Chapter – 2

Review of Literature

This chapter is devoted to a comprehensive review of the open research literature available on the development of compression ignition engine using diesel oil as fuel in general and subsequent development in diesel engine technology using hydrogen-diesel duel fuel in particular. The review of the literature is divided in to two groups, viz., literature during the period before 1970s as development before 'energy crisis' and the literature after 1970s as development after 'energy crisis'. The division in classifying the research literature based on the pre and post energy crisis is considered due to the identification of a distinct priority shift that had taken place in research interest due to the uncertainty prevailed in the availability of primary fuel from fossil sources, especially diesel oil from crude oil.

Section 2.1 deals with development before energy crisis and Section 2.2 gives various investigations carried out after energy crisis which includes various theoretical and experimental studies on the improvement in the existing compression ignition systems using various blends of fuels. The investigations carried out during the post energy crisis showed a marked interest in the development of alternative fuels that can partially or wholly replace the diesel fuel which is a conventional fossil fuel. In this context, the hydrogen-diesel duel fuel attracted the interest of many investigators. A detailed review on the progress of investigations on the thermal performance and pollutants emission of diesel engine is carried out in Section 2.2. Based on the review, a relatively unexplored area of research on hydrogen-diesel dual fuel is identified which includes both experimental and theoretical studies. Section 2.3 gives the scope of the proposed investigation based on the review of literature carried out and presented in Sections 2.1 and 2.2.

2.1 Investigations before 'Energy Crisis of 1970s'

The historical development of diesel engine and diesel fuel took place in latter part of nineteenth century. Thus the era of pre energy crisis spans between the latter part of nineteenth century and 1970s. In 1971, the world saw an unprecedented shortage in the availability crude oil (the primary source of energy) worldwide except in few oil producing nations. The "oil shock" of 1970s gave an impetus to researchers to look for alternative sources and their effective utilization in systems. It is therefore, worthwhile to divide the research literature with reference to pre and post energy crisis era. Therefore, this section deals only with the review of historical development of diesel engine technology since inception up to 1970.

2.1.1 Diesel Engine and Diesel Fuel

In 1878, Rudolf Diesel heard about the poor efficiency of the steam engine in a lecture on thermodynamics given by Carl Linde, the steam engine efficiency at the time was around 12 percent. During this time, he studied a theory by the French Military engineer Leonard Sadi Carnot, who conceived an ideal cyclic process which promised considerably higher energy efficiency in heat engines. The result of this was that Rudolph Diesel was prompted to develop a theory that revolutionized the engines of his day. He imagined an engine in which air is compressed in the cylinder such that there is a large rise in air temperature. When fuel, under pressure, was introduced into the piston chamber containing this air, the fuel was ignited by the high temperature of the air, causing it to ignite and thereby forcing the piston down. The piston force could then be converted via mechanical systems into useful work [1].

In February 1893, Rudolph Diesel was granted a patent, Patent No. 67207 "Working Method and Design for Combustion Engines". This, together with contracts from Frederick Krupp and Machinenfabrik Augsburg Nurnberg (MAN), Rudolf Diesel began the development and building of working models of an engine. As early as July 1893, a test engine was completed, which could however, not run under its own power. This failure resulted in continued development, and experimentation continued until February 1897, when the first model ran under its own power with 26 percent thermal efficiency; remarkably more than double the efficiency of the steam engines of that period [2]. Figs. 2.1 and 2.2 show the first diesel engine of the world and the diesel engine inventors and patent for the engine.

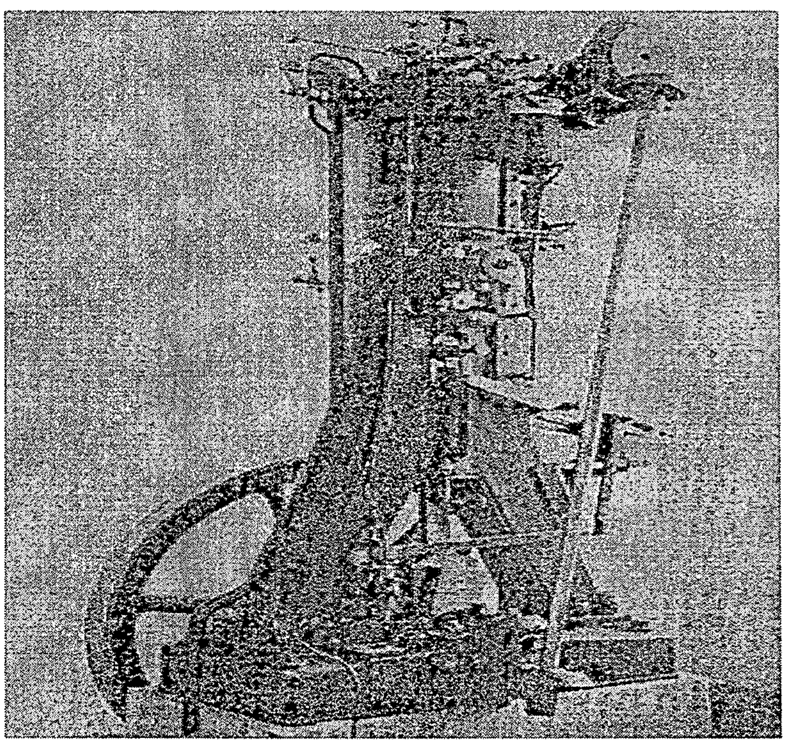
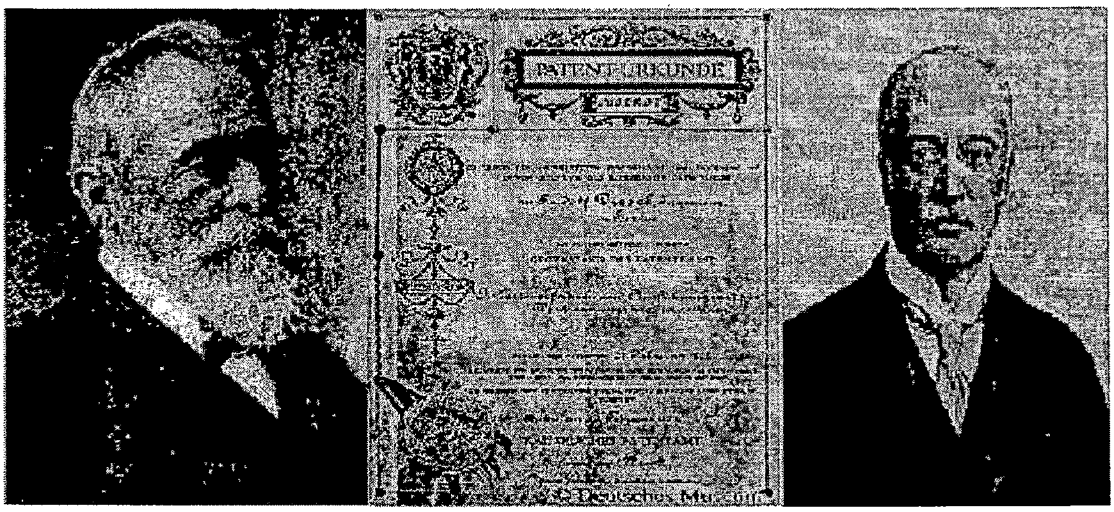


Fig. 2.1 First Diesel Engine in the World
(1893 by courtesy of MAN Co., Ltd.) [2]



a- Carl von Linde (1842-1934) ***b- German Patent No. 67207 of Diesel Engine in 1893*** ***c- Rudolf Christian Karl Diesel (1858-1913)***

Fig. 2.2 Diesel Engine Inventors and Patent

Although efficient, the engine was heavy in relation to its power output. The engine weighed 4,500 kg and had a power output of 15 kW. This is a specific weight of 300 kg/kW which was very poor in relation to modern diesel engines that had specific weights in the range 2.5 to 50 kg/kW. One reason for the high specific weight of the engine was the higher pressures that occur in the cylinder, which could only be controlled by a sturdier design. However, the main reason lay in the introduction of the fuel into the cylinder under high pressure. The only feasible method was to introduce fuel using pressurized air, and this was only possible with auxiliaries that were not only heavy but also part of the engine.

This high specific weight meant that practical diesel engines were only applied for stationary use. In the years 1910 to 1922, the stationary diesel engine continued to be used and improved upon and in 1922 Robert Bosch began the development of a fuel injection system for the diesel engine. By 1927, Robert Bosch finally had an acceptable fuel injection pump, leading to a massive improvement in the specific weight of diesel engines, thus opening the field of application to mobile use. The result of these efforts was a massive increase in the versatility of diesel engines in practical applications. Rudolf Diesel's theory and designs were not able to realize the efficiency levels of the Carnot cycle. However, the diesel engine remained the most economical practical thermal engine.

The majority of all land and sea freight, construction, mining, remote/standby power generation and military operational functions were accomplished using equipment powered by diesel engines. Modern diesel engines are highly efficient (35% to 50%) and are currently built to generate powers from less than 1 kW up to 80,000 kW. The diesel engine's versatility, efficiency and power range make it a workhorse throughout industry. Throughout the industrialized world, there is a massive conversion of fuel (chemical energy) into motive energy and electrical energy, and this is typically a significant cost to each economy. This cost is measured in terms of both economic and environmental impact. Due to these costs, there is a push towards more efficient use of energy [3].

2.1.2 Hydrogen as Alternative Fuel

Hydrogen (H_2) is a colorless and odorless gas at normal temperature and pressure. It is the lightest of all elements and is one of the chemical constituents of water. The importance of hydrogen as a vehicle fuel arises from the fact that it is combustible and that the products of combustion contain principally water vapor and only trace oxides of nitrogen as shown in Eqs. 2.1 and 2.2 respectively. The absence of oxides of carbon (carbon monoxide and carbon dioxide) and particulate matter (soot) in the tailpipe emissions from a hydrogen burning engine make it very attractive for use in internal combustion engines powering road vehicles. The combustible properties of hydrogen play a very important role when hydrogen is used in diesel engines.

$$2H_2 + O_2 \rightarrow 2H_2O \qquad 1.1$$

$$H_2 + XO_2 + 3.762\,X\,N_2 \rightarrow H_2O + 3.762X\,NO_X \qquad 1.2$$

Although hydrogen was prepared many years earlier, it was first recognized as a substance distinct from other flammable gases in 1766 by Henry Cavendish, who was credited with its discovery. However, it was named 'hydrogen' by A. L. Lavoisier in 1783.

An extensive historical background sketch of this development in hydrogen research was given by Clerk [4]. According to him, the first operating internal combustion engine in the world is believed to have been the hydrogen engine of the Rev. W. Cecil, M.A, fellow of Magdalen College, Cambridge, England [5]. A paper describing the engine was read at the meeting of the Cambridge Philosophical Society on 27 November, 1820 which was entitled "On the application of hydrogen gas to produce a moving power in machinery, with a description of an engine which is moved by the pressure of the atmosphere upon a vacuum caused by explosions of hydrogen gas and atmospheric air".

Interest in hydrogen was revived in 1920's, by which time the internal combustion engine had been developed to a large extent in its current form. Investigators of note were Ricardo and Burstall, who established that hydrogen could be used successfully as an engine fuel. Serious work on hydrogen vehicles began in the 1930s when Rudolph Erren converted over 1000 vehicles to hydrogen and hydrogen/gasoline operation in England and Germany. During the period of World Wars I and II, the priority changed and research efforts on hydrogen as fuel slackened. The resurgence of research and experimental activity came in the late 1960s and early 1970s as Japan, West German, and United States began funding hydrogen programs especially after the energy crisis which happened in 1971. Since 1974, the strongest hydrogen vehicle development efforts were in Japan and Germany [6-9]. As a summery to above historical research and development of hydrogen as alternative fuel can be divided in to two stages:

<u>1st stage (1817- 1900)</u>

- 1820, Cecil developed engine which used hydrogen as fuel.
- 1854, Bursanti and Matteucci used free piston type to burn hydrogen.
- 1856, Benini built a prototype hydrogen engine.
- Otto used hydrogen in his work with gaseous fuels.

<u>2nd stage (world war 1 and 2)</u>

- 1920, Erren built a direct hydrogen injection method to reduce the back fire.
- 1930, Erren and hastings Campbell wrote about, advantage, pollution, and fossil fuel consumption.
- 1940, Soviet Union built tanks used hydrogen as a fuel.

In spite of a long history of the research and development on hydrogen as an alternative option as fuel, a number of issues related to its use as a viable fuel in engines in general and diesel engine in particular remained unresolved. The use of hydrogen as a supplementary fuel in diesel engine has attracted investigator's attention during the latter part of twentieth century and continued till date. However, a number of issues related to substitution of hydrogen partially or wholly as fuel are yet to be resolved. The pollution, conventional fuel depletion and efficiency are important international community criteria in diesel engine research in general and the hydrogen – diesel research in particular. There are important hydrogen development programmes currently active in Europe, Canada, Russia, India, Japan and United States. The use of hydrogen in spark ignition, compression ignition and Wankel engines partially or wholly are being investigated. The use of hydrogen in fuel cell and hybrid engines are other important area of current research. Indian Institute Technology, Delhi is one of the academic institutes in India where studies related to hydrogen as a fuel and its applications are active since 1978. Since then, many premier institutions like I.I.Ts and Universities like Anna University, Chennai with the financial assistance from Ministry of Non-conventional Energy Sources, New Delhi are involved in hydrogen fuel technology.

2.2 Investigations after 'Energy Crisis of 1970s'

The oil shock of 1970s prompted many countries to revive the research activities to find viable alternative to substitute partially or wholly the primary fuel sources like crude oil. In this context, 'hydrogen research' gained considerable momentum. Section 2.2.1 reviews various experimental investigations reported since energy crisis of 1970s till date on various aspects of hydrogen supplementation. They include attempts to develop clean, green engine wholly run by hydrogen fuel for automobiles, hydrogen supplementation techniques for hydrogen diesel dual fuel systems, and other combination systems. Fig. 2.3 is a flow chart illustrating various alternative options.

The introduction of hydrogen in to a diesel engine partly to supplement the fuel or aid the fuel to perform better is an active area of research since 1970s. There are a number of such supplementing techniques developed and a number of investigations on the thermal performance and pollutant emission are carried out so far.

2.2.1 Experimental Investigations on Hydrogen Supplementation

Fig. 2.3 gives the various options available for the hydrogen supplementation in diesel engine to improve the performance and to control the pollutants emissions. Mainly, supplementing techniques may be divided into direct injection and indirect injection/induction.

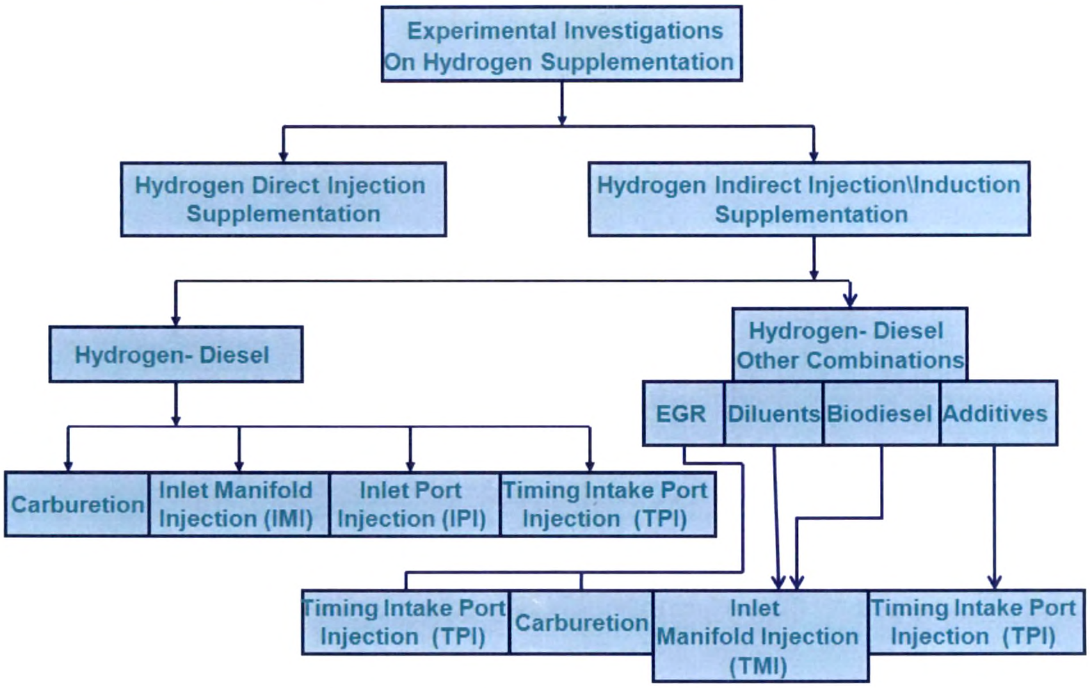


Fig. 2.3 Various Options of Hydrogen Supplementation Techniques Employed During Experimental Studies

In case of diesel engine, the hydrogen direct injection is carried out at the end of air compression and for this reason; the injection pressure for hydrogen is extremely high of the order of 60 bar and beyond. Indirect injection / induction techniques are employed on either hydrogen-diesel or hydrogen –diesel with other combination. Carburation, Inlet Manifold Injection (IMI), Inlet Port Injection (IPI) and Timing Port Injection (TPI) are the techniques of indirect injection/induction carried out on both of the above dual fuel engines. The injection/ induction pressure in the cases of indirect injection is moderate and just above the atmospheric pressure. The conventional methods of fuel injection techniques can also be applied to engine operation with a non-conventional alternative fuel, such as hydrogen. Of these methods; carburetion by the use of a gas carburetor has been the simplest and the oldest technique. Other combinations of supplementing technique include Exhaust Gas Re-circulation (EGR), addition of Diluents, Bio-diesel-Hydrogen-Diesel blends, etc. The essential points considered in these techniques are the safety, engine specification and desirable combustion parameters. H. B. Mathur and L. M. Das [10] reviewed research literature on the hydrogen supplementing techniques for spark and compression ignition engines.

2.2.1.1 Hydrogen Direct Injection Technique

Nowadays, hydrogen driven automobiles are on the roads of many countries. This is due to many research and development efforts of various investigators from universities, R&D institutions and most importantly from automobile manufacturing giants like BMW, Nissan, Ford etc. The collaborative efforts of these systems have successfully brought out "Green Automotives" which has a zero potential for toxic emissions unlike fossil fuel driven vehicles. One of the first studies carried out to develop hydrogen automobile engine since the post energy crisis of 1970 is due to S. Furuhama and his associates [11, 12, 15, 16, 18, 19, 29-31]. They investigated both direct and indirect injection techniques to come out with a practically viable hydrogen driven compression ignition engine.

Furuhama et al. [11] discussed some aspects of the technical problems associated with hydrogen fuelled internal combustion engines. They discussed the phenomena of abnormal combustion and presented a correlation between the abnormal combustion and NO_X formation. Elimination of these problems was accomplished after several engine modifications and by an experimentally-developed "combined combustion process". The characteristics of a hydrogen-oxygen engine with a hydrogen rich fuel mixture were also studied. Hydrogen equivalence ratio vs. volumetric efficiency, NO_X vs. access air ratio and P-V diagrams were plotted to show the abnormal combustion and NO_X generation. This engine was found to have an unexpectedly narrower range of operation than hydrogen – air engine. The developing of a "combined process" which uses pre-mixed hydrogen and air along with high pressure injection of pure hydrogen succeeded in lessening both abnormal combustion and NO_X emissions.

Furuhama [12] summarized has research efforts since 1970 in the field of hydrogen as a fuel in internal combustion engines. The following characteristics of the hydrogen fueled engine can be noticed:

- It is better in terms of exhaust gas emission control; i.e. they are nearly free of CO, HC, Soot, odor and CO_2 emission. NO_X emission of partial load is negligible.
- Owing to the ability of lean mixture combustion, the thermal efficiency is higher.
- The pumping loss is smaller since it is almost unnecessary to choke the intake air.

Homan et al. [13] investigated experimentally the feasibility of converting a diesel engine to hydrogen fueled operation without providing a timed ignition system. Use was made of a glow plug and a multiple-strike spark plug. The work was done with an ASTM-CFR engine, the diesel head of which was modified to resemble the geometry of a D399 series Caterpillar diesel engine. Engine speed was 1240 rpm. The glow plug was found to provide reliable ignition and smooth engine operation. It caused the hydrogen to ignite almost immediately upon the start of injection. Indicated mean effective pressures were on the order of 1.3 MPa for equivalence ratios Ø between 0.1 and 0.4 at a compression ratio of 18. This is significantly higher than the corresponding result obtained with diesel oil (about 0.6 MPa for $0.3 < Ø < 0.9$). Indicated thermal efficiencies were of the order of 0.4 for hydrogen and 0.2-0.25 for diesel oil. Operation with multiple-strike spark system yielded similar values for IMEP and efficiency, but gave rise to large cycle-to-cycle variations in the delay between beginning of injection and ignition. Large ignition delays were associated with large amplitude pressure waves in the combustion chamber. Figs. 2.4 and 2.5 show schematic diagrams of head of ASTM diesel engine and the modification in the cylinder head respectively.

The measured NO_X concentrations in the exhaust gas were of the order of 50-100 ppm. This was significantly higher than the corresponding results obtained with premixed hydrogen and air at low equivalence ratios. Compression ignition could not be achieved even at compression ratio of 29.

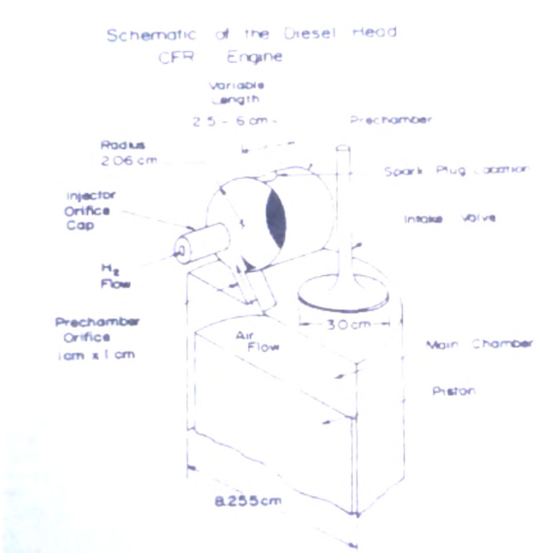


Fig. 2.4 Schematic Diagram of Diesel Head of ASTM CFR Engine [13]

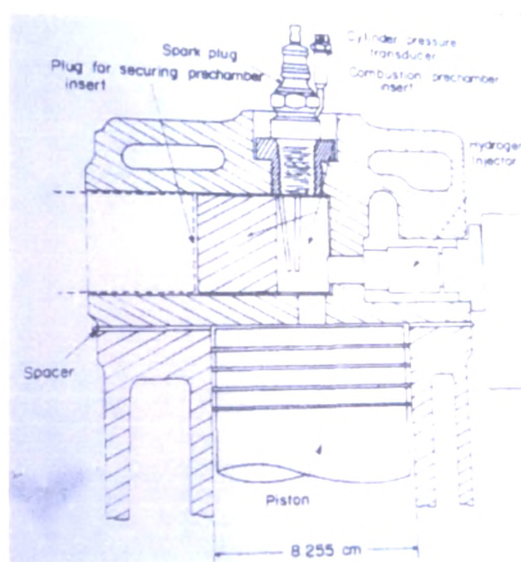


Fig. 2.5 Modified Head Configuration [13]

M. Ikegami et al. [14] investigated the possibility of establishing hydrogen fuelled compression ignition engine investigated experimentally by using a conventional swirl chamber diesel engine. Two different attempts were included, viz., one dealing with compression ignition on air-aspirated engine system, and the other with an engine operating with an argon-oxygen charge. In the former, the effect of preliminary fuelling was clarified in detail. They suggested that both pilot injection and fuel leakage from injector could aid ignition of the hydrogen fuel, brining about a smooth operation. Mechanism of stabilizing ignition from the viewpoint of thermal interactions between the engine cycles was discussed. In the latter attempt, a closed- cycle engine system was oriented and simulated by supplying 21% oxygen containing mixture to the test engine. The result indicated satisfactory ignition and engine operation without any ignition aid. A considerable gain had also been proved in thermal efficiency of using the argon mixture. Also, the practical feasibility of a closed- cycle compression ignition engine were also discussed.

S. Furuhama and Y. Kobayashi [15] developed a hydrogen car system consisting of a LH_2 tank, LH_2 pump injector to inject high pressure and low temperature hydrogen gas into a two stroke engine.

Fig. 2.6 shows direct injection hydrogen system for two stroke engine used in the car. The system was then applied to a mini car equipped with a 0.55 l engine. As a result of pressurizing the cold hydrogen gas by small LH_2 pump and injection it into the cylinders of two stroke engine immediately after closing the exhaust port. An increase in brake thermal efficiency and lower NO_X were obtained.

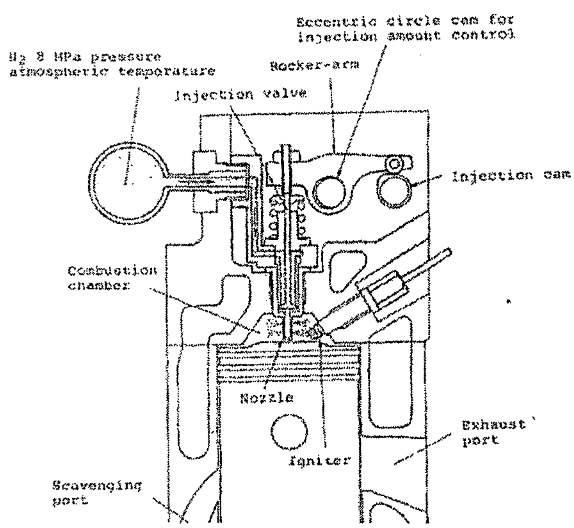


Fig. 2.6 Direct Injection System Developed for Two Stroke Engine [15]

Furuhama and Kobayashi [16] converted a 3-cylinder, 1100 cc two stroke gasoline engine into a hot surface ignition hydrogen injection diesel engine for a new hydrogen car named Musashi 5. This engine had a compression ratio of 12:1, and the high pressure hydrogen at 6 MPa was injected into an open combustion chamber near the TDC. In practice, it showed some problems in terms of the high pressure liquid hydrogen pump, the hot surface ignition and efficient combustion. Efforts were made to solve the problems, and the results were as follows: (i) a high pressure pump was obtained through the precise finish on the sliding surfaces of the barrel and plunger, and by the combination of appropriate material and dimensions; (ii) a gentle diesel ignition was attained by blowing hydrogen gas onto the platinum wire at 1000°C from a close location, and (iii) the mixture formation was improved, and the maximum power equivalent to 125% of gasoline was obtained by a proper selection of combustion chamber shape, number of injection nozzles, direction of injection, etc.

K. S. Varde and G. A. Frame [17] designed and developed a high-pressure hydrogen injector which was hydraulically operated by a separate pump. Measurement of injection characteristics on a bench stand showed repetitive performance of the injector. The injection system was used to supply hydrogen fuel to a single-cylinder spark ignition engine. Results of the tests showed that the engine performance was superior to that achieved with carbureted gasoline fuel.

S. Furuhama and T. Fukuma [18] developed a high power two stroke H_2 diesel turbo engine. This engine was made capable of high power output by the following method. The liquid H_2 stored in the LH_2-tank was pressurized by a well designed pump and was directly injected into combustion chamber. The H_2 was ignited on the hot surface and with the aid of turbocharger; the engine was able to produce high power output. They concluded that the hot surface ignition hydrogen diesel engine with a turbocharger has advantages such as, the improvement in the mixture formation of injected hydrogen and air got after a modification to the shape of combustion chamber and injection nozzle. After the modification, the output power improved. The choice of hot wire position led to an improvement in durability and electricity consumption. The exhaust manifold was altered to the blow down system, which made high output performance possible by utilizing a turbocharger. The maximum torque of this engine at 2000 rpm was 50% higher than that of a not applicable hot surface ignition engine and twice as high as that of a not applicable four stroke gasoline spark ignition engine.

The modified of LH_2 pump for obtaining high pressure hydrogen meant the plunger was fixed and the barrel could reciprocate. As a result, the thickness of the reciprocating rod could be reduced and thus the heat inflow to the tank became smaller. Fig. 2.7 shows this system of injection.

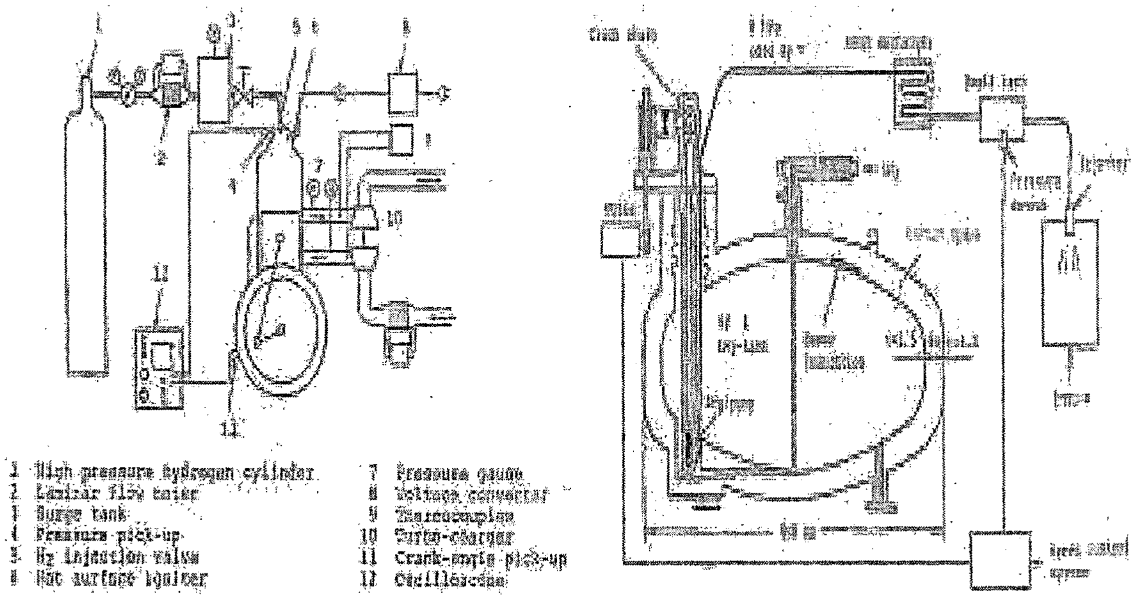


Fig. 2.7 Injection Set Up and LH_2 Tank Location [18]

Based on the investigations spanning about 20 years, **Furuhama** [19] proposed two systems for hydrogen fuel engine for land vehicles. They were (i) a substitute for gasoline engine in which LH_2 tank was pressurized by evaporated H_2 gas with its inner pressure at 1 MPa, and LH_2 was delivered from bottom of the tank. Cold hydrogen (about -30°C) was injected at 1 MPa into the cylinder during the first half of the compression stroke, and then it was ignited by a spark. Its maximum power to be attained was 10-20% more than that of gasoline engine, and its thermal efficiency under the partial load became higher than the gasoline engine because of lean combustion, and (ii) a substitute for diesel engine which included system LH_2 tank at low pressure, LH_2 pump for high pressure injection and spark igniter. The high pressure hydrogen injector principle is shown in Fig. 2.8. He concluded and recommended that the maximum output was the same as that of a gasoline engine, the optimum compression ratio of 12:1 which was determined by considering performance, vibration and NO_X, was also applicable. They further proposed to develop a high pressure hydrogen expander for obtaining useful power and cold hydrogen. According to them, for a successful development of practical hydrogen engine, further research and development efforts must be carried out on cryogenic systems.

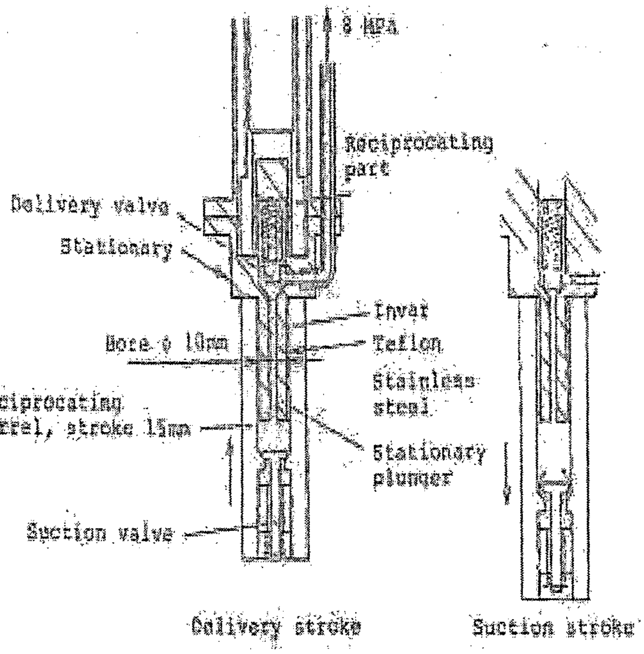


Fig. 2.8 High Pressure Injector Hydrogen System [19]

Wong [20] investigated experimentally the using of hydrogen as a sole fuel in a direct injection diesel engine. A compression ignition engine cooled by air and made by Lister STI was modified to operate as a low heat rejection engine for this study. Using a compression ratio of 17.9:1 and running the test engine at 2100 rpm, a maximum compression temperature of approximately 900 K was achieved. Under these operating conditions, all lubricants tested were found to burn. Lowering the speed to 1450 rpm and the compression ratio to 17.1:1, lubricant combustion and hot spots were successfully eliminated. The maximum compression temperature, when compression ignition of hydrogen was tried, was in the 800 K range. The corresponding ceramic surface temperature was estimated to reach 600-700 K. Only sporadic compression ignition of hydrogen was achieved. He concluded that use of hydrogen as a sole fuel in direct injection without an ignition source diesel engine is not practical or feasible.

Yi et al. [21] tested the in-cylinder direct injection method by using a solenoid valve which was fabricated and designed and installed on single cylinder research engine. The experimental work was performed to compare the performance and the emission characteristics between the intake port injection type and in-cylinder injection type with variation of fuel-air equivalence ratio. The effects of spark timing on the in-cylinder injection type hydrogen engine were also investigated in these experiments. They described in detail all the description of solenoid valve and technical specifications. The relation between volumetric efficiency, brake mean effective pressure and coefficient of variation in indicated mean effective pressure COV_{IMEP} vs. air-fuel equivalence ratio were plotted. As well as, the relations of cylinder pressure, IMEP, mass fraction burned vs. crank angle plotted. IMEP, NO concentration vs. spark timing were plotted. They concluded that the most distinct differences of the intake port injection type over in-cylinder injection type were the enhanced volumetric efficiency of the in-cylinder injection type at high load, the higher engine output and higher level of NO emissions at stoichiometry. The performance of the in-cylinder injection type is superior to the intake port injection type as the fuel-air equivalence ratio goes to stoichiometry.

Dorer et al. [22] investigated experimentally mixture formation, the ignition and burning processes in two different experimental setups. Experiments were conducted to get information about the highly transient concentration distribution of hydrogen during the injection process. The experimental techniques used were an application of Laser-Induced Fluorescence (LIF) on tracer molecules and the Schlieren/Schatten method. For this purpose, a combustion chamber with equivalent dimensions to the planned ship C.I. engine, having a diameter of 240 mm and a volume which represents the volume in the cylinder at top dead center were designed. This chamber had a maximum of five windows, one at the bottom and four around the diameter, to give an optimal optical access for laser measurements. The pressurized hydrogen was injected into the cold compressed air through a hydraulic controlled needle valve. The experiments results were used to optimize the injection system that is the number and position of the injection holes and also the injection direction.

The second setup was a single stroke rapid compression machine called EET which simulates the compression stroke of the planned ship C.I. engine. It had an optical accessible combustion chamber and a moving piston with a quartz window. The machine had balanced masses, and allowed the observation of the compression stroke with realistic piston velocities with sensitive optical measurement techniques. It had a cylinder capacity of ~~14l.~~ 1.41. A compression end pressure up to 150 bar and a maximum combustion pressure up to 200 bar. The design of this setup allowed a fast variation of experimental parameters, which means any compression ratios up to 25 could be adjusted. Swirl and turbulence in the combustion chamber could be induced through tangential inlets. Simple variation of experimental parameters like boost pressure, compression ratio, injection time, injection duration and nozzle geometry allowed fast and effective examination of various boundary conditions. A simulation part of this work is discussed Section 2.2.2.1.

They concluded that the developed experimental setups and the numerical simulations allowed a detailed analysis of the mixture formation and of the combustion processes in a combustion ignition engine. Using the experimental setup, comparisons of different combustion concepts were carried out. The results gave immediate references for the improvement of nozzle layouts and combustion parameters. The experiments also showed that the compression ignition with direct injection of hydrogen could be reached. The ignition delay depended on the compression ratio. With higher compression ratio a full-proof ignition could be realized. An injection of hydrogen near T.D.C. should be reached to avoid a good hydrogen-air mixture before the temperature for self ignition has arrived. If this cannot be achieved, a hard combustion or detonation would be the result.

Prechtl et al. [23] studied experimentally the use of hydrogen in diesel engine by using a rapid compression machine (RCM) and large bore, four stroke engine. They used optical technique to analyze the combustion and ignition inside combustion chamber. By using high speed video camera and RCM and varying the nozzle geometry, injection timing, compression ratio, swirl and turbulence, investigations were carried out and captured photo images of inside of the combustion chamber to show the progress of combustion and flame with time in millisecond at different operation condition when the hydrogen was injection directly. Pressure with time was also plotted to show the pre ignition or abnormal combustion due to hydrogen pre ignition. The time lead to estimate the turbulence of flame and comparison with speeds of flame at varied rate of injection and pressure and proportion were recorded. High pressure injection system allowed a detailed analysis of all relevant processes and had different ignition delays. The auto-ignition of hydrogen was observed. High pressures and temperatures had a positive influence on a short ignition delay. Turbulences and swirls support the propagation of the flame over the whole combustion chamber and regulate the combustion for smoother pressure rates.

Prechtl et al. [24] tested a large-bore, four-stroke engine, with high pressure injection and compression ignition, running with hydrogen, is a modern concept for clean energy conversion without CO_2 emission. The key processes for reliable engine operation are a good mixture formation, a reliable ignition and efficient combustion. The investigations of these processes were carried out in a rapid compression machine, with modern optical measurement techniques. In a first phase, the experiments were carried out in the RCM by varying of the compression ratio, the load pressure and the flow condition (variation of the swirl and the turbulence). The compression ratio reached a value up to 22, and the compression end pressure was between 5 and 11 MPa. The temperature reached values over 950 K. The hydrogen was injected with a pressure between 25 and 33 MPa, and maximum injection duration of 15 ms. In the next step, the influence of the injector geometry was analyzed. For these experiments nozzles with hole number of 6 up to 24 and a slot nozzle with nearly equivalent cross-sections were manufactured. These measurements were carried out under the same pressure conditions. They concluded that, high pressures and temperatures have a positive influence on a short ignition delay. Turbulence and swirl support the propagation of the flame over the whole combustion chamber and regulate the combustion for smoother pressure rates.

Combined nozzles containing 18 bores with different diameters seem to be the best injection geometry for small variations of the ignition delay and of the pressure. However, the current ignition behavior of hydrogen in a C.I. engines without ignition sources is not applicable yet. Therefore it still requires further improvement for a smooth and safe engine operation. Modern injection concepts with their possibilities of pilot-injection and slow-opening rates offer additional options for improvement. However, further ignition sources for hydrogen under late internal mixing conditions have to be considered and should be investigated.

Naber and Siebers [25] investigated the auto ignition and combustion of hydrogen in a constant volume combustion vessel under simulated direct injection (DI) diesel engine conditions. The parameters varied in the investigation included the injection pressure and temperature, the orifice diameter, and the ambient gas pressure, temperature and composition. The results showed that the ignition delay of hydrogen under DI diesel conditions has a strong Arrhenius dependence on temperature; however, the dependence on the other parameters examined was small. For gas densities typical of top dead center TDC in diesel engines, ignition delays of less than 1.0 ms were obtained for gas temperatures greater than 1120 K with oxygen concentrations as low as 5% (by volume). These data confirmed that compression ignition of hydrogen is possible in a diesel engine at reasonable TDC conditions. In addition, the results showed that DI hydrogen combustion rates are insensitive to reduced oxygen concentration and are significant because it offered the potential for a dramatic reduction in the emission of nitric oxides from a compression ignited DI hydrogen engine through use of exhaust gas recirculation.

Verhelst and Sierens [26] converted a GM/Crusader V8 SI engine for hydrogen use, to be built in a city bus. The first tests were carried out with an external mixture formation system (Venturi type) for natural gas, hydrogen and hythane. A sequential timed multipoint injection system was implemented and the corresponding electronic management system, the necessary power output of the engine in order to drive a city bus was reached, without danger of backfire. Attention was directed towards special characteristics related to the use of hydrogen as a fuel in IC engines, viz. ignition properties (smaller spark plug gap), injection pressure (dependent on the means of storage: compressed gas or liquid), the deterioration of the lubricating oil (due to higher blow- by volumes, a substantial amount of hydrogen was present in crankcase), addition calibration of oxygen sensors (very lean operating conditions) and the advantage of lean mixtures to operate at low load conditions without a throttle valve. The disadvantage was found to be that of increased hydrogen concentration in the exhaust gases at idling. A power regulation by charging the air to fuel ratio (as for diesel engines), as compared to throttle regulation (SI engines) were judged.

Huang et al. [27] investigated experimentally the combustion characteristics under various injection timings of a direct-injection engine fueled with natural gas-hydrogen blends at fixed injection duration and fixed ignition timing. They study showed that early injection decreased the excessive-air ratio and makes leaner mixtures. The brake mean effective pressure increased with the advancement of fuel-injection timings. The brake mean effective pressure reached a maximum value at an injection timing of 190 °CA BTDC and maintained this maximum value with the further advancement of fuel-injection timings. For specific injection timing, an increase in the hydrogen fraction decreased the brake mean effective pressure when the hydrogen fraction was less than 10%, whereas the brake mean effective pressure tended to increase when the hydrogen fraction was larger than 10%. Combustion durations decreased with the advancement of fuel-injection timing. When the hydrogen fraction was less than 10%, combustion durations increased with increasing hydrogen fractions; conversely, combustion durations decreased with increasing hydrogen fractions when the hydrogen fraction was larger than 10%. The amounts of NOx and CO_2 increased with advancing fuel-injection timing, and the CO concentration experienced small variations under various fuel-injection timings. The addition of hydrogen in natural gas can reduce the CO_2 concentration.

Masood et al. [28] tested interfaced single cylinder diesel engine with variable compression ratio (16.35, 18.35, 20, 22 and 24.5), compression ignition engine to optimize the performance characteristics and to find the useful higher compression ratio (UHCR) with hydrogen- diesel dual fuel mode. They used direct injection technique to inject the hydrogen inside combustion chamber via suitable injector previously used to inject the natural gas in engine. This technique allowed substituting the type of fuel to be 100% of hydrogen. So, they replaced the conventional diesel oil at (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% by volume) simultaneously with hydrogen. For these blends all engine thermal performance and exhaust emission were studied. Experimentations were conducted on five different compression ratios and the performance characteristics were calculated. The effect of blending on NO_X, HC, CO and particulate matter were measured, reported and plotted. The rate of heat release and speed of combustion with increase in compression ratio with simultaneous increase in hydrogen substitution were measured. Intake temperature of air was increased and for three different temperature 65, 75 and 85°C. The effect of increase in temperature of air-hydrogen mixture on NO_X was studied. They drew the following conclusions based on this experimental investigation, the brake thermal efficiency was increased with the increasing percentage of hydrogen for all the compression ratios. Hydrogen performed better at high compression ratios. CO, HC and particulate matter continuously decreased with the increase in hydrogen percentage for all compression ratios and loads while NO_X was increased. The heat release and peak pressure were maximum at 24.5 compression ratio and 100% hydrogen. Further, it was found that, there was a sharp increase in the NO_X value as the inlet temperature was increased from 65 to 85 °C.

2.2.1.2 Hydrogen Indirect Injection / Induction Techniques

Furuhama [12] summarized his research efforts since 1970 in the field of hydrogen as a fuel in internal combustion engines. During that time, the first hydrogen car was developed. Furuhama and his team participated in the student engineered economy design (SEED) rally held for 5 days during August 1975 on the west coast of the United States, and succeeded in the completion of the race which covered approximately 2800 km in a sub-compact passenger car equipped with four stroke engine and liquid hydrogen (-235°C) storage tank. The engine of this car was modified as shown in Fig. 2.9.

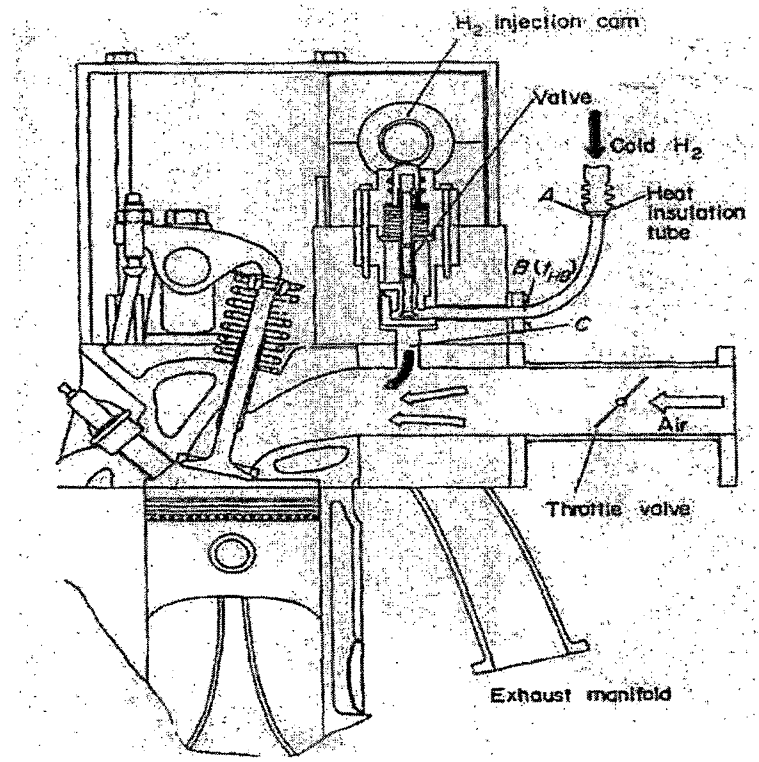


Fig. 2.9 Four Stroke Engine Used Intake Injection Port Technique [12]

The four stroke engine was converted using premixed hydrogen injected in the intake port. During the running of the system under high load or during idling, it was found that flash back in the intake manifold through which premixed hydrogen was injected. **Furuhama et al.** [29-31] explained more details about the modification of this car and its performance and emission under different hydrogen injection scenario. Fig. 2.10 shows the first hydrogen car design.

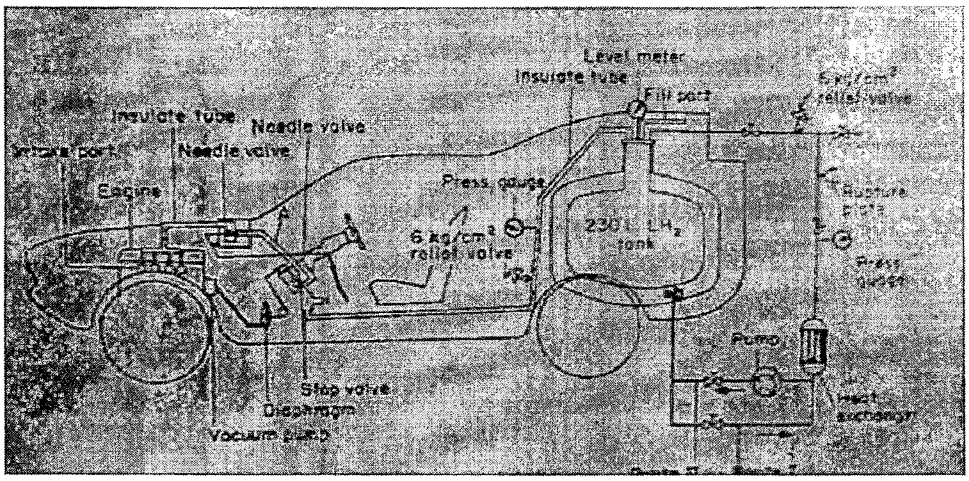


Fig 2.10 Furuhama's Hydrogen Car Used Intake Port Injection Technique [12]

Haragopala Rao et al. [32] inducted the hydrogen as substitute fuel into the cylinder through the intake manifold along with intake air and a small quantity of diesel fuel was injected at the end of compression to initiate the ignition. For the effective utilization of substitute fuels, it was necessary to have a clear understanding of the manner in which the substitute fuel burns in the cylinder along with injected diesel fuel. They found, the maximum proportion of substitute fuel that could be inducted depends on its self ignition temperature and oxidation characteristics. Alcohols, with their evaporate cooling characteristics; permit large substitution of diesel fuel. Fig. 2.11 shows some of this investigation results.

Haragopala Rao et al. [33] carried out experiments to burn hydrogen in compression ignition that were operated on a dual fuel principle. Hydrogen was supplied along with intake air in small proportions and ignition was initiated by injection diesel fuel in the conventional manner. For testing, they used a single cylinder compression ignition engine was operated throughout its load range inducing small proportion of hydrogen in intake air. They used the intake manifold to inject that amount of hydrogen which resulted in the increase of thermal efficiency at full load, a reduction in exhaust temperature and an increase in maximum cylinder pressure. Nitrogen oxides in the exhaust were observed to increase though the hydrocarbon emissions reduced as expected. Also, they tested flame speed in separate vessel to study the effect of adding a hydrocarbon to hydrogen-air mixture on the flame propagation velocities. The effect of increasing the proportion of hydrogen in the hydrogen-hydrocarbon-air mixture was observed to increase the flame propagation velocity.

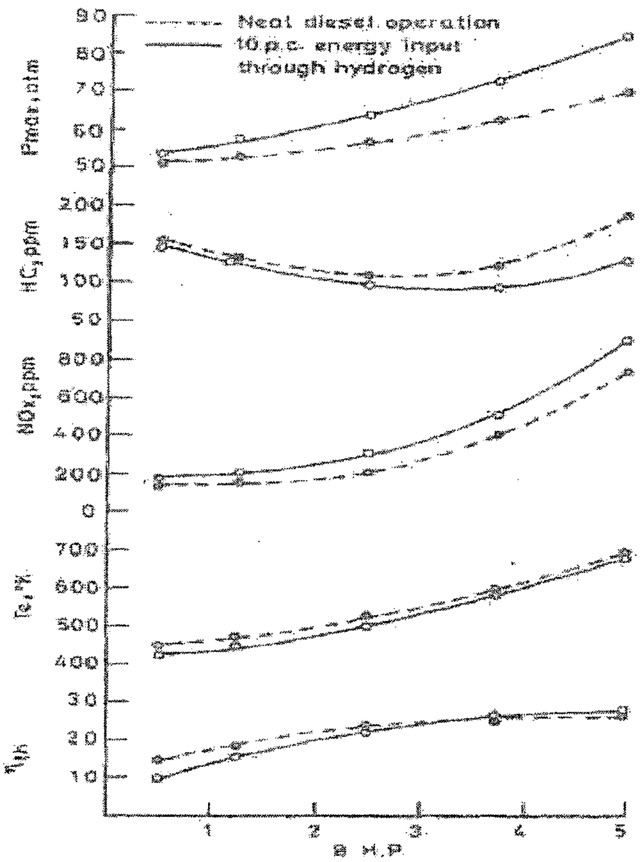


Fig. 2.11 Experimental Results for Indirect Manifold Induction of Hydrogen [32]

Varde and Frame [34] studied experimentally, the effect of small quantity of hydrogen induction on the formation of soot in single cylinder diesel engine. The induction of hydrogen caused less proportion of soot for many reasons. High temperature inside combustion chamber led to burned some of soot. And, as a clean fuel produce only H_2O soot proportion decreased when hydrogen burned. Then, hydrogen might work in lean mixture. Experimental evidence indicates that oxygen, in sufficient quantity, suppresses soot formation. They plotted the relations of brake thermal efficiency, peak pressure, noise, NO_X, HC, and soot against the ratio of hydrogen energy to total energy consumption at full load and 85% load of engine. The injection of conventional diesel fuel stayed constant at 22° BTDC. They concluded that a small quantity of hydrogen when induced in diesel engine manifold caused to improve the brake thermal efficiency, decreased the soot and HC but increased the NO_X ratio.

Varde and Frame [35] studied experimentally, the use of electronic hydrogen fuel injection in the intake manifold of a single cylinder spark-ignition engine. The purpose of the study was to investigate cyclic variations and backfiring and to determine if timed manifold injection provides any advantages over hydrogen carburation. It was found that injection improved cyclic pressure variations and practical lean operating range. A small improvement in thermal efficiency was also observed in the lean region. Based on limited work using timed port injection, it seemed that backfiring could be controlled.

Jin-Ding et al. [36] tested experimentally the hydrogen-gasoline, hydrogen- diesel oil mixtures in the engine to improve the combustion process. They studied the smoke and peak pressure at varied hydrogen proportions and different engine speed. By plotting the relation of peak pressure, smoke emissions and brake thermal efficiency they concluded that, an increase in the compression ratio brings about wider back fire-free range of engine output, an increase in thermal efficiency, and reduction in the temperature of exhaust gases. The use of gasoline – hydrogen mixed fuels widens the ignition limits of mixture and rapid burning of lean mixtures, and results in an improvement both in efficiency and in emissions of the engine. Smoke can be reduced by using diesel oil-hydrogen mixed fuels (rather than oil alone). Under low speed high load conditions the results were better.

Prabhukumar et al. [37] represented one solution to the output power limitation of a hydrogen-diesel dual-fuel engine by the onset of knock as the percentage of heat input derived from hydrogen increases beyond a certain limit. Earlier work carried out indicates that this knock sets in when the inducted hydrogen exceeds about 60% of input energy at a pilot diesel quantity of 30% of full load diesel amount. At higher rates of hydrogen induction, the richer hydrogen-air mixture is more prone to knocking. Hardly any information was available on the possibilities of improving the knock limited power output of a hydrogen-diesel dual-fuel engine. Water could serve as a powerful internal coolant in decreasing the unburned mixture temperature because of its high latent heat. They presented the results of the experimental investigation on improving the knock limited power output when water is inducted with the intake charge of a hydrogen-diesel dual-fuel engine, The change in the combustion characteristics were also reported.

Lambe and Watson [38] did experimental work as well as modeling work. A diesel engine was converted to dual fuel hydrogen operation, ignition being started by a pilot quantity of diesel fuel, but 65-90% of the energy was supplied as hydrogen. Delayed port admission of the gas, later injection timing and modified combustion chamber allowed 15%

increase in efficiency. A solid water injection technique was employed to curb knock under full load conditions when the power output equaled or exceed that of the engine with diesel fuel alone. The indicator diagrams under these conditions closely approach those of the Otto cycle. The green house gases were shown to be reduced by more than 80%, nitrogen oxides by up to 70%, and exhaust smoke by nearly 80%. These single cylinder engine test results and application of vehicle simulation model allow forecasts to be made of the on-road performance of a converted diesel engine. Small energy gains were predicated with substantial reduction in emissions under urban and highway driving conditions. Fig. 2.12 shows the intake port injection setup.

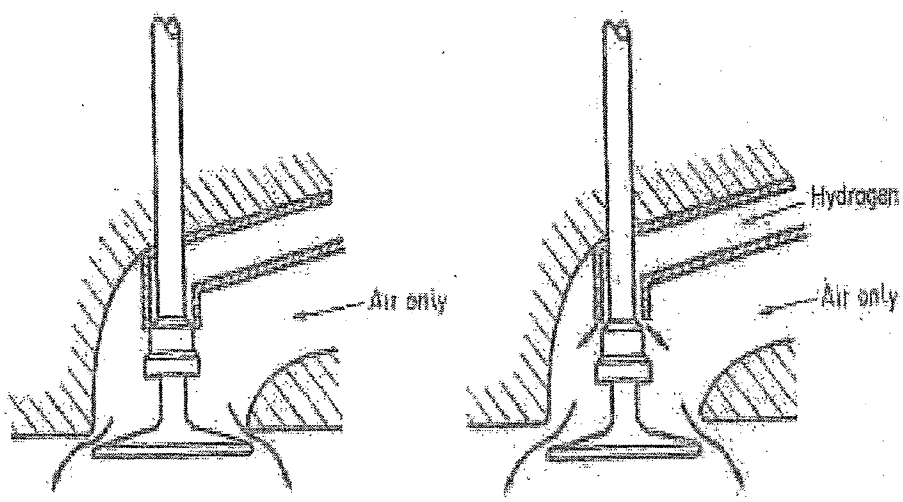


Fig. 2.12 Intake Port Injection Set-up [38]

Lee et al. [39] carried out experimental tests on the intake port injection method by constructed and installed injection system on the intake port of single cylinder engine prior to the development of in-cylinder using a solenoid as the driving source of injection valve. To minimize the possibility of flash back occurrence, injection timing of the hydrogen injection valve was set within the duration of intake valve opening. The hydrogen was supplied while the intake valve was kept opened so that as much hydrogen quantity as possible could be injected into the combustion chamber. Within this system, combustion characteristics of hydrogen combustion in the internal combustion engine were investigated and flash back phenomena were also studied by measuring the intake and exhaust pressures simultaneously. Cylinder pressure, brake mean effective pressure were plotted with respect to crank angle and equivalence ratio respectively. With the hydrogen supply system adopting a solenoid driven valve, the engine was operated successfully and the amount of hydrogen supplied could be controlled very easy by changing the duration of the solenoid driving signal. But severe flash back was observed near stoichiometric fuel –air equivalence ratio. The case of flash-back is thought to be a hot spot, such as lubricant deposit or spark plug rather than the high temperature residual gas itself.

Yi et al. [40] designed hydrogen fuel supply system and investigated it experimentally. The intake port injection and in-cylinder injection methods were tested and compared in single cylinder special research engine. The effect of mixture formation on the performance of hydrogen-fuelled engines was tested. The equivalence ratio was changed by changing the amount of air that entered the engine at fix load. The relations of indicated mean effective pressure IMEP indicated thermal efficiency, unburned H_2 concentration, Coefficient of variation in indicated mean effective pressure COV_{IMEP} and thermal efficiency with respect to fuel-air ratio were plotted and discussed. Indicated thermal efficiency and Coefficient of variation in indicated mean effective pressure were plotted vs. IMEP and discussed. Brake thermal efficiency and COV_{IMEP} with respect to port injection ratio were also discussed. They concluded that in-cylinder injection method can satisfy the high load condition without abnormal combustion. The thermal efficiency and engine operation stability are superior with the intake port injection at low load region.

Tomita et al. [41] studied the effects of injection timing, ignition delay and ignition for different gaseous mixture experimentally. The gaseous fuel of propane, methane and hydrogen mixed with air was studied. The ignition delay affected the initial combustion and the following combustion process and exhaust emissions. These gases were inducted into the cylinder and light oil was injected in the cylinder as ignition source. When methane or propane was mixed with intake air, the ignition delay became long because the temperature of compressed gas decreased due to the decrease in the ratio of specific heats. When hydrogen was mixed with air, ignition delay became long because molar concentration of oxygen decreased. The concept of Livengood- Wu can be applied to the combustion in dual fuel engines by changing the value of a constant A. In these kinds of dual fuel engine, the fluctuation of the ignition timing occured due to the oxidation of thermal mixture near the TDC at retarded injection timing.

Tomita et al. [42] investigated hydrogen induction in intake port of diesel engine and ignited it with diesel oil that is injected into the engine cylinder. The study is a continuation of their previous work on ignition delay of diesel oil injection into the mixture of air and gaseous fuel (propane, methane or hydrogen). The injection timing was changed within a very wide range including extremely early injection timing. The heat release rate was obtained from the pressure in the cylinder and exhaust emissions. Including smoke, the nitrogen oxide NO_X, hydrocarbon HC, CO and CO_2 were measured. The relations between heat release rate and exhaust emissions were discussed. This study focuses on the very low exhaust emissions when the injection timing was extremely advanced although these problems may remain. They concluded that the maximum value and gradient of the heat release rate are smaller in general than those in ordinary diesel combustion. The ignition delay increased when hydrogen is inducted from the intake manifold. This was mainly because the mole fraction of hydrogen was so large that oxygen in the intake air was reduced. When the injection timing of diesel oil into the cylinder was extremely advanced, the diesel oil was well mixed with air or hydrogen-air mixture and the initial combustion became mild. NO_X emissions decreased because lean premixed combustion without the region of high temperature of burned gas such as seen in ordinary diesel operations.

Stefaan et al. [43] conducted experimental study on a single cylinder research engine in order to critically assess the emission potential of alternative fuels. Hydrogen and methane were compared in terms of power production, fuel consumption and emissions. The engine parameters (ignition timing, injection start and duration) were optimized for each fuel. It was shown that the internal combustion engine, particularly the spark ignition engine, was very suitable for the use of hydrogen as a fuel. One has to take into account the hydrogen specific combustion properties. Some of these properties were advantageous like the wide flammability range (omitting throttle), high burning velocity (efficiency), high auto ignition temperature (compression ratio) and high diffusivity (mixture formation and safety). Other properties involved some difficulties like low ignition energy caused pre-ignition and backfire, small quenching distance caused power loss and storage problems. The purpose was to make the most of the 'good' properties and to conquer the drawbacks caused by the undesirable characteristics of hydrogen. Particularly, measures were to be taken to prevent the early occurrence of pre-ignition or backfire.

Milen and Kiril [44] carried out experiments to evaluate the influence of the addition of hydrogen – oxygen mixture (obtained from electro chemically decomposed water) to the inlet air of a single cylinder direct injection diesel engine. Addition of hydrogen to the intake or delivery into the cylinder of diesel engine could improve combustion process due to superior combustion characteristics of hydrogen in comparison to conventional diesel fuels. The paper described the dynamometer tests results of a study where a small amount of hydrogen – oxygen mixture, produced by hydrogen – oxygen generator was added to the intake of a diesel engine.

Saravanan et al. [45] investigated experimentally, a diesel engine using hydrogen as fuel with diesel as an ignition source of hydrogen. Hydrogen was injected into intake port, while diesel was injected directly inside the cylinder. They used timing port injection system (TPI) to inject the hydrogen in the intake port with specified time and period. The parameters such as injection timing and injection duration of hydrogen were varied for a wider range at constant injection timing of 23^{0} before injection top dead center (BITDC) for diesel. The hydrogen flow rate was kept constant at 10 l/min for varied load conditions. For each time of injection and duration of injection of hydrogen, the relation between specific energy consumption, brake thermal efficiency, NO_X concentration, HC, smoke, CO, CO_2 and peak pressure with varied load were plotted. They optimized injection time as well as the duration period. They concluded that an injection duration of 90 crank angle and start of injection at 5^{0} ATDC gave the best results both performance and emission wise. The smoke emission reduced from 6.8 BSN to 2.3 BSN and NO_X emission decreased from 1806 to 888 ppm at full load. Hence simultaneous reduction of NO_X and smoke was possible using hydrogen in the duel fuel mode. Brake thermal efficiency increased from 23.59% to 29% at optimized conditions. The emissions such as CO, CO_2 and HC reduced significantly with negligible concentrations. In this paper, the pressure variation showed that due to hydrogen fuelled operation the peak pressure increased but with proper injection timing and injection duration the peak pressure could be reduced and maintained within the limit to achieve knock free combustion.

Chiriac et al. [46] investigated by experimental researches the petrol and a diesel engine where gasoline and diesel fuel were mixed with a hydrogen rich gas produced by the dynamic electrical dissociation of water. The hydrogen rich gas analysis showed the presence of hydrogen and oxygen together with high reactive species like OH, HO_2, H_2O_2. Experiments had been performed at different engine loads and speeds. Detailed results of the measurements were shown, viz. engine torque and efficiency, exhaust emissions, cyclic variability, heat release rates and combustion duration. The possibilities of improving engines performance and emissions in correlation with the amount of hydrogen rich gas and the mixing parameters, the equivalence ratio and the engines operating condition were thus outlined.

Saravanan et al. [47] compared between the results for the injection of hydrogen by using the timing port injection and carburetor injection system. Both types of injection systems were studied with respect to the parameters such as specific energy consumption, brake thermal efficiency and emission factors such as NO_X, CO_2, CO, HC, and smoke. All the parameters were plotted against the brake power. A single cylinder, four stroke, water cooled and direct injection type compression ignition engine were used for this purpose.

At full load, the specific energy consumption (SEC) decreased by 15% compared to baseline diesel in TPI technique. This was due to uniform mixing of hydrogen with air resulting in complete combustion of fuel and SEC in carburetion technique was higher by around 6% compared to baseline diesel with hydrogen at a flow rate of 20 l/min. The brake thermal efficiency in TPI technique was around 17% higher at full load compared to baseline diesel at the flow rate of 20 l/min which was due to better mixing of hydrogen with air. In carburetion technique the brake thermal efficiency was 5% lower compared to baseline diesel with hydrogen flow rate at 20 l/min at full load. With neat diesel fuel the NOx level varied from 625 ppm at no load to 1980 ppm at full load whereas in TPI technique it varied from 213 to 2655 ppm at 20 l/min flow rate of hydrogen. The NOx emission from carburetion method was 8% higher than baseline due to diesel operation in carburetion technique for the flow rate of 20 l/min of hydrogen.

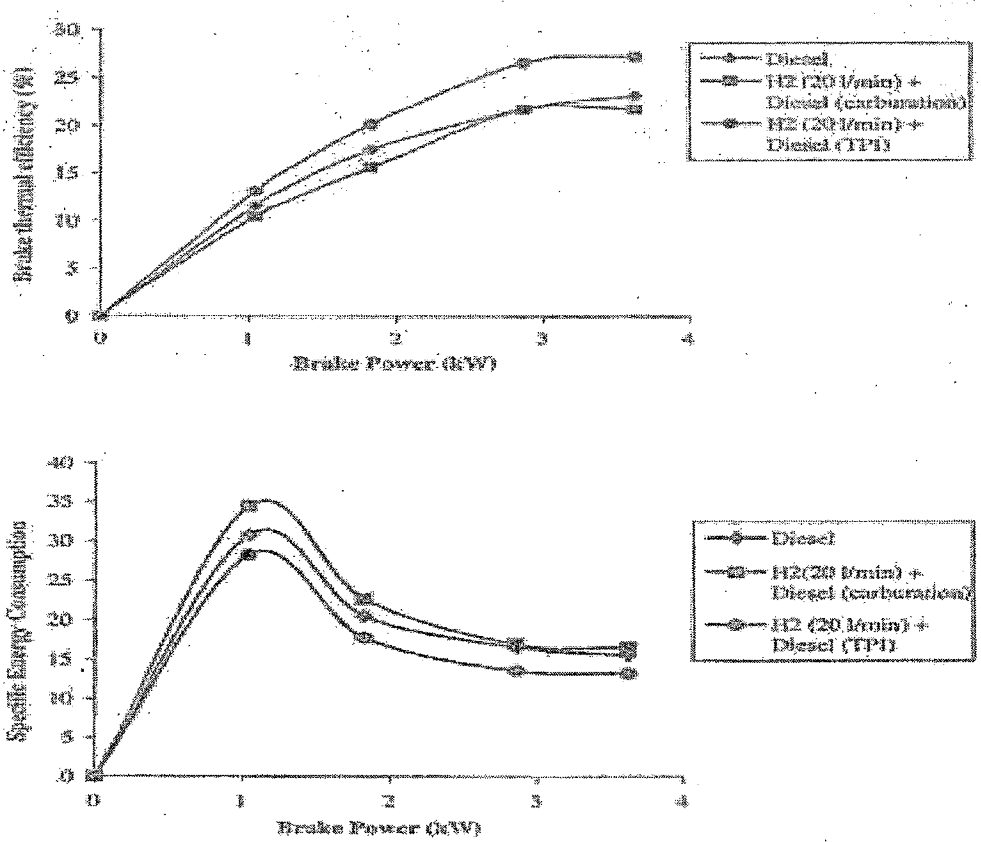


Fig. 2.13 Comparison of the Variation in Brake Thermal Efficiency and Specific Energy Consumption using Carburetion and Intake port Techniques [47]

Fig. 2.13 shows the comparison of thermal break efficiency and specific energy for carburetion and IPT techniques. In IPT technique, the smoke level varied from 2.1 to 3.5 BSN with a reduction of 45% at full load compared to diesel fuel. In carburetion technique the smoke level was 8% lower compared to that of baseline diesel with hydrogen flow rate of 20 l/min. The hydrocarbon emission was 67% lower in IPT technique at the flow rate of 20 l/min. In carburetion technique the HC was lowered by 11% for the flow rate of 20 l/min when compared with diesel fuel. The carbon monoxide emission was 80% lower in this technique for the flow rate of hydrogen at 20 l/min. In carburetion technique 25% reduction were observed. This was due to the absence of carbon in hydrogen and some traces of CO might be produced due to the use of diesel fuel for ignition purpose. The CO2 emission was 33% lower in this technique at the flow rate of hydrogen of 20 l/min. In carburetion technique 8% reduction in CO emission was noticed for the flow rate of hydrogen of 20 l/min. They summarized their findings by stating that inlet manifold is better than the carburetor technique. Fig. 2.14 shows comparison of gas emission constituents for carburetion and intake port technique.

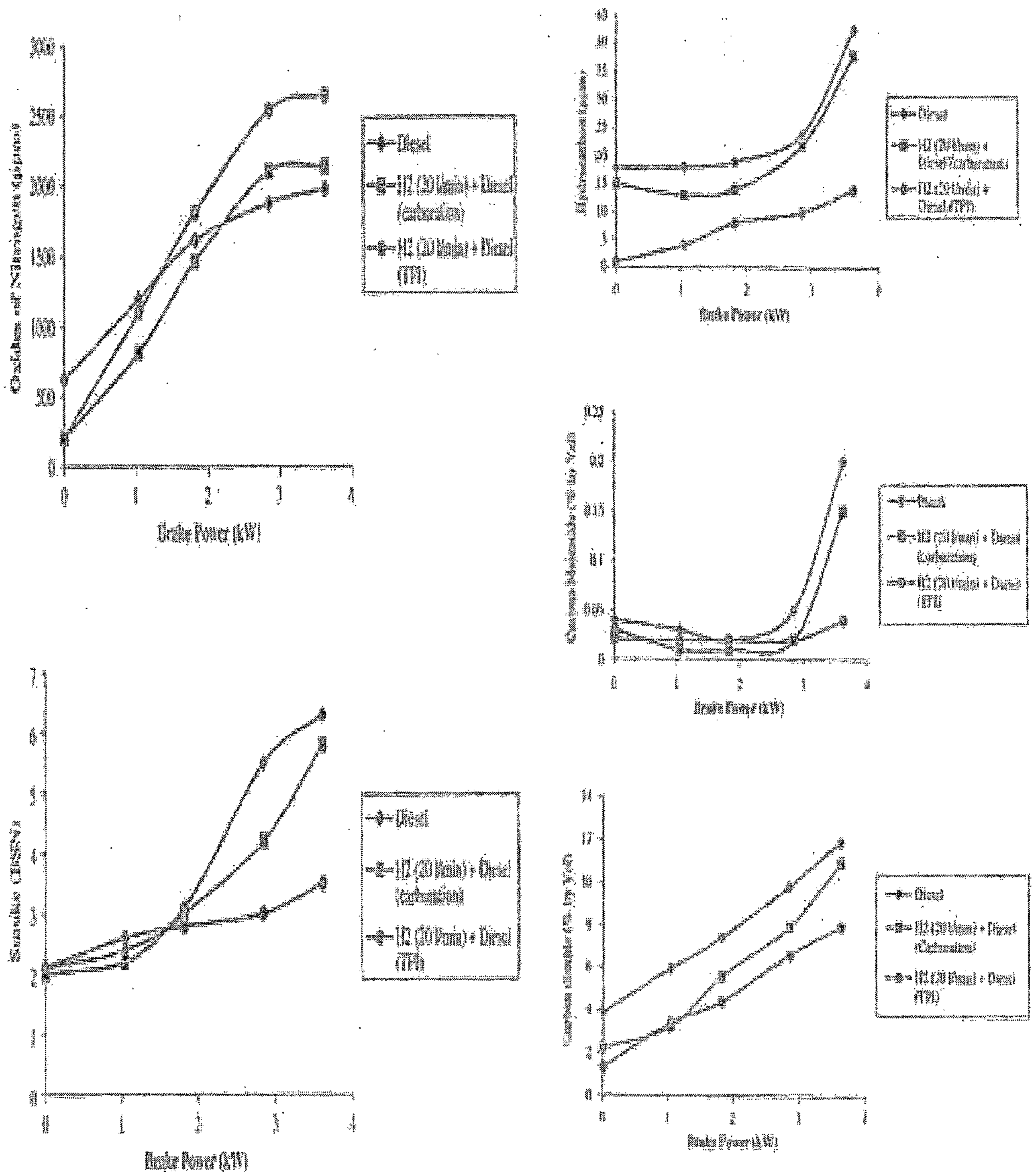


Fig. 2.14Variation in NO_X, HC, CO, Smoke, and CO_2 with Brake power Using Carburetion and Intake Technique [47]

Saravanan and Nagarajan [48] tested experimentally the using of hydrogen as a fuel in diesel engine. By added the hydrogen in intake port at varied load and varying percentage of conventional fuel (diesel) (10%, 30%, 50%, 70%, 80% and 90%) by volume. They studied the performance and emission characteristics of the hydrogen-enriched engine. They figured the relations between the brake thermal efficiency, brake specific fuel consumption, NO_X, HC, smoke and particulate emissions with the variation of engine load. Also, the pressure and heat released with crank angle were figured. Brake thermal efficiency increased to 29.1% with 90% hydrogen enrichment, but resulted in knocking. Best results were obtained with 30% hydrogen: an efficiency of 27.9% was achieved without knocking over the entire load range. Specific energy consumption decreased with increase in hydrogen percentage over the entire range of operation. NO_X concentration decreased with lean mixtures of hydrogen. A low NO_X level of 579 ppm was noticed at 70% load with 90% enrichment. Particulate matter decreased significantly from 4 to 1 g/kWh with 90% hydrogen enrichment. A significant reduction in smoke intensity was observed with increase in hydrogen enrichment with the lowest smoke level of 2.6 BSN with 90% enrichment.

Antunes et al. [49] studied on the operation of a compression ignition (CI) engine in homogeneous charge compression ignition (HCCI) mode using hydrogen fuel. Factors that were investigated include engine efficiency, emissions and mechanical loads. Hydrogen was found to be a possible fuel for operation of a CI engine in HCCI mode. The heat release rate was extremely high, which leads to high ignition timing control requirements. The ignition timing was controlled using heating of the inlet air, and satisfactory performance was demonstrated using this method. Some cycle-to-cycle variations were, however, observed due to the difficulty in achieving accurate control of ignition timing. Use of hydrogen in HCCI engines allowed operation with very lean air–fuel mixtures, giving extremely low emissions of nitrogen oxides and other pollutants. Operation with an excess air ratio of 6 was demonstrated, and a maximum fuel efficiency of 45% was achieved with an excess air ratio of 3. The maximum power of the engine in HCCI mode was, however, quite modest, being limited by the need for inlet air heating to ensure auto ignition, which reduced the air mass flow through the engine. There were also mechanical limitations to the operation of the HCCI hydrogen engine at high loads due to higher rates of pressure rise and in-cylinder peak pressures compared to conventional diesel mode. It was found that the peak in-cylinder pressures and the rates of pressure rise were higher in the HCCI hydrogen engine than for conventional operation on diesel fuel, limiting the HCCI engine to part load operation and potentially requiring design changes to maintain engine reliability. The fuel efficiency obtained was, however, significantly higher than that obtained when operating as a conventional diesel-fuelled engine, and high efficiency was obtained even with very lean cylinder charges. The inlet air had to be heated in order to ensure auto ignition, and it was demonstrated that the inlet air temperature was the most useful variable to control ignition timing. Engine emissions were measured and it was shown that negligible levels of all exhaust emissions were produced, including nitrogen oxides, compared to conventional diesel fuelled operation.

Saravanan and Nagarajan [50] injected hydrogen into intake manifold by using an injector and electronic control unit (ECU) the injection timing and the duration were controlled. From the results, it was observed that the optimum injection timing was at gas exchange top dead center (GTDC).

After drawing the relation between brake thermal efficiency, specific energy consumption, NO_X, smoke, CO, CO_2, exhaust gas temperature and peak pressure with variation of load graphically. They concluded the following points: The efficiency improved by about 15% with an increase in NO_X Emission by 3% compared to diesel. The smoke emission decreased by almost 100%. A net reduction in carbon emission was also noticed due to the use of hydrogen. By adopting manifold injection technique the hydrogen- diesel duel fuel engine operates smoothly with a significant improvement in performance and reduction in emissions. Fig. 2.15 shows the inlet manifold injection technique set up.

Saravanan and Nagarajan [51] conducted experiments to determine the optimized injection timing, injection duration, and hydrogen flow rate. It was observed that the optimum timing in port injection was 5° before gas exchange top dead center (BGTDC) with an injection duration of 30° crank angle (CA) and in manifold injection at gas exchange top dead center (GTDC) with an injection duration of 30° CA. Hydrogen flow rate was varied from 2 to 9.5 l/min with above the above-optimized conditions for both port and manifold injection. The optimized hydrogen flow rate was found to be 7.5 l/min for both port and manifold injection. Flow rates higher than 9.5 l/min showed an improvement in performance and reduction in emissions, but the onset of knock was observed; hence, the flow rate was limited to 9.5 l/min. At 75% load the brake thermal efficiency increased by 21% in port injection and 18% in manifold injection.

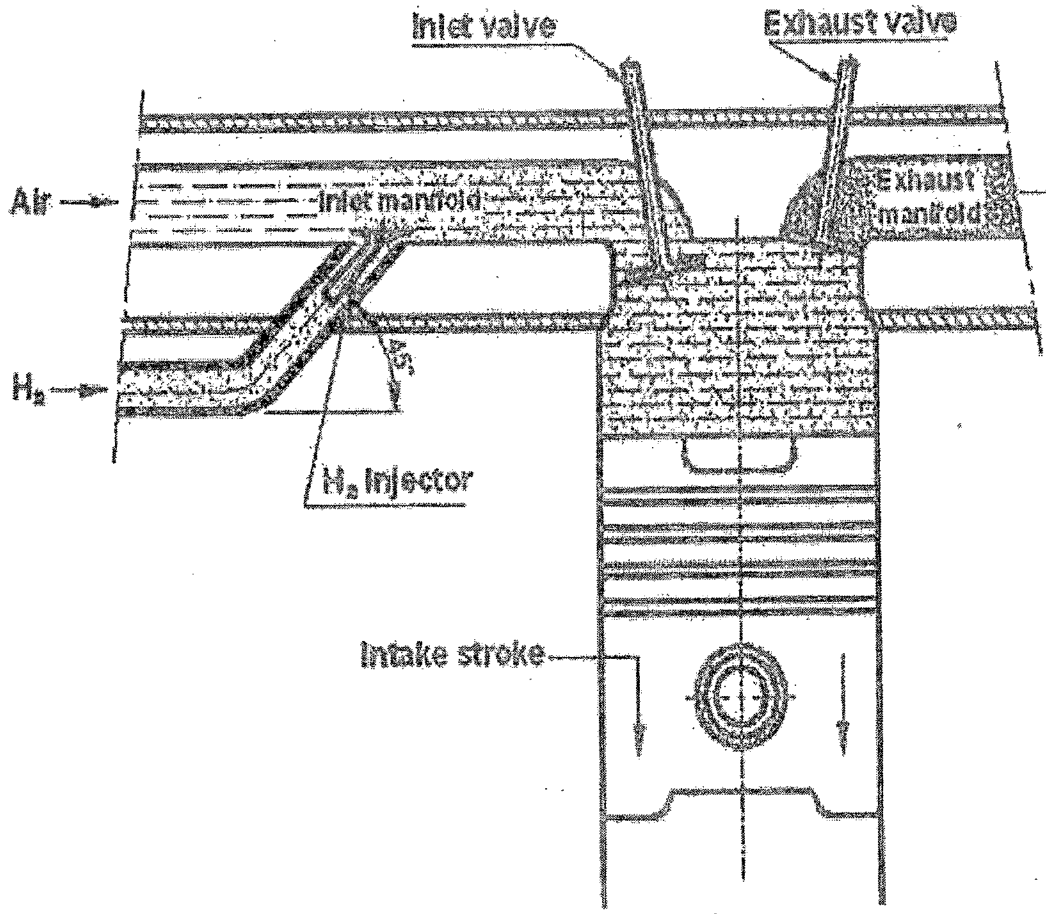


Fig. 2.15 Inlet Manifold Injection Technique Set-up [50]

NO_X emission was reduced by 2% in port injection and 4% in manifold injection compared to diesel at full load. At full load, smoke was reduced by 45% in both port injection and manifold injection. In the entire load spectra a reduction in CO by about 50% was noticed in both port and manifold injection. Ignition delay or a delay period was found to be 11° or 1.22 ms for diesel and 10° or 1.11 ms in both port and manifold injection. Figs. 2.16-2.18 show the variation of specific energy consumption, brake thermal efficiency, NO_X, HC, CO, and CO_2 vs. load and start injection and injection duration respectively.

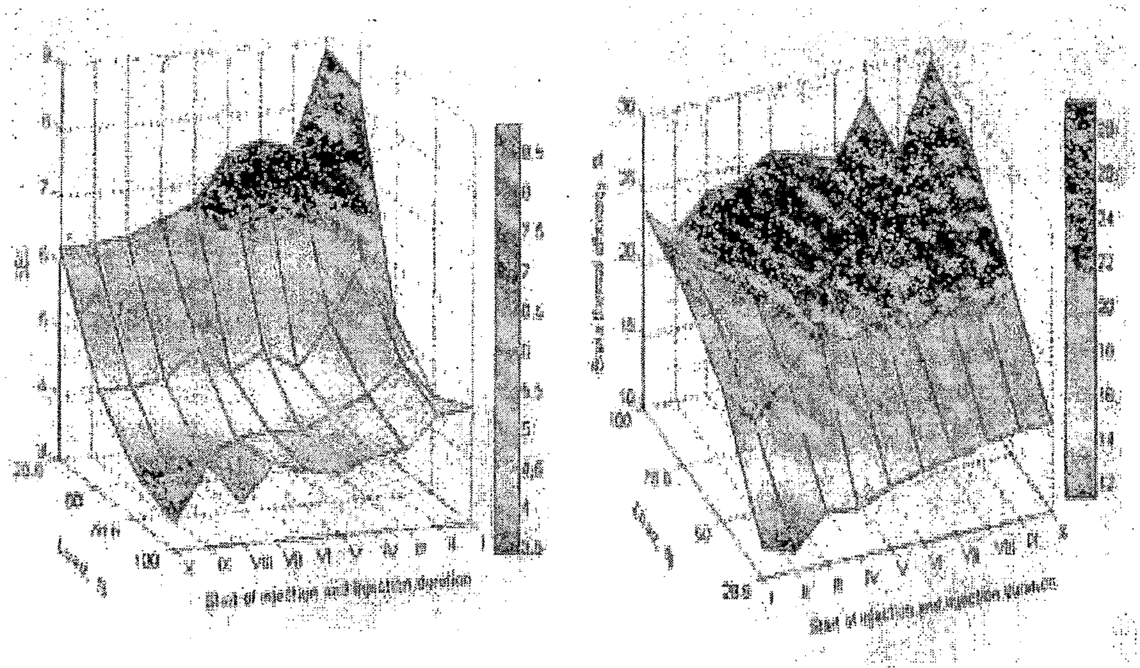


Fig. 2.16 Variation in Specific Energy Consumption and Brake Thermal Efficiency with Various Load, Start Injection and Injection Duration [51]

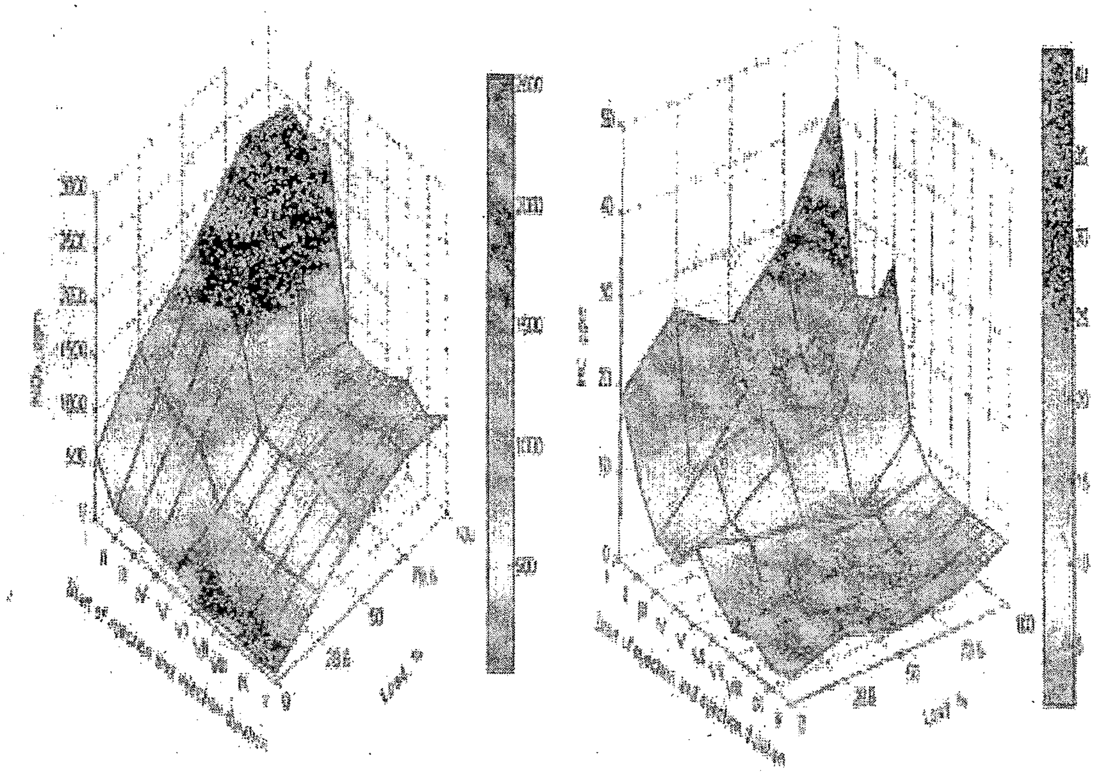


Fig. 2.17 NO_X and HC vs. Load and Start Injection and Injection Duration [51].

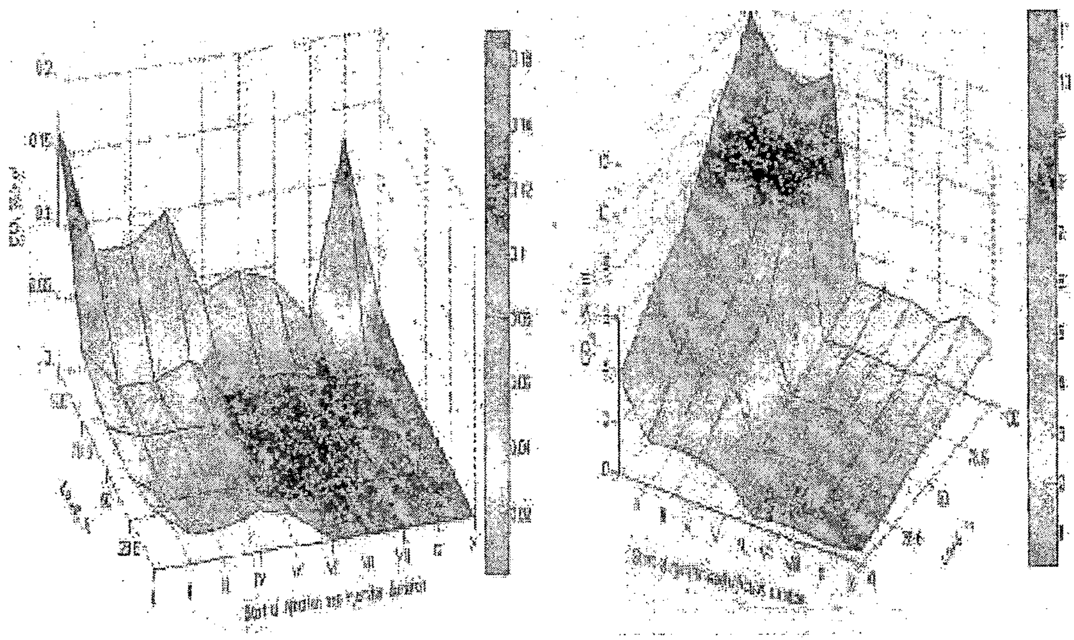


Fig. 2.18 Variation in CO and CO_2 with Load, Start Injection and Injection Duration [51]

2.2.1.3 Hydrogen and Other Fuel Combinations

Apart from the direct and indirect methods of supplementation techniques investigated over a period of time during post energy crisis of 1970s, various other techniques involving combination substances were investigated primarily to improve thermal performance along with the control of pollutants emission. They include exhaust gas recirculation with hydrogen-diesel, diluents with hydrogen-diesel, bio-diesel/biogas with hydrogen diesel and additives with hydrogen diesel or with diesel alone. The following sections present the review of various experimental investigations carried out on each of the combination techniques.

2.2.1.3.1 Exhaust Gas Recirculation (EGR) with Hydrogen-Diesel

Tsolakis and Megaritis [52] studied the application of the exhaust gas fuel reforming process in diesel engines as a way to assist the premixed charge compression ignition operation by substituting part of the main fuel with hydrogen-rich gas. The technique involved the injection of hydrocarbon fuel into a catalytic reformer fitted into the exhaust gas recirculation (EGR) system, so that the produced gas mixture was fed back to the engine as reformed EGR (REGR). First, experiments with simulated REGR were conducted by them with diesel as well as biodiesel as the main engine fuel. Then, experiments with the product gas of a monolith reformer were carried out. In both cases, REGR resulted in a higher premixed combustion rate and reduction of the diffusion combustion phase. The potential of the technique in terms of achieving reduction of smoke and NO_x emissions and improved fuel economy were shown and discussed in the paper.

Abu-Jrai et al. [53] reported experimental results obtained when 1%Pt/Al_2O_3 low temperature hydrocarbon-SCR catalyst was used to treat exhaust gas from a diesel engine operating with addition of simulated REGR (two different compositions). Their investigations revealed that while REGR can directly improve engine performance and emissions by promoting the PCCI combustion mode, it can also benefit the performance of the SCR catalysts due to the presence of un-burnt H_2 in the exhaust gas.

Saravanan and Nagarajan [54] tested experimentally, the intake port hydrogen injection with EGR and without it at 7.5 l/min + 5^0 BTDC (before top dead center) and duration of 30 crank angle degree. The results were compared with the base fuel case of neat diesel. Brake thermal efficiency, specific energy consumption, NOX, smoke, CO, CO_2, exhaust gas temperature and peak pressure were figured with variation of load. The brake thermal efficiency in port injection varied from 15% to 23.11% with 20% EGR as compared to 15.6% to 24.2% without EGR. The NOx emission in port injection varied from 99 ppm to 526 ppm with 20% EGR as compared to 184 ppm to 2212 ppm without EGR. The NOx emission reduced with increase in EGR flow percentage this was due to the presence of inert gases (CO_2 and H_2O) inside the combustion chamber. The smoke emission reduced with increase in hydrogen percentage and increases with increase in EGR percentage. The smoke varied from 0.1 BSN to 4.9 BSN with 20% EGR compared to without EGR of 0 BSN to 2 BSN and 0.3 BSN to 3.6 BSN in diesel. The optimum EGR percentage was found to be 20% at part loads, which gave lesser smoke compared to diesel with higher NOx reduction. The CO emission varied from 0.04% to 0.74% with 20% EGR as compared to without EGR of 0.02% to 0.09% and 0.08% to 0.14% in diesel. The HC was found to increase by 12% to 19% with 20% EGR as compared to without EGR.

Saravanan et al. [55] investigated experimentally, hydrogen-enriched air as intake charge in a diesel engine adopting exhaust gas recirculation (EGR) technique with hydrogen flow rate at 20 l/min. They used air carburetor to mix the air-EGR-hydrogen together. Experiments were conducted in a single cylinder, four stroke, water cooled, direct injection diesel engine coupled to an electrical generator. Performance parameters such as specific energy consumption, brake thermal efficiency, were determined and emissions such as oxides of nitrogen, hydrocarbon, carbon monoxide, carbon dioxide and smoke were measured. The graphs were plotted to show the relations of that parameters at varied engine loads and for 15%, 25% and non EGR respectively. They used this technique in order to minimize the emission of NO_X as a pollutant. They observed an increment in brake thermal efficiency by about 6% without EGR, while it's the peak value was found to be 25% and 15 % with and without EGR as well as neat diesel fuel's brake thermal efficiency. There was a reduction in the specific energy consumption. NO_X concentration decreased with EGR technique and minimum concentration of NO_X was 464 ppm with 25% EGR. The reduction in NO_X was due to the presence of insert gas from EGR. Reduction in CO, smoke and HC at non EGR mode reached to 50%, 48% and 58% respectively. Figs. 2.19-2.21 show the variation of specific energy consumption, brake thermal efficiency, NO_X, HC, CO, and CO_2 vs. load and various EGR ratio.

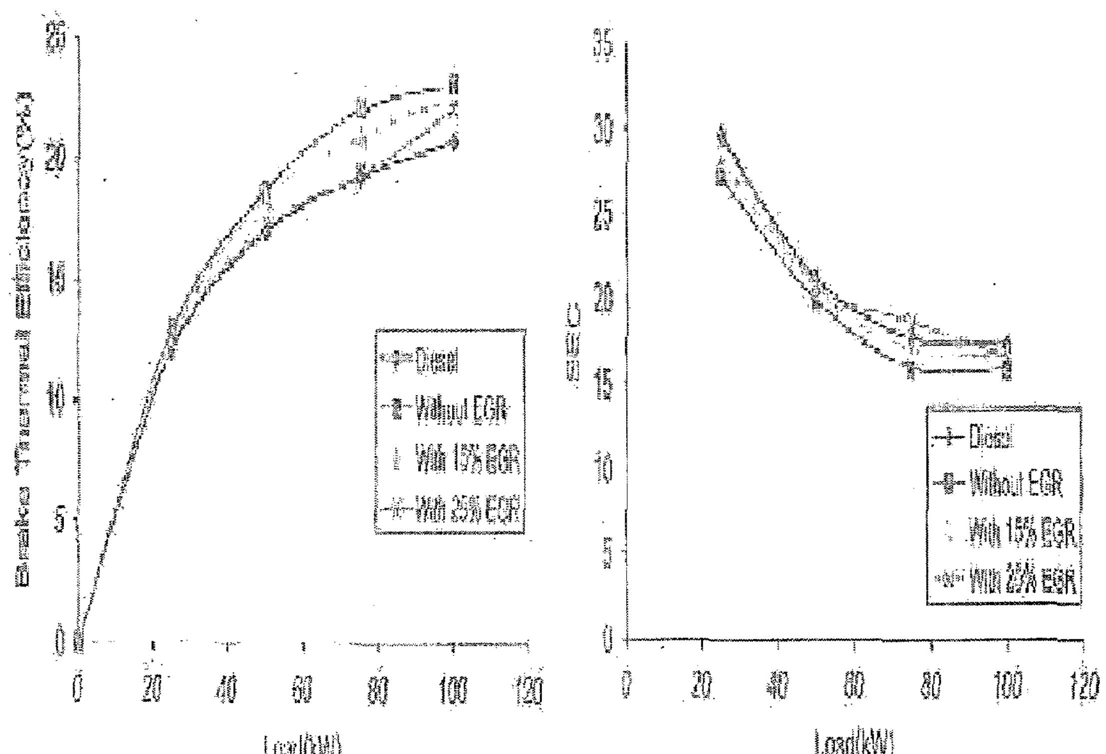


Fig. 2.19 Brake Thermal Efficiency and Specific Energy Consumption vs. Load at different EGR ratio [55].

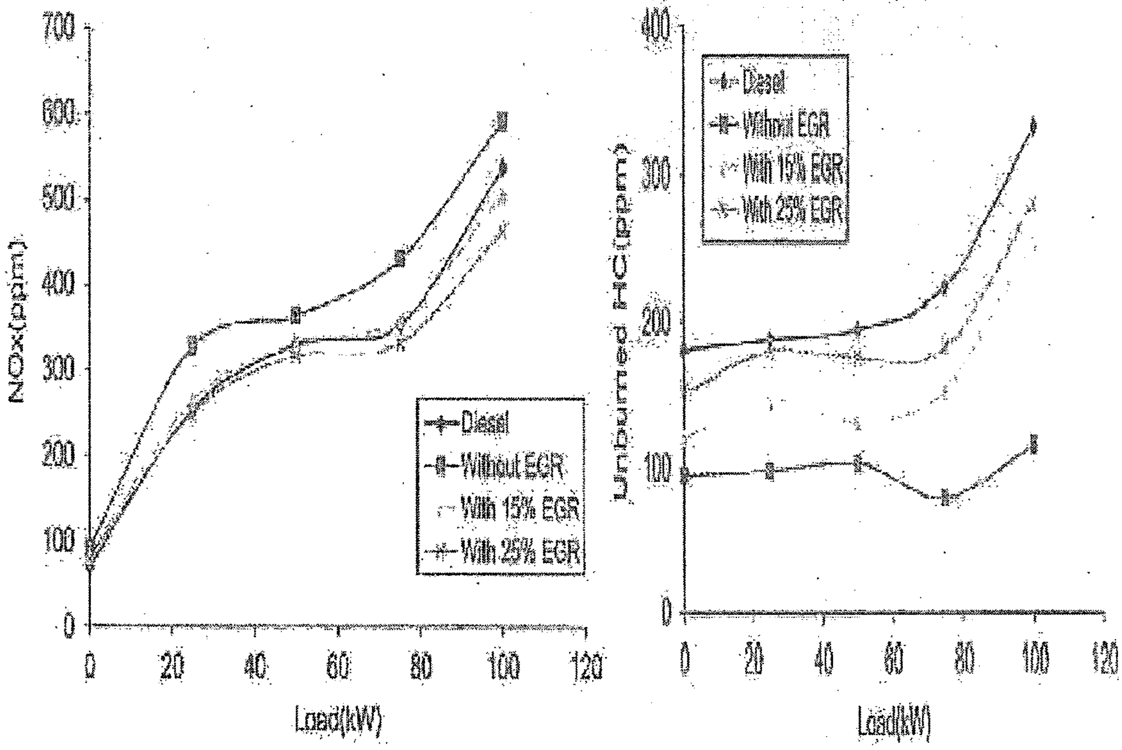


Fig. 2.20 NO_X and HC vs. Load vs. Load at different EGR ratio [55].

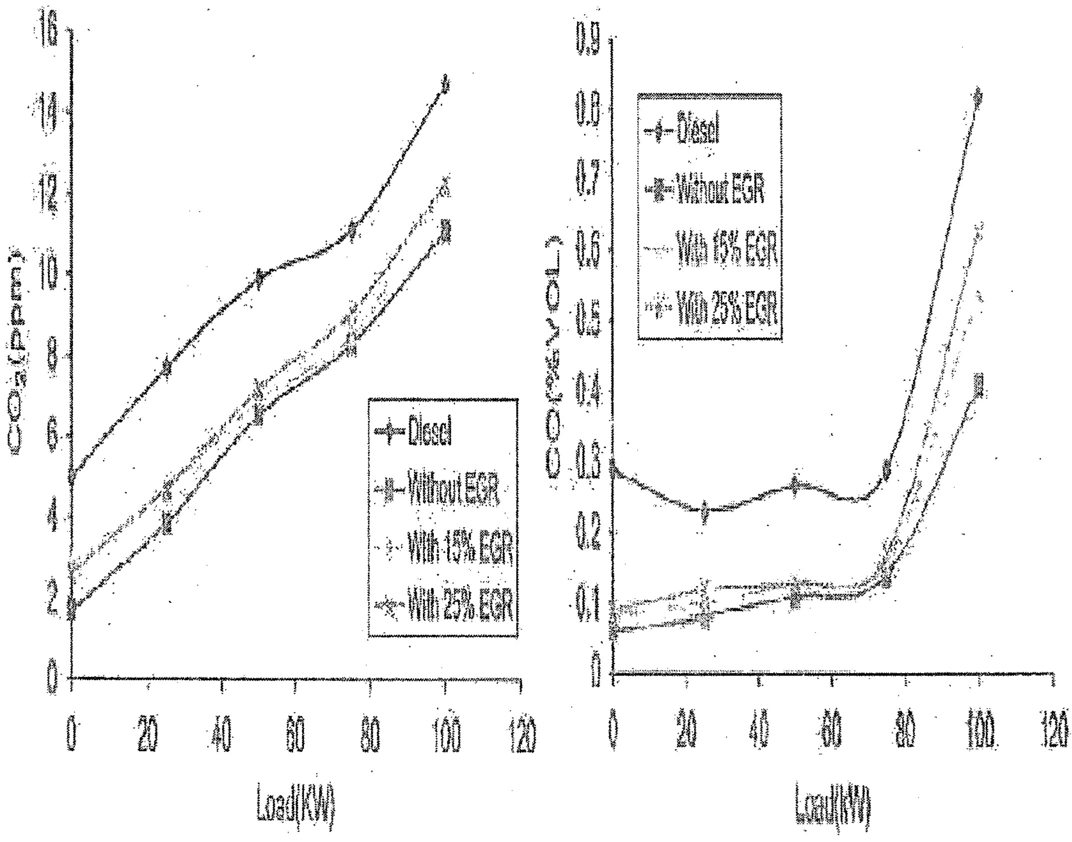


Fig. 2.21 Variation in CO and CO_2 with Load at different EGR ratio [55]

Bose and Maji [56] conducted using diesel–hydrogen blend. A timed manifold induction system with electronic control was developed to deliver hydrogen on to the intake manifold. The solenoid valve was activated by the new technique of taking signal from the rocker arm of the engine instead of cam actuation mechanism. Hydrogen-enriched air was used in a diesel engine with hydrogen flow rate at 0.15 kg/h. As diesel was substituted and hydrogen was inducted, the NOx emission was increased. In order to reduce NOx emission, an EGR system was developed. In the EGR system, a lightweight EGR cooler was used instead of bulky heat exchanger. In this experiment, performance parameters such as brake thermal efficiency, volumetric efficiency, BSEC were determined and emissions such as oxides of nitrogen, carbon dioxide, carbon monoxide, hydrocarbon, smoke and exhaust gas temperature were measured. Dual fuel operation with hydrogen induction coupled with exhaust gas recirculation resulted in lowered emission level and improved performance level compared to the case of neat diesel operation. They claim that good enhancement in the engine performance was achieved and simultaneously the emissions levels generally decreased.

2.2.1.3.2 Diluents with Hydrogen - Diesel

Mathur and Das [57] reported their experimental results on the effect of diluents like helium, nitrogen and water in various proportions on smoke and oxides of nitrogen (NO_X) emissions in such an engine. They studied the possibility of controlling the exhaust emission parameters of a small power hydrogen fuelled diesel engine by using various diluents type mixed with inducted charge. The hydrogen varied at 20, 30, 40, 50 and 60 liter/min . The amounts of gaseous diluents – helium and nitrogen – were in proportions of 10%, 20% and 30% by volume of hydrogen flow rate, while water was induced in concentrations of 600, 1260 and 2460 ppm. They drew the smoke and NO_X against engine rated load with various hydrogen flow rate at different diluents type and concentrations. As a result, helium showed a positive effect on controlling these pollutants, while nitrogen only reduced smoke emission levels. Water was found to be the best diluent which permitted up to 66% full load energy substitution by hydrogen without engine knock and considerably brought down the exhaust smoke density and NO_X emission level when inducted in very small proportions, of the order of parts of million.

Mathur et al. [58] tested small end-utility compression ignition (CI) engine generator system operated with hydrogen fuel substitution. The system performance and emission characteristics were evaluated and analyzed. Helium, nitrogen and water were used to improve the engine operation and bring down the emission levels. The hydrogen varied at 20, 30, 40, 50 and 60 l/min. The amounts of gaseous diluents – helium and nitrogen – were in proportions of 10%, 20% and 30% by volume of hydrogen flow rate, while water was induced in concentrations of 600, 1260 and 2460 ppm. The knock happened at 60 l/min. The brake thermal efficiency and optimum injected hydrogen energy were studied in the performance part , while the smoke and exhaust temperature studied in emission part of the study. Their conclusions were: hydrogen can be advantageously used as a supplementary fuel from both the point of view of conservation of diesel oil and elimination of exhaust pollutants such as carbon monoxide, hydrocarbons and sulphur compounds found in diesel exhaust. Addition of diluents improves the knock-limited engine operation, thereby increasing the optimum hydrogen energy substitution percentage. Nitrogen is the best diluent from an engine performance point of view, while from standpoint of emission level, water appears to score over a nitrogen diluent. Water injection in as small a proportion as 2460 ppm can be profitably employed to achieve around 66% hydrogen energy substitution along with a smooth knock free engine operation and drastic reduction of exhaust smoke and NO_X emissions.

Mathur et al. [59] conducted experiments to explore, through various charge diluents, the possibility of improving the performance, percentage hydrogen substitution and knock-limited power output of hydrogen-fuelled diesel engine. They used single cylinder, water cooled, direct injection type small horsepower diesel engine. Helium as diluent was found to control the engine knock, but the thermal efficiency and percentage of optimum hydrogen energy substitution exhibited no positive gain. Nitrogen showed the best influence on engine performance and knock limited power output improvement. Water induction, in small concentrations, demonstrated the highest percentage full-load hydrogen energy substitution, although the engine thermal efficiency and knock limited power output were marginally affected. They tested the engine on diesel fuel mode firstly then at 20, 30, 40, 50, and 60 liter/min and injected 10, 20, 30 % volume by volume of hydrogen. 10% nitrogen and 600, 1260 and 2460 ppm water were injected.

2.2.1.3.3 Biodiesel with Hydrogen-Diesel

Kumar et al. [60], tried to solve the problems using vegetable oils in unmodified diesel engines by added a small quantity of hydrogen where the use of oil alone leads to reduced thermal efficiency and increased smoke levels. Experimental studies were carried out to evaluate the performance while using small quantities of hydrogen in a compression ignition engine primarily fuelled with a vegetable oil, namely Jatropha oil. A single cylinder water-cooled direct-injection diesel engine designed to develop a power output of 3:7 kW at 1500 rpm was tested at its rated speed under variable load conditions, with different quantities of hydrogen being inducted. The Jatropha oil was injected into the engine in the conventional way. Results indicated an increase in the brake thermal efficiency from 27.3% to a maximum of 29.3% at 7% of hydrogen mass share at maximum power output. Smoke was reduced from 4.4 to 3.7 BSU at the best effciency point. There was also a reduction in HC and CO emissions from 130 to 100 ppm and 0.26–0.17% by volume respectively at maximum power output. With hydrogen induction, due to high combustion rates, NO level was increased from 735 to 875 ppm at full output. Figs. 2.22-2.24 present the brake thermal efficiency, exhaust temperature, volumetric efficiency, smoke, HC and No vs. hydrogen mass share at different biodiesel-diesel blends respectively.

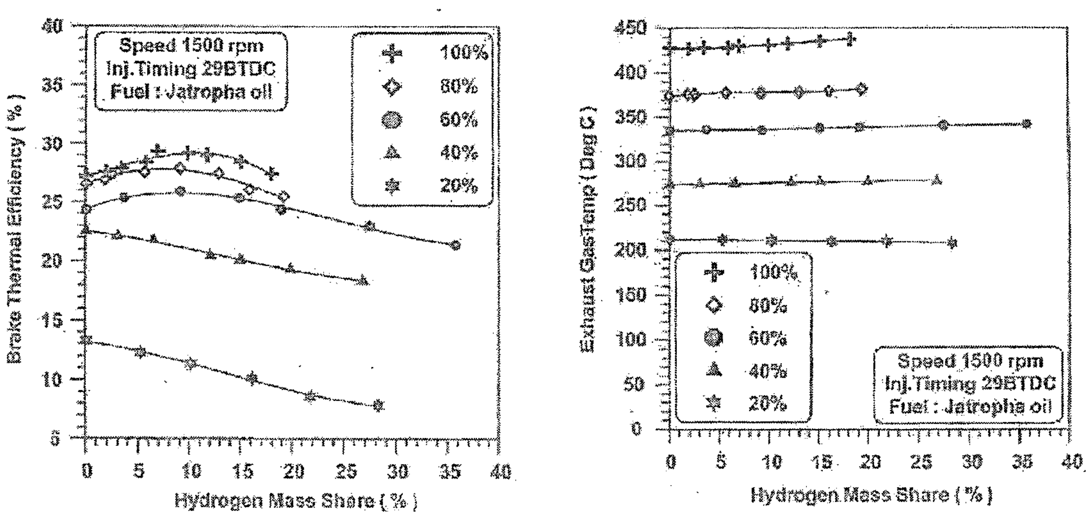


Fig. 2.22 Variation in Brake Thermal Efficiency and Exhaust Temperature for Various Blends with Hydrogen Mass Share Percentage [60]

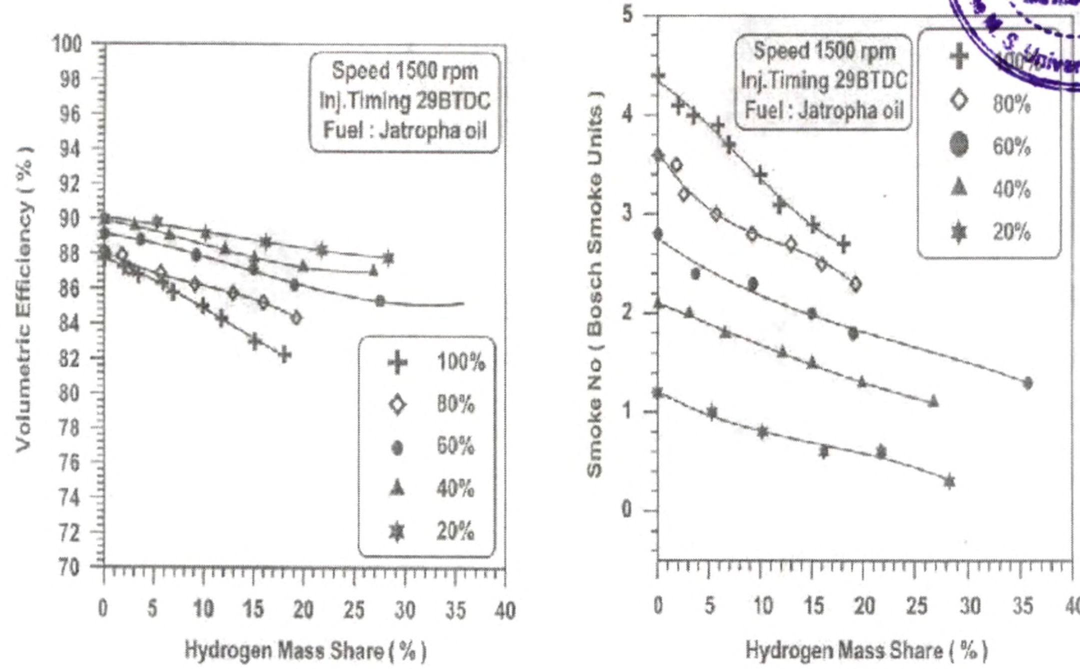


Fig. 2.23 Variation in Volumetric Efficiency and Smoke for Various Blends with Hydrogen Mass Share Percentage [60]

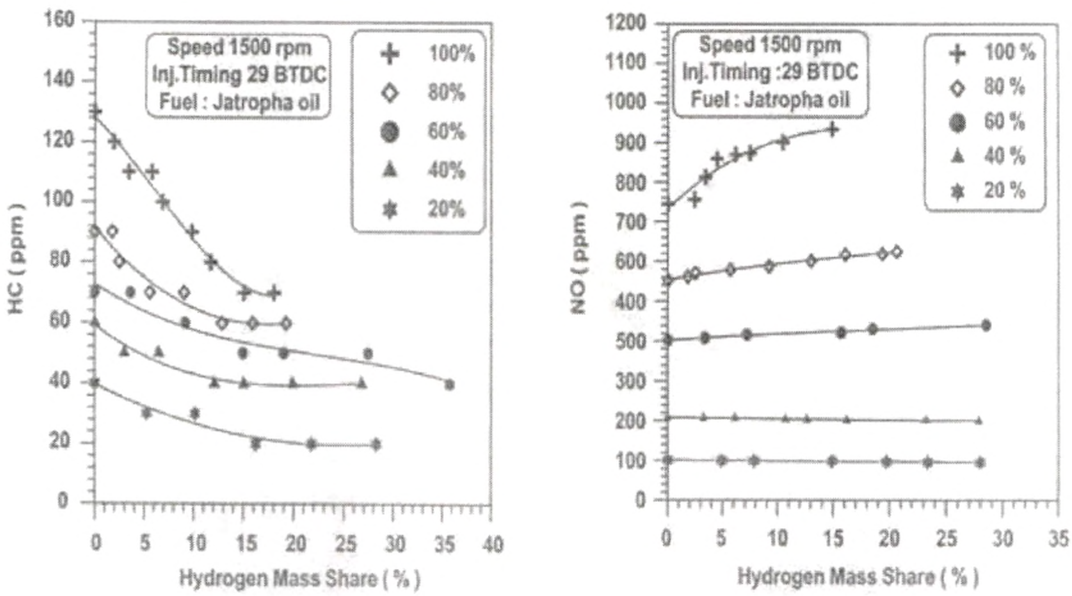


Fig. 2.24 Variation in HC and NO for Various Blends with Hydrogen Mass Share Percentage [60]

Ignition delay, peak pressure and maximum rate of pressure rise were also increased in the dual fuel mode of operation. Combustion duration was reduced due to higher flame speed of hydrogen. Higher premixed combustion rate was observed with hydrogen induction. Comparison was made with diesel being used as the pilot fuel instead of vegetable oil. In the case of diesel the brake thermal efficiency was always higher. At the optimum hydrogen share of 5% by mass, the brake thermal efficiency went up from 30.3–32%. Hydrocarbon, carbon monoxide, smoke emission and ignition delay were also lower with diesel as compared to vegetable oil. Smoke level decreased from 3.9 to 2.7 BSU with diesel as pilot at the optimum hydrogen share. Peak pressure, maximum rate of pressure rise, heat release rate and NO levels were higher with diesel than Jatropha oil. On the whole, it was concluded that induction of small quantities of hydrogen can signilcantly enhance the performance of a vegetable (Jatropha) oil/diesel fuelled diesel engine.

Geo et al. [61] investigated experimentally the using of hydrogen as the inducted fuel and rubber seed oil (RSO), rubber seed oil methyl ester (RSOME) and diesel were used as main fuels in a duel fuel engine. Dual fuel operation of varying hydrogen quantity with RSO and RSOME resulted in higher brake thermal efficiency and significant reduction in smoke levels at high outputs. The maximum brake thermal efficiency was 28.12%, 29.26% and 31.62% with RSO, RSOME and diesel at hydrogen energy share of 8.39%, 8.73% and 10.1% respectively. Smoke was reduced from 5.5 to 3.5 BSU with RSOME and for RSO, it was from 6.1 to 3.8 BSU at the maximum efficiency point. The peak pressure and maximum rate of pressure rise increased with hydrogen induction. Heat release rate indicated an increase in the combustion rate with hydrogen induction. On the whole, it was concluded that hydrogen could be inducted along with air in order to reduce smoke levels and improve thermal efficiency of RSO and its bio-diesel fuelled diesel engines.

2.2.1.3.4 Additives with Hydrogen-Diesel or with Diesel Alone

Keith et al. [62] tested the physical and chemical properties of neat methylal and for blends of methylal in conventional diesel fuel were presented. Methylal was found to be more volatile than Y diesel fuel, and special precautions for distribution and fuel tank storage are discussed. They used methylal (CHs-O-CHz-O-CH) also known as dimethoxymethane or DMM, is a gas-to-liquid chemical that had been evaluated for use as a diesel fuel component. Methylal contained 42% oxygen by weight and is soluble in diesel fuel. Steady state engine tests were also performed using an unmodified Cummins B5.9 turbocharged diesel engine to examine the effect of methylal blend concentration on performance and emissions. Substantial reductions of .particulate matter emissions had been demonstrated 3r IO to 30%

blends of methylal in diesel fuel. This research indicated that methylal might be an effective blend for diesel fuel provided design changes were made to vehicle fuel handling systems.

Teng et al. [63] analyzed chemical and thermochemical properties of dimythel ether (DME) as an alternative fuel for compression ignition engines. On the basis of the chemical structure of DME and molecular thermodynamics of fluids, equations had been developed for most of the DME thermophysical properties that would influence the fuel system performance. These equations were easy to use and accurate in the pressure and temperature ranges of CI engine applications. They noticed that DME spray in the engine cylinder would differ significantly from that of diesel fuel due to the thermodynamic characteristics of DME. The DME spray pattern would affect the mixing and combustion process in the engine cylinder, which, in turn, will influence emissions from combustion.

Ahmed [64] used the ethanol as a blend fuel with the diesel to reduce the diesel fuel emissions. He showed that formation of these air pollutants could be significantly reduced by blending oxygenates into the base diesel. Ethanol blended diesel (e-diesel) was a cleaner burning alternative to regular diesel for both heavy duty (HD) and light duty (LD)compression ignition (CI) engines used in buses, trucks, etc. He created a stable ethanol–diesel blended fuel with the help of pure Energy's Puranol additive system, and then generated transient emissions data for an evaluation of different oxygen content based on ethanol content. The tests showed that over 41% reduction in PM, 27%reduction in CO, and 5% reduction in NO_X from a HD diesel engine and higher emissions reductions were observed from smaller engines

Mitsuru et al. [65] studied experimentally the diethyl ether blends on diesel engine. The ignition and combustion process of a direct injection CI engine fuelled with DME was observed, using a high speed video camera system. Oxidation and pyrolysis characteristics of DME were also investigated by in –cylinder gas sampling. Better gas emission results were seen by them.

Saravanan et. al. [66] carried out the combustion analysis on a direct injection (DI) diesel engine using hydrogen with diesel and hydrogen with diethyl ether (DEE) as ignition source. The hydrogen was injected through intake port and diethyl ether was injected through intake manifold and diesel was injected directly inside the combustion chamber. Injection timings for hydrogen and DEE were optimized based on the performance, combustion and emission characteristics of the engine. The optimized timing for the injection of hydrogen was 5° CA before gas exchange top dead center (BGTDC) and 40° CA after gas exchange top dead center (AGTDC) for DEE. From the study, it was observed that hydrogen with diesel resulted in increased brake thermal efficiency by 20% and oxides of nitrogen (NO_X) showed increase of 13% compared to diesel. Hydrogen- DEE operation showed a higher brake thermal efficiency of 30 % with significant reduction in NO_X compared to diesel. Figs 2.25-2.27 present the relation between brake thermal efficiency, specific energy consumption, NOX, smoke, CO and CO2 for hydrogen DEE blends.

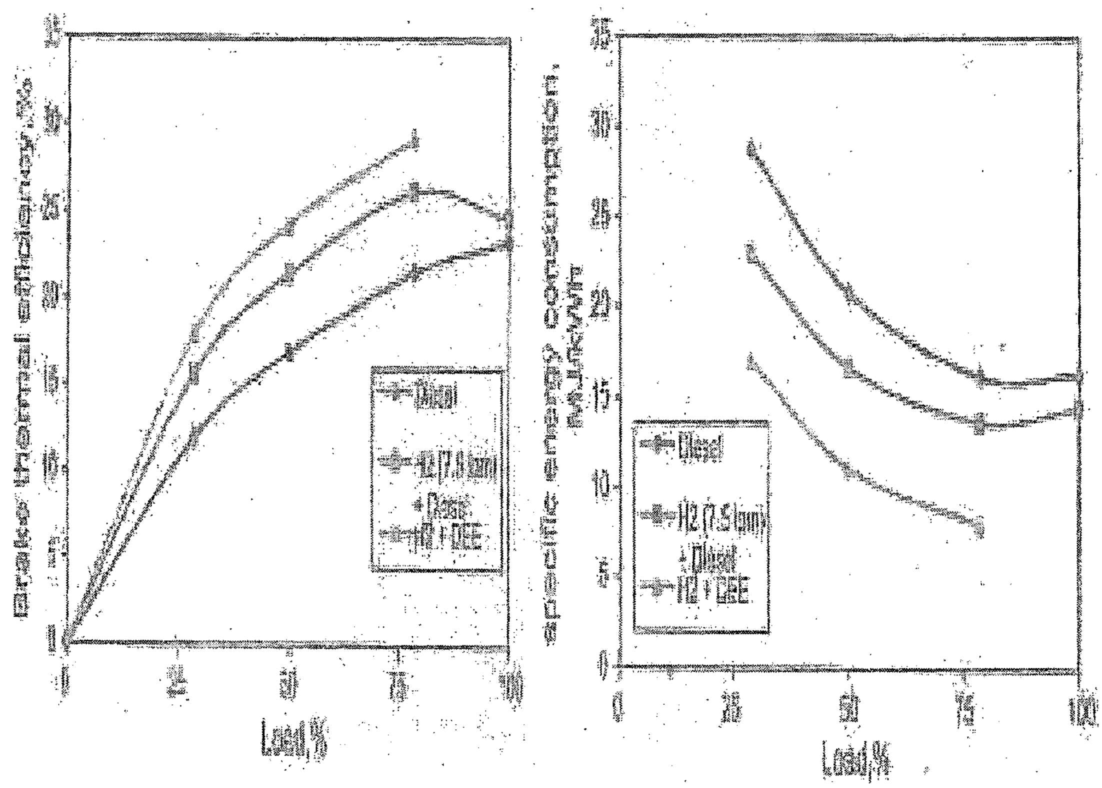


Fig. 2.25 Variation of Brake Thermal Efficiency and Specific Energy Consumption with Load Using Hydrogen DEE Blends [66]

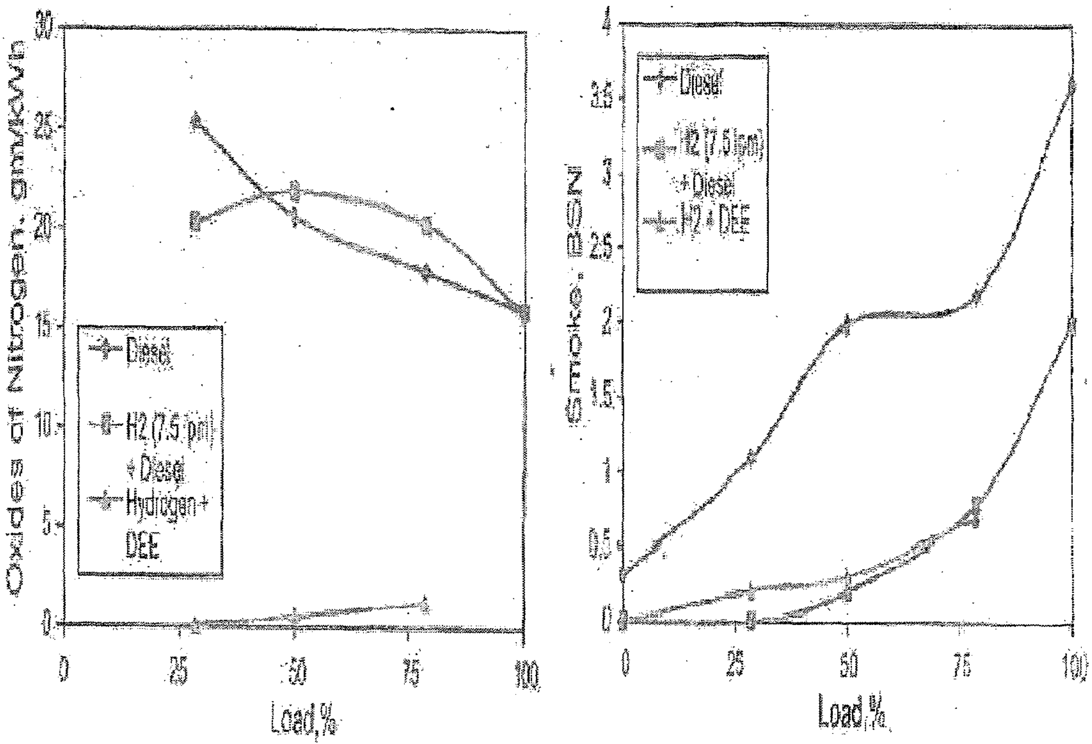


Fig. 2.26Variation of NO_X and Smoke with Load Using Hydrogen DEE Blends [66]

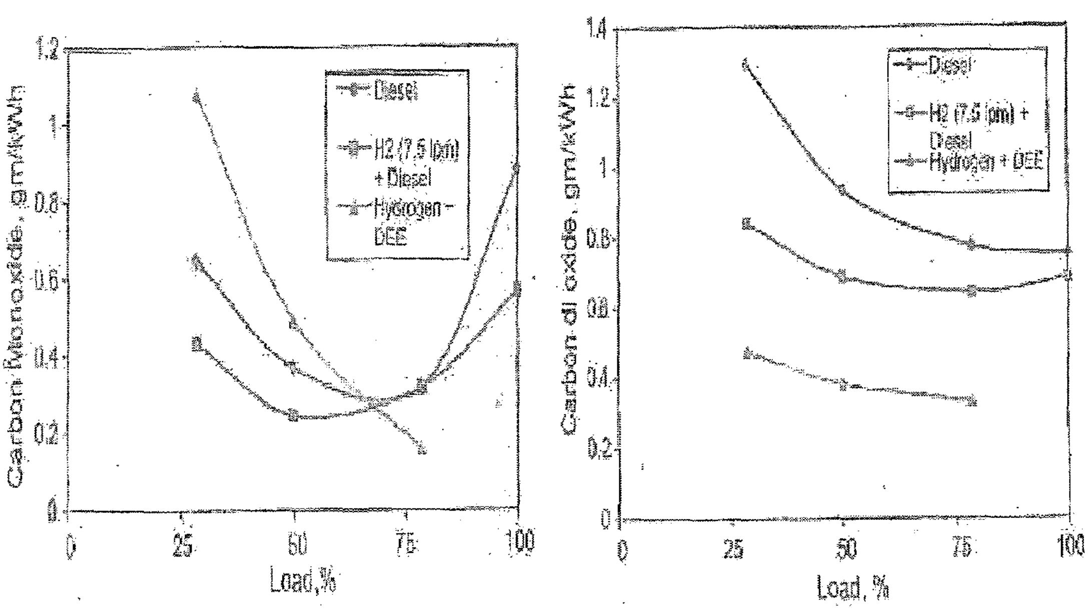


Fig. 2.27 Variation of CO and CO_2 with Load Using Hydrogen DEE Blends [66]

2.2.2 Theoretical Investigations

Post energy crisis era also saw a number of theoretical investigations attempted using various methods to predict the thermal performance and emission characteristics of compression ignition engines. They include modeling and simulation, artificial neural network and genetic algorithm optimization. Fig. 2.28 illustrates the three distinctly different approaches that are adopted for the theoretical investigations. Specific attempt is made to identify research literature relevant to area of hydrogen-diesel supplementations

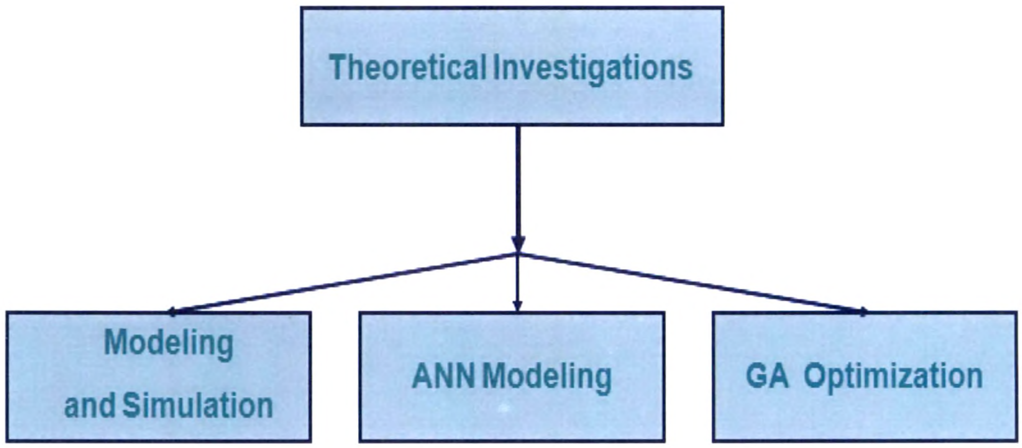


Fig. 2.28 Various Options of Theoretical Investigations

2.2.2.1 Modeling and Simulation

During the period of active experimental research carried out by Furuhama and associates [11, 12, 15, 16, 29-31] for the development of hydrogen engine for automobiles, in the latter part of 1970s and earlier part of 1980, there were no theoretical studies reported in open literature. One of the earliest studies reported is due to **Steinberg and Scott** [67], in 1984, who built a computer simulation which could realistically model the operation of a diesel- electronic locomotive. The simulation contained mathematical models of the track, tractive resistance and the propulsion system.

In order to test modeling accuracy, the simulation was run using the parameters of a representative system of known performance. Subsequent to the verification of the technical mode, it was run on the same rail line simulating hydrogen fueled diesel-electric and alkaline fuel cell locomotives. The fuel consumption information resulting from these runs were used in an economic analysis which compared the projected investment merits of these alternative technologies. This appraisal was considered a prerequisite to the ultimate objective; a comparison of "direct" and "indirect" electrification including a thorough examination of fuel cell locomotive economics.

Patro [68] developed model to analyze hydrogen enriched diesel combustion in a DI diesel engine with the help of a P- θ trace. The model applied to the test operation with hydrogen energy substitution, with and without various charge diluents like helium, nitrogen and water in a small diesel engine showed good agreement with experimental observations. The heat release model, along with the second derivative of the pressure data gave an acceptably accurate diagnosis of the hydrogen fueled diesel engine combustion process. Due to hydrogen fuel substitution, ignition delay increases; the delay period increased with increase in hydrogen energy substitution to a certain limit, after which it remained almost unaffected by further increase in hydrogen energy substitution. The proportion of hydrogen energy substitution was limited by the rate of pressure rise and perturbed manner of combustion heat release. Helium used as diluent reduced the ignition delay of hydrogen-diesel combustion. However, the percentage amount of hydrogen energy substitution might not be improved much. Nitrogen when used with the fuel-air mixture, reduced the ignition delay period considerably. It gave the highest peak mean pressure and the rate of heat release was a maximum. Finally, the cycle efficiency and power output for nitrogen as diluent were the best.

Patro [69] further, derived the burning rate from the experimental P-V diagram and its application to a hydrogen-enriched dual-fuel diesel engine to assess its combustion process. It gave good detail of the mode of the hydrogen fuel burning mechanism for six different cases of engine fuelling. The method can be used for simulation of dual-fuel engines for development/modification purposes. This computer aided cycle simulation could be a tool to design and develop the diesel engines. In this work, the data had been obtained for a small horsepower diesel engine results of previous tests were adopted from where the engine was operated with a fixed maximum load with varying rates of hydrogen induction into the engine intake manifold. In second sets of test, the hydrogen flow rate was kept fixed while the load on the engine was varied until knock was encountered. In the third series of tests, various diluents were tried with varying hydrogen flow rate to achieve maximum knock-limited power output at the best thermal efficiency. He concluded that the burning rate of fuel mass can be determined from experimental P-V diagrams. The methodology was easier in terms of the calculations and mathematics involved, which can save a lot of time and at the same time give good detail of the burning mechanism.

He found that when the hydrogen in lower volumetric supplementation rate of around 30 l/min burns predominantly in the premixed mode. However, when the flow rate of hydrogen supplementations was higher, of the order of 50 l/min or so, diffusion combustion of hydrogen fuel was quite noticeable. And, when charge diluents like helium, nitrogen, or water in an appropriate proportion were used along with the hydrogen fuel, the engine knocking tendency was suppressed and burning efficiency improved. Nitrogen was very effective in reducing ignition delay and shortening the flame length. Water causes the burning to occur at low temperature and pressure conditions, helping towards a better mixture formation rate and so, higher combustion efficiency. Water as diluents was quite advantageous for fuel economy measures.

Dorer et al. [22] along with their experimental studies presented three dimensional numerical flow simulations with the code TASC flow from ASC. The simulation allowed a variation of different or additional parameters, which could not been easily adapted in the experiments. One of these parameters was the shape of the piston. In the experimental setups, only flat pistons were in use to allow optical access in direction of the stroke. A grid of a piece of the combustion chamber with an omega trough piston and a part of the injection nozzle with one hole was simulated. This grid has approximately 150 000 volume elements. A powerful HP workstation needs CPU time of approximately 500 hours to calculate 10 ms of simulation time of this very fine mesh at that time. Also simulations with different kinds of swirl, different nozzle layouts and a variation of the boundary conditions had been carried out to gain information of the mixture formation and the temperature distribution. The analysis of the ignition delay was implemented in the flow simulation with a zero dimensional simulation of the reaction kinetics.

The program could estimate the ignition delay dependent on the temperature and concentration of hydrogen in air at a given pressure. The method allowed the definition of areas of the injection jet where self ignition conditions were present. These simulation gained information to develop an optimized injection system at given compression ratios of engines which will be converted from diesel fuel to hydrogen.

Jie Ma et al. [70] developed a comprehensive computer simulation to predict the performance of a vehicle's hydrogen engine. The effects of various coefficients, such as compression-ratio, excessive air parameter and ignition advancing, to the engine's performance were calculated and then the optimal parameters of the engine structure were determined. The simulation and analysis showed several meaningful results. Hydrogen engine might achieve a lean-combustion. While the portion of hydrogen in the mixture was large, the cylinder pressure would increase quickly and the thermal efficiency would decline. It had a higher thermal efficiency in the range of 35–50%. Its cylinder diameter had got an optimal value between 0.07 and 0.09 m. Its spark advance angle had no considerable effect on the engine's performance. The thermal efficiency grows with the increase of compression ratio.

Tsolakis and Megaritis [71] studied the smoke and NO_X from diesel engine and decreased it by using the product gas which is rich of hydrogen. When simulated reformer product gas rich in hydrogen was fed to the engine, a reduction of both NOx and smoke emissions could be achieved. The optimization of the reforming process by water addition in the reactor was presented. Using a prototype catalyst at 290°C reactor inlet temperature, up to 15% more hydrogen in the reformer product was obtained compared to operation without water. The process was found to be mainly a combination of the fuel oxidation, steam reforming and water gas shift reactions. The reforming process efficiency was shown to improve considerably with water addition up to a certain level after which the adverse effects of the exothermic water gas shift reaction became significant. They concluded that the production of hydrogen by exhaust gas assisted fuel reforming of diesel fuel at typical engine exhaust gas temperatures can be increased by water addition into the reforming reactor. Using a prototype catalyst at 290°C catalyst bed inlet temperature, the reactor product contained up to 15% more hydrogen compared to operation without water. The process was found to be mainly a combination of complete oxidation of the fuel at the inlet of the catalyst bed followed by endothermic steam reforming while the water addition promoted the water gas shift reaction as well. The hydrogen content of the reactor product was predicted by theoretical estimation of the hydrogen produced by steam reforming and the water gas shift reaction. The predicted total produced hydrogen levels were in very good agreement with the experimental results. Then, water addition up to a certain level enhanced the hydrogen produced by steam reforming.

Further increase of the water addition resulted in the increase in hydrogen production by the water gas shift reaction while it did not result in a significant increase of the hydrogen produced by steam reforming. The carbon monoxide produced by steam reforming was not fully consumed in the water gas shift reaction. Optimization of the process and the catalyst to achieve full conversion of the carbon monoxide to hydrogen by the water gas shift reaction would increase the produced hydrogen levels even further. This would be possible only at reactor temperatures favorable for the forward water gas shift reaction.

The power losses from the conversion of diesel to hydrogen-rich gas can be reduced significantly with water addition into the reforming reactor and optimization of the exhaust gas, fuel and water flow rates. The exothermic water gas shift reaction extends the hydrogen production but it can result in a reduction of the engine-reactor system overall efficiency.

Masood et al. [72] discussed the effect of blending hydrogen with diesel in different proportions on combustion emissions. A comparative study was carried out to analyze the effect of direct injection of hydrogen into the combustion chamber with that of induction through the inlet manifold for dual fuelling. Percentage of hydrogen substitution varied from 20% to 80%, simultaneously reducing the diesel percentages. CFD analysis of dual fuel combustion and emissions were carried out for both the said methods using the CFD software FLUENT, meshing the combustion chamber was carried out using GAMBIT. The standard combustion and emission models were used in the analysis. The second part of this paper was to study the effect of injection angle in both the methods of hydrogen admission, on performance, combustion and emissions were analyzed. The experimental results were compared with that of simulated values and a good agreement between them was noticed. So, the CFD analysis along with the experimental investigations carried out to compare the hydrogen-diesel dual fuel combustion and emissions by induction and direct injection methods. Fig 2.29 shows the brake thermal efficiency vs. hydrogen substitution for direct injection and inlet manifold induction. Fig. 2.30 shows the variation of combustion speed vs. the hydrogen substitution. Fig. 2.31 presents the comparison between the CFD model and experimental results for the values of NO emission.

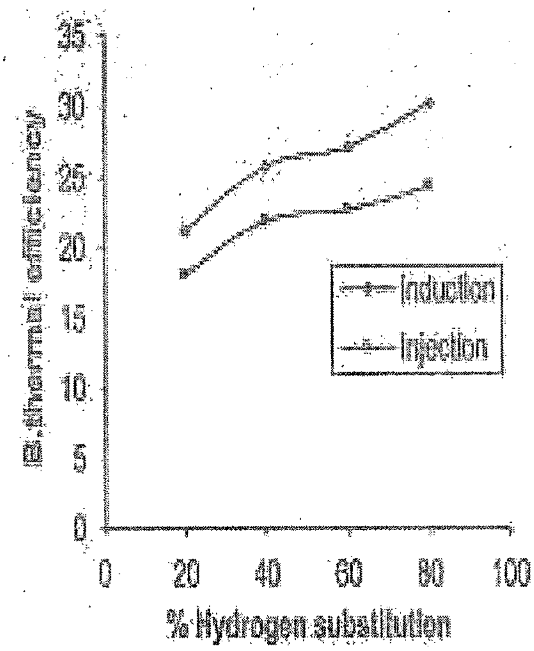


Fig. 2.29 Variation of Brake thermal Efficiency with Hydrogen Substitution Using Induction and Injection Technique [72]

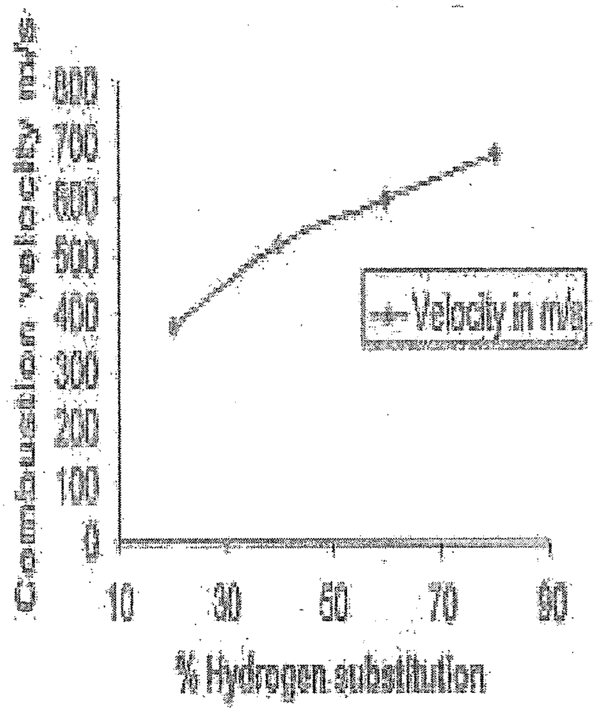


Fig. 2.30 Variation of Combustion Velocity with Hydrogen Substitution [72]

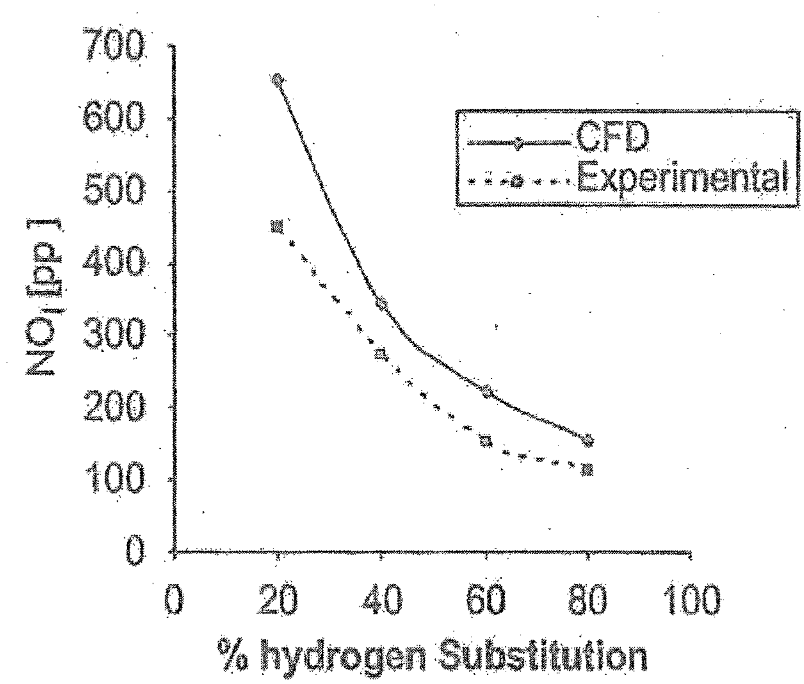


Fig. 2.31 Comparison between CFD Model and Experimental Results [72]

However, there exist many areas which are unaddressed by the model. At low and high percentages of hydrogen and during transition between diesel and hydrogen the model predictions were not very clear; this eventually showed the limitation of the model and might open doors for further investigation. The hydrogen – diesel co-fueling would perhaps solve the drawback of lean operation of hydrocarbon fuels such as diesel, which are hard to ignite and results in reduced power output, by reducing misfires, improving emissions, performance and fuel economy. However handling and storing two fuels separately posed practical difficulty. The brake thermal efficiency was around 19% higher in the induction method when compared to that of direct injection method. CFD analysis of both the methods showed that the combustion velocity increased with higher hydrogen substitutions. The predicted combustion velocities for the induction method were at least 23% higher than that of the direct injection method. The CFD analysis carried out revealed that the NO_X formation tendency was higher in case of induction than in direct injection and this tendency confirmed by the practical results obtained. The experimental results showed that pressure rise and heat released rate per crank angle in case of induction was around 17% higher than that of direct injection.

Masood and Ishrat [73] studied the problem of the drawback of lean operation with hydrocarbon fuels which reduced the power output. Lean operation of hydrocarbon engines has additional drawbacks. Lean mixtures were hard to ignite, despite the mixture being above the low fire (point) limit of fuel. This resulted in misfire, which increased un-burned hydrocarbon emissions, reduced performance and wastes fuel. They presented that; hydrogen could be used in conjunction with compact liquid fuels such as gasoline; alcohol or diesel provided each was stored separately. Mixing hydrogen with other hydrocarbon fuels reduced all of these drawbacks. They involved the simulation program for determining the mole fraction of each of the exhaust species when the hydrogen was burnt along with diesel.

The results of this programme were presented. The proportion of hydrogen in the hydrogen-diesel blend affecting the mole fraction of the exhaust species was also simulated. Experimental investigations were carried out, in hydrogen-diesel dual fuel mode, which showed a good agreement between the predicted and experimental results. The programme code developed is valid for any combination of dual fuels. They concluded that for all equivalence ratios except for 1.2 and 1.4 the mole fraction of CO_2 increased between 20% and 40% hydrogen substitution and then decreased with further increase in hydrogen percentage. As the value of equivalence ratio increased the mole fraction of NO_X decreased for both for both temperatures of 1500 K and 2000 K. The mole fraction of H2O increased with hydrogen substitution which resulted in the decrease in peak combustion temperatures.

Eichlseder et al. [74] worked in collaboration with BMW and Graz University of Technology for furthering the advancement of combustion processes utilizing hydrogen as a fuel and direct injection. The main focus was laid on the prospects and challenges referring to the application of high-pressure DI. They aimed at the development of hydrogen combustion systems for passenger cars providing highest efficiency and power density, both outranging the respective values of today's modern gasoline and diesel engines. By means of data obtained from both simulation and experiment, the progress in the field of combustion system development for hydrogen direct injection concepts was documented. In particular the methodology of a closed-loop development-process "3D-CFD simulation - optical measurement - single cylinder thermodynamic research engine" was shown based on concrete examples and results.

The 3D-CFD method - applied on both mixture formation and combustion - provided valuable inputs referring to promising layouts for both injector- and piston-geometry. To more precisely validate the results obtained from the mathematical models chosen within the CFD-code an optical accessible single cylinder research engine is additionally employed. For more detailed information regarding engine efficiency, emissions and specific power output the layouts found via the help of the aforementioned methods finally were extensively tested in various test series on a single cylinder thermodynamic research engine. The properties of different combustion chamber- and injector nozzle-geometries and their impacts on engine related parameters were compared to one another for both self-ignited and compression-ignited combustion systems. Due to conceptually different approaches, differences to some extent occurred regarding the results of wall heat transfer and/or conversion rates, which in turn affected the prediction of the engine efficiency achievable with the respective layout.

2.2.2.2 Artificial Neural Network Modeling

Artificial neural network (ANN) modeling is a powerful modeling technique that investigators employed in many engineering /technological research studies. Few studies concerned with the application of ANN are reported predicting the thermal performance and pollutants emissions for conventional diesel engines. Following are the literature available chronologically related to diesel engines.

Brace [75] developed three applications of neural networks to the prediction of diesel engine fuel consumption and emissions. According to him, the uses of ANN are quite distinct although all three applications used the same experimental data as the modeling. One network was successfully trained to predict transient changes in emissions levels following rapid changes in engine operating condition. The second was used to predict emissions during a legislative drive cycle. The final example presented was used in a power train controller to identify the ideal set point for engine speed and load to minimise fuel consumption and emissions during steady driving. He predicted the constituents of unburned hydrocarbon, HC, NO_X, particular matter, smoke and fuel [illegible]. With the mean absolute error at 2.78, 4.43, 5.42, 6.26, 2.53 and 6.26% respectively. He discussed the hardware and software arrangement and the statistical method to find the error.

Mu and Yu [76] studied the performance of a granule-based H_2-producing up flow anaerobic sludge blanket (UASB) reactor and simulated the same using neural network and genetic algorithm. A model was designed, trained and validated to predict the steady-state performance of the reactor. Organic loading rate, hydraulic retention time (HRT), and influent bicarbonate alkalinity were the inputs of the model, whereas the output variables were one of the following: H_2 concentration, H_2 production rate, H_2 yield, effluent total organic carbon, and effluent aqueous products including acetate, propionate, butyrate, valerate, and caporate. Training of the model was achieved using a large amount of experimental data obtained from the H_2-producing UASB reactor, whereas it was validated using independent sets of performance data obtained from another H_2-producing UASB reactor.

Subsequently, predictions were performed using the validated model to determine the effects of substrate concentration and HRT on the reactor performance. The simulation results demonstrate that the model was able to effectively describe the daily variations of the UASB reactor performance, and to predict the steady-state reactor performance at various substrate concentrations and HRTs.

Karri and Ho [77] investigated the use of artificial intelligent models as virtual sensors to predict relevant emissions such as carbon dioxide, carbon monoxide, un-burnt hydrocarbons and oxides of nitrogen for a hydrogen powered car. The virtual sensors were developed by means of application of various Artificial Intelligent (AI) models namely; AI software built at the University of Tasmania, back-propagation neural networks with Levenberg–Marquardt algorithm, and adaptive neuro-fuzzy inference systems.

These predictions were based on the study of qualitative and quantitative effects of engine process parameters such as mass airflow, engine speed, air-to-fuel ratio, exhaust gas temperature and engine power on the harmful exhaust gas emissions. All AI models showed good predictive capability in estimating the emissions. However, excellent accuracy was achieved when using back-propagation neural networks with Levenberg–Marquardt algorithm in estimating emissions for various hydrogen engine operating conditions with the predicted values less than 6% of percentage average root mean square error.

Ghobadian et al. [78] conducted a comprehensive combustion analysis to evaluate the performance of a commercial DI engine, water cooled two cylinders, in-line, naturally aspirated, RD270 Ruggerini diesel engine using waste vegetable cooking oil as an alternative fuel. In order to compare the brake power and the torques values of the engine, tests were conducted under same operating conditions with diesel fuel and waste cooking biodiesel fuel blends. The results were found to be very comparable. The properties of biodiesel produced from waste vegetable oil was measured based on ASTM standards. The total sulfur content of the produced biodiesel fuel was 18 ppm which was 28 times lesser than the existing diesel fuel sulfur content used in the diesel vehicles operating in Tehran city (500 ppm). The maximum power and torque produced using diesel fuel was 18.2 kW and 64.2 Nm at 3200 and 2400 rpm respectively. By adding 20% of waste vegetable oil methyl ester, it was noticed that the maximum power and torque increased by 2.7 and 2.9% respectively, also the concentration of the CO and HC emissions have significantly decreased when biodiesel was used.

An (ANN) was developed based on the collected data of this work. Multi layer perceptron network (MLP) was used for nonlinear mapping between the input and the output parameters. Different activation functions and several rules were used to assess the percentage error between the desired and the predicted values. The results showed that the training algorithm of Back Propagation was sufficient enough in predicting the engine torque, specific fuel consumption and exhaust gas components for different engine speeds and different fuel blends ratios. It was found that the R2 (R: the coefficient of determination) values are 0.99994, 1, 1 and 0.99998 for the engine torque, specific fuel consumption, CO and HC emissions, respectively.

Obodeh and Ajuwa [79] evaluated the capabilities of ANN as a predictive tool for multi-cylinder diesel engine NOx emissions. ANNs were trained on experimental data and used to predict the oxides of nitrogen NO_x emissions under various operating variables. Fraction of variance and mean absolute percentage error were used for comparison in the sensitivity analysis. The Levenberg-Marquardt LM algorithm with 11 neurons produced the best results. Among the examined combinations of learning criteria in different architectures of back propagation designs, a set of 0.05, 0.05 and 0.3 for learning rate, momentum and weight respectively, gave the best-averaged accuracy. For pre-specified engine speeds and loads with LM algorithm, mean absolute percentage errors were found to be between 0.68 and 3.34%.

Hidayet et al. [80] developed an ANN to apply on automotive sector as well as many different areas of technology aiming to overcome difficulties of the experiments, minimize the cost, time and workforce waste. They gathered the experimental data for diesel fuel, biodiesel, B20 and bioethanol-diesel fuel having different percentages 5%, 10%, and 15% and biodiesel to use in development of artificial neural network. Mixtures were also controlled for their fuel properties and motor experiments were performed to collect the reference values. Power, moment, hourly fuel consumption and specific fuel consumption were estimated by using the artificial neural network developed by using the reference values. Estimated values and experiment results are compared. As a result, from the performed statistical analyses, it was seen that realized ANN model is an appropriate model to estimate the performance of the engine used in the experiments. Reliability values were calculated as 0.9994 and mean absolute error is 5% by using statistical analysis.

Hari Prasad et al. [81] used ANN technique to model and predict the exhaust emissions of diesel engine operated by biodiesel. Acquire data was used to train and test the proposed ANN. A single cylinder, four-stroke test engine was fuelled with biodiesel blended with diesel and operated at different loads. Using some of the experimental data for training, an ANN model based on feed forward neural network for the engine was developed. Then, the performance of the ANN predictions were measured by comparing the predictions with the experimental results which were not used in the training process. They observed that the ANN model can predict the engine exhaust emissions quite well with correlation coefficients, with very low root mean square errors. This study showed that, as an alternative to classical modeling techniques, the ANN approach can be used to accurately predict the performance and emissions of internal combustion engines.

Recently, **Manjunatha et al. [82]** conducted technical analysis to model diesel engine exhaust emissions by using ANN. They studied the effectiveness of various biodiesel fuel properties and engine operating conditions on diesel engine combustion towards the formation of exhaust emissions. The experimental investigations were carried out on a single cylinder Direct Injection combustion ignition engine using blends of biodiesel methyl esters from Pongamia, Jatropha and Neem oils. The performance parameters such as brake power, brake thermal efficiency, brake specific fuel consumption, volumetric efficiency and exhaust gas temperature are measured along with regulated and unregulated exhaust emissions of CO, HC and NOx. They developed the ANN base on the available experimental data. Multi layer perceptron neural network was used for nonlinear mapping between input and output parameters of ANN.

Biodiesel blend percentage, calorific value, density, Cetane number of each biodiesel blend and operating load are used as inputs to train the neural network. The exhaust gas emissions like NOx, CO and HC were predicted for the new fuel and its blends. They used different activation functions and several rules to train and validated the normalized data pattern and an acceptable percentage error was achieved by Levenberg-Marquardt design optimization algorithm. The results showed that training through back propagation was sufficient enough in predicting the engine emissions. It was found that Regression Coefficient values were 0.99, 0.95 and 0.99 for NOx, CO and HC emissions, respectively. Therefore, the developed model can be used as a diagnostic tool for estimating the emissions of biodiesels and their blends under varying operating conditions.

From the existing open literature, it is observed that the use of ANNs is a powerful modeling tool that has the ability to identify complex relationships from input–output data. However, no investigation to predict the thermal performance or gas emissions constituents for diesel engine operated by hydrogen-diesel mix using ANN approach appears to have been published in the literature so far.

2.2.2.3 Genetic Algorithm Optimization

Many of techniques for optimization are available. Optimization using genetic algorithm (GA) has gained momentum since the beginning of the 21st century in almost all areas of engineering field. A review of literature related to optimization using GA applied to the thermal performance and emission characteristics of internal combustion engines show that there are only a few studies reported in general and diesel engines in particular. Further, the optimization studies on thermal performance and pollutant emissions of diesel – hydrogen blends appears to have not been carried out.

Setnes and Roubos [83] offered description to the use of GAs and other evolutionary optimization methods to design fuzzy rules for systems modeling and data classification that received much attention in recent literature. They had focused on various aspects of these randomized techniques, and whole scales of algorithms were proposed. They commented on some recent work and describe a new and efficient two-step approach that leads to good results for function approximation, dynamic systems modeling and data classification problems. First fuzzy clustering was applied to obtain a compact initial rule-based model.

Then this model was optimized by a real-coded GA subjected to constraints that maintain the semantic properties of the rules. They considered four examples from the literature; viz., a synthetic nonlinear dynamic systems model, the iris data classification problem, the wine data classification problem, and the dynamic modeling of a diesel engine turbocharger. The results were compared to other recently proposed methods.

Risi et al. [84] proposed the optimization method consisting of a multi-objective genetic algorithm combined with an experimental investigation carried out on a test bench, using a DI Diesel engine. The genetic algorithm selected the injection parameters for each operating condition whereas the output measured by the experimental apparatus determined the fitness in the optimization process. The genetic algorithm created a random population, which evolved combining the genetic code of the most capable individuals of the previous generation. They presented each individual of the population by a set of parameters codified with a binary string. The evolution was performed using the operators of crossover, mutation and elitist reproduction. This genetic algorithm allows competitive fitness functions to be optimized with a single optimization process. For the determination of the overall fitness function the concept of Pareto optimality had been implemented. They selected the input variables for the optimization method as injection parameters like start of pilot and main injection, injection pressure and duration. The engine used was a FIAT 1929 cc DI diesel engine, in which the traditional injection system had been replaced by a common rail high pressure injection system. The competitive fitness functions were determined based on the measured values of fuel consumption, emissions levels of NOx, soot, CO, CO2, and HC, combustion noise and overall engine noise, for each operating conditions. The optimization was performed for different engine speed and torque conditions typical of the EC driving cycles.

Hiroyasu et al. [85] developed GA computer code to optimize diesel engine emissions and fuel economy with the existing techniques, such as exhaust gas recirculation (EGR) and multiple injections. They found that a computational model of diesel engines named HIDECS was incorporated with the genetic algorithm GA to solve multi-objective optimization problems related to engine design. The phenomenological model, HIDECS code was used for analyzing the emissions and performance of a diesel engine. An extended genetic algorithm called the 'Neighborhood Cultivation Genetic Algorithm' (NCGA) was used as a optimizer due to its ability to derive the solutions with high accuracy effectively.

The HIDECS-NCGA methodology was used to optimize engine emissions and economy and simultaneously. The multiple injection patterns were included, along with the start of injection timing, and EGR rate. They found that the combination of HIDECS and NCGA is efficient and low in computational costs. The Pareto optimum solutions obtained from HIDECSNCGA are very useful to the engine designers. They show that it is possible to reduce emissions without increasing the fuel consumption by the optimization of exhaust gas recirculation (EGR) and multiple injections.

Hiroyasu et al. [86] applied the multi-objective genetic algorithm MOGA and phenomenological model for parameter searching of diesel engine combustion problems. The proposed system was applied to heavy-duty diesel engine design. He simulated the MOGA and derived the Pareto optimum solutions successfully. And the users could derive the information of the relationship between the objective functions from the derived Pareto optimum solutions. This information was very useful for diesel engine designers. For example, there is a trade-off relationship between specific fuel consumption SFC and NOx. On the other hand, the relation between SFC and SOOT was linear. As the sensitivities with respect to each objective are derived, even when designers know that a trade-off relationship exists between the objectives, it was possible to choose an appropriate design candidate from the Pareto optimum solutions. He presented the derivation of the Pareto optimum solutions by GAs that required a large number of calculation iterations. Also, the phenomenological model could simulate diesel engine combustion precisely. He selected boost pressure, start and duration angle of injection, EGR, and swirl ratio were chosen as design variables. With increase in the number of design variables, the search space became larger. This indicates that user can obtain a large design space with a higher number of design variables. On the other hand, it incurred a high calculation cost. GA can be used to treat these design variables in the simulations.

Kesgin [87] prepared a computer program to calculate the amount of NO_X emissions based on a reaction kinetic model which was developed. The validity of this program was verified by measurements from a turbocharged, lean-burn, natural gas engine. By using the results from this program, the effects of operational and design parameters of the engine were investigated. Then a wide range of engine parameters were opitimised using simple genetic algorithm regarding both efficiency and NO_X emissions. Due to the large computation requirements especially for NO_X level determination, an artificial neural network model based on results of these investigations was used to predict the engine efficiency and NO_X emissions. The results showed an increase in efficiency as well as the amount of NO_X emissions being kept under the constraint value of 250 mg/Nm3 for stationary engines.

Srinivasan et al. [88] developed a computationally efficient CFD-based tool for finding optimal engine operating conditions with respect to fuel consumption and emissions. The optimization algorithm employed was based on the steepest descent method where an adaptive cost function was minimized along each line search using an effective back-tracking strategy. The adaptive cost function was based on the penalty method, where the penalty coefficient was increased after every line search. The parameter space was normalized and, thus, the optimization occurs over the unit cube in higher dimensional space. The application of this optimization tool was demonstrated for the Sulzer S20, a central-injection, non-road DI diesel engine. The optimization parameters were the start of injection of the two pulses, the duration of each pulse, the duration of the dwell, the exhaust gas recirculation rate and the boost pressure. They used a zero-dimensional engine code to simulate the exhaust and intake strokes to predict the conditions at the closure of the inlet valves. These data were then used as initial values for the three-dimensional CFD simulation which, in turn, computes the emissions and specific fuel consumption. Simulations were performed for two different cost functions with different emphasis on the fuel consumption. The best case showed that the nitric oxide and the particulates could be reduced by over 83% and almost 24%, respectively, while maintaining a reasonable value of specific fuel consumption. Moreover, the path taken by the algorithm from the starting point to the optimum was investigated to understand the influence of each parameter on the process of optimization.

Samadani et al. [89] used the genetic algorithm in diesel engine field. They optimized the engine performance and emissions using multi objective genetic algorithm technique. This technique was implemented on a closed cycle two zone combustion model of a DI diesel engine. The combustion model was developed by Matlab programming and validated by single cylinder Ricardo data obtained from the engine. The main outputs of this model were NO_X, soot, and engine performance. The optimization goals were to minimize NO_X and soot at the same time while maximizing the engine efficiency. Injection timing, injection duration and air/fuel ratio were selected from engine inputs as design variables. a neural network model in a wide range of engine operation. Design variables were optimized using genetic algorithm and three common algorithms for multi objective optimization were applied and results were compared.

From the above review, it is seen that GA is a suitable optimization tool that has the ability to identify complex relationships from input–output data. However, the powerful optimization tool appears to have not been exploited in the theoretical studies related to hydrogen-diesel supplementation. No investigation to optimize performance and/or emission gas constituents of diesel engine operated by hydrogen-diesel mix is found in the open literature.

2. 3. Scope for the Present Investigation

A detailed and systematic review of the literature concerned with the development of diesel engines as an important prime mover and the thermal performance evaluation and pollutant emission characteristics of hydrogen – diesel blends in diesel engines are given in Sections 2.1 and 2.2. They were grouped based on the developments that took place before and after the 'energy crisis of 1970s. Hydrogen as a substitute for diesel oil or hydrogen supplementation with diesel for reducing the consumption of diesel oil became a priority for the investigators due the 'oil shock' of 1970s. Fig. 2.32 depicts the various routes of the experimental and theoretical investigations took place during the last 40 years in the area of hydrogen-diesel dual fuel. Table 2.1 gives the summary and comparison of the investigations reviewed to identify the probable research area.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E*	T*		
8	K. S. Varde and G. A. Frame	1983	✓		Indirect injection – inlet manifold induction	Reduction of soot came as a result to: combustion chamber high temperature led to burn some soot, H2 produce only H2O so soot decreased with H2 burning rate, H2 might work in lean mixture.
9	K. S. Varde and G. A. Frame	1984	✓		Direct injection – inlet manifold injection	Improved in brake thermal efficiency and controlled of back firing.
10	S. Furuhama and Y. Kobayashi	1984	✓		Direct injection	proper selection of combustion chamber shape, number of injection nozzles, direction of injection, etc.; effected on maximum power value.
11	B. A. Steinberg and D. S. Scott	1984		✓		Simulation of hydrogen – diesel blend was done to help in understand the combustion and emission characteristics.
12	K. S. Varde and G. A. Frame	1985	✓		Direct injection	Developed high pressure injector, caused engine performance enhancement.
13	Furuhama and T. Fukuma	1986	✓		Direct injection	Turbo charger was adopted to enhance the air- hydrogen mixture, hot surface was used to ignite the hydrogen in combustion chamber. LH_2 pump was developed to provide high pressure.
14	Li Jin-Ding et al	1986	✓		Indirect injection – inlet manifold induction	Diesel smoke reduced by hydrogen supplementation. And low speed and high load is better than other running conditions.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E*	T*		
15	G. P. Prabhukumar et al.	1987	✓		indirect injection- inlet manifold induction	Avoided the back flash by add some percentage of water to quench the flue gases in the combustion chamber and give a chance for further H_2 induction.
16	S. Furuhama	1989	✓		Direct injection	Proposed hydrogen fuel system for diesel engine which included LH_2 tank at low pressure, LH_2 pump for high pressure injection and spark igniter.
17	J. K. S. Wong	1990	✓		Direct injection	Using of hydrogen as a sole fuel in direct injection without an ignition source diesel engine is not practical or feasible
18	H. B. Mathur and L. M. Das	1991	✓		Indirect injection inlet manifold injection with diluent	Water was found to be the best diluent which permitted up to 66% full load energy substitution by hydrogen without engine knock.
19	H. B. Mathur et al.	1992	✓		Indirect injection inlet manifold injection with diluent	Addition of diluents improves the knock-limited engine operation. Nitrogen is the best diluent from an engine performance point of view, while from standpoint of emission level, water appears to score over a nitrogen diluents
20	S. M. Lambe and H. C. Watson	1992	✓		Indirect injection- intake port injection	Supplied 65-90% of required energy by H_2 in diesel engine. Delayed port admission of the gas, later injection timing and modified combustion chamber allowed 15% increase in efficiency. Water injection helped to avoid back flash.
21	T. N. Patro	1993		✓		With the help of a P- θ trace, the model applied to the test hydrogen energy substitution, with and without various charge diluents in diesel engine.
23	T. N. Patro	1994		✓		Derived the burning rate from the experimental P-V diagram and its application to a hydrogen-enriched dual-fuel diesel engine to assess its combustion process.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E*	T*		
24	S. J. Lee et al.	1995	✓		Indirect injection – intake port injection	Noticed the hot spot, such as lubricant deposit or spark plug rather than the high temperature residual gas itself caused the flash back.
25	H. S. Yi et al.	1996	✓		Direct injection and indirect-intake port injection	Solenoid valve developed to inject H_2 directly, engine performance and emission for direct injection and indirect injection are compared. Performance of the direct injection type is superior to the intake port injection type as fuel-air equivalence ratio goes to stoichiometry.
26	F. Dorer et al.	1998	✓		Direct injection	Laser-Induced Fluorescence (LIF) on tracer molecules and the Schlieren/Schatten method ae used to test the hydrogen – air mixture and moniter high ressure H_2 in combustion chamber.
27	Peter Prechtl et al.	1998	✓		Direct injection	Optical technique to analyze the combustion and ignition of H2 inside combustion chamber of diesel engine are used. Turbulences and swirls supported propagation of the flame over the whole combustion chamber and regulate the combustion for smoother pressure rates.
28	Peter Prechtl et al.	1998	✓		Direct injection	High pressures and temperatures for hydrogen have a positive influence on a short ignition delay.
29	Peter Prechtl et al.	1998		✓		Three dimensional numerical flow simulations with the code. The simulation allowed a variation of different or additional parameters, which could not been easily adapted in the experiments.
30	J. D. Naber and D. L. Siebers	1998	✓		Direct injection	DI hydrogen combustion rates are insensitive to reduced oxygen concentration and are significant because it offered the potential for a dramatic reduction in the emission of nitric oxides
31	Keith at al.	1999	✓		Diesel with addative	Methylal might be an effective blend for diesel fuel provided reduction in emission and enhancement in performance.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E	T		
32	Eiji Tomita et al.	2000	✓		Indirect injection intake port injection	The mixture of hydrogen-air had ignition delay which became long because molar concentration of oxygen decreased.
33	Magne Setnes and Hans Roubos	2000		✓		Model was optimized by a real-coded GA subjected to constraints that maintain the semantic properties of the rules.
34	Eiji Tomita et al.	2001	✓		Indirect injection intake port injection	Ignition delay increased when hydrogen is inducted from the intake manifold because the mole fraction of hydrogen was so large that oxygen in the intake air was reduced.
35	S. Verhelst and R. Sierens	2001	✓		Direct injection	Converted a GM/Crusader V8 SI engine for hydrogen use, to be built in a city bus
36	Ho Teng et al.	2001	✓		Diesel + additive	DME spray in the engine cylinder would differ significantly from that of diesel fuel due to the thermodynamic characteristics of DME.
37	Irashad Ahmed	2001	✓		Diesel + additive	Over 41% reduction in PM, 27%reduction in CO, and 5% reduction in NO_X from a HD diesel engine used ethanol- diesel blend.
38	Mitsuru et al.	2001	✓		Diesel + additive	Reduction in gas emission.
39	Arturo de Risi et al.	2002		✓		Optimization method consisting of a multi-objective genetic algorithm combined with an experimental investigation carried out on a test bench, using a DI Diesel engine.
40	Tomoyuki Hiroyasu et al.	2002		✓		Developed GA computer code to optimize diesel engine emissions and fuel economy with the existing techniques, such as exhaust gas recirculation (EGR) and multiple injections.
41	Hiro Hiroyasu et al.	2003		✓		Applied the multi-objective genetic algorithm and phenomenological model for parameter searching of diesel engine combustion problems.
42	M. Senthil Kumar et al.	2003	✓		Indirect injection inlet manifold injection with biodiesel	Hydrogen induction with biodiesel-diesel blends led to increasing the efficiency and reduced the hydrocarbon emission.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E*	T*		
43	Jie Ma et al.	2003		✓		Developed a comprehensive computer simulation to predict the performance of a vehicle's hydrogen engine.
44	Verstraeten Stefaan	2004	✓		Indirect injection intake port injection	Optimized the ignition timing, injection start and duration for hydrogen fuel.
45	Mihaylov Milen and Barzev Kiril	2004	✓		Indirect injection	Addition of hydrogen to the intake or delivery into the cylinder of diesel engine could improve combustion process due to superior combustion characteristics of hydrogen in comparison to conventional diesel fuel.
46	A. Tsolakis and A. Megaritis	2004	✓		Indirect injection – inlet manifold injection with EGR	Achieving reduction of smoke and NO_x emissions and improved fuel economy.
47	Uger Kesgin	2004		✓		computer program to calculate the amount of NO_X emissions based on a reaction kinetic model which was developed. Optimization by using simple genetic algorithm regarding both efficiency and NO_X emissions.
48	A. Tsolakis and A. Megaritis	2005		✓		Simulated and optimized reformer product gas rich in hydrogen was fed to the engine, a reduction of both NOx and smoke emissions could be achieved
49	Zuohua huang et al.	2006	✓		Direct injection	H_2 fraction was less than 10%, combustion durations increased with increasing hydrogen fractions; conversely, combustion durations decreased with increasing hydrogen fractions when the hydrogen fraction was larger than 10%.
50	Seshasai Srinivasan et al	2006		✓		Developed CFD-based tool for finding optimal engine operating conditions with respect to fuel consumption and emissions. Opitimization techniques used to minimize the fuel consumption and emissions.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E*	T*		
51	M. Masood et al.	2007	✓		Direct injection	Hydrogen performed better at high compression ratios. a sharp increase in the NO_X value as the inlet temperature was increased from 65 to 85 °C. CO, HC and particulate matter continuously decreased with the increase in hydrogen percentage for all compression ratios and loads while NO_X was increased.
52	N. Saravanan et al.	2007	✓		indirect injection- timing port injection	Injection duration of 90 crank angle and start of injection at 5° ATDC gave the best results both performance and emission wise.
53	Radu Chiriac et al.	2007	✓		indirect injection- inlet manifold induction	A strong relation between equivalence ratio, mixing quality and the performance of hydrogen diesel blend
54	N. Saravanan et al.	2008	✓		indirect injection- timing port injection and carburetion	A comparison between the results for the injection of hydrogen by using the timing port injection and carburetor system is presented. Timing port technique showed better results in performance and emission wise
55	N. Saravanan et al.	2008	✓		indirect injection- intake port injection	A significant reduction in smoke intensity was observed with increase in hydrogen enrichment with the lowest smoke level.
56	J. M. Gomes Antunes et al.	2008	✓		indirect injection- intake port injection	The inlet air had to be heated in order to ensure auto ignition, and it was demonstrated that the inlet air temperature was the most useful variable to control ignition timing.
57	N. Saravanan and G. Nagarajan	2008	✓		Indirect injection – intake port with EGR	The optimum EGR percentage was found to be 20% at part loads, which gave lesser smoke compared to diesel with higher NOx reduction.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E	T		
58	N. Saravanan et al.	2008	✓		Indirect injection – intake port with EGR with carburetion	There was a reduction in the specific energy consumption. NO_X concentration decreased with EGR technique.
59	V. Edwin Geo et al.	2008	✓		Indirect injection inlet manifold injection with biodiesel	Hydrogen could be inducted along with air in order to reduce smoke levels and improve thermal efficiency of biodiesel fuelled diesel engines
60	M. Masood et al.	2008		✓		CFD analysis of dual fuel combustion and emissions were carried out for both the said methods using the CFD software FLUENT. Comparison held with the experimental results
61	M. Masood and M.M. Ishrat	2008		✓		Mixing hydrogen with other hydrocarbon fuels reduced of lean mixture and misfire. Full simulation mode developed to predict performance and emission of hydrogen diesel blends
62	Helmut Eichlseder et al.	2008		✓		3D-CFD simulation/optical measurement-single cylinder thermodynamic research engine" was shown modeling to performance and emission.
63	Ehsan Samadani et al.	2008		✓		optimized the engine performance and emissions using multi objective genetic algorithm technique
64	N. Saravanan and G. Nagarajan	2009	✓		Indirect injection inlet manifold timing injection	Optimum injection timing was at gas exchange top dead center. A significant improvement in performance and reduction in emissions.

*E- experimental, T- theoretical.

No.	Investigator (s)	Year	Type of Work		H_2 Supplementation Technique	Remarks
			E	T		
65	N. Saravanan and G. Nagarajan	2009	✓		Indirect injection intake port injection	Observed that the optimum timing in port injection was 5° before gas exchange top dead center. Injection duration of 30° crank angle. Hydrogen flow rate was varied from 2 to 9.5 l/min with optimized conditions for both port and manifold injection.
66	Probir Kumar Bose and Dines Maji	2009	✓		Indirect injection timed manifold induction with EGR	The solenoid valve was activated by the new technique of taking signal from the rocker arm of the engine instead of cam actuation mechanism.
67	N. Saravanan et. al.	2009			Indirect injection inlet manifold injection with additive	The optimized timing for the injection of hydrogen was 5° CA before gas exchange top dead center. and 40° CA after gas exchange top dead center (AGTDC) for DEE.
68	Vishy Karri and Tien Nhut Ho	2009		✓		Use of ANN models as virtual sensors to predict relevant emissions such as carbon dioxide, carbon monoxide, un-burnt hydrocarbons and oxides of nitrogen for a hydrogen powered car.
69	B. Ghobadian et al.	2009		✓		ANN was developed based on the collected data to predict the performance of diesel engine fuelled by biodiesel-diesel blends.
70	O. Obodeh and C. I. Ajuwa	2009		✓		ANNs were trained on experimental data and used to predict the oxides of nitrogen NO_x emissions under various operating variables.
71	Hidayet et al.	2010		✓		Gathering experimental data for diesel fuel, biodiesel, B20 and bioethanol-diesel fuel having different percentages 5%, 10%, and 15% and biodiesel was used to develop artificial neural network.
72	T. Hari Prasad et al.	2010		✓		ANN technique to model and predict the exhaust emissions of diesel engine operated by biodiesel.
73	R.Manjunatha et al.	2010		✓		ANN base on the available experimental data was developed to predict the diesel engine emissions.

*E- experimental, T- theoretical.

It can be seen that a number of investigations are reported for hydrogen as fuel to substitute for diesel and direct injection of hydrogen in diesel engine. A number of studies using hydrogen supplementation indirectly using port injection are also reported extensively. No experimental investigations however, are appeared to have been reported on the indirect induction of hydrogen in the manifold of diesel engine using diesel oil with and without Mythelal as additive enhance. Similarly, no theoretical studies using the experimental data on indirect hydrogen induction in manifold of diesel engine using diesel oil with and without an additive either to optimize using genetic algorithm or to model using artificial neural network are reported. The present research work is an attempt in those directions. Fig. 2.33 gives the route for the proposed investigation.

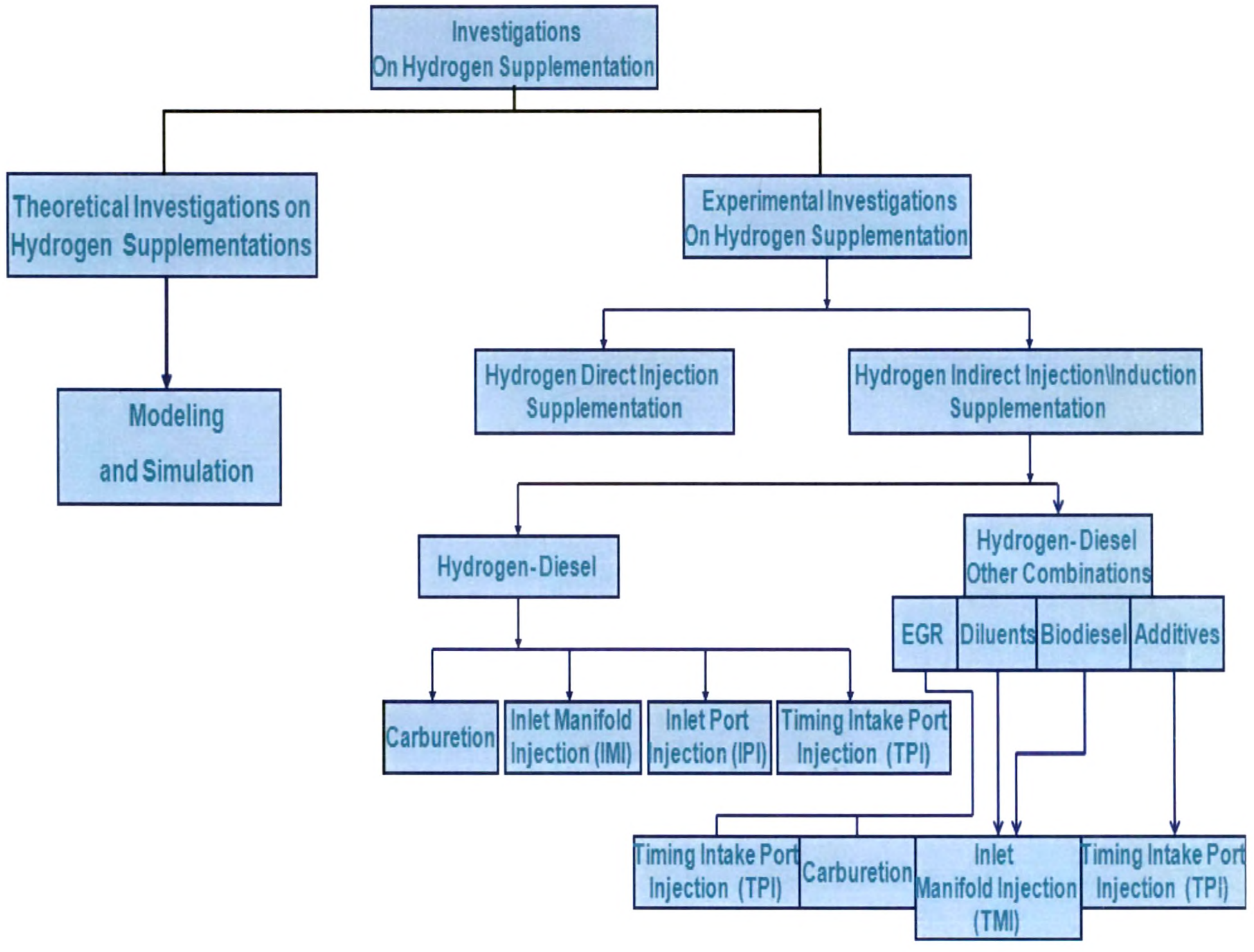


Fig. 2.32 Research on Hydrogen Supplementation

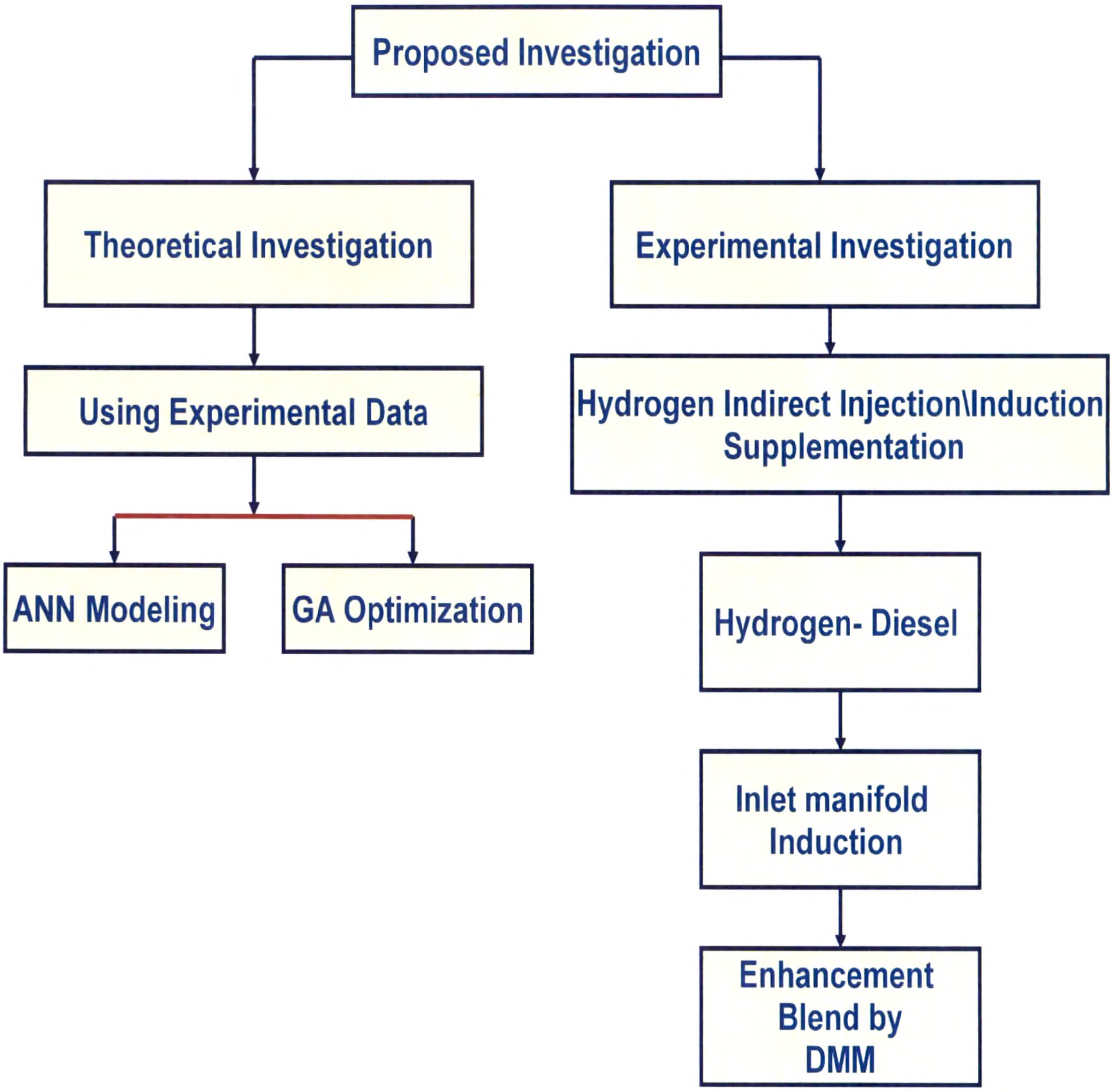


Fig. 2.33 Scope of the Proposed Experimental & Theoretical Study

2.3.1 Objectives of the Present Study

The following are the objectives of the present study.

1. To experimentally evaluate 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. To experimentally evaluate 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.

3. To experimentally optimise 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.
4. To develop a theoretical model using artificial neural network model for predicting engine performance and emissions.
5. To optimize the experimentally captured data using single and multi objective genetic algorithm techniques to find the optimum operation conditions with reference to engine performance together with pollutants emissions.