International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

A Review on Hydrogen Supplementation in Compression Ignition Engines

Haroun A.K. Shahad† and Emad D. Aboud†*

†Department of Mechanical Engineering, College of Engineering ,University of Babylon, Babylon, Iraq

Accepted 15 April 2015, Available online 25 April 2015, **Vol.5, No.2 (April 2015)**

Abstract

This paper highlights the Hydrogen utilization in internal combustion engines and mainly focuses on compression ignition engines. This hydrogen utilization is either pure or as supplemented. Further, the paper tries to synchronize the past experience of the researchers to very recent efforts of the experts of this area. Mainly the paper also discusses the various undesirable phenomena and its effects on engine performance and emission variations and their remedies with reference to hydrogen introduction and induction in compression ignition engines. Also presents the importance of direct and indirect injection with reference to application of alternative fuels. The study is divided to include, theoretical and experimental investigations on hydrogen supplementation. Theoretical studies included the modeling and simulation, artificial neural network modeling and genetic algorithm optimization while the experimental investigations included the hydrogen direct injection technique, hydrogen indirect injection / induction technique, exhaust gas recirculation (EGR) with hydrogen-diesel, diluents with hydrogen-Diesel, biodiesel with hydrogen-diesel or with diesel alone and additives with hydrogen-diesel or with diesel alone.

Keywords: *Hydrogen, supplemented fuel, Internal Combustion engine, compression ignition engine.*

1. Introduction

The trio of conventional fossil fuels, viz., petroleum, natural gas and coal which meet most of the world's energy demand today, are being depleted rapidly. Also, their combustion products are causing global problems, such as the greenhouse effect, ozone layer depletion, acid rains and pollution, which are posing great danger for our environment, and eventually, for the total life on our planet. However, it has become apparent over last decades that the harmful effects of exhaust gas emissions constituents, both in terms of the damage to the environment and human health, is such that worldwide legislation has been put in place. This has therefore meant that the development on diesel engines have been driven by the need to reduce the exhaust gas emissions.

Alternative fuels, known as non-conventional or advanced fuels, are any materials or substances that can be used as fuels, other than conventional fuels. Some well-known alternative fuels include biodiesel, bio alcohol such as methanol, ethanol, butanol, chemically stored electricity such as batteries and fuel cell, hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil and other biomass sources. And also, there are alternative fossil fuels such as compressed natural gas (CNG).

*Corresponding author: **Emad D. Aboud**

Hydrogen is thought to be a major energy resource of the future due to its clean burning nature and eventual availability from renewable sources. Combustion of hydrogen can lead to higher thermodynamic efficiency on account of its higher flame speed when compared to conventional liquid fuels. Thus, hydrogen can also be used to enhance the combustion rate of slow burning fuels. The wide flammability limits of hydrogen can lead to low hydrocarbon and carbon monoxide emissions when it is used along with other fuels. The implementation of duel fuelling of hydrogen-diesel is one of the many methods investigated to control the emission and enhance the diesel engine efficiency. The supplementing of hydrogen in compression ignition engine serves to reduce the greenhouse emission, reduce the conventional fossil diesel consumption and enhance the engine performance.

Development of more efficient compression ignition engines is based on experimental and theoretical investigation. Alongside experimental investigations, with the advancement in computing techniques, the theoretical, simulation, modeling and optimization studies applied to engine performance are attempted by many investigators. Simulation, modeling and programming for performance, fuel consumption, exhaust temperature, toxic emissions and other factors are built, today, many techniques, packages and codes are used for diesel-hydrogen mixtures or blends.

2. Theoretical Investigations

Post energy crisis era saw a number of theoretical investigations attempted 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. Specific attempt is made to identify research literature relevant to area of hydrogen-diesel supplementations.

2.1 Modeling and Simulation

A simple method to determine the burning rate from the experimental P-V diagram and its application to a hydrogen-enriched dual-fuel diesel engine was derived by (T. N. Patro, 1993). He gave good details 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. The data had been obtained for a small horsepower diesel engine. The engine was operated with a fixed maximum load with varying rates of hydrogen induction into the engine intake manifold. In a second set of tests, the hydrogen flow rate was kept fixed while the load on the engine was varied until knock was encountered. In the a series of tests, various diluents were tried with varying hydrogen flow rate to achieve maximum knock-limited power output at the best thermal efficiency. The methodology was easier in terms of the calculations and mathematics involved, which can save a lot of time and at the same time gave good details of the burning mechanism.

He found that 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. A comprehensive computer simulation was developed by (Jie Ma *et al*, 2003) to predict the performance of a hydrogen engine. The effects of various coefficients, such as compression-ratio, excessive air parameter and ignition advancing, on engine 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. The engine 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, and, its spark advance angle had no considerable effect on the engine performance. The thermal efficiency increased with the increase of compression ratio. Al-Dawoodi [M. F. Al-Dawoodi, 2006] studied theoretically, the effect of hydrogen addition on the performance and emission of a diesel engine. A multi-zone combustion model to simulate a four stroke cycle of a diesel engine fueled with hydrogen-diesel mixture was developed. The effect of dissociation of combustion products and rate kinetics is accounted for in this model. A computer program written in Fortran 90 language had been developed to predict the performance and emission levels in diesel engine working with three types of fuels, ie. Diesel, diesel-hydrogen mixture and hydrogen. It was found that the addition of 12 % by mass of hydrogen is an optimum hydrogen/diesel ratio. The addition of hydrogen caused an increase in the maximum (pressure, zonal temperature, and rate of heat release) .This is due to the increase in the rate of mass burning, therefore, the time required to complete the combustion is reduced. It was also found that the addition of 12% by mass of hydrogen caused reduction in the soot and CO concentrations in the exhaust gases. Soot was reduced by 33% while CO was reduced by 65%. This is attributed to the reduction in the carbon atoms concentration in the mixture of hydrogen-diesel fuel. However, the NO_x concentration was increased due to the increase in the peak zonal temperature level caused by faster heat release and the reduction in the time required to dissociate NO to N_2 and O_2. In general, the addition 10% hydrogen by mass gave a maximum improvement in the power and efficiency and a maximum reduction in specific fuel consumption 60%.

(M.M. Rahman *et al*, 2009) focused on the effect of air-fuel ratio on the performance of four cylinder hydrogen fueled direct injection internal combustion engine. They developed a model for direct injection engine. Air-fuel ratio was varied from rich limit to a lean limit and the rotational speed of the engine was varied from 2500 to 4500 rpm. The acquired results showed that the air fuel ratio had great influence on the brake mean effective pressure (BMEP), brake efficiency (BE), brake specific fuel consumption (BSFC) as well as the maximum cylinder temperature. The test engine was modeled utilizing the GT- Power software.

The variation of brake mean effective pressure and brake thermal efficiency with air fuel ratio for various engine speeds is shown in figure (1) The air-fuel ratio AFR was varied from rich limit (AFR = 27.464:1 based on mass where the equivalence ratio $\emptyset = 1.2$) to a very lean limit (AFR =171.65 where $\emptyset = 0.2$) and engine speed varied from 2500 rpm to 4500 rpm. BMEP was a good parameter for comparing engines with regard to design due to its independence on the engine size and speed. It is shown that BMEP decreased with increased in AFR and speed.

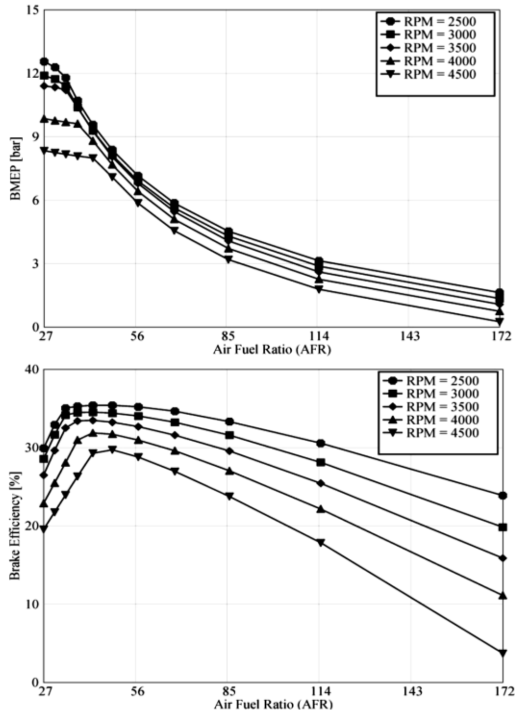


Fig. 1 Variation of brake mean effective pressure and brake thermal efficiency with air fuel ratio for various engine speeds

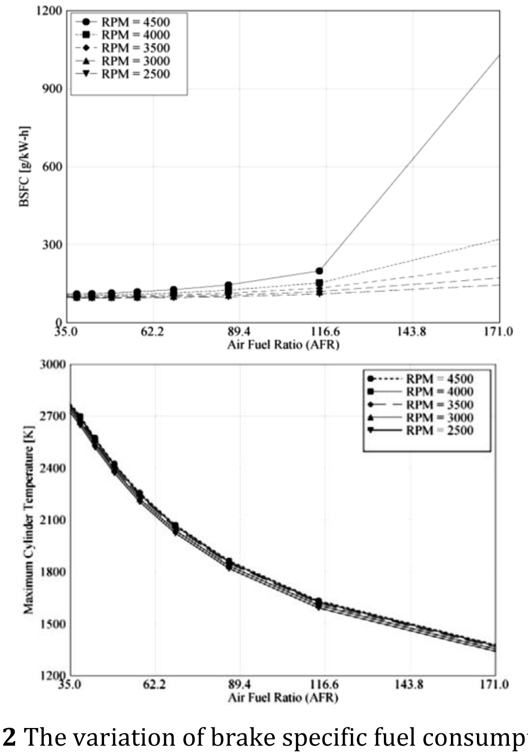


Fig. 2 The variation of brake specific fuel consumption and maximum cylinder temperature with air fuel ratio for different engine speeds

The brake thermal efficiency reached it's maximum at (AFR ≅ 35) and then decreased with increased in AFR and speed. The variation of brake specific fuel consumption and maximum cylinder temperature with air fuel ratio for different engine speeds is shown in figure (2).

2.2 Artificial Neural Networks Modeling

Artificial Neural Network (ANNs) have been developed for number of years and now widely used in various application areas. ANN offers a way to simulate nonlinear, or uncertain, or unknown complex system without requiring any explicit knowledge about input/output relationship. It can approximate any continuous or nonlinear function by using certain network configuration. It can be used to learn complex nonlinear relationship from a set of associated input/output vectors. Recently, ANNs have been used in internal combustion engines for engine performance, exhaust temperature, fuel consumption analysis and prediction. Chris Brace (Chris Brace 1998) developed three applications of neural networks to the prediction of diesel engine fuel consumption and emissions. The 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 powertrain controller to identify the ideal set points for engine speed and load to minimize fuel consumption and emissions during steady driving. He predicted the constituents of unburned hydrocarbon, NO_x, particulate matter, and smoke. With the mean absolute error at 2.78, 4.43, 5.42, 2.53 and 6.26% respectively. O. Obodeh *et al,* (2009) evaluates the capabilities of ANN as a predictive tool for multi-cylinder diesel engine NOx emissions. The experiments were carried out with a stationary light-duty Nissan diesel engine test-rig. ANNs were trained on experimental data and used to predict the oxides of nitrogen (NOx) emissions under various operating variables. Gorkem K. *et al*, (2009) developed an artificial neural network (ANN) structure using the back propagation (BP) learning algorithm and radial basis function (RBF) to predict the emissions and exhaust temperature for DI diesel engines with emulsified fuel. The experimental results were obtained from a real diesel engine. They compared the ANN performance, the network outputs with experimental results. The results showed that the emissions and exhaust temperature were estimated with a very high accuracy by means of the designed neural network structures. The use of artificial intelligent models as virtual sensors to predict relevant emissions such as carbon dioxide, carbon monoxide, unburnt hydrocarbons and oxides of nitrogen for a hydrogen powered car was investigated by (V. Karri *et al*, 2009) . The virtual sensors are 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 system. These predictions are based on the study of qualitative 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 emission. All ANN models show 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 less than 6% of average root mean square error. T.Hari Prasad *et al*, (2010) used artificial neural network (ANN) modeling of a diesel engine to predict the exhaust emissions of the engine. Acquired 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. Figure (3) showed that the network produces results parallel to the experimental ones.

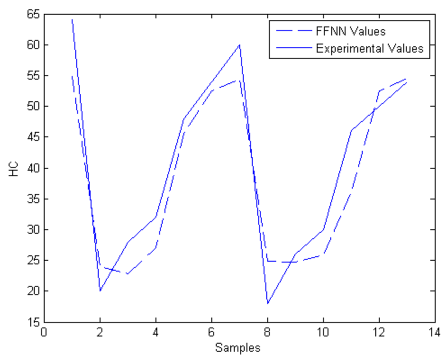


Fig. 3 Comparisons of experimental values with ANN values of HC emissions

Technical analysis were conducted by (R. Manjunatha *et al*, 2012) to model diesel engine exhaust emissions by using artificial neural networks (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 (DI) compression ignition (CI) engine using blends of biodiesel methyl esters from Pongamia, Jatropha and Neem oils. The performance parameters such as brake power (BP), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), volumetric efficiency and exhaust gas temperature (EGT) were measured along with regulated and unregulated exhaust emissions of CO, HC and NOx. They developed the Artificial neural network (ANN) based 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 were used as inputs to train the neural network. The exhaust gas emissions - 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 R (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. Anant *et al*, (2012) presented an overview of applications of artificial neural networks (ANN) in the field of engine development. Various approaches using ANN were highlighted that resulted in better modeling of engine operations. discusses ANN approach, algorithms and importance of architecture. This will also help in advancing ANN research. They discussed ANN approach, algorithms and importance of architecture. This will also help in advancing ANN research. A. Kean *et al*, (2012) studied the exhaust emissions control and engine parameters optimization using artificial neural network virtual sensors for a hydrogen-powered vehicle. Experimental data were first obtained through a comprehensive experimental and tuning procedure for neural network training and validation. The optimization layer-by-layer neural network was used to construct two ANN virtual sensors; the engine and emissions models. Simulation results showed that the exhaust emissions can be regulated by optimizing simple engine process parameters. They presented an alternative tool for vehicle tuning applications for a hydrogen-powered vehicle.

2.3 Genetic Algorithm Optimization

Genetic Algorithm (GA) is the first evolutionary optimization technique introduced by (Holand J. 1975), which is based on Darwinian principle of the " survival of fittest" and the natural process of evolution through reproduction. T. Hiroyasu *et al*, (2002) established a multi-objective optimization problem for engine design using the phenomenological model and genetic algorithm (GA). The Hiroyasu Diesel Engine Combustion Simulation (HIDECS) code which was based on the phenomenological model was used for analyzing the diesel engine. The Neighborhood Crossover Genetic Algorithms (NCGA) which was an extended model of GA was applied in the model. In this simulation, the amount of SFC, NOx and soot were minimized by changing the rate of fuel injection. They emphasized three topics with applying the optimization technique to an emission problem of a diesel engine. Firstly, the multiple injections control the objectives. Secondly, the multi-objective optimization was very useful in an emission problem. Finally, the phenomenological model had a great advantage for optimization. Experimental investigation was carried out by (Arturo de Risi *et al*, 2002) to develop a multi-objective genetic algorithm on a test bench, using a DI diesel engine. The genetic algorithm selects the injection parameters for each operating condition whereas the output, measured by the experimental apparatus, determines the fitness in the optimization process. 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, emission levels of NOx, soot, CO, CO_2 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. H. Hiroyasu *et al*, (2003) developed HIDECS-GA computer code to optimize diesel engine emission 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 can be incorporated with the genetic algorithm 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 an optimizer due to its ability to derive the solutions with high accuracy effectively. The HIDECS-NCGA methodology was used to optimize engine emission and economy 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 with low computational costs. The Pareto optimum solutions obtained from HIDECS-NCGA are very useful to the engine designers. They showed that it is possible to reduce emissions without increasing the fuel consumption by the optimization of exhaust gas recirculation (EGR) and multiple injections. Computationally efficient CFD-based tool for finding optimal engine operating conditions with respect to fuel consumption and emissions was developed by (S. Srinivasan *et al*, 2006). 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 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.

3. Experimental Investigations on Hydrogen Supplementation

The various options available for the hydrogen supplementation in diesel engine to improve the performance and to control the pollutants emissions are shown in figure (4).

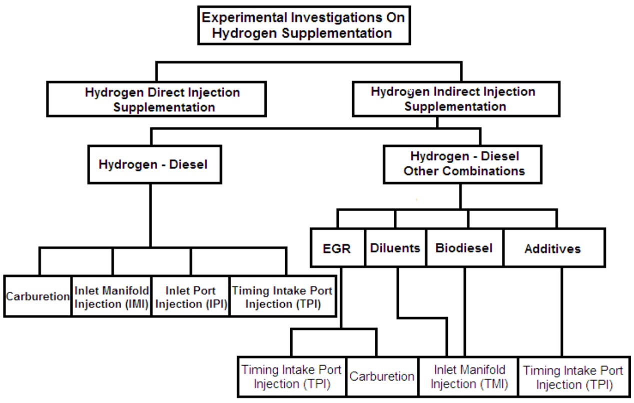


Fig. 4 Various Options of Hydrogen Supplementation Techniques Employed During Experimental Studies

Basically, supplementing techniques may be divided into direct injection and indirect injection/induction. 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 techniques include Exhaust Gas Recirculation (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.

3.1 Hydrogen Direct Injection Technique

In direct in-cylinder injection, hydrogen is injected directly inside the combustion chamber with the required pressure at the end of compression stroke. As hydrogen diffuses quickly the mixing of hydrogen takes flame instantaneously. For ignition either diesel or spark plug is used as a source. The problem of drop in power output in manifold induction/injection can be completely eliminated by in-cylinder ignition. During idling or part load condition the efficiency of the engine may be reduced slightly. This method is the most efficient one compared to other methods of using hydrogen. The power output of a direct injected hydrogen engine was 20% more than for a gasoline engine and 42% more than a hydrogen engine using a carburetor. With hydrogen directly injected into the combustion chamber in a compression ignition (CI) engine, the power output would be approximately double that of the same engine operated in the pre-mixed mode. The power output of such an engine would also be higher than that of a conventionally fuelled engine, since the stoichiometric heat of combustion per standard kilogram of air is higher for hydrogen (approximately 3.37 MJ for hydrogen compared with 2.83 MJ for gasoline). While direct injection solves the problem of pre-ignition in the intake manifold, it does not necessarily prevent pre-ignition within the combustion chamber. In addition, due to the reduced mixing time of the air and fuel in a direct injection engine, the air/fuel mixture can be non-homogenous. A schematic diagram illustrating the operation of direct injection is shown in figure (5).

An experimental study was undertaken by (K. S. Varde *et al*, 1983) to investigate the possibility of reducing diesel particulates in the exhaust by aspirating small quantities of gaseous hydrogen in the intake of a diesel engine. A single cylinder, direct injection type diesel engine, four stroke was used in the experiments. Hydrogen flow rates equivalent to about 10% of the total energy substantially reduced smoke emissions at part loads. At the full rated load, reduction in smoke levels was limited; this was believed to be due to the lower amounts of excess air available in the cylinder.

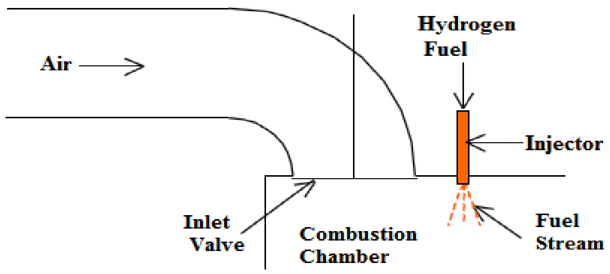


Fig.5 Direct injection system

It was found that the engine thermal efficiency was dependent on the portion of hydrogen energy, out of the total input energy, supplied to the engine. There was no significant change in the hydrocarbon emissions but oxides of nitrogen in the exhaust increased with an increase in hydrogen energy. S. Furuhama *et al*, (1986) developed a high power two-stroke H_2 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 the combustion chamber. The H_2 was ignited on the hot surface and with the aid of a 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 obtained after a modification to the shape of combustion chamber and injection nozzle. After the modification, the output power improved. 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.

Based on the investigations spanning about 20 years, S. Furuhama (1989) proposed two systems for hydrogen fuel engine for land vehicles. They were: (1) a substitute for gasoline engine in which liquid hydrogen (LH_2) tank was pressurized by evaporated H_2-gas with its inner pressure at 1 MPa, and liquid hydrogen (LH2) 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 the gasoline engine, and its thermal efficiency under the partial load becomes higher than the gasoline engine because of lean combustion. (2) a substitute for diesel engine in which the system consists of a liquid (LH_2) tank at low pressure, liquid hydrogen (LH_2) pump for high pressure injection and spark igniter. The high pressure hydrogen injector is shown in figure (6). He concluded and recommended that the maximum output power was the same as that of a gasoline engine, the optimum compression ratio of

(12:1) which was determined by considering performance, vibration and NOx was also applicable. He further proposed to develop a high pressure hydrogen gas expander for obtaining useful power and cold hydrogen. According to the researcher, for a successful development of practical hydrogen engine, further research and development efforts must be carried out on cryogenic system.

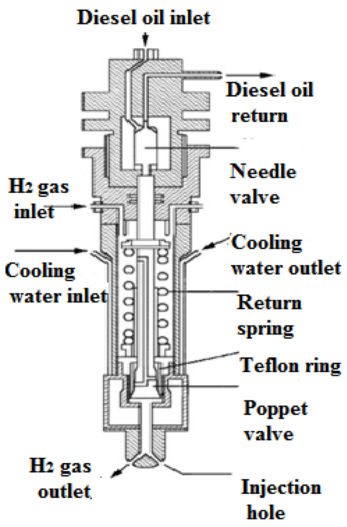
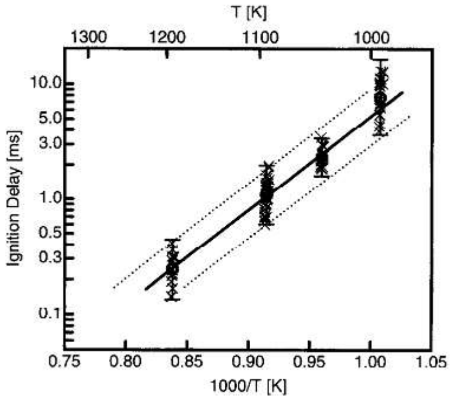
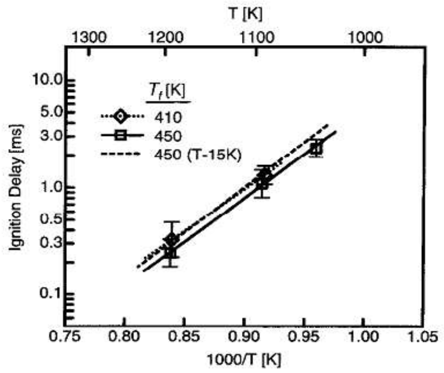


Fig.6 High pressure hydrogen injector

An experimental investigation by using the hydrogen as a sole fuel in a direct injection diesel engine was performed by (J. K. S. Wong 1990). In this study, a compression ignition engine cooled by air and made by lister (STI) was modified to operate as a low heat rejection engine. The compression ratio of this engine was (17.9:1) and running at (2100 rpm), a maximum compression temperature of approximately (900 K) was achieved. Under these operation 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 researcher concluded that the use of hydrogen as a sole fuel in direct injection without an ignition source diesel engine is not practical or feasible. H. S. Yi *et al*, (1996) designed and constructed a solenoid-drive type in-cylinder gas injection system. The injection system was installed on a 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 effect of spark timing on the in-cylinder injection type hydrogen engine were also investigated in these experiments. They described in detail the solenoid valve and its 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 were 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. The auto ignition and combustion of hydrogen was studied by (J.D. Naber *et al*, 1998) in a constant volume combustion vessel under simulated direct injection (DI) diesel engine conditions. They focused on the combustion delay and hydrogen concentration under Direct Injection compression Ignition diesel engine. Specially designed disc shaped combustion chamber with transparent windows to access the internal mechanism during combustion of hydrogen. From figure (7) (a) and (b), it was observed that, the ignition delay was less for such applications, where gas temperature was more than 840°C and oxygen concentration is in between 5-21%. It was also understood that with increase in fuel temperature the effect on ignition delay was also small.



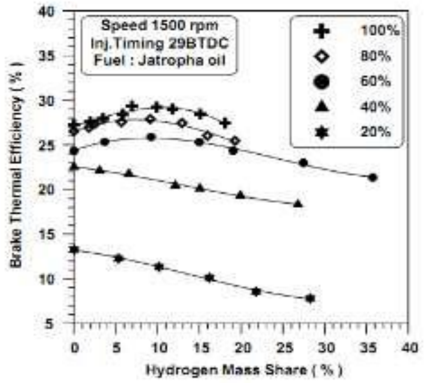
(a)



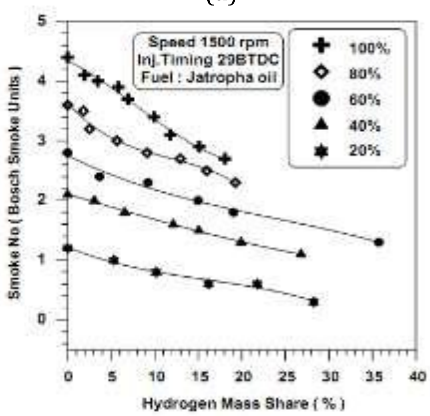
(b)

Fig.7 (a) Effect of gas temperature on the ignition delay (b) Effect of fuel temperature on ignition delay

Kumar *et al*, (2003) conducted experiments on a 3.7 KW single cylinder, four stroke, direct injection, compression engine with diesel and Jatropa oil are as pilot fuels and hydrogen as a supplement fuel. In this paper, as shown in figure (8-a), they claimed that the brake thermal efficiency of Jatropa oil as a pilot fuel was increased from 27.3% to 29.4 % at full load with 7% hydrogen mass share. Whereas with diesel fuel as a pilot fuel the brake thermal efficiency (BTE) was increased from 30.3% to 32% at 5% mass share of hydrogen and the same time their brake thermal efficiency was reduced at lower out puts. It was be observed from figure (8-b) that smoke levels with Jatropa reduced from 4.4 to 3.7 Bosch Smoke Units (BSU), whereas with diesel it was reduced from 3.9 to 2.2 Bosch Smoke Units (BSU).



(a)



(b)

Fig.8 (a) Variation of BTE with Hydrogen Mass share. (b) Variation of Smoke No. with Hydrogen Mass share

Figure (9), shows that hydrocarbons (HC) with Jatropa decreased from, 130 to 100 ppm, and carbon monoxide (CO) from 0.26% to 0.17% at peak power condition whereas with diesel hydrocarbons (HC) decreased from 100 to 70 ppm and carbon monoxide (CO) from 0.2% to 0.1%. The Nitrous Oxides (NOx) levels increased from 735 to 875 ppm with Jatropa and 785 to 894 ppm with diesel at optimum efficiency level. This is because of combustion temperature increase due to burning of Hydrogen in the combustion chamber. Peak cylinder pressure increased from 62 bar with diesel to 66 bar under dual fuel operation at maximum efficiency points. Ignition delay for the Jatropa oil was more when compared to diesel at single fuel operation but it increased under dual fuel mode.

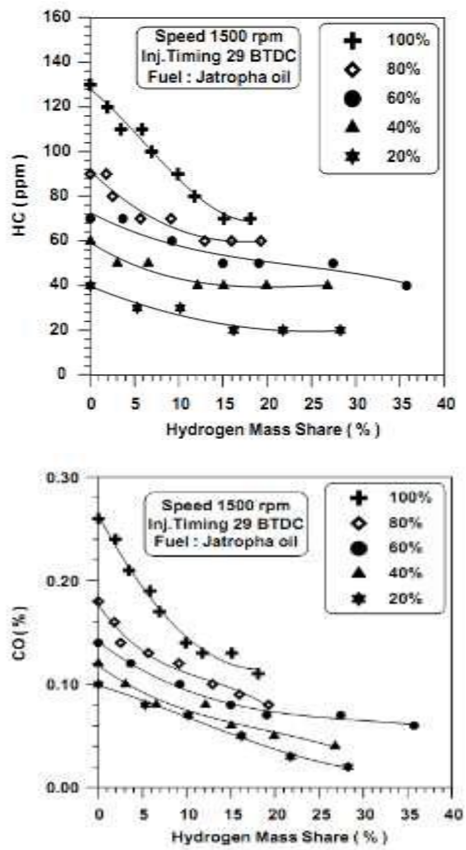


Fig.9 Variation of Green House Gases (GHG) with hydrogen mass share

The combustion characteristics under various injection timings of a direct-injection engine fueled with natural gas–hydrogen blends was studied by (Zuohua Huang *et al*, 2006) at fixed injection duration and fixed ignition timing. This 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 a 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. A description of an experimental setup a testing study of a diesel engine in direct injection hydrogen-fuelled mode was carried out by (J.M. Gomes *et al*, 2009). Test results showed that the use of hydrogen direct injection in a diesel engine gave a higher power to weight ratio when compared to conventional diesel-fuelled operation, with the peak power being approximately 14% higher. The use of inlet air heating was required for the hydrogen-fuelled engine to ensure satisfactory combustion, and a large increase in the peak in-cylinder gas pressure was observed. A significant efficiency advantage was found when using hydrogen as opposed to diesel fuel, with the hydrogen-fuelled engine achieving a thermal efficiency of approximately 43% compared to 28% in conventional, diesel-fuelled mode. the nitrogen oxides formation was low at low loads, for which the cylinder charge was lean and in-cylinder temperatures are lower, but increases sharply with increasing load. A clear NOx emissions advantage for the hydrogen-fuelled engine could be seen over the full load range, with the NOx levels being approximately 20% lower than those obtained under diesel-fuelled operation as shown in figure (10).

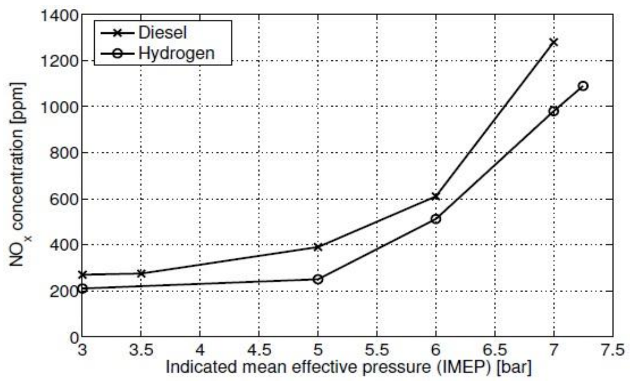


Fig.10 Measured NOx emissions for hydrogen-fuelled and diesel operation

Investigation was carried out by (P. Kumar *et al*, 2012) on the combustion and performance analysis of hydrogen direct injection with diesel as an ignition source at a particular injection timing with varying injection durations. The engine used for the investigation was a four stroke water-cooled, single cylinder, direct injection, vertical diesel engine developing a rated power of 5.2 kW at a rated speed of 25 rps. The engine was coupled to an electrical dynamometer and resistance loading. A solenoid-operated hydrogen gas injector was fitted onto the engine cylinder head. It was placed just above the intake valve at a distance of 15 mm from the intake valve seating position. A three injection timing was chosen to gauge the impact of injection timing on the performance and combustion parameters of the dual fuel engine. They were 10 degree, 50 degree and 80 degree, after TDC during the IVO to IVC period. The choice of 10 degree ATDC injection was made to capture most of the available induction period and simultaneously sacrifice a few degree of crank angle of induction to allow the cooling of any active hotspots by the incoming air prior to hydrogen induction which could have resulted in pre-ignition. The observation of pressure Vs crank angle data for the experimental engine running on diesel only at various loads showed that the maximum suction vacuum pressure occurred at around 45-50 degree ATDC on an average. In order to capture the maximum suction effect and promote homogeneous mixture of hydrogen and air, standard value of 50 degree ATDC was chosen as second choice of gas injection. The choice of 80 degree ATDC was to investigate the impact on performance and combustion parameters by the delay injection of hydrogen. Each of gas injection strategies of 10, 50, and 80 degrees at various hydrogen flow rates corresponding to the available induction period in each case was repeated at 15%, 35%, 50%, 65%, 85% and 100% load. (Vinod *et al*, 2013) investigated, hydrogen-enriched air as intake charge in a C. I. engine. Experiments were conducted in a single-cylinder, four-stroke, air-cooled, stationary direct-injection diesel engine Kirlosker TAF1 with 1500 rpm and 4.4 kW capacity coupled to an electrical generator. The injection timing and flow rates of hydrogen were (80, 120, 150 g/hr) to find out the optimum condition for hydrogen enrichment to meet the best performance.

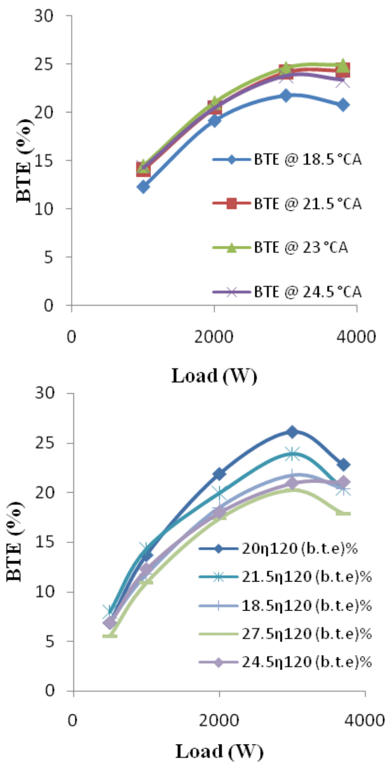


Fig.11 (a) Load v/s BTE (pure diesel). (b) Load v/s BTE (hydrogen enrichment)

Experimental results showed that hydrogen enriched engine gave maximum brake thermal efficiency and minimum brake specific energy consumption at 16.4 % H2 or 120 g/hr flow rate with 20° CA injection timing. The variation of brake thermal efficiency with load for neat diesel with different injection timing is shown in figure (11-a). It has been observed that the increase in engine load leads to increasing brake thermal efficiency at loads between 1100-3800 W , while increasing load more than 3800 W lead to a decrease in the brake thermal efficiency. The variation of brake thermal efficiency with load for hydrogen enrichment with different injection timing is shown in figure (11-b).

It was observed that as flow rate of hydrogen started increasing, there was decrease in flow rate of diesel but at the higher hydrogen enrichment condition, engine shut down at high loads due to reduced availability of oxygen. It was observed that 120 g/hr was the optimum flow rate of hydrogen on which engine gave best performance. Increase in thermal efficiency was attributed to improved combustion because of enhanced combustion rate due to high flame velocity of hydrogen. It was found that at 20° BTDC and 120 g/hr flow rate of hydrogen, engine gave slightly higher thermal efficiency in comparison to pure diesel.

3.2 Hydrogen Indirect Injection / Induction Technique

The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port by using mechanically or electronically operated injector, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. Electronic injectors are robust in design with a greater control over the injection timing and injection duration with quicker response to operate under high speed conditions. In port injection, the air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots . Since less gas (hydrogen or air) is in the manifold at any one time, any pre-ignition is less severe. The inlet supply pressure for port injection tends to be higher than for carbureted or central injection systems, but less than for direct injection systems. A schematic diagram illustrating the operation of inlet port injection is shown in Figure (12).

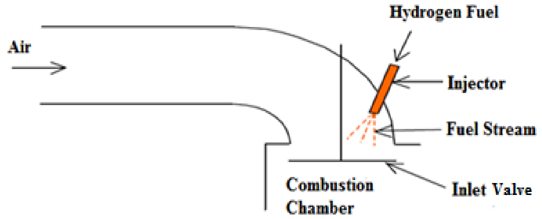


Fig.12 Inlet manifold and inlet port injection

In inlet manifold or port injection methods of fuel induction, the inducted volume of air per cycle is kept constant and the power output can be controlled by the amount of fuel injected into the air stream, thus allowing lean operation. The fuel can either be metered by varying the injection pressure of the hydrogen, or by changing the injection duration by controlling the signal pulse to the injector.

B. HaraGaopal *et al*, (1983) reported experimental results on a single cylinder, water cooled, compression Ignition engine with compression ratio 16.5:1, constant speed engine. They considered Hydrogen proportion to be with 10% of the total energy input of the engine. It was observed that, thermal efficiency only increased at peak loads when comparing to part loads. Exhaust temperature at all loads decreased. Concentration of NOx increased due to increase in cylinder temperature because of faster energy release of Hydrogen fuel inside the combustion chamber. Further, it was observed that at full load conditions, with increase in supplementation of Hydrogen the ignition delay reduced. Rate of pressure rise and peak cylinder pressure were not affected. Maximum supplementation of Hydrogen was to be 30% of the total energy, and beyond that the engine started knocking. They also conducted separate experiments in a closed vessel on hydrogen supplementation, and identified that flame propagation problems, especially in dual fuel mode, were considerably increased with increasing dose of hydrogen utilization. Performance and Emission parameters are shown in figure (13).

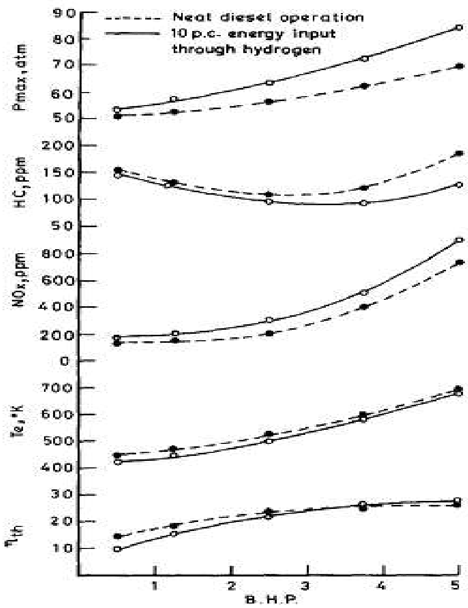
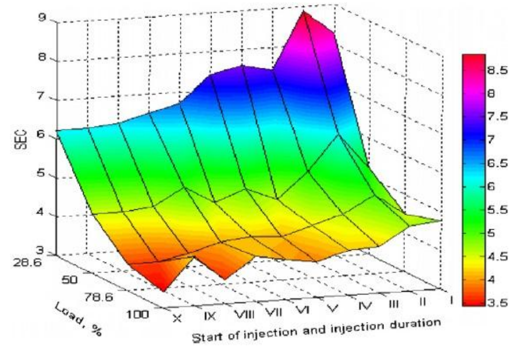


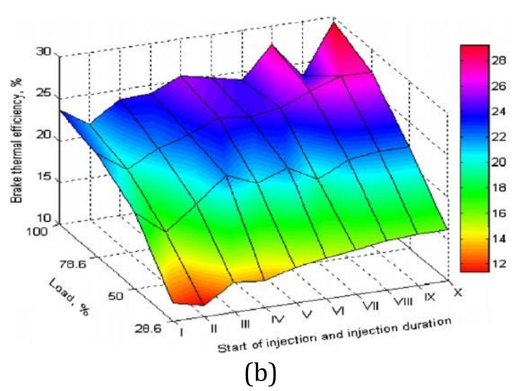
Fig.13 Effect of introducing Hydrogen into intake air on engine performance and emissions

The performance of dual injection hydrogen fueled engine by using solenoid in-cylinder injection and external fuel injection techniques were studied by (Lee *et al*, 1995). The external fuel mixture preparation has the advantage that it is simple and gives higher efficiency but it produces low power output due to the occurrence of backfire at high loads. In turn, direct in-cylinder injection produces higher power output with the elimination of backfire but its thermal efficiency becomes relatively lower due to poor hydrogen air mixing rate. It was observed that at 50 % load the thermal efficiency of external mixture was 27 % compared to direct in-cylinder injection of 23 %. A lower value of thermal efficiency in direct injection is due to shorter hydrogen air mixing duration. To overcome the problems with external mixture injection and direct cylinder injection the authors have tried dual injection by combining both external and direct injection at a ratio of 30 % (mass of external fuel to total fuel) and a spark timing of 10^{o} BTDC. The maximum pressure in dual injection was found to be 48 bar compared to 45 bar in direct in-cylinder injection. The increase in thermal efficiency for dual injection was about 22 % at low loads and 5 % at high loads compared to direct injection. Authors suggested that by considering the dual injection, the stability and maximum power of direct injection cylinder with maximum efficiency of external mixture hydrogen engine could be obtained. An experimental study on a single cylinder, four-stroke diesel engine operated in dual fuel mode was conducted by (Eiji Tomita *et al*, 2001). Hydrogen was inducted into the intake port along with air and diesel oil was injected into the cylinder. A wide range of injection timing was studied. When the injection timing was advanced, the diesel oil was well mixed with hydrogen air mixture and initial combustion became mild. NOx emissions decreased because of lean premixed combustion without the region of high temperature burned gas. Emissions such as CO, HC and CO2 decreased without emitting smoke, while brake thermal efficiency was marginally lower than that in ordinary diesel combustion.

Several attempts on various fuel induction methodologies such as carburetion, continuous manifold injection (CMI), timed manifold injection (TMI), low pressure direct cylinder injection (LPDI) and high pressure direct cylinder injection (HPDI) were carried out by (L.M. Das, 2002). From the test results, it was observed that carburetion is not suitable for gas engines because of its uncontrolled combustion. As far as CMI is concerned the engine did not show different response from carburetion. The variation in indicated thermal efficiency was found to be 40 % for TMI compared to 32 % for CMI at an equivalence ratio of 0.35. In direct cylinder injection with LPDI, it was very tough for the injector to survive on severe thermal environment of the combustion chamber over a prolonged engine operation and time for mixing hydrogen with air was less resulting in a drop in brake thermal efficiency. Hence TMI was selected which gave a maximum brake thermal efficiency of 39 % at a compression ratio of 9:1 with an equivalence ratio of 0.575 at 1600 rpm, compared to 33 % for LPDI system and the NOx emission was found to be 100 ppm. Further increase in equivalence ratio from 0.575 to 1.0 resulted in NOx emission to increase upto 1400 ppm. A study on a single cylinder research engine in order to critically assess the emission potential of alternative fuels was conducted by (V. Stefaan *et al*, 2004). Hydrogen and methane are compared in terms of power production, fuel consumption and emissions. An Audi-NSU diesel engine was adapted to the use of hydrogen and methane. The engine specifications were of bore of 77.02 mm, stroke of 86.385 mm and of 11:1 compression ratio. The original compression ratio of 16:1 was reduced to 11:1. An injection system, placed in the inlet manifold close to the inlet valve, was implemented. The injector was a very compact GSI (gaseous sequential injection) injector from Koltec-Necam. The injector, originally developed for use with LPG, had a working pressure of 1 to 2 bar. The fuel was supplied from a steel bottle with compressed hydrogen or methane at 200 bars. The gas was expanded in two pressure reducing valves, placed in series, and then admitted to a reservoir. They concluded that the hydrogen specific combustion properties must be taken into account. Some of these properties are advantageous like the wide flammability range (omitting throttle), high burning velocity (efficiency), high autoignition temperature (compression ratio) and high diffusivity (mixture formation and safety). Other properties involve some difficulties like low ignition energy caused pre-ignition and backfire, small quenching distance and density 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.



(a)

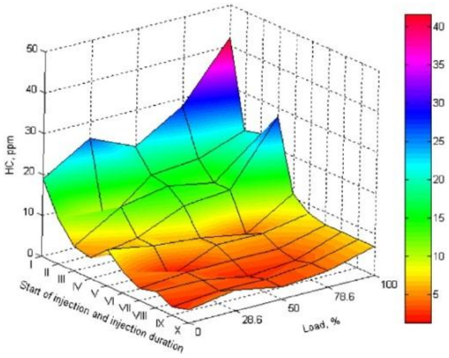


(b)

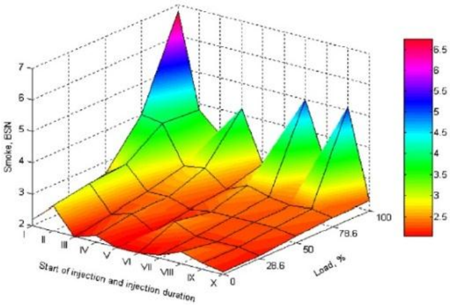
Fig.14 (a) Variation of SEC with Load. (b) Variation of BTE with Load

Some experiments were performed by (Saravanan *et al*, 2007) to study the performance and emissions of a 3.7kW, single cylinder, four stroke, water cooled, indirect injection- diesel engine. Hydrogen injector was placed at about 13 mm from the intake valve seating position. Hydrogen injection starts from 5^o BTDC and remains 15^0 ATDC and duration was controlled from 30^0 CA to 90^0 CA. Figure (14-a), showed that the Specific Energy Consumption (SEC) decreased from 4.7 to 3.4 MJ/kW-hr at full load for the Hydrogen injection timing of 5^0 ATDC with injection duration of 30^0 CA. This is because of better combustion in the combustion chamber due to uniformity in hydrogen mixing with air. Figure (14-b) showed that the Brake Thermal Efficiency (BTE) increased from 23.6% to 31.67% at 15^0 ATDC with 60^0 CA duration.

NOx emissions were reduced from 1806 ppm with pure diesel operation to 705 ppm at full load with 60^0 CA, because of leaner equivalence ratio. From figure (14-c), (d) and (e), HC were reduced from 42 ppm to 7ppm at full load condition, smoke was reduced from 2 BSN to 0.4 BSN at 75% load condition because of absence of carbon in hydrogen and homogeneous mixture of hydrogen with diesel rather than heterogeneous mixture like diesel. CO and CO_2 were reduced from 0.17 vol% to 0.01 vol% and 9.5 vol% to 2.1 vol% at 75% load at start of injection at 50 ATDC with 90^0 injection duration for supplementation of hydrogen and pure diesel operations. From figure (14-f) Performance parameters like peak pressure was increased from 71.7 to 73.7 bar at full load for hydrogen supplementation and pure diesel operation. The increase in peak pressure is due to higher burning velocity of hydrogen, which makes combustion to be almost instantaneous, resulting in increased pressure.

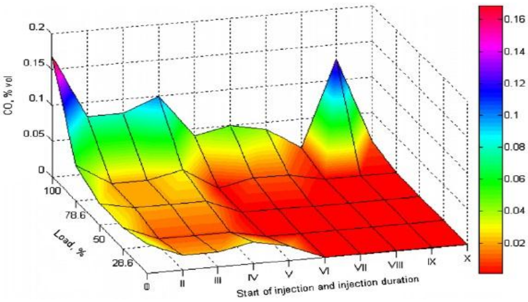


(c)

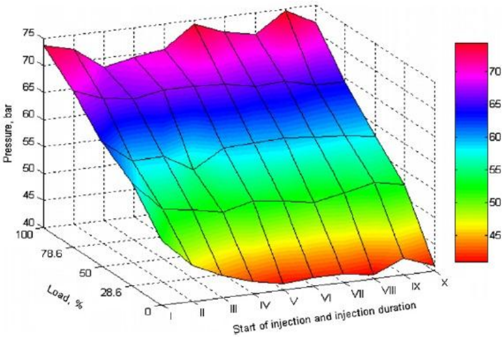


(d)

Fig.14 (c) Variation of HC with Load. (d) Variation of Smoke with Load



(e)



(f)

Fig.14 (e) Variation of CO with Load. (f) Variation of Peak Pressure with Load

N. Saravanan *et al*, (2008) compared the results for the injection of hydrogen by using the timing port injection and carburetor injection system. Both types of injection system were studied with respect to the parameters such as specific energy consumption, brake thermal efficiency and emission factors such as NOx, CO_2, CO, HC, and smoke. All parameters were plotted against the brake power. A single cylinder, four stroke, water cooled and direct injection type compression ignition engine was 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 flow rate of 20 1/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 1/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 1/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 1/min flow rate of hydrogen. The NOx emission from carburetion method was 8% higher than baseline diesel operation in carburetion technique for the flow rate of 20 1/min of hydrogen. An experimental test on the use of hydrogen as a fuel in diesel engine, by adding the hydrogen in intake port at varied load and varying percentage of conventional fuel (diesel) (10%, 30%, 50%, 70%, 80% and 90%) by volume was undertaken by (N. Saravanan *et al*, 2008). They studied the performance and emission characteristics of the hydrogen-enriched engine. They plotted 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 plotted. 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.

The Hydrogen injection into the intake manifold by using an injector with electronic control unit (ECU) was experimentally studied by (N. Saravanan *et al*, 2009). 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). 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% with decrease in carbon emissions due to the use of hydrogen. By adopting manifold injection technique the hydrogen–diesel dual fuel engine operates smoothly with a significant improvement in performance and reduction in emissions. M. Mohon Roy *et al*, (2010) focused on the engine performance and emissions of a supercharged engine fueled by hydrogen and ignited by a pilot amount of diesel fuel in dual-fuel mode. Experiments were carried out at a constant pilot injection pressure and pilot quantity for different fuel-air equivalence ratios and at various injection timings without and with charge dilution. The experimental strategy was to optimize the injection timing to maximize engine power at different fuel-air equivalence ratios without knocking and within the limit of the maximum cylinder pressure. The engine was tested first with hydrogen-operation condition up to the maximum possible fuel-air equivalence ratio of 0.3. A maximum IMEP of 908 kPa and a thermal efficiency of about 42% were obtained. Equivalence ratio could not be further increased due to knocking of the engine. The emission of CO was only about 5 ppm, and that of HC was about 15 ppm. However, the NOx emissions were high, 100–200 ppm or more. The charge dilution by N_2 was then performed to obtain lower NOx emissions and 100% reduction of NOx was achieved. Due to the dilution by N_2 gas, higher amount of energy could be supplied from hydrogen without knocking, and about 13% higher IMEP was produced than without charge dilution. The combustion process and engine performance parameters of an engine fuelled with diesel and hydrogen at different loads (2, 4, 6, 8, 10, and 12 kg) were studied by (M. Deb 2012). The work was done on single cylinder, water cooled, four stroke, direct injection diesel engine with the rated power of 5.2 kW, a compression ratio of 17.5:1 and a rated speed of 1500 rpm. The results showed that the brake thermal efficiency was increased for all hydrogen injection strategies compared to base diesel at all load operations and reached a maximum of 30% at full load conditions. The increase in brake thermal efficiency was due to hydrogen enrichment with air. The increase in thermal efficiency was also attributed to improved combustion because of enhanced combustion rate due to high flame velocity of hydrogen. The value of BSFC for base diesel was 0.28 kg/kWh at full load conditions but with the introduction of hydrogen strategy it was reduced and reached to a minimum value of 0.18 kg/kWh. BSFC decreased with the increase in brake power. BSFC was less compared to base diesel operation at all loads which was a clear indicative of better mixing of hydrogen with air resulting in complete combustion of fuel.

Experimental results also showed that the BSEC with net diesel was higher at all load operating conditions compared to all hydrogen introduction strategy. The lower specific energy consumption for hydrogen-diesel dual fuel was due to better mixing of hydrogen with air resulting in complete combustion of fuel. The volumetric efficiency of the engine was found to be less when hydrogen was inducted with the main fuels. The reason for low volumetric efficiency was of the high velocity and lower density of hydrogen ($0.08 kg/m^3$) which tends to displace the air. The volumetric efficiency of diesel at full load condition was 81% while it became 73% at injection of hydrogen since more hydrogen was taking part in the combustion which displaced more amount of air and thus reduced the breathing capacity of the engine.

3.3 Some Emission Control Techniques

A part 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. These included 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.

3.3.1 Exhaust Gas Recirculation (EGR) with Hydrogen-Diesel

In internal combustion engines, exhaust gas recirculation (EGR) is a nitrogen oxide (NOx) emissions reduction technique used in petrol/gasoline and diesel engines. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. In a gasoline engine, this inert exhaust displaces the amount of combustible matter in the cylinder. The schematic view of the exhaust gas recirculation (EGR) unit is shown in figure (15).

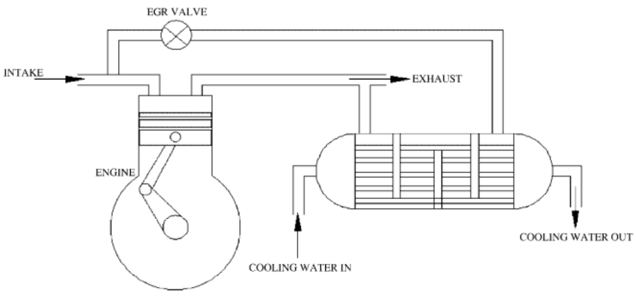


Fig.15 Schematic view of the exhaust gas recirculation (EGR) unit

In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. Because NOx forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature, the lower combustion chamber temperature caused by EGR reduces the amount of NOx the combustion generates (though at some loss of engine efficiency).

Gasses re-introduced from EGR systems will also contain near equilibrium concentrations of NOx and CO. The small fraction initially within the combustion chamber inhibits the total net production of these and other pollutants when sampled on a time average. Most modern engines now require exhaust gas recirculation to meet emissions standards. James Heffel (2003) conducted experiments on a ford ZETEC 4 cylinder, 12.1 compression ratio engine, specially designed to run on pure hydrogen using a lean burn fuel metering electronic port injector. Experiments were conducted to ascertain the effect of exhaust gas recirculation and a standard 3–way catalytic converter on NOx emissions and engine performance. The air fuel ratio varied from 100:1 to 50:1, further increase in lean burn condition was limited to the onset of knock. The maximum torque obtained without EGR was 94 N-m compared to 88 N-m with EGR. NOx emission without EGR was 2500 ppm and with EGR, it was reduced to 496 ppm with a drop in brake thermal efficiency from 38 % to 34 % for the same operating conditions. From the results, it was observed that with EGR and a standard 3-way catalytic converter system, the NOx emissions from a hydrogen fueled engine could be reduced even to 1 ppm. N. Saravanan *et al*, (2008) investigated, the effect of hydrogen-enriched air, as intake charge in a diesel engine adopting exhaust gas recirculation (EGR) technique with hydrogen flow rate at 20 l/min on engine performance. Experiments were conducted on a single-cylinder, four-stroke, water-cooled, direct-injection diesel engine coupled to electrical generator. Performance parameters such as specific energy consumption, brake thermal efficiency were determined and emissions such as oxides of nitrogen, hydrocarbon, carbon monoxide, particulate matter, smoke and exhaust gas temperature were measured. Using of hydrogen in dual fuel mode with EGR technique resulted in lower smoke level, particulate and NOx emissions. An experiments to determine the optimized injection timing, injection duration and injection quantity of the fuel in manifold and port injected hydrogen-operated engine using diesel as ignition source were conducted by (N. Saravanan *et al*, 2009). The results showed that in manifold injection technique the optimized condition was, start of injection at gas exchange top dead centre (GTDC) with injection duration of 30º (CA) with hydrogen flow rate of 7.5 liters/min while In port injection technique, the optimized condition was, start of injection at 5º before gas exchange top dead centre (5ºBGTDC) with injection duration of 30º CA with hydrogen flow rate of 7.5 liters/min. It was observed with the above optimized timings of port and manifold injection , the brake thermal efficiency in port injection was increased by 13 % and 16 % in manifold injection at 75 % load while at full load the brake thermal efficiency was decreased by 1 % in port injection and 8 % in manifold injection. The reduction in NO_X emission was 3 times in both port and manifold injection at 75 % load while the reduction in NO_X emission was 4 times in port injection and 7 times in manifold injection at full load. Smoke emission increased with increasing EGR percentage. At full load, smoke increased by 36 % in port injection and by 44 % in manifold injection. At 75 % load the smoke emission decreased by 13 % in port injection and 9 % in manifold injection. The ignition delay for both port and manifold injection were 12º or 1.33 ms while for diesel it was 11º or 1.22 ms. Port injection system with diesel as ignition source operates smoothly and shows improved performance and emit lesser pollution than diesel. Probir K. Bose *et al*, (2009) conducted test by using a four stroke, water cooled, single cylinder, vertical diesel engine running at a rated power of 5.2 kW and at a rated speed of 1500 rpm. A timed manifold induction system with electronic control was developed to deliver hydrogen in 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 rat at 0.15 kg/hr. As diesel was substituted and hydrogen was inducted, the NO_X emission was increased. In order to reduce NO_X 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 emission 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.

3.3.2 Dilution of Hydrogen-Diesel Blended Fuel

Use of water diesel emulsion in diesel engines is one of the methods for simultaneous reduction of both NOx and smoke without any penalty in fuel consumption. Brake thermal efficiency was improved by the use of emulsified fuels at certain operating conditions. Water has also been introduced in diesel engines by injecting it directly into the cylinder or in the intake manifold. H.B. Mathur *et al*, (1992) investigated experimentally the possibility of controlling the exhaust emission parameters of a small horsepower hydrogen fueled diesel engine using various diluents mixed with the inducted charge . They reported their experimental results on the effect of diluents like helium, nitrogen and water in various proportions on smoke and oxides of nitrogen (NOx) emissions in such an engine. 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 concentration of 600, 1260 and 2460 ppm. They plotted the smoke and NOx concentration against engine rated load with various hydrogen flow rate at different diluents type and concentrations as showed in figure (16). 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 NOx emission level when inducted in very small proportions, of the order of parts per million.

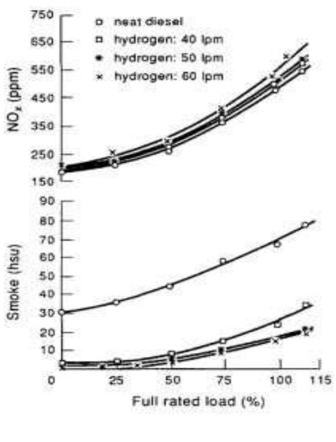


Fig.16 Emission Characteristics at 2460 ppm of water injection as a Knock diluents

A small testing at the end-utility compression ignition (CI) engine generator system operated with hydrogen fuel substitution carried out by (H.B. Mathur *et al*, 1992). The system performance and emission characteristics were evaluated and analysed. Different diluents such as, 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 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. The brake thermal efficiency and optimum injected hydrogen energy were studied in the performance part, while the smoke and exhaust temperature were studied in emission part of the study. They concluded that 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 was 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 NOx emissions. H.B. Mathur *et al*, (1993) investigated experimentally, through various charge diluents, the possibility of improving the performance, percentage hydrogen energy substitution and knock-limited power output of a 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 at 20, 30, 40, 50 and 60 liter/min and injected 10, 20, 30% by volume of hydrogen. 10% nitrogen and 600, 1260 and 2460 ppm water were injected. An experimental investigation was performed by (R. Adnan *et al*, 2012) to study the effects of variable water injection timing on performance and emission characteristics of hydrogen fueled compression ignition (HFCI) engine In this research, experiments were conducted comprises of two main parts namely, without and with water injection. For the first part, the test engine is operated using diesel and hydrogen fuels. Initially, the engine is set to operate at the speed of 1500 rpm by applying load until it is stabilized. These procedures will be repeated with engine speeds of 2000, 2500 and 3000 rpm and incremental load of 1 kW. As for the second part of the experiment, the conducts of experiments will be repeated accordingly to similar procedures with water injection system at the same range of engine speeds and loads. The experiment was done on a YANMAR direct injection (DI) CI engine that utilizes mechanically-actuated injection fuel delivery system. Injection pressure and start of injection (SOI) of diesel fuel were fixed at 19.6 MPa and 13 BTDC, respectively. They concluded that:

1- Water injection timing of 20 ATDC and duration of 20 CA improved the engine performance due to increase in gross indicated work and indicated thermal efficiency.
2- Water injection timing of 20 BTDC and duration of 40 CA showed the highest heat release rate and the longest ignition delay.
3- Water injection timing of 0 CA and duration of 40 CA indicated the highest in O_2 and SO_2 emissions, and the lowest NOx emission for higher speed range.
4- Water injection timing of 20 ATDC and duration of 20 CA showed the lowest in exhaust gas temperature throughout entire speed range.

3.3.3 Biodiesel with Hydrogen-Diesel or with Diesel Alone

The limited and fast diminishing resources of petroleum fuels, increasing prices of crude oil and environmental concerns were the reasons for exploring the use of biodiesel as a substitute for petroleum based fuel. Even though biodiesel is gaining worldwide acceptance as a good substitute for oil, the cost of biodiesel is the main undesirable aspect associated with biodiesel usage. The main reason for high price is the raw materials used for the production. Hence biodiesel produced from cheap feed stocks viz., waste animal fat and greases could be used to fulfill the energy demand. In all countries financial assistance is extended for pursuing research in biodiesel. M. S. Kumar *et al*, (2005) evaluated the effect of fuel inlet temperature on performance, emission and combustion characteristics of a single cylinder 4-stroke air-cooled diesel engine producing a power output of 2.8 kW using preheated animal fat as fuel. Experiments were conducted at the fuel inlet temperatures of 30, 40, 50, 60 and 70°C. Animal fat at low temperature resulted in longer ignition delay and combustion duration than diesel. But preheated animal fat showed reduced ignition delay and combustion duration. Peak pressure and rate of pressure rise were found to be high with preheated animal fat at high fuel inlet temperatures. At low temperature, animal fat resulted in lower smoke emissions than diesel. Preheated animal fat further reduced smoke levels at all temperatures. Hydrocarbon and carbon monoxide emissions were higher with animal fat at low temperature as compared to diesel. However fuel preheating reduced these emissions. NO emission was found to be lesser with animal fat at low temperature and fuel preheating increased the emission. However, the level was still lower than diesel even at high temperatures. V. Edwin Geo *et al*, (2009) investigated the use of hydrogen as the inducted fuel and rubber seed oil (RSO), rubber seed oil methyl ester (RSOME) and diesel as main fuels in a dual fuel engine. A single cylinder diesel engine with rated output of 4.4 kW at 1500 rpm was converted to operate in the dual fuel mode. The results showed that, higher brake thermal efficiency and significant reduction in smoke levels at high outputs were obtained when using the dual fuel of varying hydrogen quantity with RSO and RSOME . 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 is reduced from 5.5 to 3.5 BSU with RSOME and for RSO it is from 6.1 to 3.8 BSU at the maximum efficiency point. The peak pressure and maximum rate of pressure rise increase with hydrogen induction. Heat release rate indicates an increase in the combustion rate with hydrogen induction. On the whole it was concluded that the hydrogen can be inducted along with air in order to reduce smoke levels and improve thermal efficiency of RSO. The effect of biodiesel obtained from non-edible animal tallow as fuel in diesel engines was examined by (C. Öner *et al*, 2009). Fuel properties of biodiesel and its diesel blend were determined. It was found that viscosity and density were closer to that of diesel and the calorific value was marginally lower. Experimental investigation was carried out and as a result, it was observed that the thermal efficiency of engine decreased and specific fuel consumption increased with the addition of biodiesel, due to the lower heating value and higher viscosity of biodiesel. Emissions like carbon monoxide (CO), oxides of nitrogen (NOx), sulphur dioxide (SO_2) and smoke were found to be reduced by 15 %, 38.5 %, 72.7 % and 56.8 % respectively. With lowest emission, B20 blend was selected as optimum blend and was concluded that animal tallow methyl esters and their diesel blends could be used in direct injection diesel engines without any engine modifications. Gürü M. *et al*, (2010) studied the impact of chicken fat biodiesel with magnesium as additive in a single-cylinder, direct injection (DI) diesel engine by analysing the performance and emission characteristics. Since the homogenous catalysts improved the rates of biodiesel reaction, a two-step catalytic process namely acid catalyst (sulphuric acid) and alkaline catalyst (sodium hydroxide) were chosen for the production of biodiesel. Organic based synthetic magnesium additive of 12 μmol/L was doped into the biodiesel blend. Engine tests were run with a blend of 10 % chicken fat biodiesel and diesel fuel (B10) at full load conditions by varying the engine speed from 1800 to 3000 rpm. The results showed that, the engine torque was not significantly changed with the addition of 10 % chicken fat biodiesel, while the specific fuel consumption increased by 5.2 % due to lower heating value of biodiesel. Further, the in-cylinder peak pressure rose marginally and emissions like CO and smoke decreased by 13 % and 9 % respectively with increase in NOx emission by 5 %.

3.3.4 Additives with Hydrogen-Diesel or with Diesel Alone

The chemical and thermophysical properties of dimethyl ether (DME) as an alternative fuel for compression-ignition engines was analyzed by (Ho Teng *et al*, 2001). On the basis of the chemical structure of DME and the 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 for 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 processes in the engine cylinder, which, in turn, will influence emissions from combustion. Irshad A. (2001) used ethanol as a blending 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. He created a stable ethanol-diesel blended fuel with the help of pure energy's fuel additive products, and then generated transient emission data for an evaluation of different oxygen content based on ethanol content, The test showed that over 41% reduction in PM, 27% reduction in CO, and 5% reduction in NOx from a HD diesel engine and higher emissions reductions were observed from smaller engines. The combustion analysis in a direct injection (DI) diesel engine using hydrogen with diesel and hydrogen with diethyl ether (DEE) as ignition source was experimentally investigated by (N. Saravanan *et al*, 2008).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 (NOx) by 13% compared to diesel. Hydrogen- DEE operation showed a higher brake thermal efficiency of 30% with significant reduction in NOx compared to diesel.

4. Conclusion based on literature survey

1- A wide variety of engines varying from 5kW to 265 kW, single cylinder to multi cylinder, fueling from conventional diesel to different alternative fuels like Straight Vegetable Oil (SVO), Diethyl Ether (DEE), Rubber Seed Oil (RSO), Rubber Seed Oil Methyl Ester (RSOME) and Natural Gas (NG) etc. using different fuel induction techniques; carburetion system to High Pressure Direct Injection system have been studied. The results are promising to represent hydrogen as good alternative fuel as sole and supplemented fuel.

2- Hydrogen as sole fuel utilization would requires major modifications starting from engine material compatibility to utilization of hydrogen, its safety and economical aspects.

3- In supplemented mode hydrogen gives better substitution in transition phase (short term perspective) to switch over to the sole hydrocarbon engines. The supplemented hydrogen engines would require minor hardware modifications.

4- The supplementation by hydrogen in a given engine using conventional and alternative fuels, increases efficiency. This is directly related to injection strategy of hydrogen fuel in the engine either by direct injection in the combustion chamber or the port injection in the inlet manifold. Hence, it is very essential to understand the increase in efficiency with respect to injection strategy, varying load and speed and for the considered fuel along with its properties.

5- Hydrogen supplemented CI engine operating on the conventional or alternative fuels would require an approach to be developed considering optimization of heat release with optimal proportion of hydrogen to supplement the conventional and/or alternative fuelled CI engines to enhance their performance and emissions.

6-The tests of Dual-fuel mode of operation, demonstrated that hydrogen can be used simultaneously with diesel oil as a source of ignition, improving the thermal engine efficiency, and the emissions even in small induced quantities.

7-The hydrogen fast burn characteristics allow its use in high speed CI engines as there is no charge preparation time required by the diesel fuel, therefore allowing an increase in power output with a reduced penalty for lean cylinder charges.

8-The thermodynamic and heat transfer characteristics of hydrogen are accompanied by higher final compression temperatures contributing to improvements in engine efficiency and lean mixture operation.

9- The injector is the main important part for mixture preparation, multi-hole injector and/or multi-injector can give better hydrogen distribution and hence better homogeneous mixture, especially for low-pressure injection. Also reduces the hydrogen injection pressure.

10- Electronically controlled injectors are more versatile compared to hydraulically operated or mechanically operated injectors in terms of performance, response and flexibility in timings.

11- Higher cooling loss in hydrogen combustion is due to the effect of higher burning velocity and shorter quenching distance. The thermal efficiency is affected due to the effect of high cooling loss.

12- Optimum injection timing and injection duration is necessary for gas injection system in order to get proper mixing of fuel with air.

13- Hydrogen combustion produces high temperatures and hence high nitrogen oxides. Therefore, it is necessary to control NOx formation by controlling the mixture concentration.

14- The performance, emissions and combustion characteristics of a dual fuel engine is significantly affected by the nature of the primary gaseous fuel and the pilot fuel.

15- EGR and water injections are effective methods to decrease the tendency of backfire.

16- EGR cause an increase in ignition delay and a shift in the location of the start of combustion. This makes the products of combustion spending shorter period at high temperatures, which lowered the NOx formation rate.

17- Charge diluents, such as intake manifold water injection and EGR can increase the gas substitution rate.

18- The addition of diluents (nitrogen, helium, water) improves the knock limited engine operation.

References

T. N. Patro (1993), Burning Rate Assessment of Hydrogen-Enriched Fuel Combustion in Diesel Engine, *Int. J. Hydrogen Energy*, 19(3), pp 275-284.

Jie Ma, Yongkang Su, Yucheng Zhou and Zhongli Zhang (2003), Simulation and prediction on the performance of a vehicle's hydrogen engine, *Int. J. Hydrogen Energy*, 28(1), pp 77–83.

Al-Dawoodi Mohamed Fadhil (2006), Modeling of a four stroke diesel engine operated with hydrogen blended fuel, M.Sc. thesis, University of Babylon, Iraq.

M. M. Rahman, Mohammed K. Mohammed and Rosli A. Bakar (2009), Effect of Air Fuel Ratio on Engine Performance of Single Cylinder Port Injection Hydrogen Fueled Engine: A Numerical Study, *Int. Multi Conference of Engineers and Computer Scientists*, Vol II.

Chris Brace (1998), Prediction of Diesel Engine Exhaust Emissions using Artificial Neural Networks, IMech E. Seminar S591, Lucas Electrical and Electronic Systems, Solihull-University of Bath.

O. Obodeh and C. I. Ajuwa (2009), Evaluation of Artificial Neural Network Performance in Predicting Diesel Engine Nox Emissions, *R. J. of Applied Sciences, Engineering and Technology*, 1(3), pp 125-131.

Gorkem K., Erhan A. and Vezir A. (2013), Prediction of emissions and exhaust temperature for direct injection diesel engine with emulsied fuel using ANN, *Turkish J. of Electrical Engineering & Computer Sciences*, Vol. 21, pp 2141-2152.

Vishy Karri, Tien Nhut Ho (2009), predictive models for emission of hydrogen powered car using various artificial intelligent tools, *Neural Computing & Applications*, 18(5), pp 469-476.

T.Hari Prasad, K. Hema Chandra Reddy and M. Muralidhara Rao(2010), Performance and Exhaust Emissions Analysis of a Diesel Engine Using Methyl Esters of Fish Oil with Artificial Neural Network Aid, *Int. J. of Engineering and Technology* , 2(1), pp 1793-8236.

R. Manjunatha, P. Badari Narayana, K. Hema Chandra Reddy, K. Vijaya Kumar Reddy(2012), Radial Basis Function Neural Networks in Prediction and Modeling of Diesel Engine Emissions Operated for Biodiesel Blends under Varying Operating Conditions, *Indian Journal of science and Technology*, 5(3).

Anant Bhaskar Garg, Parag Diwan and Mukesh Saxena (2012), Artificial Neural Networks based Methodologies for Optimization of Engine Operations, *Int. J. of Scientific & Engineering Research*, 3(5).

W. Kean Yap, Tien Ho, and Vishy Karri (2012), Exhaust emissions control and engine parameters optimization using artificial neural network virtual sensors for a hydrogen-powered vehicle, *Int. J of Hydrogen Energy*, 37(10), pp 8704–8715.

Holland, J.H. (1975), Adaptation in Natural and Artificial Systems, Ann Arbor, MI: The University of Michigan Press. 2nd edn. (1992) Boston, MA: MIT Press.

T. Hiroyasu, M. Miki, J. Kamiura, S. Watanabe and H. Hiroyasu (2002), Multi-Objective Optimization of Diesel Engine Emissions and Fuel Economy using Genetic Algorithms and Phenomenological Model, 02FFL-183, *Society of Automotive Engineers (SAE)*, Inc.

Arturo de Risi, Paolo Carlucci, Teresa Donateo and Antonio Ficarella (2002), A Combined Optimization Method For Common Rail Diesel Engines, *ASME transaction*.

H. Hiroyasu, H. Miao, T. Hiroyasu, M. Miki, J. Kamiura and S. Watanabe (2003), " Genetic Algorithms Optimization of Diesel Engine Emissions and Fuel Efficiency with Air Swirl, EGR, Injection Timing and Multiple Injections, *Society of Automotive Engineers, of Japan (JSAE)*, Inc. 01-1853.

S. Srinivasan, F. X. Tanner, J. Macek and M. Polacek (2006), Computational Optimization of Split Injections and EGR in a Diesel Engine Using an Adaptive Gradient-Based Algorithm, *Society of Automotive Engineers (SAE)*, Inc, 01-0059.

Technology, Volume 01, Issue 10, Pages 1691-1698 December 2014.

K. S. Varde and G. A. Frame (1983), Hydrogen Aspiration in a Direct Injection Type Diesel Engine – Its Effects on Smoke and Other Engine Performance Parameters, *Int. J. of Hydrogen Energy*, 8(7) pp 549--555.

S. Furuhama and T. Fukuma (1986), High output power hydrogen engine with high pressure fuel injection, hot surface ignition and turbocharging, *Int. J. of Hydrogen Energy*, 11(6), pp 399-409.

S. Furuhama (1989), Hydrogen Engine system for Land Vehicles, *Int. J. of Hydrogen Energy*, 14(12), pp 907-913.

J. K. S. Wong (1990), Compression Ignition of Hydrogen in a Direct Injection Diesel Engine Modified to Operate as a Low-Heat-Rejection Engine, *Int. J. of Hydrogen Energy*, 15(7), pp 507-514.

H. S. Yi, S. J. Lee, E. S. Kim (1996), Performance Evaluation and Emission Characteristics of In-cylinder Injection Type Hydrogen Fueled Engine, *Int. J. of Hydrogen Energy*, 21(7), pp 617-624.

J.D. Naber and D.L. Siebers (1998), Hydrogen combustion under diesel engine conditions, *Int. J. of Hydrogen Energy*, 23(5), pp 363-371.

M. Senthil Kumar, A. Ramesh and B. Nagalingam (2003), Use of Hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine, *Int. J. of Hydrogen Energy*, 28(10), pp 1143-1154.

Zuohua Huang, Jinhua Wang, Bing Liu, Ke Zeng, Jinrong Yu, and Deming Jiang (2006), Combustion Characteristics of a Direct-Injection Engine Fueled with Natural Gas–Hydrogen Blends under Various Injection Timings, *J. of Energy Fuels*, 20(4), pp 1498–1504.

J.M. Gomes Antunes, R. Mikalsen, A.P. Roskilly (2009), An experimental study of a direct injection compression ignition hydrogen engine, *Int. J. of Hydrogen Energy*, 34(15), pp 6516-6522.

Probir Kumar, Rahul Banerjee, and Madhujit Deb (2012), Combustion and performance analysis of hydrogen direct injection with diesel as an ignition source at a particular injection timing with varying injection durations, *Int. J. of Mechanical Engineering and Robotics Research*, 1(3).

Vinod SinghYadav S. L. Soni and Dilip Sharma (2013), Engine Performance of Optimized Hydrogen-Fuelled Direct Injection Engine, *Int. J. of Scientific and Engineering Research*, 4(6).

B. HaraGopala Rao, K. N. Shrivastava and H.N. Bhakta (1983), Hydrogen for dual fuel engine operation, *Int. J. of Hydrogen Energy*, 8(5), pp 381-384.

Lee, S.J., H.S. Yi, E.S. Kim (1995), Combustion characteristics of intake port injection type hydrogen fueled engine, *Int. J. of Hydrogen Energy*, 20(4), pp 317–322.

Eiji Tomita, Nobuyuki Kawahara, Zhenyu Piap, Shogo Fujita and Yoshisuke Hamamoto (2001), Hydrogen Combustion and Exhaust Emissions Ignited with Diesel Oil in a Dual Fuel Engine, *Fall SAE Fuels and Lubricants Meeting and Exhibition*, Paper No.2001-01-3503, pp 1-8.

Das, L.M. (2002), Hydrogen engine: research and development (R&D) programmes in Indian Institute of Technology (IIT), Delhi, *Int. J. of Hydrogen Energy*, 27(9), pp 953-965.

V. Stefaan, S. Roger, and V. Sebastian (2004), A High Speed Single Cylinder Hydrogen Fuelled Internal Combustion Engine, *FISITA World Automotive Congress*, Barcelona 23-27.

N. Saravanan, G. Nagarajan, C. Dhanasekaran, K.M. Kalaiselvan (2007), Experimental investigation of hydrogen port fuel injection in DI diesel engine, *Int. J. of Hydrogen Energy*, 32(16), pp 4071 – 4080.

N. Saravanan, G. Nagarajan, and S. Narayanasamy (2008), An experimental investigation on DI diesel engine with hydrogen fuel, *Renewable Energy*, 33(3), pp 415–421.

N. Saravanan, G. Nagarajan (2008), An experimental investigation of hydrogen-Enriched Air Induction in a diesel engine System, *Int. J. of Hydrogen Energy*, 33(6), pp 1769 – 1775.

N. Saravanan and G. Nagarajan (2009), Performance and emission study in manifold hydrogen injection with diesel as an ignition source for different start of injection, *Renewable Energy*, 34(1), pp 328–334.

Murari Mohon Roy, Eiji Tomita, Nobuyuki Kawahara, Yuji Harada, Atsushi Sakane (2010), An experimental investigation on engine performance and emissions of a supercharged H2-diesel dual-fuel engine, *Int. J. of Hydrogen Energy*, 35(2), pp 844–853.

Madhujit Deb (2012), Hydrogen-Diesel Combustion On a Single Cylinder Diesel Engine, *J. of Applied Sciences Research*, 8(9), pp 4806-4814.

James W. Heffel (2003), NOx emission and performance data for a hydrogen fueled internal combustion engine at 1500 rpm using exhaust gas recirculation, *Int. J. of Hydrogen Energy*, 28(8), pp 901–908.

N. Saravanan, G. Nagarajan (2008), An Experimental investigation on performance and emissions study with port injection using diesel as an Ignition source for different EGR flow rates, *Int. J. of Hydrogen Energy*, 33(16), pp 4456-4462.

N. Saravanan and G. Nagarajan, (2009), Experimental Investigation in Optimizing the Hydrogen Fuel on a Hydrogen Diesel Dual-Fuel Engine, *Energy and Fuels*, 23(5), pp 2646-2657.

Probir Kumar Bose and Dines Maji (2009), An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation, *Hydrogen energy*, 34(11), pp 4847 – 4854.

H.B. Mathur, L.M. Das and T.N. Patro (1992), Effects of charge diluents on the emission characteristics of a hydrogen fueled diesel engine, *Int. J. of Hydrogen Energy*, 17(8), pp 635-642.

H.B. Mathur, L.M. Das and T.N. Patro (1992), Hydrogen fuel utilization in CI engine powered end utility systems, *Int. J. of Hydrogen Energy*, 17(5), pp 369–374.

H.B. Mathur, L.M. Das and T.N. Patro (1993), Hydrogen-fuelled diesel engine: Performance improvement through charge dilution techniques, *Int. J. of Hydrogen Energy*, 18(5), pp 421–431.

R. Adnan, H. H. Masjuki and T.M.I. Mahlia (2012), Performance and emission analysis of hydrogen fueled compression ignition engine with variable water injection timing, *Energy*, 43, pp 416-426.

M. S. Kumar, A. Kerihuel, J. Bellettre, M. Tazerout (2005), Experimental investigations on the use of preheated animal fat as fuel in a compression ignition engine, *Renewable Energy*, 30(9), pp 1443–1456.

V. Edwin Geo, G. Nagarajan, B. Nagalingam (2008), Studies on dual fuel operation of rubber seed oil and its bio-diesel with hydrogen as the inducted fuel, *Int. J. of Hydrogen Energy*, 33(21), pp 6357–6367.

Cengiz Öner, Şehmus Altun (2009), Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine, *Applied Energy*, 86(10), pp 2114–2120.

Gürü, M.; Koca, A.; Can, Ö.; Çınar, C.; Şahin, F. (2010), Biodiesel production from waste chicken fat based sources and evaluation with Mg based additive in a diesel engine, *Renewable Energy*, 35(3), pp 637–643.

Ho Teng, James C. McCandless and Jeffrey B. Schneyer (2001), Thermochemical Characteristics of Dimethyl Ether — An Alternative Fuel for Compression-Ignition Engines, *SAE*, World Congress, Detroit, Michigan.

Irshad Ahmed (2001), Oxygenated Diesel: Emissions and Performance

Characteristics of Ethanol-Diesel Blends in CI Engines, *Society of Automotive Engineers*, Inc.(SAE) 01-2475.

N. Saravanan, G. Nagarajan, G. Sanjay, C. Dhanasekaran and K.M. Kalaiselvan (2008), Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode, *Fuel*, 87(17-18), pp 3591–3599.