Chapter - 3

Experimental Study

An experimental study is carried out to assess the thermal performance of diesel engine along with the level of pollutant emission constituents working on hydrogen –diesel dual fuel incorporating indirect induction of hydrogen continuously in to the engine through the air intake manifold. For this purpose, an experimental set up is designed, fabricated and commissioned. The detailed description of the set up is given in Section 3.1. Section 3.2 gives the step by step procedure followed during the various experimental studies. The details of the experimental programme are described in Section 3.3. The results and discussion of the experimental study are given in section 3.4.

3.1 Description of the Experimental Set Up

The experimental set-up consists of three main systems integrated, viz., a 37 HP, four cylinder, four stroke diesel engine with an engine loading system, various measuring instruments for the evaluation of the engine performance and emissions constituents, and hydrogen induction system. Figs.3.1 (a) and (b) show~~s~~ the schematic of the experimental setup. Plates 3.1 and 3.2 respectively give front and rear view images of the set up. Section 3.1.1 gives the technical description of the diesel engine. Various measuring instruments for the evaluation of the engine performance and emission constituents are explained in Section 3.1.2. The arrangement for indirect induction of hydrogen in to the intake manifold is described in Section 3.1.3.

3.1.1 Diesel Engine

The test engine is a 37 hp (26.7 kW) compression ignition engine with four cylinders, four stroke, vertical, naturally aspirated, water cooled one basically designed to run on diesel oil directly injected. The engine, commercially known as Stride Engine 1.5 E2DSL, is manufactured and tested by Hindustan Motors Limited, India. The engine is mounted on an engine test bed equipped with suitable lubrication and cooling water supply systems. Plates 3.3 and 3.4 show the front and rear view images of the diesel engine. Table 3.1 gives the technical specification of the diesel engine.

Table 3.1 Engine Specification

Make and Model	Stride Engine 1.5 E2 DSL
General details	Four cylinder, four stroke, compression ignition, vertical, water cooled, indirect injection combustion chamber type.
Bore	73 mm
Stroke	88.9 mm
Clearance volume	16.913 cm^3
Compression ratio	23:1
Max. power	37hp @ 4000 rpm
Max. torque	83.4 Nm @2250 rpm
Capacity	1489 cm^3
Static injection timing	15 degree BTDC
Injection pressure	145 +/- 5 kg/cm^2
Lubricating oil	SAE 30/SAE 40
Ratio of connecting rod length to crank radius (R)	4.13

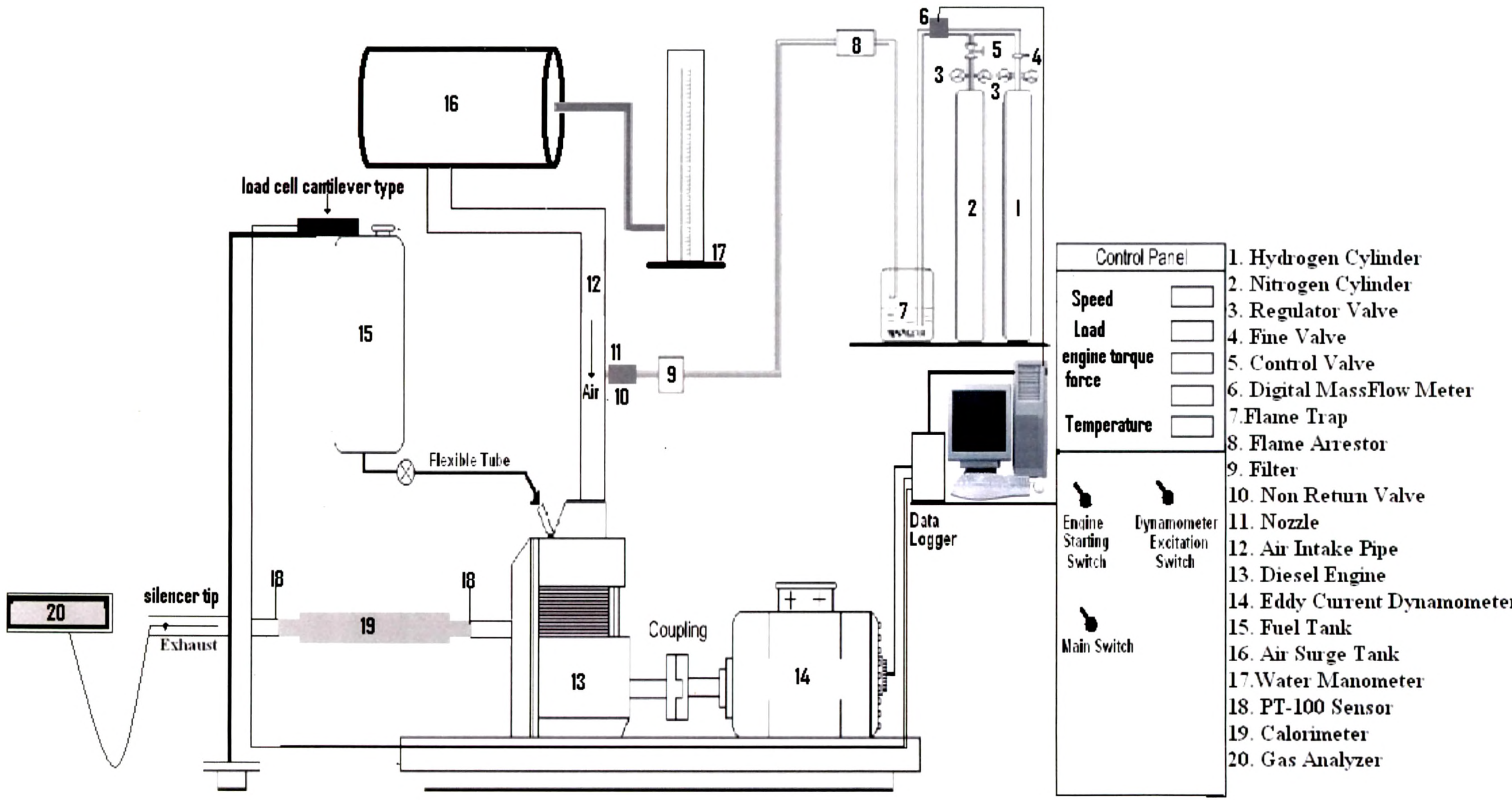


Fig. 3.1(a) Experimental Setup

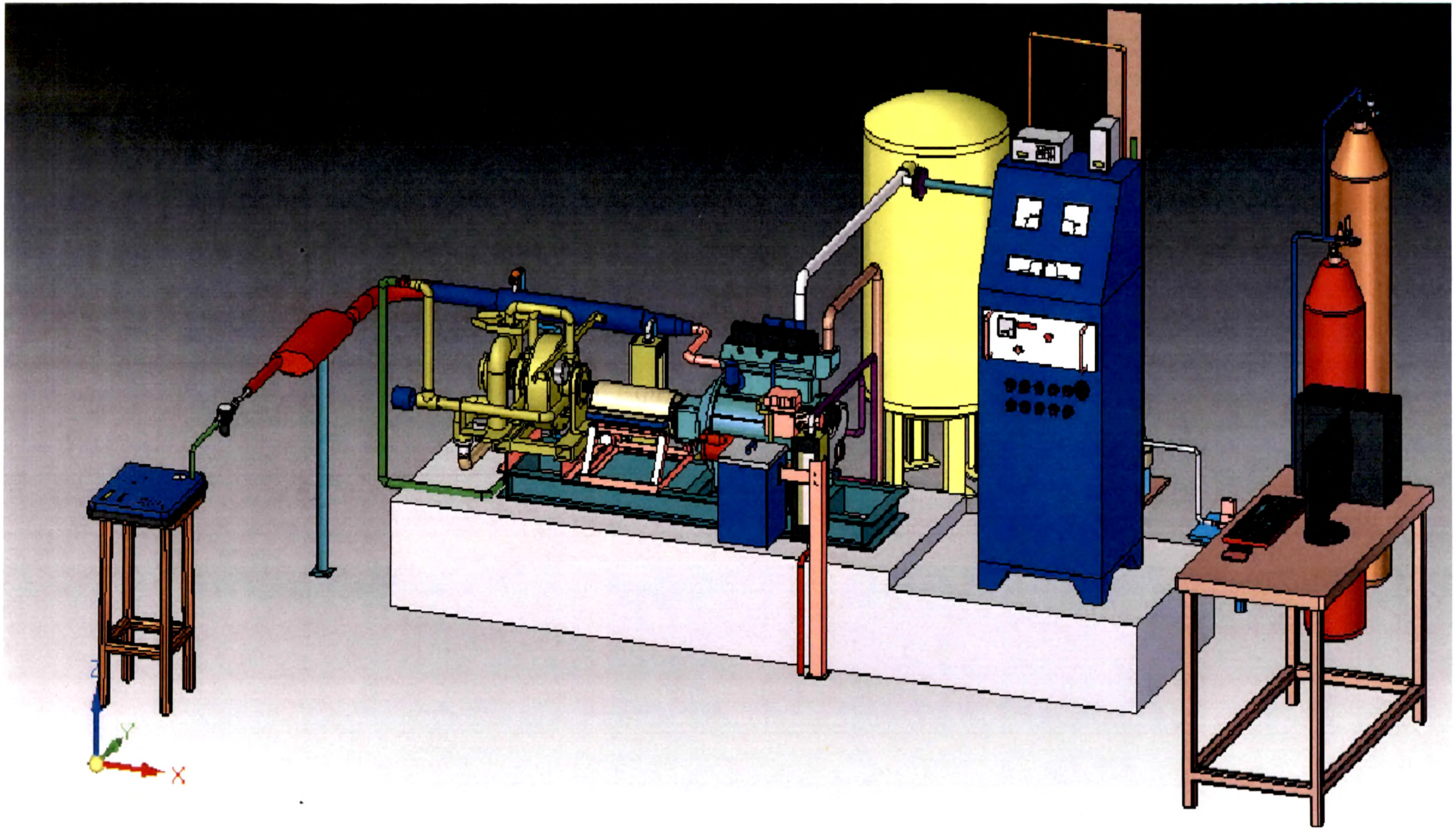
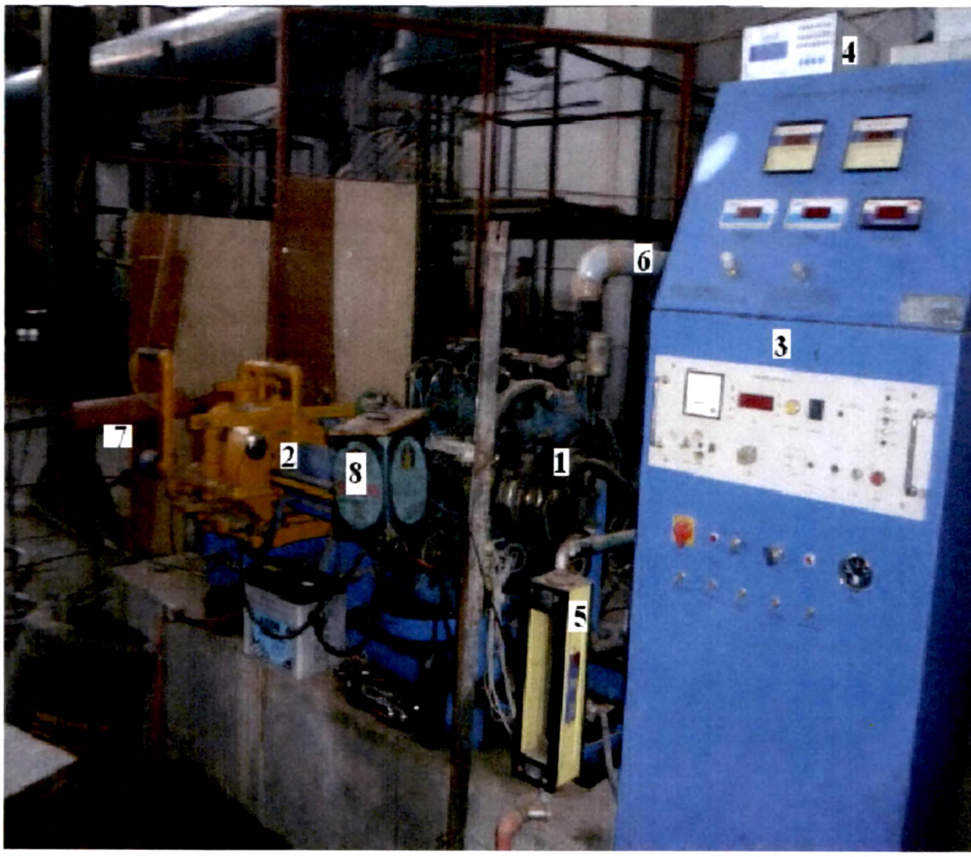
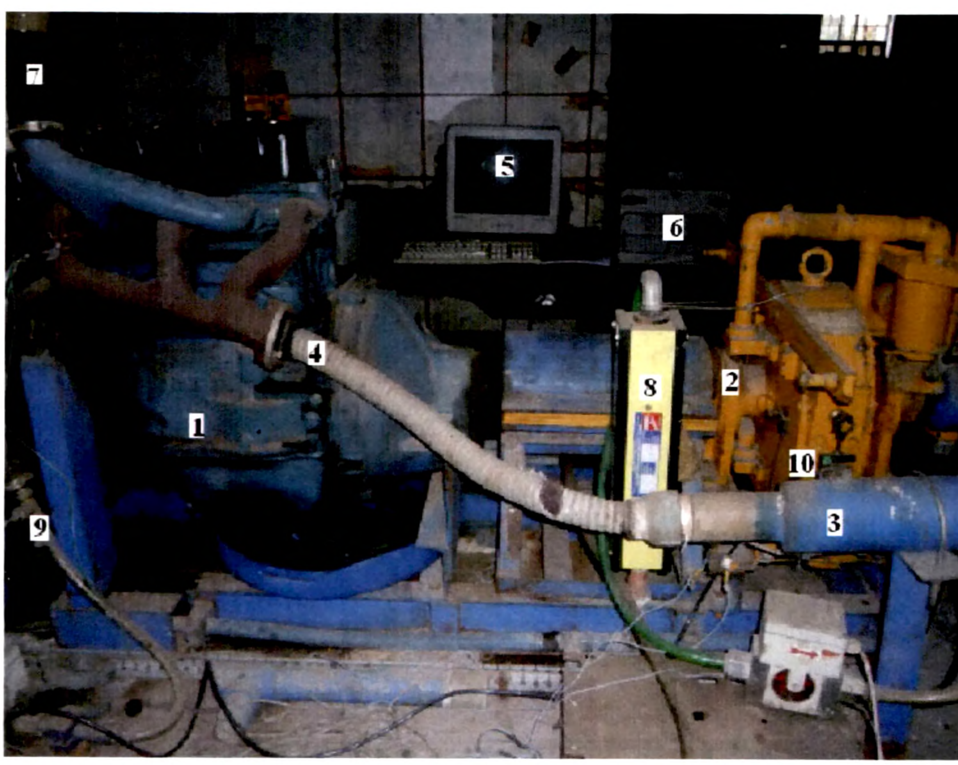


Fig. 3.1 (b) Experimental Setup



1. Four Cylinder - Diesel Engine
2. Eddy Current Dynamometer
3. Electronic Control Unit
4. Data Logger
5. Water Flow Meter
6. Engine Intake Air Pipe
7. Silencer
8. Fuel Tank

Plate 3.1 Front View of the Experimental Set Up



1. Four Cylinder - Diesel Engine
2. Eddy Current Dynamometer
3. Calori meter
4. Exhaust Line
5. PC
6. Gas Analyzer
7. Air Intake Manifold
8. Calorimeter Water Flow Meter
9. Engine Outlet Water Temperature Sensor
10. Eddy Current Dynamometer Strain Guage

Plate 3.2 Rear View of the Experimental Set Up

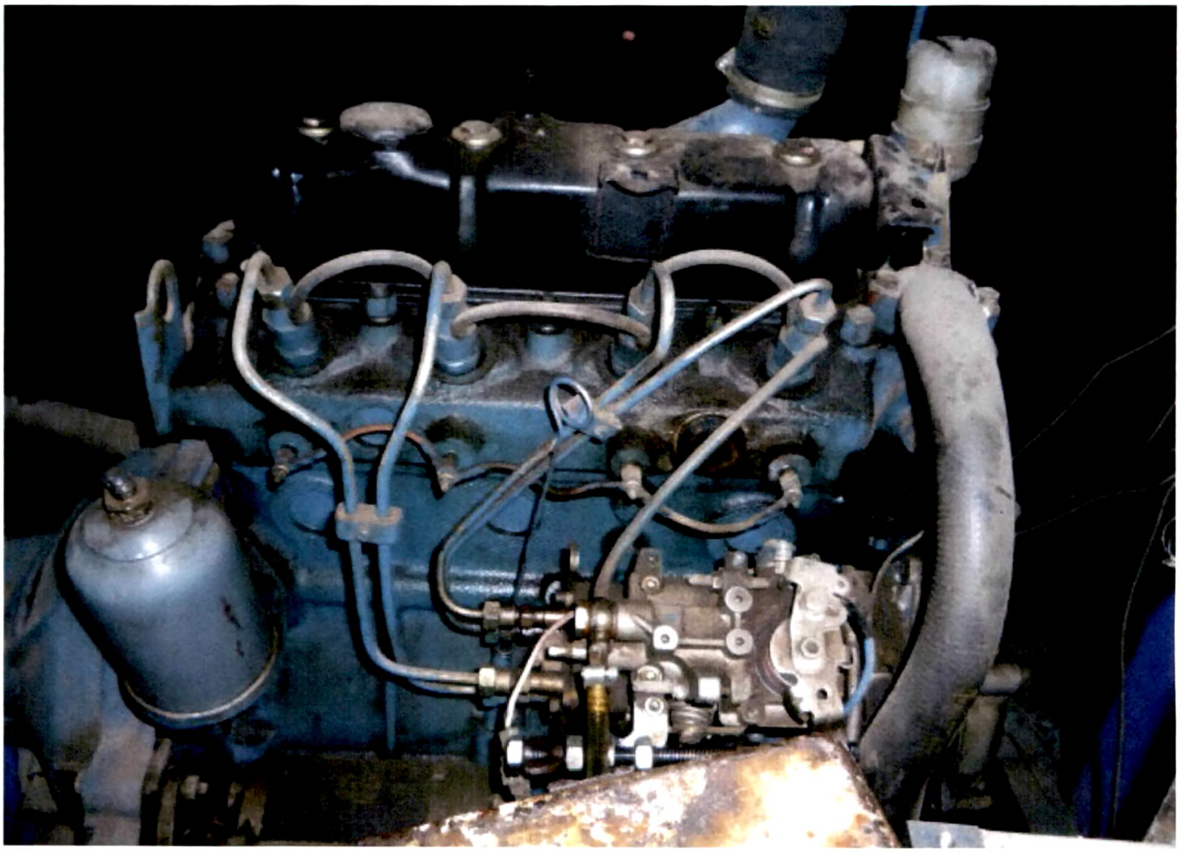


Plate 3.3 Four Cylinder, Four Stroke Diesel Engine- Front View

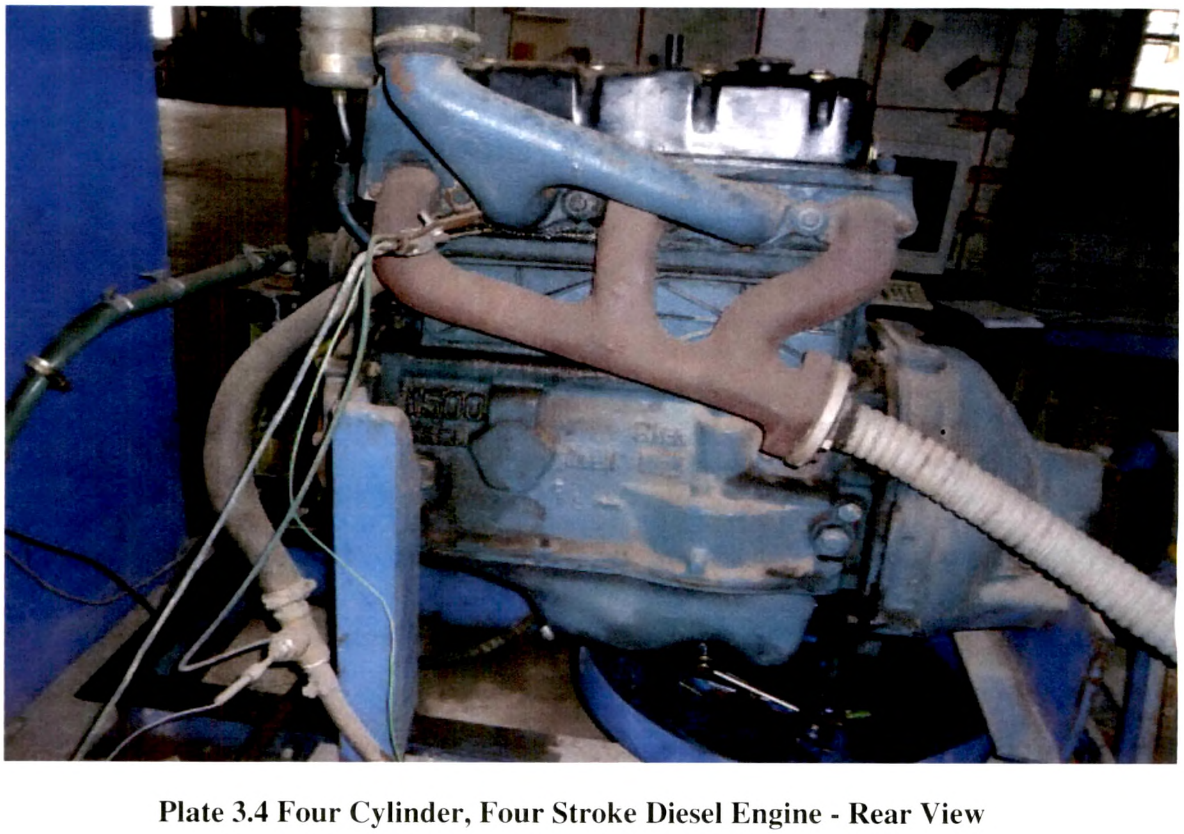


Plate 3.4 Four Cylinder, Four Stroke Diesel Engine - Rear View

3.1.2 Measurement Systems for Thermal Performance Evaluation

The experimental study proposed to be carried out consists of the thermal performance evaluation along with the emission characteristics of the diesel engine working on indirect continuously inducted hydrogen in the air intake manifold with diesel as fuel and diesel with suitable additives. There are, therefore, a few measurement systems incorporated with the diesel engine. This section describes them systematically based on the three different groups of variables that are identified through the "Design of Experiment". The three groups of variables are control variables, environment variables and response variables. Fig. 3.2 illustrates the interaction of the three groups of variables with the system (diesel engine) under consideration.

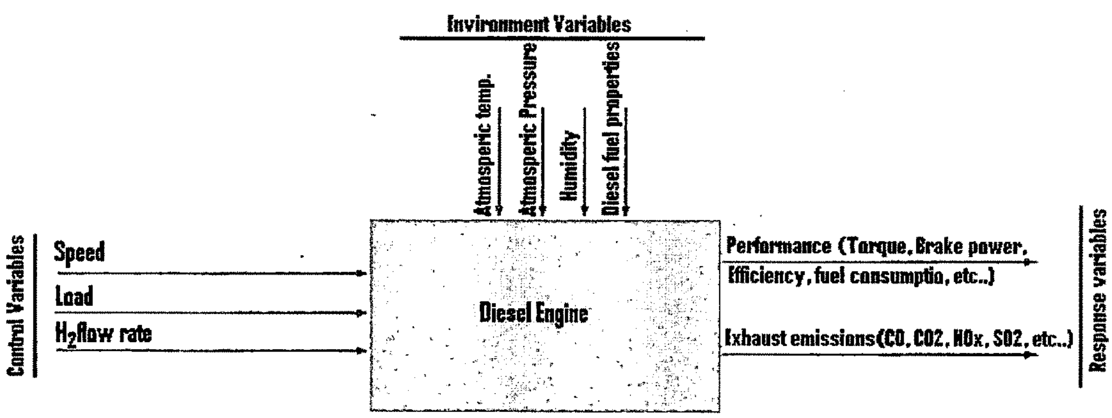


Fig. 3.2 Control, Environment and Response Variables of the System (diesel engine)

3.1.2.1 Input Control Variables

The control variables in the present experimental study are the load, the speed and the hydrogen induction rate. The measurement systems for these variables are described in this section.

- **Eddy Current Dynamometer as Loading System:**

Eddy current dynamometer is used as the loading system for the diesel engine. The diesel engine is coupled directly to an eddy current dynamometer with arrangement to vary the speed and the load. The eddy current dynamometer works on the principle of Eddy-

Current (Fleming's law of right hand). A schematic of eddy-current electro brake is shown in Fig. 3.3. The dynamometer is provided with a toothed disc rotor which is driven by the prime mover (diesel engine) which is to be loaded. Magnetic poles (stators) are located outside on both the sides covering the rotor with a gap. A coil circumferentially enveloping the rotor – stator assembly excites the magnetic pole. When a current passes through the coil, a magnetic flux loop is formed around the exciting coil through the pole stator and the rotor. The rotation of rotor produces a current density difference, thereby eddy-current flows through the stator. This, in turn, generates an electromagnetic force in the opposite direction of the rotation of the rotor. A braking effect results in due to the product of the eddy-current and the vector of magnetic flux.

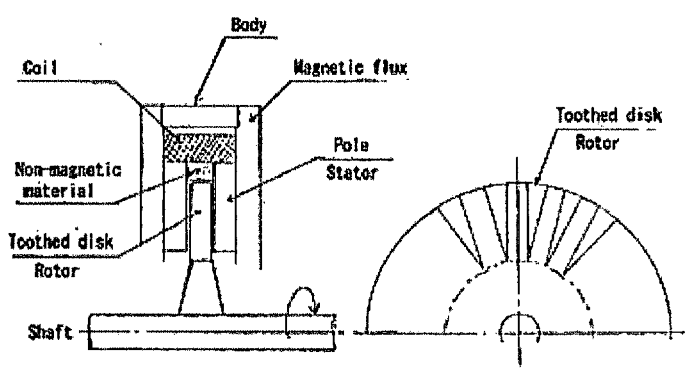
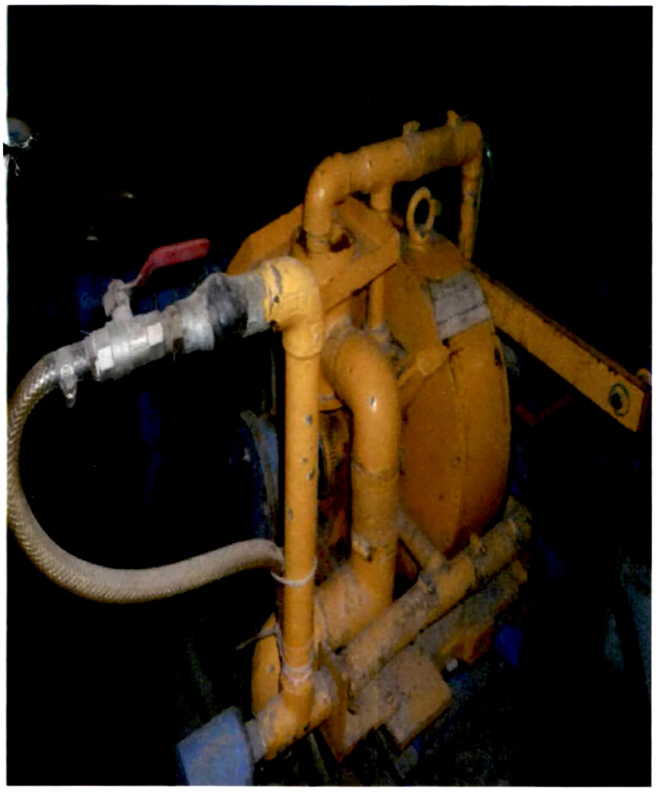


Fig. 3.3 Eddy Current Dynamometer

The eddy current dynamometer transfers the braking effect as a torque force on the stain gauge which is fixed on a distance of 22 cm from the axial shaft of the dynamometer. A strain gauge (S type load cell), having high sensitivity and accuracy, senses this force and transfers it through a suitable transmitter to a data logger or a scanner and then to a computer. Plates 3.5 and 3.6 give the two views of the dynamometer.

An electronic centre unit (ECU) consisting of a current controller and a switch to adjust the current flow provides steady regulated electric current supply to the dynamometer. The ECU panel shows the current variation from 0 Ampere to 4.0 Ampere which represents the range of the engine load in terms of current or eddy current. A water circulation system provides cooling of the eddy current dynamometer. Over-heat limit switch provided stops the working of the dynamometer in case of overheating due to short supply of cooling water.



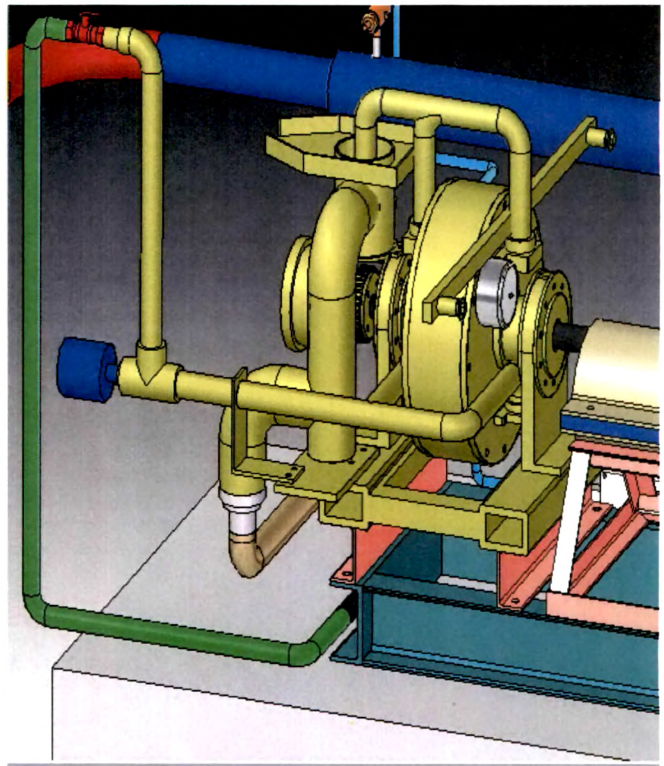
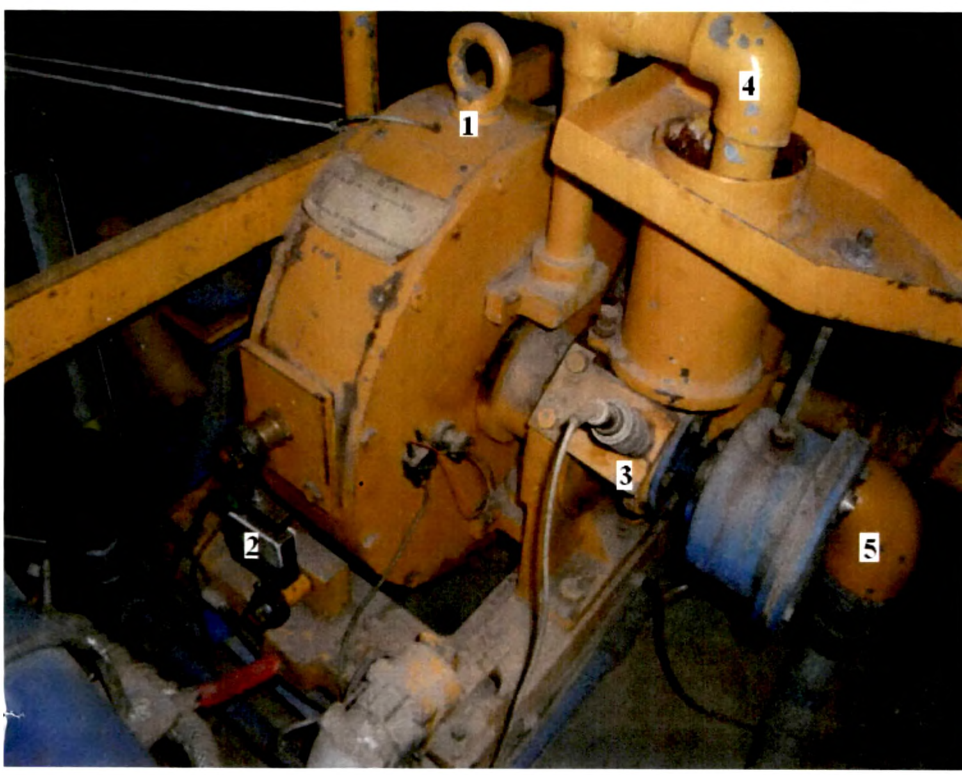


Plate 3.5 Eddy Current Dynamometer- Front View



1. Eddy Current Dynamometer

2. Strain Guage To Measure Engine Brake Force.

3. None Contact Tacho Speed meter

4. Inlet Cooling Water Pipe

5. Outlet Cooling Water Pipe

Plate 3.6 Eddy Current Dynamometer- Rear View

Plate 3.7 Eddy Current Dynamometer Control Unit

The loading on the engine shaft can be adjusted with reference to the current at the dynamometer in steps from 0, 0.5, 1.0, 1.5 and 2.0 Ampere for all rate speeds. In the case of the multi-speed engines, there is a maximum load for each speed. For the present experimental study, the load values are selected to be equal for all experimental rated speeds so as to avoid over load on the engine. Further, the possibility of the hydrogen pre-ignition and back fire should also be eliminated as a result of the over loading.

- **Non-contact Tachometer as Speed Measuring System:**

Engine speed is measured using a non contact tachometer. This high sensitivity device connected on the eddy current dynamometer is used to measure the actual engine speed at no load and load conditions. Plates 3.8 and 3.9 give the images of the non-contact type tachometer and the speed display unit on the control panel. The motion sensing probes work on the principle of Faraday's laws of electromagnetic induction. That is to say that when a ferromagnetic object enters permanent magnetic field, it distorts the flux causing it to cut the coil windings thereby generating a voltage.

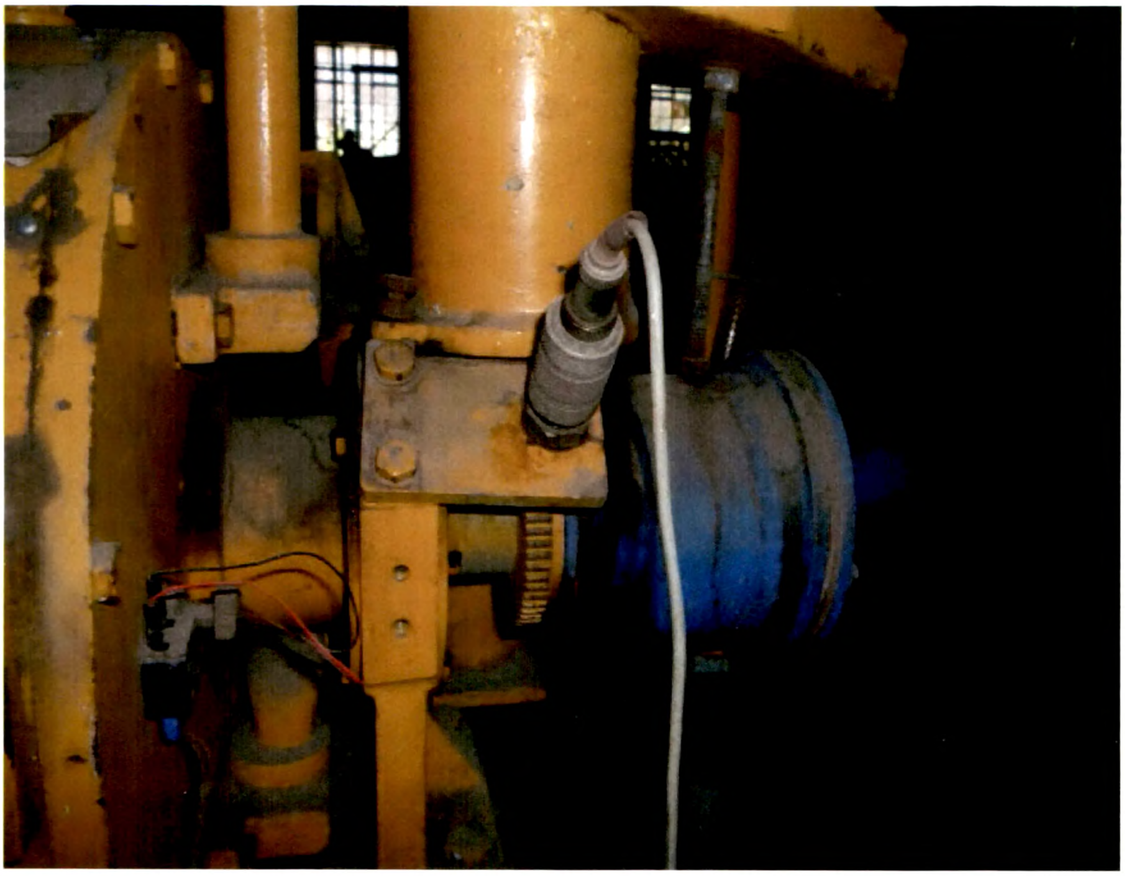


Plate 3.8 Non Contact Tachometer.

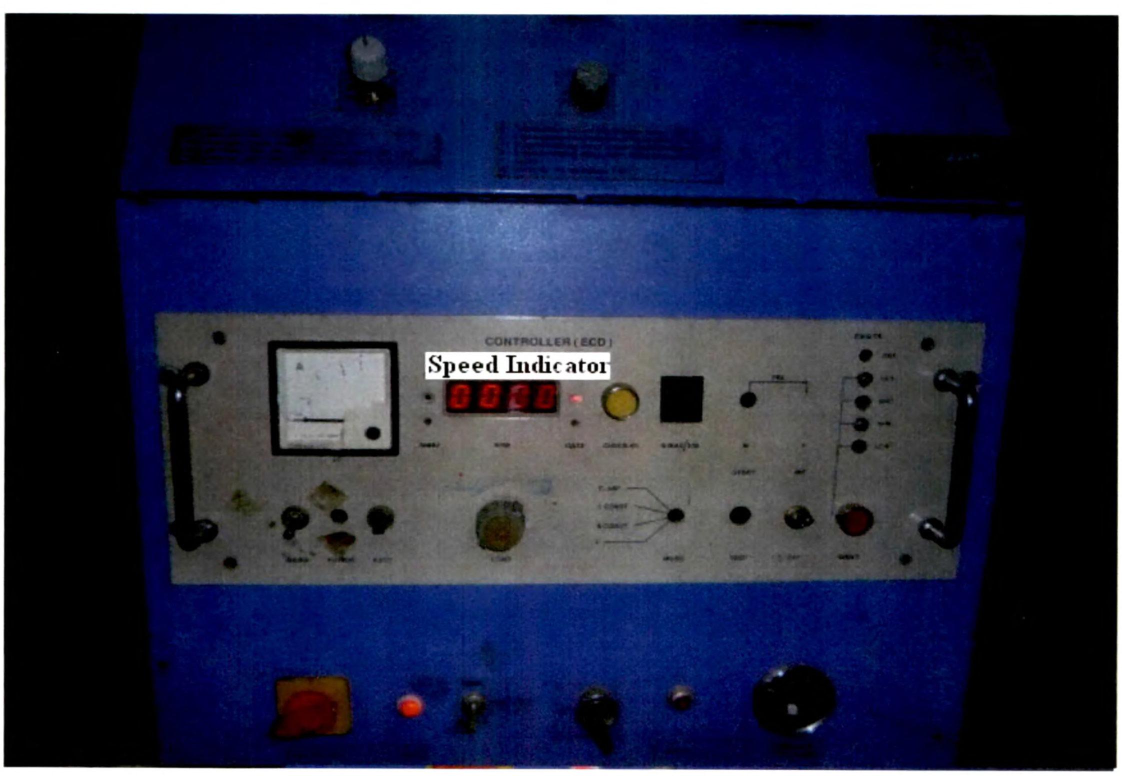


Plate 3.9 Speed Display Screen

This voltage is proportional to the strength of the magnet and the number of wire turns in the coil (these being a constant in the probes) and the speed at which the ferrous target passes through the flux. The generated voltage is also inversely proportional to the square of the distance between the target and the probe. The signal of this tachometer amplifies and sends to the ECU which it displays it on the panel by digital screen. The engine speed is changed by varying the fuel paddle in the injection pump by screw it clock wise and counter clock wise to increase and decrease the engine speed. The variation is carried out mechanically to adjust the proper engine speed. In the present experimental study, the speed of engine is selected at 1000, 1250, 1500, 1750, and 2000 rpm to avoid a pre- ignition of hydrogen and the back flame. It includes the normal range of diesel engine used on automobile applications.

- **Hydrogen Induction Rate Measurement System**

There are number of hydrogen supplementation methods employed in diesel engines with and without additives which was described in Chapter 2. They are grouped into direct cylinder injection and indirect injection/induction. The indirect injection/induction is further classified in to carburetion, continuous manifold injection, timed intake port injection (TPI), timed manifold injection (TMI). In the present investigation, the continuous induction of hydrogen in gaseous phase in to the air intake manifold is selected as hydrogen supplementation technique. 99.9 % pure hydrogen is continuously inducted in to the air intake manifold using an induction system. Hydrogen fuel was often associated with either the Hindenburg or the challenger disasters or even the hydrogen bomb. It should be noted that other fuels such as gasoline and natural gas also pose similar dangers. In fact, hydrogen actually has a good overall safety record due to strict adherence to regulations and procedures and good training for persons who handle hydrogen. For overall safety during hydrogen operation some safety devices must be adopted for hydrogen induction. According to the technical and safety needs, the hydrogen induction system must have the following:

1- Hydrogen cylinder of capacity 7 m^3 (0.5 kg) of hydrogen gas under pressure of 150 bar. This cylinder worked as hydrogen tank to store enough hydrogen for carrying out the experiments.

2- Nitrogen cylinder contains 7 m^3 of nitrogen gas at 150 bar. Nitrogen gas is used to purge the manifold of hydrogen induction system. The purging is carried out in the system starting from the point of connection with hydrogen cylinder to the induction point in the inlet manifold to avoid any probability of ignition of hydrogen traces.

3- Two single stage pressure regulators to reduce the pressure of hydrogen and nitrogen from their respective cylinders to a pressure in the range from 1 to 4 bar based on the flow requirements.

4- Fine flow control valve to adjust the quantity of hydrogen flow from hydrogen storage cylinder via pressure regulating valve to the induction system.

5- Digital thermal mass flow meter to measure the quantity of hydrogen that flow in the induction system to the diesel engine.

6- Water flame trap after fine control valve to quench the back hydrogen flame and reduce the temperature of hydrogen gas when transferred to intake port.

7- Flash arrestor after flame trap to prevent the back flame to reach the hydrogen cylinder

8- Non return valve after flame arrester to prevent the flame to reach the hydrogen cylinder.

9- Nozzle after non-return valve to induct hydrogen gas in to the air intake port of diesel engine.

10- High pressure flexible tubes with proper clamps are used to connect all the induction system apparatus.

Fig. 3.4 gives a schematic of the hydrogen induction points along the length of the air intake manifold of the diesel engine. Hydrogen is induced in to the air intake manifold from the hydrogen storage tank and is allowed to mix with the air in the duct before the air-hydrogen mixture is directed in to the engine cylinder. The intake manifold then distributes the mixture in various cylinders of the multi cylinder engine. The hydrogen flow rate is regulated using a fine valve which allows the flow rate to be adjusted in steps of one l/min. There are four locations along the length of the manifold where hydrogen induction in to air passage can be carried out. These four locations are provided to experimentally determine the best possible location where the hydrogen induction will give a good air-hydrogen mixture.

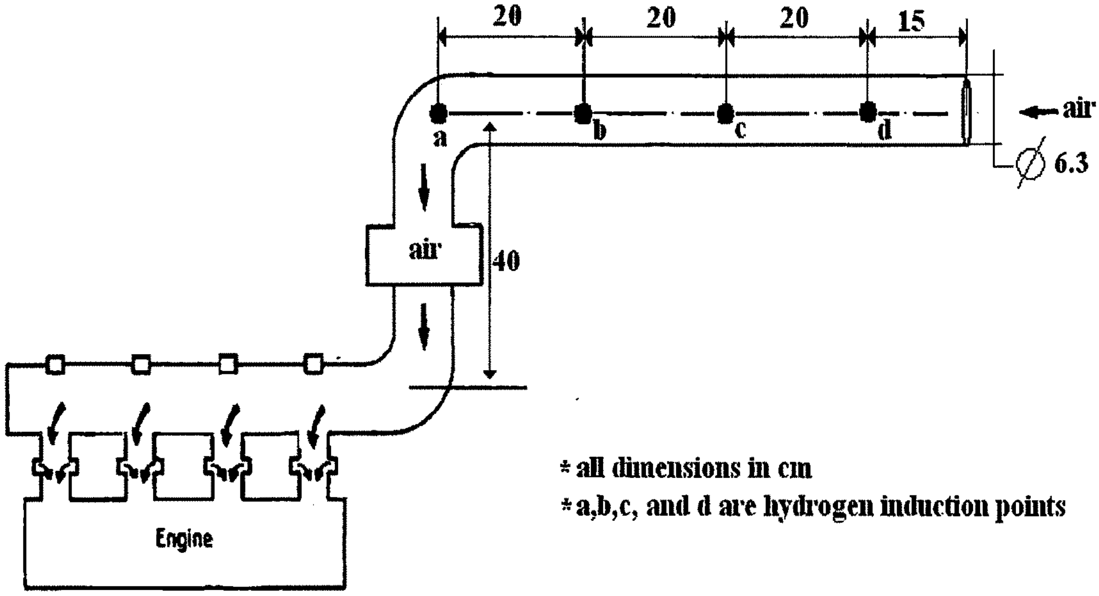


Fig. 3.4 Locations of Continuous Hydrogen Induction Points in Intake Manifold

Hydrogen from 7 m^3 (0.5 kg) capacity storage cylinder in which hydrogen is stored at a pressure of 50 bar passes through a pressure regulator which decreases the pressure to 1 to 4 bar and enters a fine valve which is used to control the hydrogen flow rate. A digital mass flow placed down stream the line measures hydrogen mass flow rate. Fig. 3.5 and plate 3.10 give the hydrogen induction set up of this work. Plate 3.11 gives images of the digital thermal mass flow meter and its display used in the hydrogen induction system. Hydrogen then enters a flame arrestor which prevents any back fire to travel towards hydrogen storage cylinder pipeline. Hydrogen then flows through the water which acts as a flame trap and then through a second flame arrestor and then is filtered in a filtering device for any impurities as hydrogen flow to the injector should be free from any impurities. A non return valve (NRV) in the down stream prevents any back flow of hydrogen or flame towards the storage cylinder. Hydrogen then passes through a nozzle to the intake port to mix with the air continuously. It should be noted that the continuous induction of hydrogen causes an increase in engine speed. Adjustment in the speed so as to keep it at constant level during experimentation is therefore needed.

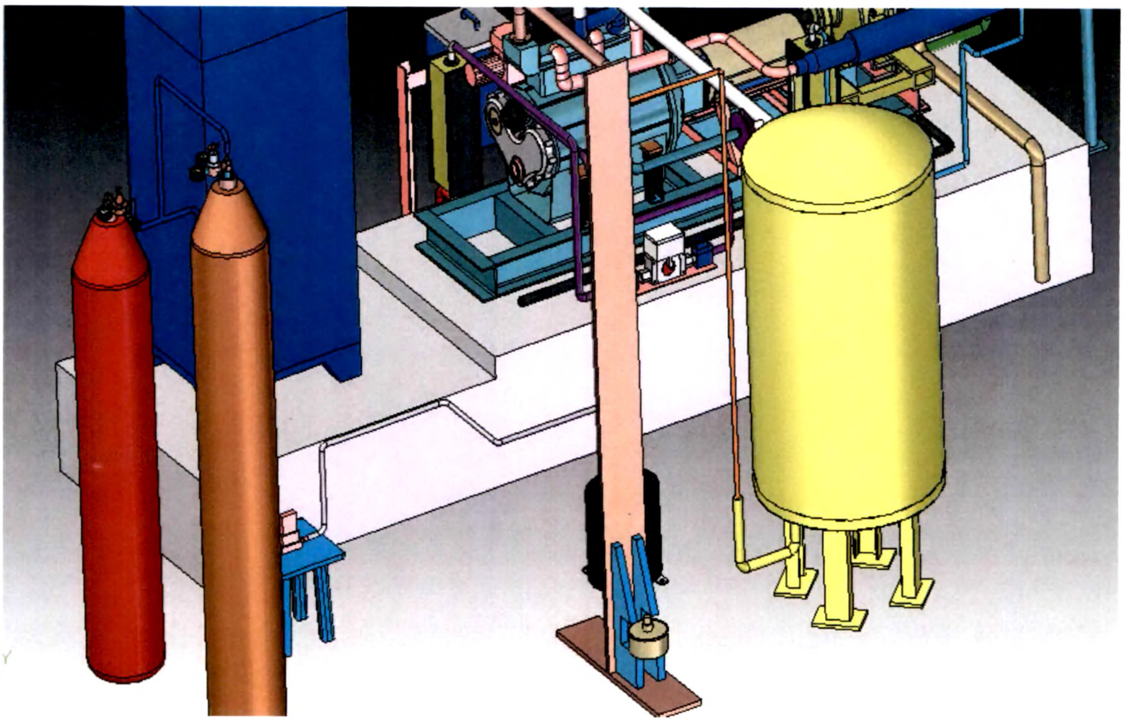


Fig. 3.5 Hydrogen Induction Setup

Plate 3.10 Hydrogen Induction Setup

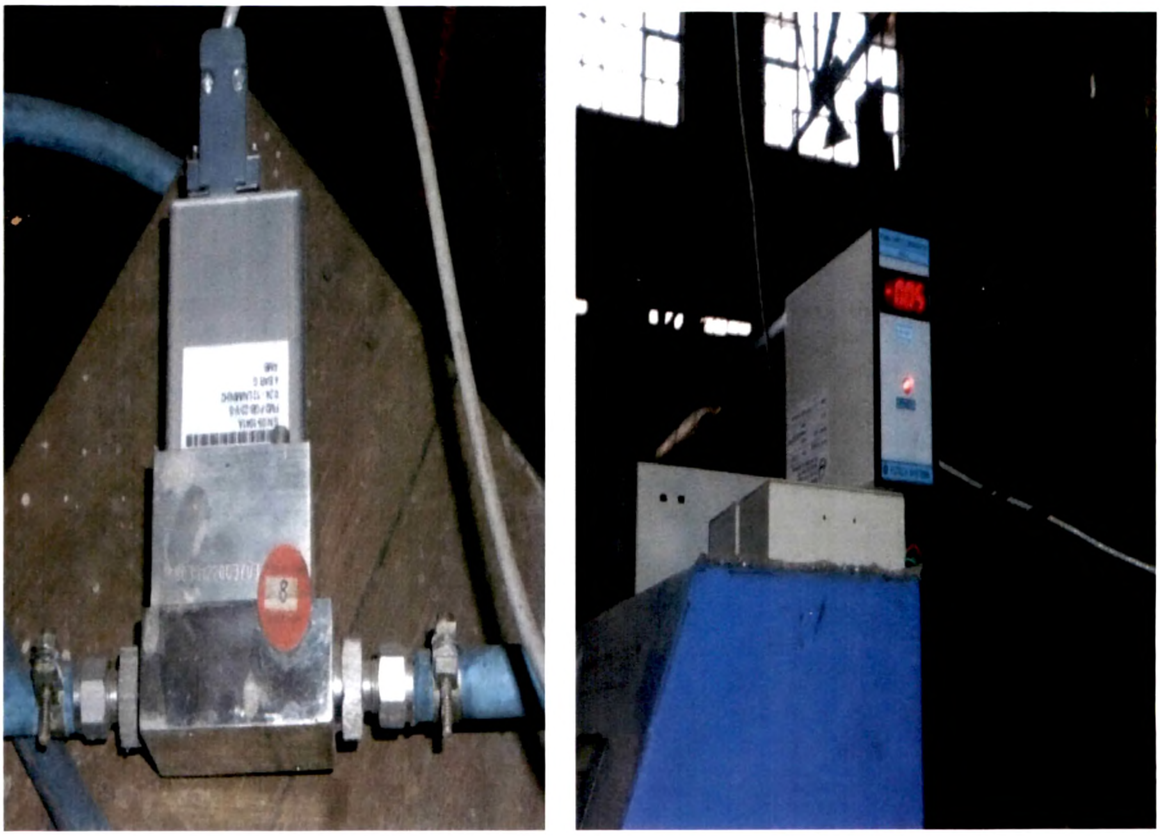


Plate 3.11 Digital Thermal Mass Flow Meter and its Display Screen

3.1.2.2 Environmental Variables

Environmental variables are atmospheric pressure, atmospheric temperature, and diesel fuel properties. Plate 3.12 gives the image of the barometer used to measure the atmospheric pressure. PT100 thermometer is used to measure the atmospheric temperature. Diesel fuel used during the experimental study is from the same lot acquired from the same refinery to ensure consistency in properties.

The fuel tests are carried out from a recognized laboratory to measure density, viscosity, caloric value, cloud point, flash, point, pour point, cetane number, and acidity of fuel sample. The properties of diesel and hydrogen are tabulated in Table 3.2.

Plate 3.12 Barometer

3.1.2.3 Response Variables

The response variables are categorized in to two based on the thermal performance prediction and the emission constituents during the running of the system. The response variable for the thermal performance are engine torque and brake power, fuel consumption rate, engine exhaust temperature and air or air-hydrogen mixture flow rate while that of the emission constituents are CO, CO_2, SO_2 and NO_X. The following sections describe the measuring systems used for each one of them.

3.1.2.3.1 Measurement Systems for Thermal Performance Evaluation

The experimental studies for the evaluation of the engine performance with and without indirect induction of hydrogen in to the diesel engine running with diesel alone and diesel- additive mixture need the measurement of engine torque and brake power, fuel consumption rate, cooling water temperature rise, calorimeter temperature, exhaust gas temperature and air/air-hydrogen flow rate

Table 3.2 Diesel and Hydrogen Properties

Sr.	Properties	Diesel	Hydrogen
1	Chemical formula	$C_nH_{1.8n}$	H_2
2	Molecular weight	170	2.016
3	Density (at 16 °C, 760 mm Hg) [kg/m^3]	833-881	0.0838
4	Specific gravity	0.84-0.88	0.0051
5	Kinematic viscosity (m^2/s)	$3*10^{-7}$	0.001
6	Dynamic viscosity (kg/m.s)	0.0025	$8.75*10^{-5}$
7	Thermal conductivity (W/m.K)	0.1768	0.1805
8	limits of combustion in air by volume [%]	0.7-5	4-75
9	Minimum ignition energy in air [mJ]	-	0.02
10	Self ignition temperature [K]	530	858
11	Flame temperature in air [K]		2318
12	Flame speed in air at normal condition [cm/s]	30	265-325
13	Hydrogen Diffusion in air at normal conditions [cm^2/s]	-	0.63
14	Limits of flammability (Equivalence ratio)	-	0.1-7.1
15	Quenching gap in NTP air (cm)	-	0.064
16	Stoichiometric air/fuel ratio on mass basis	14.5	34.3
17	Air/fuel ratio (in unit of volume)	-	2.38
18	Net heating value (MJ/kg)	42.5	119.93
19	High heating value (MJ/kg)	44.8	142
20	Low heating value (MJ/kg)	42.5	120
21	Heat of vaporization (kJ/kg)	270	-
22	LHV of stoichiometric mixture (MJ/kg)	2.74	2.83
23	Flame luminosity	High	Low
24	Octane number	30	130
25	Cetane number	40-55	-
26	Specific heat (kJ/kg.K)	2.2	1.44 (C_p)
27	Flash point (°C, K)	> 62	<-253,20
28	Pour point	-35 to -15	
29	Boiling point	188 -343	-253, 20
30	Cloud point	-15 to - 5	-

- **Engine Torque and Brake Power**

Eddy current dynamometer is used to load the engine which in turn may be used to estimate the brake power. The angular speed and the torque are measured for this purpose. The torque is estimated from the force applied during each loading and is equal to the product of the perpendicular distance between the centre axis of the eddy current dynamometer and that of the strain gauge. The torque is the force that the engine tries to apply against the force excited by the dynamometer. 0 to 50 kg Strain gauge (S beam type) is used to measure the torque.

The strain gauge has a bridge circuit which is excited from the transmitter and the load will change this balance, this change will be amplified and filtered from the transmitter and sent it to the data logger or the scanner as output. Plate 3.13 is an image of the load cell mounted on the system to measure torque.

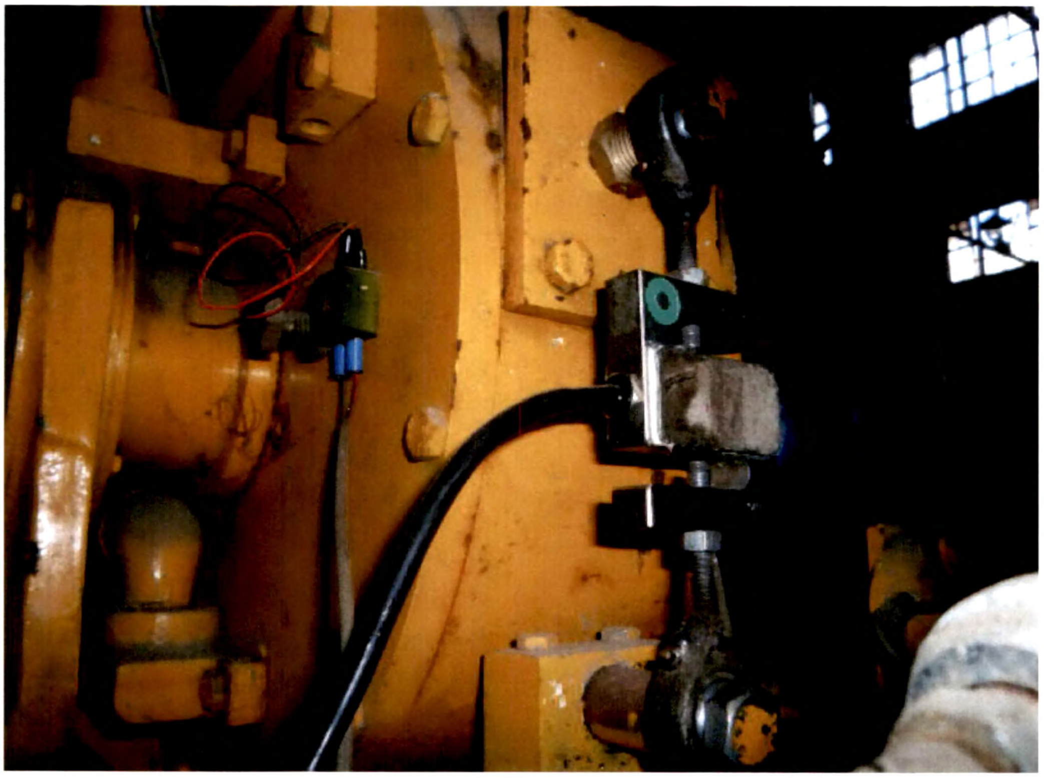


Plate 3.13 Load Cell Mounted on the System to Measure the Torque Developed

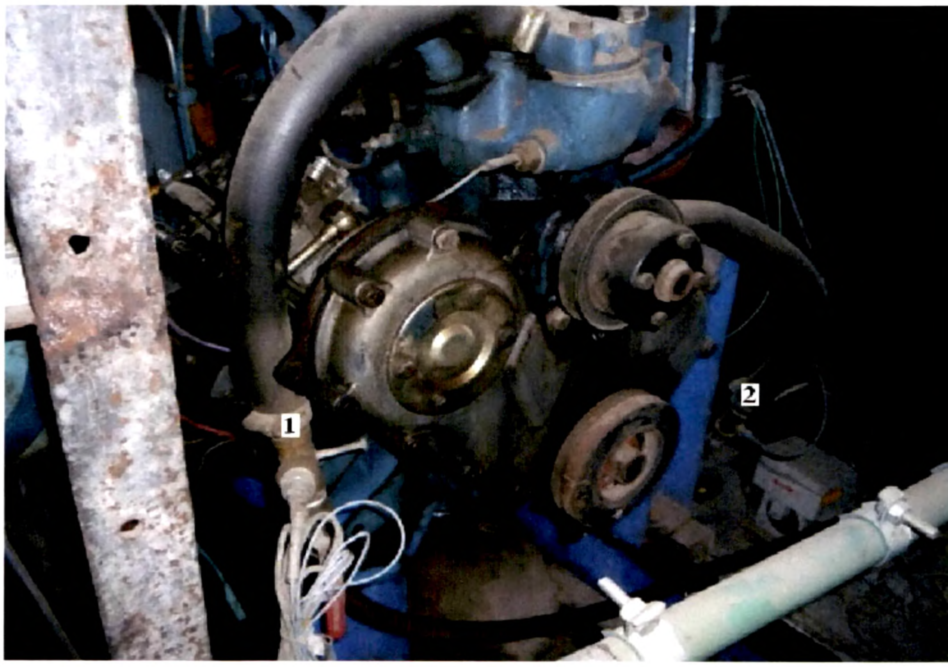
- **Fuel Consumption Rate**

Measurement system for the fuel consumption rate consists of a fuel tank provided with cantilever load cell (strain gauge), a transmitter and a data logger. The cantilever load cell mounted on the fuel tank senses the weight reduction of the fuel tank due to the fuel consumption rate during the running of the engine and transmits the signal to a data logger via a transmitter. The transmitter excites the strain gauge by the application of a small amount of voltage to create a balance in the bridge of the strain gauge. The loading of the strain gauge results in the unbalancing of one of the resistances of the bridge. The difference of voltage on the resistance gets amplified and filtered and transmits out signal to data logger or scanner. The data logger/scanner transmits the data to a computer which in turn is processed to recognize the consumption rate using suitable software. The load for the strain gauge is 0 to 3000 gram. For this reason, the weight of fuel plus the tank weight should not exceed 3000 gram to avoid damage of the strain gauge. The fuel consumption rate is the difference between the final and initial weights of the fuel in the tank during an interval of time. Plate 3.14 gives an image of the cantilever type load cell mounted on the fuel tank.

Plate 3.14 Cantilever Type Strain Gauge Mounted on Fuel Tank

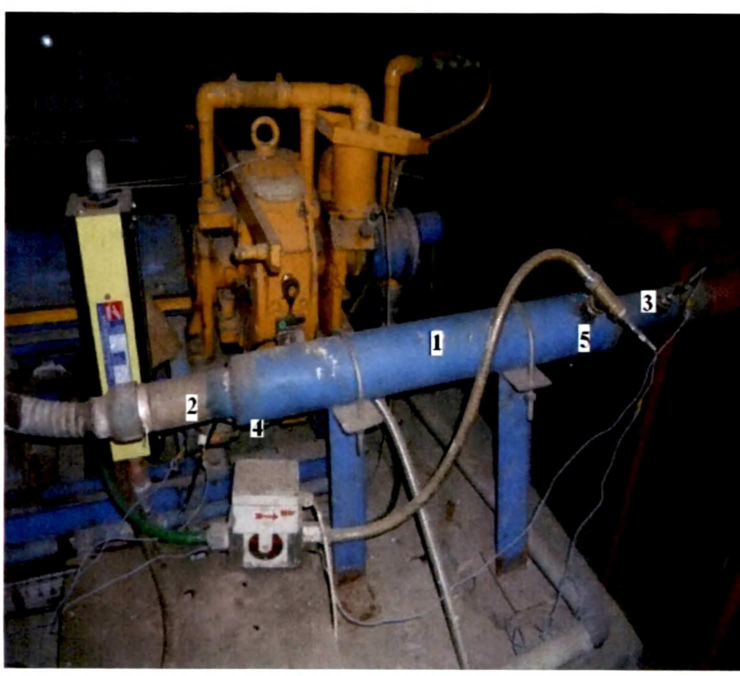
- **Temperature & Temperature Rise**

A major part of the heat energy released during combustion of the fuel is lost to surroundings through exhaust gases and through the engine cylinder surface wherein cooling water is circulated through jackets to keep the material of construction of the engine cylinder intact with respect to metallurgical point of view. Thus it is necessary to measure the rise in temperature of the cooling water circulated through the water jacket and the exhaust gas temperature from the engine to assess the lost energy. The exhaust temperature also indicates the steady nature of the engine condition during the normal operation. PT 100 temperature sensors are used to measure all the temperatures. The inlet and exit temperatures on the exhaust gas side as well as cooling water side of the calorimeter are also measured. Plates 3.15 and 3.16 are the images of the mounting locations of PT 100 temperature sensors for cooling water circulation loop across the water jacket and calorimeter respectively.



1. Inlet Cooling Water Temperature Sensor
2. Outlet Cooling Water Temperature Sensor

Plate 3.15 Mounting Locations of Temperature Sensors across Water jacket



1. Calorimeter
2. Inlet Exhaust Temperature Sensor
3. Outlet Exhaust Temperature Sensor
4. Inlet Cooling Water Temperature Sensor
5. Outlet Cooling Water Temperature Sensor

Plate 3.16 Mounting Locations of Temperature Sensors on Calorimeter

- **Air Flow Rate**

Natural aspirated diesel engine works with excess air. The amount of air entering the engine varies with the speed and the load. An air surge tank with water manometer is used to measure the air flow rate. The air surge tank has an orifice with 25 mm diameter and is connected to water manometer to measure the difference in the pressure across the orifice due to the air sucked by engine.

3.1.2.3.2 Measurement System for Constituents of Engine Exhaust Emission

The constituents of engine exhaust emission are measured and analyzed using a multi gas analyzer. Plate 3.17 shows the images of multi gas analyzer and the connectivity of the sample acquisition systems. Electro chemical sensors are used to analyze the constituent gases. The analyzer can analyze the following constituent gases: percentage O_2 in the range of 0 to 25 % with 1 % resolution, percentage CO_2 in the range of 0 to 2 % with 0.001% resolution, SO_2 in ppm in the range of 0 to 2000 ppm with 1 ppm resolution, NO in ppm in the range of 0 to 2000 ppm with 1 ppm resolution, NO_2 in ppm in the range 0 to 2000 ppm with 1 ppm resolution, percentage HC (hydrocarbons) (CH_4) in the range of 0 to 5% with 0.01 % resolution. The percentage CO_2 can be estimated.

Plate 3.17 Multi Gas Analyzer & Gas Sampling Unit

3.1.2.4 Data Acquisition System

A low speed data logger is used to capture the data consisting of input control variable and transfer the same to a personal computer for synthesis and storage. The data logger is a 24 channel logger with appropriate software. Seven PT 100 temperature sensors, two strain gauges, and hydrogen digital mass flow meter are connected to the data logger. The system saves the data in its database in an interval of 5 seconds and stores in a Microsoft excel file. Plate 3.18 shows the data acquisition system used in the experimental investigation.

All the measuring sensors and instruments discussed in the previous section and used in the present experimental study are calibrated against traceable standards in recognized laboratories. Appendix I gives the photocopy of the calibration certificates.

Plate 3.18 Data Acquisition System

3.2 Experimental Procedure

The experimental procedure followed in the present study for thermal performance evaluation and constituent emission measurements for the three different experimental programs on compression ignition engine with only diesel fuel, hydrogen induction in engine manifold with diesel fuel injection and hydrogen induction in engine manifold with dimethoxymethane DMM (methylal) as additive to diesel are as under:

3.2.1 Diesel Oil only as Fuel

1. Check all the instruments, connections to all piping for leakage, fuel level, oil level and cooling water line.
2. Switch on all the digital and electric instruments.
3. Check the cooling, lubricating and fuel systems of the engine for their smooth operation.
4. Run the engine on no load condition for few minutes to warm up the system.
5. Select a predetermined speed under no load condition and wait for the steady state condition to attain. The steady state condition is said to have achieved when the exhaust temperature becomes steady and constant.
6. Record all the input control variables and environmental variables through the various systems that are incorporated with the engine. Most of the variables are fed in to the computer via the data logger.
7. Repeat the observations under different loading conditions using eddy current dynamometer.
8. Bring the engine to no load condition before switching off the engine.

3.2.2 Diesel Oil Supplemented with Indirect Hydrogen Induction in Manifold

1. Check the hydrogen induction system for its experimental preparedness. For this, check the working of pressure regulators, filtering device, hydrogen flow control valve, mass flow meter, the flash arrester, the flame trap and nozzle.

2. Check all the connection between various units of the induction system to prevent any leakage of hydrogen. It should be noted that hydrogen has highest diffusivity characteristics of about 3 to 8 times in air. Any hydrogen leakage will result in quicker dispersion in air compared to that of hydrocarbon dispersion. Hence, formation of cloud of hydrogen vapor in the working space should be prevented. Good ventilation around the induction system is essential during the engine running condition. The hydrogen cylinders are also stored away from the working environment for safety reasons.

3. Repeat the steps 2 to 5 of Section 3.2.1.

4. Start the induction system by suitably adjusting the opening of the hydrogen pressure regulator valve. The pressure difference between the hydrogen intake line and air intake manifold should be adjusted for a continuous induction rate.
5. Set a predetermined flow rate of hydrogen by adjusting the opening of fine flow control valve.
6. Repeat the steps 6 to 8 of Section 3.2.1.

3.2.3 Diesel Oil with Additive and Supplemented with Indirect Hydrogen Induction in Manifold

1. Blend a proper proportion of dimethoxymethane DMM (methylal) with diesel oil.
2. Repeat the steps 1 to 6 given in Section 3.2.2.

3.3 Experimental Programme

The experimental programme planned for the present research consists of the following:

1. Experimental evaluation of the thermal performance and engine exhaust gases emission characteristics using various indirect and continuous hydrogen induction rate into the engine manifold of diesel engine operated with diesel oil and compare the same with that of engine operating with only diesel fuel,
2. Experimental evaluation of the thermal performance and engine exhaust gases emission characteristics using various indirect and continuous hydrogen induction rate into the engine manifold of diesel engine operated with diesel oil and di-methoxymethane (DMM) (Commercial name is methylal) as additive and compare the same with that of engine operating with only diesel fuel and with and without hydrogen induction.
3. Experimental optimization of the thermal performance and engine exhaust gases emission characteristics using various indirect and continuous hydrogen induction rate into the engine manifold of diesel engine operated with diesel oil and DMM as additive.

3.3.1 Comparative Study of Diesel Engine Performance & Emission with and without Hydrogen Induction

Few preliminary experiments are carried out to check the proper functioning of all the instruments incorporated in the compression ignition system.

3.3.1.1 Conventional Test

The conventional experimental studies on performance and emission on compression ignition engine with only diesel is carried out for the following range of input control and environmental variables.

1. Engine speed at a constant level ranging from 1000 rpm to 2000 rpm in steps of 250 rpm.
2. Engine load ranging from no load to maximum load condition which is indicated by the current range from 0 to 2 Ampere in steps of 0.5 Ampere at the eddy current dynamometer.

There are therefore, 25 sets of experimental test run conducted by keeping speed constant and varying the load applied from no load to maximum load condition.

3.3.1.2 Tests on Hydrogen Induction with Diesel Fuel

The hydrogen-air mixture is important factor affecting the engine performance and exhaust emissions. The hydrogen and air are assumed to homogenously mix before reaching the combustion chamber during the intake stroke. The pressure and temperature of hydrogen air mixture increase during the compression stroke. However, the hydrogen-air mixture cannot ignite due to the high ignition temperature and low cetane number of hydrogen. Hence, the diesel fuel injected during the compression acts as a pilot to ignite the hydrogen. A homogenous air-hydrogen mixture leads to high heat and pressure release during combustion. Therefore, the location of hydrogen induction in air intake port is important to get a homogenous mixture. Thus, one of the important preliminary tests is the experimental determination of the location of the induction of hydrogen in to air intake manifold. The arrangement as shown in Fig. 3.4 is used to experimentally locate the position of hydrogen induction. For this purpose, four locations 20 cm apart along the length of the straight portion of the air intake manifold having a diameter of 6.3 cm are chosen. Hydrogen at the same rate is inducted through each of these locations keeping all the control and environmental variables at the same level. It is found that the performance is not significantly affected with the hydrogen induction location. Therefore to ensure a better straight length of the air and hydrogen mixing , position 'd' is selected for the hydrogen induction for all the experimental studies.

The experimental studies on performance and emission on compression ignition engine with indirect induction of hydrogen in air intake manifold of compression ignition engine using diesel oil as fuel is carried out for the following range of input control and environmental variables.

1. Engine speed at a constant level ranging from 1000 rpm to 2000 rpm in steps of 250 rpm. The hydrogen induction will cause an increase in the speed which has to reset for the chosen speed.
2. Engine load ranging from no load to maximum load condition which is indicated by the current range from 0 to 2 Ampere in steps of 0.5 Ampere at the eddy current dynamometer.
3. Hydrogen induction rate ranging from 1 to 18 l/min in steps of 1 l/min for each chosen speed as well as load.

There are therefore, 450 sets of experimental test run conducted by keeping each speed constant and each hydrogen induction rate while varying the load applied from no load to maximum load condition. Table 3.2 gives the data captured during steady state working condition of the engine for diesel and diesel hydrogen blends.

3.3.1.3 Tests on Hydrogen Induction with Diesel + DMM Fuel Blends

Methylal or dimethoxymethane DMM ($C_3H_8O_2$) is one potential alternative oxygenated diesel fuel or blend component that has attracted some interest. DMM has a high oxygen fraction, high cetane number, and exists in a liquid state in normal conditions, making it convenient for blending with diesel, storage and transportation. DMM can be manufactured by oxidation of methanol or by the reaction of formaldehyde with methanol.

It can also be produced via the catalytic oxidation of dimethyl ether (DME). It should be noted that methanol can be synthesized from bio- source thus eliminating the use of fossil fuel for its production. Table 3.3 gives the DMM properties.

Table 3.3 Properties of DMM

Property	Value
Molecular Formula	$C_3H_8O_2$ or $CH_3OCH_2OCH_3$
Molecular weight	76.10
Density (kg/m^3)	860
Caloric Value (MJ/kg)	25.67
Vapour pressure at 20 ° C (kPa); of;	43.99
Oxygen contains (% by weight)	42.47
Flash point (°C)	-17 °
Melting point (° C)	104.8
Boiling point (° C)	42.3
Others	colorless liquid a similar chloroform odor, soluble in diesel

The researchers used a compression ignition engine in their study at different level of diesel/DMM blends: 5 to 50% by volume. With increasing DMM content, the oxygen content of the fuel blends increases, ranging from 2.16 to 21.36%, but decreases the heating values and decreases cetane number. Normally these fuel blends are tested under different loads and engine speeds. It is also found that brake specific fuel consumption (BSFC) together with cyclic fuel injection increases along with the DMM volume fraction while keeping the power output unchanged. While the 10 to 15% DMM blend reduced smoke, CO and CO_2, it is found that the volume fraction of DMM more than emission increases NO_x and HC emission. However, the use of the 40 to 50% DMM blend would require modifications to the engine, such as 15% enlargement of the diameter of the pump plunger to supply more fuel in order to, to avoid power loss.

The experimental studies on performance and emission on a compression ignition engine with indirect induction of hydrogen in air intake manifold of compression ignition engine using diesel/DMM blend as fuel is carried out for the following range of input control and environmental variables.

1. Engine fuelled with diesel blended by 10% DMM by volume.

2. Engine speed at a constant level ranging from 1000 rpm to 2000 rpm in steps of 250 rpm.

3. Engine load ranging from no load to maximum load condition which is indicated by the current range from 0 to 2 Ampere in steps of 0.5 Ampere at the eddy current dynamometer.

4. Hydrogen induction rate ranging from 0 to 18 l/min in steps of 1 l/min for each chosen speed as well as load.

Therefore, there are 75 sets of experimental test run conducted by keeping each speed constant and each hydrogen induction rate while varying the load applied from no load to maximum load condition.

Experimental test data for the operation of CI engine operated with diesel alone, diesel with hydrogen induction rate varying from 1 l/min to 18 l/min and diesel/DMM blend with and without hydrogen induction at a constant speed of 1500 rpm under various loads are given in Appendix II. The complete data set is presented in a compact disc provided with the thesis. The calculated response variables based on the chosen control and environmental variables are also presented. It should be noted that the environmental variables are noted and incorporated as per the requirements. Table 3.4 represents the maximum and minimum uncertainty for test at 1500 rpm. Appendix III gives the uncertainty analysis carried out based on the experimental data for few selected test runs. The analysis is based on the method suggested by Kline and McClintock [90] on single sample experiment. Appendix IV gives a sample calculation.

Table 3.4 Uncertainty of Some Quantity at Maximum and Minimum Load for 1500 rpm

Quantity	Uncertainty at Maximum Load (%)	Uncertainty at Minimum Load (%)
Brake thermal efficiency	2.00	2.00
Volumetric efficiency	4.94	5.25
Equivalence Ratio	5.34	5.27
Brake Specific Energy Consumption	2.00	2.00

3.4 Results and Discussion

3.4.1 Using Diesel Oil as Fuel

The conventional experimental test run is carried out on the four cylinder compression ignition engine by using diesel oil as fuel. The results of the test run are primarily used to validate the system capability and readiness to carry out further experimental study on hydrogen-diesel dual fuel without and with additives. The experimental results are presented in two parts.

Firstly, the results of the thermal performance tests are presented in terms of the variation of brake power, diesel fuel consumption, brake thermal efficiency, volumetric efficiency, brake specific energy consumption and exhaust temperature with load for different chosen speeds. The load applied due to the eddy current dynamometer during the experiment is presented in terms of eddy current (Ampere).

Secondly, the exhaust gas emission constituents for each of the test runs conducted in the first case is presented in terms of percentage and ratio for the constituents like O_2, CO, CO_2, unburned HC, SO_2 , NO_2, NO and NO_x . The following sections give the details of the results of the experiments conducted on the engine using diesel oil as fuel.

3.4.1.1 Thermal Performance

- **Brake Power**

The power delivered by the engine and absorbed by dynamometer is the product of torque and angular speed. This power is the usable power delivered by the engine to the load exerted by the dynamometer rotor.

Fig. 3.6 presents the variation in brake power with load for different chosen speed. The trend observed is in conformity with that of a conventional compression ignition engine operated with diesel oil.

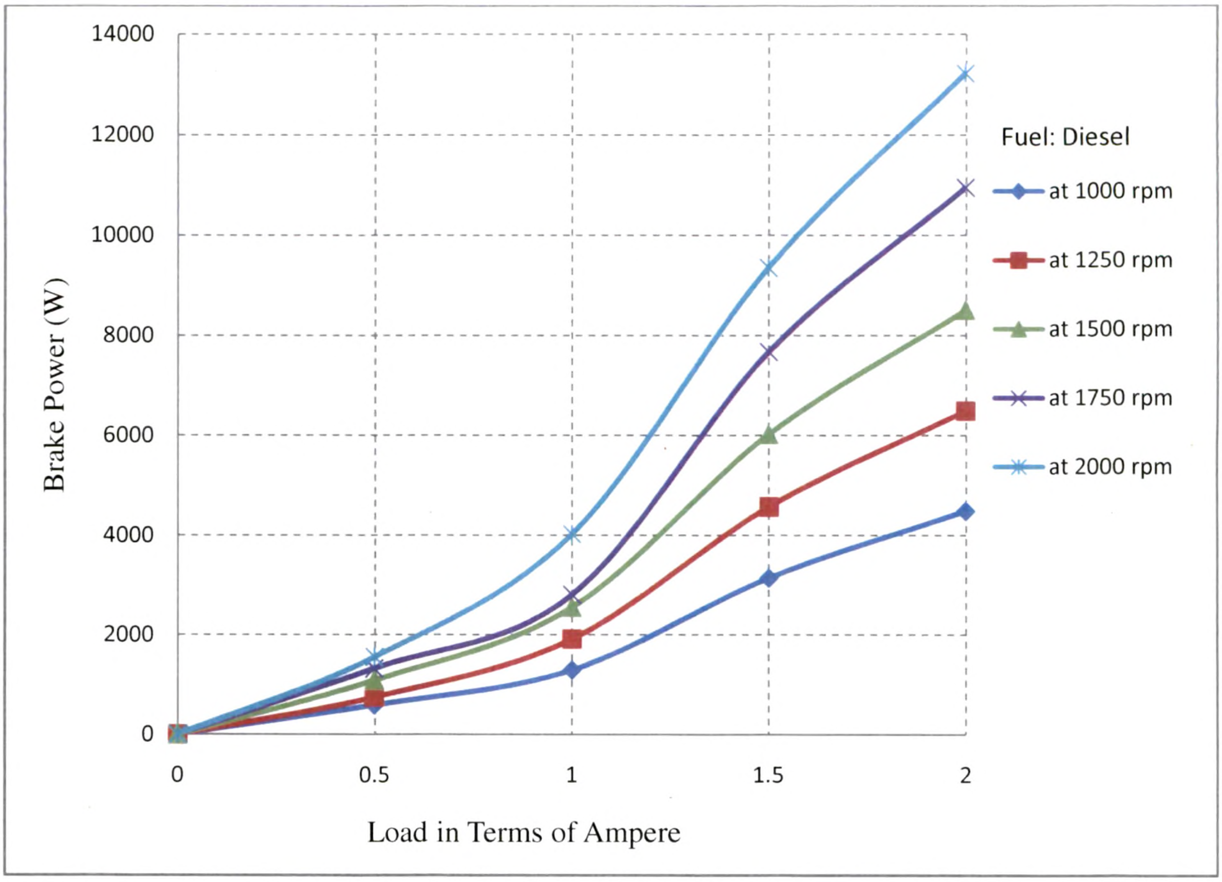


Fig. 3.6 Variation of Brake Power With Load at Different Engine Speeds

The variation in brake power with load, when the load applied is small of the order of 0.5 Amp. and less, is seen to be gradual and almost independent of the selected speed in the range from 1000 rpm to 2000 rpm. For the larger loading beyond the load of 0.5Amp., there is a significant increase in brake power with load. It is a well known fact that as the speed of the engine increases, the amount of air (and hence oxygen) intake in to the engine along with the injected fuel increases which results in an increase in power output. For these reasons, the brake power increases. Further, as the speed increases with the applied load held constant, it is seen that the brake power increases, the increase is larger at higher loading, as expected. It can also be seen that, the brake power output of the engine running at a constant speed of 2000 rpm increases by about 2.25 times when the load is increased from 0.5 Amp. to 2.0 Amp.

- **Diesel Fuel Consumption**

Fig. 3.7 gives the variation in diesel fuel consumption with the load at different speed. At smaller loads ranging from nearly no load to 1.0 Amp., the increase in diesel consumption is found to be gradual. However, the consumption rate increases significantly at higher loads as expected. The diesel fuel consumption increases 2.7 times from 376×10^{-6} kg/s to 1018×10^{-6} kg/s when the load increases from 0 Amp. to 2Amp. with the speed at 2000 rpm. The no load consumption rate is found to increase by about 2 times when the engine speed is increased from 1000 rpm to 2000 rpm.

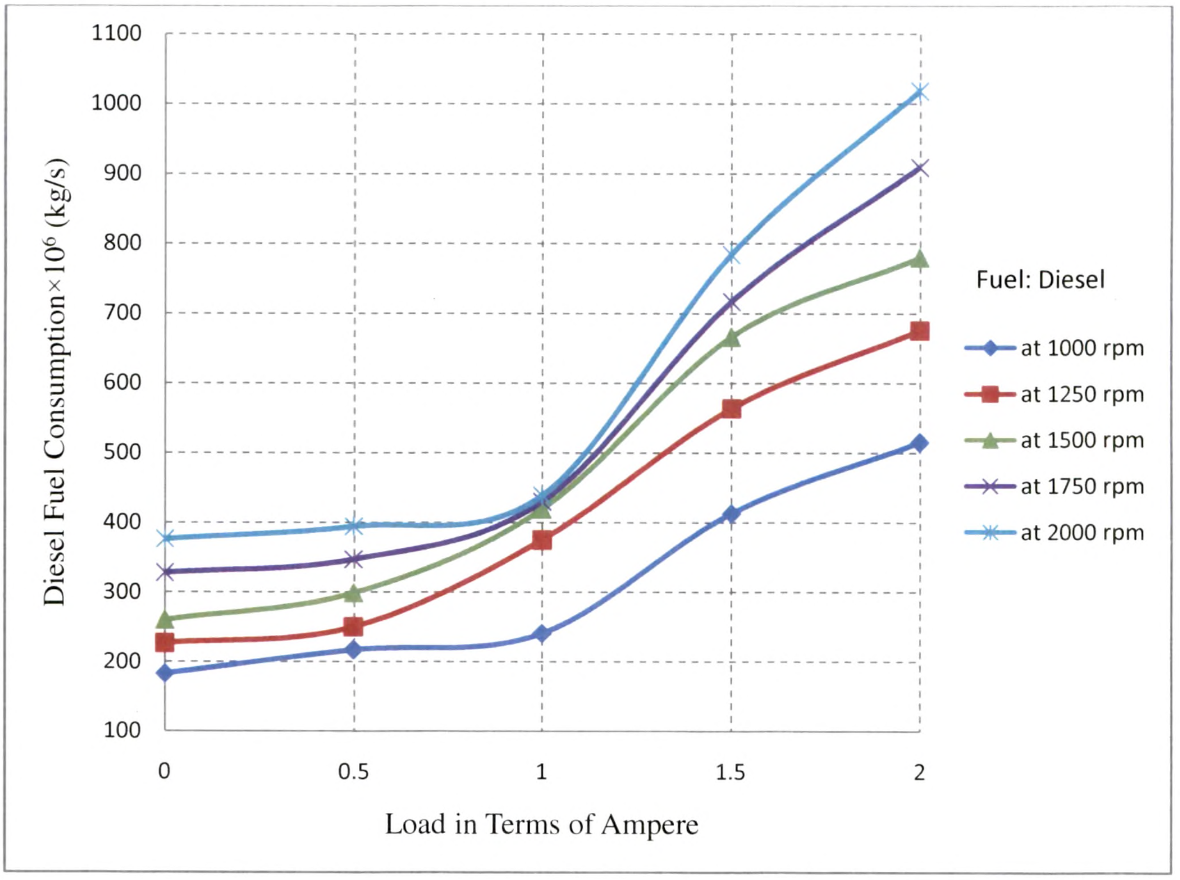


Fig. 3.7 Variation of Diesel Fuel Consumption with Load at Different Engine Speeds

- **Brake Thermal Efficiency**

Brake thermal efficiency is a parameter that indicates the efficiency of transforming process of the input energy which is released by chemical reaction in the form of heat to useful output power. Fig. 3.8 illustrates the variation of brake thermal efficiency with load at different speed.

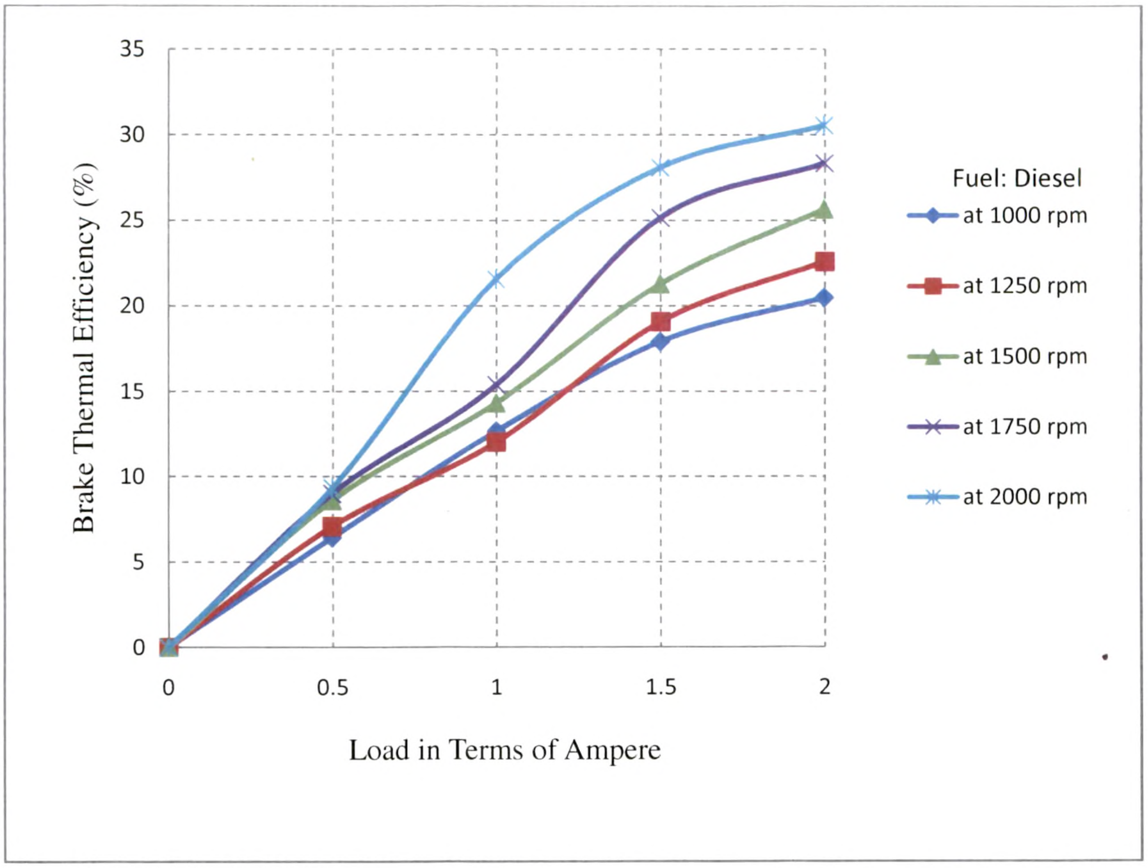
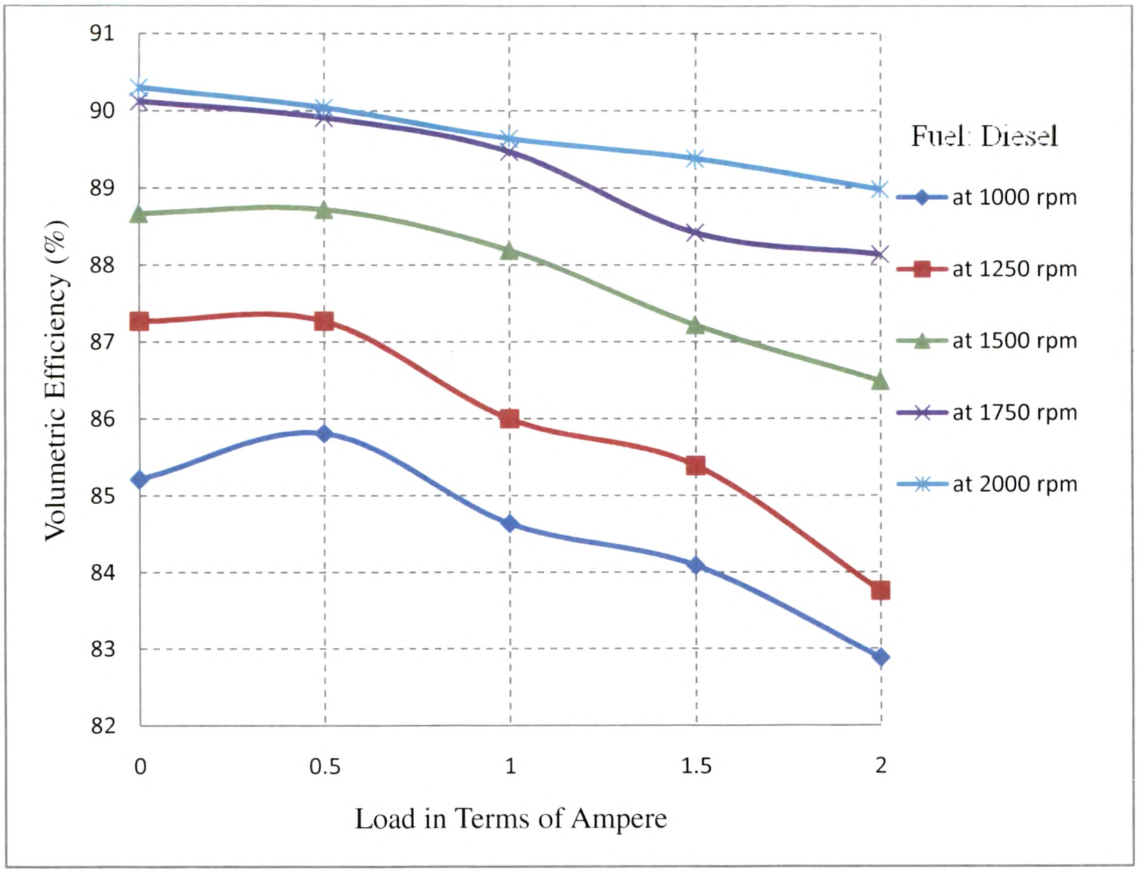


Fig. 3.8 Variation of Brake Thermal Efficiency with Load at Different Engine Speeds

It can be noted that at smaller load between nearly no load to about 0.5Amp. load, there is insignificant change in brake thermal efficiency with engine speed. However, at higher loads ranging from about 0.5 Amp. to 2.0 Amp., the brake thermal efficiency is found to be significantly higher at higher speeds. Brake thermal efficiency is found to be 20.49% and 30.55% respectively when the engine is operated at 1000 rpm and 2000 rpm with an applied load of 2.0 Amp. It should be noted that the brake thermal efficiency of the test engine at 30.55 % is within the values of the theoretical efficiency of 28 to 32% when operated at the maximum load and speed.

- **Volumetric Efficiency**

Combustion process mainly depends on the amount of oxygen in the combustion chamber which has to be sufficient to complete the fuel oxidation process. The atmospheric air contains 21% oxygen by volume as one of its components. Volumetric efficiency represents the ratio between the actual quantity of air passes through the intake valve of the engine and the theoretical design quantity which is represented by swept volume. The increase in volumetric efficiency indicates an increase in the oxygen content. Fig. 3.9 gives the variation in volumetric efficiency with load at different speeds.



3.9 Variation in Volumetric Efficiency with Load at Different Engine Speeds

The volumetric efficiency is maximum at no load and decreases as the engine load increases. The reason for such a trend may be attributed the increase in residual exhaust gases present in the combustion chamber as the load increases. At higher speed, the volumetric efficiency is found to be higher due to the increase in differential pressure between the combustion chamber and atmosphere which leads to drawing of more air in to engine. The increase in volumetric efficiency from 85.1% to 90.3% when the engine speed increases from 1000 rpm to 2000 rpm at no load is as expected.

- **Equivalence Ratio**

It is a ratio between actual and stoichoimetric fuel/air fraction and is an indicator to fuel/air blend strength or weakness. Generally, diesel engine operates with excess air which leads to make the fuel/air mixture weak or lean. Fig. 3.10 shows the variation of equivalence ratio with load at various engine speeds.

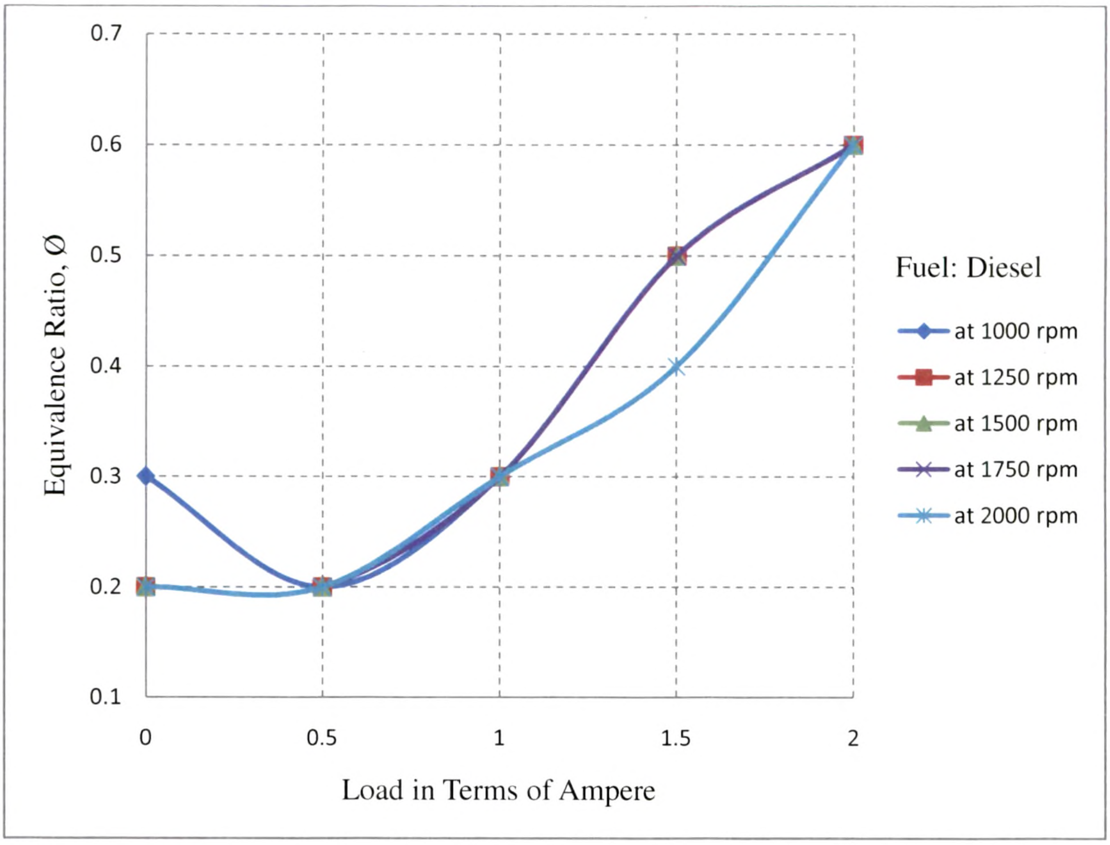


Fig. 3.10 Variation of Equivalence Ratio with Load at different Engine Speeds

The variation in equivalence ratio with load is as expected barring few experimental error observed. This variation is due to the increase in conventional fuel consumption. The equivalence ratio has the same values for all engine speeds approximately. The ratio varies between 0.2 and 0.6 which indicates that the engine has approximately the same actual fuel to air ratio at all speeds.

- **Brake Specific Energy Consumption (BSEC)**

The brake specific energy consumption (BSEC) may be used to indicate the quantity of energy required to produce useable power. Brake specific fuel consumption (BSFC) is replaced with BSEC due to the reason that the present investigation is planned to use energy from two sources, viz., hydrogen and diesel oil as input. Fig.3.11 depicts the variation of

BSEC with load at different engine speeds. It can be noted that BSEC decreases as the load increases. Further, it is seen that the BSEC decreases when the speed is increased. The above trends are in conformity with any compression ignition engine running with diesel oil as fuel.

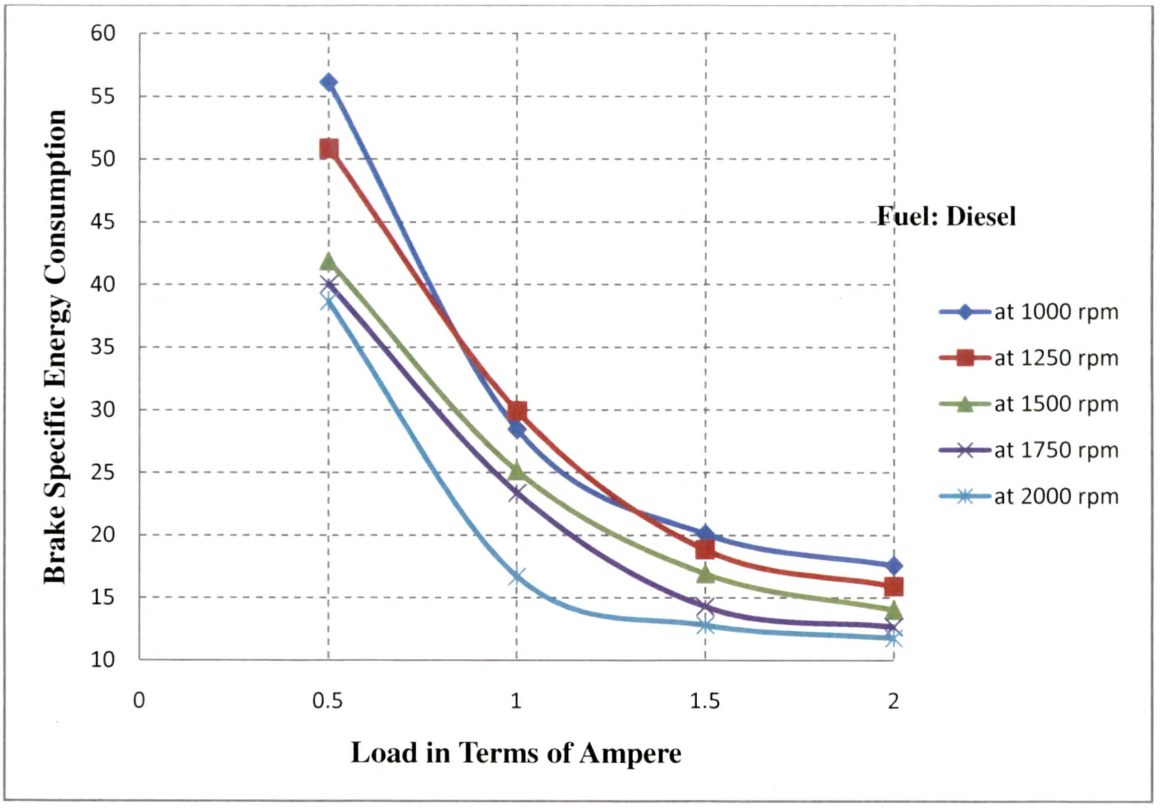


Fig. *3.11 Variation of Brake Specific Energy Consumption with Load at Different Speeds*

- **Exhaust Temperature**

Exhaust temperature represents the temperature of flue gases that comes out of the engine and can indicate the effectiveness of combustion process. Fig. 3.12 shows the variation of exhaust temperature with load at different engine speeds. With increases in load and speed, the exhaust temperature increases indicating enhancement in combustion process. At no load, the exhaust temperatures are found to be 73.09°C, 80.54°C, 87.88°C, 103.89°C and 115.27 °C for the engine speed at 1000, 1250, 1500, 1750 and 2000 rpm respectively while at a load of 2.0 Amp., the exhaust temperatures are at 177.83°C, 200.09°C, 242.89°C, 285.24°C and 370°C for the engine speed at 1000, 1250,1500, 1750 and 2000 rpm respectively. Thus, the minimum and maximum exhaust temperatures are respectively at 73.09°C at no load and 1000 rpm and 370°C at 2.0 Amp. load and 2000 rpm.

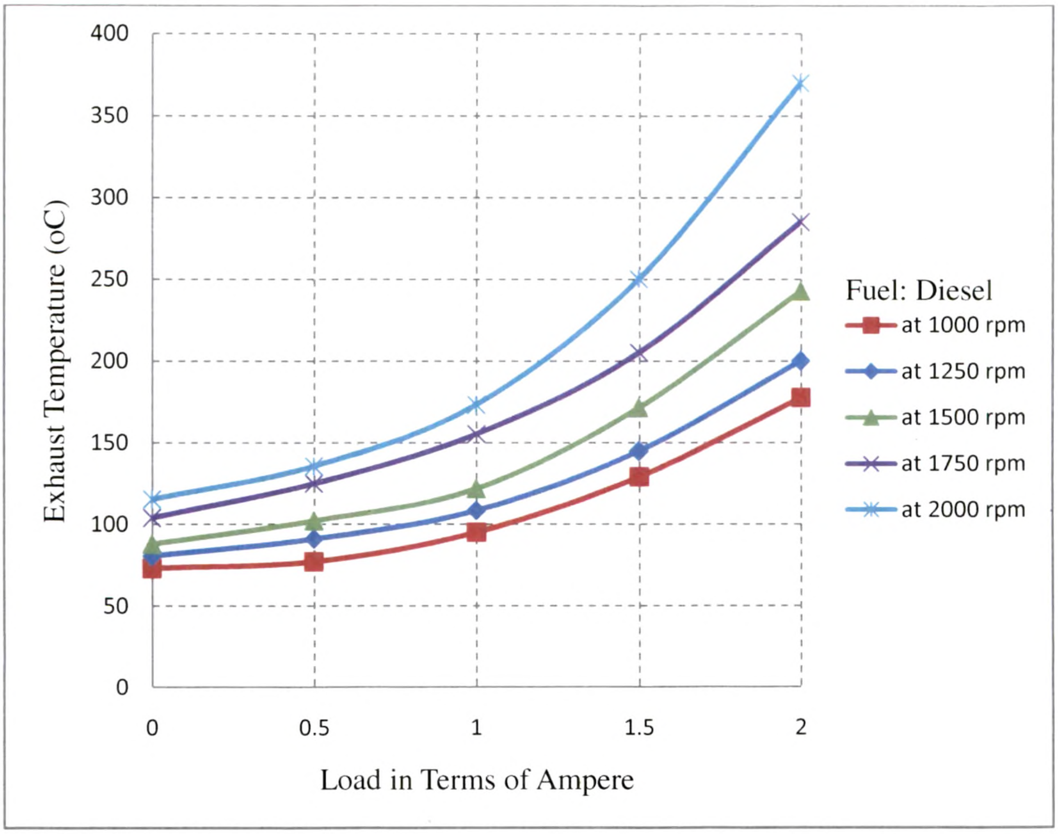


Fig. 3.12 Variation of Exhaust Temperature with Load at Different Engine Speeds

3.4.1.2 Constituents of Exhaust Gas Emission

While analyzing the constituents of exhaust gas emission, the focus is on the nitrogen oxides and soot more than the carbon oxides and unburned hydrocarbons in the case of compression ignition engines while in the case of spark ignition engines, the consideration is on carbon oxides. The present experimental study focuses on eight constituent gases, viz., O_2, CO, CO_2, HC, SO_2, NO_2. NO, NO_X in the exhaust of the CI engine. The constituent gases such as O_2, CO, CO_2 and HC are measured in terms of per cent of the exhaust while SO_2, NO_2. NO, NO_X are measured in part per million (ppm).

- **Oxygen (O_2) in the Exhaust**

It is a known fact that some of the oxygen present in the intake air to engine is not used in the combustion and get exhausted with flue gases. Fig. 3.13 gives the variation of oxygen in the exhaust with the load at different engine speeds. The per cent Oxygen content in the

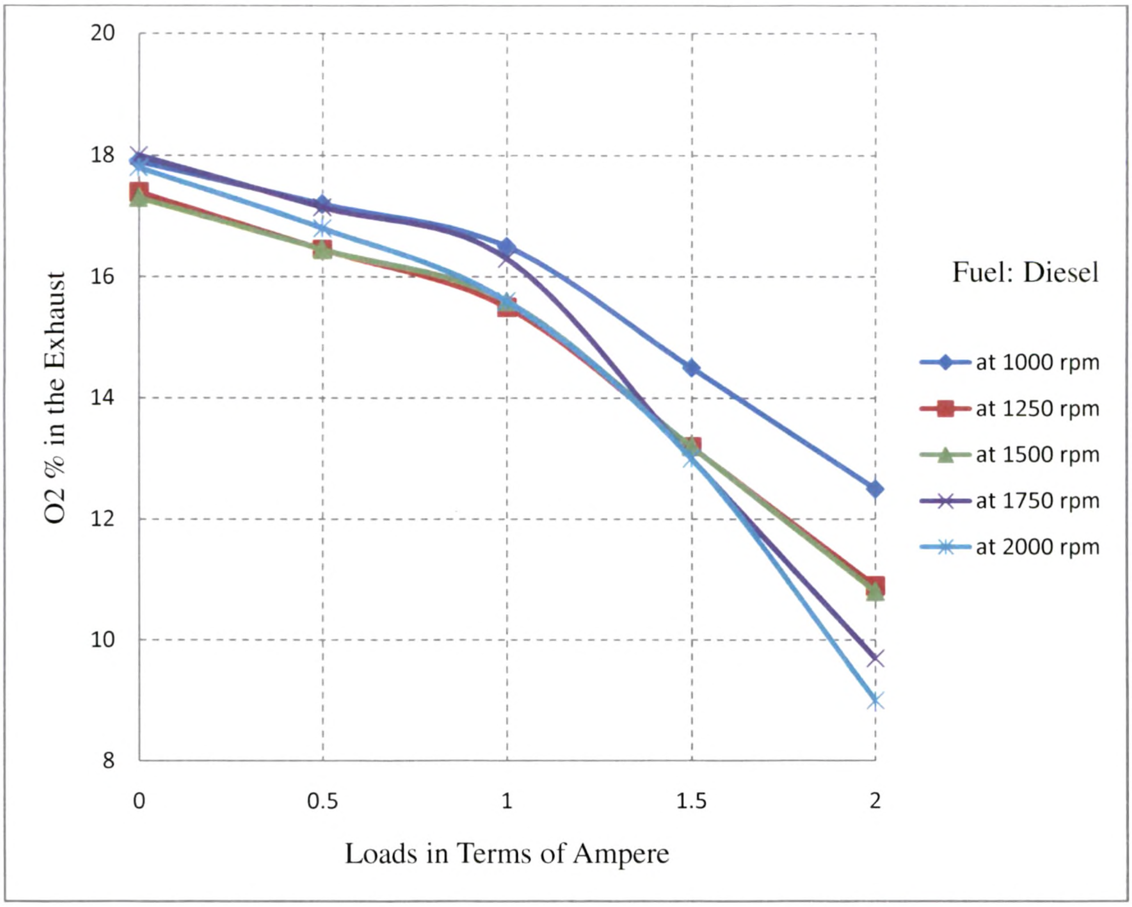


Fig. 3.13 Variation of Oxygen in Exhaust with Load at Different Engine Speeds

exhaust is found to decrease with increase in load and speed which is an indication of the enhancement in the consumption of O_2 during combustion process. At no load or smaller loads, i.e below the load of 1A, the percentage decrease in oxygen content is low ranging between 18% and 16% for all speeds. However, at higher load, the reduction is significant and is found to range between 16% and 9%.

- **Carbon Monoxide (CO) in the Exhaust**

The presence of CO in the exhaust gas is comparatively low and is found to be significantly lower at higher engine speeds of 1750 rpm and 2000 rpm. This trend may due the conversion of CO in to CO_2 when there is sufficient air supply through the intake manifold. Fig. 3.14 gives the variation of the presence of CO in exhaust with load at different speeds.

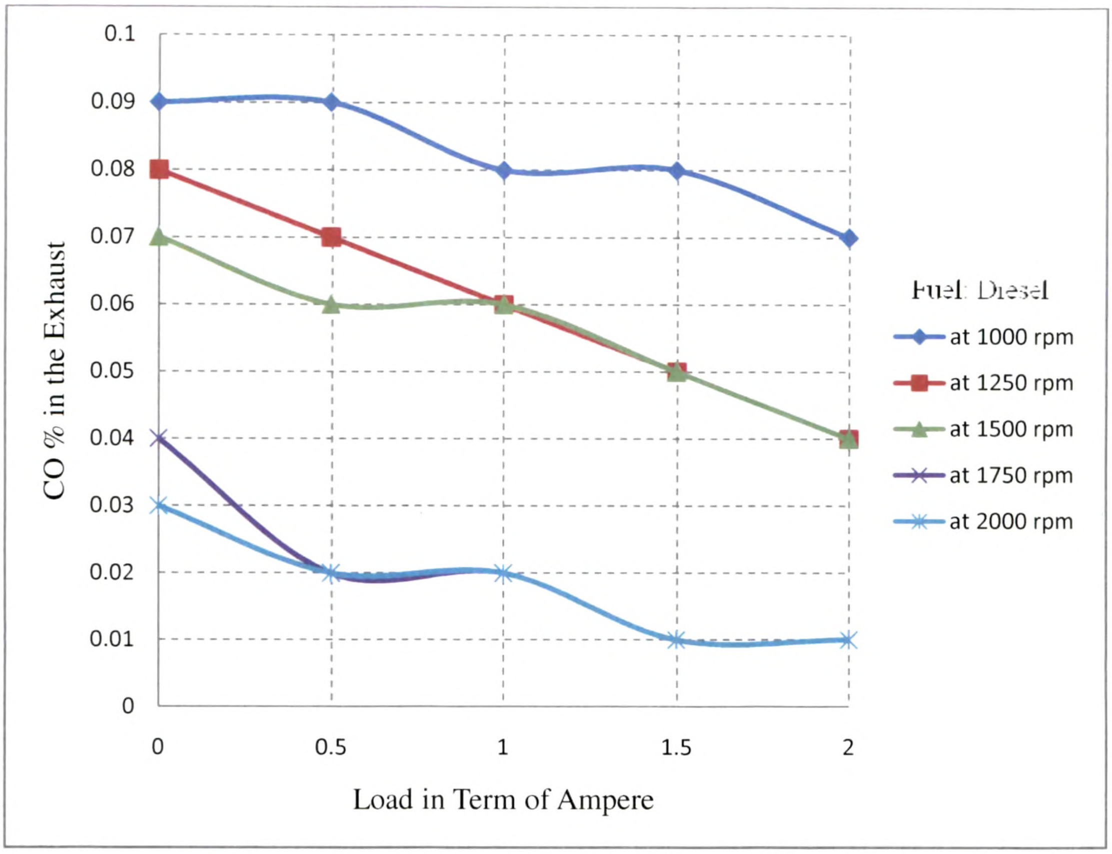


Fig. 3.14 Variation of Per cent CO in Exhaust with Load at different engine speeds

- **Carbon Dioxide (CO_2) in the Exhaust**

CO_2, one of the green house gases, is a trace gas with a presence of only 0.038% in the atmospheric air. The hydrocarbon fuel combustion invariably leads to the formation of CO_2, CO and HC. If the combustion takes place near stoichiometric condition, then the formation of CO_2 is significant as compared to CO and HC. The formation of CO and HC will be prominent if the combustion is farther away from stoichiometric condition. Fig 3.15 presents the variation of CO_2 with load at different engine speeds. It can be observed that there is a significant increase in CO_2 emission with load due to the increase the diesel oil consumption which results in an enhancement in the combustion process as compared to that at small loads. The conversion of CO and HC to CO_2 takes place when the combustion occurs in proper way or near the stoichiometric limit. Lean or weak mixture produces less CO_2 and high CO and HC emission. As the speed increases, there is significant increase in CO_2 emission which is due to the increase in fuel consumption. A Maximum of 8.0 % CO_2 emission is recorded at high load and speed.

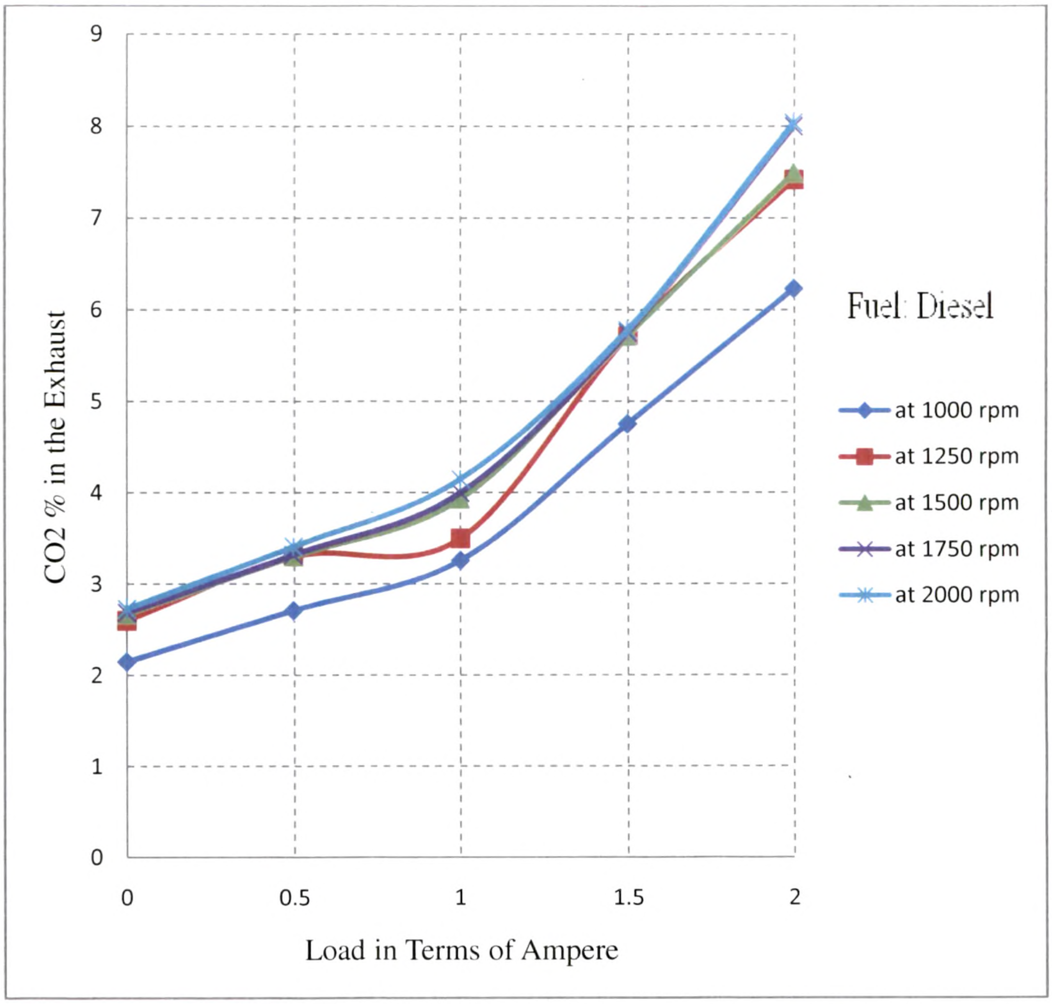


Fig. 3.15 Variation of Percent CO_2 in Exhaust with Load at Different Engine Speeds

- **Unburned Hydrocarbon (HC) in terms of CH_4 in the Exhaust**

The unburned hydrocarbon might be having many forms, one of that forms is the CH_4. In this investigation, the unburned hydrocarbon sensor measured HC in terms of CH_4. Fig 3.16 shows the variation of unburned hydrocarbon in per cent with load at different engine speeds. It can be seen that with the per cent HC content in gas emission decreases with load and speed. The reason for such a trend may be attributed to the enhancement in the combustion at high load and speed.

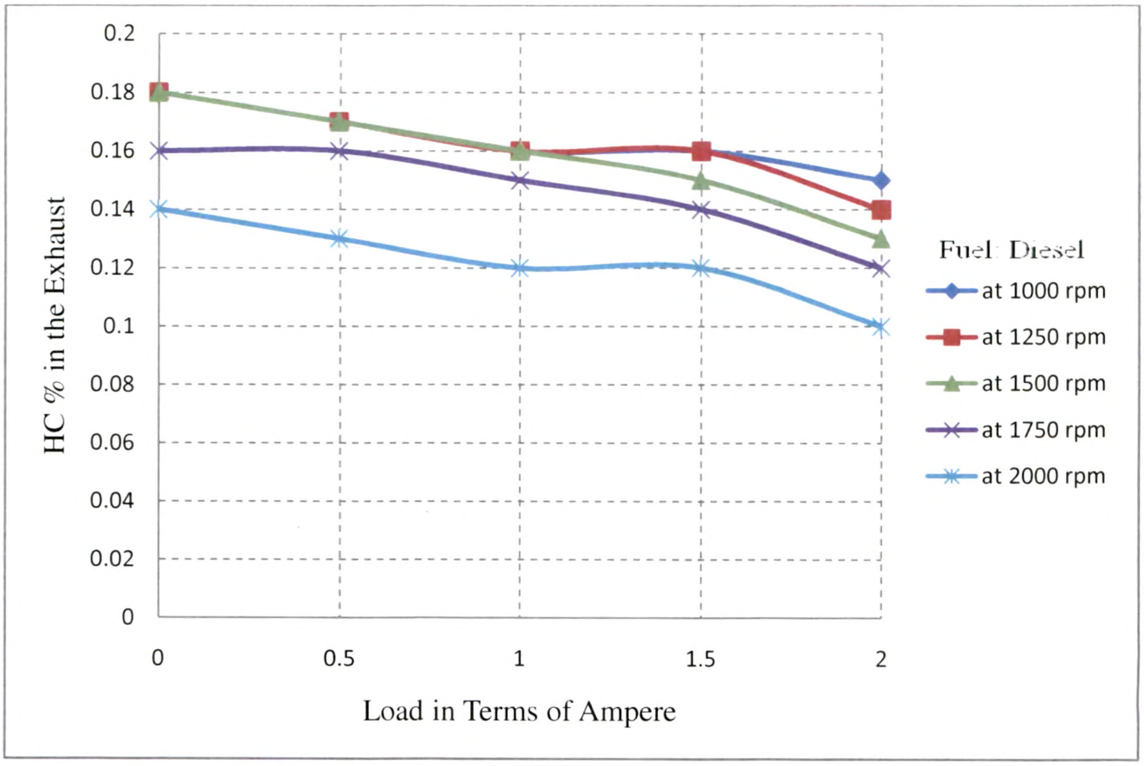


Fig. 3.16 Variation of Per cent Unburned Hydrocarbon in Exhaust with Load at Different Engine Speeds

- **Sulphur Dioxide (SO_2) in the Exhaust**

Sulfur is a naturally occurring element in hydrocarbon fuels. It is associated with asphaltenic fuels and correlated with vanadium content. Sulfur generally occurs in large aromatic molecules. Because of this, it is concentrated in residual oils or HFO.

In the combustion process, sulfur forms sulfur dioxide (SO2). This compound is relatively benign. However, it enters an equilibrium reaction with oxygen to form SO3 which combines with water to form sulfuric acid (H2SO4). The chemical reactions are as follows:

$$S^{-2} + O2 \longrightarrow SO2$$

$$SO2 + \tfrac{1}{2}\, O2 \longrightarrow SO3$$

The variation of SO_2 content in exhaust gases with load at different engine speeds is given in Fig. 3.17. It can be observed that with increase in load and speed, SO_2 percentage in the exhaust gases emission decreases. SO_2 content in exhaust gases significantly decreases with increase in speed from 1000 rpm to 2000 rpm under no load operating condition. For the speeds at 1500 rpm, 1750 rpm and 2000 rpm, the SO_2 content in exhaust gases varies from about 20 ppm to 10 ppm while the content increases by 7 times when the speed is decreased to 1000 rpm at no load condition. However, the SO_2 content in exhaust gases decreases drastically from about 140 ppm to about 60 ppm when the load is applied from nearly no load to full load at 2.0 Amp. with the engine speed at 1000 rpm.

At low engine speeds, SO_2 can be absorbed onto particulate matter (PM). The lower SO_2 value for diesel oil at low engine speed may be due to the higher level of PM produced by the fuel. At higher speeds, the SO_2 content in exhaust gases is very small and hence is incapable of holding PM. Further, at higher speeds such as 1750 rpm and 2000 rpm, an induction choking effect can reduce the amount of air and hence the availability of oxygen resulting in lower SO_2 emissions. It is to be noted that as SO_2 increases CO content in emission gases reduces.

- **Nitrogen Oxide (NO_2) in the Exhaust**

The formations of NO_2, NO and NO_X (the addition of NO_2 to NO) depend on the exhaust gas temperature and the percentage of oxygen content of atmospheric air inducted in combustion engine.

Fig. 3.18 presents the variation of NO_2 with load at different engine speeds. The increase of load leads to decrease in the NO_2 emission. Although the exhaust gas temperature increases, the NO_2 decreases due to the decrease in oxygen . As the speed of the engine increases, NO_2 converts in to NO and hence its content in the emission gases decreases. The increase in exhaust gas temperature gives the proper conditions for the formation of NO.

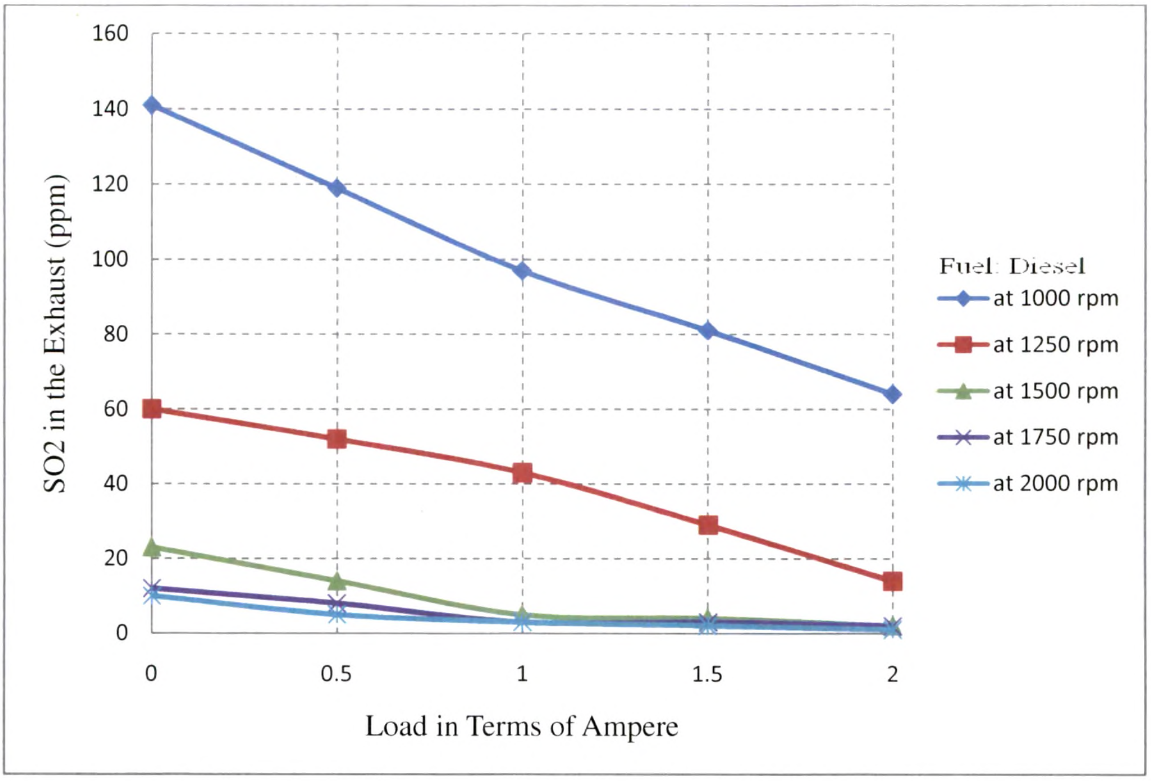


Fig. 3.17 Variation of SO_2 in ppm in Exhaust with load at Different Engine Speeds

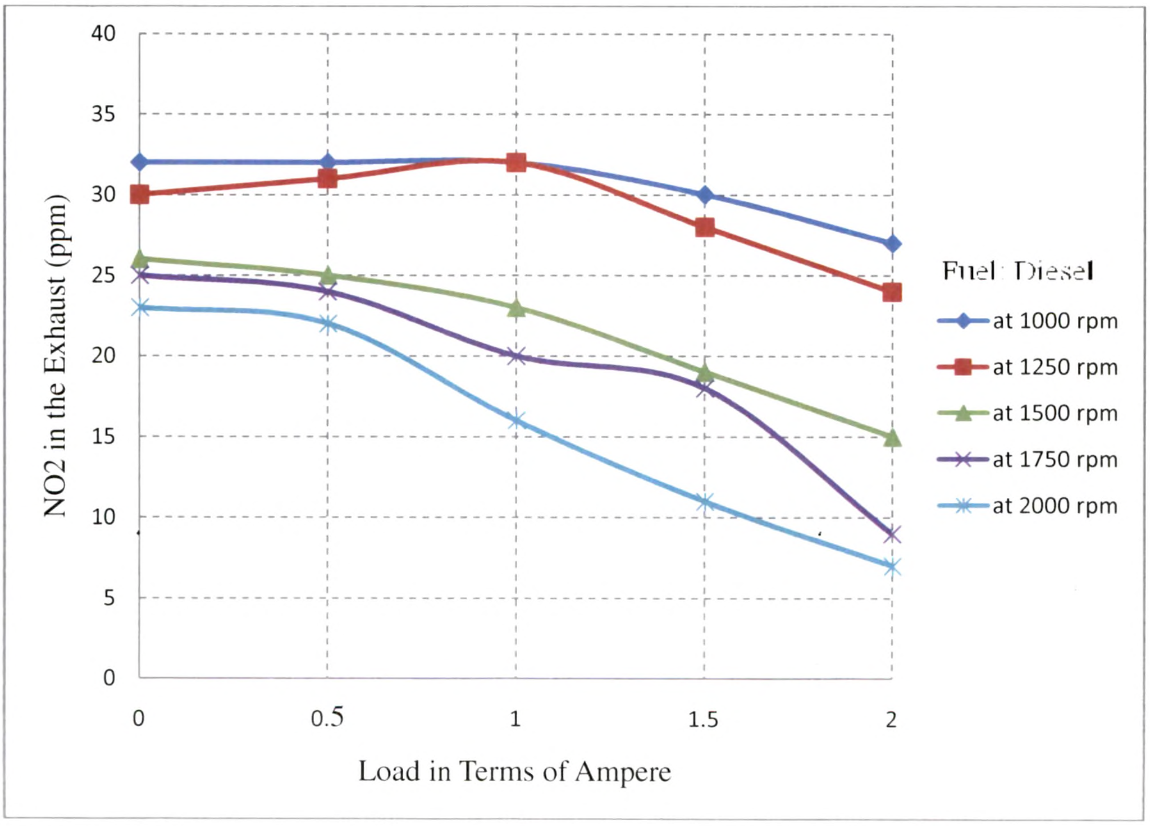


Fig. 3.18 Variation of NO_2 in ppm in Exhaust with load at Different Engine Speeds

- **Nitrogen Monoxide (NO) in the Exhaust**

Fig 3.19 shows the variation of NO content in the exhaust gases with load at different engine speeds. NO emissions increase with engine load and speed, as expected, which is due to the dependency of NO emissions on temperature. The value of NO content is found to be high, probably, due to high oxygen content in exhaust. NO emissions tended to be lower for those speeds at which O_2 emissions are high.

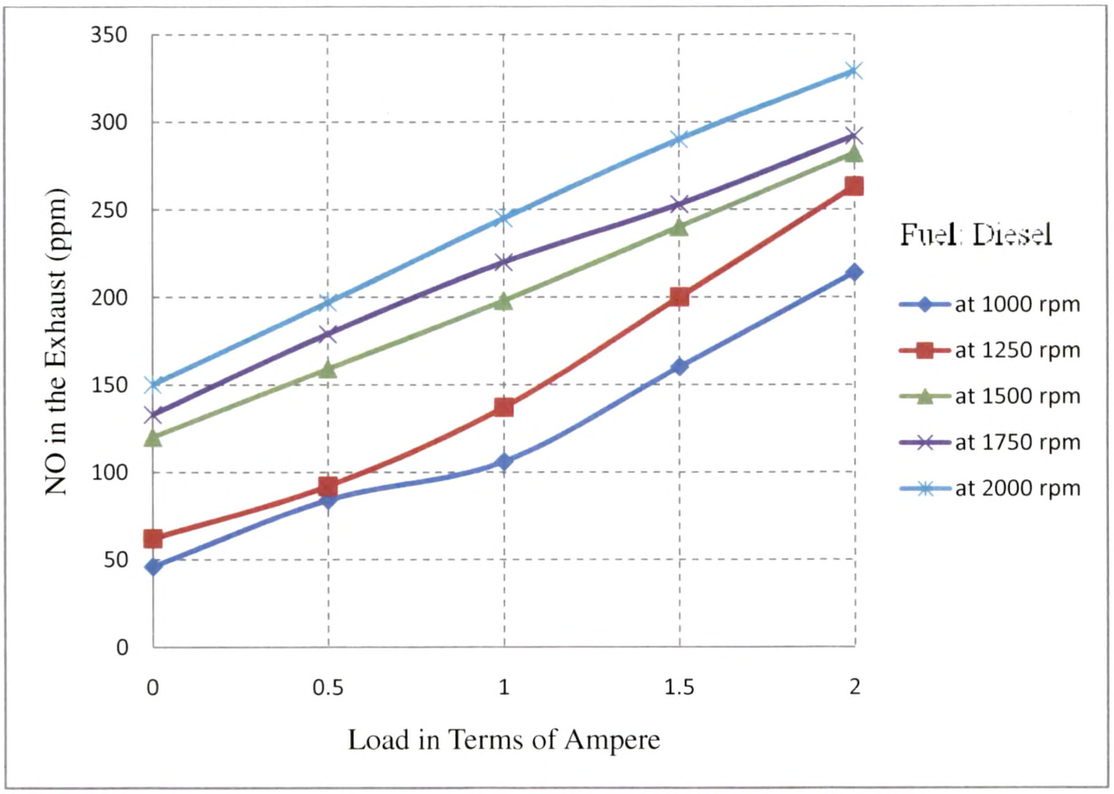


Fig 3.19 Variation of NO in ppm in Exhaust with Load at Different Engine Speeds

- **Nitrogen Oxides (NO_X) in the Exhaust**

Fig. 3.20 gives the variation of NO_X with load at different engine speeds. NO_X is the result of the presence of NO_2 and NO in exhaust gases. It can be noted that the formation of NO_X in the exhaust emission is due to largely the presence of NO rather than NO_2. As expected, the reason for the increase in NO_x content in the exhaust is due to the high oxygen content. The higher oxygen level available oxidises more nitrogen and increases the combustion temperature which results in the higher NO_X emission levels.

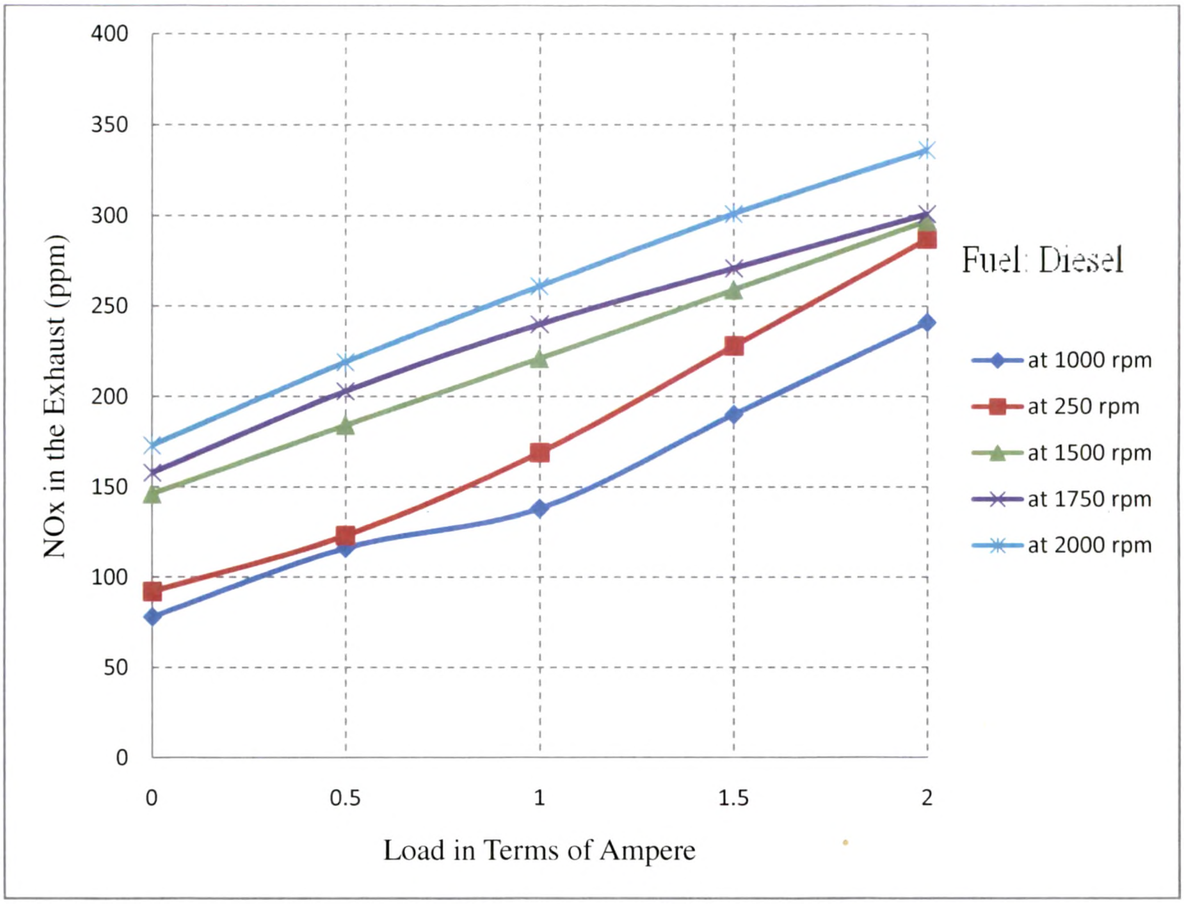


Fig 3.20 Variation of NO_X (ppm) in Exhaust with Load at Different Engine Speeds

3.4.2 Hydrogen Induction in the Inlet Manifold

Section 3.4.1 dealt with the conventional experimental study on a compression ignition engine using diesel oil as fuel to primarily verify the system preparedness through the evaluation of chosen thermal performance parameters and exhaust gas emission constituents for further investigations on hydrogen-diesel dual fuel without and with additives. The effect of the addition of hydrogen gas in the air intake manifold along with the inducted air on engine thermal performance together with exhaust gas emission is the subject of investigation in this section. Variation in thermal performance parameters such as brake power, brake thermal efficiency, diesel fuel consumption, volumetric efficiency, the equivalence ratio, specific energy consumption and engine exhaust temperature are studied along with gas emission constituents such as O_2, CO, CO_2, HC, SO_2, NO_2, NO and NO_X with load and speed. Section 3.4.2.1 gives the results and discussion on the various thermal performance parameters under consideration while that on the exhaust gas emission constituents are discussed in Section 3.4.2.2.

3.4.2.1 Thermal Performance Evaluation

- **Brake Power**

Figs. 3.21 to 3.25 show, respectively, the variation of brake power with hydrogen induction rate for various loading of compression ignition engine and different speeds of 1000 rpm, 1250 rpm, 1500 rpm, 1750 rpm and 2000 rpm. Hydrogen induction rate is varied from no induction represented by induction at zero l/min to a maximum hydrogen induction rate of 18 l/min. It is seen that the hydrogen induction results in an increase of brake power output for all the chosen load and speed conditions as compared to that without induction. This is due to the higher heating value (calorific value) of hydrogen which is inducted in to the combustion chamber through the air intake manifold. It can further be noted that, the effect of hydrogen induction on brake power is more pronounced with the increase in both load and speed.

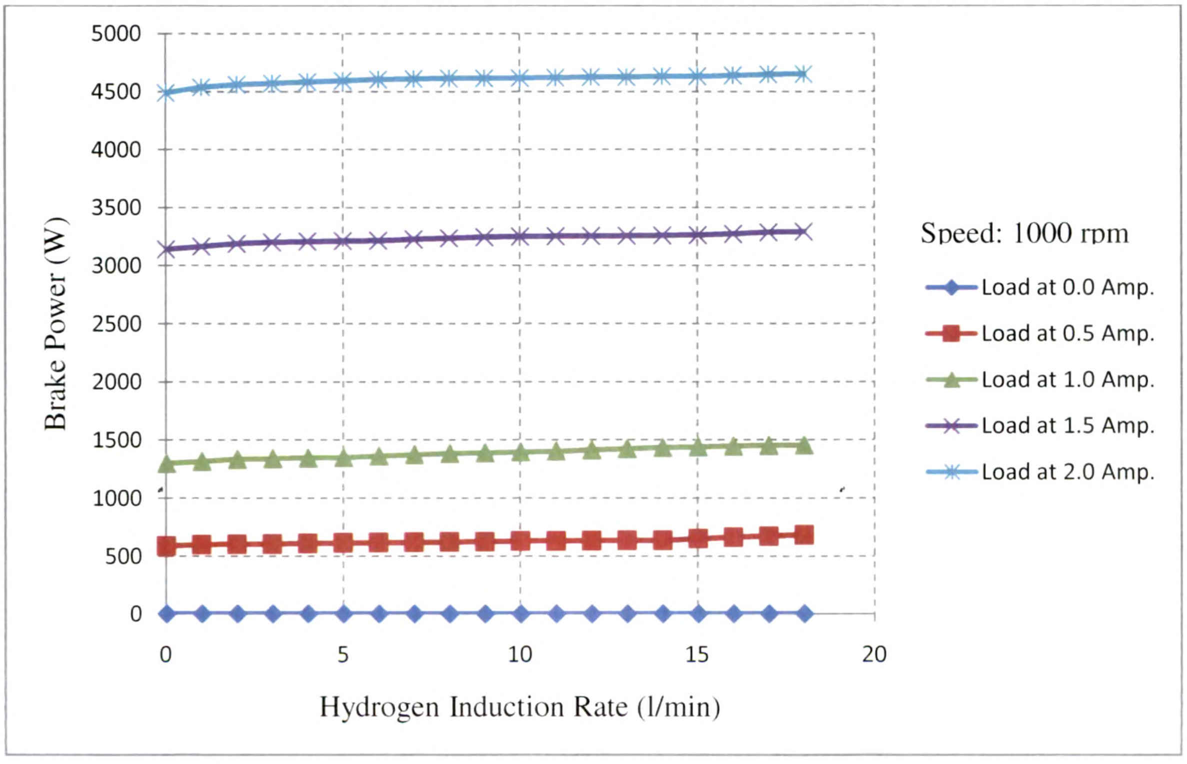


Fig. 3.21 Variation of Brake Power with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

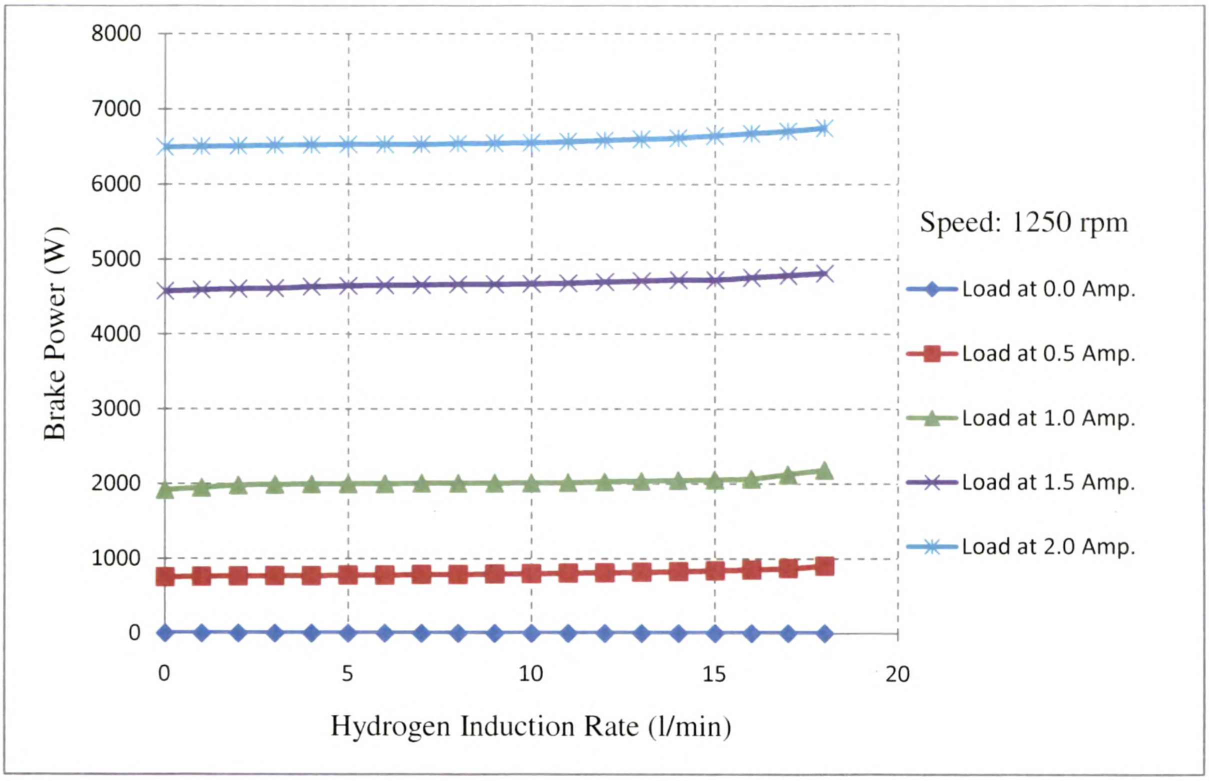


Fig. 3.22 Variation of Brake Power with Hydrogen Induction Rate for Various engine Loading and at 1250 rpm

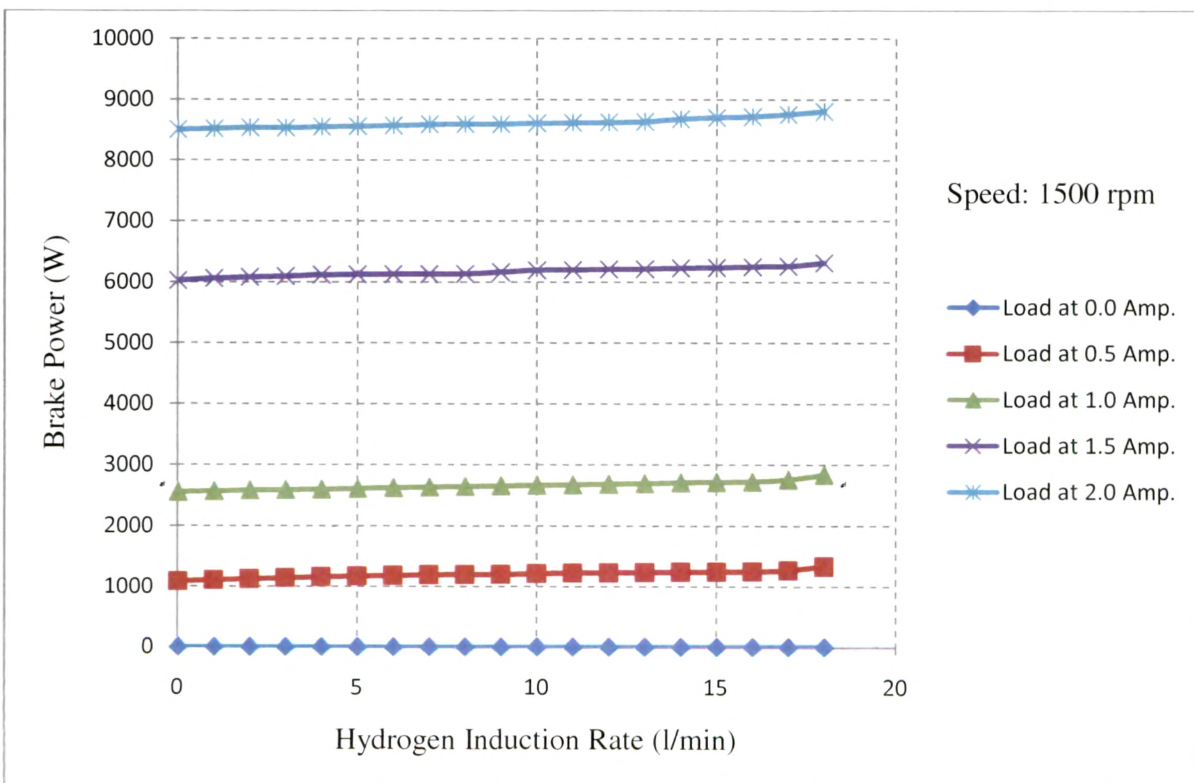


Fig. 3.23 Variation of Brake Power with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

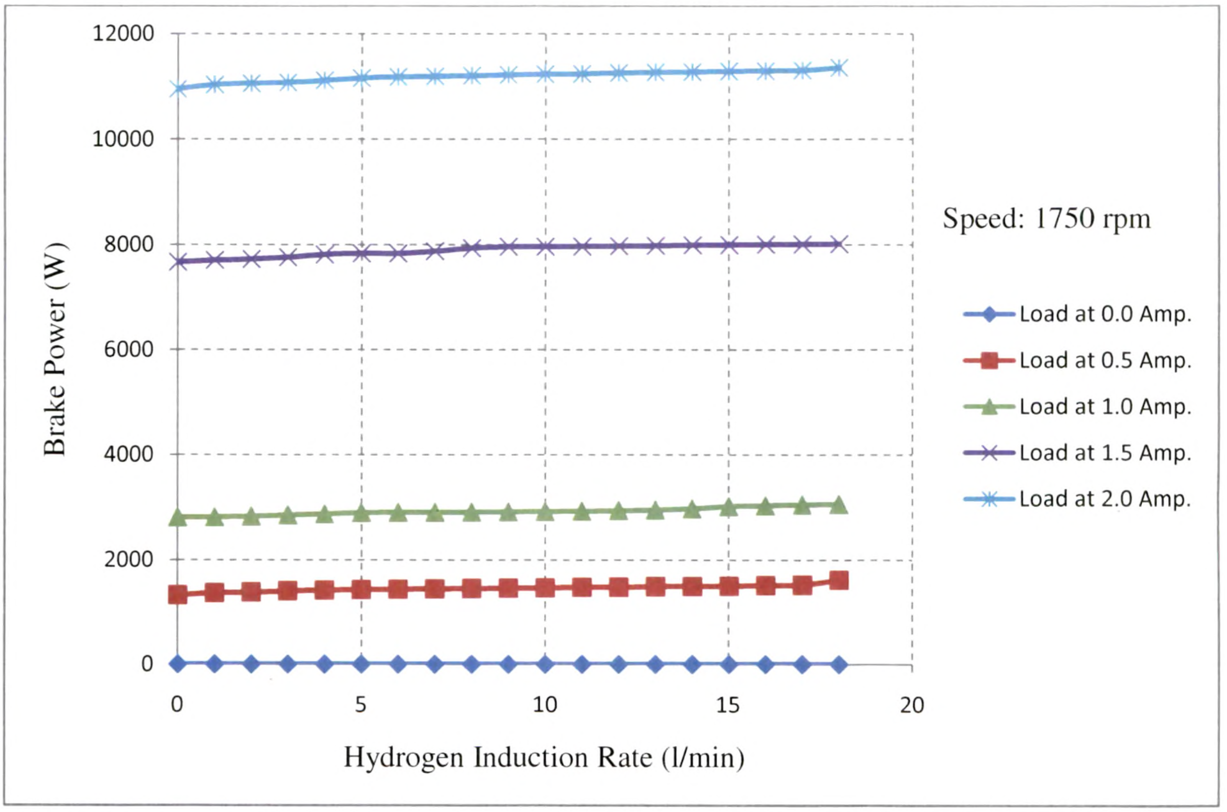
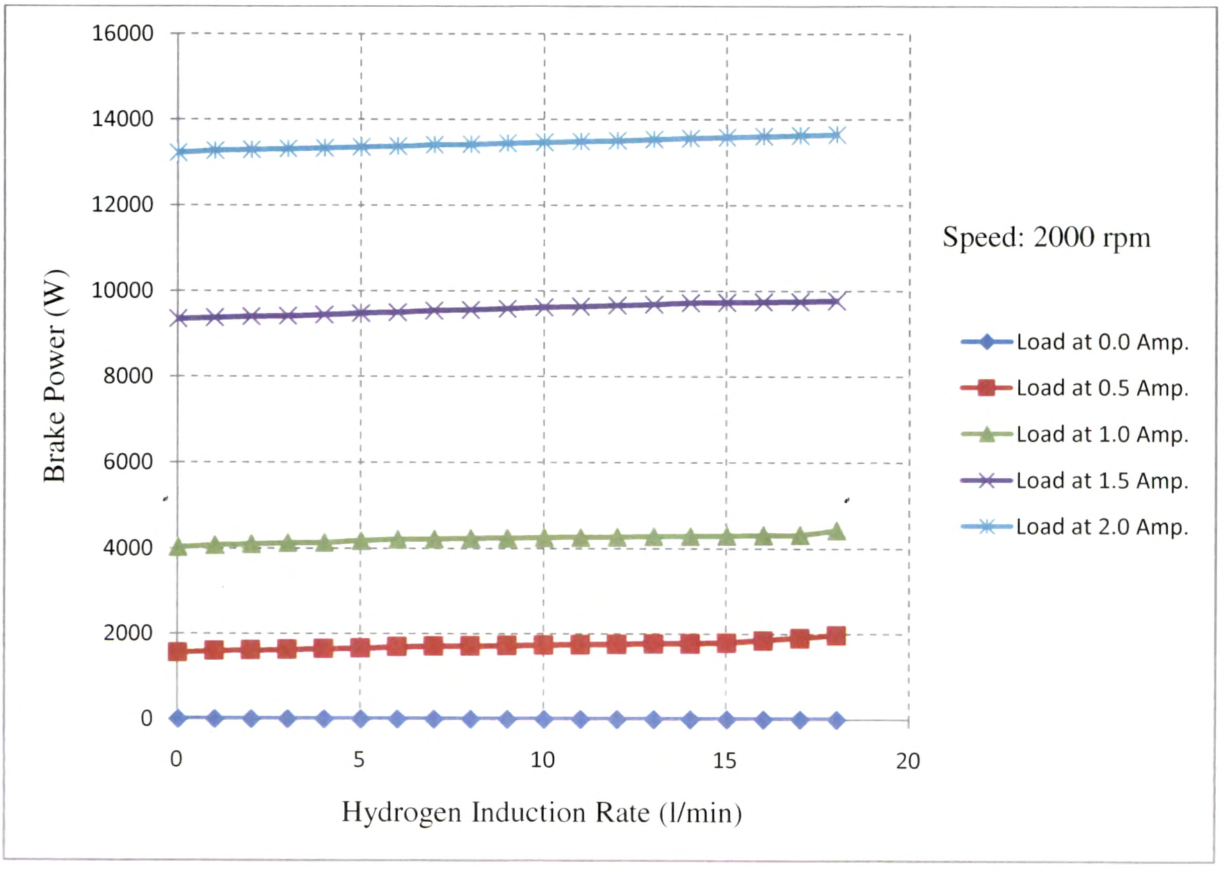


Fig. 3.24 Variation of Brake Power with Hydrogen Induction Rate with Engine Load & at 1750 rpm



3.25 Variation of Brake Power with Hydrogen Induction Rate with Load & at 2000 rpm

- **Diesel Fuel Consumption**

The variation of diesel fuel consumption with hydrogen induction rate for various loading of compression ignition engine and speed is given in Figs. 3.26 to 3.30. It should be noted that the induction of hydrogen leads to an increase in engine speed. Therefore, to keep the engine speed at uniform rate and at predetermined constant level, the engine speed paddle is to be adjusted to control the diesel fuel flow. This is carried out for the all the observations made in the present experimental study which results in a decrease in diesel oil consumption. Normally, at high load and speed the diesel fuel consumption is high as mensioned in Section 3.4.1.1. It is also observed that the decrease in diesel fuel consumption is signficant with higher hydrogen induction rate for all loads and speeds. The trend of variation is similar if the primary difference in diesel fuel consumption is considered.

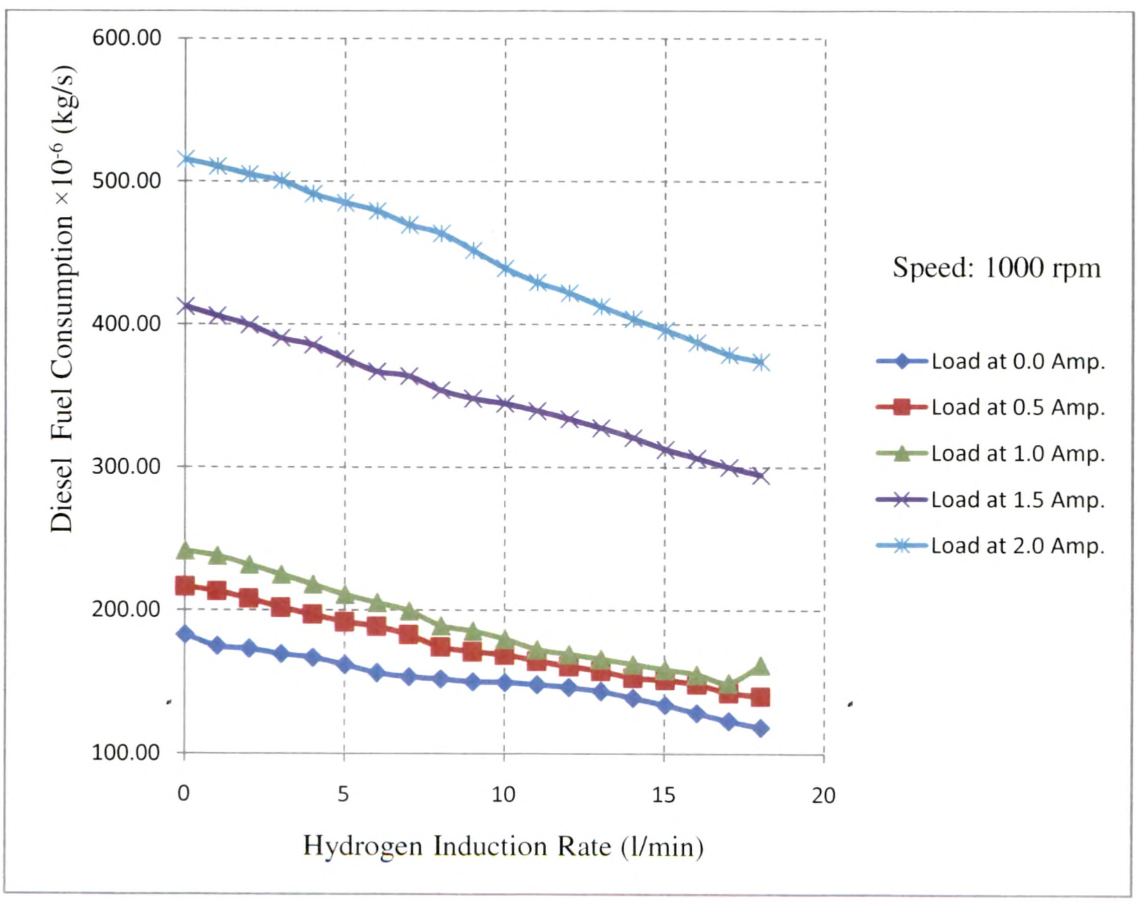


Fig. 3.26 Variation of Diesel Fuel Consumption with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

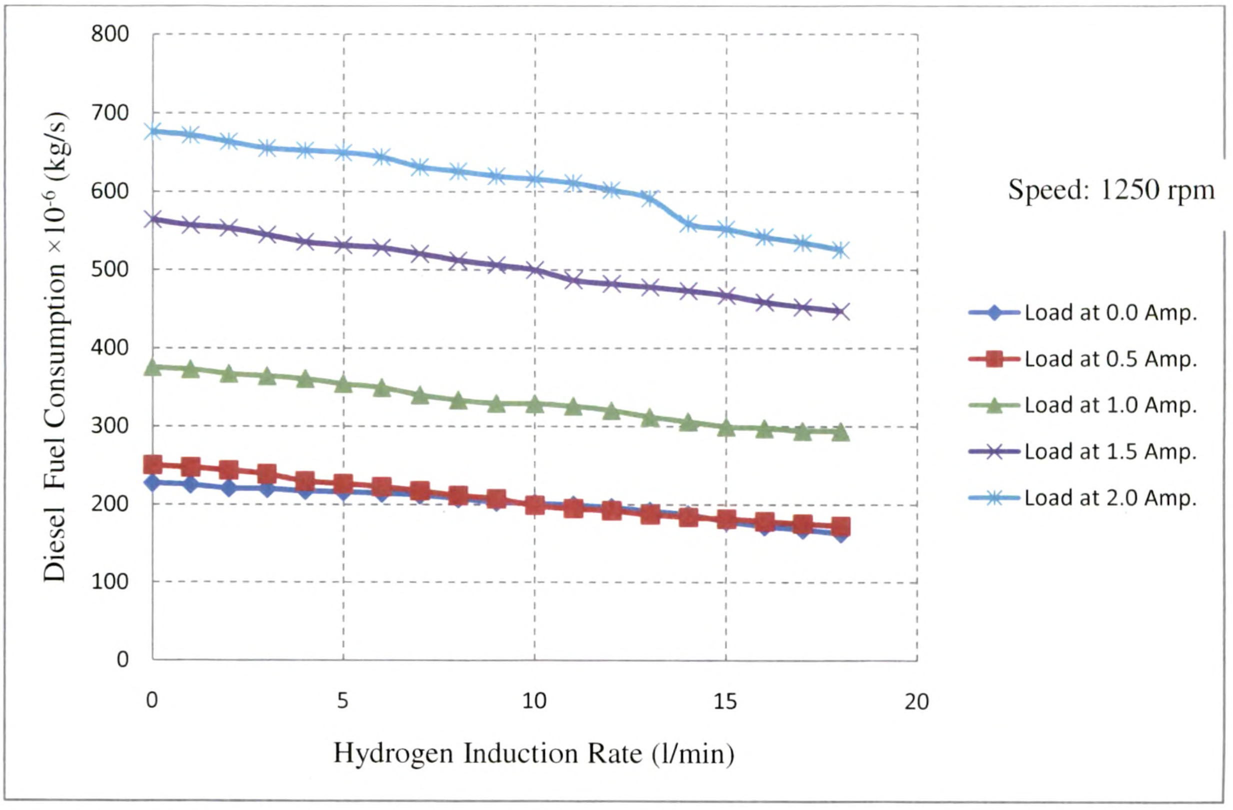


Fig. 3.27 Variation of Diesel Fuel Consumption with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

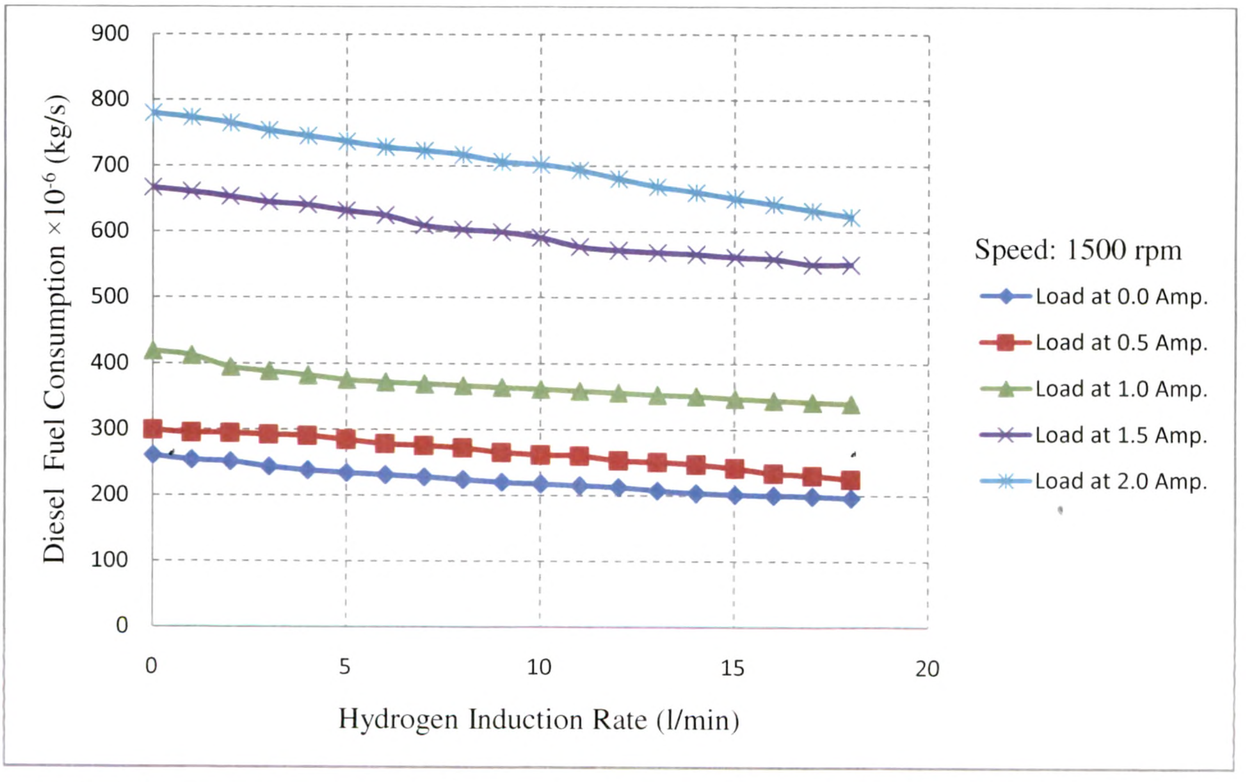


Fig. 3.28 Variation of Diesel Fuel Consumption with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

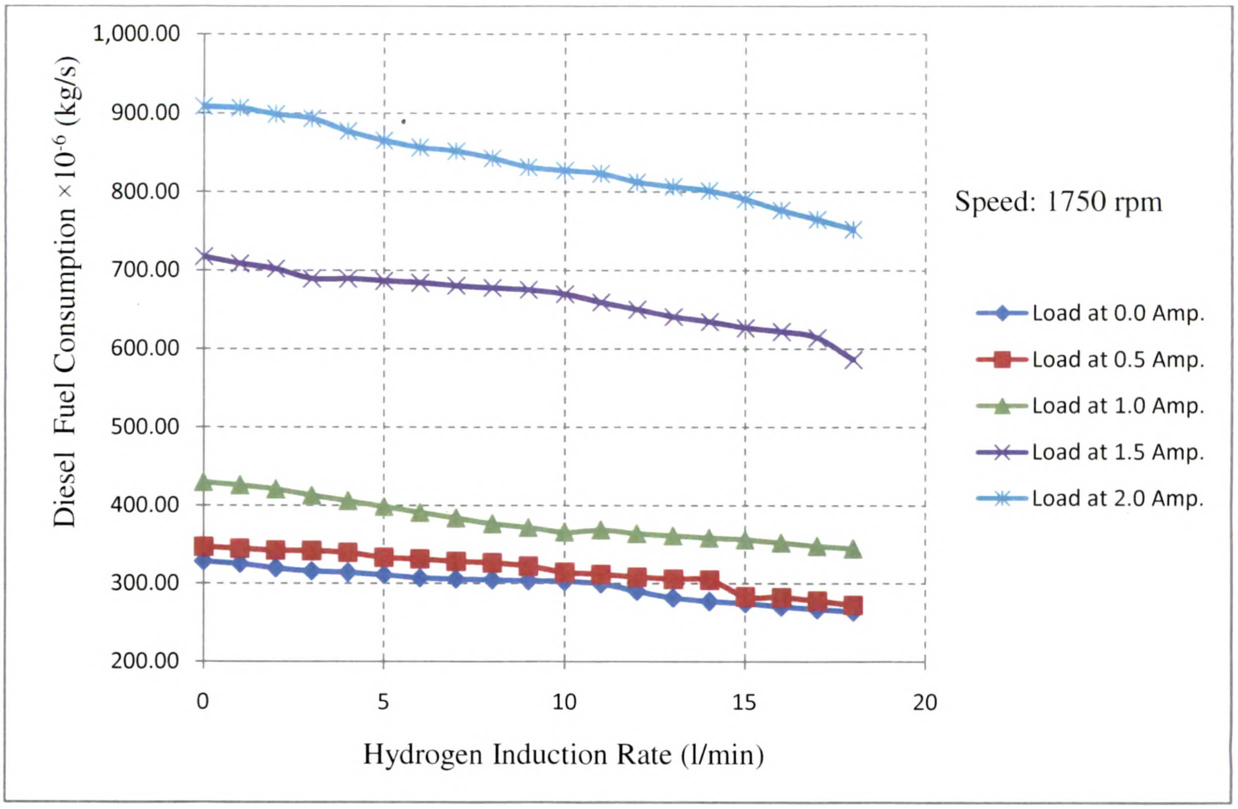
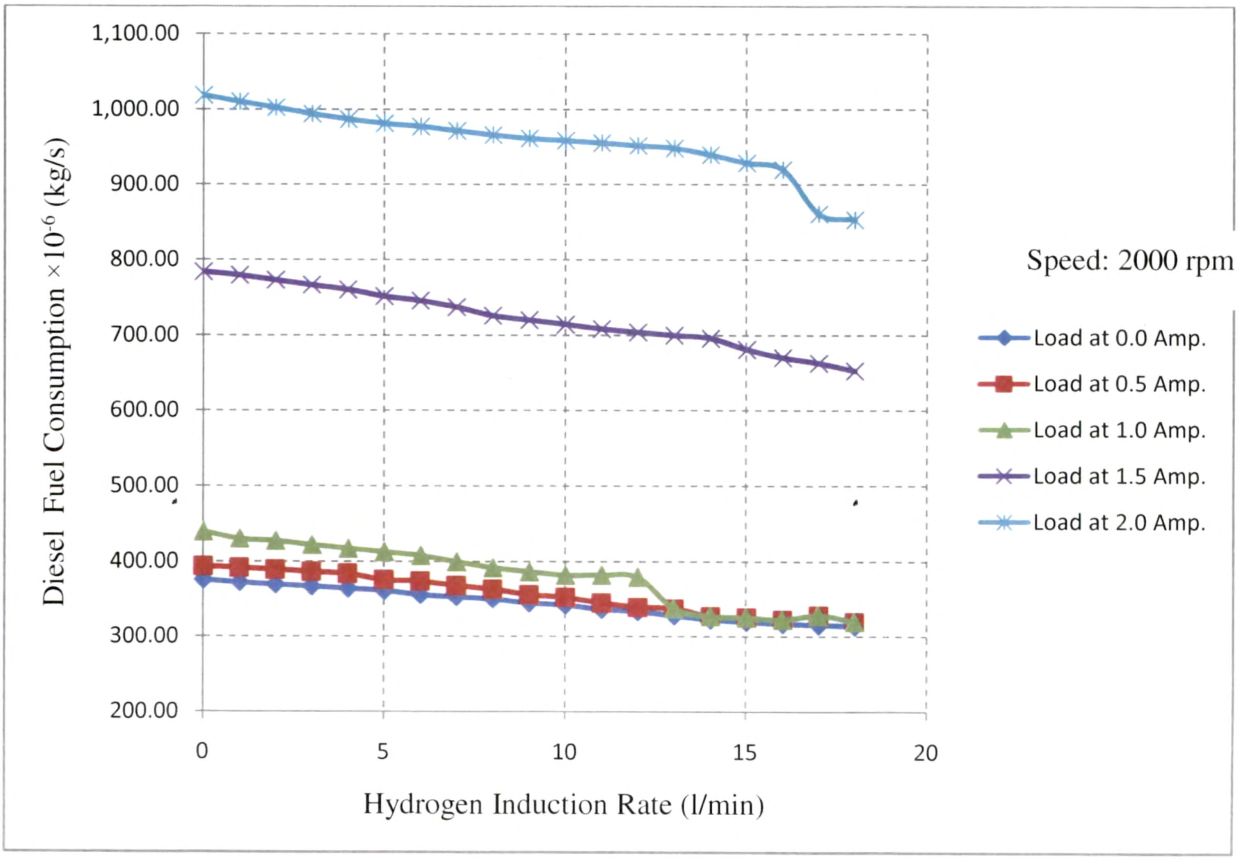


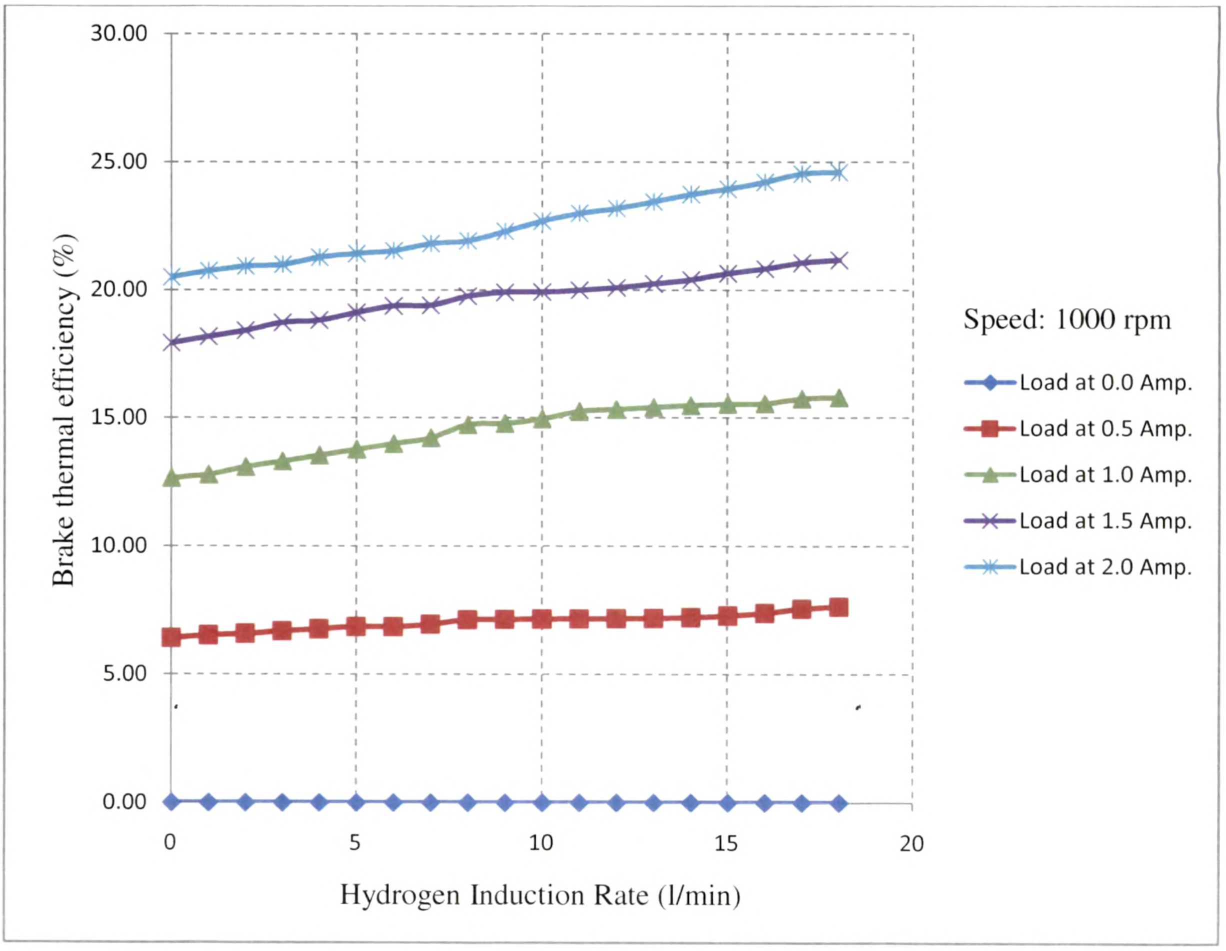
Fig. 3.29 Variation of Diesel Fuel Consumption with Hydrogen Induction Rate for Various Load



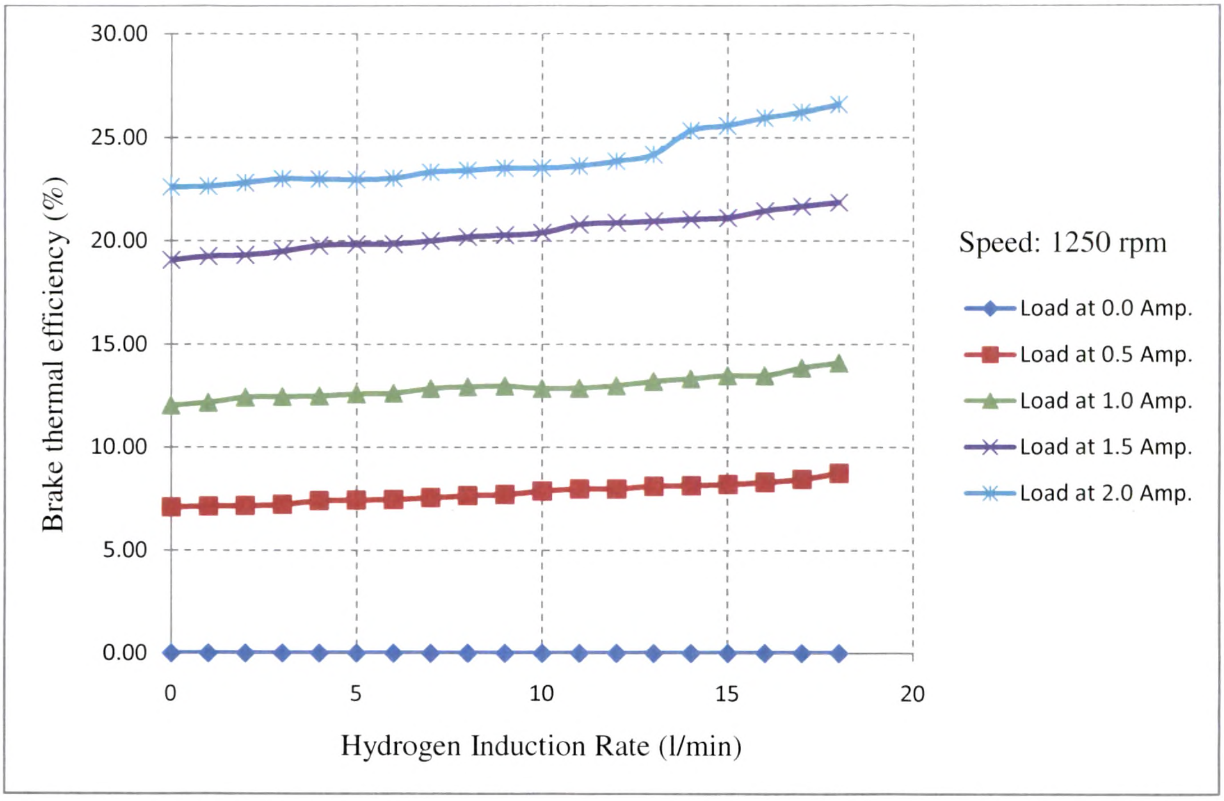
3.30 Variation of Diesel Fuel Consumption with Hydrogen Induction Rate for Various Load

- **Brake Thermal Efficiency**

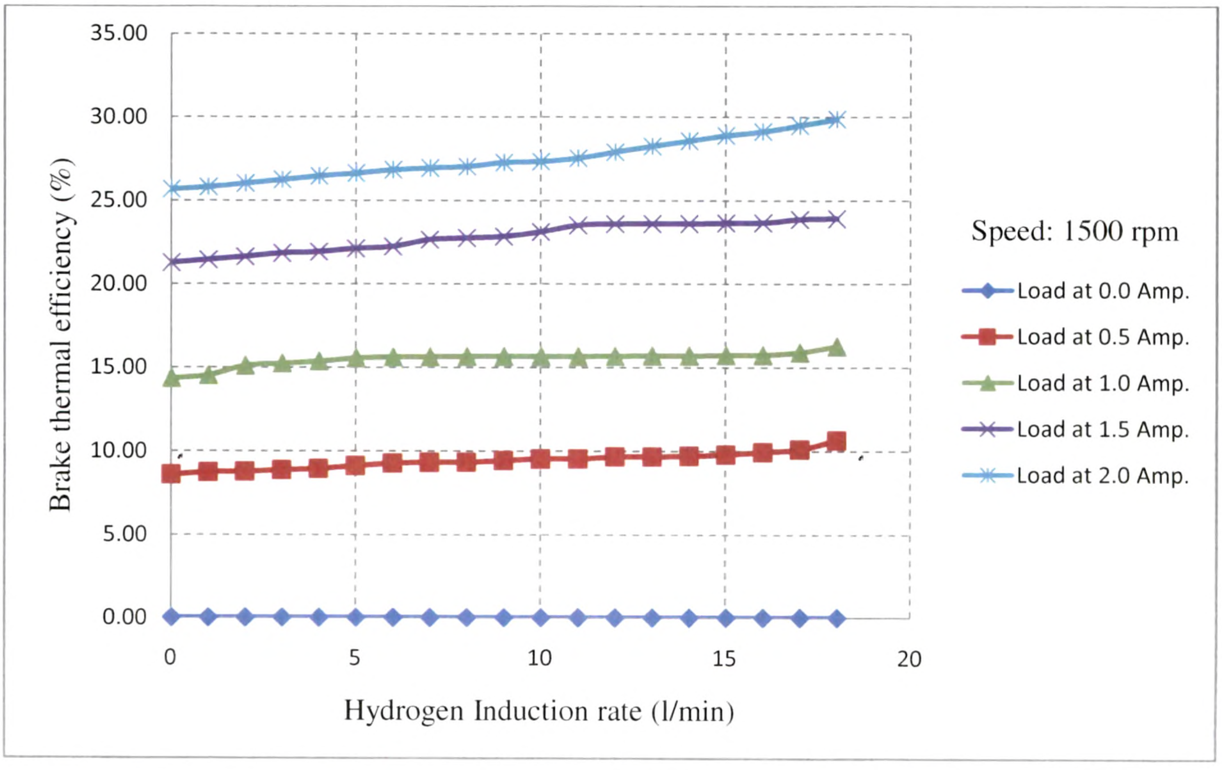
Figs. 3.31 to 3.35 illusturate the variation of brake thermal efficiency with hydrogen induction rate for various loading of the engine at different speeds.The brake thermal efficiency increases with increase in hydrogen induction as compared with only diesel oil without any hydrogen induction (i.e. the case with zero H_2 , l/min). This trend of increase is reflected at all loads. It should be noted that the heating value of hydrogen is approximately twice that of diesel oil. It is also seen that, in spite of the reduction in the diesel fuel consumption, the brake thermal efficiency increases. The induction of hydrogen in the inlet manifold thus, results in an increase in brake thermal efficiency. Normally the brake thermal efficiency increases with the load and the engine speed as a result of the increase in brake power and decrease in fuel consumption.



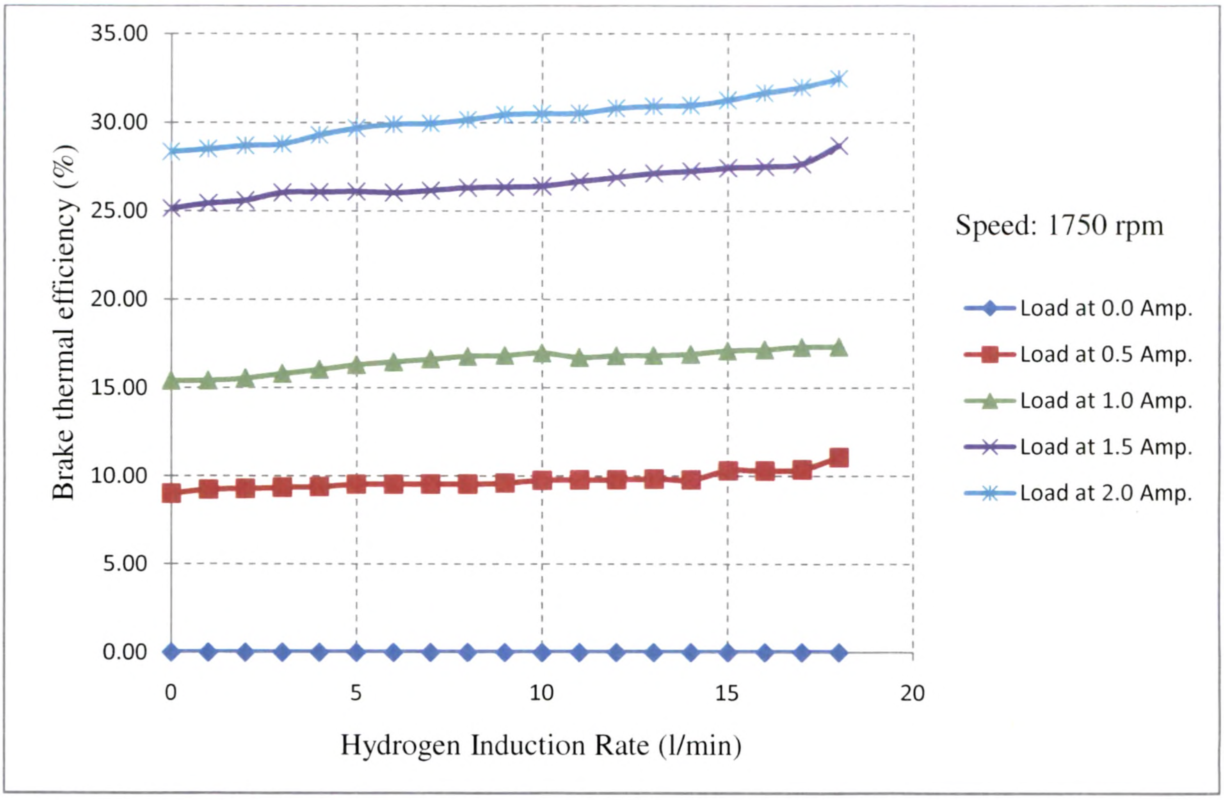
3.31 Variation of Brake Thermal Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm



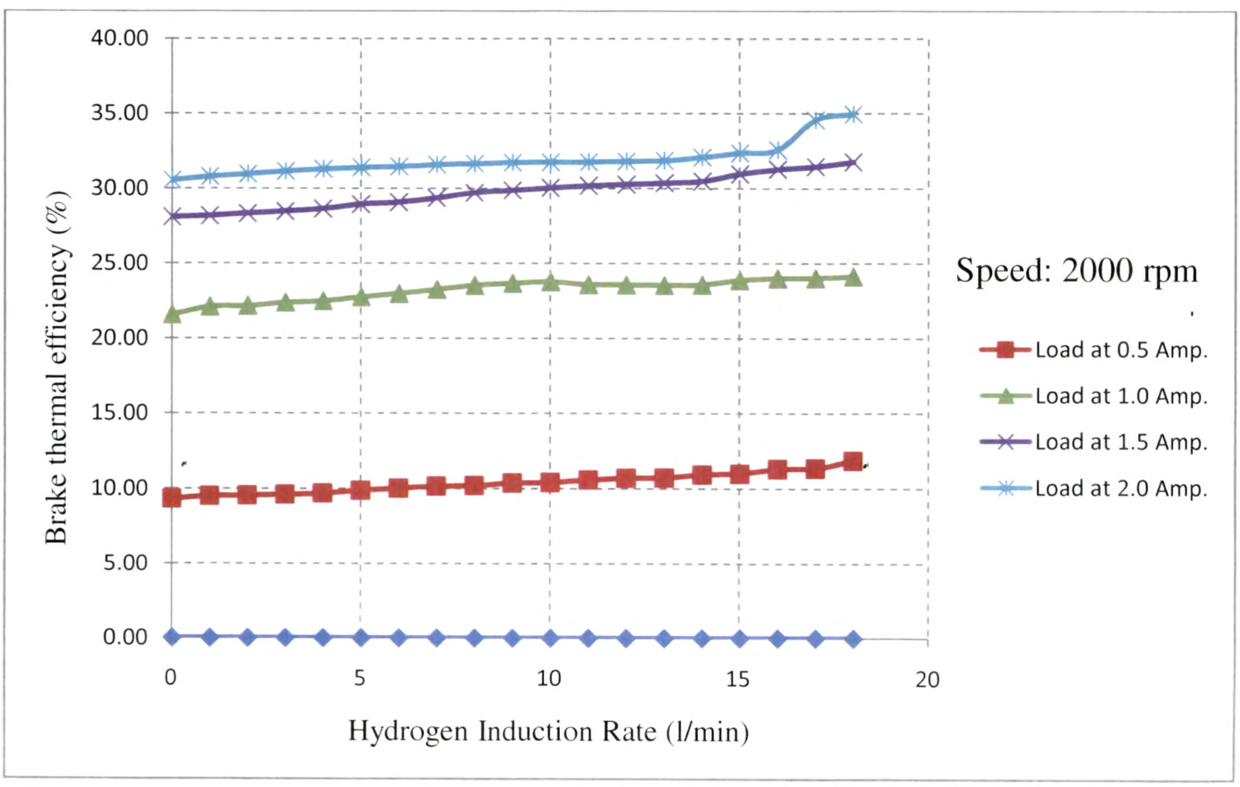
3.32 Variation of Brake Thermal Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm



3.33 Variation of Brake Thermal Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm



3.34 Variation of Brake Thermal Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm



3.35 Variation of Brake Thermal Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

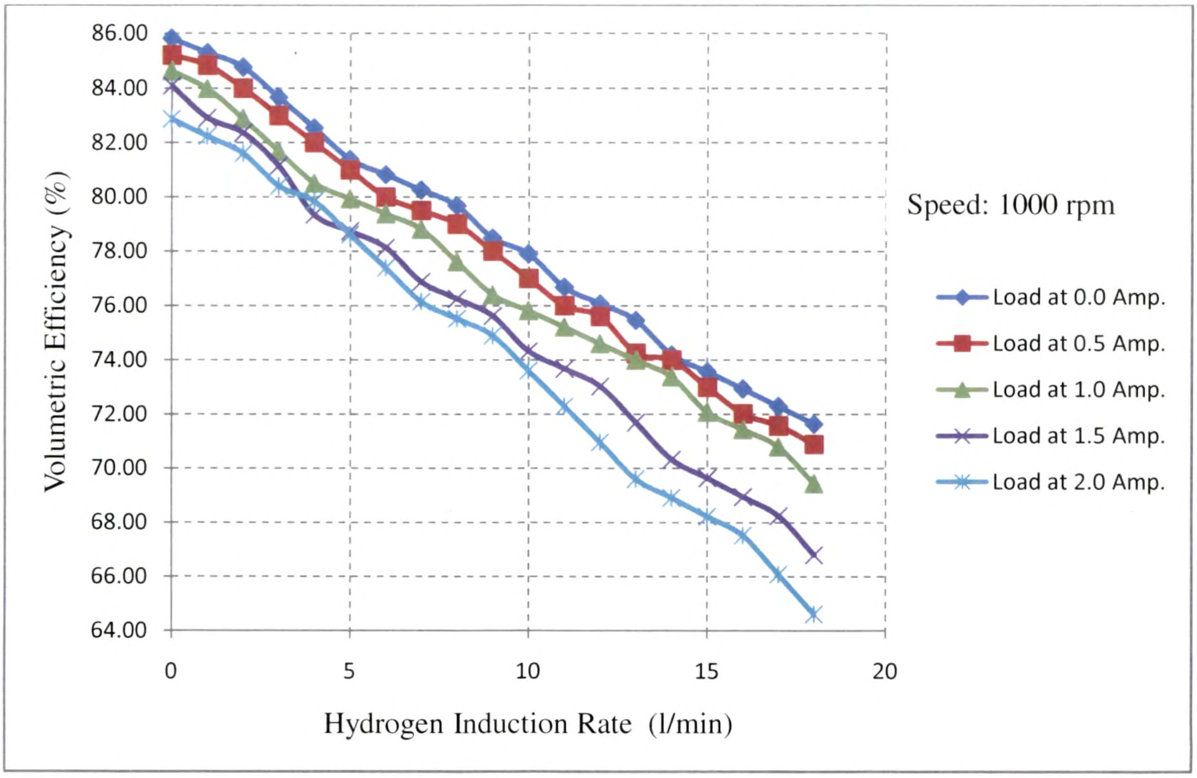
- **Volumetric Efficiency**

The variation of volumetric efficiency with hydrogen induction rate for various loading of compression ignition engine and with different speeds is given in Figs. 3.36 to 3.40. A natural aspirated compression ignition engine has a constant air suction at constant speed. In compression ignition engine, there is no governor control and the amount of air suction remains more or less constant at a given load and speed.

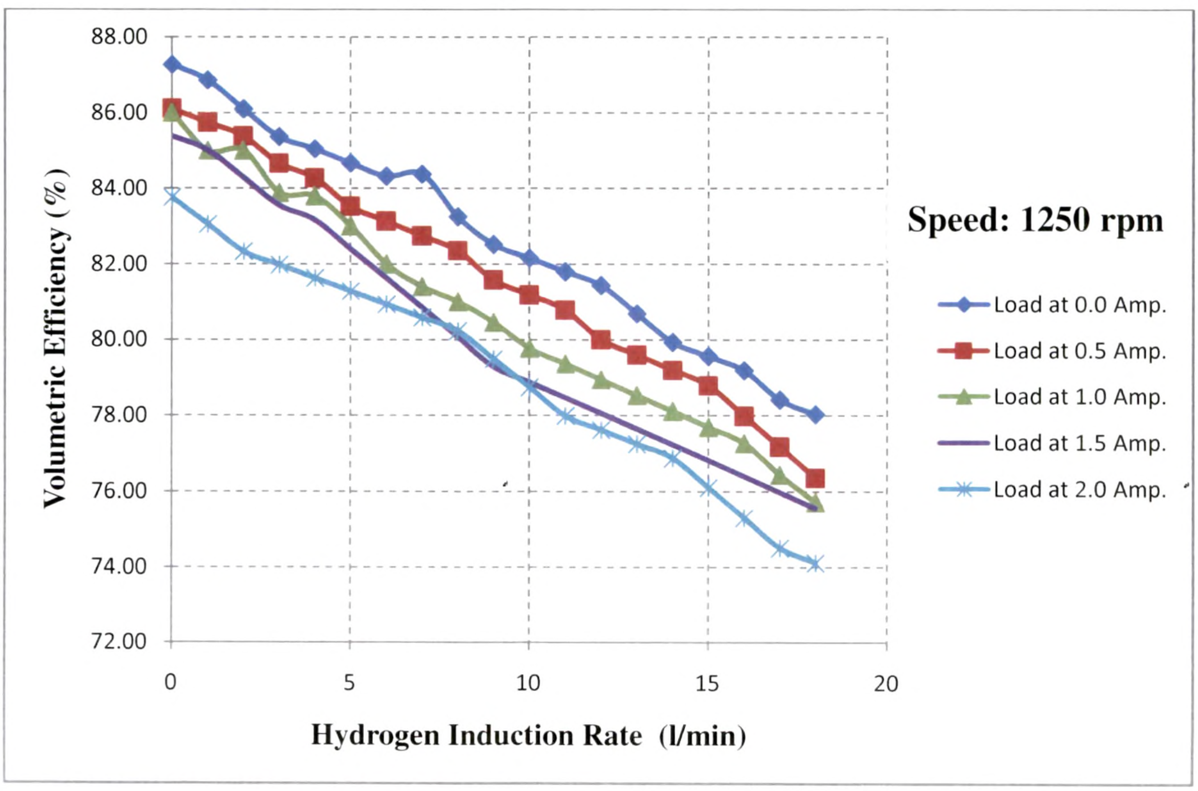
It can be noted that the actual air volume sucked changes with load. The increase of load causes decrease in actual air volume sucked which results in a decrease in the volumetric efficency whereas swept volume is constant at constant speed. The decrease in volumetric efficiency may be attributed to the increase residual flue gases occupying more volume in combustion chamber with increase in load.

The induction of hydrogen at the inlet manifold decreases the quantity of intake air which results in the decrease of the volumetric efficiency. This amount of air intake decreases with increase in the hydrogen induction rate. Thus, the higher hydrogen induction rate resulting in the decrease of air intake leads to incomplete combustion of the fuel blend in combustion chamber. A 16 % reduction in volumetric efficiency is observed with the increase in hydrogen induction rate from zero level to the maximum of 18 l/min under no load operation of the engine running at 1000 rpm.

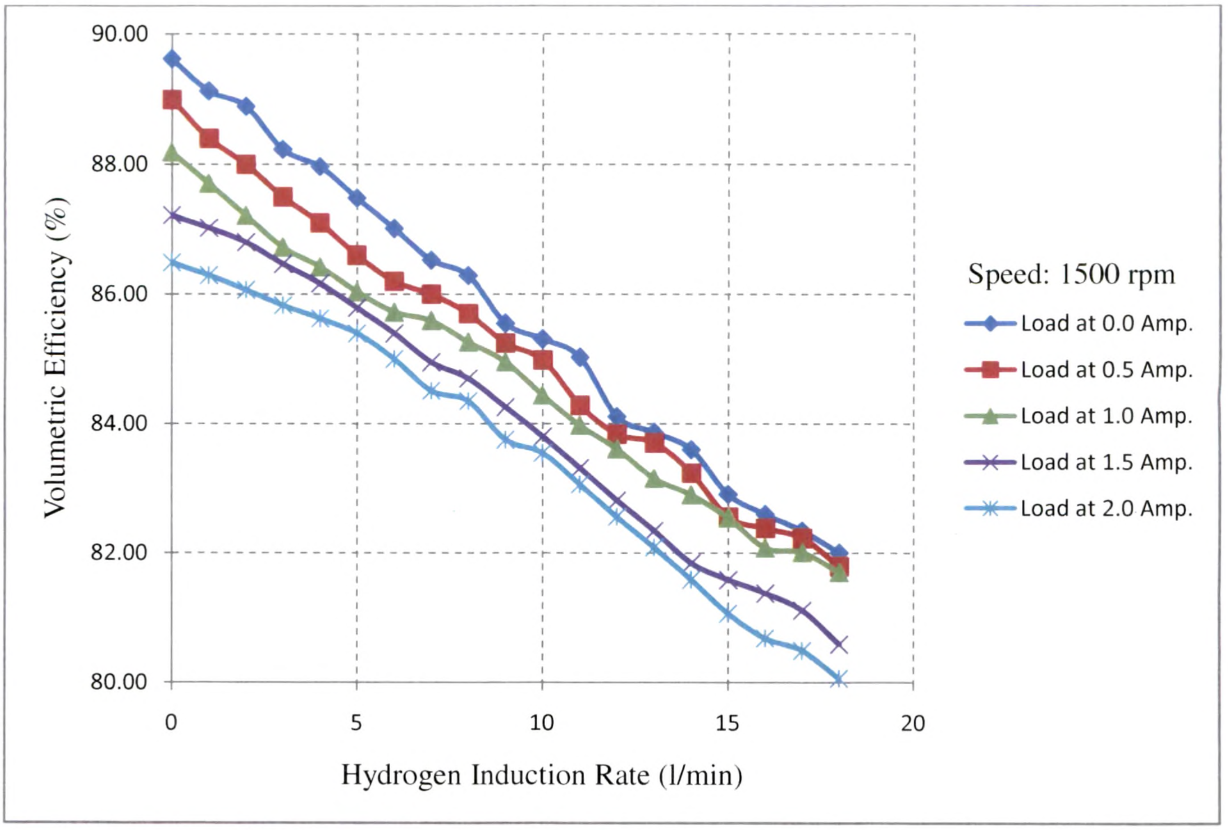
The reduction increases to about 23 % when the load applied is maximum at 2.0 A with engine running at the same speed. However, with the increase in speed, it is found that the reduction in volumetric efficiency due to hydrogen induction decreases. It is seen that at a speed of 2000 rpm with no load operating conditiion, the decrease in volumetric efficiency is only about 3.5 % when the induction rate is increased to 18 l/min. Further, it also found that the decrease in the volumetric efficiency is more or less independent of the rate of loading at higher speed.



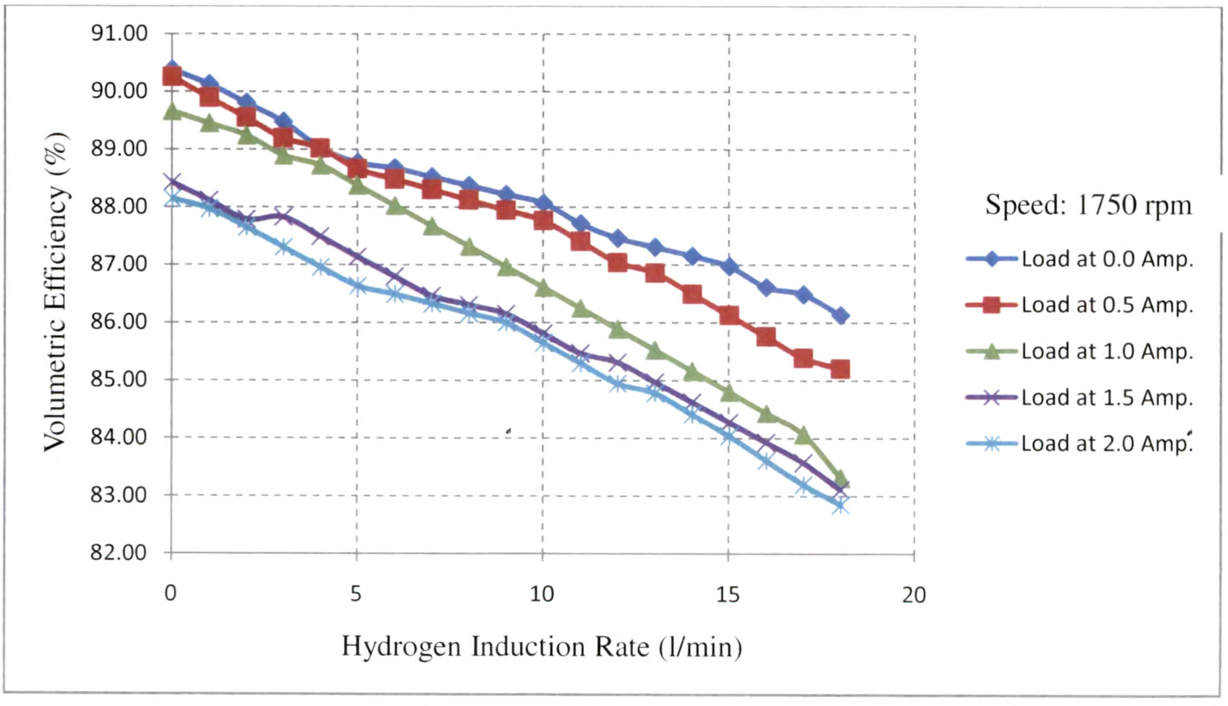
3.36 Variation of Volumetric Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm



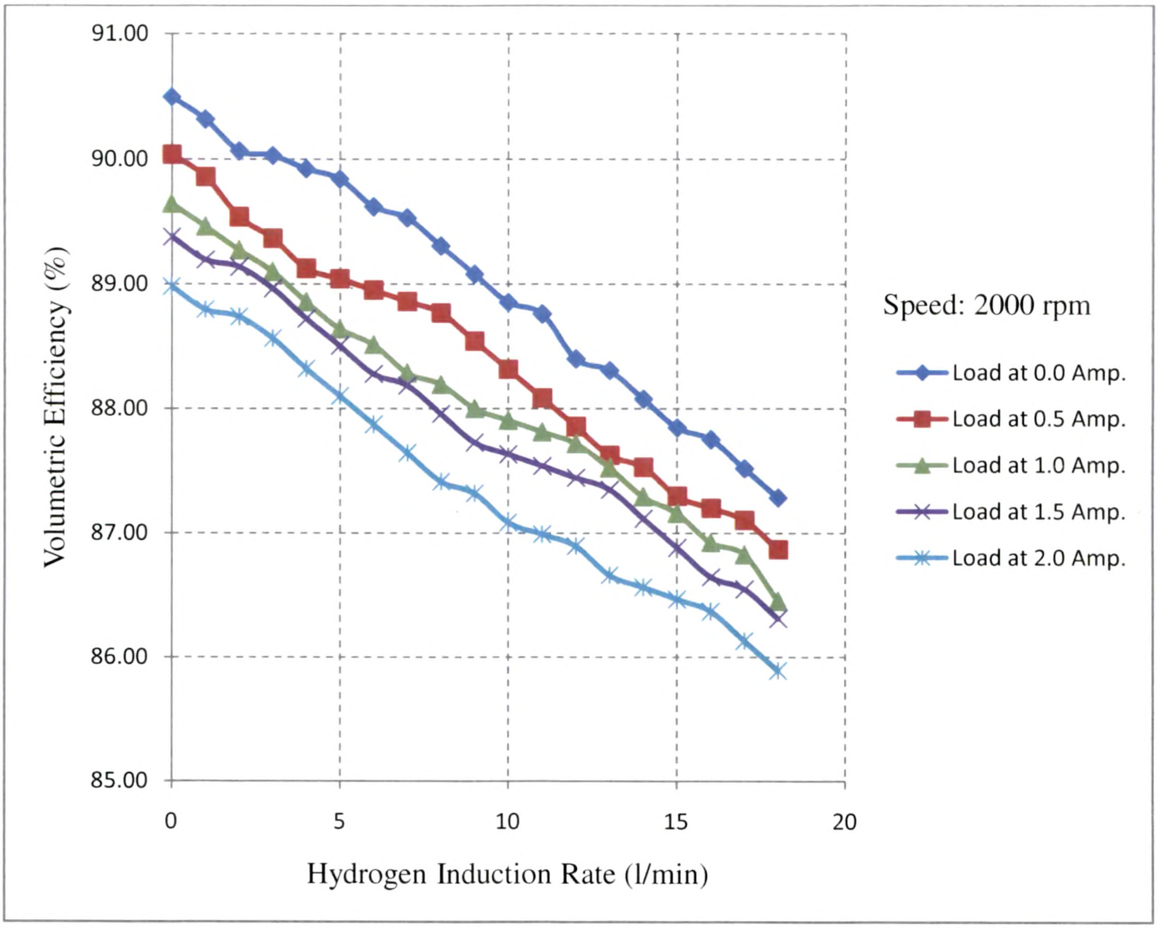
3.37 Variation of Volumetric Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm



3.38 Variation of Volumetric Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm



3.39 Variation of Volumetric Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm



3.40 Variation of Volumetric Efficiency with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Equivalence Ratio**

Figs.3.41 to 3.45 gives the variation in equivalence ratio with hydrogen induction rate when the compression ignition engine is operated at different load and speed. The hydrogen induction rate decreases the equivalence ratio and make the charge in the cylinder of the engine more lean or weak. As dicussed in Section 3.4.1.1, the increase of load and speed lead to the increase in equivalnence ratio due to the increase in the amount of the drawn air and fuel. It is known that hydrogen can work in extream lean mixture condition. Further, it is also known that the compreasion ignition engine can work with equivalence ratio in the range of $0.2 \leq \phi \geq 0.85$ [91].

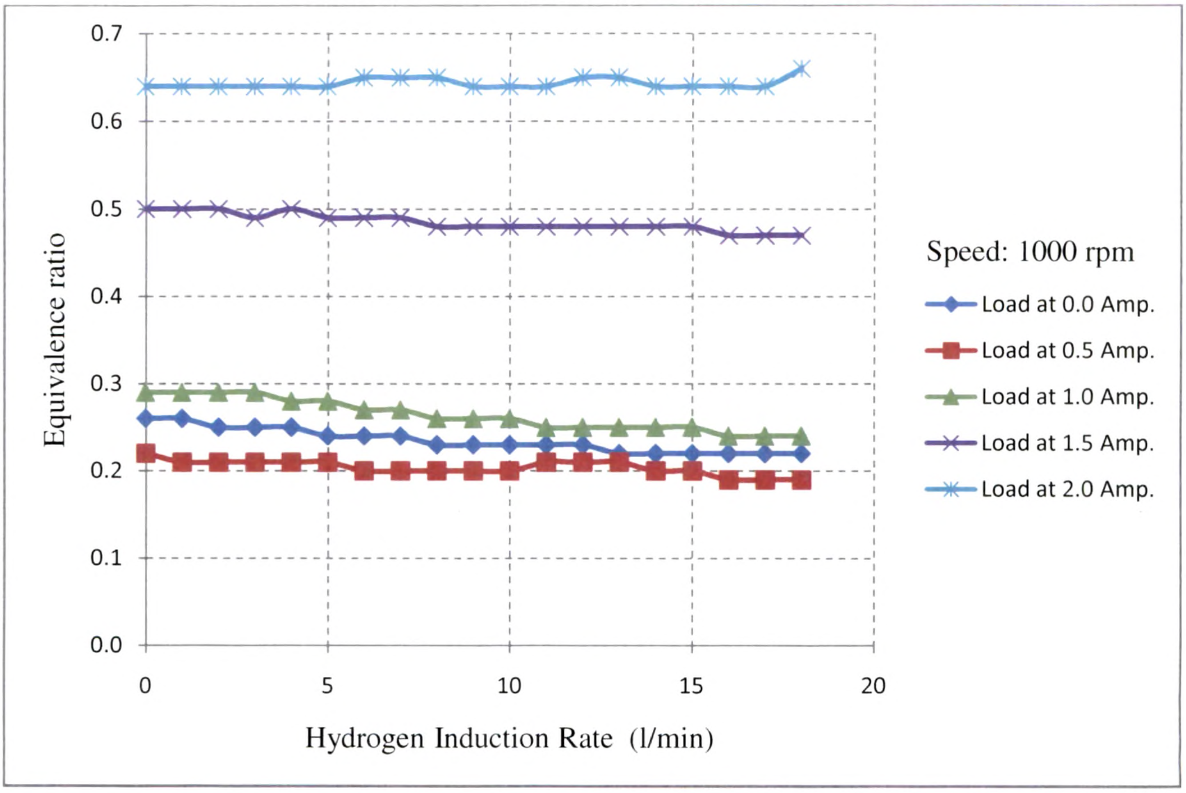


Fig. 3.41 Variation of Equivalence Ratio with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

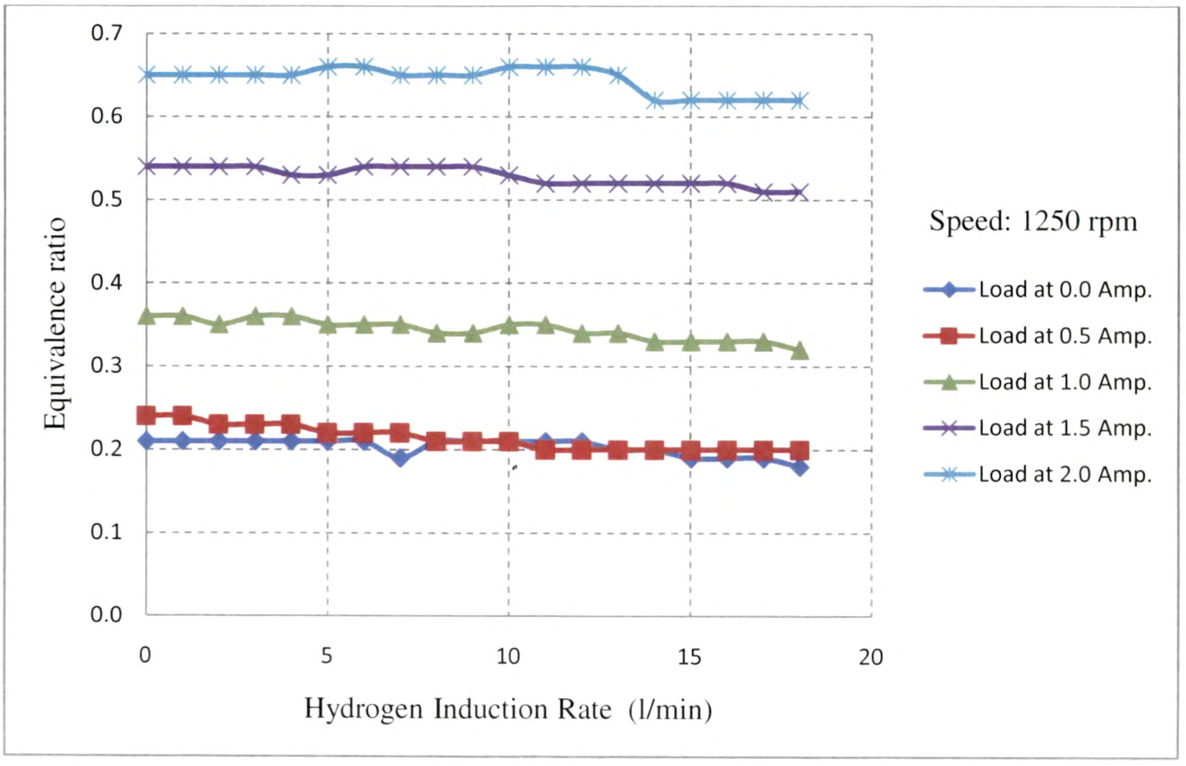
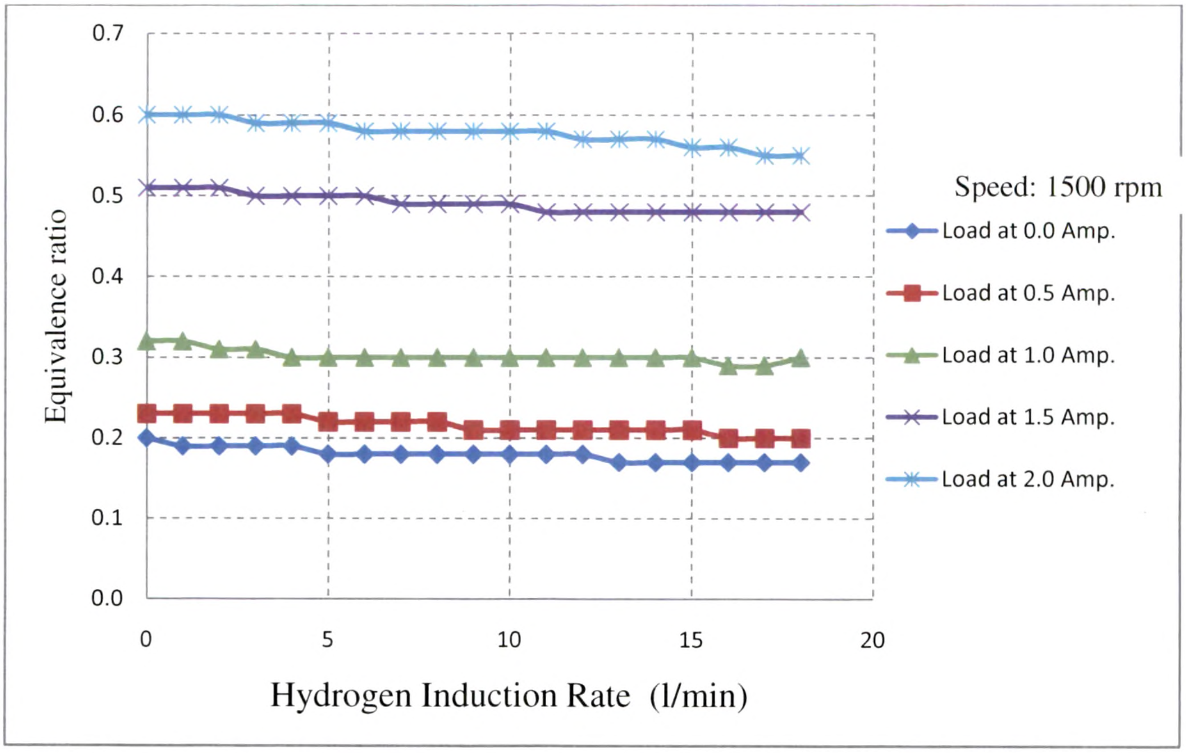


Fig. 3.42 Variation of Equivalence Ratio with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm



3.43 Variation of Equivalence Ratio with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

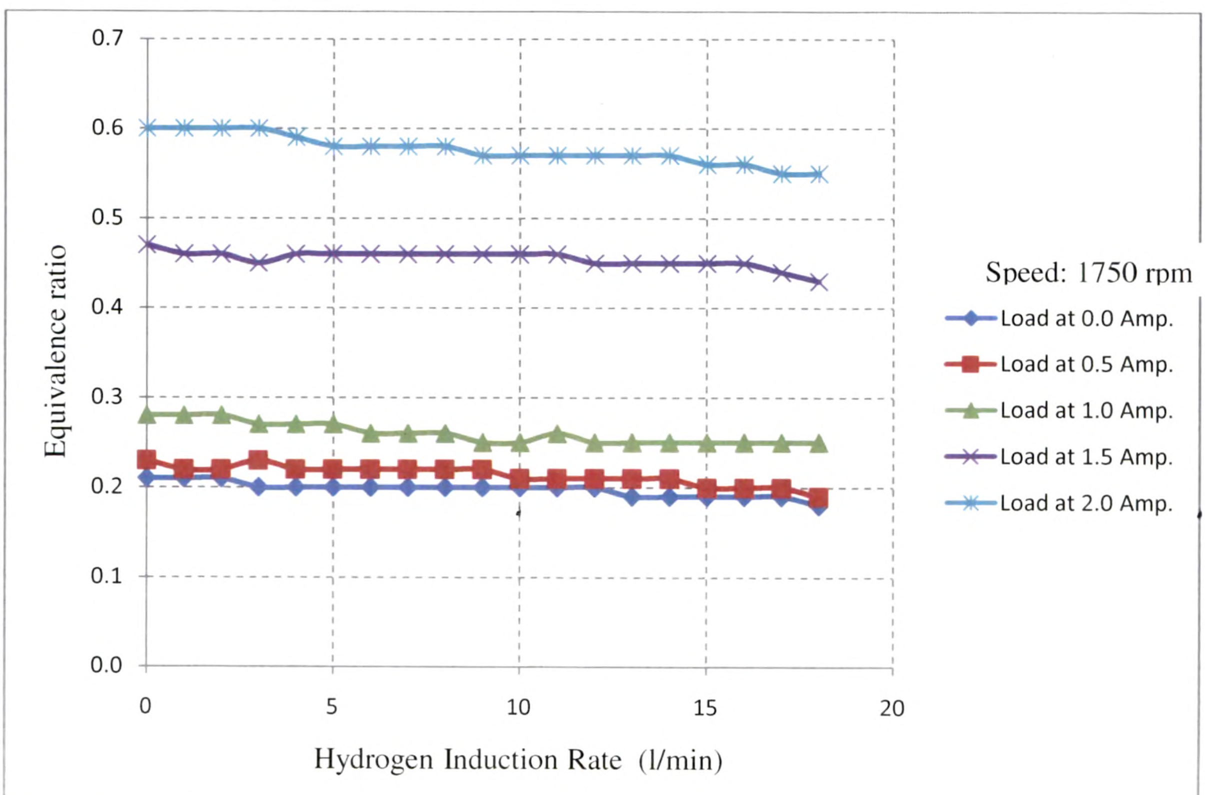


Fig. 3.44 Variation of Equivalence Ratio with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

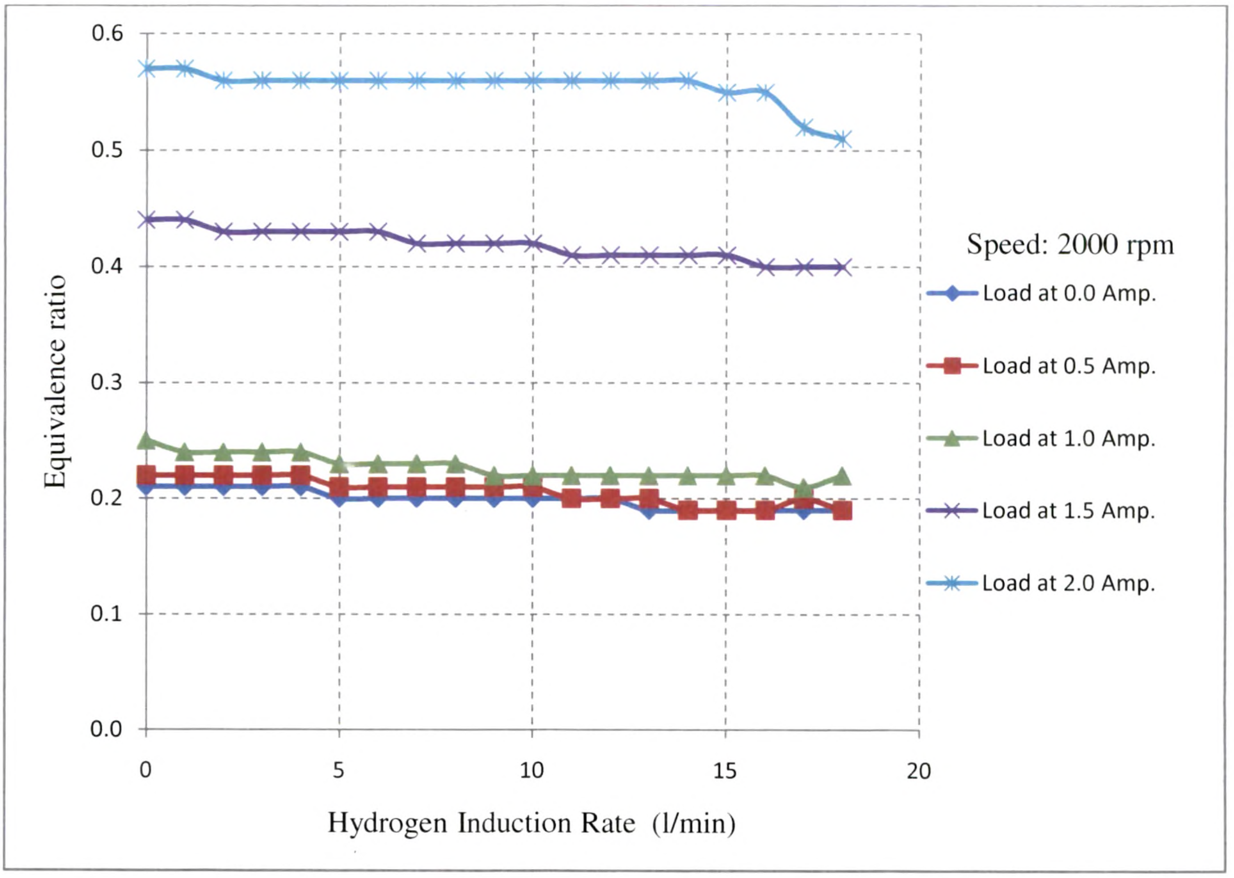


Fig. 3.45 Variation of Equivalence Ratio with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Brake Specific Energy Consumption (BSEC)**

Figs. 3.46 to 3.50 give the variation of BSEC with hydrogen induction rate for various loading of the engine at different speeds. It is seen that the hydrogen induction in the atmospheric air intake manifold of the engine enhances the consumption of energy to produce more usable power. Basically as discussed in section 3.4.1.1, BSEC decreases with increase in load with the engine running at a given constant speed. The same trend is observed with various hydrogen induction rate also. With the induction of hydrogen, the decrease in BSEC is more significant when the load applied is beyond 1.0 Amp. For a given constant speed and constant induction rate, the decrease in BSEC is of the order of about 3 times when the load is increased from 0.5 Amp. to 2.0 Amp. This is found to be fairly true for all the combination of induction rate and speed. It is seen that there is a reduction in BSEC with increase in the induction rate when the engine is running at a constant speed and load.. Further, BSEC marginally decreases as the hydrogen induction rate is increased with the engine running at a given constant speed and load.

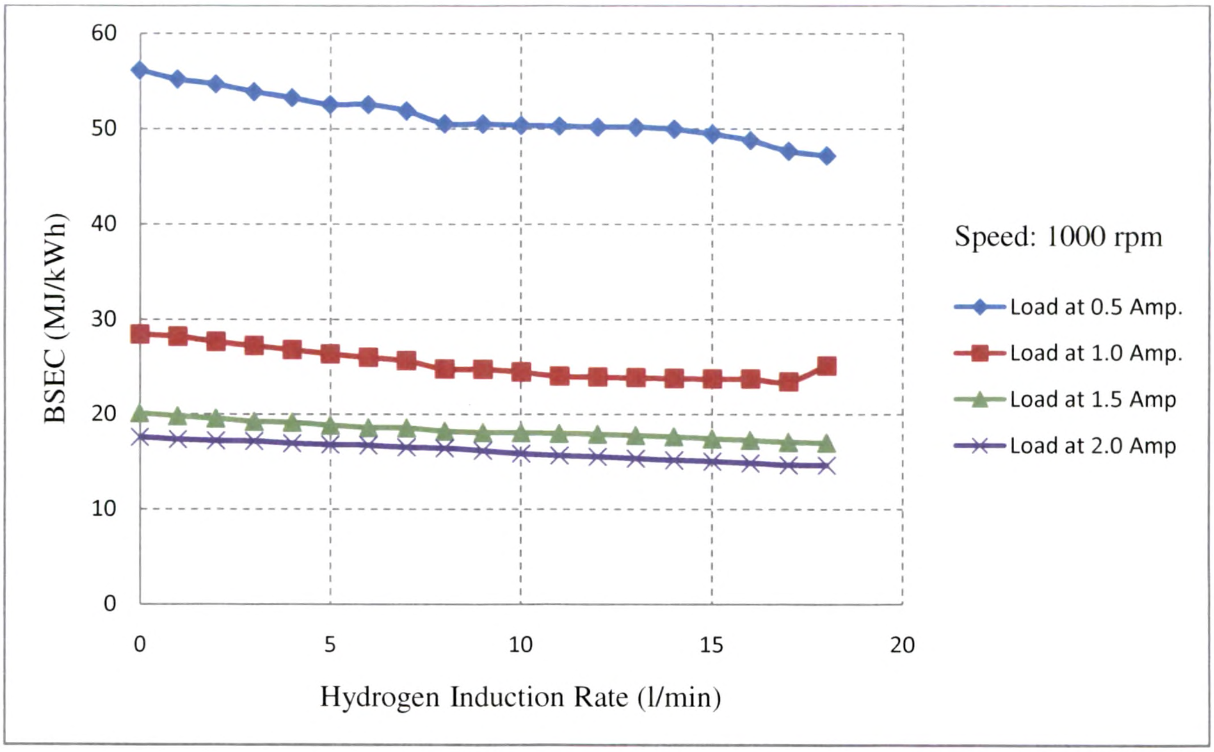


Fig. 3.46 Variation of BSEC with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

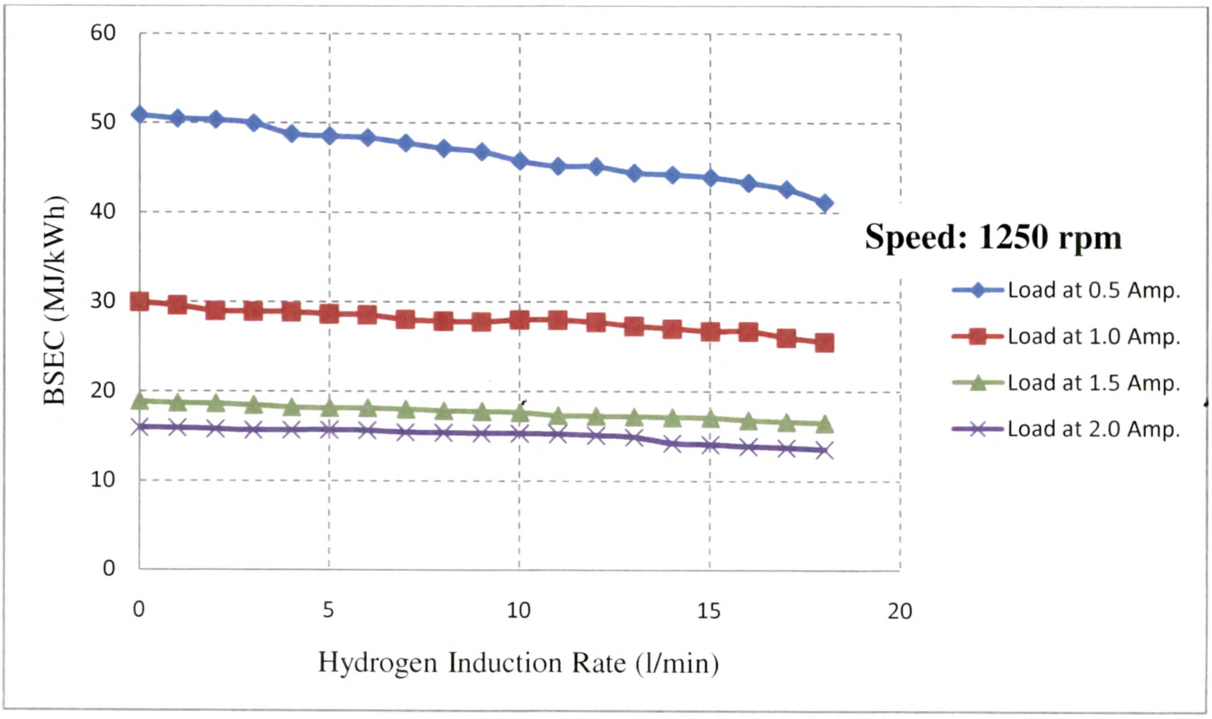


Fig. 3.47 Variation of BSEC with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

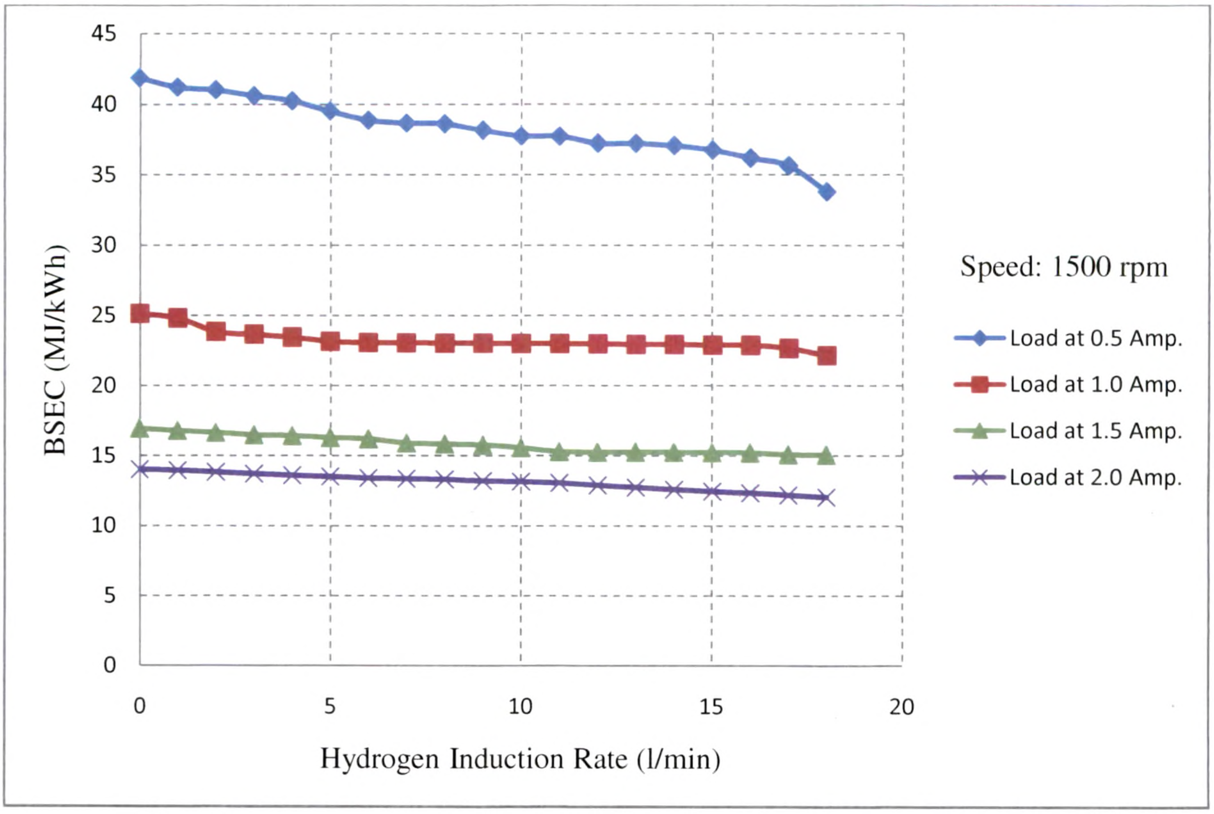


Fig. 3.48 Variation of BSEC with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

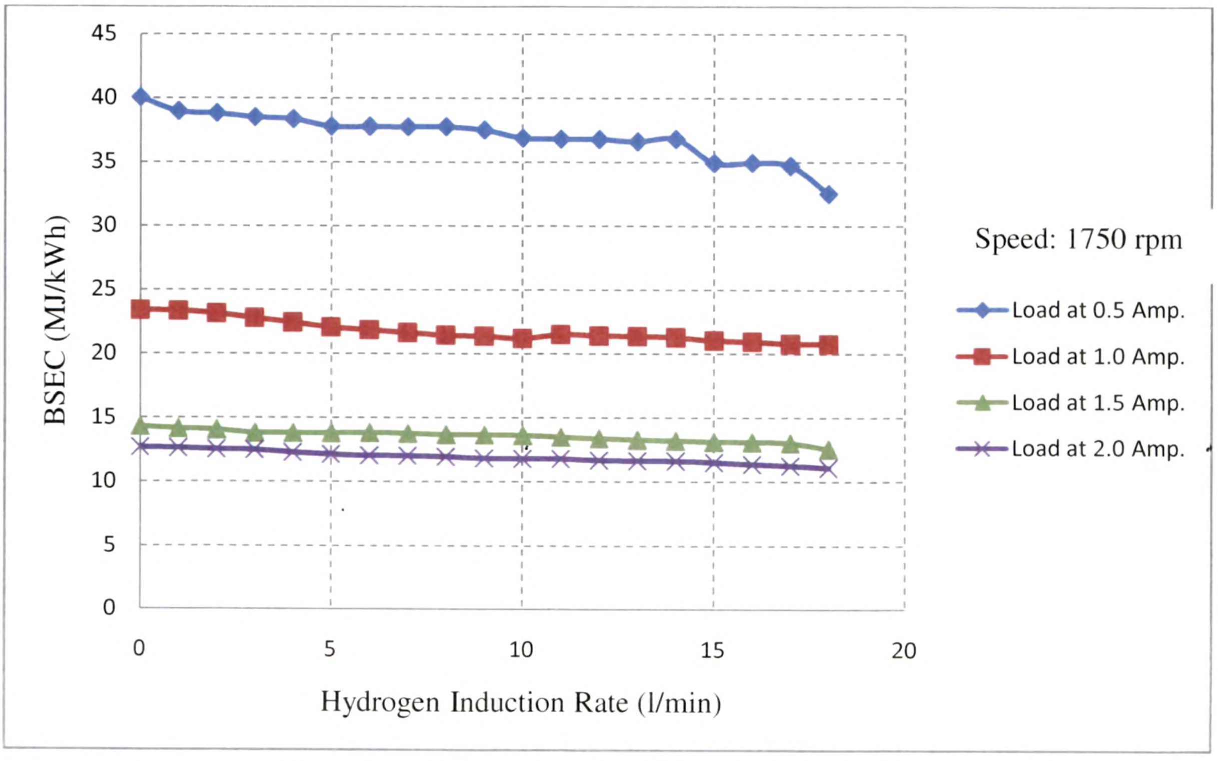


Fig. 3.49 Variation of BSEC with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

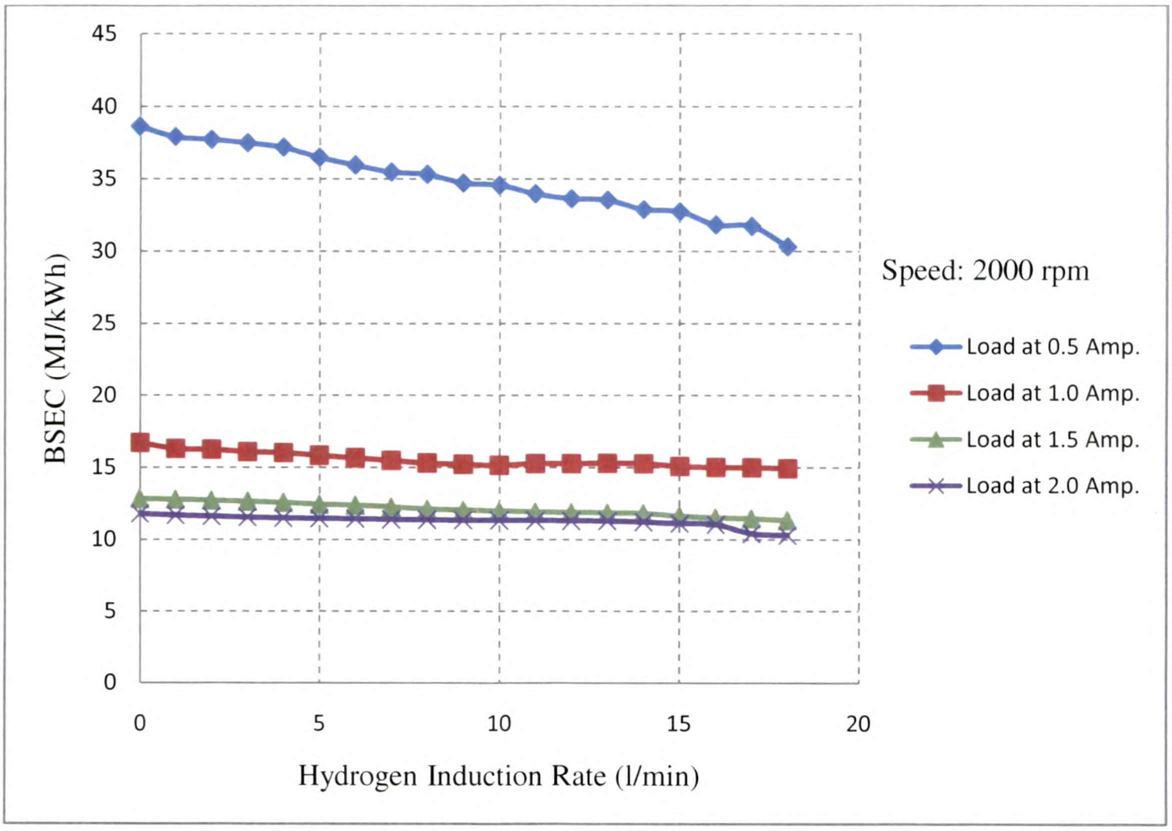


Fig. 3.50 Variation of BSEC with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Exhaust Temperature**

Figs. 3.51 to 3.55 illustrate the variation in exhaust gas temperature with the load, speed and hydrogen induction rate. In Section 3.4.1.1, it is already seen that the exhaust temperature increases with both load and speed of the engine. Similar trends are also observed when hydrogen induction is carried out in intake manifold. For the same load and speed, it is seen that there is a marginal increase in exhaust temperature. The exhaust temperature is one of engine performance indicators. The increase in exhaust temperature is a direct indicator to the increase in the energy release in the combustion chamber. The release in energy is due either increase in the energy consumption rate or/and the complete combustion of the available fuel. The increase of hydrogen induction rate leads to the increase in the exhaust temperature as a result of the higher caloric value of hydrogen. An increase in exhaust temperature from about 72 °C to 176 °C is observed when the engine is operated at 1000 rpm and no load condition without hydrogen induction takes place, while the increase is from 78 °C to 195 °C when hydrogen induction rate is 18 l/min with other conditions remain the same. The increase in exhaust temperature, when the engine is operated at 2000 rpm and no load condition with out hydrogen induction, is from 118 °C to 370 °C while the increase is from 122 °C to 405 °C when the hydrogen induction rate is 18 l/min. The rate at which the exhaust temperature increase remains fairly constant when the hydrogen induction rate is increased from no induction to the maximum induction of 18 l/min at all the combinations of speed and load conditions.

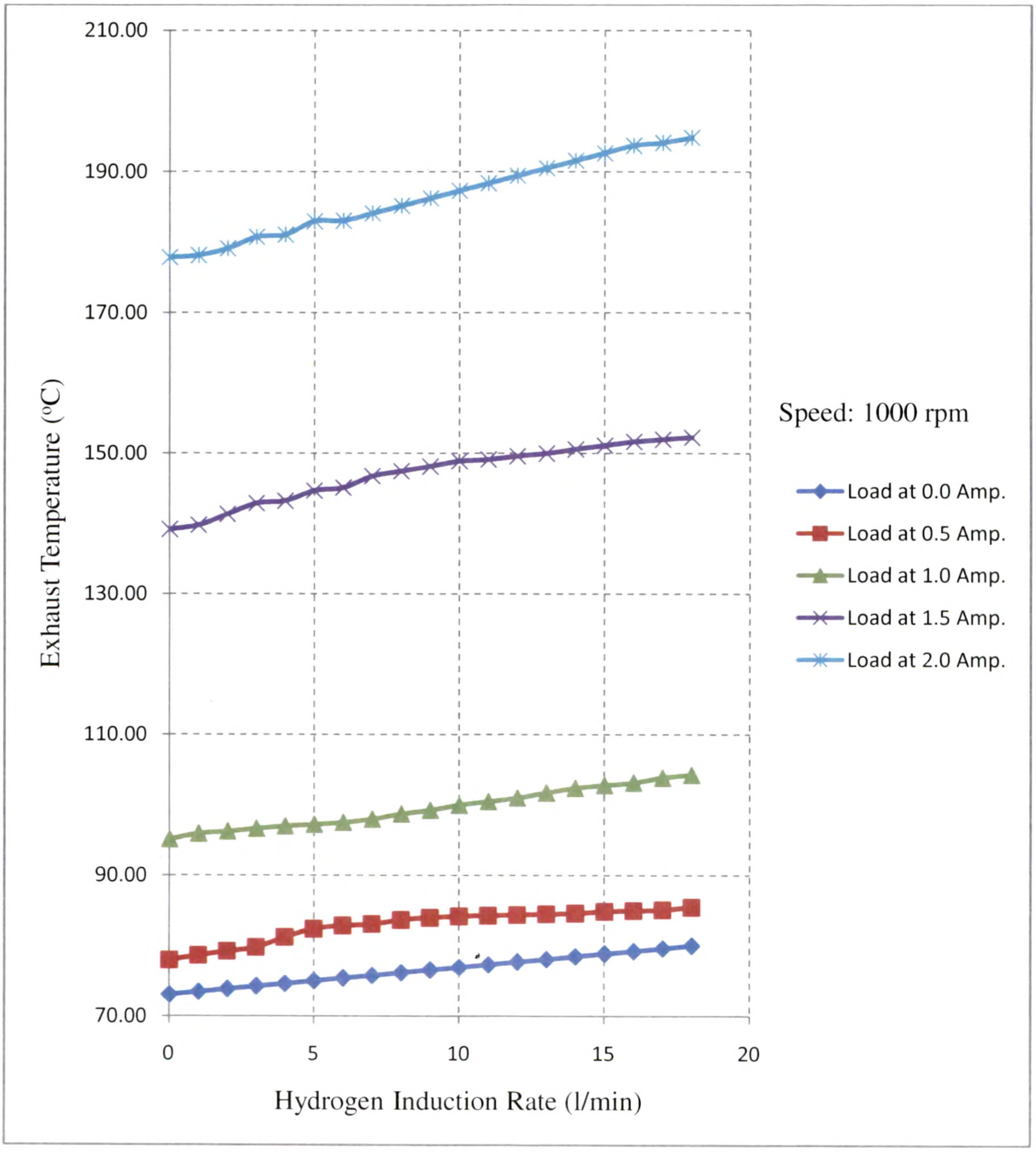


Fig. 3.51 Variation of Exhaust Temperature with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

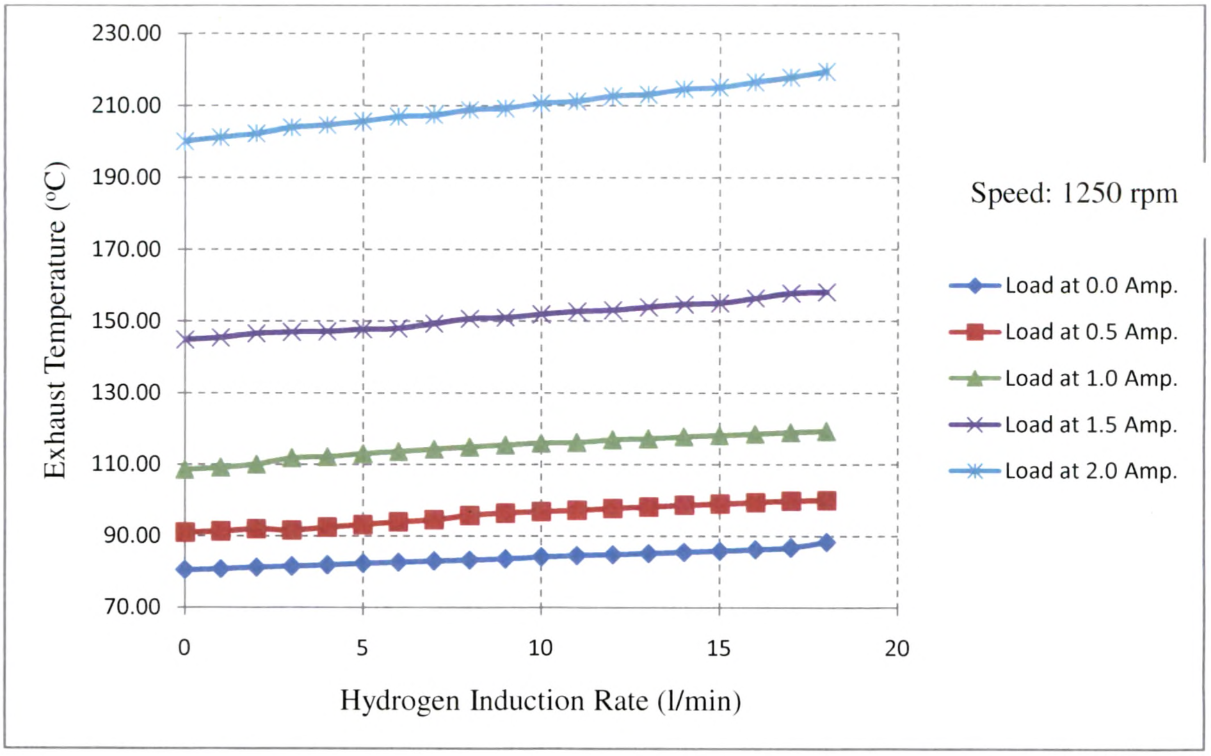


Fig. 3.52 Variation of Exhaust Temperature with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

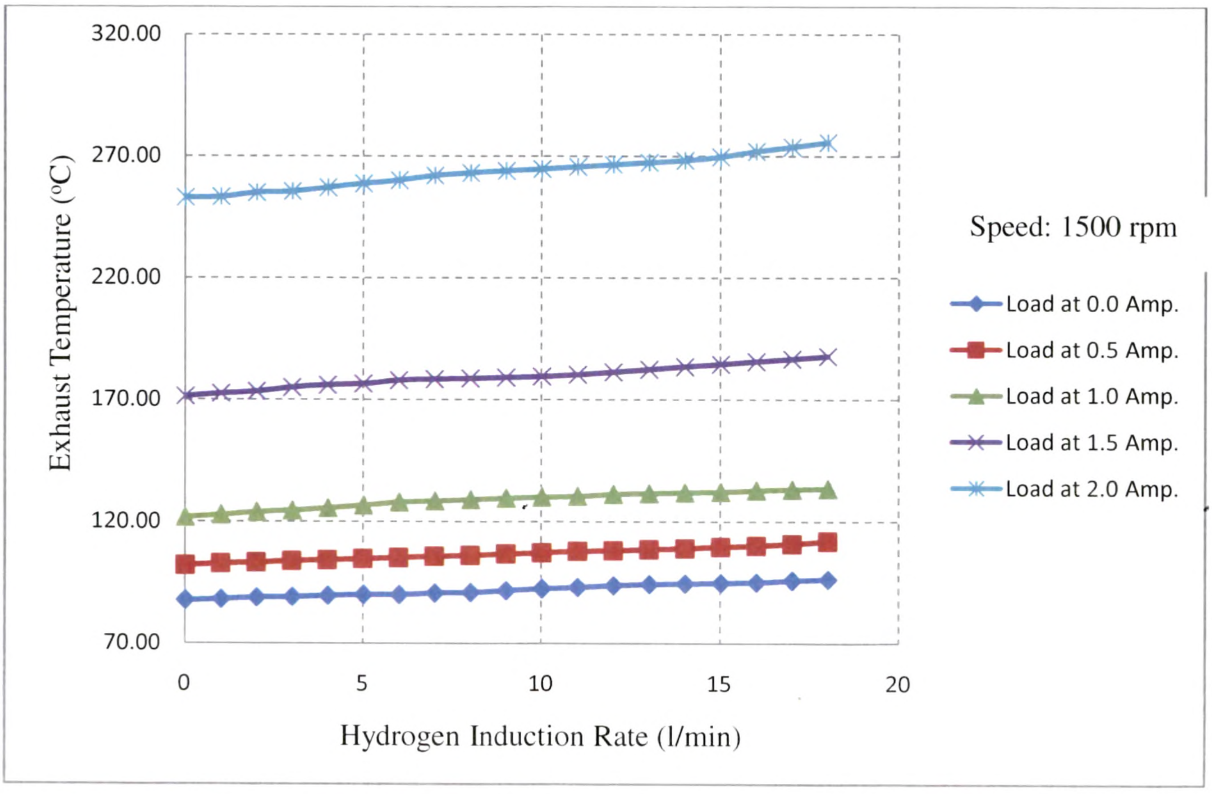


Fig. 3.53 Variation of Exhaust Temperature with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

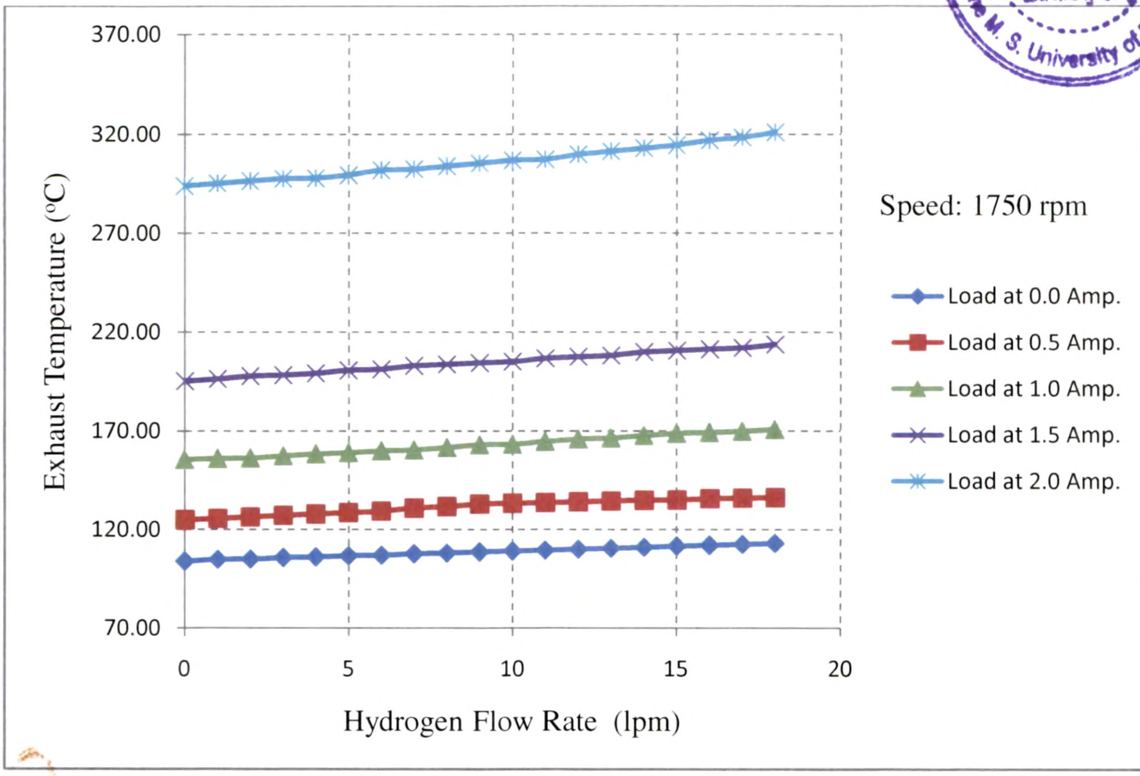


Fig. 3.54 Variation of Exhaust Temperature with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

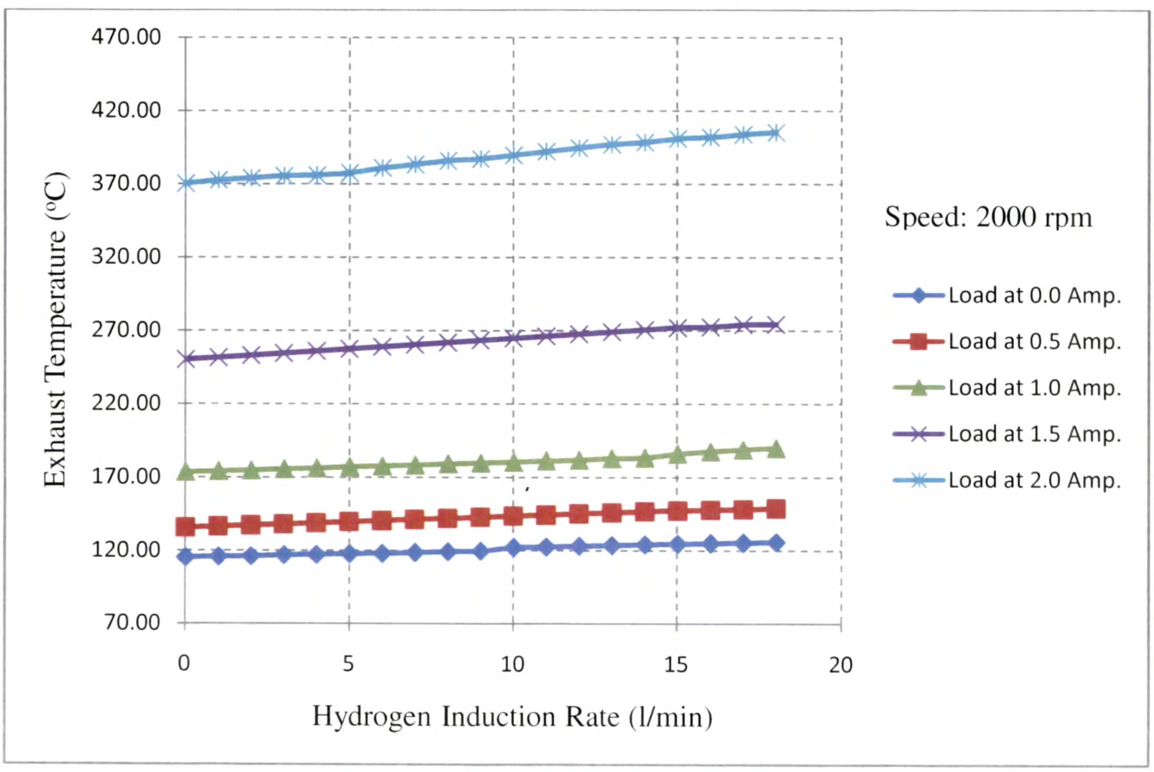


Fig. 3.55 Variation of Exhaust Temperature with Hydrogen Induction Rate for Various Engine Loading Engine and at 2000 rpm

3.4.2.2 Constituents of Exhaust Gas Emission

- **Oxygen (O_2) in the Exhaust**

Figs. 3.56 to 3.60 show the variation of per cent content of O_2 in exhaust gases with hydrogen induction rate for various engine loading and operated at different speeds. It can be seen that the per cent content of O_2 in exhaust gases marginally decraes with increase in hydrogen induction rate for agiven speed and load condition. However, as the load is increased from no load condition to the maximum of 2.0 Amp., it is found that there is a considerable reduction in the content of O_2 in exhaust gases and the rate at which the reduction takes place is more or less constant for all hydrogen induction rates. As the load is increased, more amount of atmospheric air is drawn in to the system and more amount of O_2 is consumed from the drawn air for the conversion in to useful power resulting in a decrease in the content of O_2 in exhaust gases. The increase in hydrogen induction rate, on the other hand, proportionally decreases the actual volume of air drawn which will result in the reduction of overall O_2 content in the engine. This leads to a marginal reduction in the content of O_2 in exhaust gases.

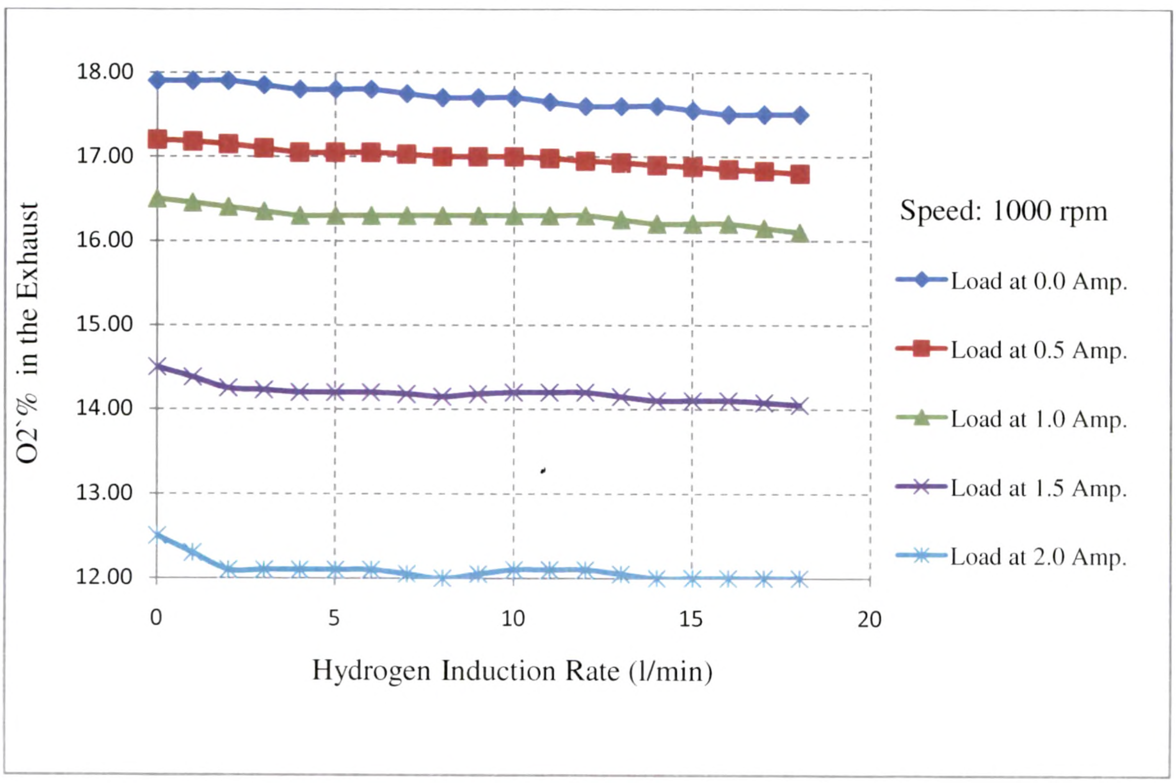


Fig. 3.56 Variation of O_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

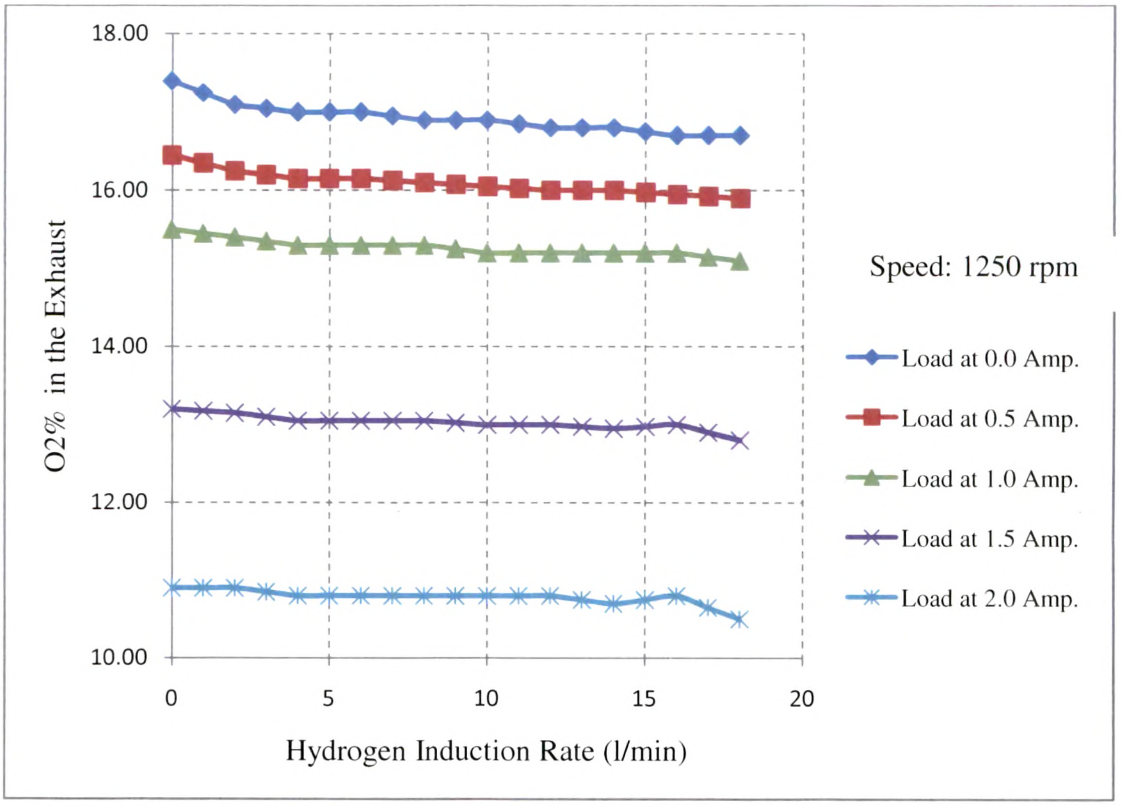


Fig. 3.57 Variation of O_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

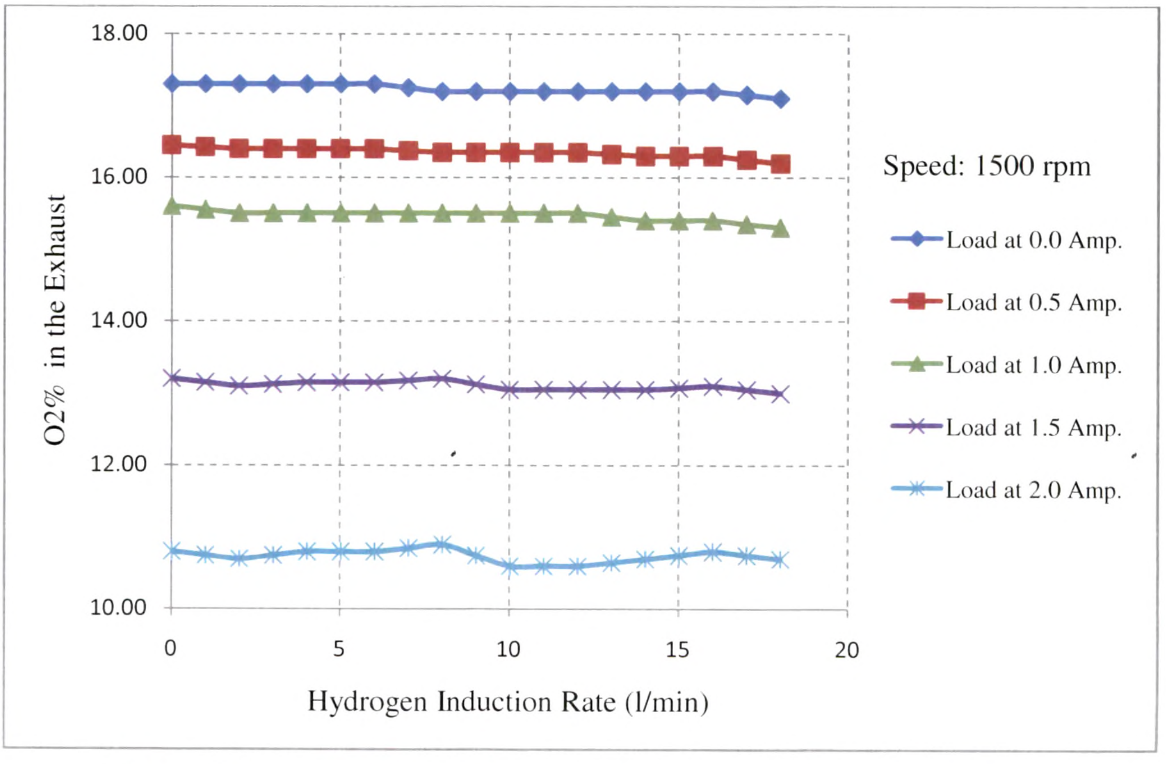


Fig. 3.58 Variation of O_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

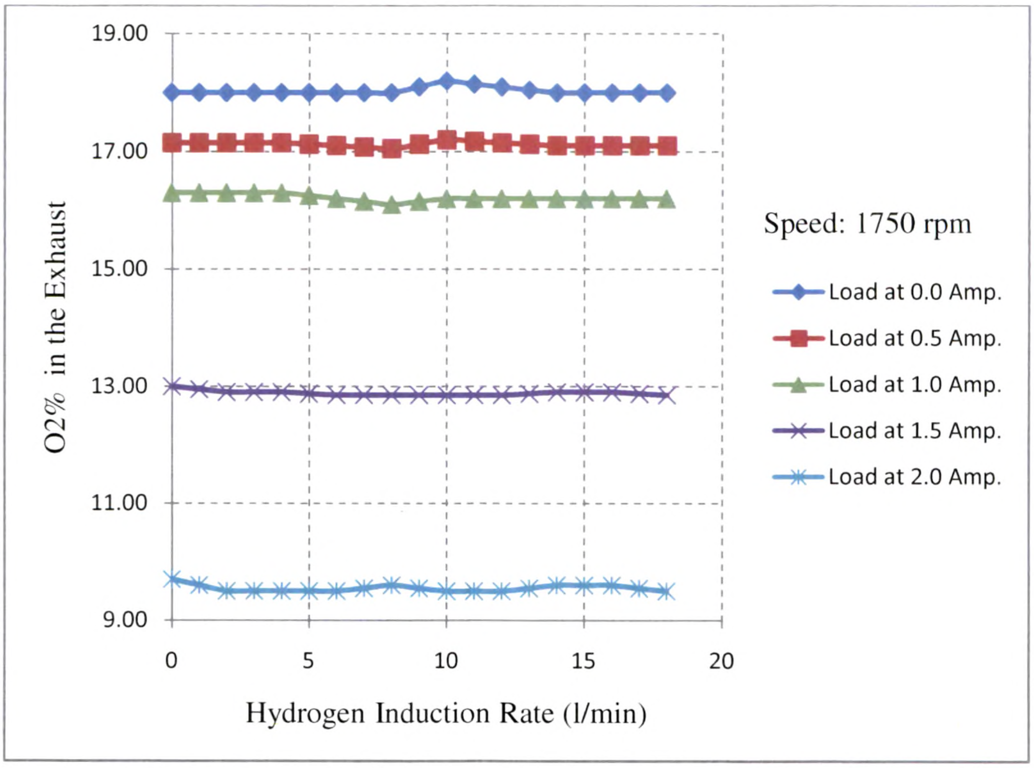


Fig. 3.59 Variation of O_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

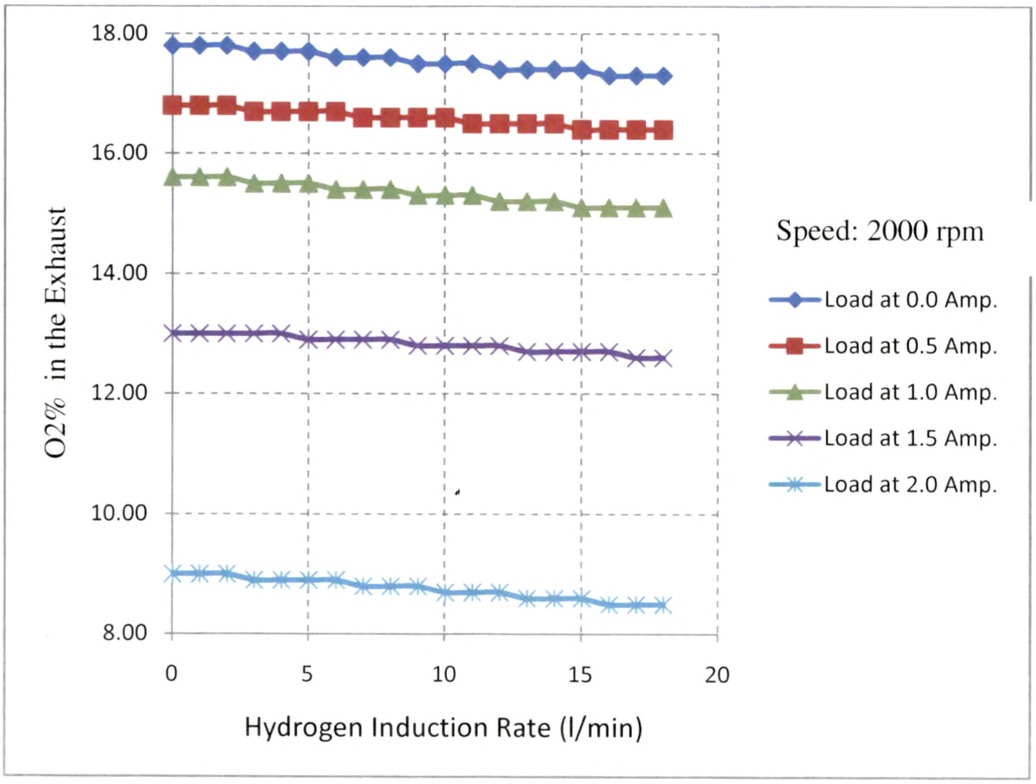


Fig. 3.60 Variation of O_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Carbon Monoxide (CO) in the Exhaust**

Generally the carbon monoxide emission is controlled primarily by the fuel/air equivalence ratio [91]. For rich mixture, CO concentration in the exhaust increases steadily with increase in equivalence ratio, as the amount of excess fuel increases. For fuel lean mixture, CO concentrations in the exhaust vary little with equivalence ratio. Diesel engine, however, always operates well on the lean side of stoichiometric. Therefore, the CO emission from diesel engine is low. Figs. 3.61 to 3.65 show the variation of percentage content of CO in exhaust gases with hydrogen induction rate for various loads and speeds. It can be observed that the content of CO in exhaust gases increases with increase in the rate of hydrogen induction when the engine operates at a specified load and speed. However, the rate of increase in the content of CO in exhaust gases decreases with increase in load and is true for all the chosen speeds between 1000 rpm and 2000 rpm. The increment in hydrogen induction rate causes reduction in the intake air which results in a displacement of some volume of the intake air. With increase in load and speed, therefore, the per cent content of CO in exhaust gases slightly decreases for a given hydrogen induction rate. This slight reduction in per cent content of CO in exhaust gases may be either due to the formation of lean mixture when only diesel is used as base fuel or/and due to the conversion of CO to CO_2.

CO formation is one of the principal steps during reaction in the hydrocarbon combustion mechanism, which can be represented as follows: [5]

$$RH \rightarrow R \rightarrow RO_2 \rightarrow RCHO \rightarrow RCO \rightarrow CO$$

Where R stands for the hydrocarbon radical. The CO formed in the combustion process via this path is then oxidized to CO_2 at a slower rate. The principal CO oxidation reaction in hydrocarbon –air flame is given by

$$CO + OH = CO_2 + H$$

According to this mechanism, the formation of CO and CO_2 might happen.

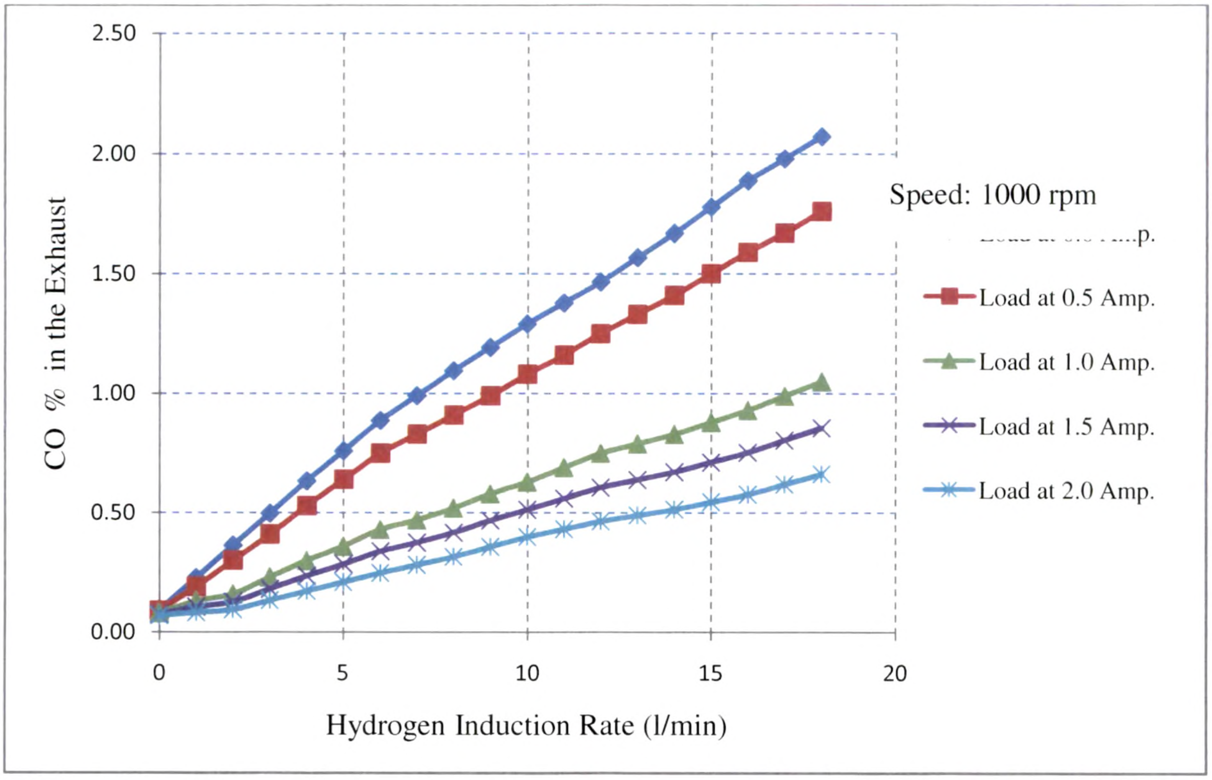


Fig. 3.61 Variation of CO% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

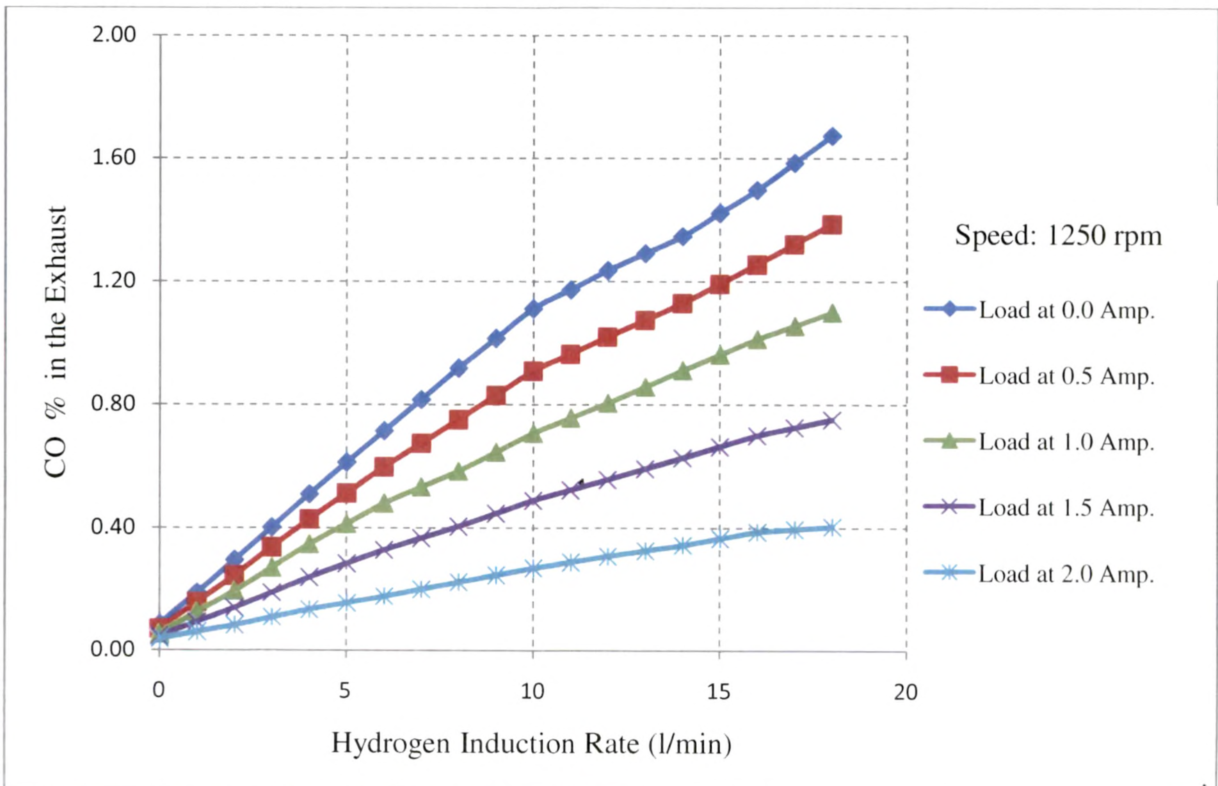


Fig. 3.62 Variation of CO% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

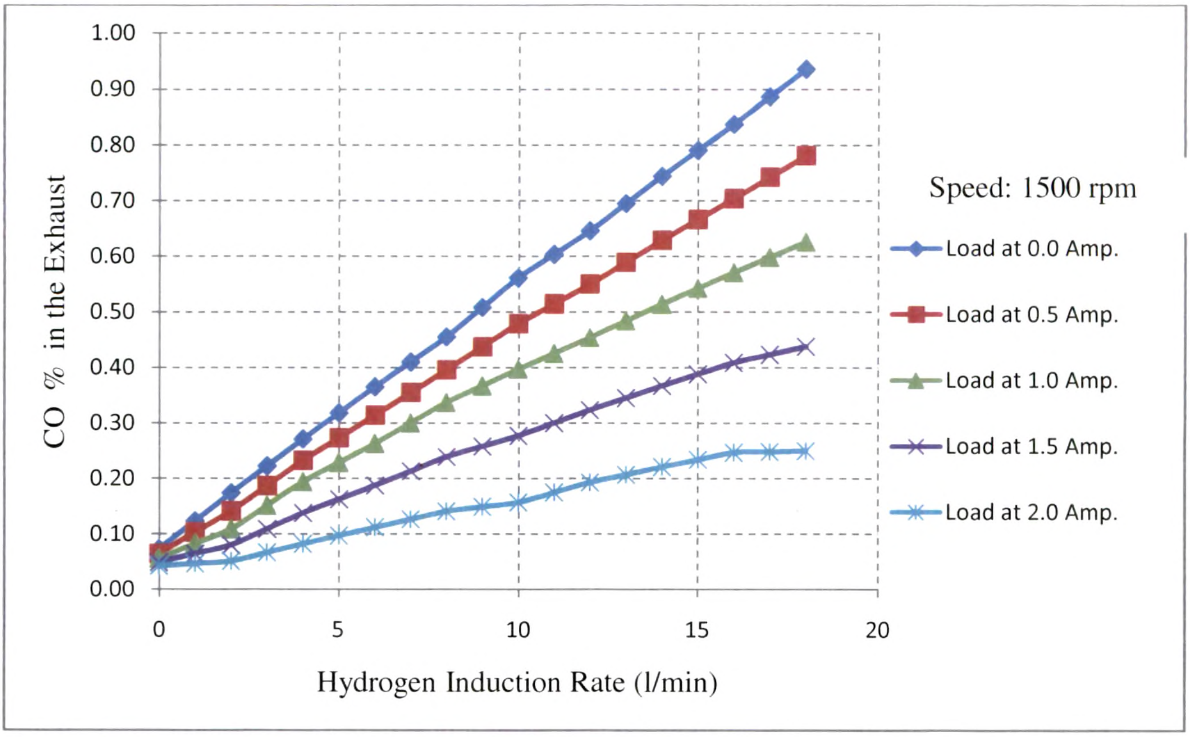


Fig. 3.63 Variation of CO% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

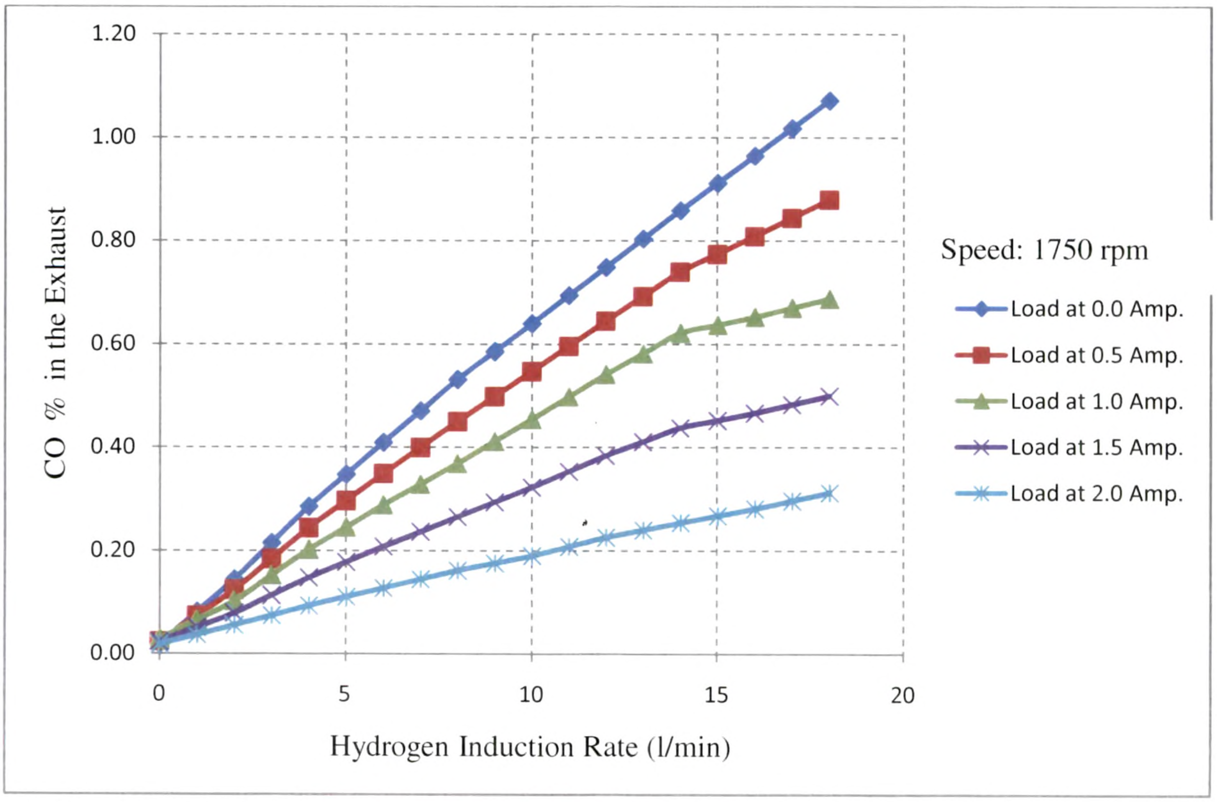


Fig. 3.64 Variation of CO% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

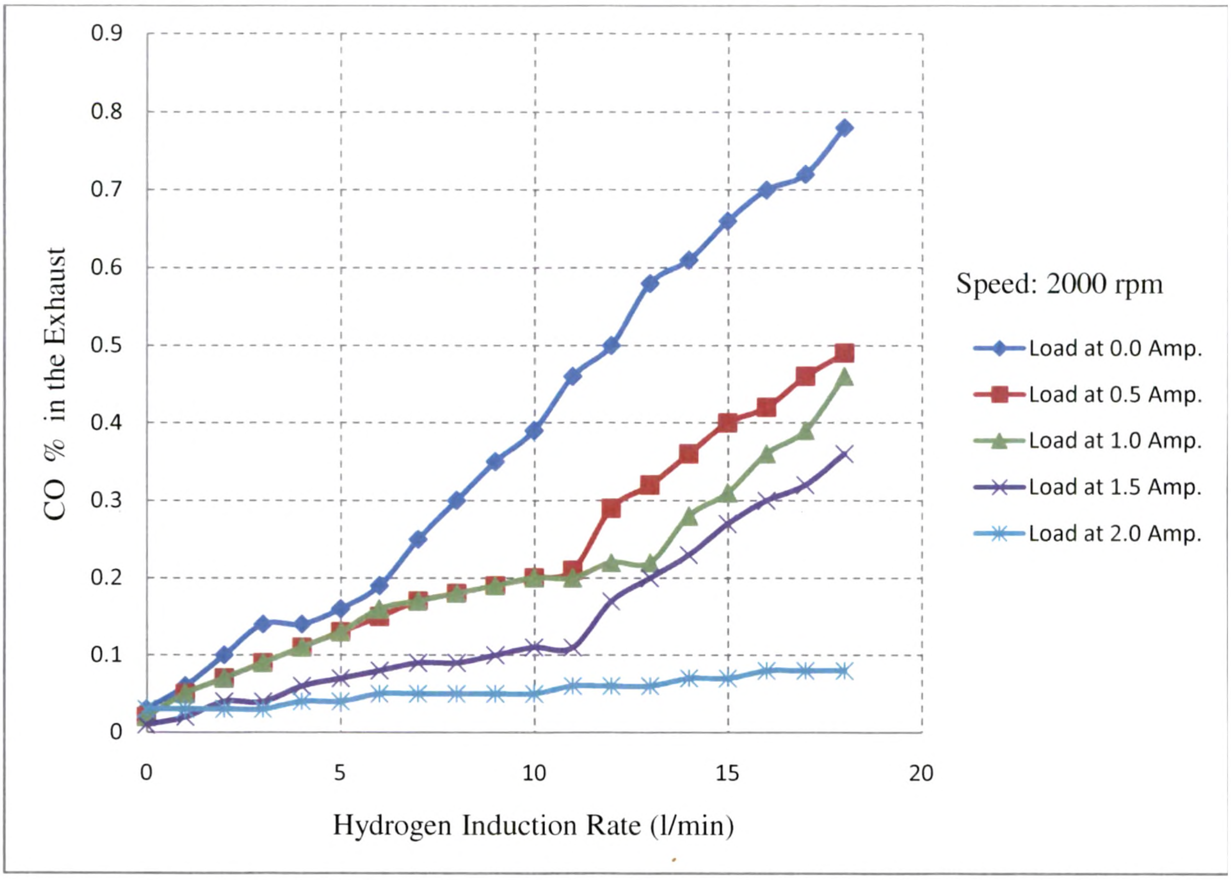


Fig. 3.65 Variation of CO% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Carbon Dioxide (CO_2) in the Exhaust**

The variation of the per cent content of CO_2 in exhaust with hydrogen induction rate for the engine operating conditions of different speed and load are given in Figs. 3.66 to 3.70. It is seen that the increase in hydrogen induction rate marginally increases the per cent content of CO_2 in exhaust for all the combinations of operating conditions of the engine. However, there is a three fold increase in the per cent content of CO_2 in exhaust when the load is increased from no load to 2.0Amp. load condition for a given constant speed of the engine. This is true for all the combinations of speed and hydrogen induction rate investigated. The reason for such trends are the same as that described for the case of CO in exhaust

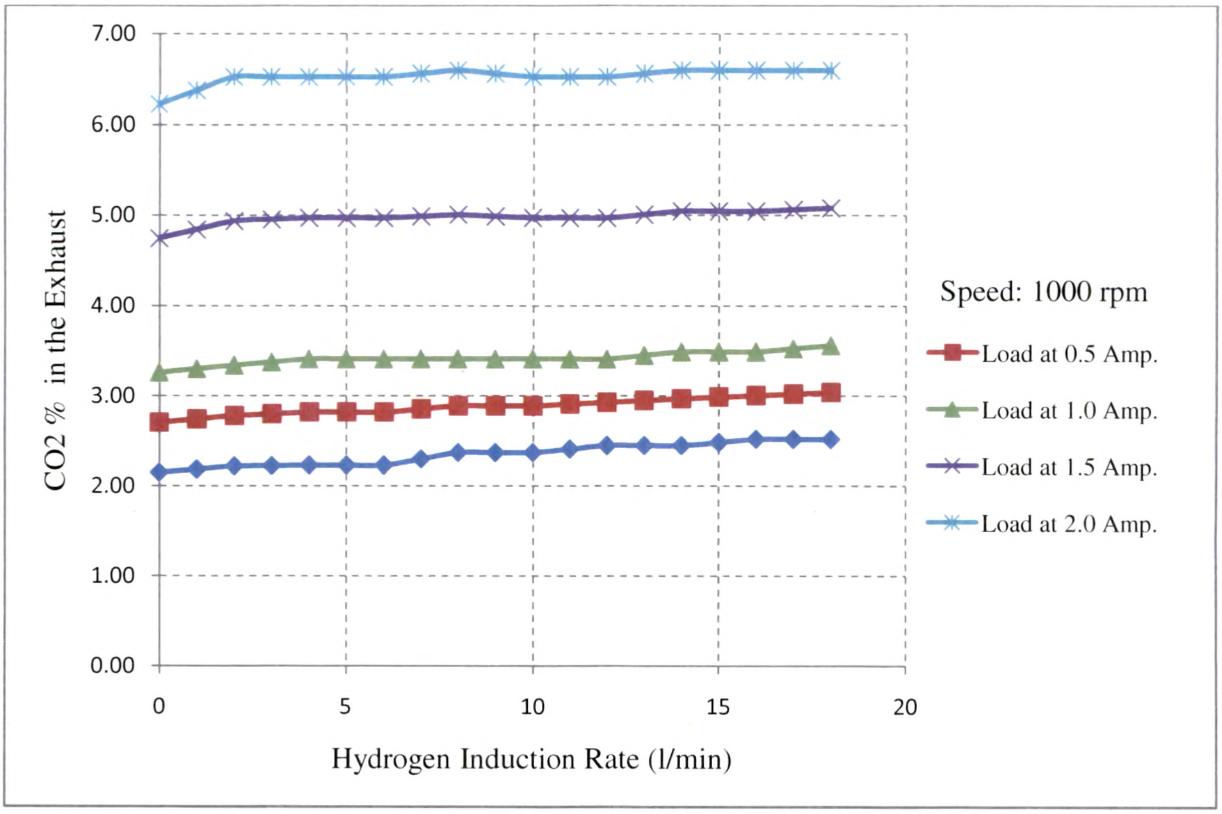


Fig. 3.66 Variation of CO_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

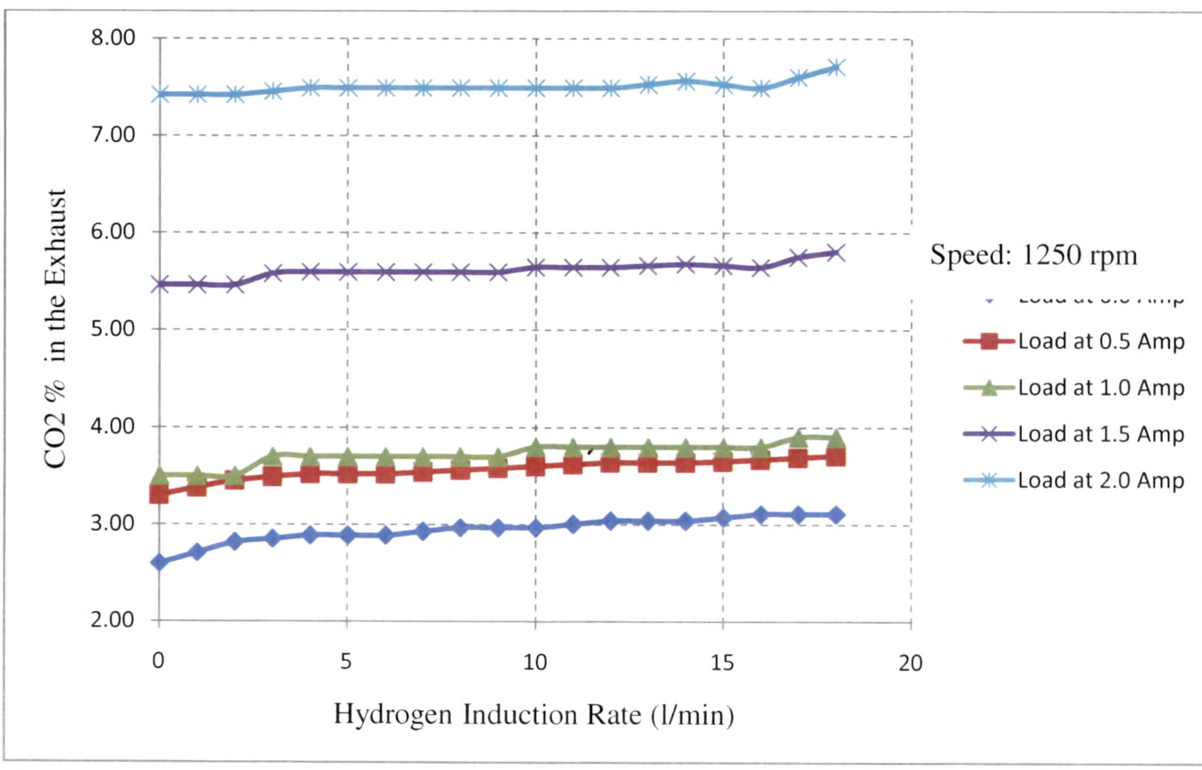


Fig. 3.67 Variation of CO_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

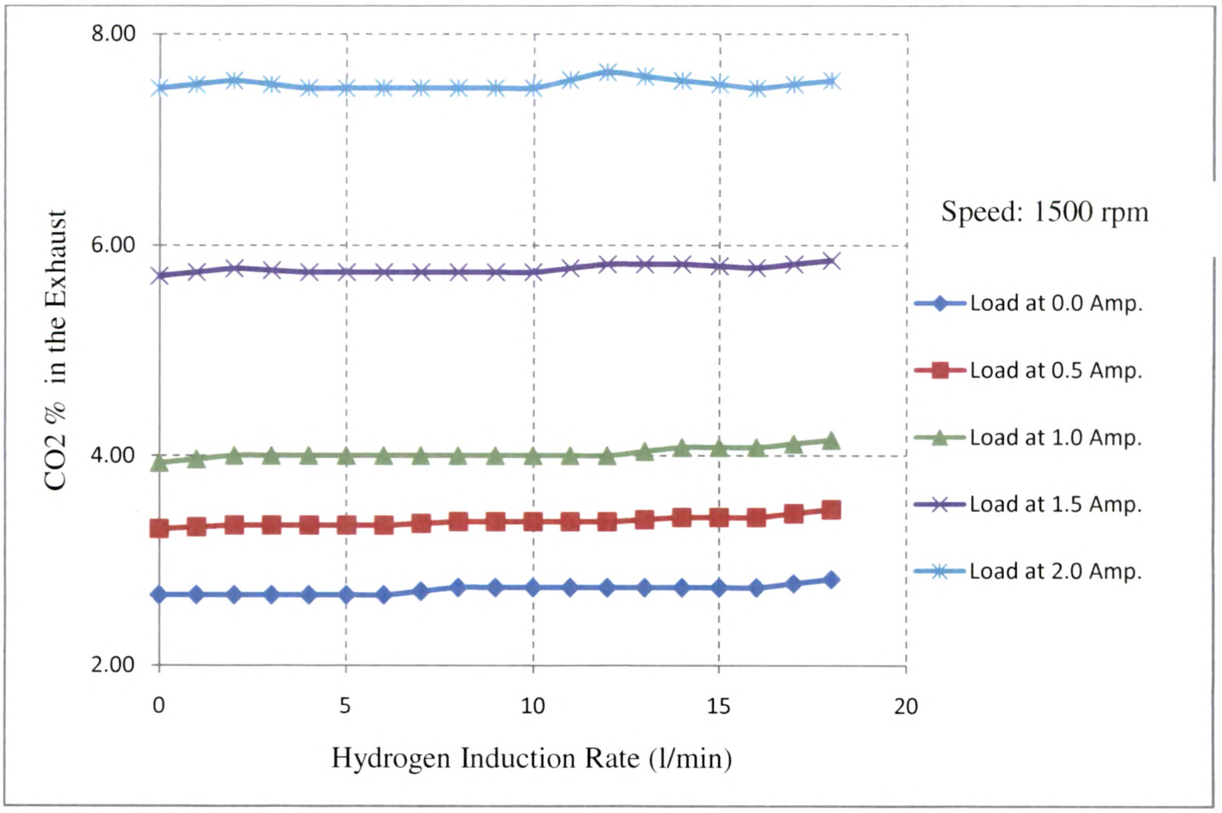


Fig. 3.68 Variation of CO_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

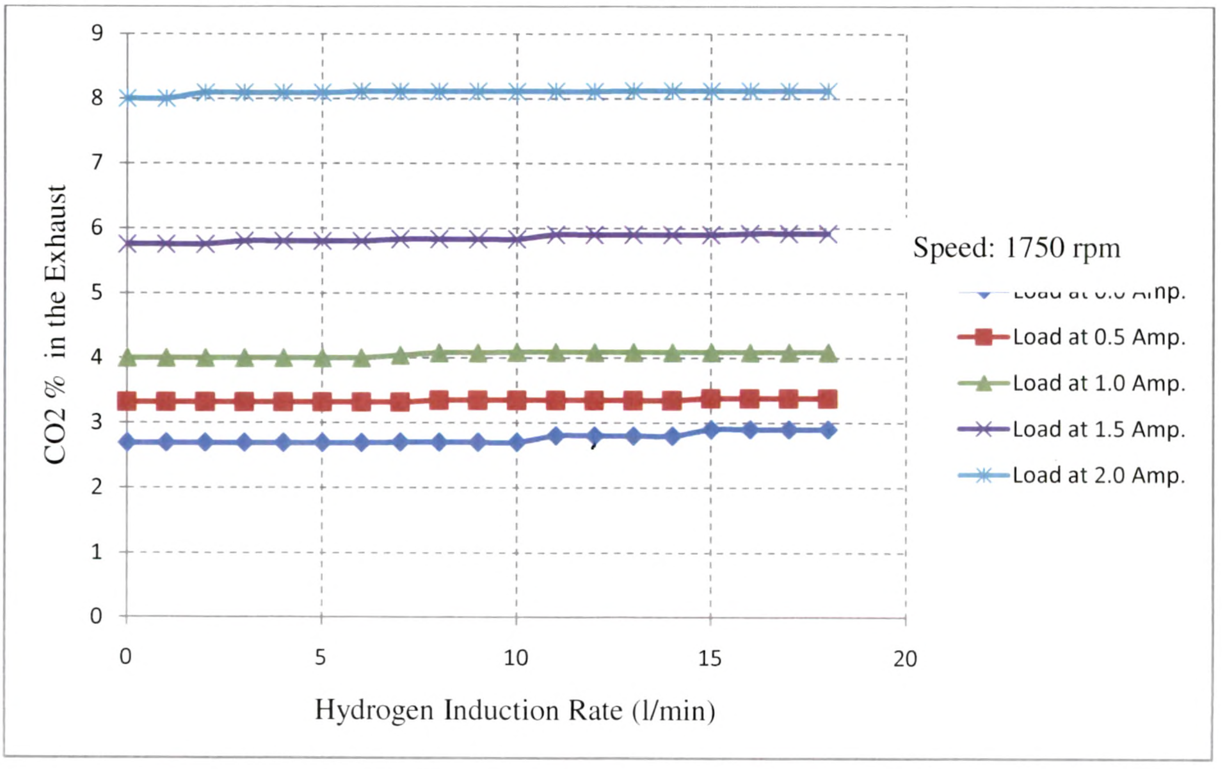


Fig. 3.69 Variation of CO_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

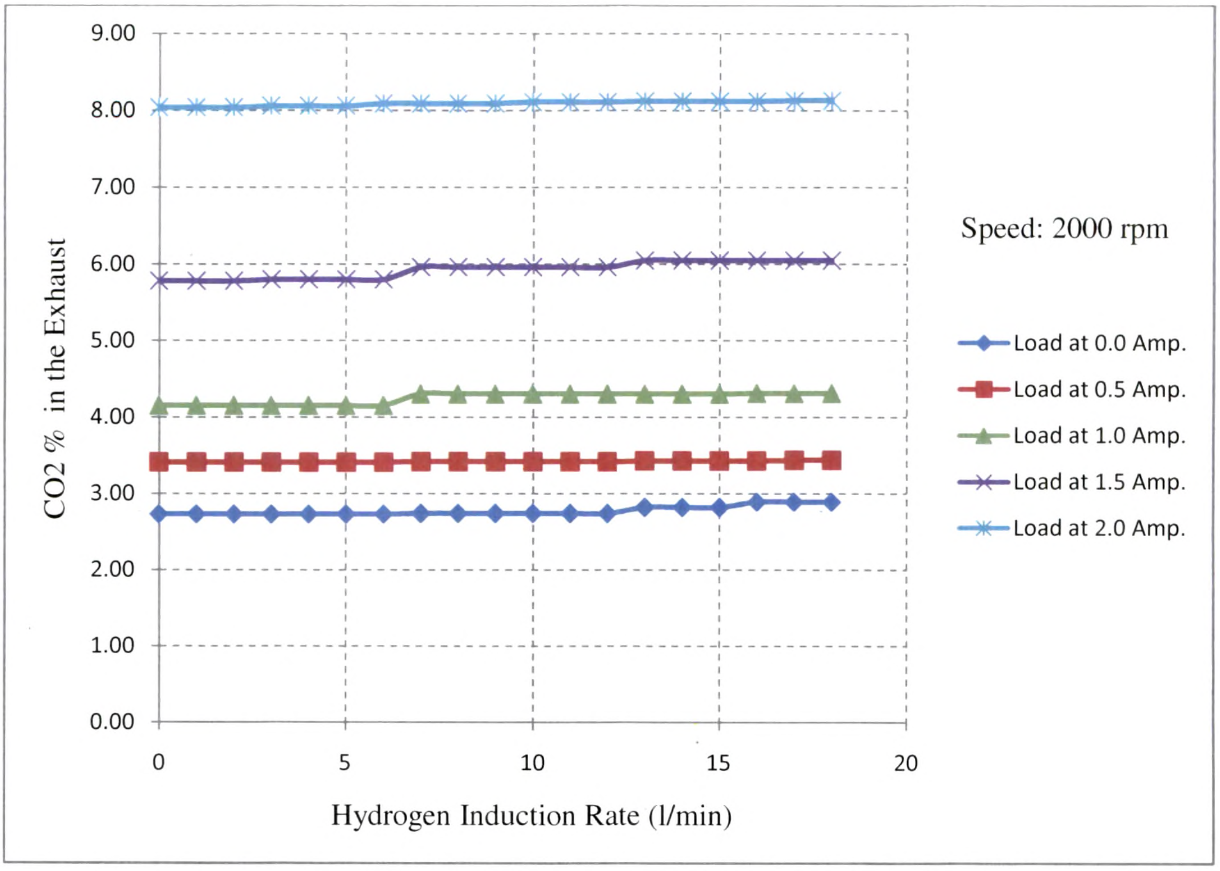


Fig. 3.70 Variation of CO_2% in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Unburned Hydrocarbon (HC) in terms of CH_4 in the Exhaust**

Figs. 3.71 to 3.75 show the variation of HC with hydrogen induction rate at various loads and speeds. It can be observed that the rate of hydrogen induction in to the intake manifold beyond 10 l/min has a pronounced effect on the un-burnt hydrocarbon content in the exhaust for all the combinations of the operating conditions of speed and load of the engine. Although the per cent content of HC is only of the order of 0.1 to 2 %, the per cent increase is significant. With an exception of the data related to the no load operation of the engine at 1250 rpm, wherein the trend of variation in the per cent HC content in the exhaust is different, all other data are indicative of a set trend in the variation of the content of HC in exhaust. Up to about an induction rate of 7 to 8 l/min, the effect of hydrogen induction in to the drawn atmospheric air in the intake manifold has no significant effect on the HC content in exhaust. However, at higher loads and speeds, the effect of the induction is significant as high rate of hydrogen induction affect the volume of the drawn atmospheric air.

From Figs. 3.70 to 3.74, it can be seen that the percent content of HC in the exhaust is of the order of 0.1 to 02. % in the range of hydrogen induction rate between no induction up to 7.5 l/min for all the combinations of load and speed with one or two exception. Beyond, the induction rate of 7.5 l/min, there is significant change in the per cent content of HC in the exhaust. Further, a maximum per cent content of HC of 1.92 % is recorded when the engine is operated at no load and speed of 1000 rpm with the hydrogen induction rate at 18 l/min. And at this state, the volumetric efficiency is found to be the minimum. in the exhaust. As discussed Section 3.4.2.1, the engine operated at high speed allows high volume of air to be drawn in to the engine which leads to an enhancement in the combustion process which results in the conversion of some of the CO and HC in to CO_2 found in the exhaust.

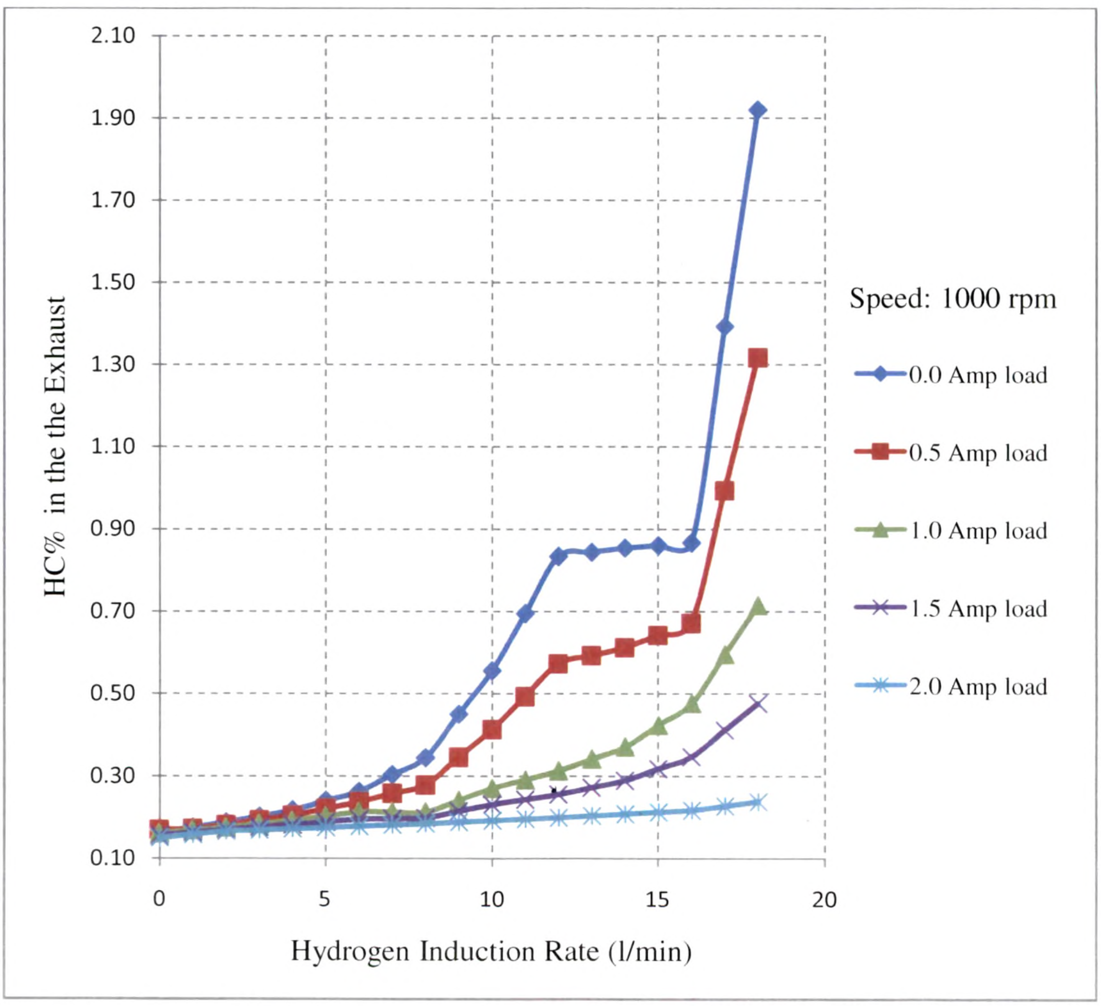


Fig. 3.71 Variation of HC % in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

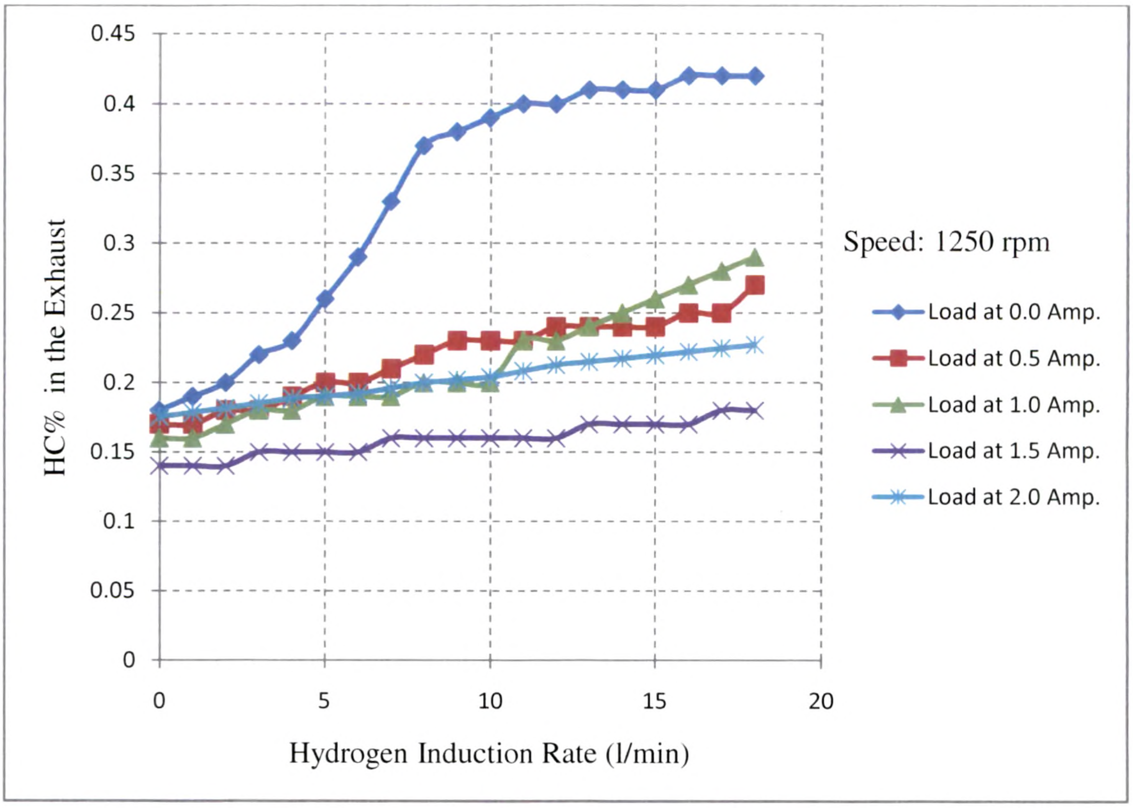


Fig. 3.72 Variation of HC % in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

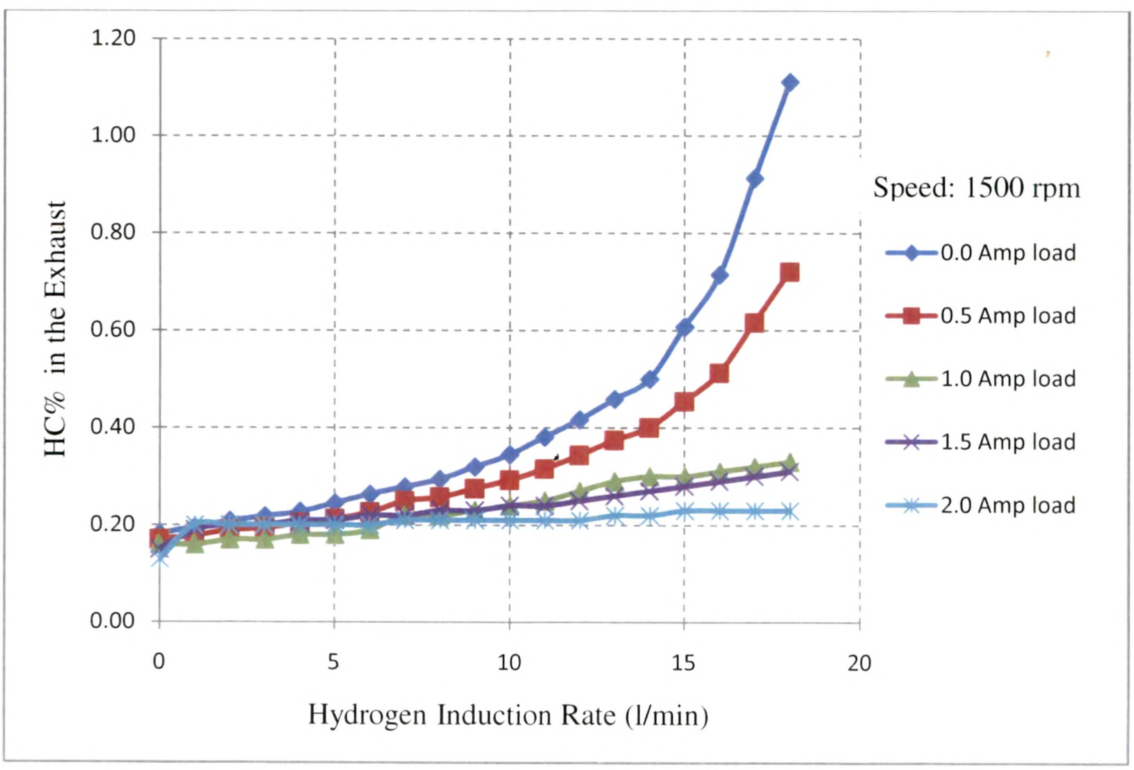


Fig. 3.73 Variation of HC % in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

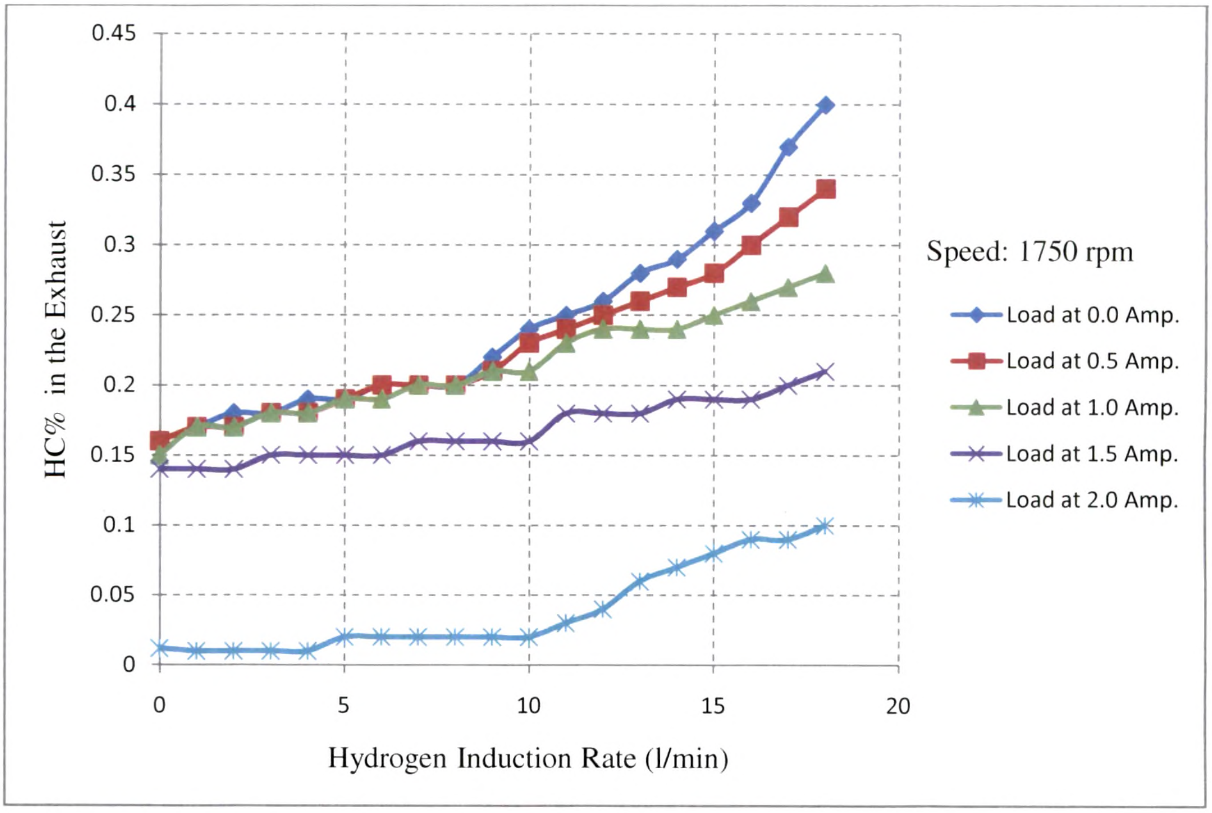


Fig. 3.74 Variation of HC % in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

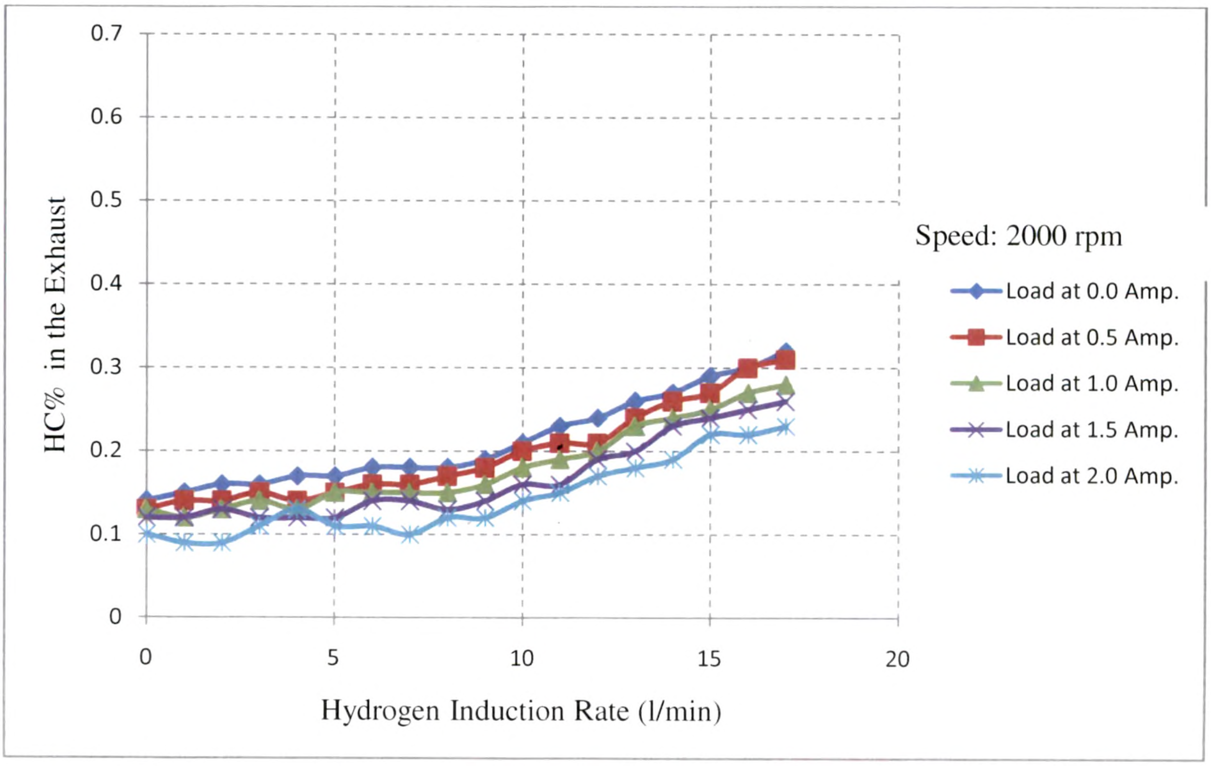


Fig. 3.75 Variation of HC % in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- **Sulphur Dioxide (SO_2) in the Exhaust**

Figs. 3.76 to 3.80 show the variation of the content of SO_2 in the exhaust with hydrogen induction rate at various loads and speeds. It is seen that the effect of hydrogen induction along with the atmospheric air in to the intake maniflod is to increase in the content of SO_2 in the exhaust. Same trend that is discussed in Fig. 3.17 of Section 3.4.1.2 are observed as far as the variation in the SO_2 traces in exhaust gases are concerned.

For a given hydrogen induction rate, SO_2 traces in exhaust gases is found to decrease with speed and load. However, with increase in hydrogen induction rate the per cent content of SO_2 in exhaust gases increases. The reason for such a decrease in SO_2 content with speed and load may be attributed to the increase in the absorption of SO_2 by particulate matter (PM) thereby reducing the content of SO_2 in the exhaust.

However, when the hydrogen induction rate is increased, there is a possibility of the saturation of PM which will allow the increase of SO_2 in exhaust. Further, the possibility of the formation of SO_3 due to the insufficient oxygen leads to the increase in SO_2 in the exhaust. The SO_2 content in exhaust is found to be 141 ppm at a constant speed of 1000 rpm and under no load condition with no hydrogen induction, The content increases to 1499 ppm which is 10 times more when the induction rate is 18 l/min with the same speed and load condition. When the speed is increased to 2000 rpm under no load condition, it is found that the SO_2 content increases from 10 ppm with no induction to 750 ppm with the induction rate at 18 l/min, an increase of 75 times.

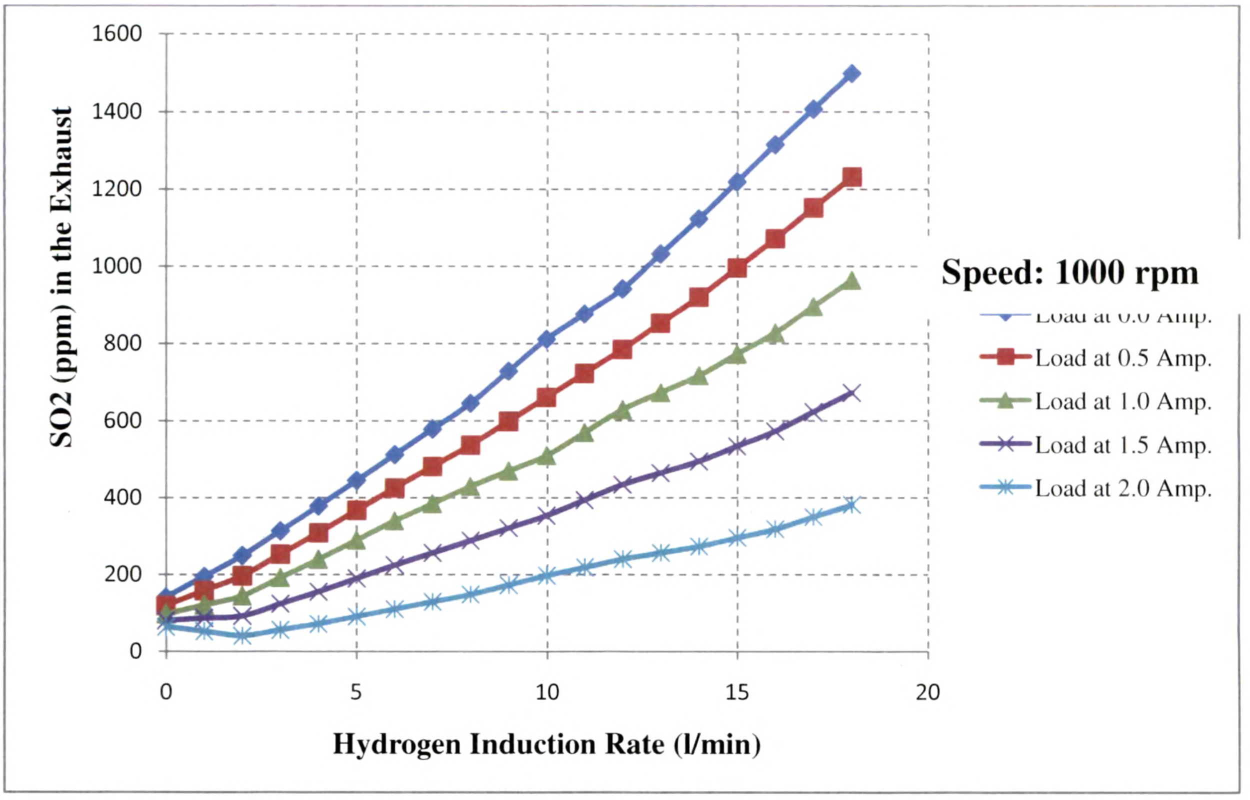


Fig. 3.76 Variation of SO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

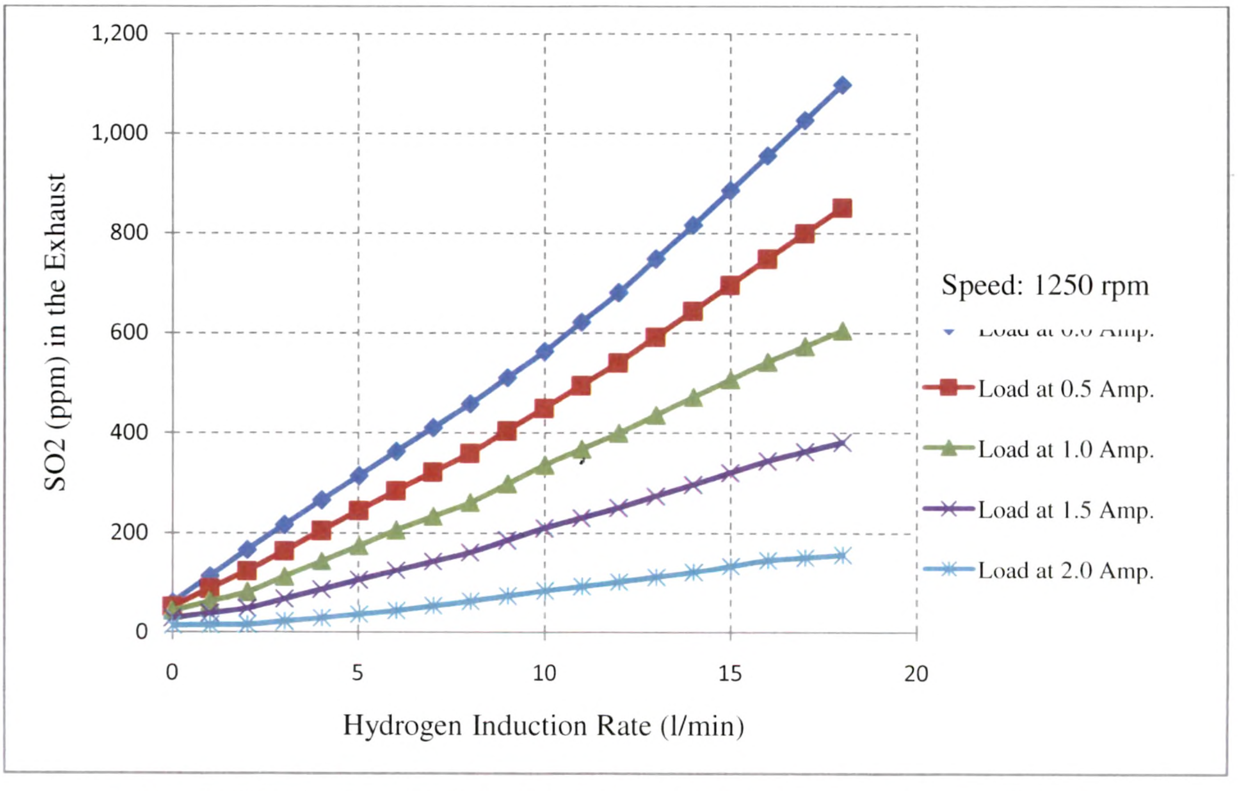


Fig. 3.77 Variation of SO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

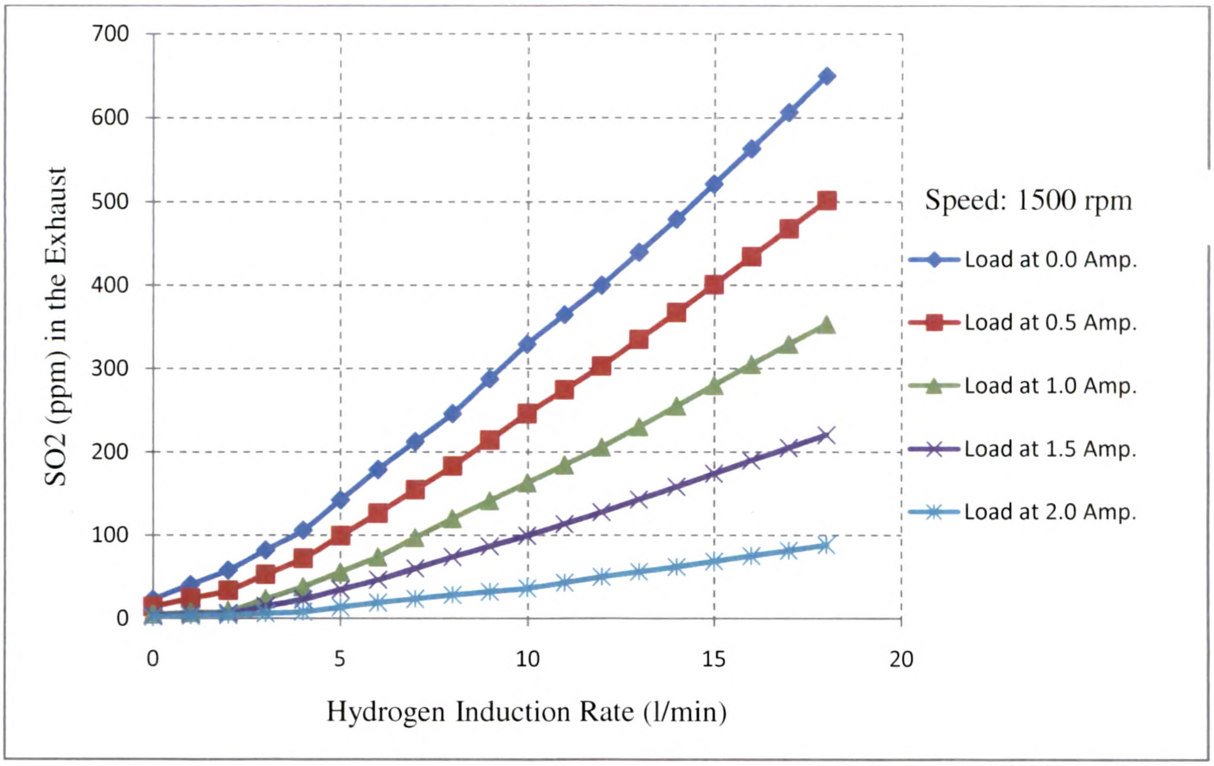


Fig. 3.78 Variation of SO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

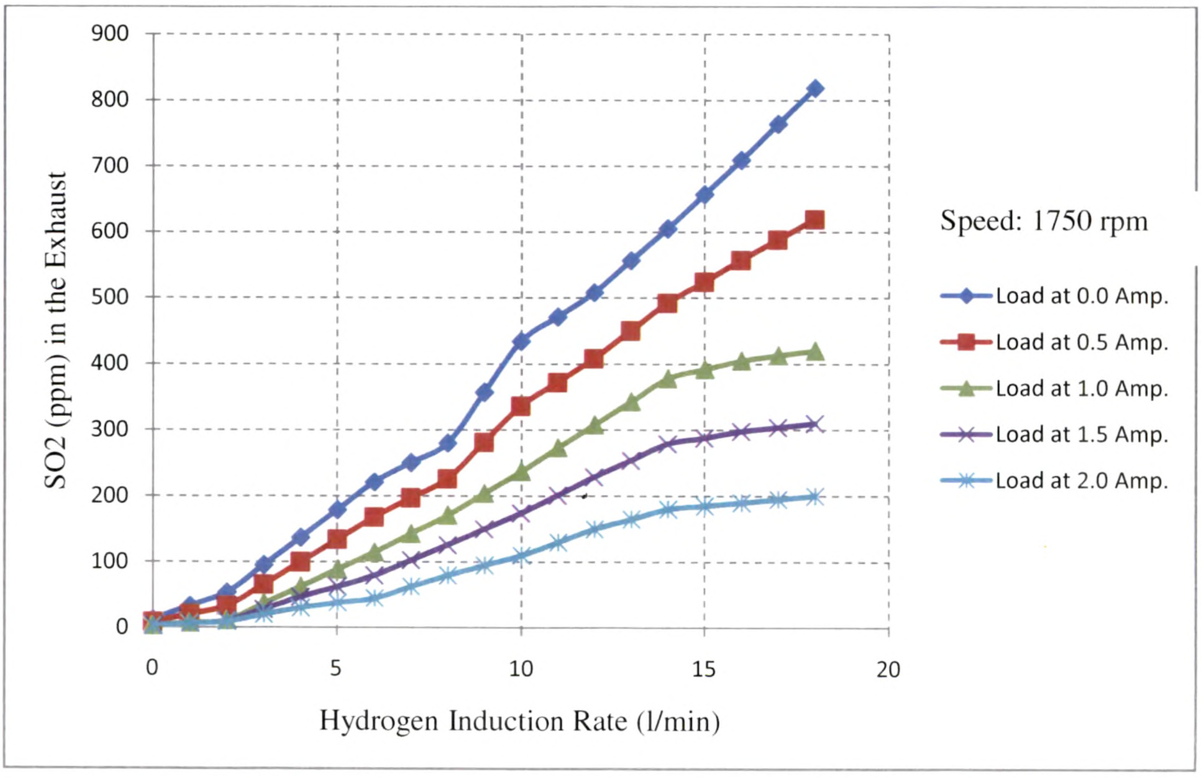


Fig. 3.79 Variation of SO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

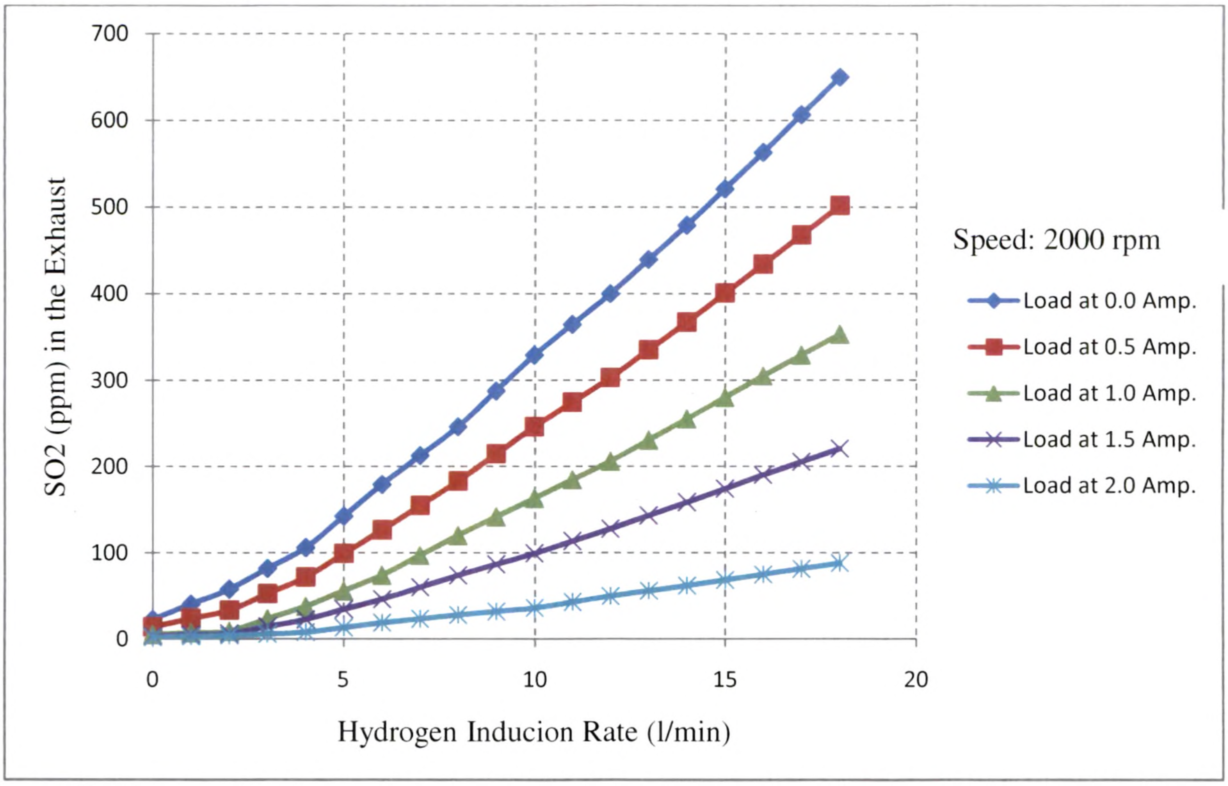


Fig. 3.80 Variation of SO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- Nitrogen Dioxide (NO_2)

Figs. 3.81 to 3.85 present the variation of the content of NO_2 in the exhaust gases with hydrogen induction rate at various loads and speeds. The formation of NO_2 and NO depend on the temperature of flue gases and the amount of oxygen inside the combustion chamber during combustion. Obviously, with an increase of load, the amount of air and hence the oxygen content in the combustion chamber decreases. As a result of this, NO_2 in exhaust decreases. However, NO_2 increases with speed. With the increase in the hydrogen induction rate, it is found that there is increase of NO2 in exhaust due to the increase in the exhaust temperature.the variation of NO_2 . It should be noted that the content of NO_2 in exhaust is significant only at high speeds and as such the quantity of NO_2 is relatively low as compared to NO. Further, one may treat NO_2 to be a part of NO_X. The trend observed in the variation of NO2 content with the increase in hydrogen induction rate is not sytematic in the low speed and low hydrogen induction rate. The observed trend may be due to partly the low levels of NO_2 content and experimental error.

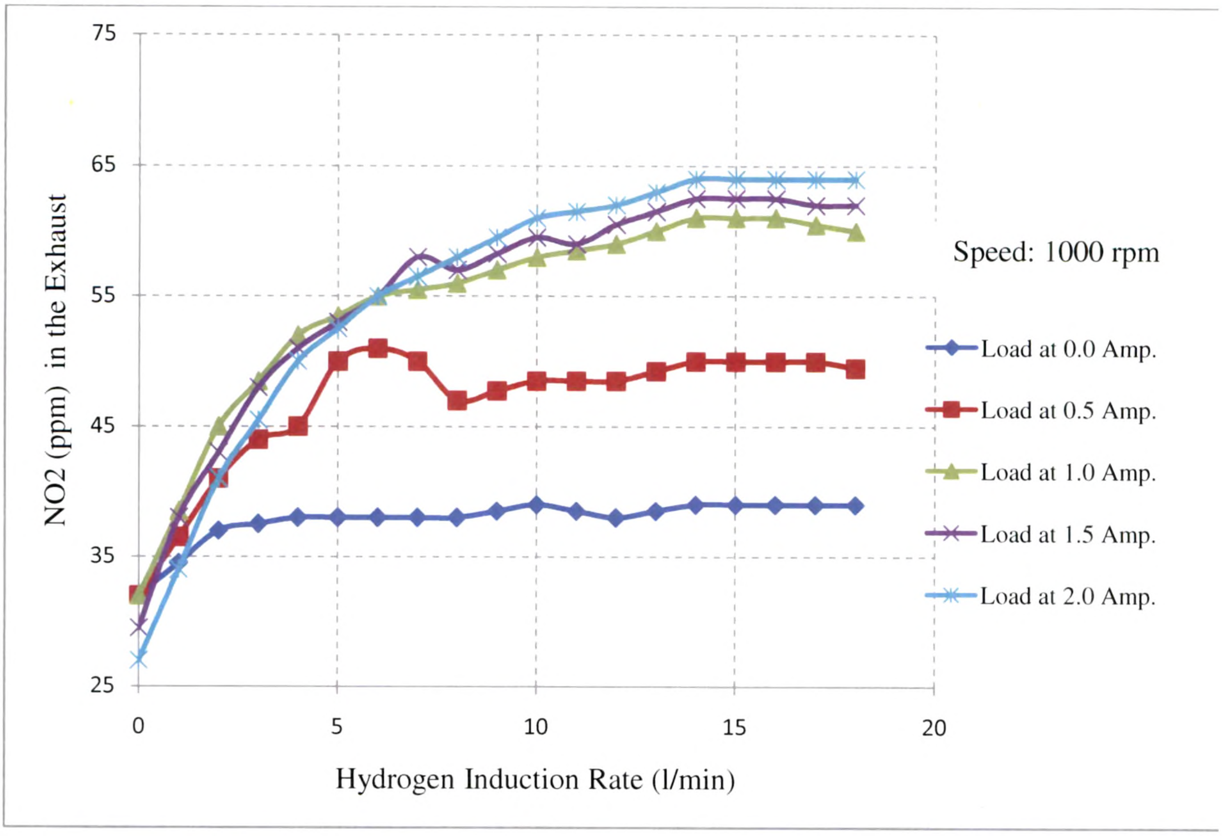


Fig. 3.81 Variation of NO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

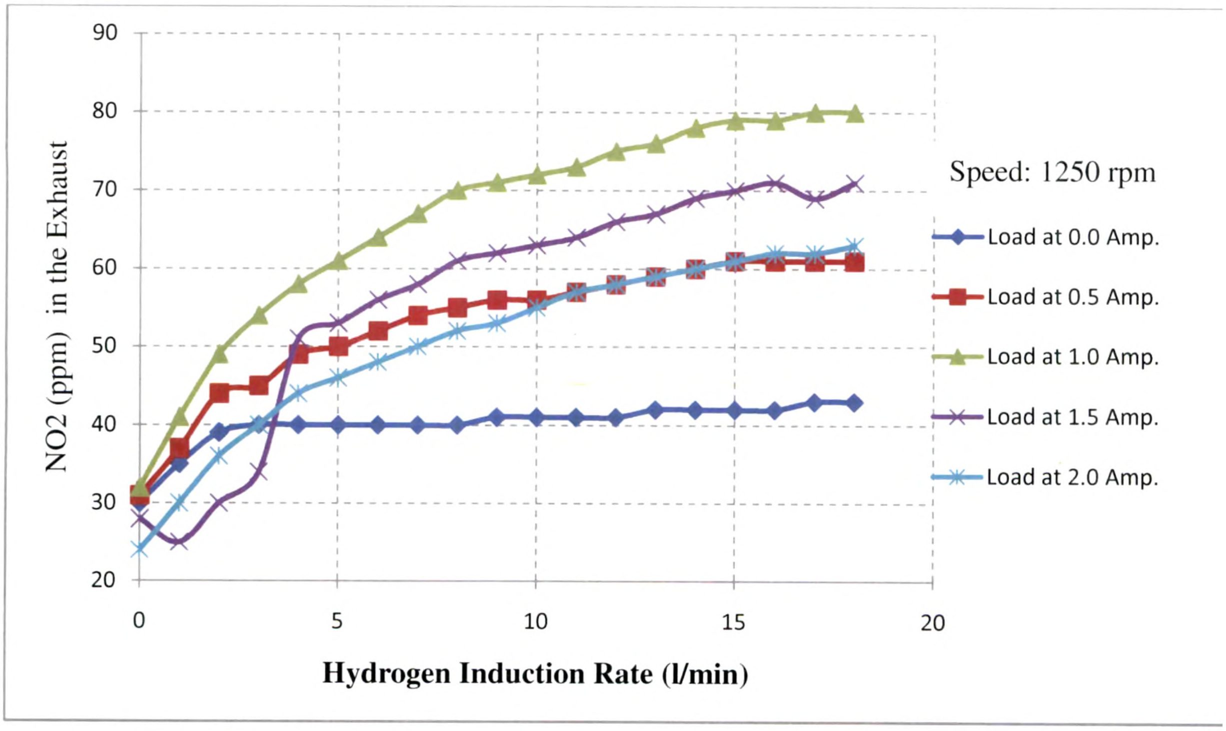


Fig. 3.82 Variation of NO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

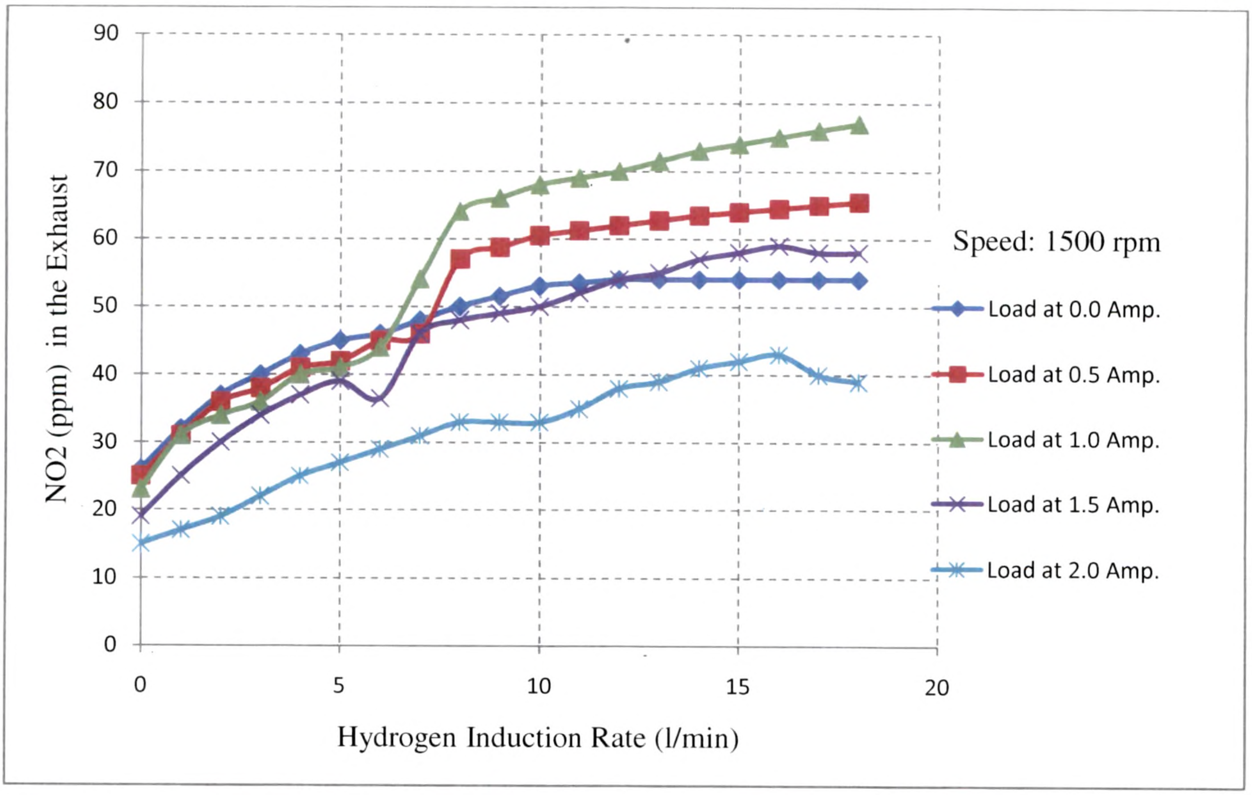


Fig. 3.83 Variation of NO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

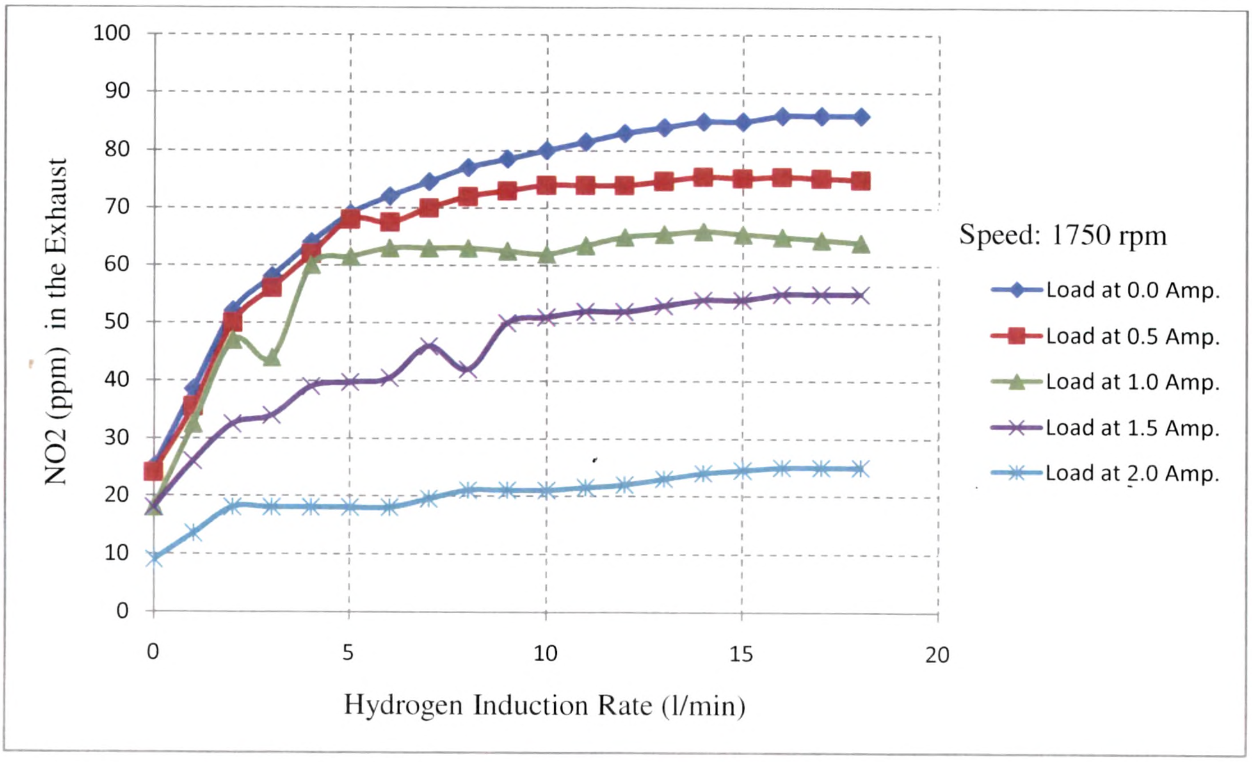


Fig. 3.84 Variation of NO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

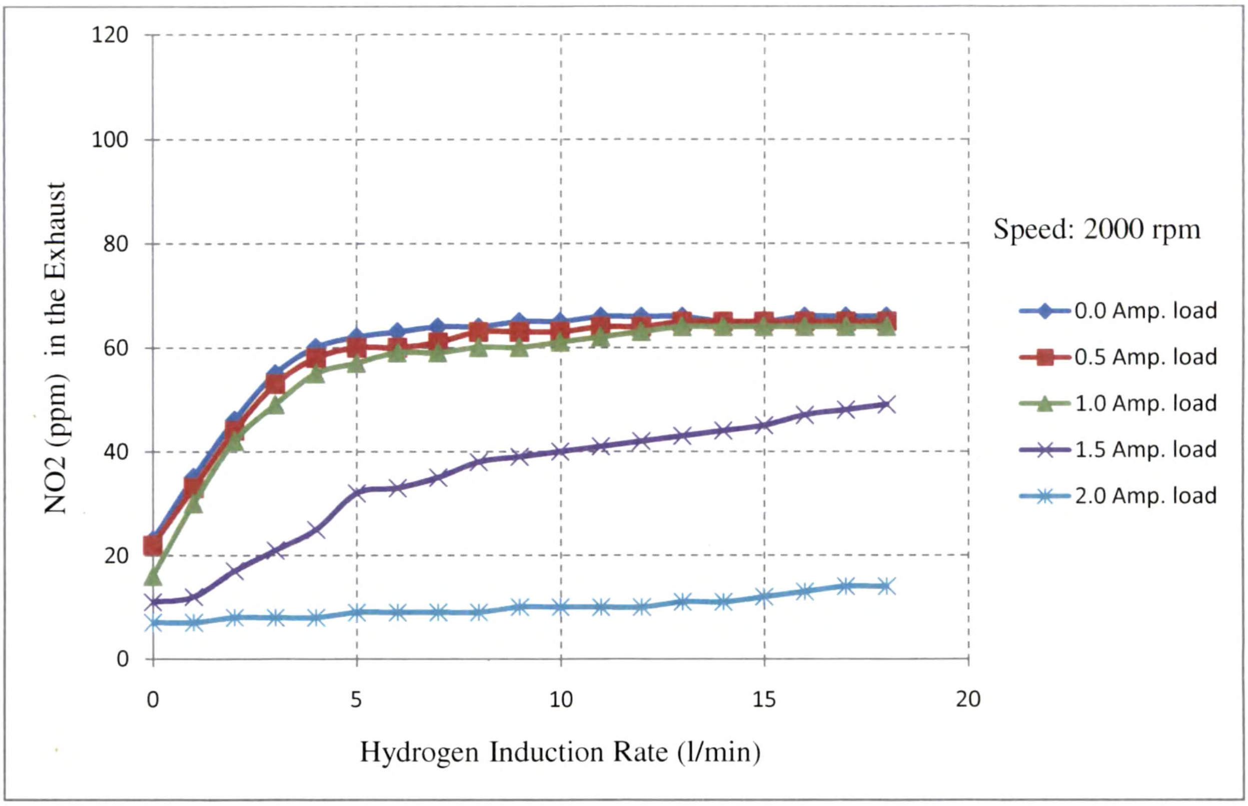


Fig. 3.85 Variation of NO_2 in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- Nitrogen Monoxide (NO)

Figs. 3.86 to 3.90 present the variation of NO with hydrogen induction rate at various loads and speeds. It can be observed that with no hydrogen induction, there is an increase in the NO content in exhaust due the excess availability of atmosphereic air and hence the oxygen in combustion chamber.

It is clear that the formation of NO depends on the availability of oxygen in the combustion chamber. The increase in induction rate of hydrogen leads to decrease in the amount of NO in the exhaust.

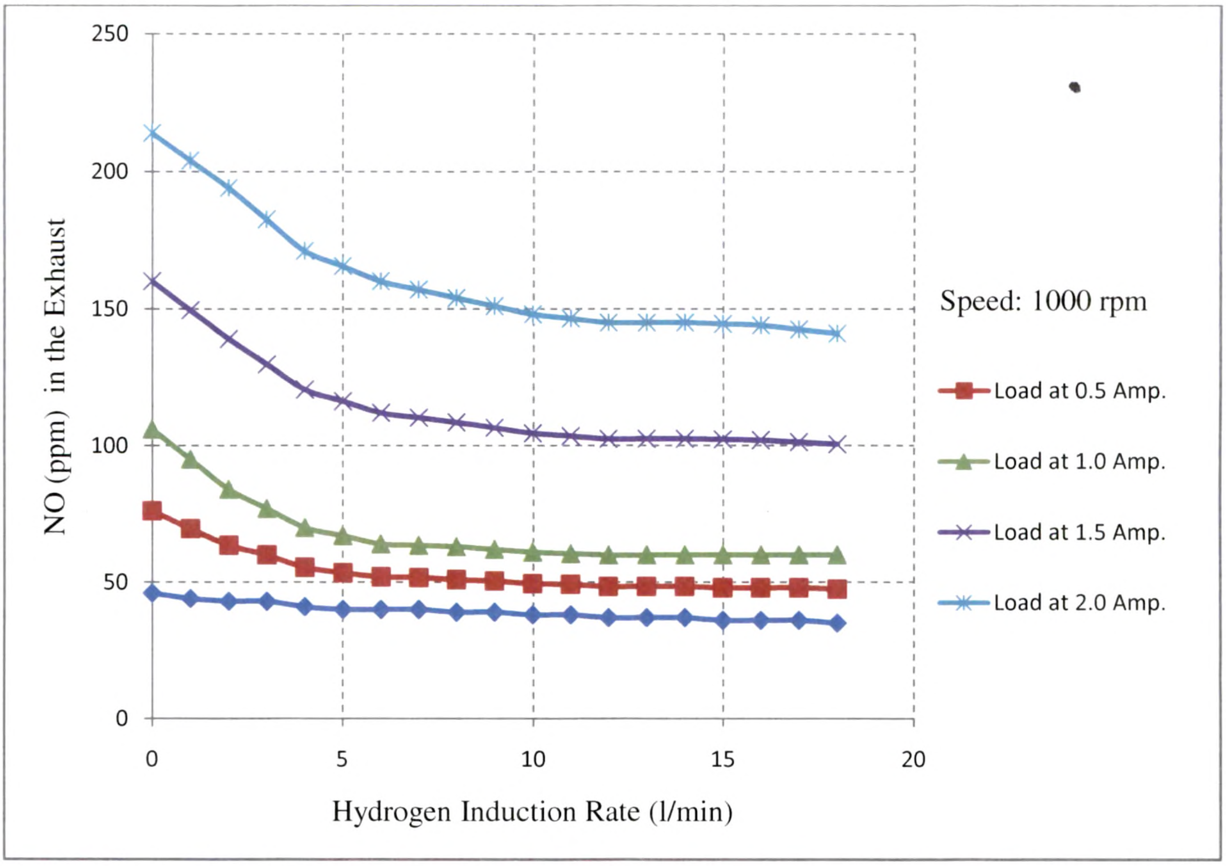


Fig. 3.86 Variation of NO in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

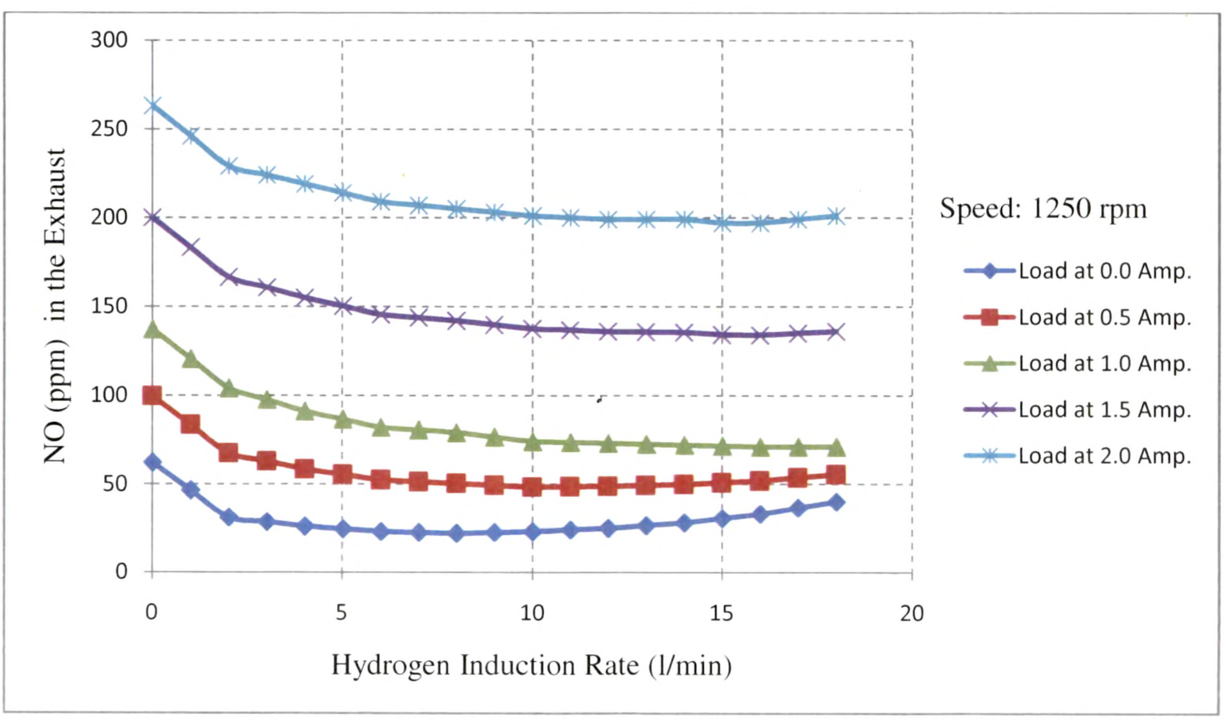


Fig. 3.87 Variation of NO in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

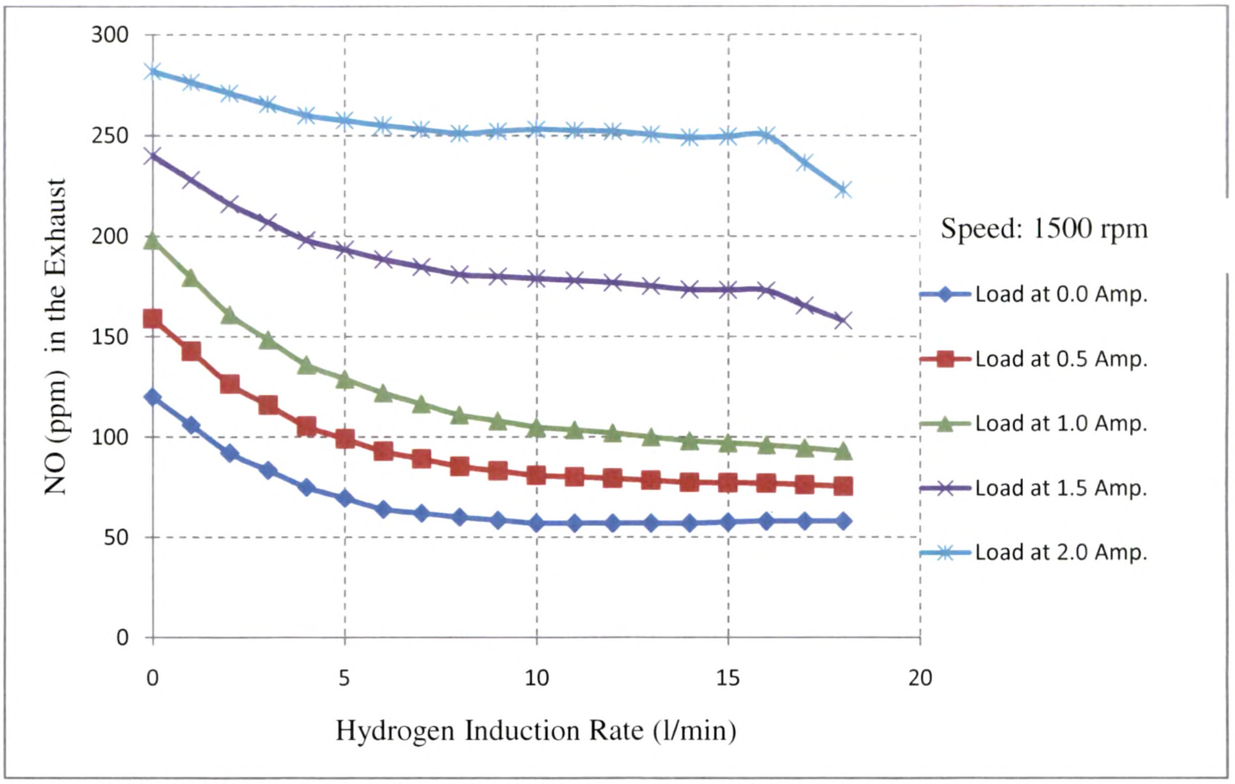


Fig. 3.88 Variation of NO in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

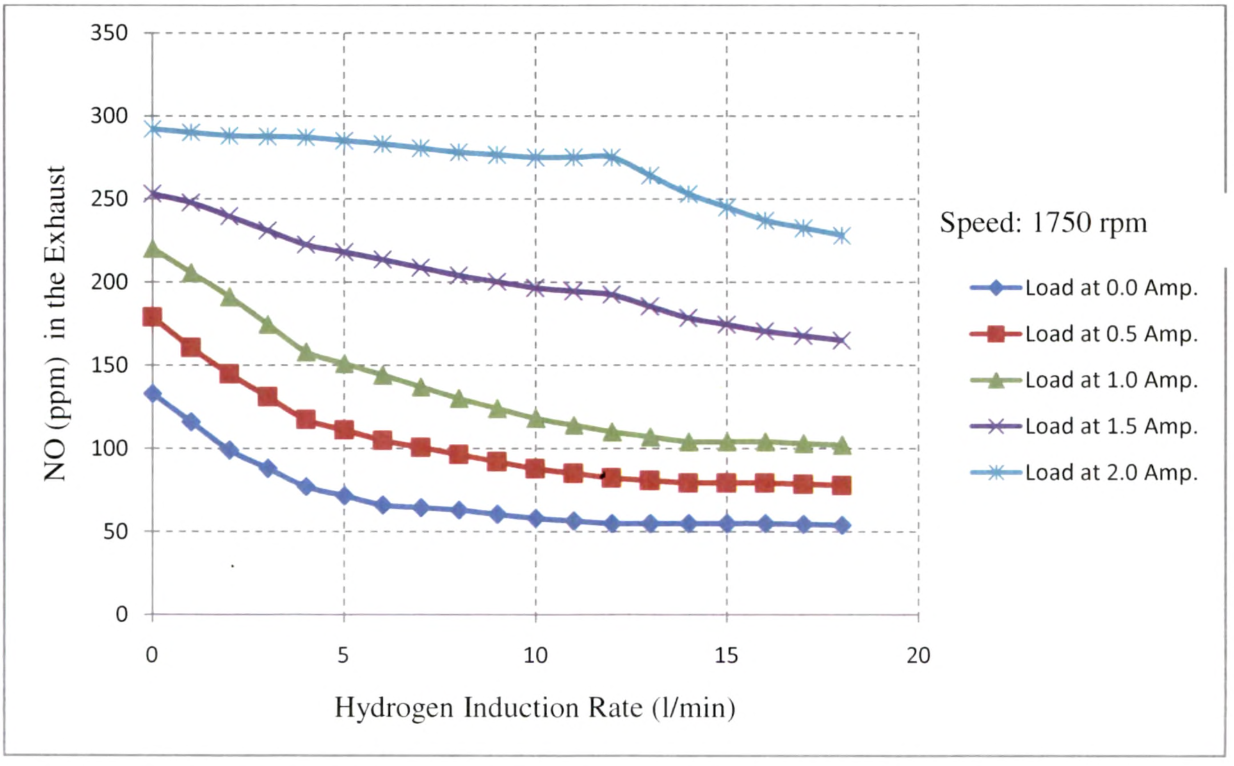


Fig. 3.89 Variation of NO in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

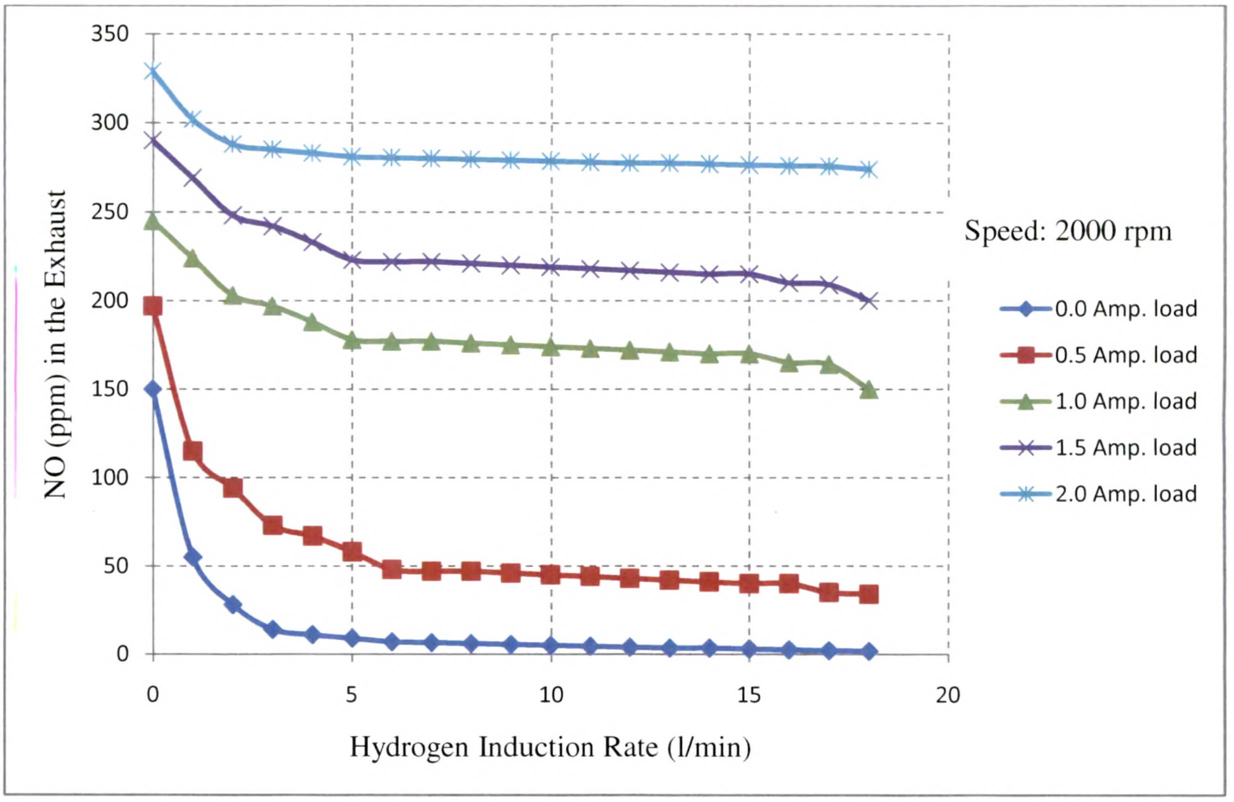


Fig. 3.90 Variation of NO in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

- Nitrogen Oxide (NO_X)

Figs. 3.91 to 3.95 present the variation of NO_X with hydrogen induction rate at various loads and speeds. NO_X is the summation of NO_2 and NO in exhaust and its formation depend on the temperature of flue gases in the combustion chamber and the amount of oxygen content in the air drawn in to the engine. The content of NO_X in exhaust follow the trend in the formation of both NO_2 and NO. However, the effect of NO is more pronounced in the formation of NO_x. It is observed that the, increase in speed causes increase in NO_X emission. The increase in hydrogen induction rate marginally decreases NO_X emission for all the combinations of load and speed.

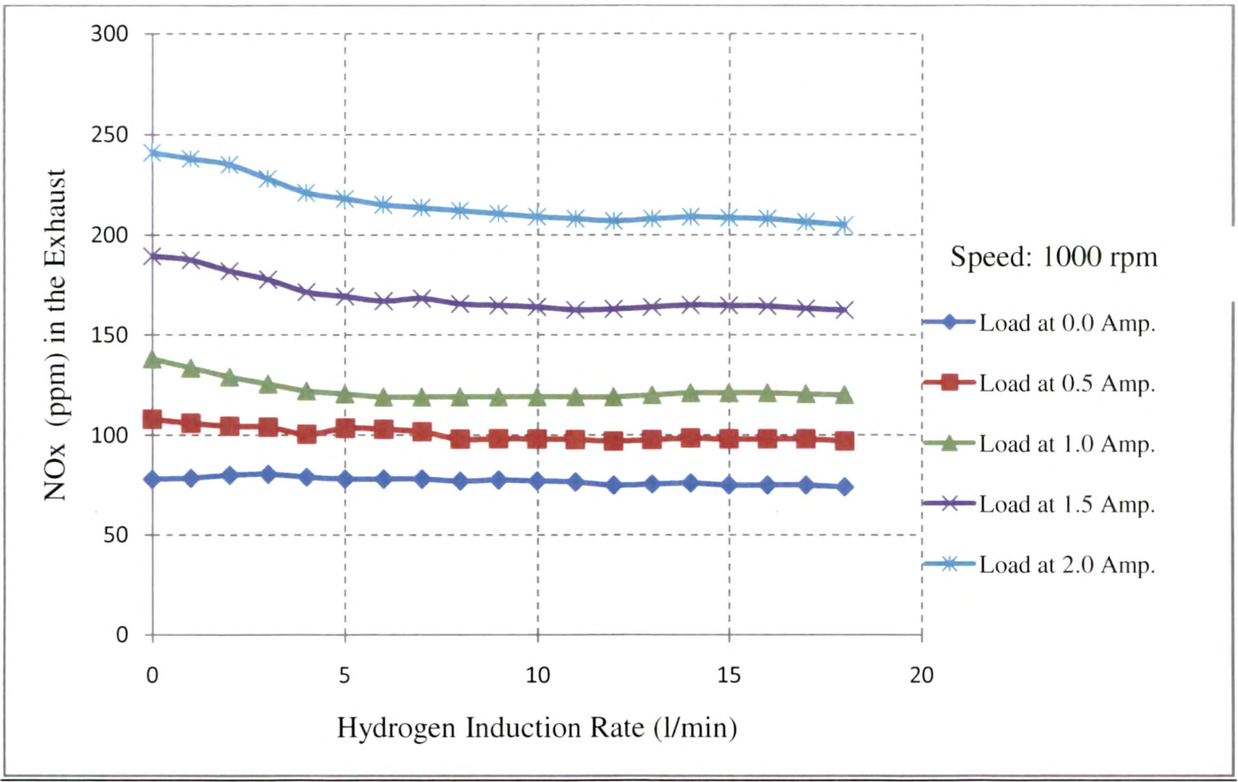


Fig. 3.91 Variation of NO_X in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1000 rpm

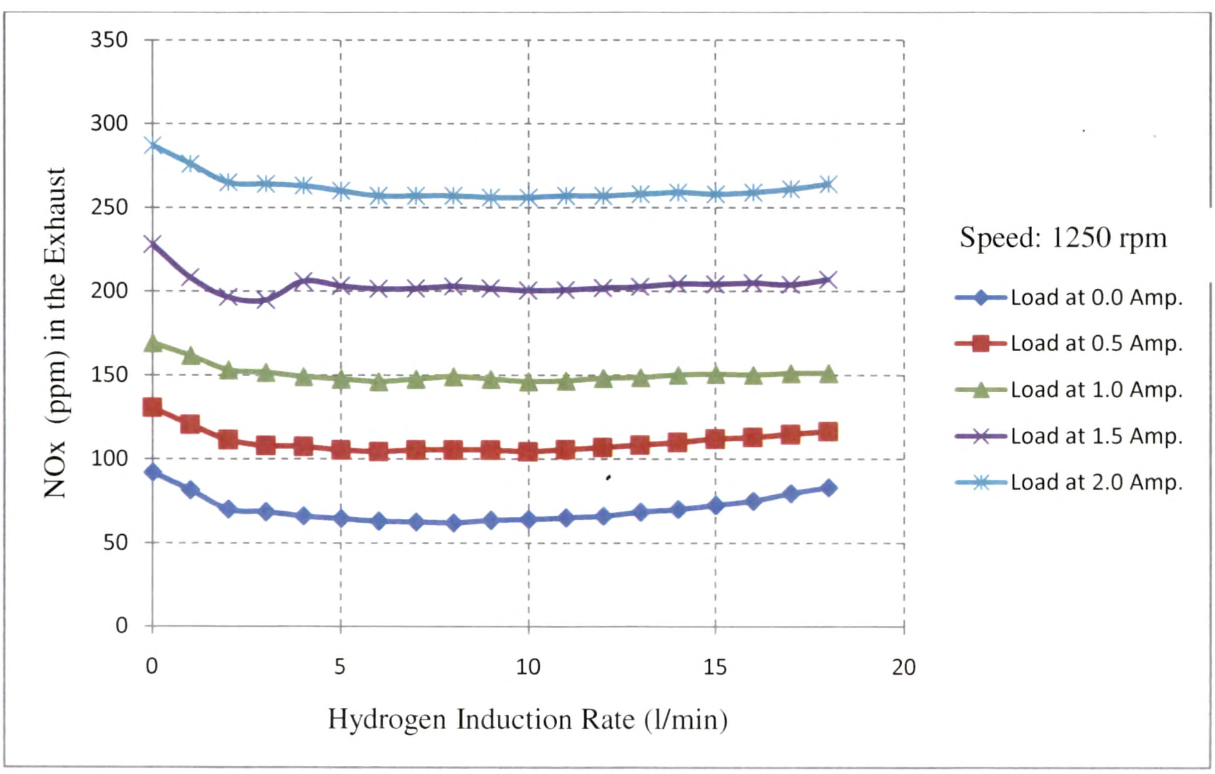


Fig. 3.92 Variation of NO_X in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1250 rpm

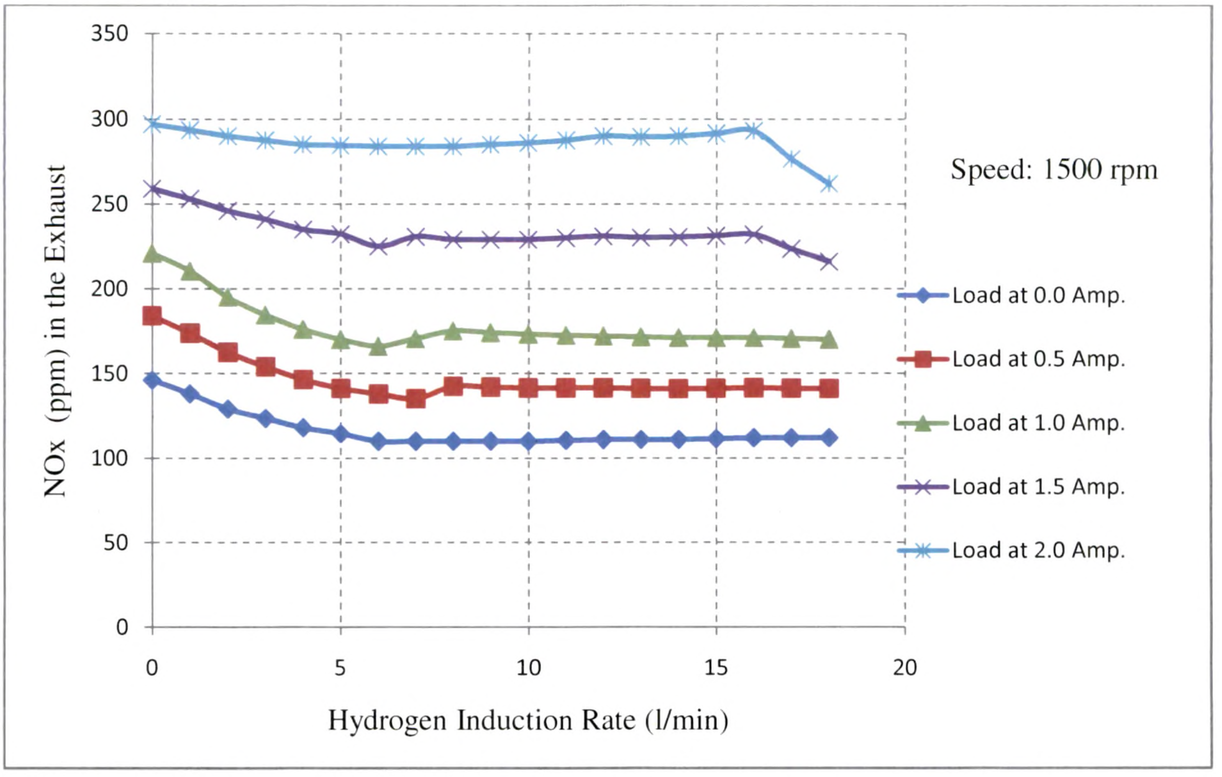


Fig. 3.93 Variation of NO_X in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1500 rpm

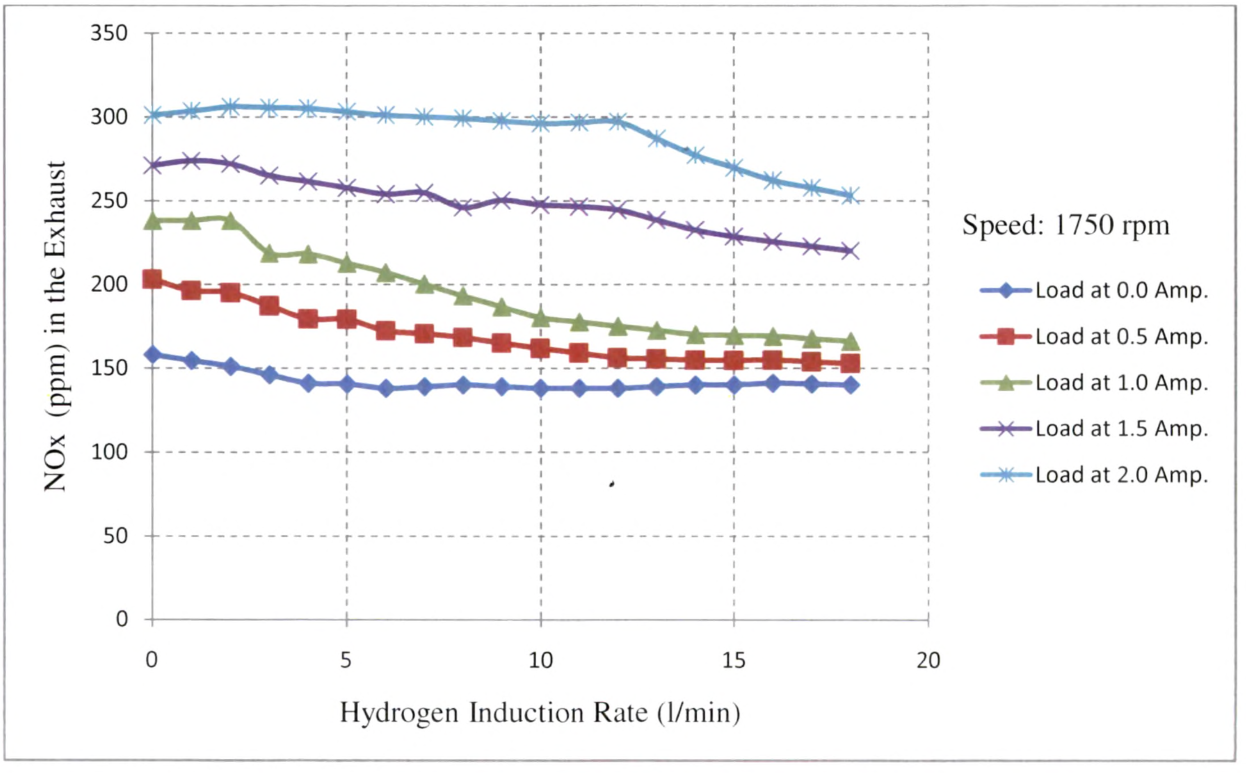


Fig. 3.94 Variation of NO_X in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 1750 rpm

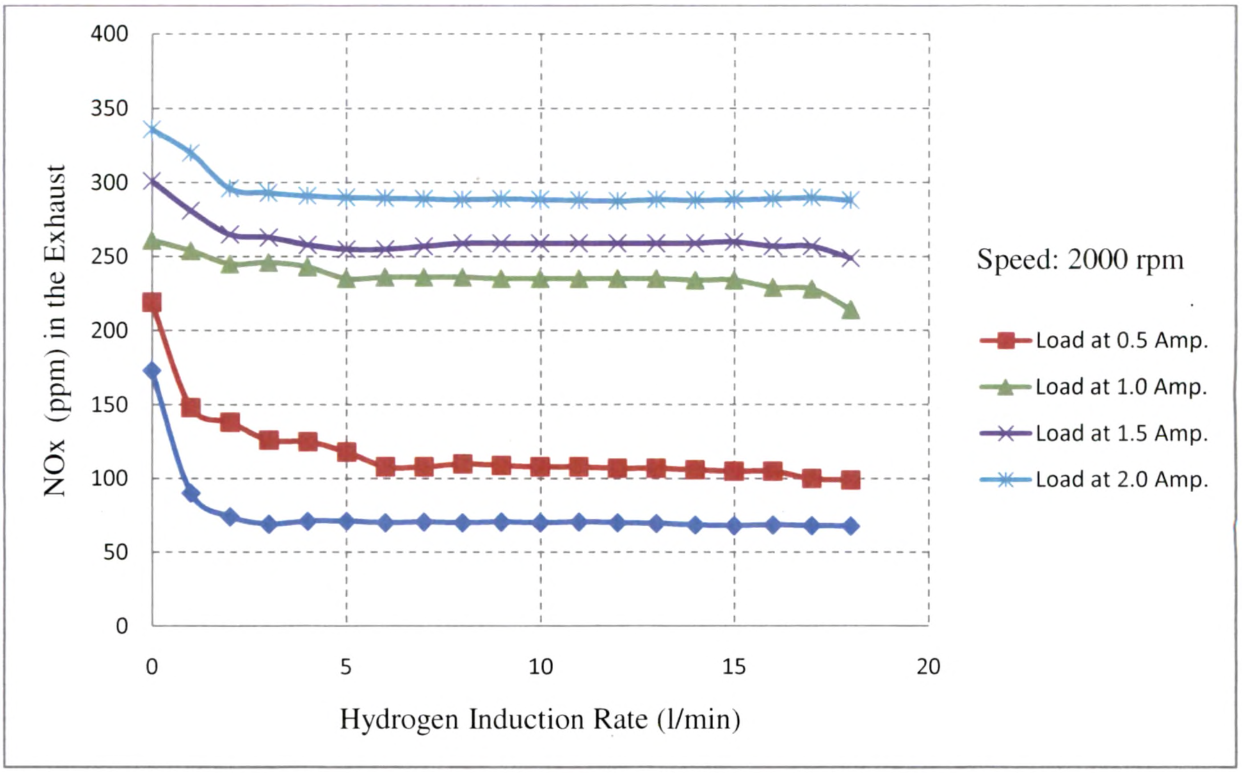


Fig. 3.95 Variation of NO_X in the Exhaust with Hydrogen Induction Rate for Various Engine Loading and at 2000 rpm

3.4.2 Hydrogen Induction Coupled with Direct Injection of Diesel / DMM Blend

Section 3.4.2 dealt with the results of the experimental study on thermal performance and constituents in exhaust gas emission of a compression ignition engine with diesel as the fuel supplemented with hydrogen induction through the intake manifold. The study is primarily targeted to find optimum hydrogen induction rate so as to operate the engine with low emission of pollutant constituents with reasonably high thermal performance. Based on both thermal performance and pollutants emission studies, it is seen that hydrogen induction rate between 7 to 8 l/min can be considered as an optimum induction rate that can give better thermal performance while keeping the emissions at a reasonably low level. Thus, a 7.5 l/min hydrogen induction rate is chosen for further investigations. It is found that at this level of induction (7.5 l/min), the constituent emission gases such as CO, CO_2, HC, SO_2 and NO_X levels does not increase significantly while with a reduction in diesel oil fuel consumption rate is observed together with an increase in brake thermal efficiency as compared to the diesel engine performance without hydrogen induction.

It is also seen that the hydrogen induction in the air intake manifold decreases the atmospheric air intake for all the combination of load and speed investigated. Thus, the inlet manifold induction technique leads to decrease in the volumetric efficiency due to reduction in the volume of intake air drawn. This leads to a decrease in the availability of oxygen in the combustion chamber. Therefore, there is a scope for further improvement in the optimum thermal and gas emission performance of the engine if the oxygen in take is improved. One may think about a suitable oxygenated fuel along with the hydrogen induction at the intake manifold to maximize the optimum performance. Various additives to primary fuel like diesel oil are available which can further improve the overall performance of the engine. DMM which has a 42.7% O_2 content by weight is one of the options as additive that will be investigated. The performance of compression ignition engine along with the gas emission constituents is studied with hydrogen induction at the intake air manifold with diesel/DMM blend as primary fuel and will be discussed in the following sections.

3.4.3.1 Thermal Performance

In this section, the result of diesel/DMM blends thermal performace is studied. The variation of the performance parameters such as brake power, diesel/DMM fuel consumption, brake power efficiency, volumetric efficiency, equivalence ratio, brake specific energy consumption and exhaust temperature with load for three cases using different fuels such as only diesel, diesel/DMM blend with no hydrogen induction and with 7 l/min and 8 l/min hydrogen induction are studied. The performance tests are carried out for five loads viz, 0.0, 0.5, 1.0, 1.5 and 2.0 in terms of ampere at a constant speed of 1500 rpm. Similar trend reported in the following paragraphs are also observed with other speeds.

- **Brake Power**

Fig. 3.96 shows the variation of brake power with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. The brake power is found to decrease with increase of load, the decrease being about 3.36 and 6.60% with the load of 2.0 Amp. and no load.

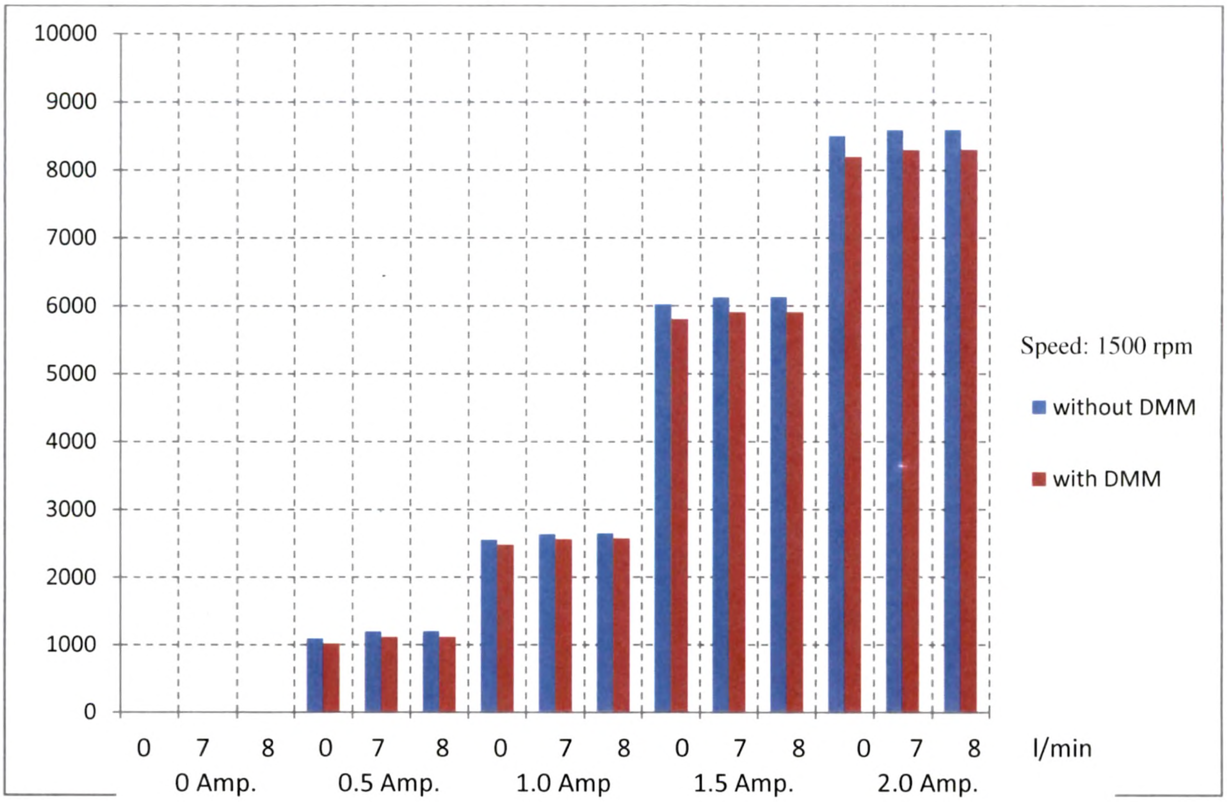


Fig. 3.96 Comparison of the Variation of Brake Power with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

- **Diesel/DMM Fuel consumption**

Fig. 3.97 shows the variation of the rate of diesel/DMM consumption with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. The addition of DMM is found to increase the consumption of fuel at all the loading conditions. Such increase in consumption rate may be due to the lowering of the overall value of calorific value of the blend. It should be noted that the calorific value of DMM is about 25.67 MJ/kg which is approximately half that of diesel oil, although DMM has high oxygen content in its structure. The increase in consumption rateis found to vary between between 1% to 2.85%.

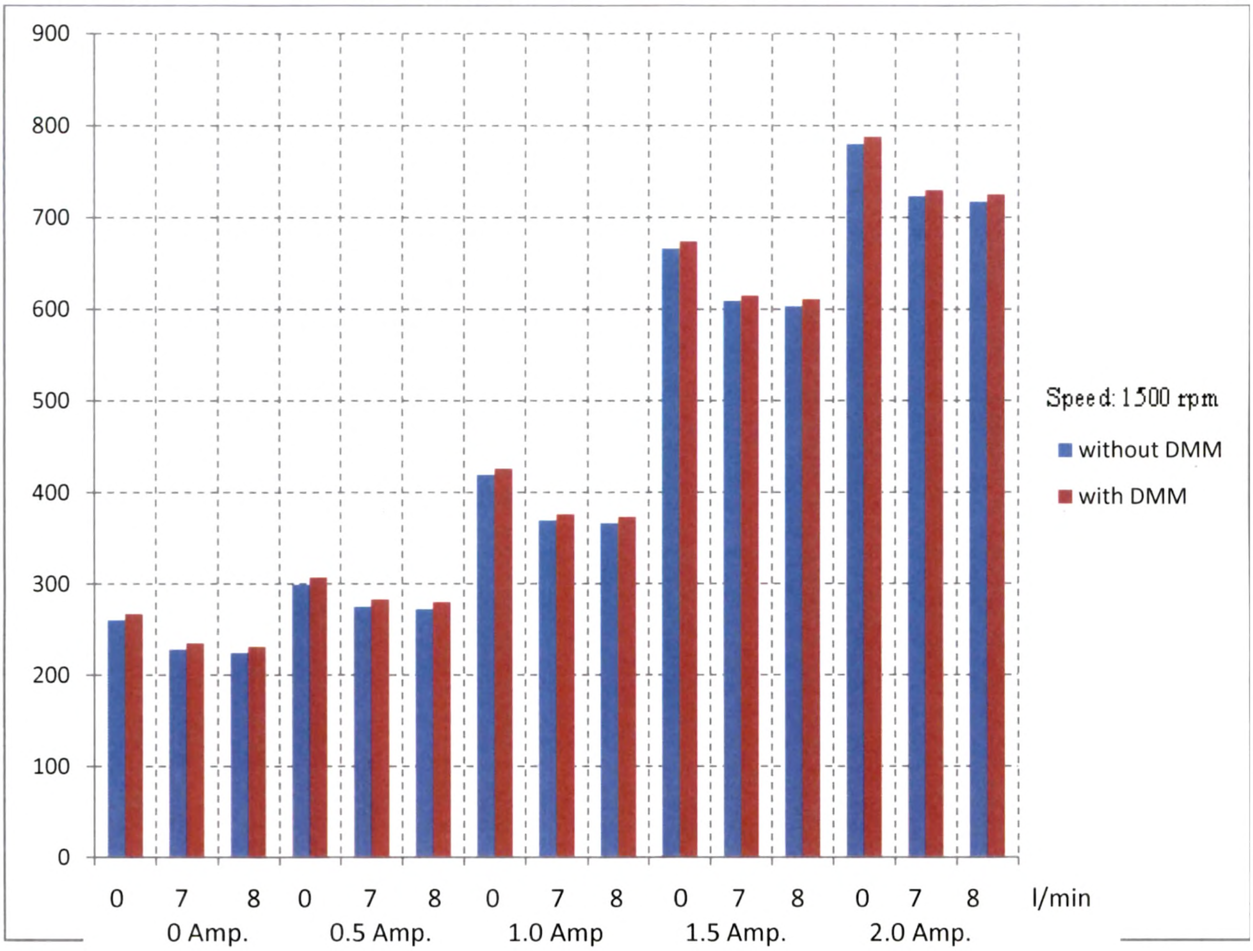


Fig. 3.97 Comparison of the Variation of Diesel/DMM Blend Consumption with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

- **Brake Thermal Efficiency**

Fig. 3.98 shows the variation of brake thermal efficiency with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500. It can be noticed that the brake thermal efficiency increases when DMM /diesel blend is used instead of only diesel for all the cases investigated. The exeption noticed in three cases may be due to experimental error. The increase in the brake thaermal efficiency is found to be more at higher loads.

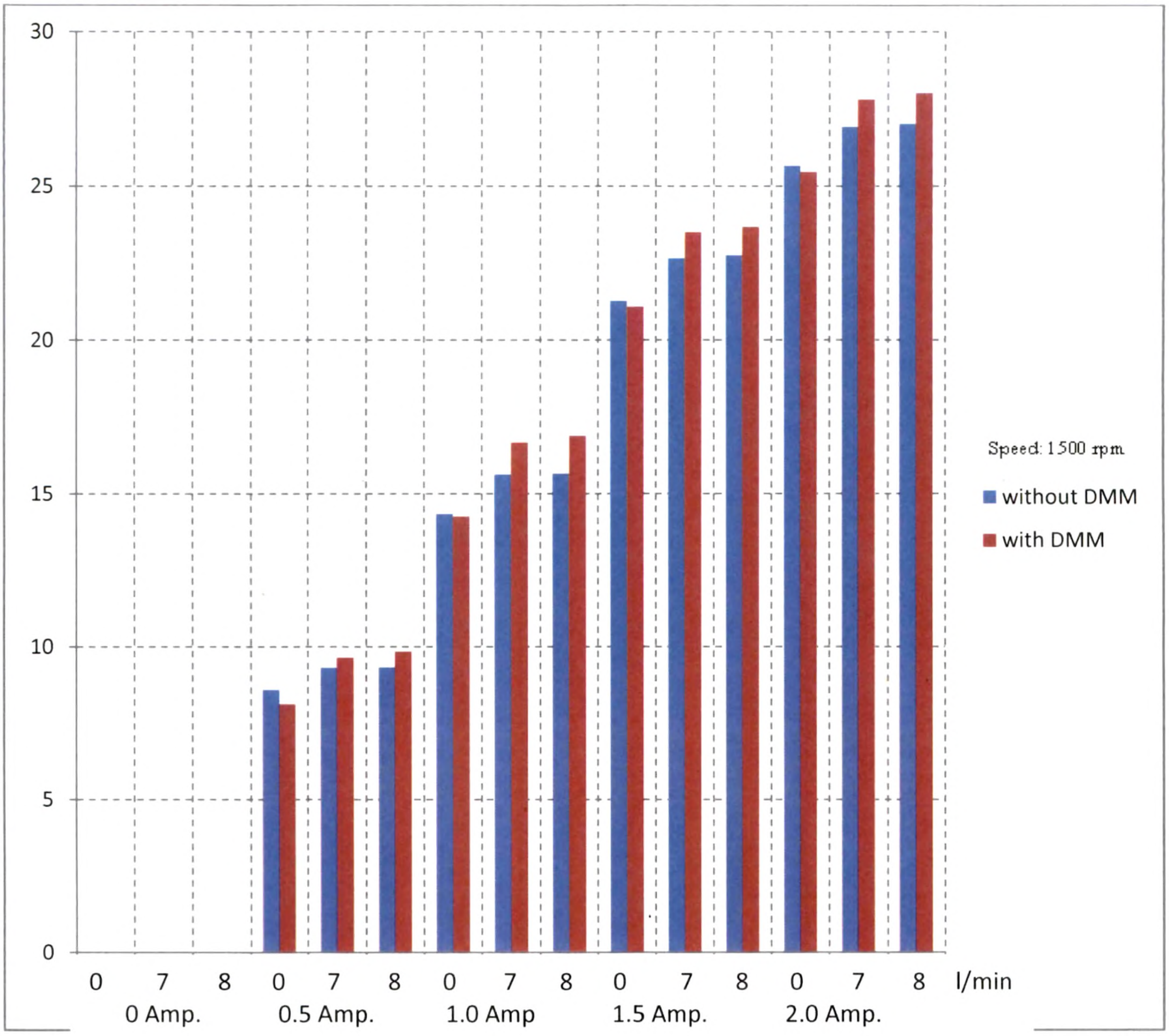


Fig. 3.98 Comparison of the Variation of Brake Thermal Efficiency with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

- **Volumetric Efficiency**

Fig. 3.99 shows the variation of voulmetric efficiency with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm.

It is seen that there is no significant change in the amount of actual air volume drawn to the compression ignition engine during its running under Diesel/DMM blend with and with out induction of hydrogen.

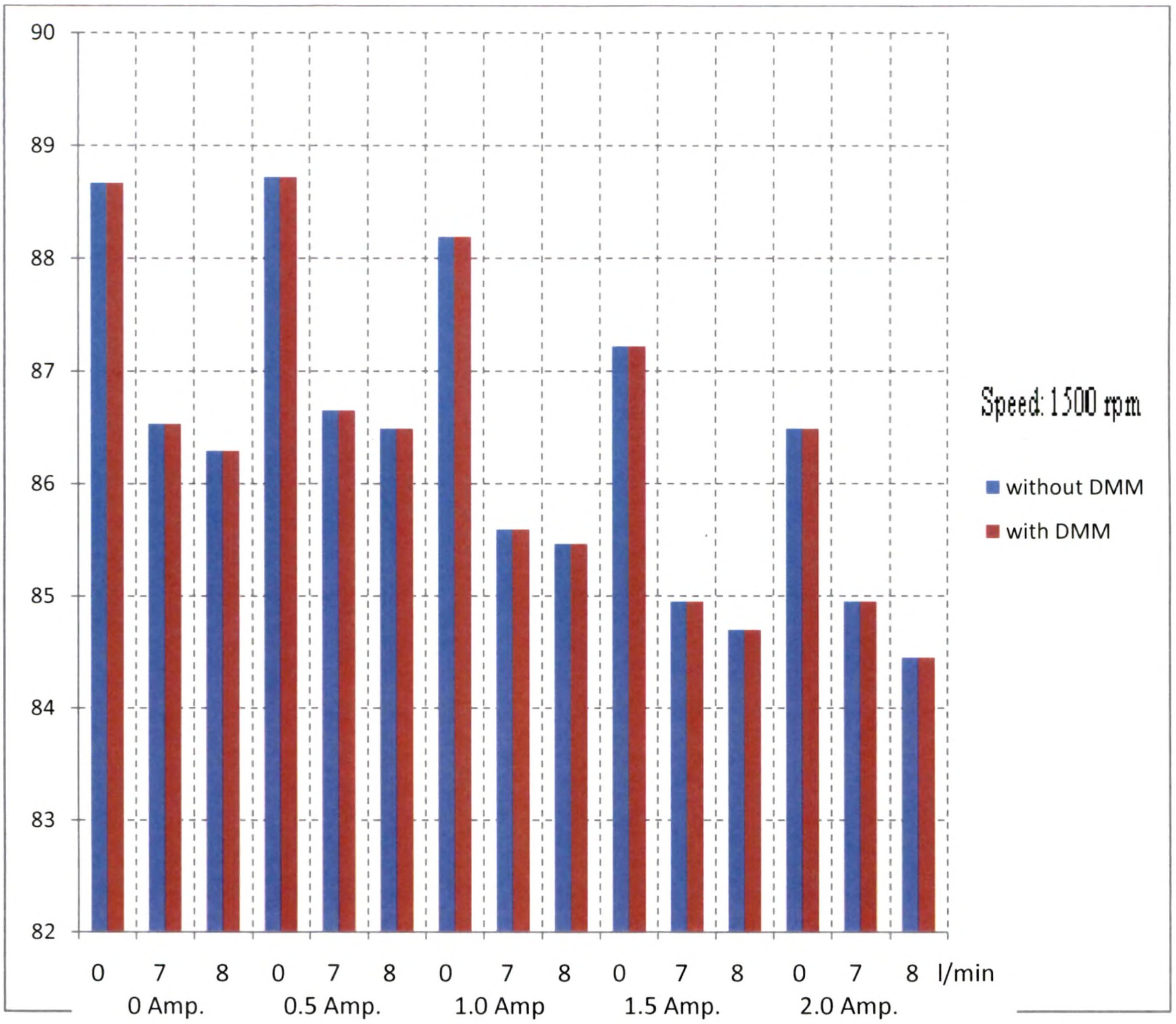


Fig. 3.99 Comparison of the Variation of Volumetric Efficiency with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

- **Equivalence Ratio**

Fig. 3.100 shows the variation of equivalence ratio with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. It is seen that there is a significant increase in equivalence ratio with the addition of DMM in diesel. Hydrogen induction rate decreases the equivalence ratio at given loading conditions while its value increases significantly with load as expected. It can be noticed that the mixture becomes more rich when DMM is added.

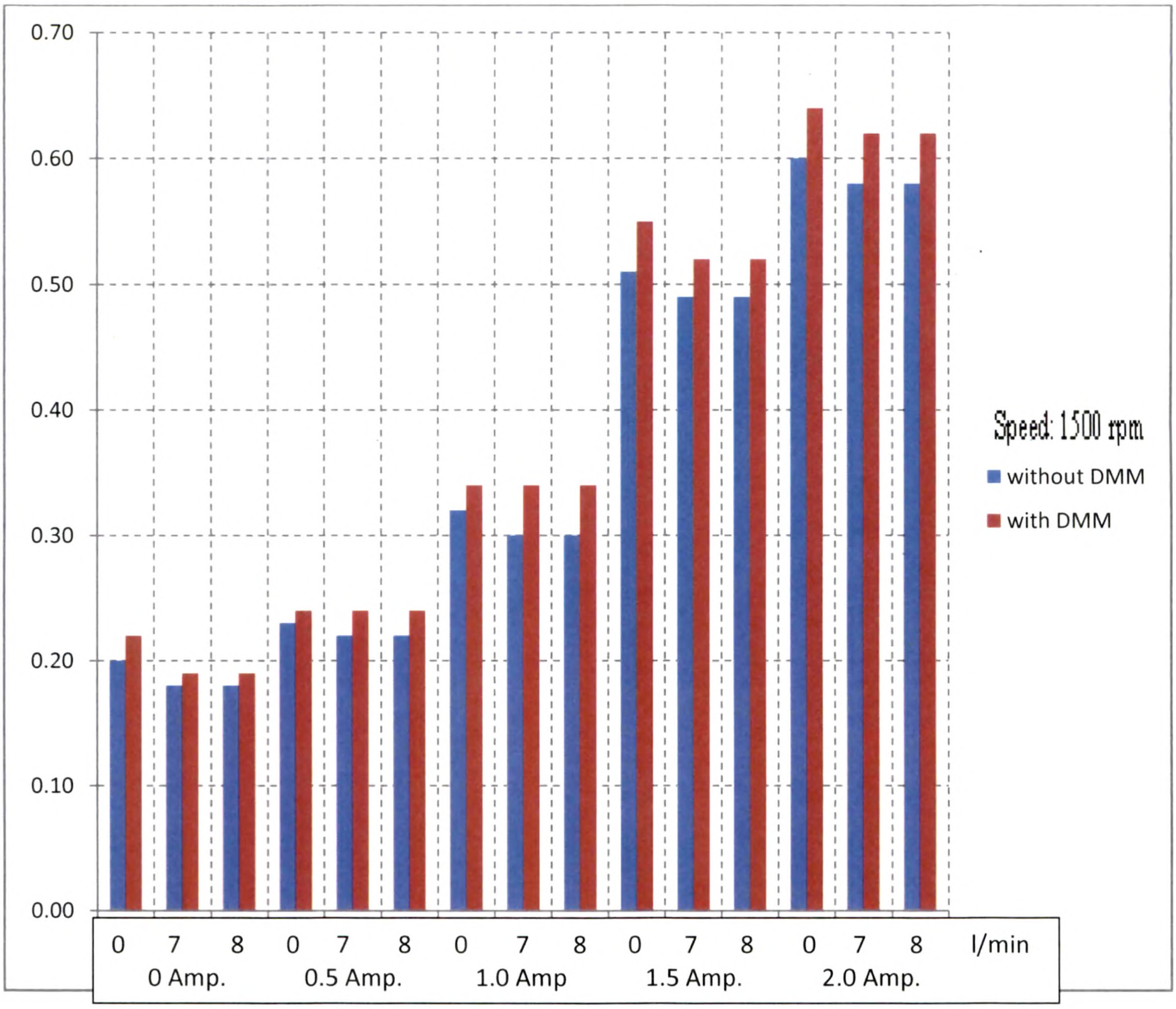


Fig. 3.100 Comparison of the Variation of Equivalence Ratio with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

- **Brake Specific Energy Consumption (BSEC)**

Fig. 3.101 shows the variation of brake power with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. The addition of DMM in diesel decreases BSEC due to the enhancement in combustion process aided by the increased availability of oxgyn provided by DMM.

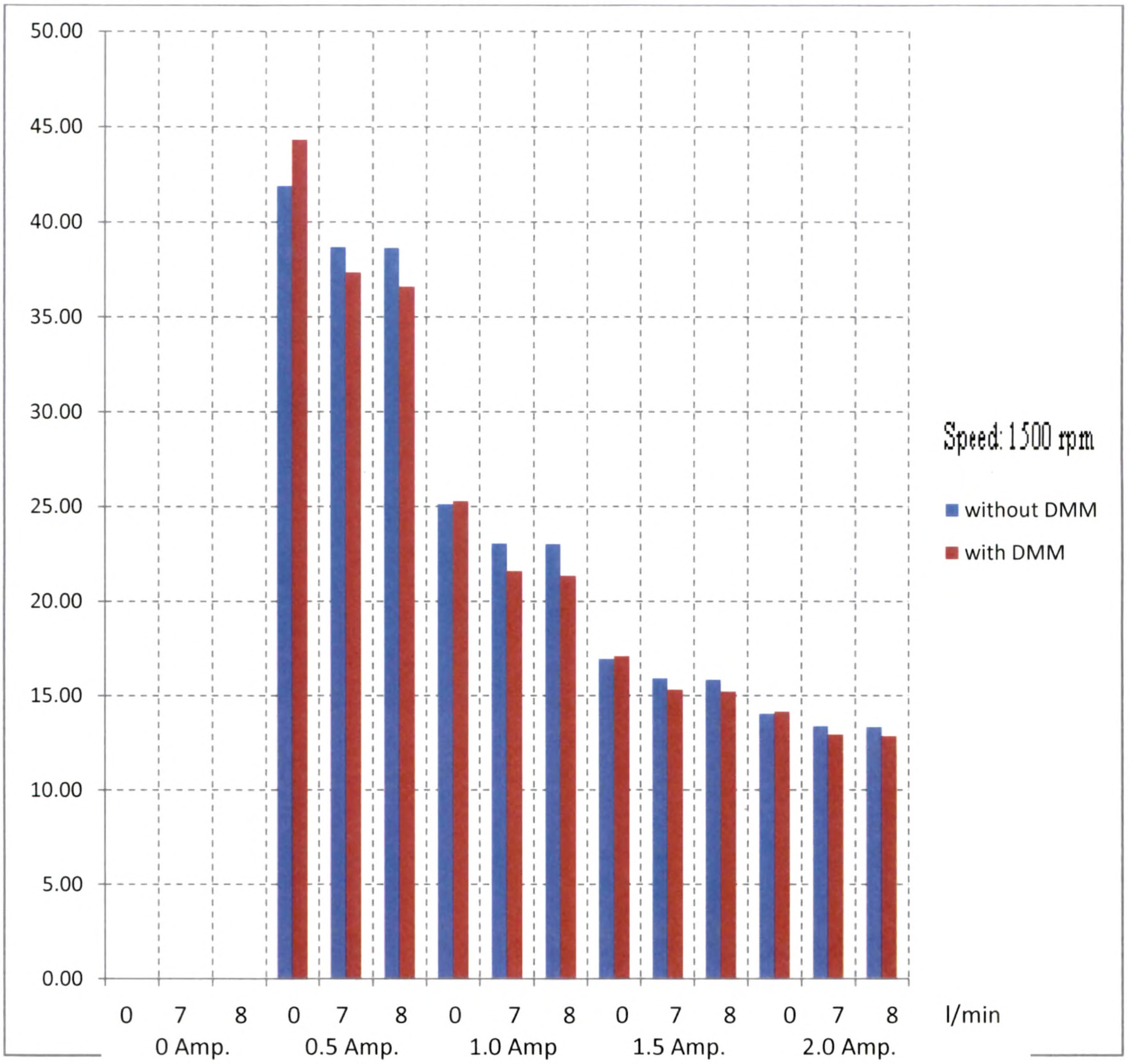


Fig. 3.101 Comparison of the Variation of BSEC with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

- **Exhaust Temperature**

Fig. 3.102 shows the variation of exhaust temperature with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm.

The increase in exhaust temperature with diesel/DMM blend as compared to diesel alone is due to the increase in the content of oxygen. This increase indicates the enhancement in the combustion process whem DMM is blended with diesel.

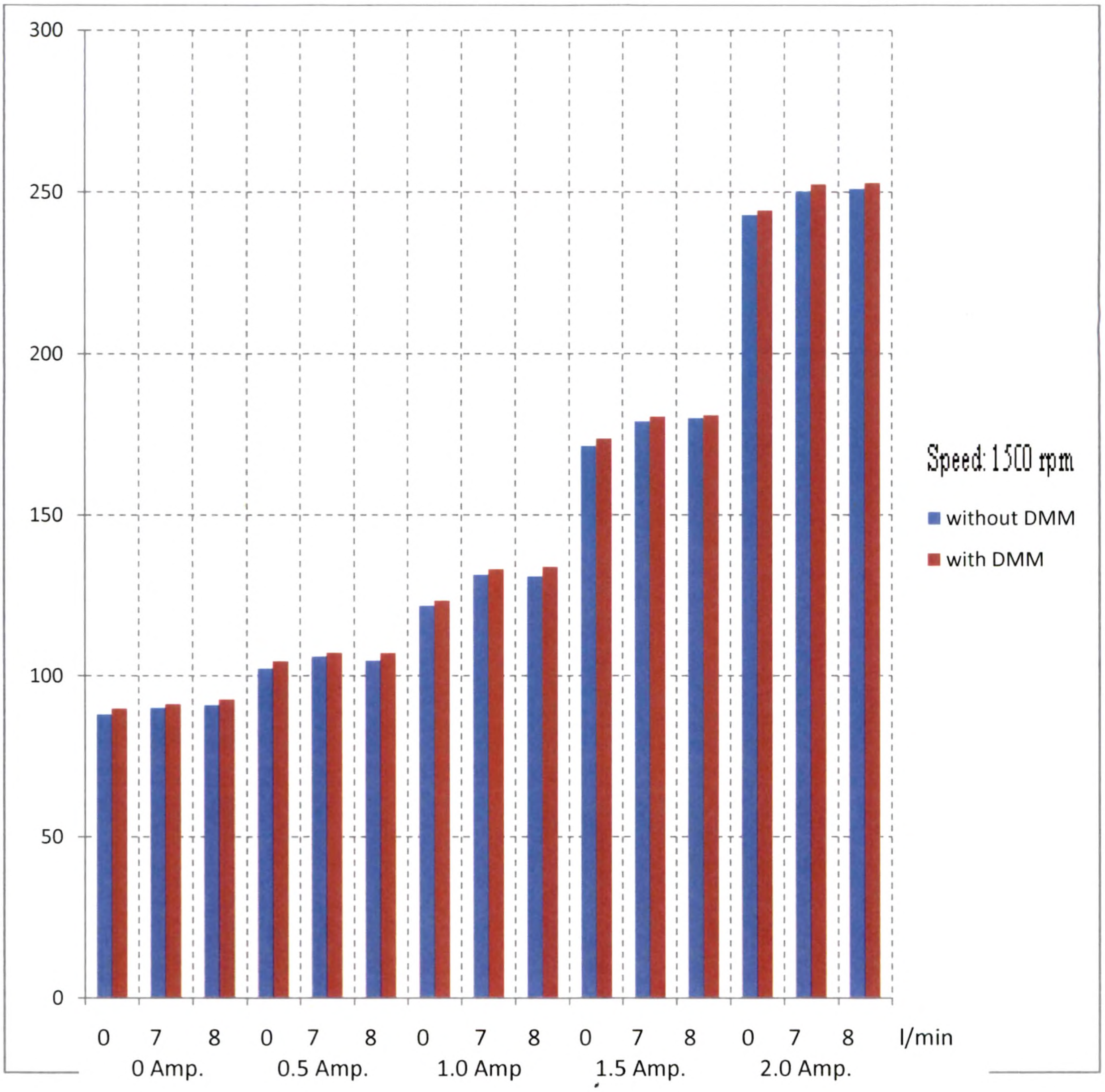


Fig. 3.102 Comparison of the Variation of Exhaust Temperature with Load for Engine Operated with Diesel and Diesel/DMM Blend running at 1500 rpm

From the above study on the influence of DMM as additive to diesel with and without hydrogen induction in the intake manifold of the engine on various thermal peformance parameters, it can be concluded that the addition of blend helps in improving the overall performance farther as compared to that of the engine operated with diesel alone as fuel with hydrogen induction. The improvement is found to be significant when the engine is operated at higher loads. The notable features of the thermal performance enhancement with diesel/DMM blend along with 7 to 8 /l/min hydrogen induction rate are on BSEC, brake thermal efficiency and equivalence ratio. While the brake thermal efficiency increased by about 7 % with diesel/DMM blend having hydrogen induction rate of 7 to 8 l/min as compared to only diesel with the same levels of induction rate, the decrease in BSEC is about 5 %. The equivalence ratio on the other hand is found to marginally decrease with 7 to 8 l/min induction as compared with diesel alone used aalong with the same induction rate.

3.4.3.2 Exhaust Gas Emission Constituents

This section deals with the effect of the addition of DMM to diesel oil on the quantities of exhaust gas emission constituents when hydrogen induction is carried out at the rate of 7 to 8 l/min in the intake manifold of the compression ignition engine. The study includes the measurement of various constituent gases in the exhaust such as O_2, CO, CO_2, HC, SO_2, NO_2, NO and NO_X .

- **Oxygen in the Exhaust**

The variation in oxygen content in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm is given in Fig. 3.103. It is seen that the exhaust gases carry marginally more oxgen from the combustion residual oxygen at all the load and hydrogen induction conditions as the DMM?diesel blend constitutes more oxygen content which partly is used for combustion and partly is carried away in exhaust.

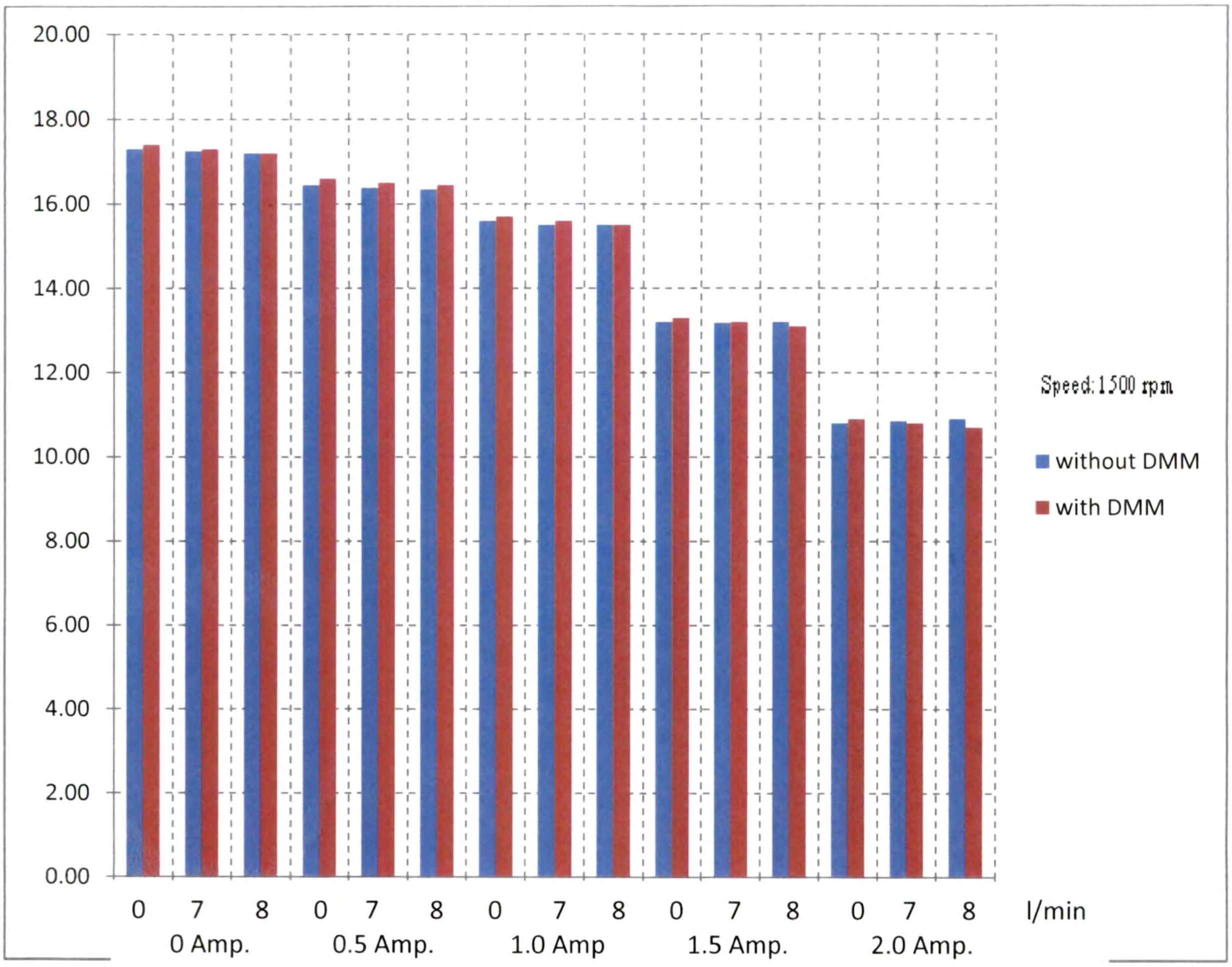


Fig. 3.103 Comparison of the Variation of 0_2 Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Carbon Monoxide in Exhaust**

The variation in carbon monoxide content in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm is given in Fig. 3.104. For all the cases of hydrogen induction rate and loads, it is found that there is a substantial percentage decrease in content of CO in the exhaust with DMM/diesel blend as compared to that with diesel alone. The same trend is observed when no induction of hydrogen is carried out. However, the CO content in the latter case is found to be an order of magnitude less that that observed with hydrogen induction. DMM additive enhances significantly CO content in the engine exhaust.

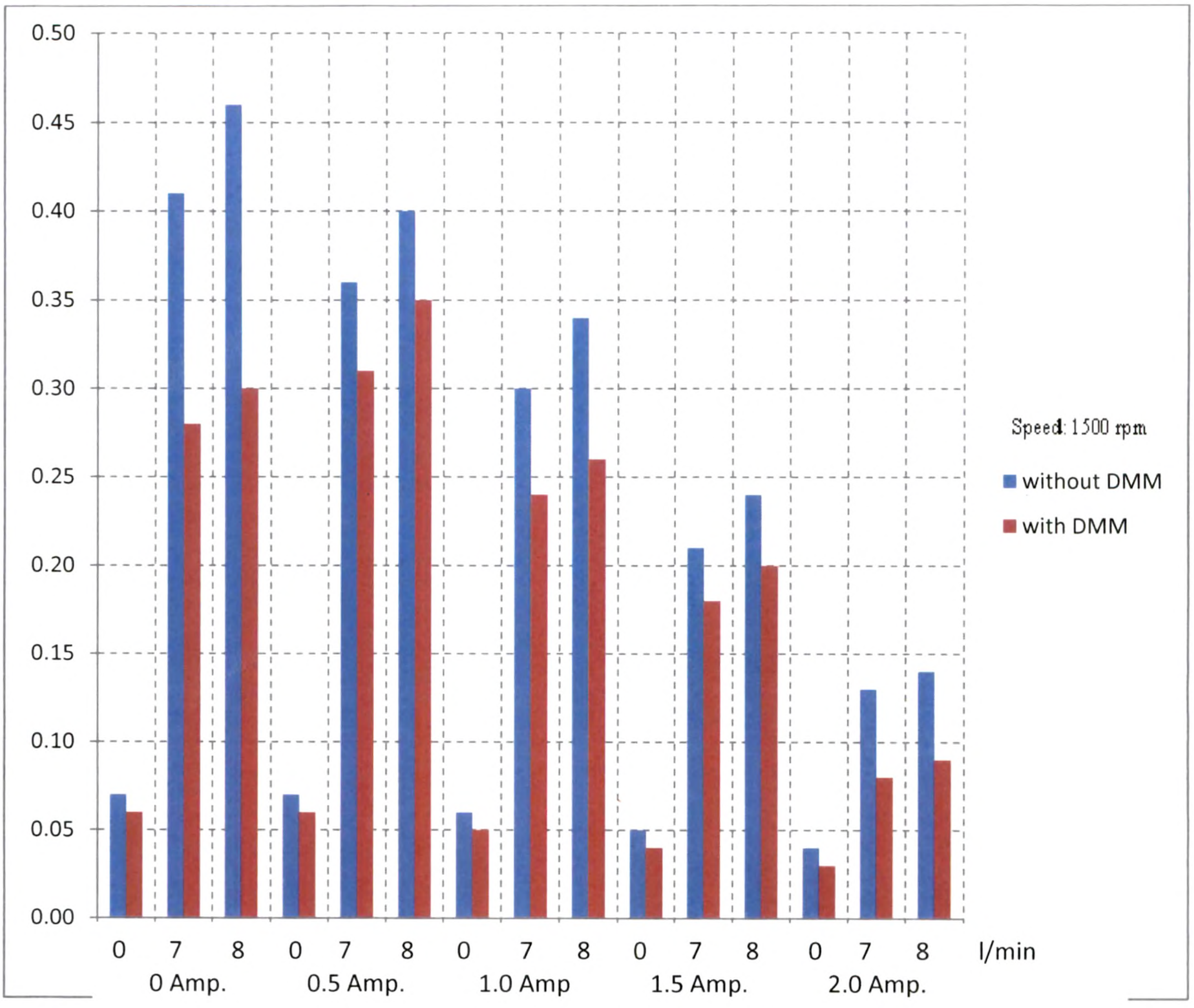


Fig. 3.104 Comparison of the Variation of CO Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Carbon Dioxide in the Exhaust**

Fig 3.105 gives the variation in carbon dioxide content in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. It can be observed that CO_2 content in exhaust decreases with DMM/diesel blend as compared with that observed when diesel alone is used as fuel at all loads. The decrease in CO_2 content in exhaust may be attributed to the larger content of oxygen in DMM and its partial utilization in the enhancement of combustion. However, there is a steady increase in the percentage CO_2 emission with load for all the cases studied.

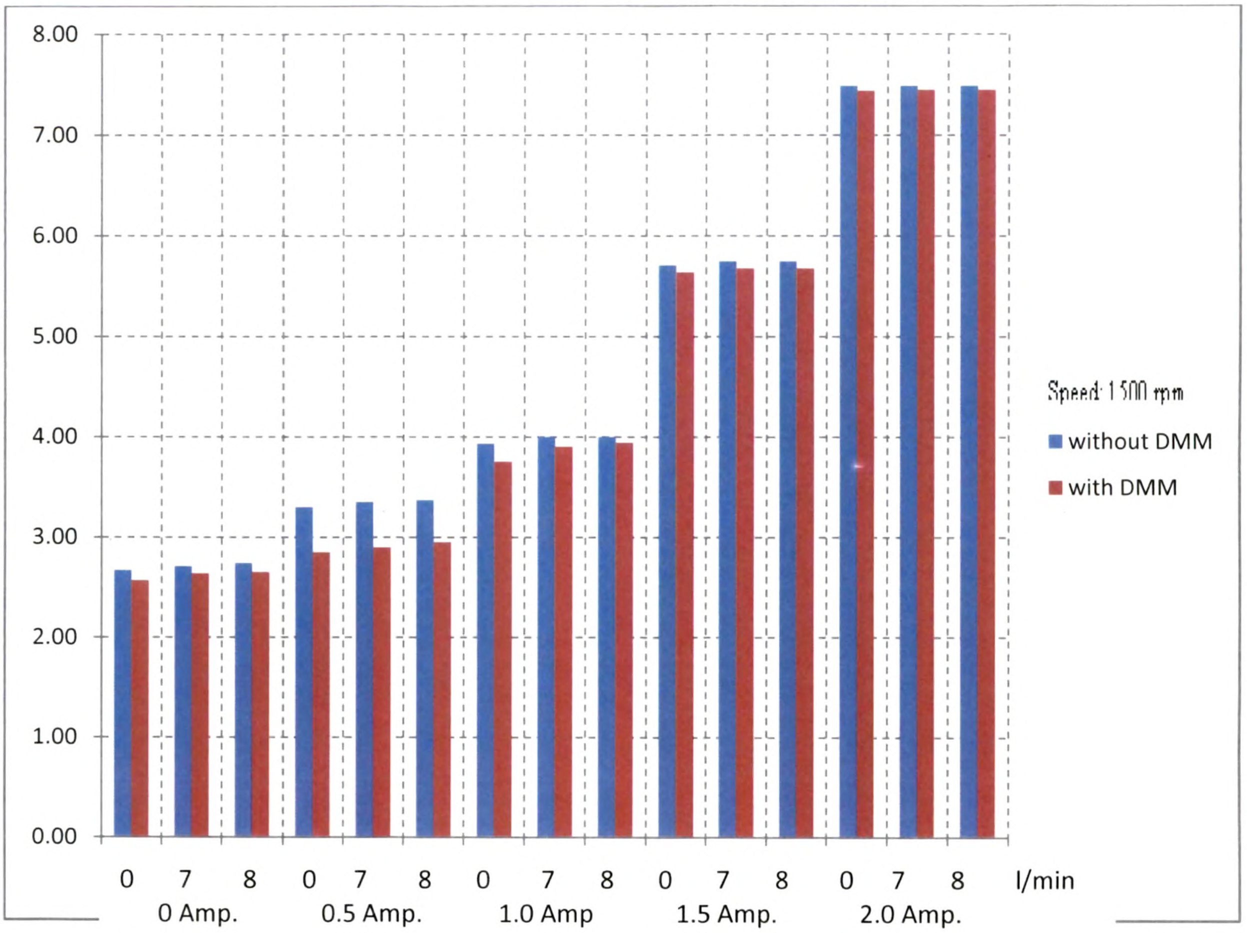


Fig. 3.105 Comparison of the Variation of CO_2 Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Unburned Hydrocarbon (HC) in the Exhaust**

Fig. 3.106 illustrates the variation in unburned hydrocarbon content in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. For all the cases of hydrogen induction rate and loads, it is found that there is a 10-15 % decrease on an average in content of HC in the exhaust with DMM/diesel blend as compared to that with diesel alone. The same trend is observed when no induction of hydrogen is carried out. However, the relative decrease in HC content in the latter case is found to be less than that observed with hydrogen induction. Although there is a decrease in HC content with DMM as additive, there is a significant increase in HC content with hydrogen induction incorporated with or without blend.

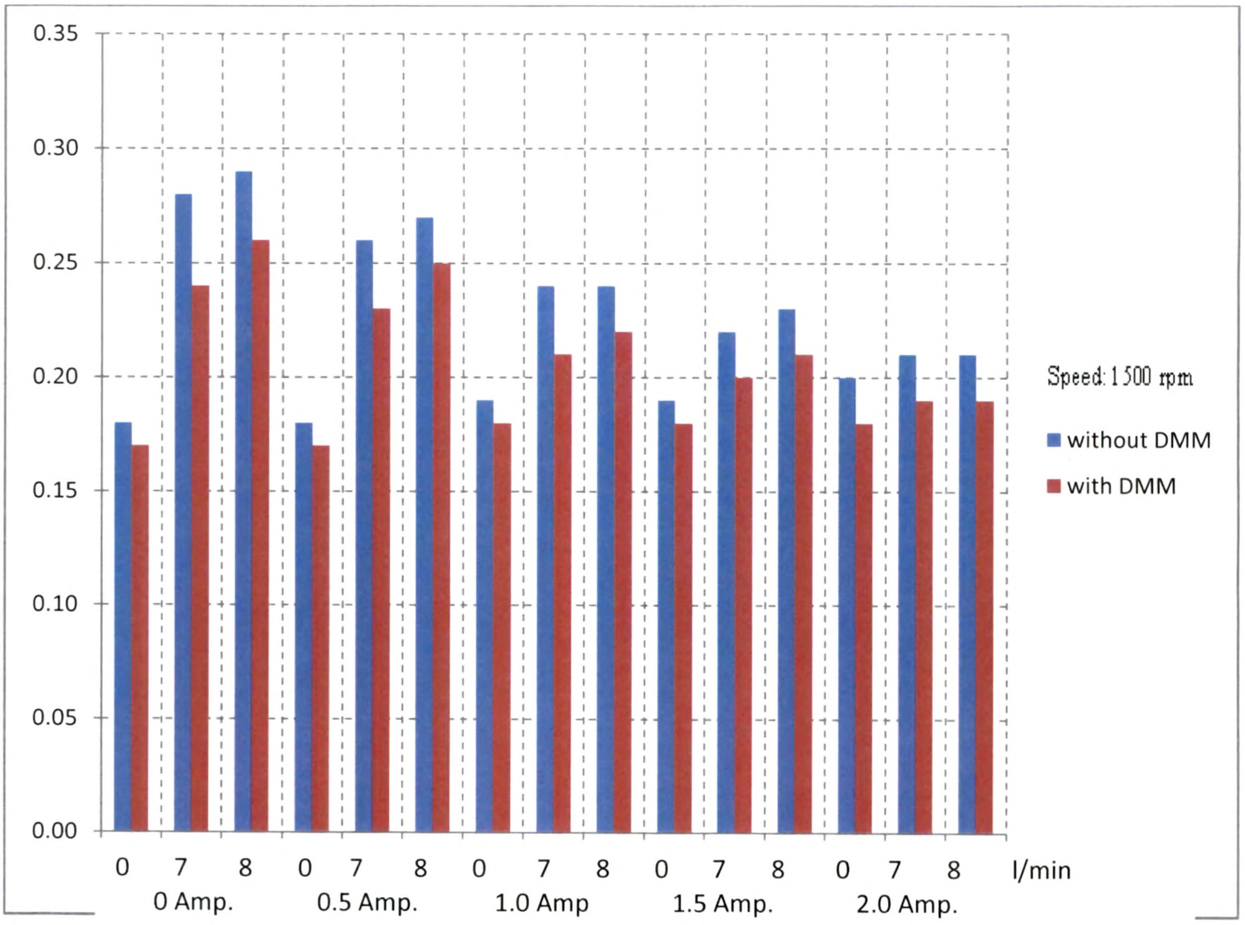


Fig. 3.106 Comparison of the Variation of HC Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Sulphur Dioxide in Exhaust**

Fig. 3.107 illustrates the variation in sulphur dioxide content in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. For all the cases of hydrogen induction rate and loads, it is found that there is a marginal decrease in the content of SO_2 in the exhaust with DMM/diesel blend as compared to that with diesel alone. The same trend is observed when no induction of hydrogen is carried out. Further, it is seen that there is a 10 times increase in the SO_2 content when hydrogen induction rate of 7 l/min and 8 l/min are carried out along with diesel alone and DMM/diesel blend at smaller loads of 0.5 and 1Amp.. However, it is found that there is a sharp decline in the per cent SO_2 content when the load is increased to

1.5 Amp. and 2.0 Amp and at full load the content is almost the same as that observed with no load condition.

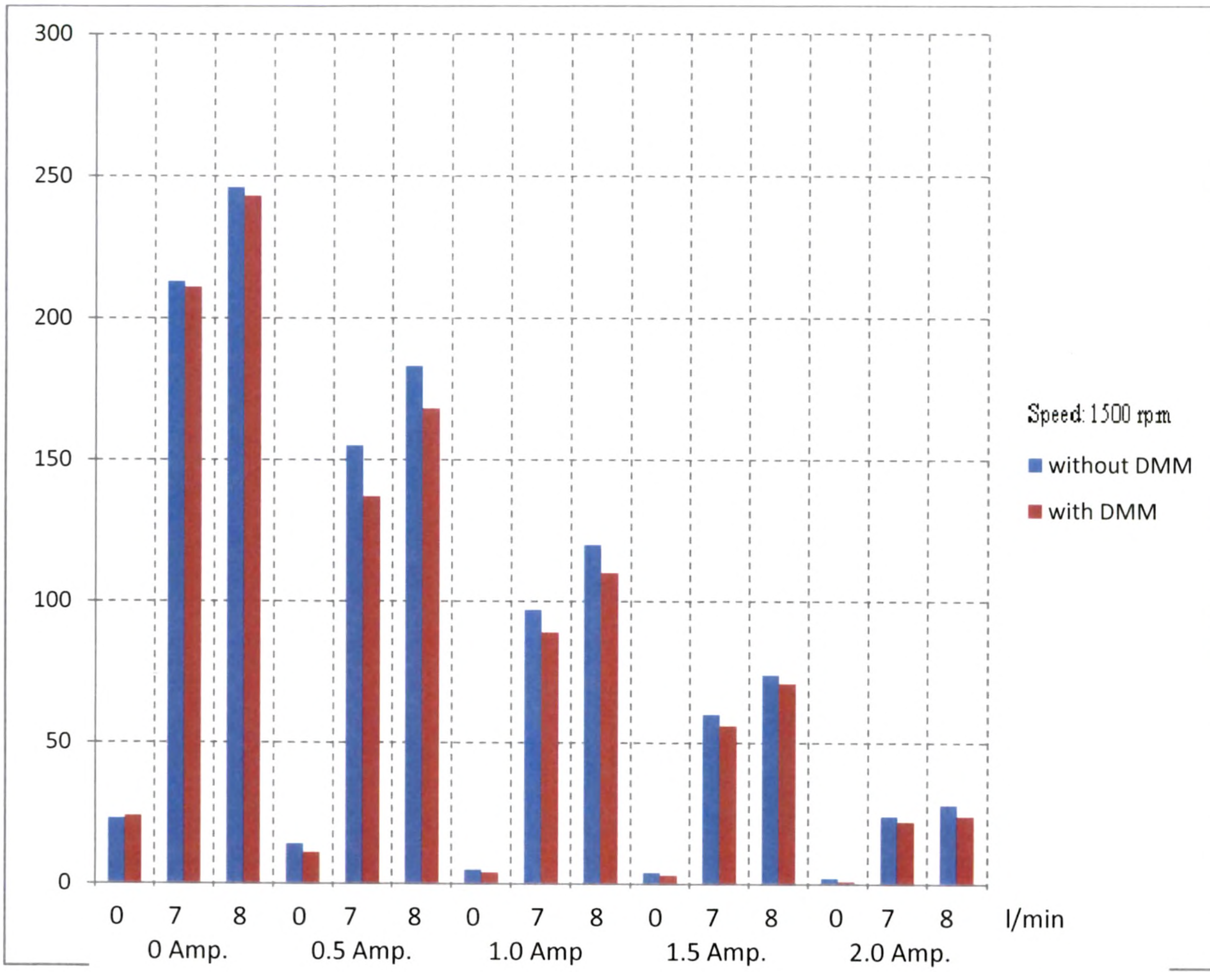


Fig. 3.107 Comparison of the Variation of SO_2 Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Nitrogen dioxide in the Exhaust**

Fig. 3-108 gives the variation of nitrogen dioxide in exhaust with/ and with out 10 % DMM blend with diesel for 7 l/min and 8 l/min hydrogen induction rate in the inlet manifold at different loads and speeds.

The additive of DMM as oxygenated fuel led to increase the NO_2 when the diesel/DMM compare with diesel alone. The induction of hydrogen led to decrease the oxygen in the combustion chamber as discussed in 3.4.2.2. This induction also kept the level of NO_2 beyond the base fuel case NO_2 level.

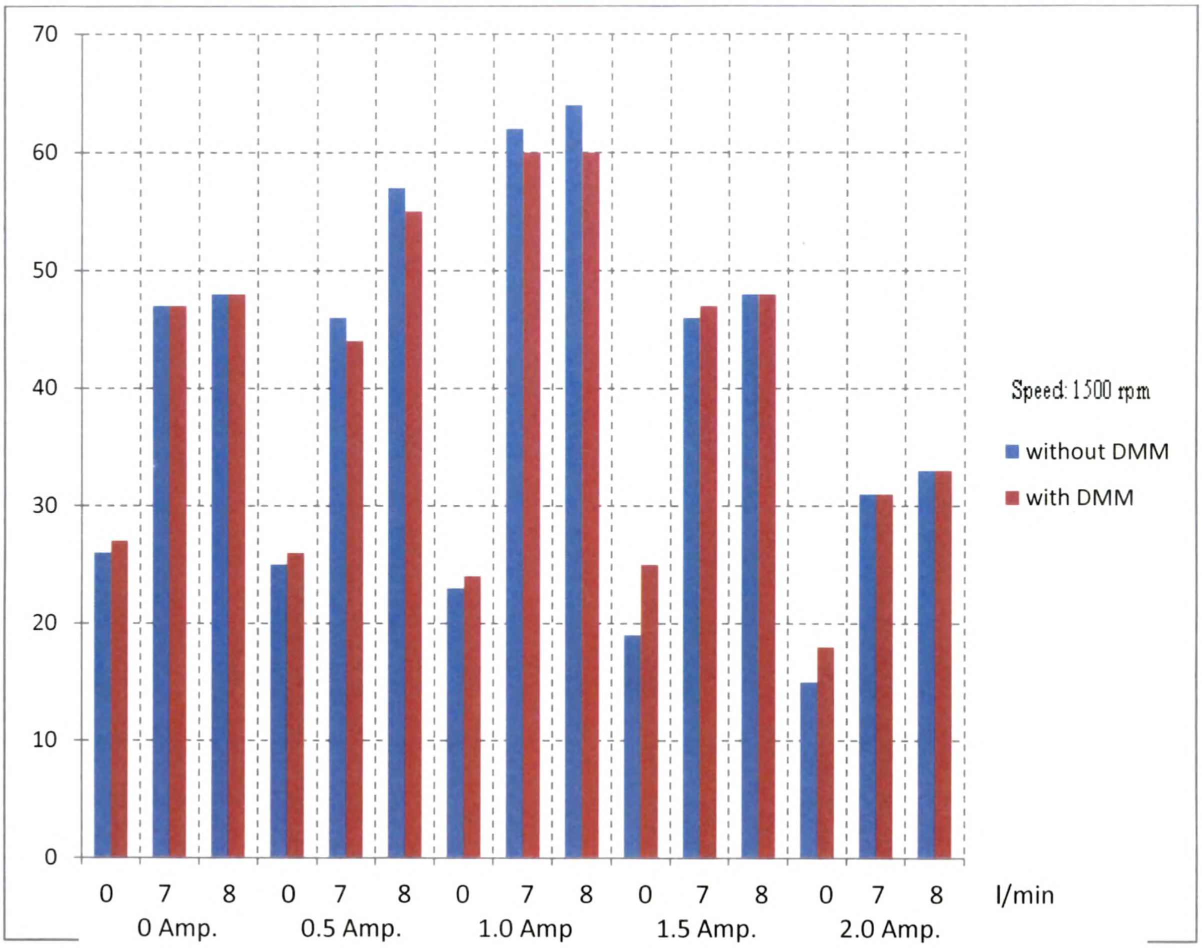


Fig. 3.108 Comparison of the Variation of NO_2 Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Nitrogen Monoxide in Exhaust**

Fig. 3.109 gives the variation in nitrogen monoxide content in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction, 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm. For all the cases of hydrogen induction rate and loads, it is found that the content of NO in the exhaust with DMM/diesel blend as compared to that with diesel alone is more or less the same. However, with the hydrogen induction rate of 7 l/min and 8 l/min, there is a significant decrease in the NO content as compared to that with no hydrogen induction. With increase in load, similar trend of increase in NO content is observed for all the cases. In spite of oxygen increase in the oxygen content due to DMM in the combustion chamber, the NO increased with diesel/DMM blend without hydrogen induction.

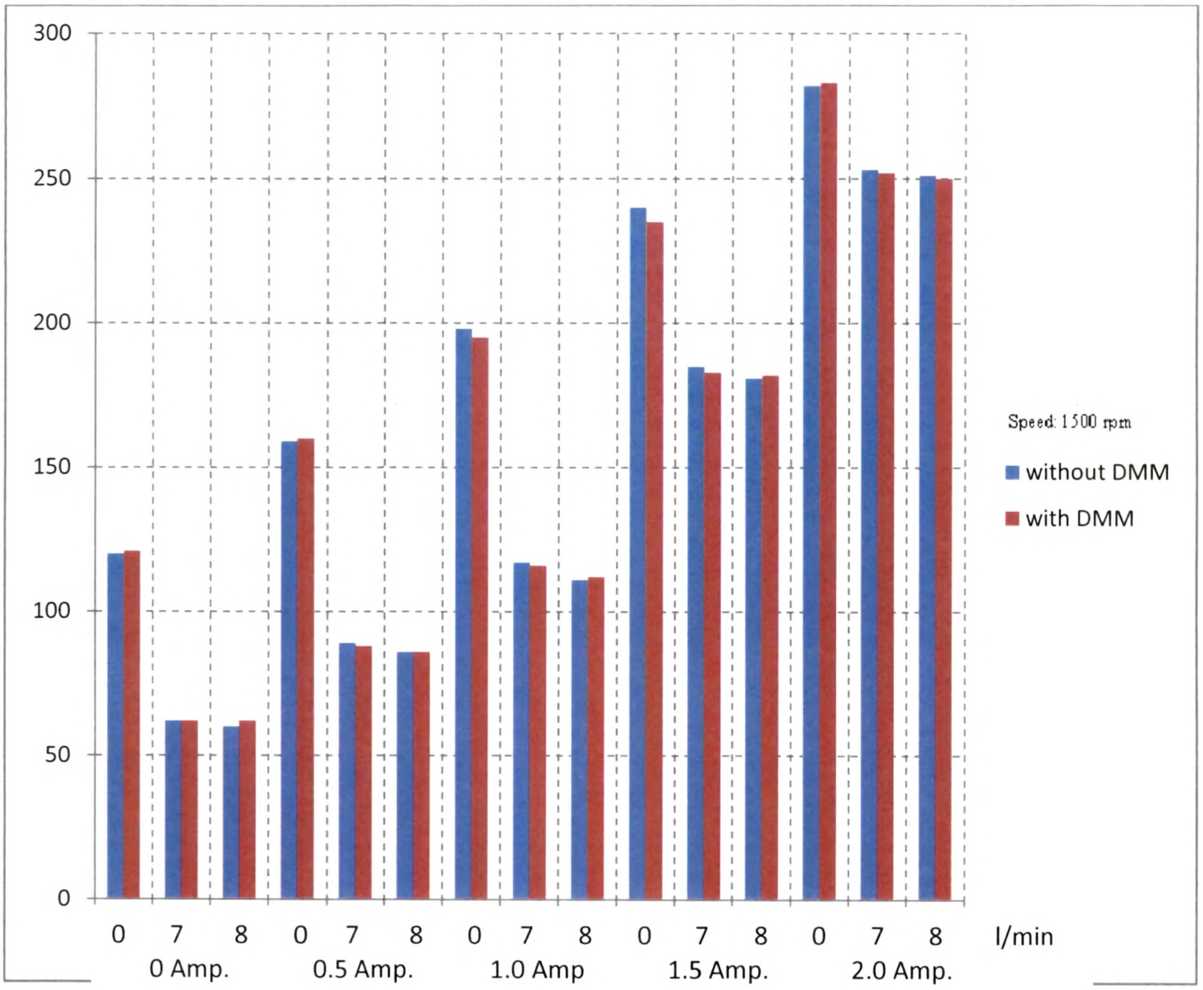


Fig. 3.109 Comparison of the Variation of NO Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

- **Nitrogen Oxides in the Exhaust**

The variation in the content of NO_x in exhaust gases with load when the engine is operated with only diesel and with 10% DMM/diesel blend for the three cases, viz. no hydrogen induction , 7 l/min and 8 l/min hydrogen induction at different loads keeping the speed constant at 1500 rpm as given in Fig. 3.110. It can be seen that the hydrogen induction decreases NOx content in exhaust gases for all the loading conditions. For all the cases of hydrogen induction rate and loads, it is found that there is a definite increase in the content of NOx in the exhaust with increase in load for both the cases of DMM/diesel blend and diesel alone. As discussed in Section 3.4.2.2, the formation of NO_X depends on NO_2 and NO. The addition of DMM to diesel oil leads to a marginal increase in NO_X emission as a result of the increase in conversion of NO to NO_X .

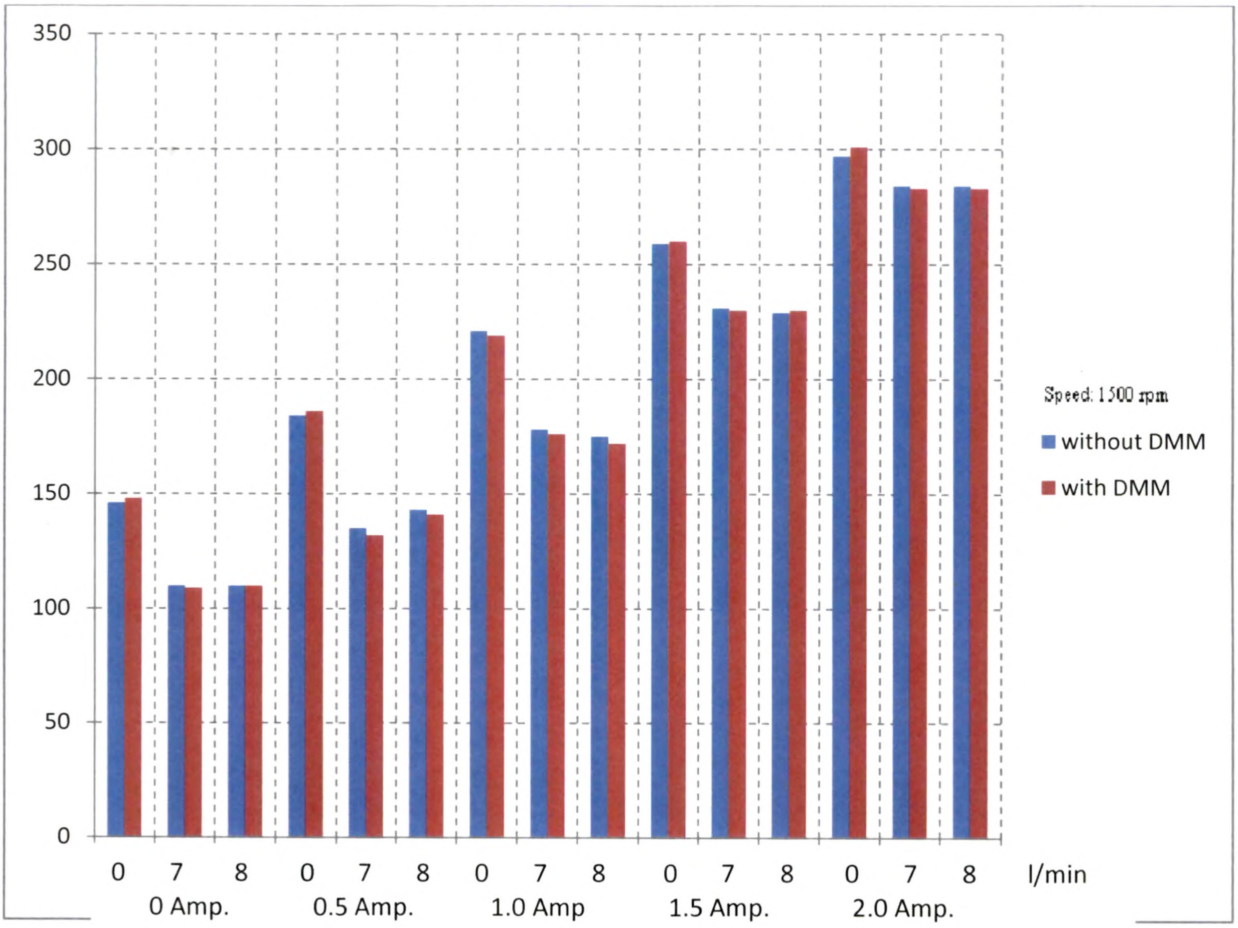


Fig. 3.110 Comparison of the Variation of NO_X Content in Exhaust with Load for the Engine Operated with Diesel and Diesel/DMM Blend and Running at 1500 rpm

3.4.4 Comparison between Various Options Investigated

A comparison between the results of the present investigations on the performance and emission constituents of a compression ignition engine operated on diesel alone, diesel/DMM blend, diesel with hydrogen induction at the intake air manifold at the rate of 7.5 l/min and diesel/DMM blend with hydrogen induction at the rate of 7.5 l/min at the intake manifold is carried out. The range of load applied during the experimental study is from no load condition to 2.0 Amp. in steps of 0.5 Amp. while the engine speed is held constant at 1500 rpm.

3.4.4.1 Thermal Performance

- **Brake Power**

Fig 3.111 shows the variation of brake power with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. It is seen that the hydrogen induction improves the brake power output while the blending of diesel with DMM reduces the brake power.

- **Diesel, Diesel/DMM Fuel Consumption**

The addition of additive in diesel increases marginally the fuel consumption rate while the hydrogen induction significantly reduces the consumption of fuel. DMM/diesel blend is found to consume marginally higher rate of fuel as compared to diesel alone with or without hydrogen induction employed. A 20-25 % reduction in diesel oil consumption is possible with the optimum hydrogen induction at the air intake manifold. Fig. 3.112 illustrates the comparison.

- **Brake Thermal Efficiency**

Fig. 3-113 compares the variation of brake thermal efficiency with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. Highest brake thermal efficiency is attained when optimum hydrogen induction at the intake manifold is carried out with DMM/diesel blend for any given operating condition of the engine considered. Thus, DMM helps to improve the brake thermal efficiency further along with the hydrogen induction.

- **Volumetric efficiency**

Fig. 3.114 compares the variation of volumetric efficiency with load for diesel, diesel/DMM blend with and without hydrogen induction. A 2-3 % decrease in volumetric efficiency is observed when hydrogen is inducted at the intake manifold irrespective of the use of diesel alone or diesel with DMM as blend. The reason for such a decrease is due the fact that the induction of hydrogen in the intake port affects the actual volume of atmospheric air drawn by engine. It should be noted that the addition of DMM in liquid form along with diesel has no effect on the volumetric efficiency.

- **Equivalence Ratio**

Fig. 3.115 illustrates the variation of equivalence ratio with load for diesel, diesel/DMM blend with and without hydrogen induction. It is seen that the addition of DMM in diesel increases the fuel/air ratio which leads to an increase in equivalence ratio while the induction of hydrogen decreases the ratio. The effect of hydrogen induction on the ratio is due the technique of induction at the intake manifold which partially decreases the intake of air in to the compression ignition engine. The weakest mixture is the diesel with 7.5 l/min hydrogen while the richest one is the diesel/DMM blend. The induction of hydrogen makes the diesel/DMM blend lean but still richer than that with diesel alone. The equivalence ratio, however, increases with increase in load for all the options considered.

- **Brake Specific Energy Consumption**

Fig. 3.116 compares the variation of BSEC with load for diesel, diesel/DMM blend with and without hydrogen induction when the engine is operated at a constant speed of 1500 rpm. It can be noted that BSEC is higher with diesel/DMM blend as compared to diesel alone irrespective of the introduction of hydrogen. This trend is due to the fact that the equivalent calorific value of diesel/DMM blend is less as compared to that of diesel alone and hence requires more energy consumption for the same operating condition. The induction of hydrogen, however, enhances the combustion and reduces the consumption of energy. The minimum consumption is found when diesel/DMM with 7.5 l/min H_2 is used. The general trend of variation in BSEC with load is same as discussed in previous sections.

- **Exhaust Temperature**

Fig. 3.117 compares the variation of exhaust temperature with load for diesel, diesel/DMM blend with and without hydrogen induction when the engine is operated at a constant speed of 1500 rpm. It can be seen that the addition of DMM as blend increases the exhaust temperature due the oxygen content in DMM.

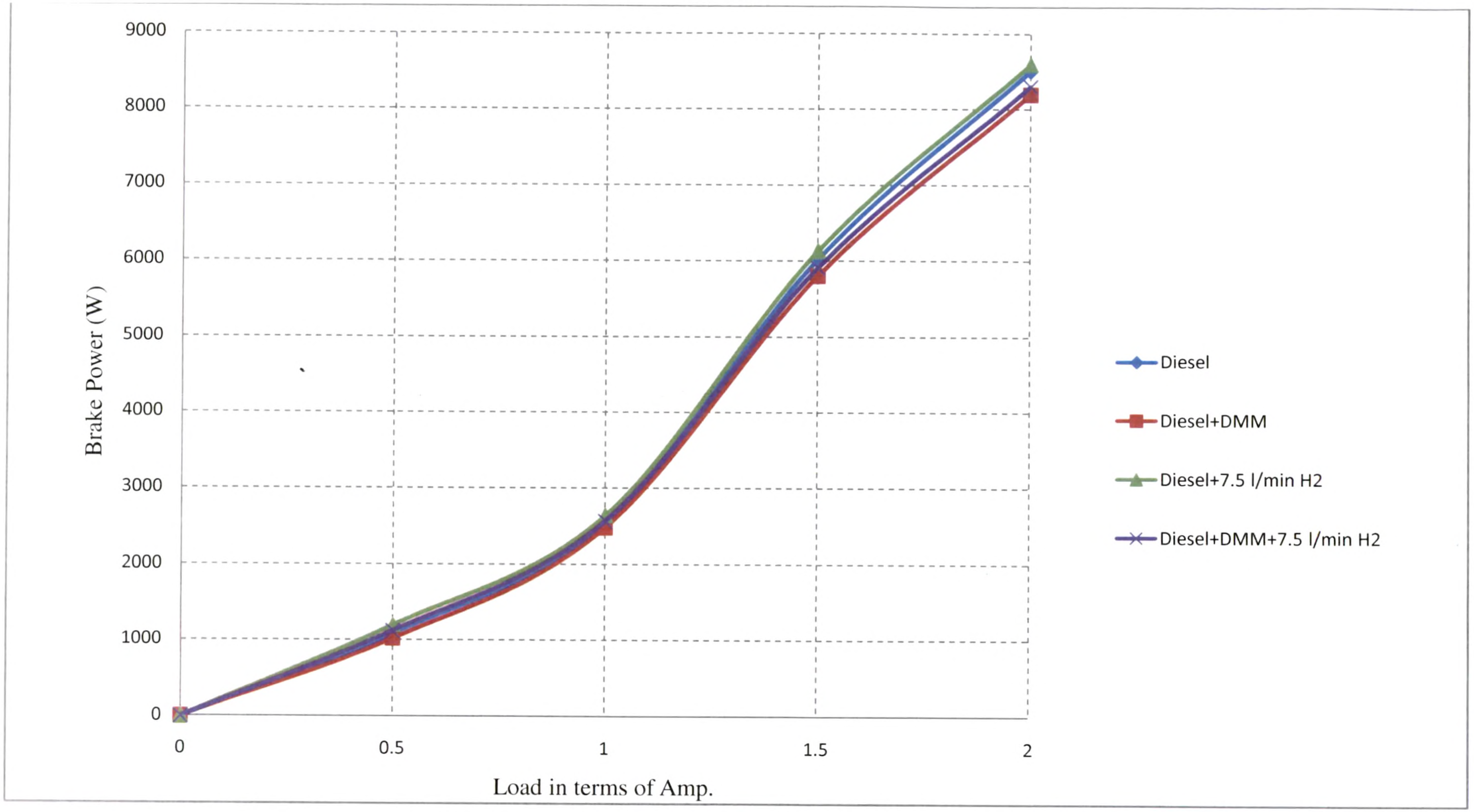


Fig. 3.111 Comparison of the Variation of Brake Power with Load for Various Options

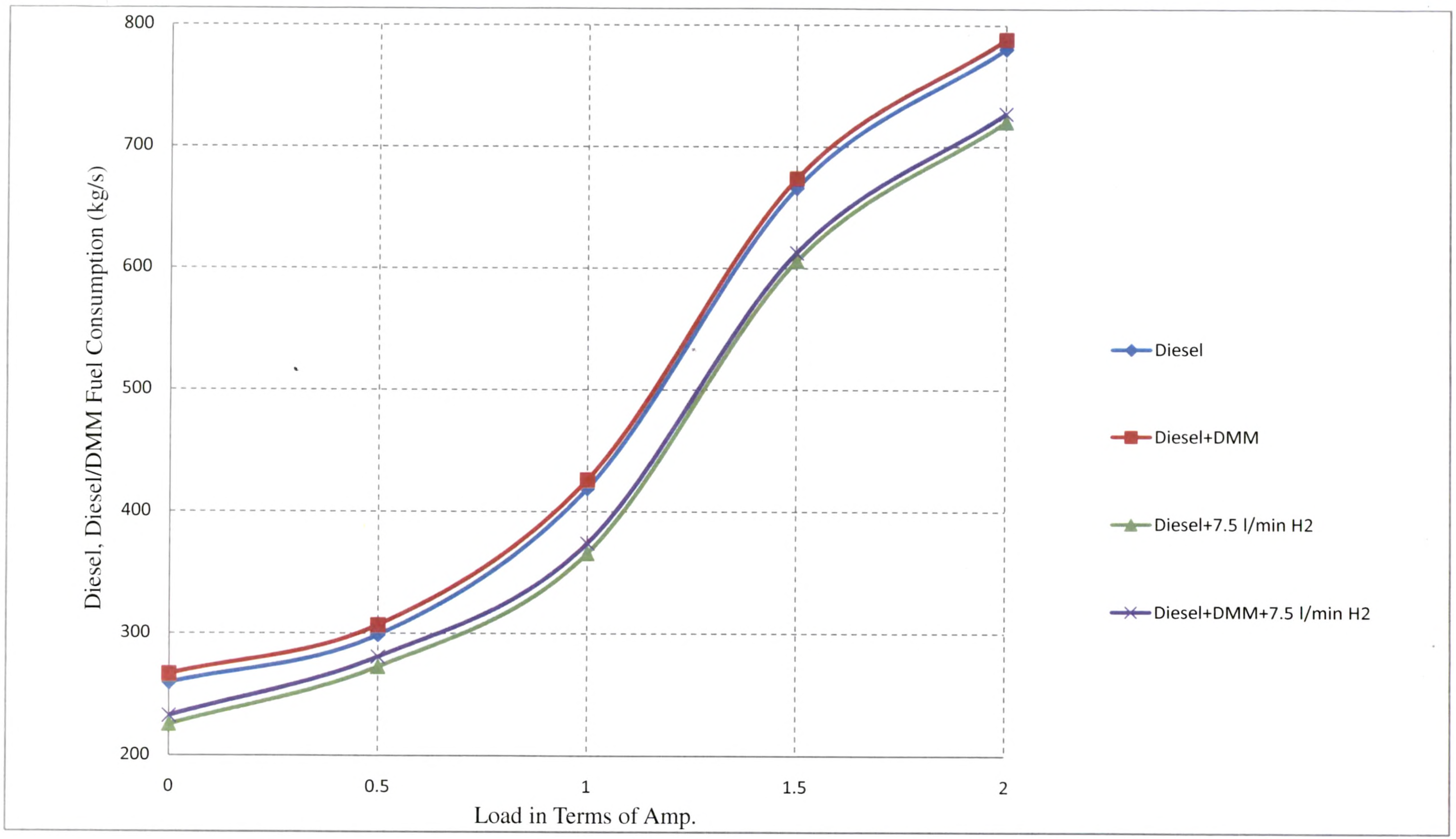


Fig. 3.112 Comparison of the Variation of Fuel Consumption with Load for Various Options

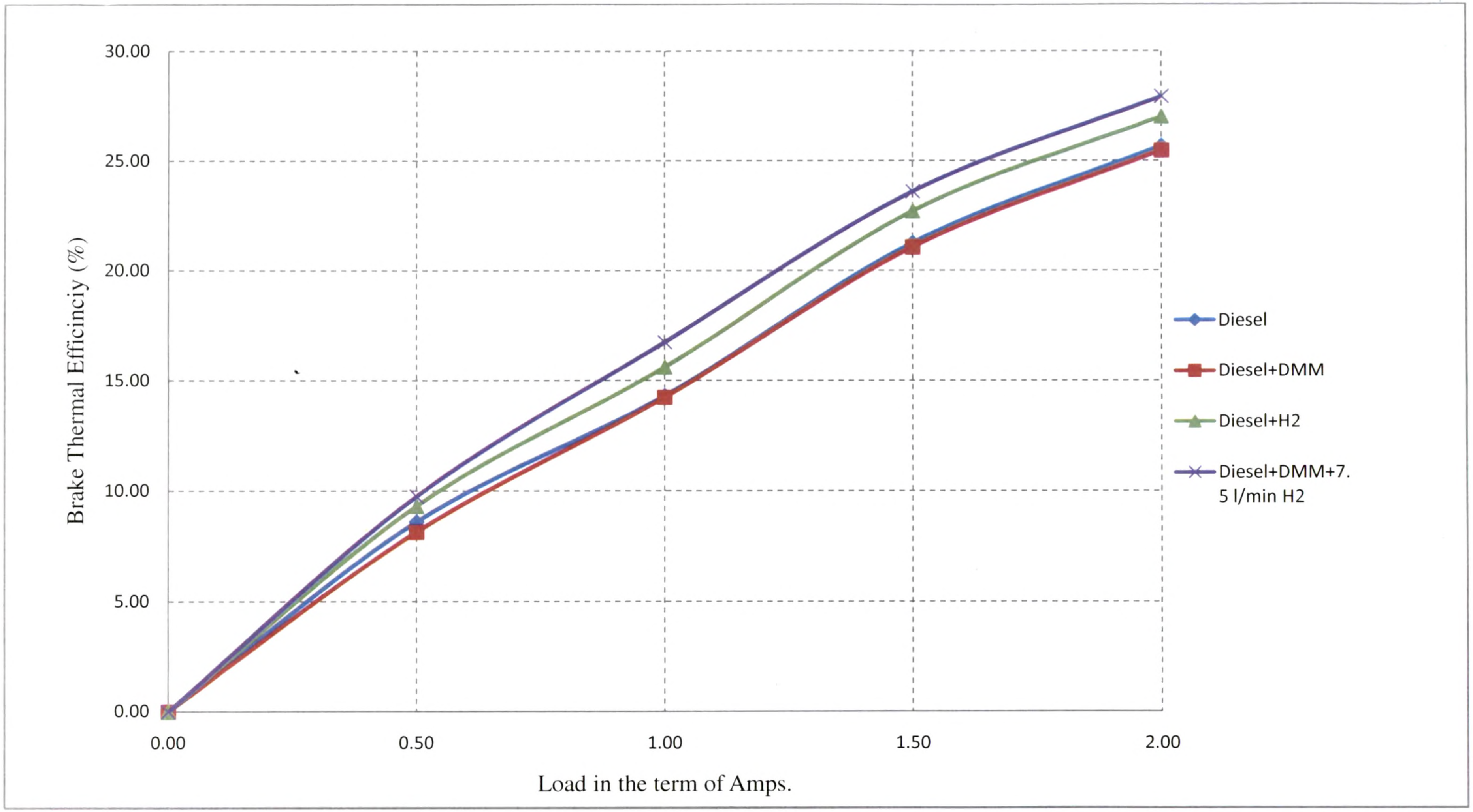


Fig. 3.113 Comparison of the Variation of Brake Thermal Efficicency with Load for Various Options

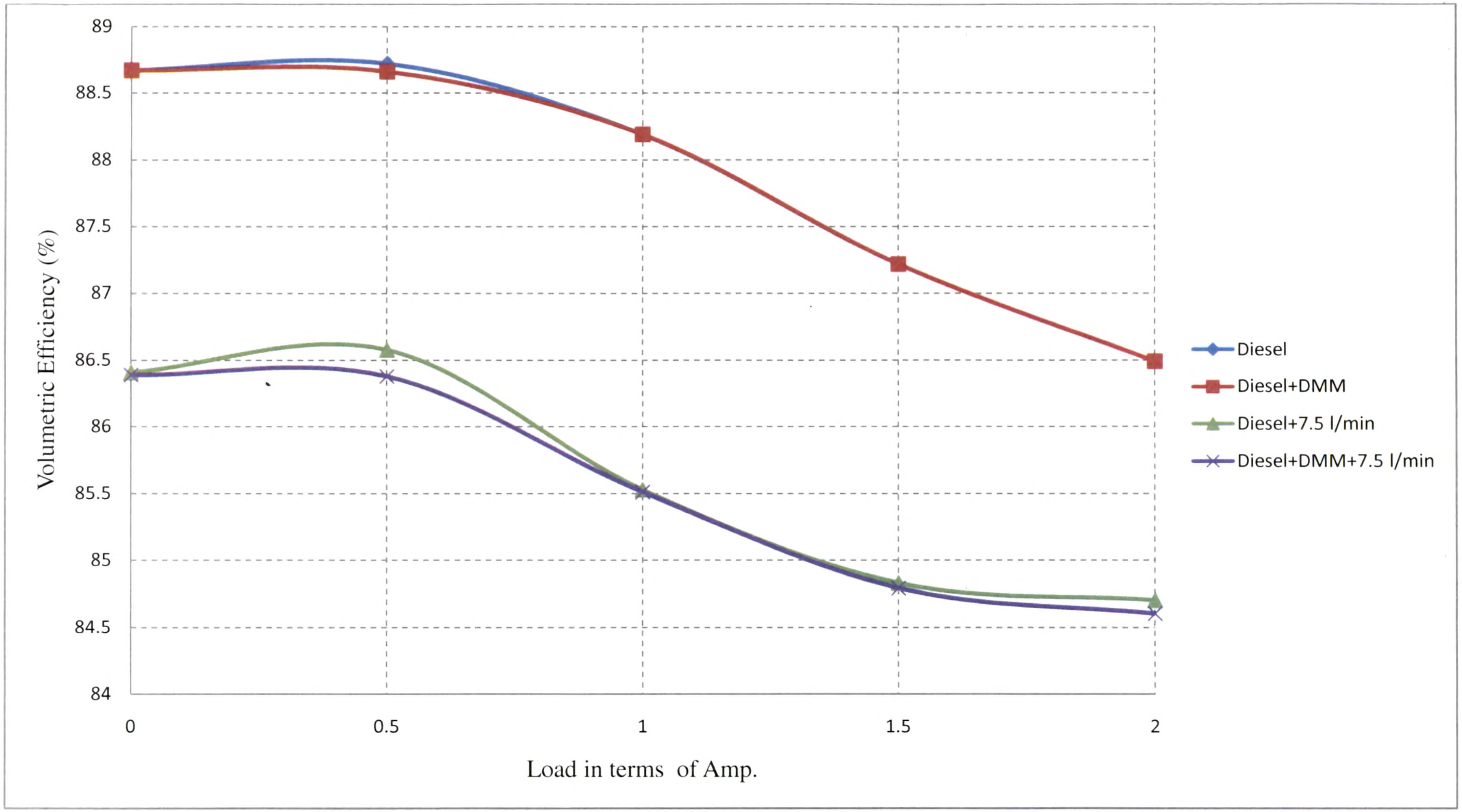


Fig. 3.114 Variation of Volumetric Efficiency with Hydrogen Induction Rate for Various options

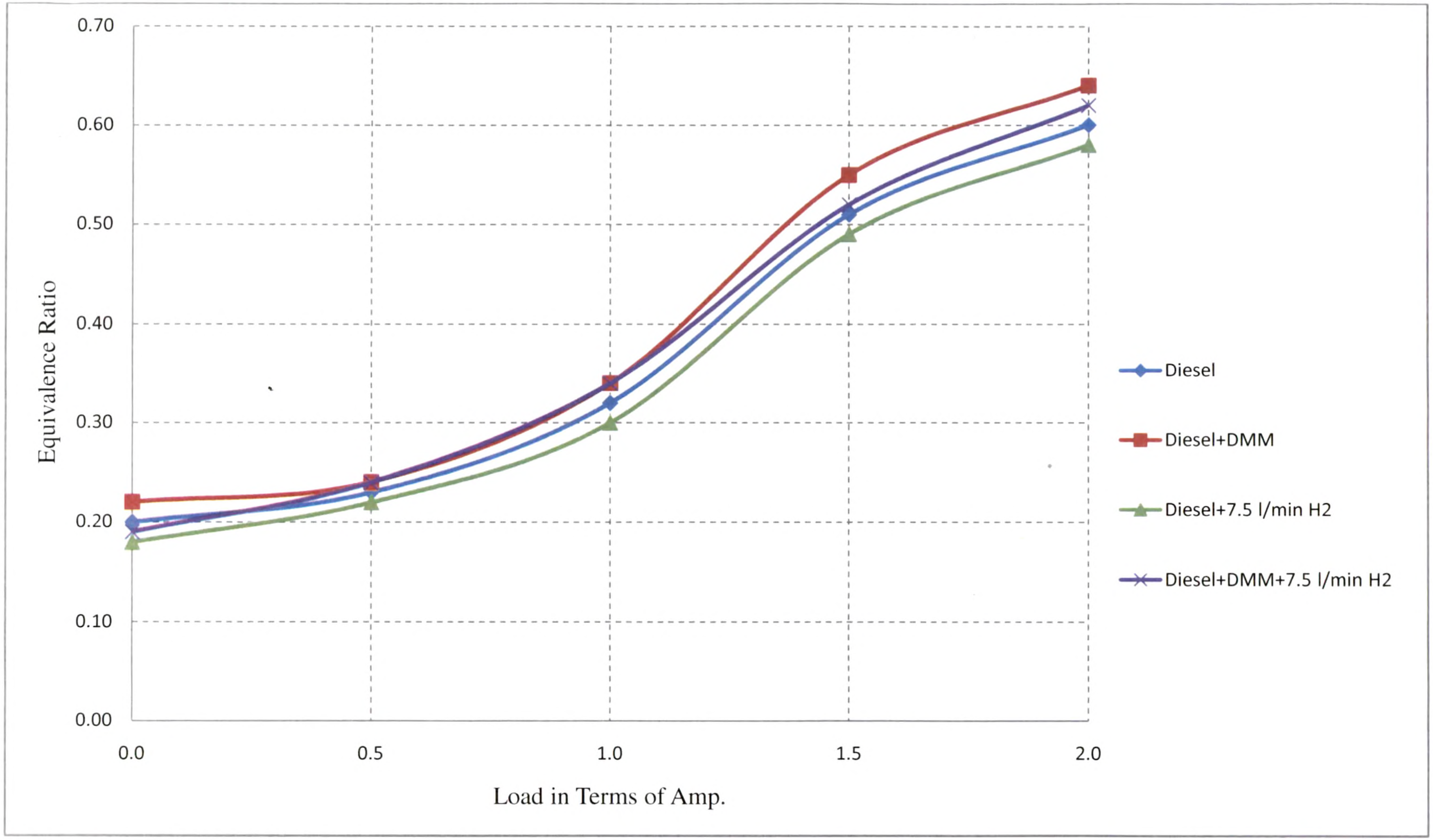


Fig. 3.115 Comparison of the Variation of Equivalence Ratio with Load for Various Options

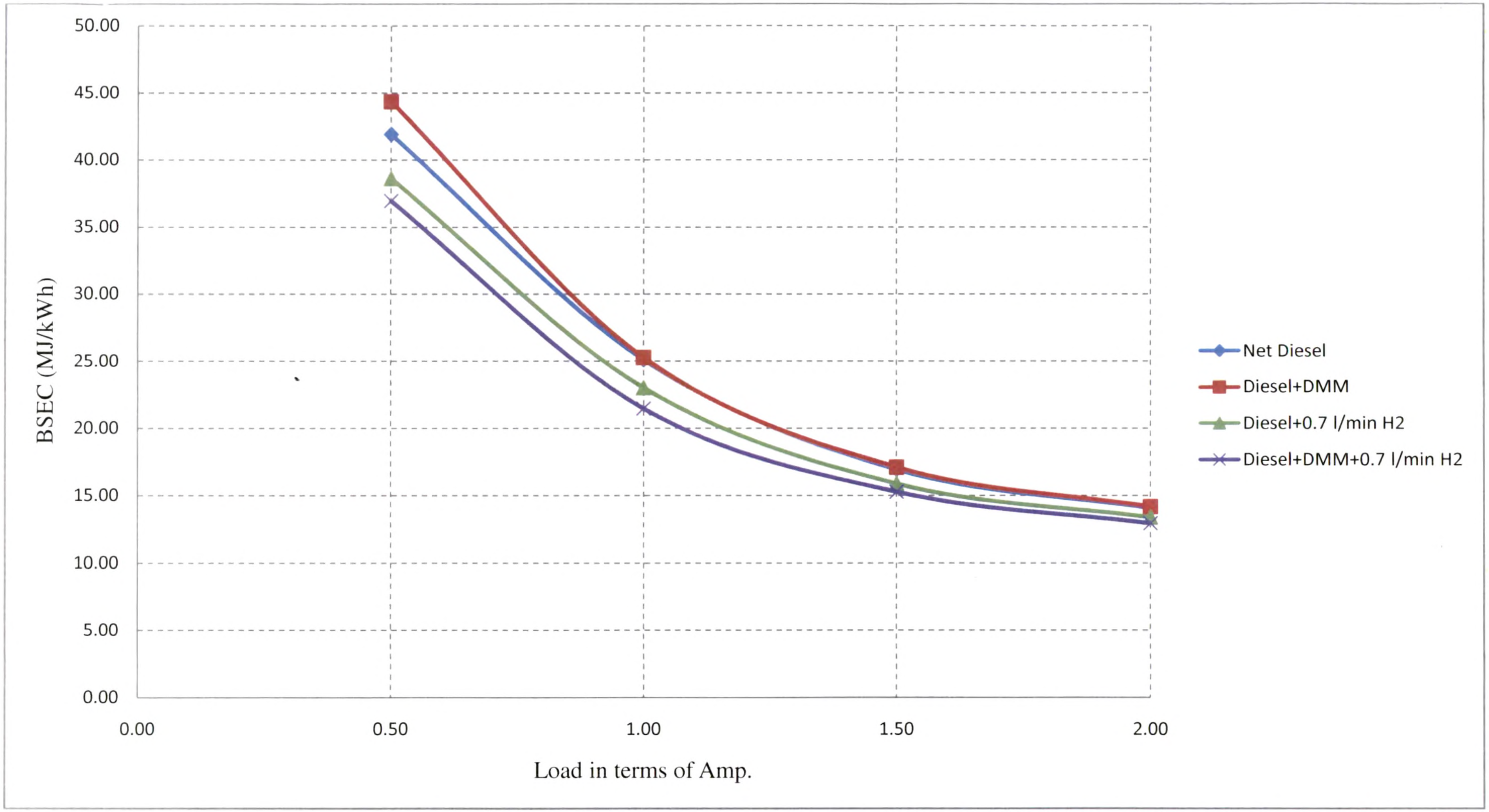


Fig. 3.116 Comparison of the Variation of BSEC with Load for Various Options

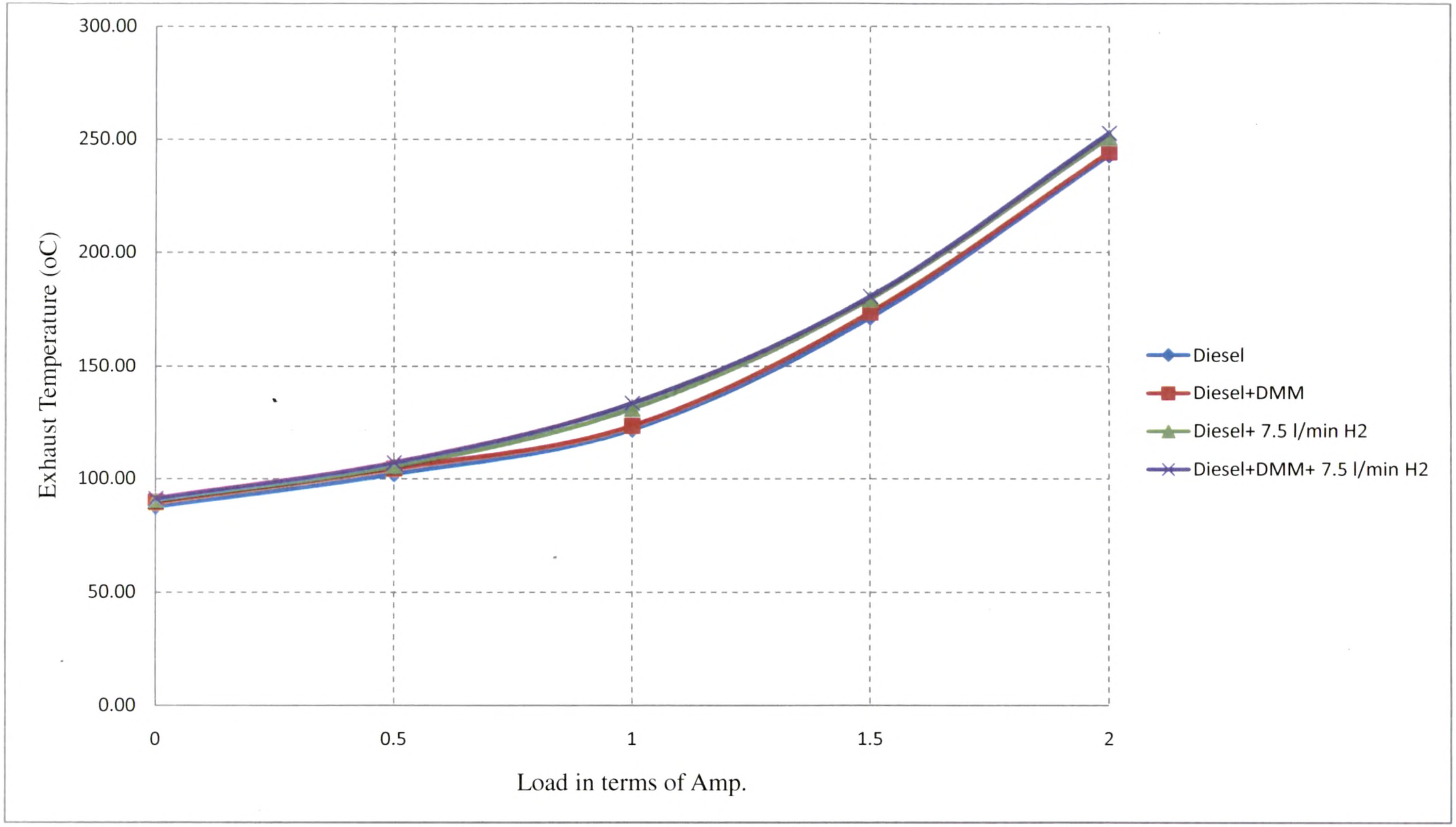


Fig. 3.117 Comparison of the Variation of Exhaust Temperature with Load for Various Options

3.4.4.2 Gas Emission Constituents

- **Oxygen in Exhaust**

Fig. 3.118 compares the variation of oxygen content in exhaust with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. The residual oxygen from combustion process found in the exhaust is more with DMM / diesel blend due to high percentage of oxygen in DMM. This oxygen enhances the combustion and residual part comes out with the exhaust. The oxygen content in exhaust decreases with increase in load due to the fact that more air is drawn during the operation with at higher load.

- **Carbon Monoxide in Exhaust**

Fig. 3.119 compares the variation of carbon monoxide content in exhaust with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. The blending of diesel by DMM decreases the carbon monoxide content in exhaust since DMM has less carbon in it than that in diesel. The hydrogen induction at the optimum level with DMM /diesel blend decreases the percentage of CO content in exhaust. However, hydrogen induction has increased the CO content substantially at lower loads. With hydrogen induction, there is a significant decrease in the content of CO at higher loads and at full load the content is only marginally more than that of the engine operated with diesel alone or diesel/DMM blend. The displacement of air due to hydrogen induction in the inlet manifold causes decrease in oxygen drawn which result in larger amount of CO formation.

- **Carbon Dioxide in Exhaust**

Fig. 3.120 represents the variation of carbon monoxide $CO_2$with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. The addition of DMM decreases the content of CO_2 in the exhaust gases. The percent of CO_2 increased due to the shortage of oxygen availability when the hydrogen is inducted in the inlet manifold. Further, the blending of diesel with DMM causes significant decrease in the CO_2 content for no load and lower loading conditions up to 1.0 Amp. while there is no significant change at higher loads.

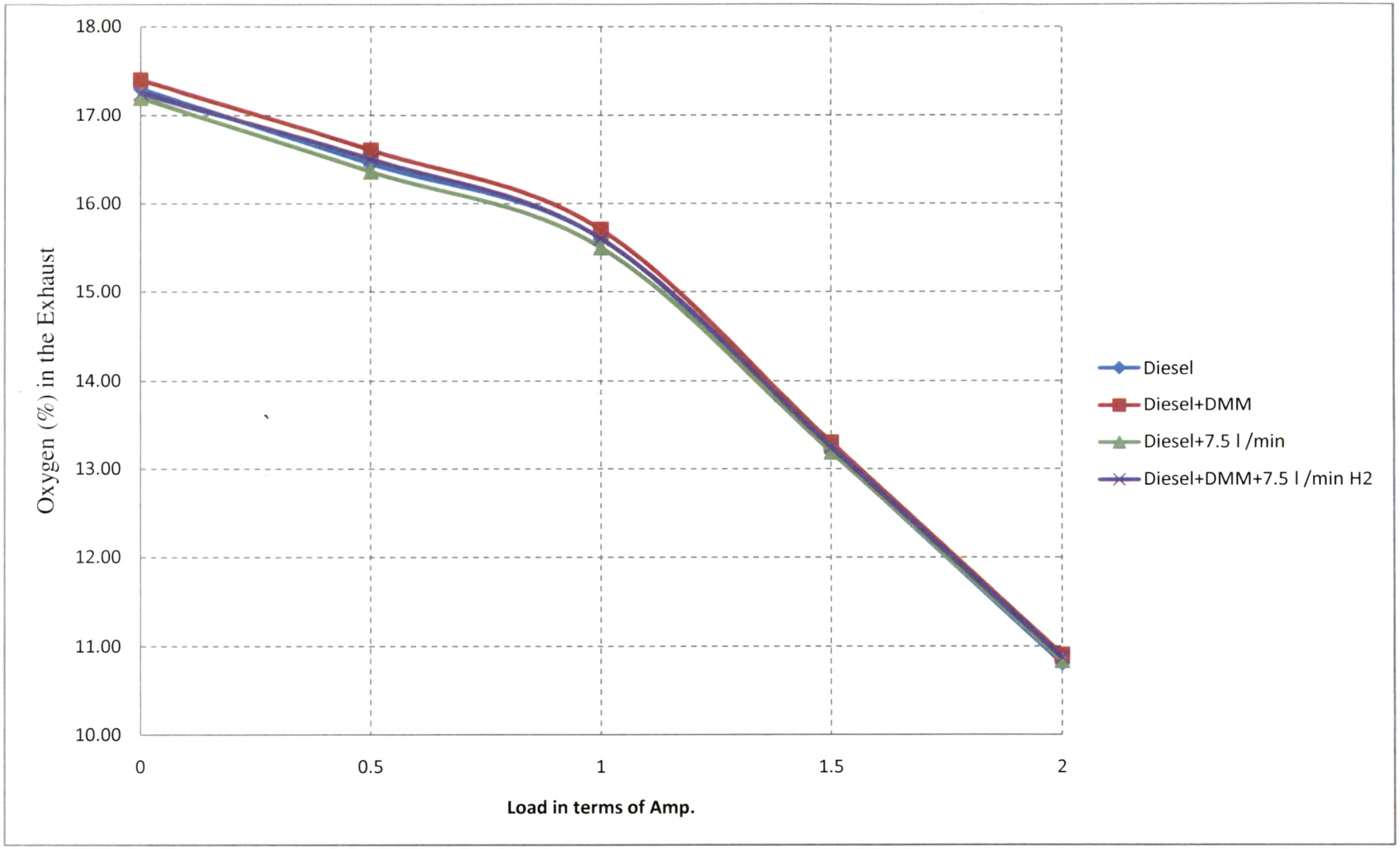


Fig. 3.118 Comparison of the Variation of Oxygen Content in Exhaust with Load for Various Options

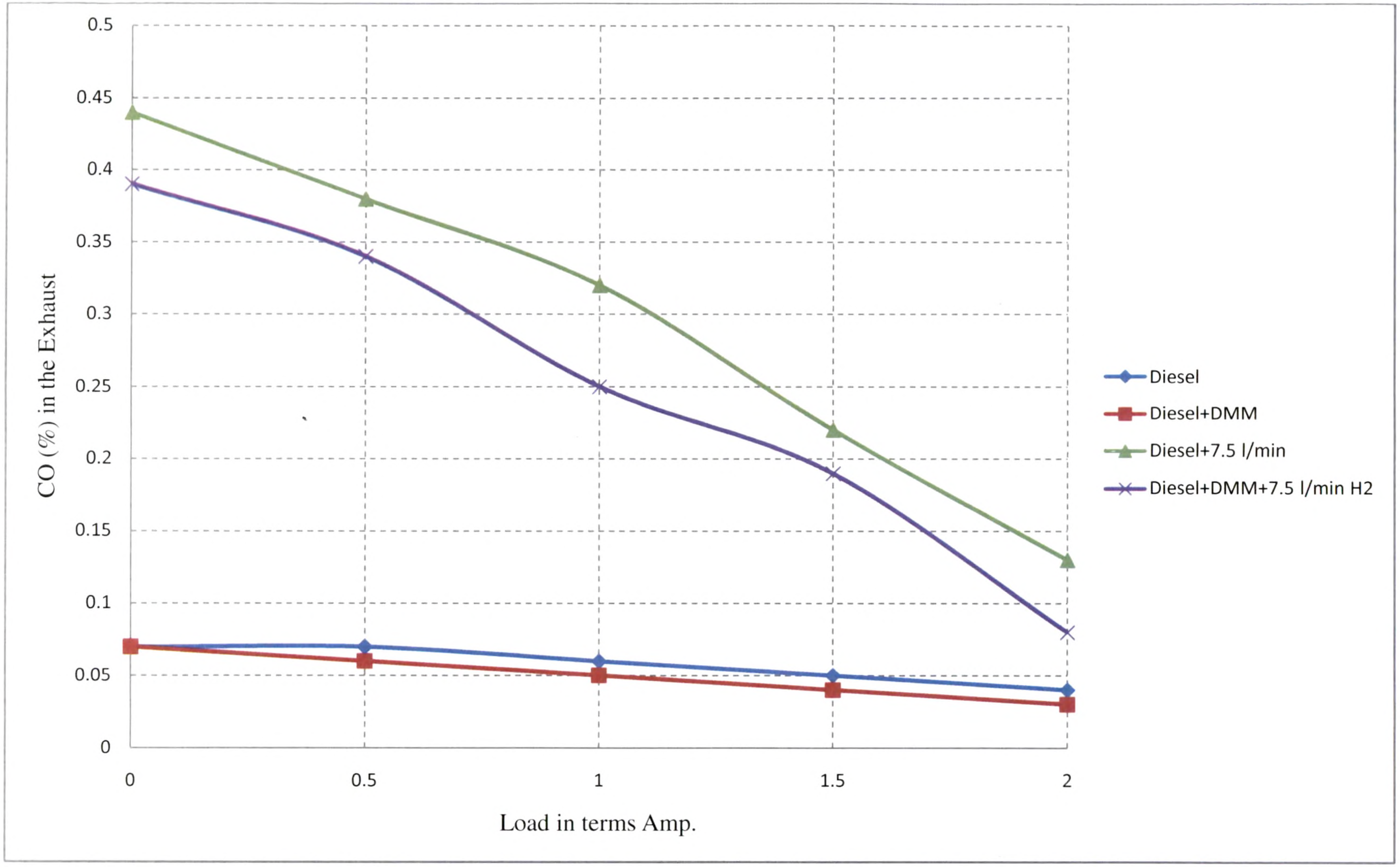


Fig. 3.119 Comparison of the Variation of CO Content in Exhaust with Load for Various Options

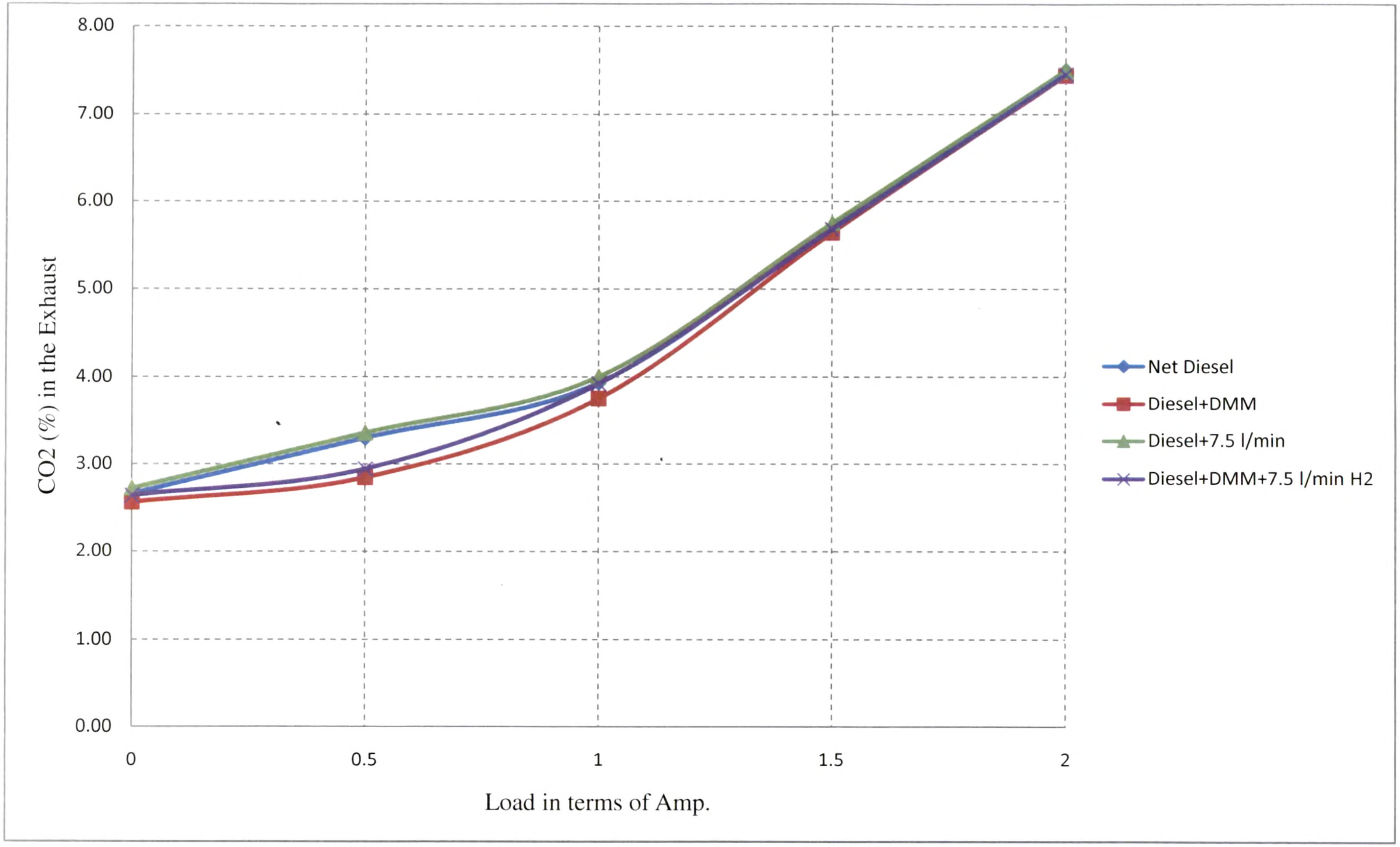


Fig. 3.120 Comparison of the Variation of CO_2 Content in Exhaust with Load for Various Options

- ***Unburned Hydrocarbon HC***

The comparison of the variation of HC content in exhaust with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm is given in Fig. 3.121. It is seen that there is a considerable increase in HC content in exhaust when hydrogen induction is carried out with and without DMM blend. The reason for the high HC content may be due to lower oxygen availability when hydrogen induction at the intake manifold is carried out. However, the blending with DMM decreases the HC content of exhaust gases as compared to that without DMM blend. This may be due to the lower carbon content of DMM, since it has less carbon in its structure.

- **Sulphur Oxide in Exhaust**

The content of SO_2 in the exhaust gases increase more than 9 times with hydrogen induction in the intake manifold of engine with diesel alone and diesel/DMM blend when the engine is operated at no load. However, it decreases as the load increases. Fig. 3.122 compares the variation of SO_2 content in exhaust with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. It can also be noted that the addition of DMM reduces the content of SO_2 in exhaust. It is clear that the formation of SO_2 depends on the oxygen availability which is possible with the DMM blending. However, it is compensated by the reduction in oxygen intake due to the reduced air intake with hydrogen induction. Thus, the formation of SO_2 is found to be more in case of DMM/diesel blend with hydrogen induction as compared with the engine operated with diesel alone.

- **Nitrogen Dioxide (NO_2) in the Exhaust**

Fig. 3.123 shows the variation of NO_2 content in exhaust with load for diesel, diesel/DMM blend with and without hydrogen induction. In this case also, the addition of hydrogen through induction at the intake manifold has resulted in an increase in NO_2 content of the order of 1.6 to 1.8 times as compared to that without hydrogen induction for all the operating conditions of load although a sudden increase is found with a load of 1.0Amp. which may be due to experimental error.

- **Nitrogen Dioxide (NO) in the Exhaust**

From Fig. 3.124, it can be seen that there is an opposite trend in the formation of NO and its content in the exhaust when hydrogen induction is carried out at the intake manifold. At no load and loading up to 1.0 Amp., it is seen that there is a significant reduction in NO formation with optimum hydrogen induction and at higher loads, this difference in rate of formation decreases. At all loading conditions, the minimum formation of NO in exhaust is found to be with diesel/DMM blend along with hydrogen induction at the intake manifold. It should be noted that the increase of NO in exhaust gas emission with load is due to the increase in the exhaust temperature reflecting a better combustion process.

- **Nitrogen Oxides (NO_X) in Exhaust**

Fig. 3.125 compares the variation of NO_x content in exhaust gas with load for diesel, diesel/DMM blend with and without hydrogen induction for the engine operated at a constant speed of 1500 rpm. The formation of NO_X is a result of the combination of NO_2 with NO. In spite of the decrease in NO_2, the content of NO_X in exhaust increases because of the effect of formation of NO more than that of NO_2. The lowest levels of NOx formation in exhaust gas is noted with the use of diesel/ DMM blend together with the chosen optimum hydrogen induction at the intake manifold.

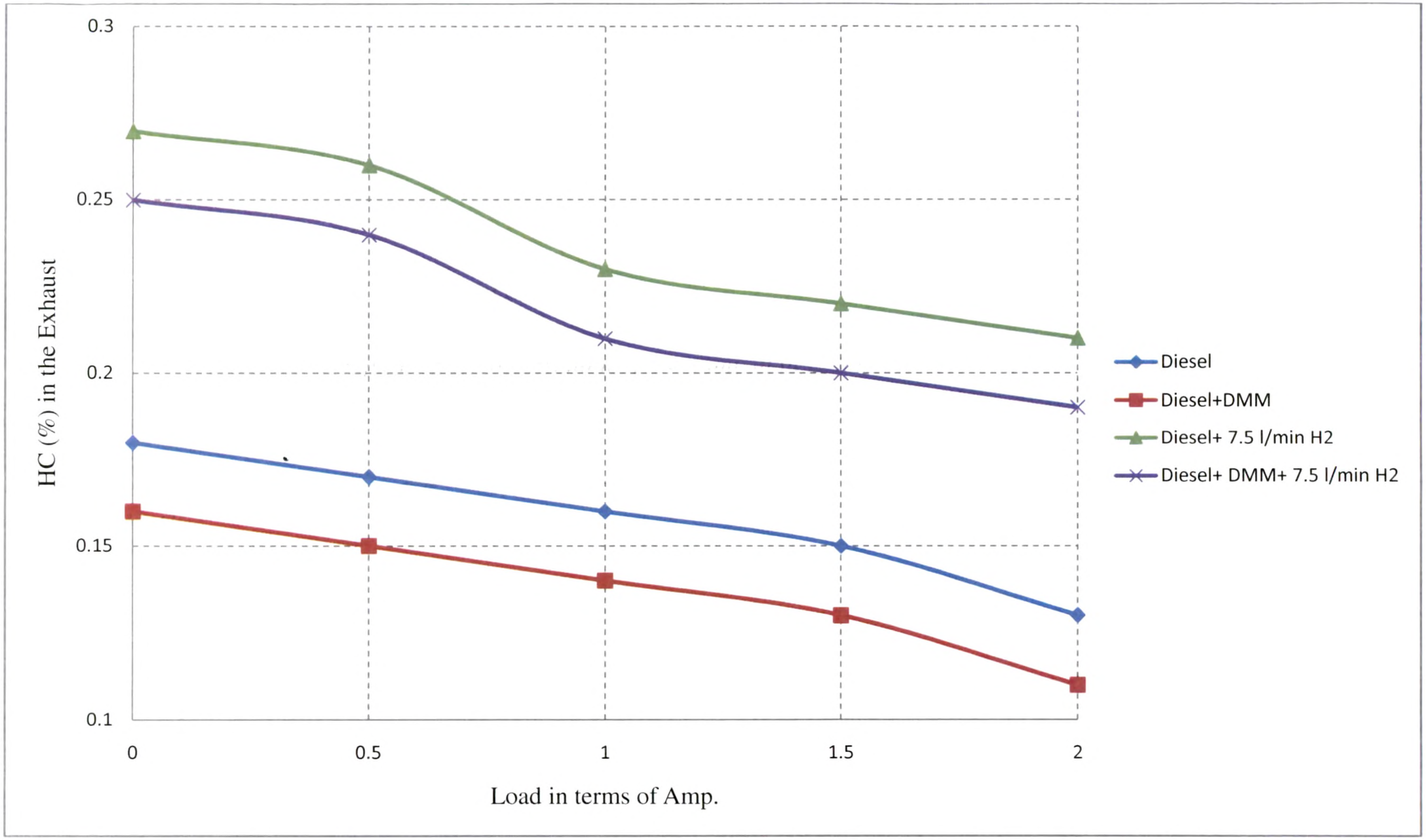


Fig. 3.121 Comparison of the Variation of HC Content in Exhaust with Load for Various Options

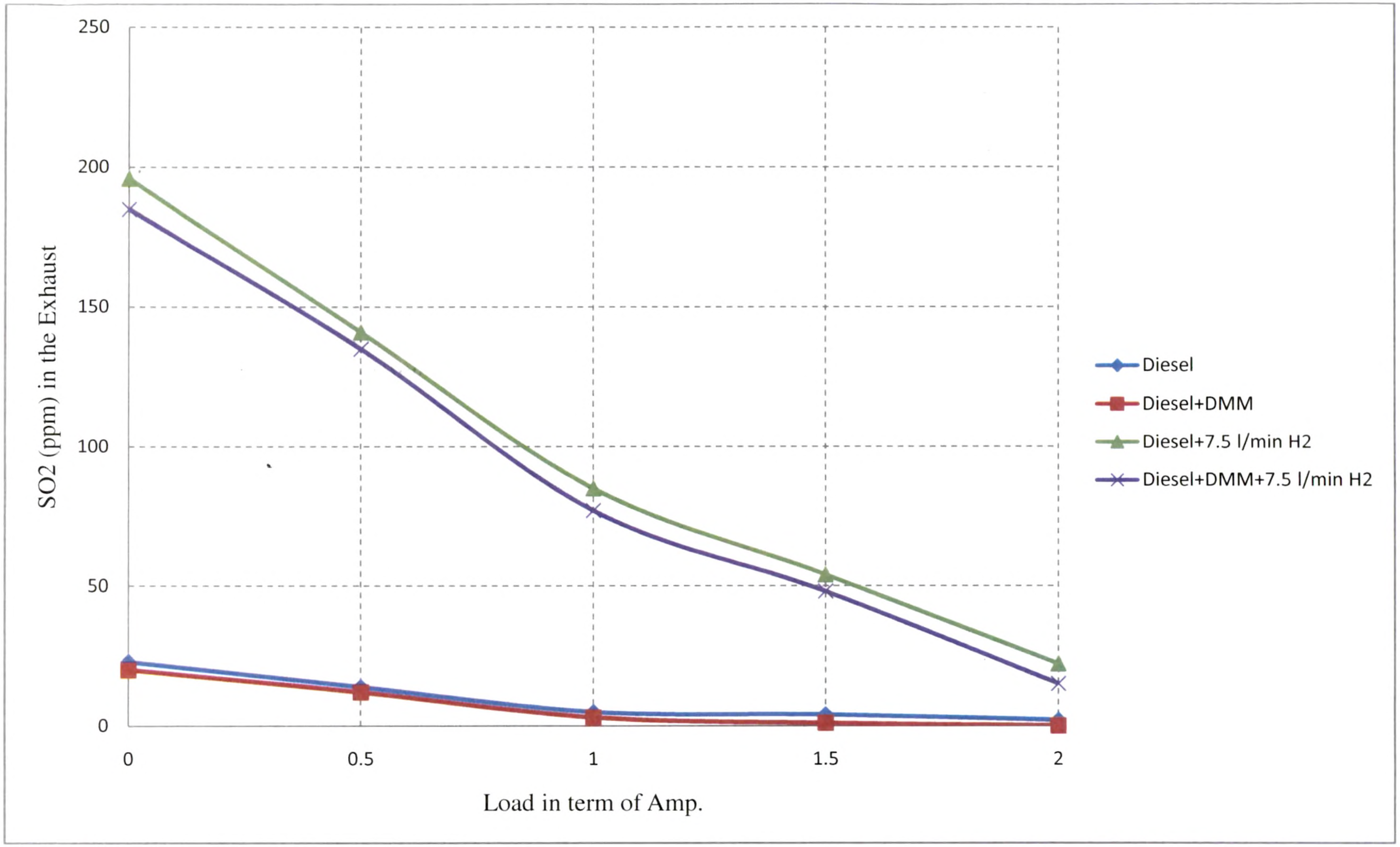


Fig. 3.122 Comparison of the Variation of SO_2 Content in Exhaust with Load for Various Options

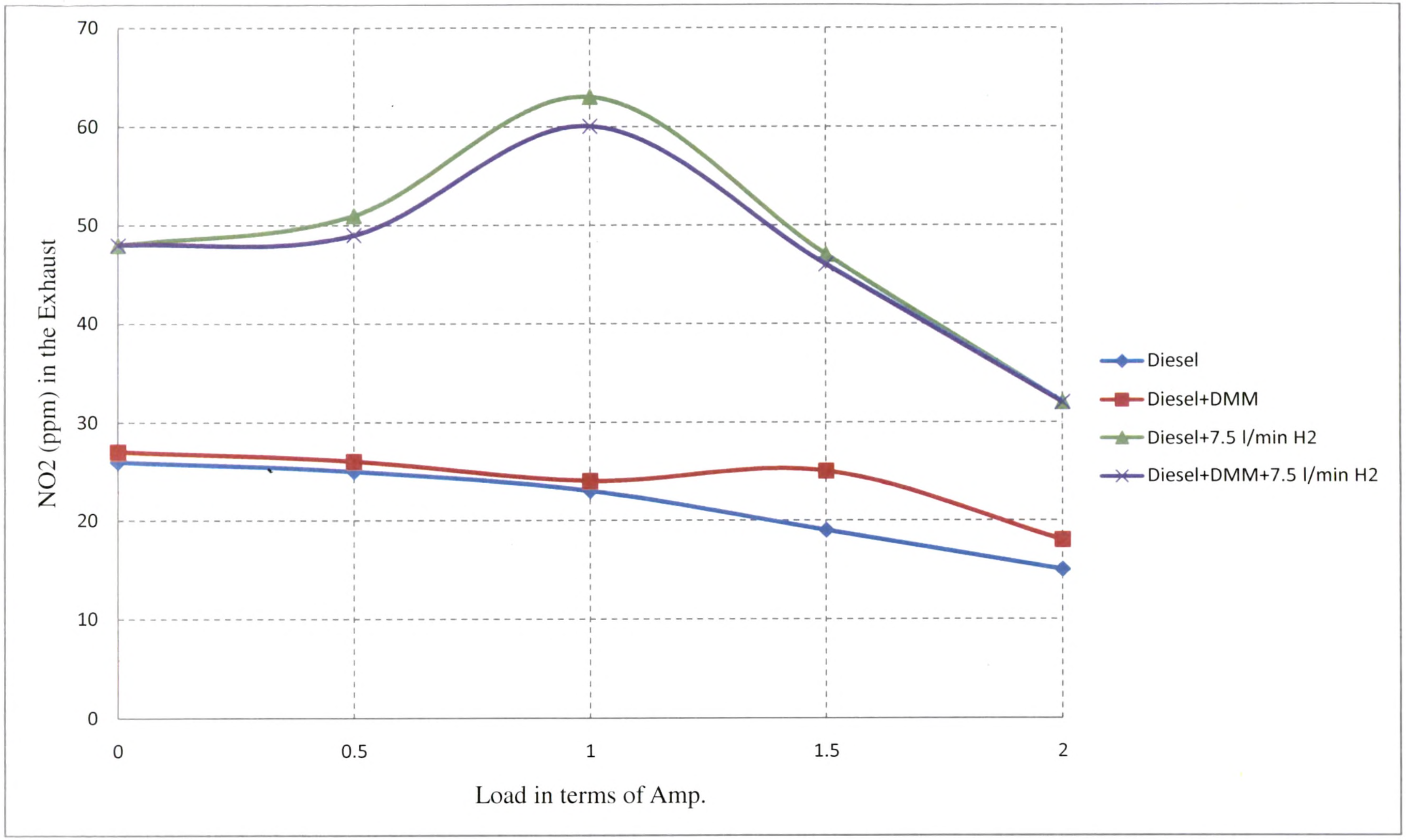


Fig. 3.123 Comparison of the Variation of NO_2 Content in Exhaust with Load for Various Options

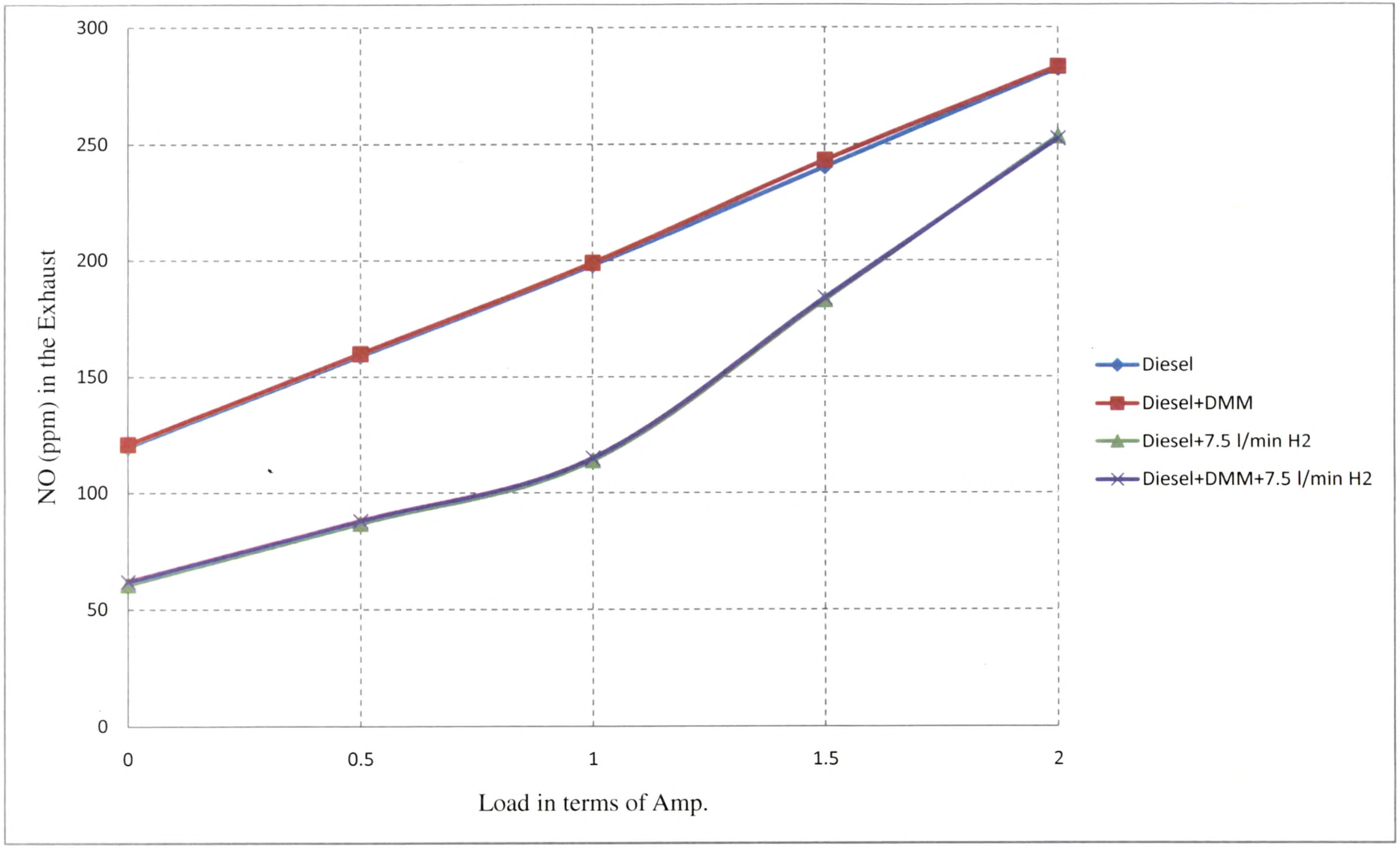


Fig. 3.124 Comparison of the Variation of NO Content in Exhaust with Load for Various Options

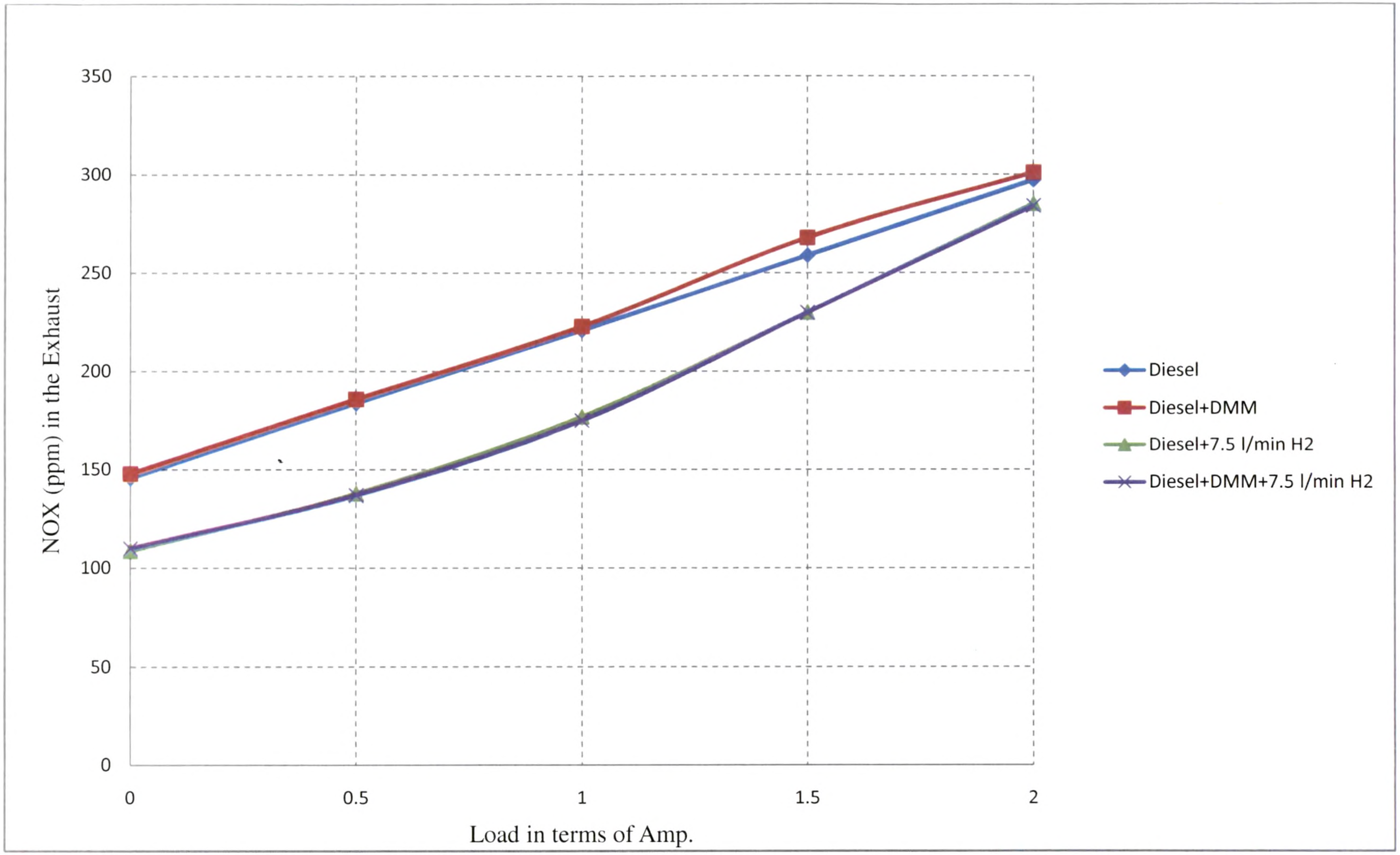


Fig. 3.125 Comparison of the Variation of NO_x Content in Exhaust with Load for Various Options

3.5 Comparison with Earlier Investigations

An attempt is made to compare the experimental results of the thermal performance and exhaust gas emissions of the present study with that of earlier comparable investigations. A review of the earlier studies reveals that the experimental studies reported by Saravanan and Nagarajan [51] and Saravanan et al. [55] are reasonably similar to the present one although all the conditions may not match one to one. It should be noted that both these earlier experimental investigations are carried out on a 3.7 kW single cylinder compression ignition engine operated at a constant speed of 1500 rpm using both intake manifold and port injection of hydrogen with various injection rates. Saravanan et al. carried out studies on the engine with inlet manifold port injection of hydrogen at the rate of 20 l/min while Saravanan and Nagarajan found that the optimum hydrogen injection in the intake manifold should be 7.5 l/min. Further, Saravanan et al investigated the effect of the introduction of portion of exhaust gas recirculation along hydrogen injection.

3.5.1 Optimum Hydrogen Induction Rate

The optimum hydrogen induction rate in the intake manifold of the multi cylinder compression ignition engine based on experimental analysis using both the thermal performance and exhaust gas emission is between 7 and 8 l/min. This is identified by considering simultaneously both reasonably low levels of exhaust gas emissions and higher levels of thermal performance parameters. Saravanan and Nagarajan [51] also found that the optimum hydrogen flow rate should be 7.5 l/min for both port and manifold injection. It should be noted that their experimental study was on a 3.7 kW single cylinder compression ignition engine. The optimum hydrogen injection rate of 7.5 l/min was found by them based on the following limitations in the engine operation at higher hydrogen flow rates which they observed.

1- Instability in engine operation due to manifold injection with high hydrogen flow rates.

2- Onset of knock during high hydrogen flow rate, and
3- Significant increase in smoke emissions at high flow rates of hydrogen at full load.

In the present study, the optimum hydrogen induction rate is obtained by studying simultaneously the variation of thermal performance parameters and exhaust gas emission constituents with hydrogen induction rate at a given operating condition of speed and load of a 27.6 kW multi cylinder compression ignition engine operated at variable speeds and load conditions. The onset of large increase in the constituent gas emission consisting primarily of CO, and HC at a given hydrogen induction rate for various speeds and loads is identified as the basis for the selection of optimum hydrogen induction rate for which the thermal performance parameters are found to be at reasonably higher levels. In the present study, no provision is made to detect or measure either the onset of knock or the instability in engine operation arising out of high hydrogen flow rates. The identification is based on the experimental results on the thermal performance parameters and simultaneous significant increase in gas constituents in exhaust emission.

3.5.2 Thermal Performance Parameters

The brake thermal efficiency and BSEC are selected for the comparison between the results of the present study and that by the earlier investigations reported in [51] and [55]. It should be noted that Saravanan et al. [51] carried out the investigation using a 3.7 kW single cylinder compression ignition engine operated at a constant speed of 1500 rpm with hydrogen injection rate of 7.5 l/min while Saravanan and Nagarajan [55] reported that their study is on the same engine with hydrogen injection rate at 20 l/min. Both the investigations were carried out using timing injection technique in the inlet manifold for the introduction of hydrogen in to the engine cylinder.

- **Brake Thermal Efficiency**

Fig 3.126 shows the comparison of the variation of brake thermal efficiency with brake power between the present work and that of Saravanan and Nagarajan [51] and Saravanan et al. [55].

The brake thermal efficiency appears to increase rapidly with brake power for both the results reported by earlier studies while for the present study, the change is gradual. It should be noted that both the earlier studies are comparable since both of them were conducted on the same 3.7 kW single cylinder engine operated at a rated speed of 1500 rpm while the present study is on a 26.7 kW multi cylinder engine whose rated speed is 4000 rpm but operated at a constant speed of 1500 rpm.

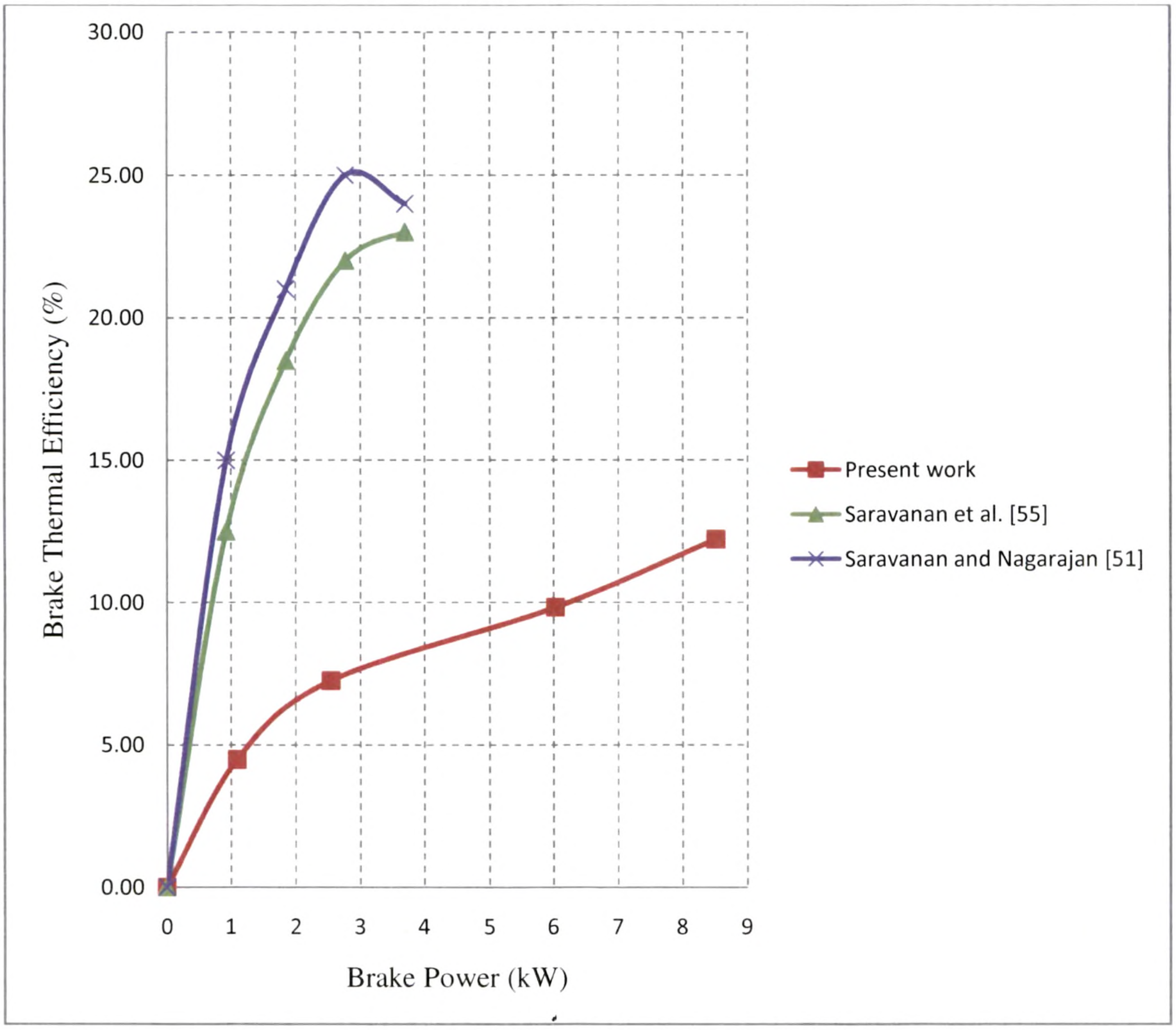


Fig 3.126 Brake Thermal Efficiency with Brake Power for Present Work, Saravanan and Nagarajan [51], and Saravanan et al. [55]

- **Brake Specific Energy Consumption (BSEC)**

Comparison of the variation of BSEC with brake power between the present work and that of reported in [51] and [55] is given in Fig. 3.127. A similarity is observed in the nature of variation of BSEC with brake power. However, BSEC is an order of magnitude greater for the present engine as compared to that of the earlier studies in the comparable range of brake power. Again, it should be noted that the BSEC for the multi cylinder engine with hydrogen induction and operated at full load condition is less than that of the single cylinder engine with hydrogen injection operated at its full load condition. The larger BSEC at lower load condition observed with the multi cylinder engine indicates the high energy consumption of larger size of engine to produce same quantity of power.

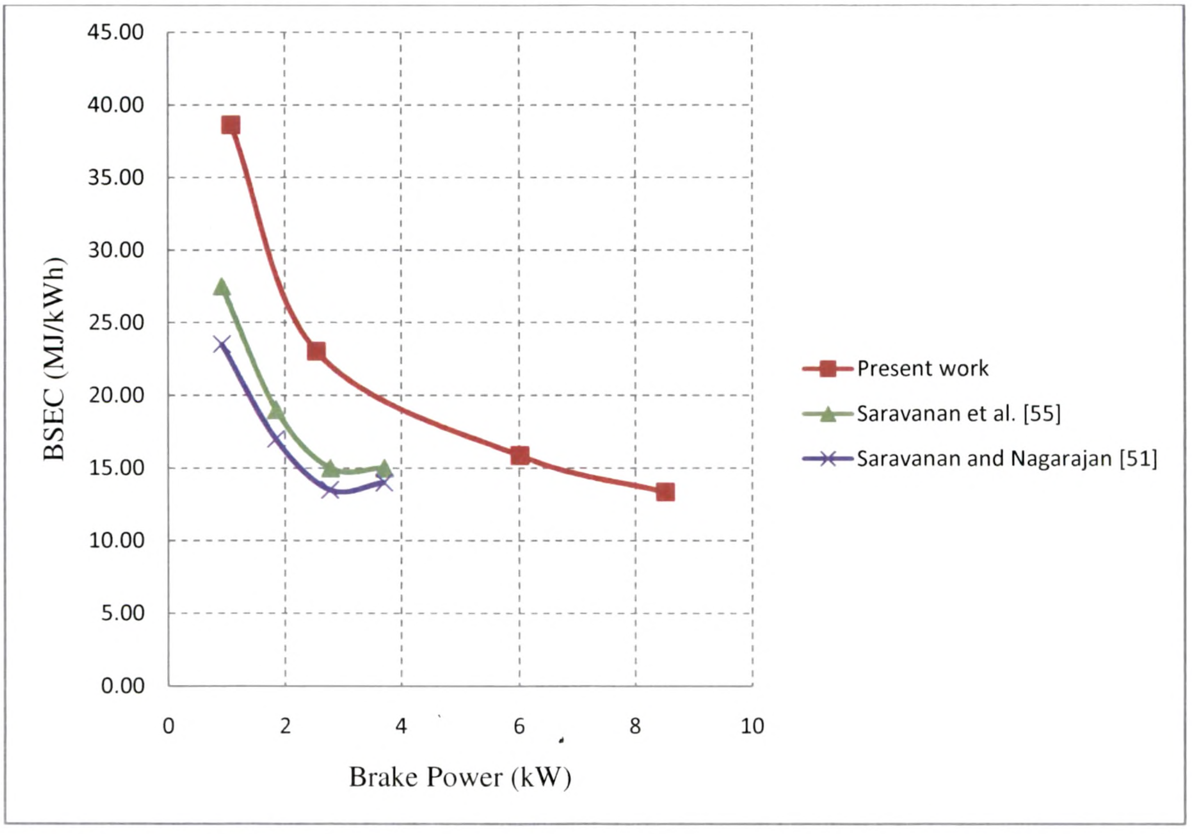


Fig 3.127 Variation of BSEC with Brake Power for Present Work, Saravanan and Nagarajan [51], and Saravanan et al. [55]

- **Carbon Monoxide in Exhaust**

Fig. 3.128 compares the variation of per cent CO in the exhaust with brake power between that observed during the present work and that of Saravanan et al. [55]. It can be seen that the per cent CO content in exhaust decreases substantially with load in the present work while CO content increases in the same range of brake power as reported by them. The reason of the trend observed in the present study is due to the decrease of oxygen supply through lesser amount of drawn air when continuous hydrogen induction takes place in inlet manifold. The formation of CO is very sensitive with the variation of oxygen. The increase in loading of engine leads to shortage of air or oxygen in combustion chamber which results in the decrease in CO formation. The hydrogen is introduced to the engine by injection technique in the manifold at higher pressure which entrains more air in the intake manifold. This may be the reason for the excess availability of oxygen which intern resulted in the formation of CO content in exhaust reported by Saravanan et al.

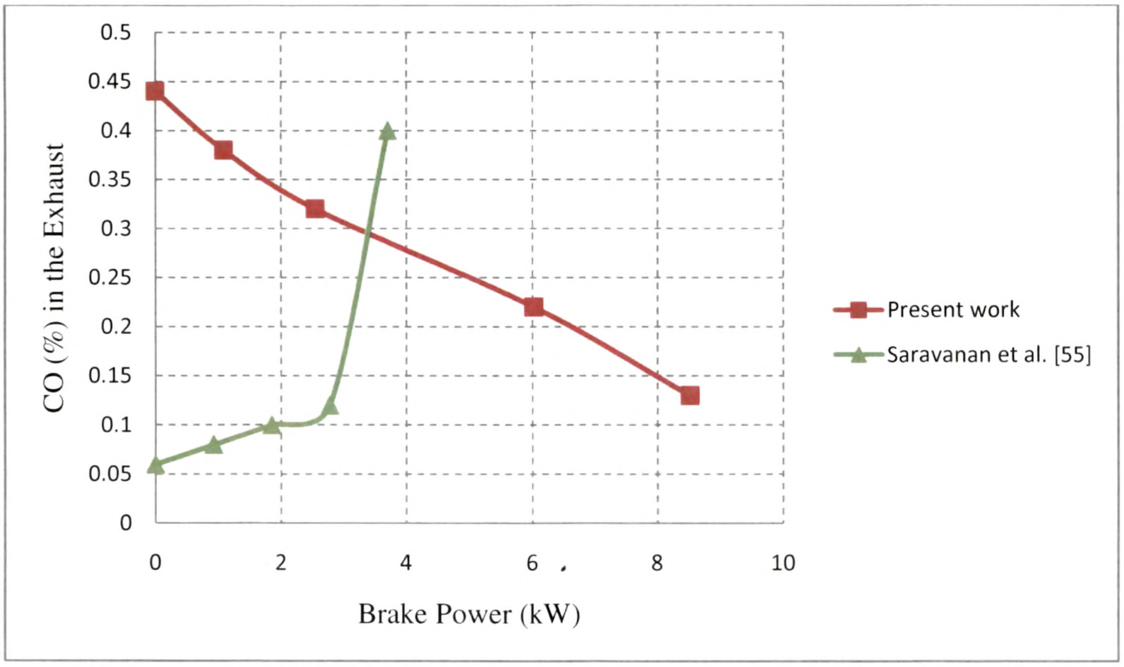


Fig. 3.128 Variation of Carbon Monoxide CO (%) in the Exhaust with Brake Power for Present Work and Saravanan et al. [55]

- **Unburned Hydrocarbon (HC) in Exhaust**

Fig. 3.129 compares the variation of per cent unburned hydrocarbon HC in the exhaust with brake power. The per cent HC content in exhaust decreases with the increase in brake power for the present study while an opposite trend is reported by Saravanan et al. The reason for such a trend is the air/oxygen shortage in combustion chamber due to the less amount of air drawn when hydrogen induction is carried out in the present study which led to decrease the formation of HC. The opposite trend of variation of CO content with brake power observed by Saravanan et al. may be due to the relatively high pressure injection technique of the introduction of hydrogen resulted in larger quantity of air/oxygen through better entrainment. It is also seen that the HC content is of much higher level during the operation of the multi cylinder compression ignition engine as compared to the single cylinder engine. This is due to the fact that large quantity of diesel is consumed in multi cylinder engine as compared to that in a single cylinder engine.

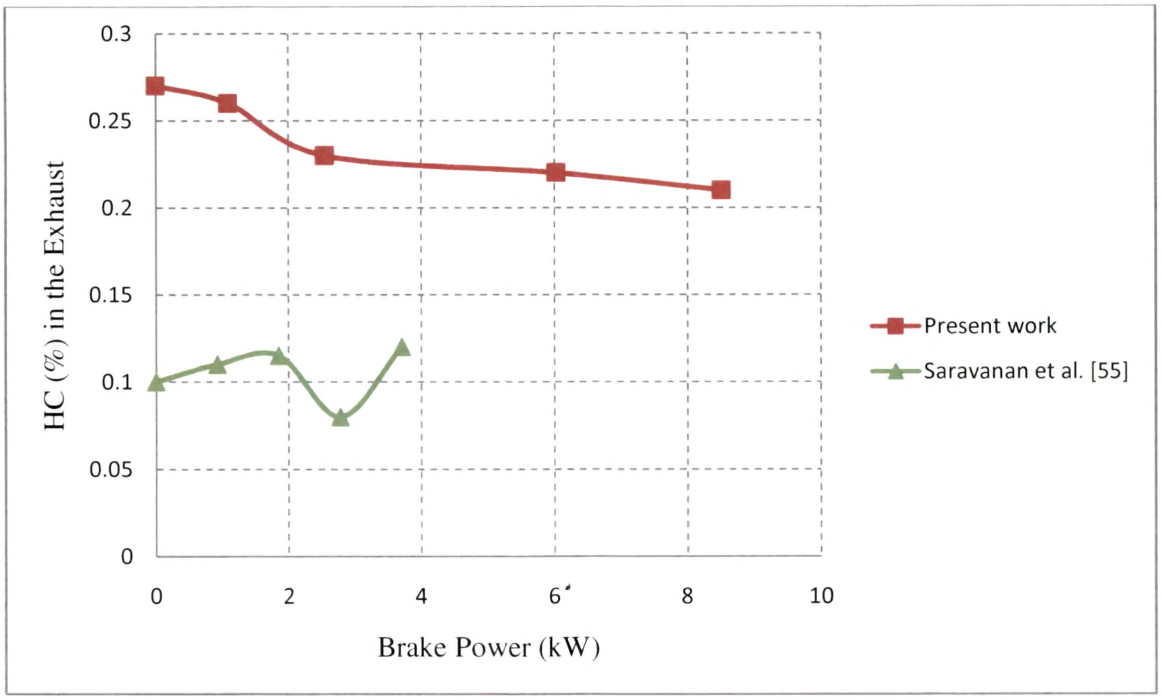


Fig. 3.129 Variation of Unburned Hydrocarbon HC (%) in the Exhaust with Brake Power for Present Work and Saravanan et al. [55]

- **Carbon Dioxide in Exhaust**

A comparison of the variation of per cent CO_2 in the exhaust with brake power is given in Fig. 3.130. A similar trend in the variation of CO_2 content with brake power is observed with both the studies although the quantity of CO_2 content in exhaust is much more with multi cylinder engine due to requirement of large amount of hydrocarbon fuel burnt as compared to that of single cylinder engine.

The formation of CO_2 is not strongly influenced by availability of the air/oxygen in the combustion chamber unlike the formation of CO and HC in exhaust. The formation of CO and HC is affected by the oxygen availability while CO_2 formation is due the quantity of hydrocarbon burned in combustion chamber. Thus, the trend observed in the formation of NO and HC during the present study can be justified and as expected.

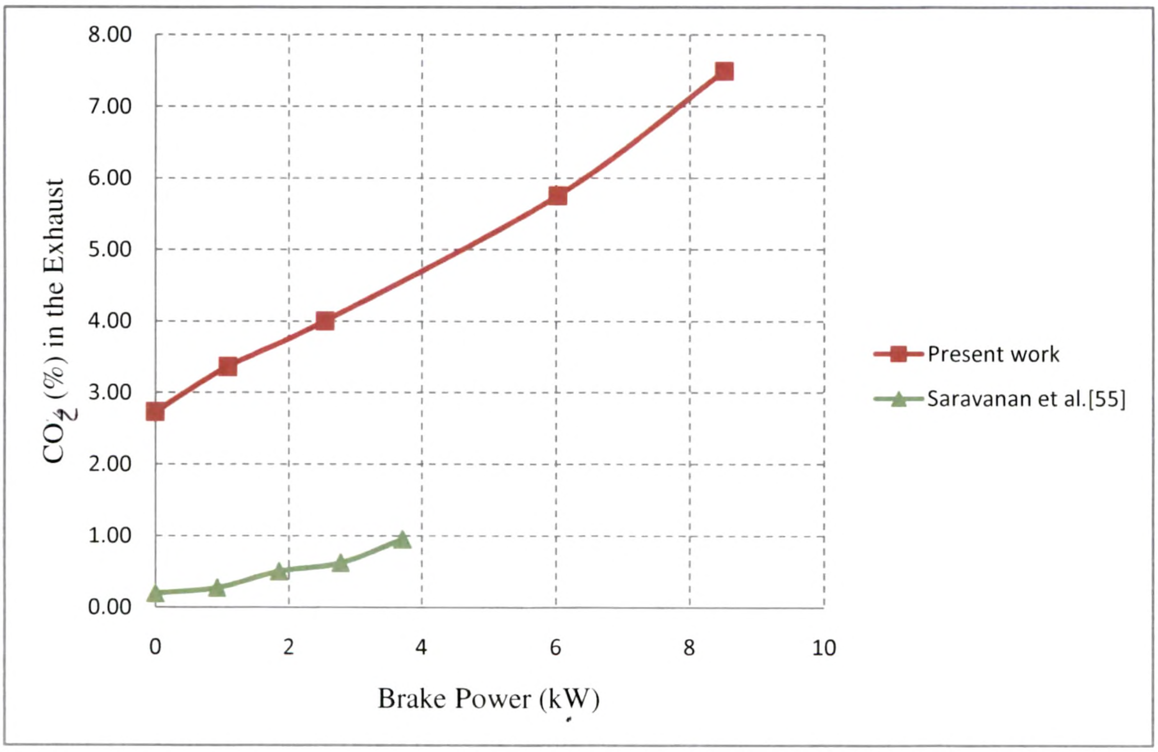


Fig. 3.130 Variation of Carbon Dioxide CO_2 (%) in the Exhaust with Brake Power for Present Work and Saravanan et al. [55]

- **Nitrogen Oxides (NO_x) in Exhaust**

Fig. 3.131 compares the variation of the content of nitrogen oxides NO_X (ppm) in the exhaust with brake power. Similar trend in the variation of NOX with brake power is seen for both the single cylinder engine of Saravanan et al. and the multi cylinder engine used in the present study. NO_X emission is found to be considerable less with the present system which may be mainly due to the less amount of oxygen available in the combustion chamber for the conversion in to NO_X

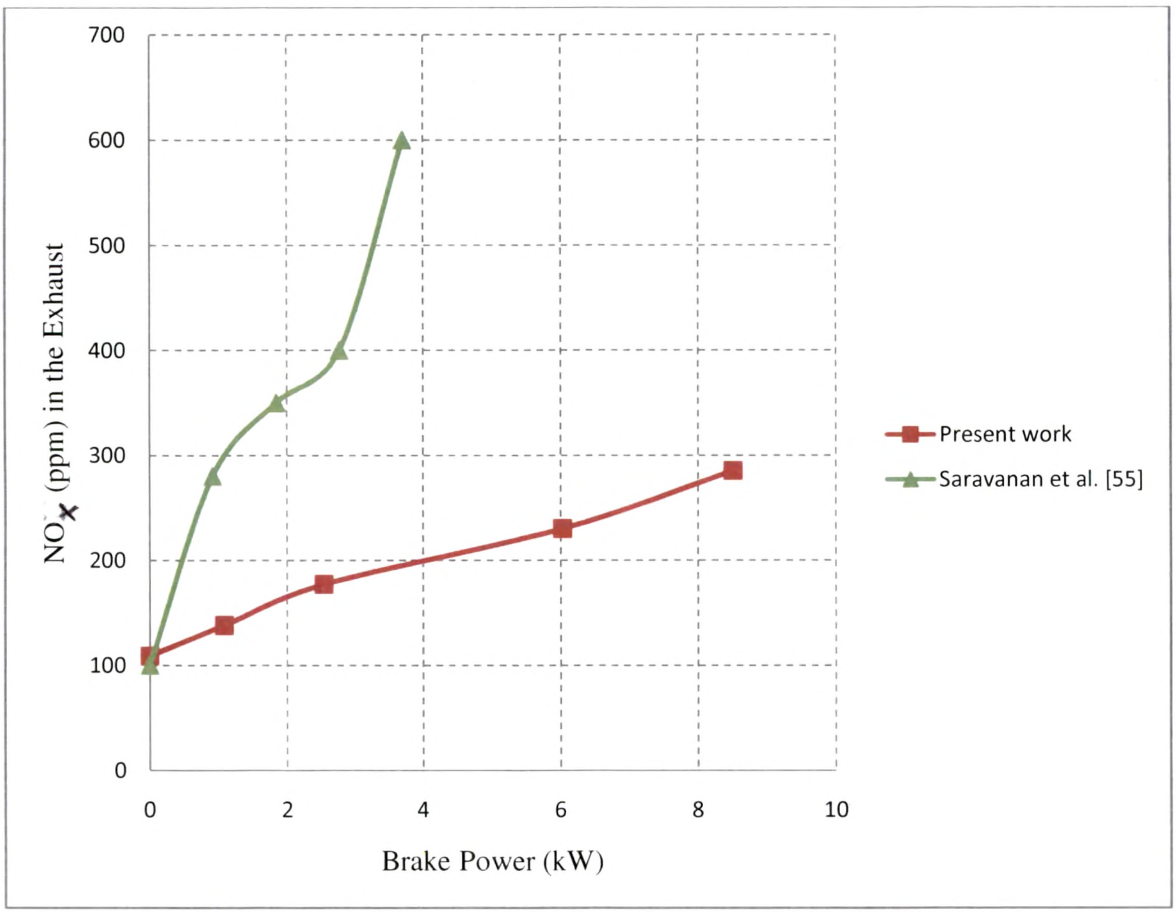


Fig. 3.131 Variation of Nitrogen Oxides NO_X (ppm) in the Exhaust with Brake Power for Present Work and Saravanan et al. [55]