable torque at the given engine speed, favorable emission characteristics are obtained. From the plots it was observed that change in rate of emission is due to changes in air fuel ratio during the combustion as depicted in theory.
2. It was also observed from the model results that excessively lean or rich air fuel ratio led to the unfavorable emission characteristics, and a loss in performance of the engine.
3. There is increase in exhaust gas flow rates, due to increase in the fuel mass injection per stroke, which confirmed the theory of combustion.
4. Power at crank increased in a stepwise due to the load being increased as crank angle increases, but the power at crank remained low in this case because of the lower speeds being selected.
5. In the simulation runs during speed test (engine load was kept constant), the onus was on frictional losses and air mass flow rate. As the engine speed increases (the frictional losses increase) there is decrease in volumetric efficiency which in turn decreases intake air mass flow rate. This causes the air fuel ratio to become more fuel rich, thus causing a drop in combustion efficiency, leading to increase in mass flow rates of emission species.
6. Exhaust mass flow rate increased, due to the increase in the intake air mass flow, while power at the crank increased almost linearly, since power at the crank is the product of engine speed and brake torque.

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