CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

India's economy is mainly based on the agriculture and this is the backbone of the country. The word agriculture and its association with India is not a new one, this was discussed even in oldest literature Rig-Veda around 1100 BC. Further, in present time also India being an agricultural based economy, approximately 43% of India's land is used for agriculture and farming sector which contributes employment nearly 2/3rd of the country's population[1].

Figure 1.1 Agriculture cultivation in India [1]

Generally, agriculture is mainly dependent on the timely availability of monsoons and the amount of rainfall in a given year. But due to uncertainty of monsoons, farmers in India resort to various irrigation techniques. Irrigation in India refers to the supply of water from rivers, tanks, wells, canals and other artificial projects for the purpose of the cultivation and agricultural activities.

India, being a vast country with much variation of geographical conditions, needs several irrigation techniques like; shallow water (head is 1- 6 meter) irrigation, deep water levels (head at 6 – 40 meter) irrigation and deep bore wells irrigation. But water pump based irrigation has serious limitations of availability of electricity and grid connectivity. These limitations forced most of the farmers to use diesel engine operated pump sets for their irrigation purposes. It is seen that from literature more than 2,00,000 engines were sold every year to make use in agricultural pump sets in India itself excluding the electrical generator sets [2] . With this background, in this present work an agricultural, stationary, single cylinder, 4 stroke, lister, water cooled, Indirect-injection, compression ignition engine was selected for experimental purpose.

1.2. DIESEL ENGINES [3]

Diesel engines also known as compression ignition engines. Basically, in compression ignition engines air is inducted into the cylinder and the fuel will be injected at the end of the compression stroke. The load control is varying by amount of fuel being injected in each cycle. The operation of a typical four stroke naturally aspirated compression ignition engine was shown below in Figure 1.2.

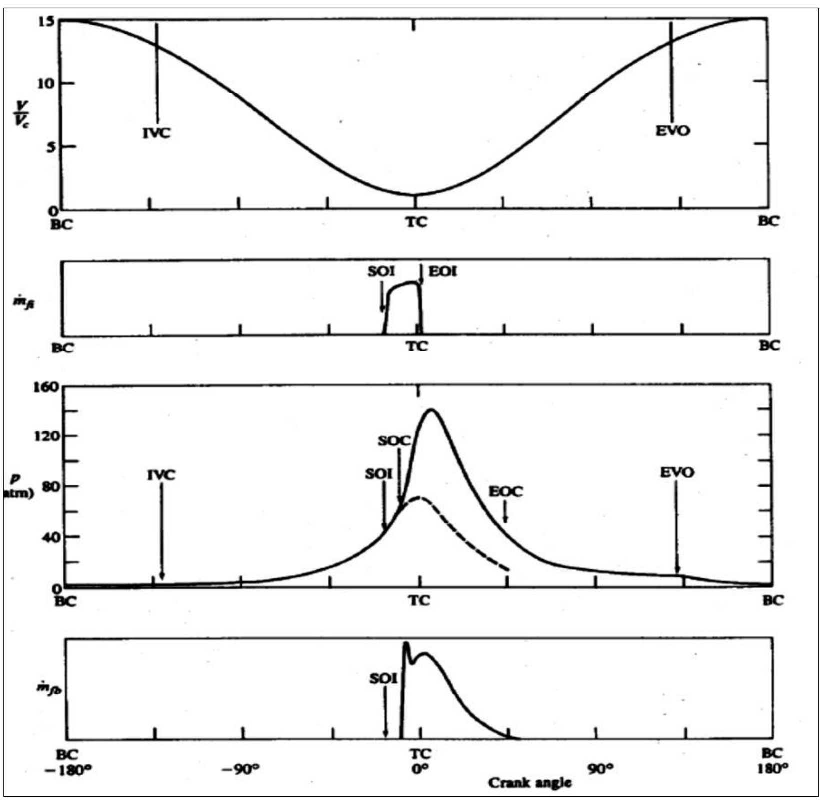

Figure 1.2 Sequence of compression, combustion and expansion processes of a naturally aspirated compression ignition engine [3]

In this operation, air will be inducted at atmospheric pressure during the intake stroke and gets compressed to a pressure about 4 MPa and temperature about 800K during the compression stroke. Generally fuel will be injected as per manufacturer's recommendation (nearly about 20^{o} bTDC). This injected liquid fuel atomizes and then mixes with air in a combustible range. After, its delay period spontaneous ignition of non-uniform fuel air mixtures initiates the combustion process, and the cylinder pressure was raised as shown in Figure 1.2, above the non-firing engine level. Then the flame spreads very rapidly through already available fuel-air mixture, where sufficient air available. During expansion process, fuel air mixture will further mixes with burned gases makes further combustion.

Basically these diesel engines are considered into two categories like: Indirect-injection (IDI) and Direct- injection (DI). In DI engines have a single open type combustion chamber into which fuel is being injected directly whereas in IDI engines, the combustion chamber was divided into auxiliary chamber or pre-chamber, available in the cylinder head and main combustion chamber in the cylinder. These two chambers are connected by either nozzle or orifice(s).

1.2.1. Direct-Injection Compression Ignition Engines

These engines are also called as open combustion chamber engines as the combustion space is essentially a single cavity with little restriction from one part of the chamber to other. Hence, no large difference in pressures between parts of the chamber during combustion. These chambers mainly consist of space formed between a flat cylinder head and the cavity in the piston crown in different shapes. The fuel is injected directly into the space provided in the combustion chamber. Generally, multiple injections used for this type of combustion chamber with relatively high pressures.

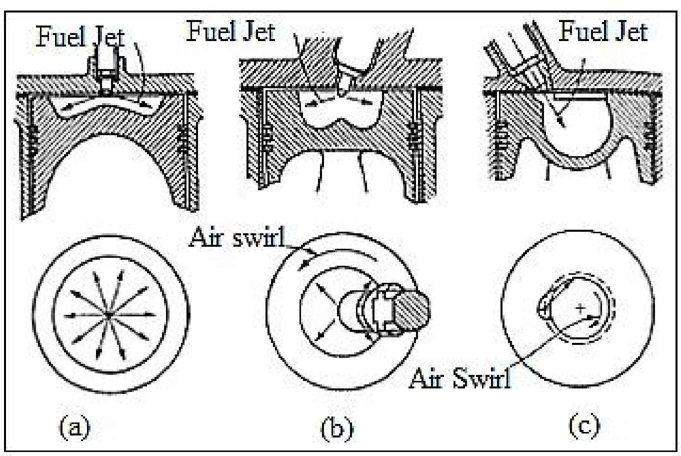

Figure 1.3 Common types of Combustion Chambers of Direct Injection Systems (a) quiescent chamber with multi- hole injector for large size engines (b) bowl- in –piston chamber with swirl and multi hole nozzle for medium to small size engines(c) bowl- in –piston chamber with swirl and single hole nozzle for medium to small size engines [3]

1.2.2. Indirect-Injection Compression Ignition Engines

Generally, these indirect-injection engines are divided into two chambers like: pre or auxiliary chamber and main combustion chamber systems. During compression, air is forced from the main chamber, available in above the piston into the auxiliary chamber through nozzle or orifice(s). Thus, at the end of the compression stroke, a vigorous flow experiences in the auxiliary chamber setup causes increase in pressure of the combustion products will rush into the main combustion chamber when fuel being injected into the auxiliary or pre- chamber, due to pressure difference of burn and un-burn charges. Generally, these auxiliary or pre-chambers available in the cylinder head accounted for 40% of the total combustion space. About 80% of energy released in the main combustion chamber. Initial shock of the combustion is limited to auxiliary chamber. Further, pre- combustion chamber engines are multi fuel capacity without any modifications of the injection systems.

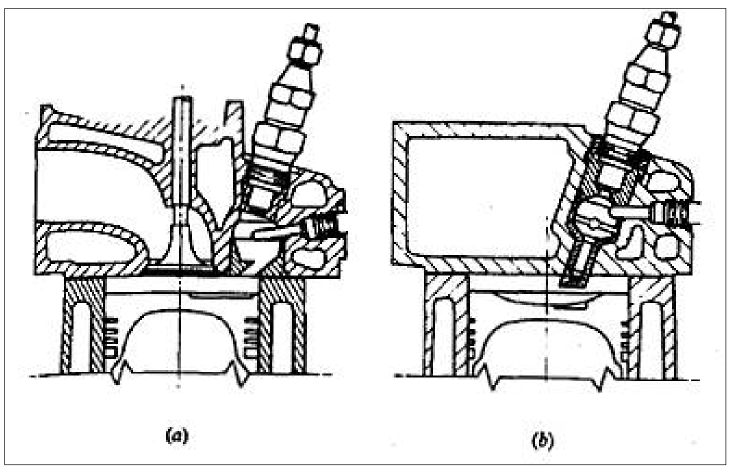

Figure 1.4 Common types of Combustion Chambers in IDI engines (a) Swirl pre-chamber (b) Turbulent pre-chamber [3]

1.3. COMPARISON OF INDIRECT-INJECTION (IDI) WITH DIRECT-INJECTION (DI) COMPRESSION IGNITION ENGINES

Though various types of combustion chamber types proposed and tried, only IDI and DI got survived due to soundness in their technical aspects of deigns. Various characteristics of common diesel engine combustion systems were shown in the Table 1.1

Table 1.1 Characteristics of Common Diesel Combustion Systems [3]

	Direct injection				Indirect injection	
System	Quiescent	Medium Swirl	High Swirl "M"	High Swirl multi spray	Swirl chamber	Pre-chamber
Size	Largest	Medium	Medium-smaller	Medium-small	Smallest	Smallest
Cycle	2/4 stroke	4-stroke	4-stroke	4-stroke	4-stroke	4-stroke
Turbocharged (TC)/supercharged (SC)/naturally aspirated (NA)	TC/SC	TC/NA	TC/NA	NA/TC	NA/TC	NA/TC
Maximum Speed (rpm)	120-2100	1800-3500	2500-5000	3500-4300	3600-4800	4500
Bore	900-150	150-100	130-80	100-80	95-70	95-70
Stroke/bore	3.5-1.2	1.3-1.0	1.2-0.9	1.1-0.9	1.1-0.9	1.1-0.9
Compression ratio	12-15	15-16	16-18	16-22	20-24	22-24
Chamber	Open or shallow dish	Bowl- in-piston	Deep bowl- in-piston	Deep bowl –in-piston	Swirl pre chamber	Single or multi orifice pre-chamber
Air-flow pattern	Quiescent	Medium swirl	High swirl	Highest swirl	Very high swirl in pre-chamber	Very turbulent in pre-chamber
Number of Nozzle holes	Multi	Multi	Single	Multi	Single	Single
Injection pressure	Very high	High	Medium	High	Lowest	Lowest

For marine and slow speed engines for power generation generally open quiescent chamber, disc shaped, 2 Stroke engines will be used, where the motion of fuel jet is responsible for distributing and mixing of the fuel. Whereas for locomotives and large trucks use a shallow dish or bowl type quiescent chamber engines will be used. These engines are mainly boosted by either through the supercharging or turbocharging to get high power.

IDI engines have been traditionally employed for long time for smallest engines where the vigorous air motion is required for high fuel-air mixing rates required. As different geometries available like swirl and turbulent pre-combustion chambers, substantial swirl was obtained in the swirl chamber during latter part of the combustion or they generate intense turbulence in the pre- chamber through small openings. Some of the advantages of Indirect-Injection over the Direct-injection were identified below:

1. Indirect-injection (IDI) engines injection pressure requirement is low when comparing to Direct-injection (DI) engines
2. Spray direction is not an important in Indirect-injection (IDI) as it is very important in Direct- injection (DI) engines.
3. Further, these Pre-combustion chamber designs have a multi fuel capability without any modification in the injection systems because of availability of high temperatures in the Pre-combustion chambers.
4. Price of the IDI engines are less when comparing to DI engines

Due to these advantages, an IDI engine with swirl Pre-combustion chamber was used for this experimental work as shown below Figure 1.5.

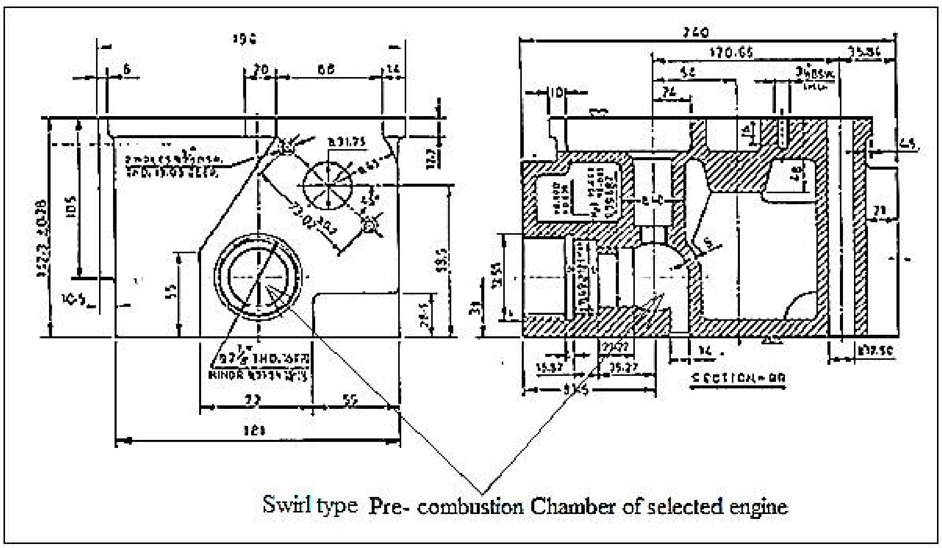

Figure 1.5 Swirl type Combustion Chamber of selected IDI engine

1.4. ALTERNATIVE FUELS USED IN EXISTING DIESEL ENGINES

The current way to meet the world's energy demand, which is based primarily on fossil fuel, is becoming increasingly untenable. Fossil fuel reserves, once hardly ever given a second thought, now are clearly exhaustible. Fossil fuel prices have never been more volatile, influenced first by economic acceleration mostly in India and China and subsequently by economic recession. The difficulty of controlling prices and the uncertain reserves are strong incentives for pursuing energy security. In present scenario, India is able to produce only 30% of total fossil fuel requirement and rest 70% is being imported from outside, which costs near about ₹ 80,000 crore every year [4]. Global warming and local pollution hot spots associated with fossil fuel usage are further significant environmental and societal problems. Being the strong drives to replace the fossil fuels with alternative fuels that to especially for agricultural side irrigation pump engines, best suitable and viable and renewable vegetable oil was considered for this experimental work.

1.4.1. Vegetable Oils

Earth's limited reserves of the fossil fuels are depleting rapidly and is a major threat due to over exploitation from the earth crust and also deteriorating the environmental conditions which have become a greater issue concerning everyone in the world. These factors influenced the researchers and scientists to think globally to search for the renewable sources of energy. Vegetable oils are good alternative for fossil fuels because they require minimum engine modifications and are readily available. Vegetable oils are almost of the same power output as that of conventional diesel that require higher fuel consumption leading to slightly lower thermal efficiency when compared to diesel. These problems can be traced back to the high viscosity, low volatility and reactivity of the unsaturated hydrocarbon chains in vegetable oils.

Among 300 varieties tree born oil seeds were identified. Some very popular easily available vegetable oils are: Corn (*Zea mays*), Cotton seed (*Gossypium hirsutum and Goossypium herbaceum*), Crambe (*Crambe abyssinica*), Jatropa (*Jatropa Curcas*), Linseed (*Linum usitatissimum*), Rapeseed (*Brassica napus*), Safflower (*Carthamus tinctorius*), Sesame (*Sesame indicum*), Babassu (*Attalea speciosa*) etc. These oil properties are mentioned in the below Table 1.2 [4].

Table 1.2 Properties of Vegetable Oil [4]

Vegetable Oil	Kinematic Viscosity at 38°C (cSt)	Cetane No.	Heating Value (MJ/kg)	Cloud Point (°C)	Pour Point (°C)	Flash Point (°C)	Density (kg/lit)
Corn	34.9	37.6	39.5	-1.1	-40.0	277	0.9095
Cotton seed	33.5	41.8	39.5	1.7	-15.0	234	0.9148
Crambe	53.6	44.6	40.5	10.0	-12.2	274	0.9048
Jatropa	37.03	-	41.27	-24	-8	240	0.915
Linseed	27.2	34.6	39.3	1.7	-15.0	241	0.9236
Peanut	39.6	41.8	39.8	12.8	-6.7	271	0.9026
Rapeseed	37.0	37.6	39.7	-3.9	-31.7	246	0.9115
Safflower	31.3	41.3	39.5	18.3	-6.7	260	0.9144

Sesame	35.5	40.2	39.3	-3.9	-9.4	260	0.9133
Soyabeen	32.6	37.9	39.6	-3.9	-12.2	254	0.9138
Sunflower	33.9	37.1	39.6	7.2	-15.0	274	0.9161
Palm	39.6	42.0	-	31.0	-	267	0.9180
Babassu	30.3	38.0	-	20.0	-	150	0.9460
Diesel	3.06	50	43.8	-	-16	70	0.8550

From the Table 1.2 it is seen that, the kinematic viscosity of various vegetable oils are ranging from 30-40 cSt at 38^{o} C, cetane number varies from 37-45 which is nearer to diesel. Chemical bound oxygen content in the vegetable oil reduces the heating values in the range of 39-41 MJ/kg. However, these values are nearer to heating value of the conventional diesel of 43.8 MJ/kg, further being non-edible, renewable, low sulphur and aromatic content and as well as biodegradability makes the vegetable oil is good alternative to the conventional diesel fuel [5]. As they possess higher flash points, these can be stored even at high temperatures, by that fire hazards can be avoided. Being an oxygenated bio-fuel, it can better participate in the combustion process also.

But at the same time, as vegetable oils are more viscous,(nearly 10-20 times more viscous than the conventional diesel) it effects its atomization and there by vaporization to participate in the combustion. Hence, poor combustion of the vegetable oil will effect the life of the engine during long run due to formation of more carbon deposits on piston, thickening and gelling of the engine lubricating oil and Injector coking with trumpet formation etc.. To overcome these identified viscosity related issues, a wide variety of approaches like; use of esters to trans-esterify the vegetable oils (bio-diesels) were considered. From the literature[6], as Comparative Life Cycle Assessment (CLA) shown that use of straight vegetable oil is more environmental friendly rather than the bio-diesel on the basis of Energy Return on Investment Index (EROI) and toxicity and non-toxicity basis. Hence, an attempt towards use of straight vegetable oils (SVO), SVO blends with diesel, pre-heated SVO and pre-heated SVO with hydrogen supplementation were considered. However, in concern with the advantages of the use of straight vegetable oil- engines, India being a tropical country and 43% of land is being used for agricultural purpose, showed very good potential. Hence, in this direction stationary diesel engines running at low speed, such as irrigation pumps and electricity generators are believed to be suitable to use straight vegetable oil (SVO) as a pilot fuel supplemented with hydrogen without any environmental burden.

Among the different identified plant species for vegetable oils, two plant species like Jatropa (*Jatropa curcas*) and Karanja (*Pungamia pinnata*) were recommended by planning commission of India, that launched bio-diesel projects in 200 districts of 18 states of India [7]. Among all, Jatropa (*Jatropa curcas*) and Karanja (*Pungamia pinnata*), were identified which can yield as oil resource of energy, Jatropa (*Jatropa curcas*) was selected for the present work as the most suitable specie for India being widely grown even in harsh climates, saline and alkaline soils. Further, this can be planted on degraded lands or waste lands or as field boundaries also.

Hence, in this present experimental investigation, selected IDI diesel engine was fuelled with pre-heated Jatropa (*Jatropa curcas*) straight vegetable oil at 90°C (PHSVO 90) with small doses of gaseous hydrogen (GH_2) supplementation.

1.4.2. Hydrogen

Hydrogen is thought to be a major energy resource of the present and the future due to its clean burning nature and eventual availability from renewable sources. Further, the use of hydrogen as an energy carrier is one of the options put forward in most governmental strategic plans for a sustainable energy system. The Indian Ministry of New and Renewable Energy [8]; the Japanese Ministry of Economy, Trade and Industry [9]; the European Commission's Directorate-General for Research [10]; the United States Department of Energy [11] and many others have formulated vision reports and published funding calls for hydrogen programs. Majorly, being a carbon free fuel having excellent combustion characteristics, hydrogen is used in internal combustion engines and is suggested as interim energy conversion strategy prior to introducing fuel cell technology [12]. Hydrogen is odorless, tasteless, colorless, non-corrosive and non-toxic element. Further, its combustive properties are discussed below.

(i) **Wide Flammability Range:** When compared to different fuels, hydrogen has wide flammability range from 4 to 75% by volume. A mixture of 4-75% by volume of hydrogen in air is sufficient to form combustible mixture at atmospheric pressure and room temperature. Whereas for gasoline, diesel, LPG, CNG, Di-ethyl ether (DEE), and bio gas are in the range of 1.4-7.6%, 0.6-5.5%, 2.15-9.6%, 5-15%, 1.9-36% and 7.5-14% respectively. Wide flammability needs to make attention towards safety in storage and handling.

This wide flammability of hydrogen enables to mix with wide range of fuels at lean mixtures of fuels to air or fuel air mixture in which amount of fuel is less than the chemically correct mixture, stoichiometric amount leads to increase in fuel economy due to more complete combustion of the fuel [13].

(ii) **Quenching Distance:** Hydrogen has a very small quenching distance of 0.6 mm, whereas for gasoline the same was increased to 2 mm, which refers to the distance from the internal cylinder wall, where the combustion extinguishes. Hence, it is very difficult to quench the hydrogen flame comparing to other fossil fuels which can highly prone to backfire, since, hydrogen flame from the available mixture more readily possess nearer to the intake valve, when comparing to Hydro carbon fuel-air mixtures [13].

(iii) **Flame Velocity and Adiabatic flame:** Hydrogen burns with high flame velocity, allowing the hydrogen engines to more closely approach the ideal cycle, when the stoichiometric mixture of hydrogen –air got burned. Further, flame velocity as depends on the fuel-air ratio as it becomes lean, the flame velocity also decreases considerably. The laminar flame speed of hydrogen is 1.9 m/s at normal pressure and temperature which is almost 5 times higher than the hydrocarbon fuels. From the above Figures 1.6 & 1.7 , it is observed that , flame velocity and adiabatic flame temperatures are very important properties to make use of hydrogen in internal combustion engines, especially in thermal efficiency, combustion stability and emissions [13-15].

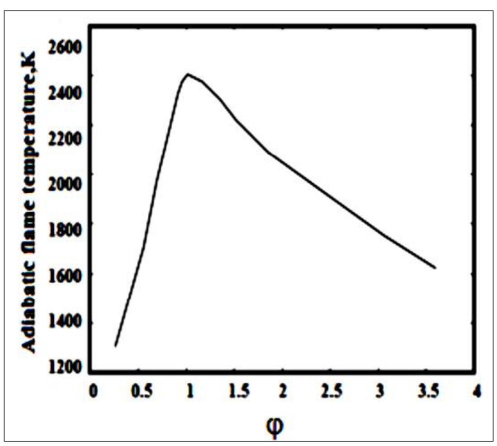

Figure 1.6 Adiabatic flame temperature for H_2-Air mixture [13-15]

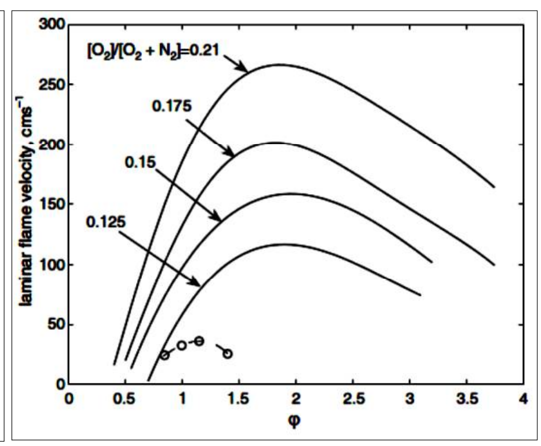

Figure 1.7 Laminar flame velocity for (—) hydrogen, oxygen and nitrogen mixtures and (◦, - -) gasoline and air mixtures [13-15]

(iv) **Minimum Ignition Energy:** Minimum ignition energy is the minimum energy required to ignite the fuel –air mixture by an ignition source. The minimum ignition energy for the hydrogen- air mixture is 0.02 mJ, whereas for gasoline is 0.24 mJ. However, this low ignition energy, causes hydrogen-air mixtures will react with available hot spots and hot combustible products may become source to premature ignition and further leads to flash back and backfire [16].

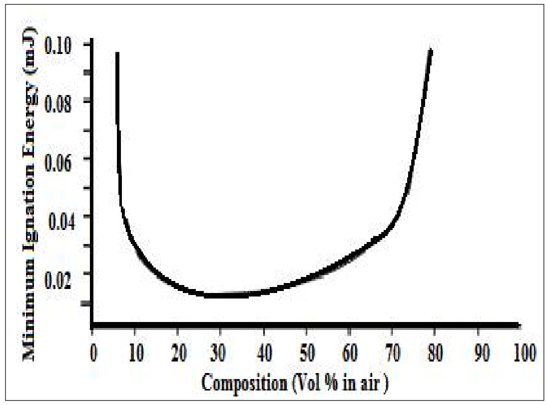

Figure 1.8 Minimum Ignition energy of H_2 –Air mixture

(v) **High diffusivity:** Hydrogen has high diffusivity when comparing to other gaseous fuels. This ability to disperse into air is considerably greater than the fossil fuels and this advantageous property will help to form the uniform mixture of air and this will further enhances the heterogeneous mixture towards the homogeneous mixture to get local combustible mixtures in CI engines, leads to improved combustion. Further, faster and complete burning of this homogeneous mixture happens nearer to TDC causing increase in brake thermal efficiency. Secondly, if the hydrogen got leaked, can easily disperse very quickly into air and may avoid the hazardous situations [17].

(vi) **Low Density:** Due to low density of hydrogen, energy per unit volume is less. Further, significant compression and conversion is required to convert into a hydrogen liquid state. Low density also implies that the fuel-air mixture has low energy density , which tends to reduce the power output of the engine [13].

(vii) **High Self-Ignition Temperature:** The self-ignition temperature is the minimum temperature required to initiate self-sustained combustion in a combustible mixture in the absence of any external ignition source. For hydrogen, the self-ignition is near about 585° C. This self-ignition temperature has important implications when a hydrogen–air mixture is compressed. Hence, self-ignition temperature is an important factor in considering the compression ratio of an engine. To ignite this high self –ignition temperature H_2-air mixtures, a high compression ratio is desirable. But on the other hand high compression ratio will leads to severe knocking in hydrogen supplemented or substituted engines [17] and [18].

Table 1.3 Comparison of Hydrogen with other fuels

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoichiometric Air-fuel ratio (kg)	Combustible range (%)	Flame Temp. (°C)	Min. Ignition Energy (mJ)	Self-ignition temp. (°C)
Methane	50.0	55.5	17.2	5-15	1914	0.30	540-630
Propane	45.6	50.3	15.6	2.1-9.5	1925	0.30	450
Octane	47.9	15.1	0.31	0.95-6	1980	0.26	415
Methanol	18.0	22.7	6.5	6.7-36	1870	0.14	460
Hydrogen	119.9	141.6	34.3	4-75	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3-7.1	2307	0.29	260-460
Diesel	42.5	44.8	14.5	0.6-5.5	2327	-	180-320

Table 1.4 Properties of Hydrogen

Properties	Diesel	Unleaded Gasoline	Hydrogen
Self- Ignition Temp. (K)	530	533 – 733	841-858
Min. Ignition energy (mJ)	-	0.24	0.02
Flammable limit (vol. % in air)	0.7 - 5	1.4 – 7.6	4 -75
Stoichiometric air fuel ratio on mass	14.5	14.6	34.3
Limits of flammability (equivalence ratio)	-	0.7 – 3.8	0.1-7.1
Density at 16^0 and 1.01 bar	833 – 881	721 – 785	0.0838
Net heating value, (MJ/kg)	42.5	43.9	119.93
Flame velocity (cm/s)	30	37-43	265-325
Quenching gap in NTP air (cm)	-	0.2	0.064
Diffusivity in air (cm^2 / s)	-	0.08	0.63
Octane number	-	92-98	130
Cetane number	44-55	13 -17	-

1.5. THESIS ORGANIZATION

The remaining chapters of this thesis have been organized in the following manner.

CHAPTER 2: Deals with literature review related to potential of using vegetable oils in diesel engines through different processes like; Use of esters of vegetable oils, use of vegetable oil blends with diesel, use of straight vegetable oils, use of pre-heated straight vegetable oils and also concentrated on prospects and perspective of gaseous hydrogen utilization in compression ignition engines to give much emphasis on to identify the hydrogen usage in sole as well as supplemented modes in compression ignition engines to augment the performance by enhancing the combustion and reduction in emissions. Further different undesirable combustion anomalies in addition to different hydrogen induction/injection techniques also considered.

CHAPTER 3: Discusses the selection of Jatropa based straight vegetable oil, gaseous hydrogen and understanding of physico and chemical properties of identified fuels along with conventional diesel . Development of Experimental set up and the associated instrumentation, like details of engine with developed self-staring system, eddy current dynamometer, smoke meter, 5 gas analyzer with sampling unit, design and development of gaseous hydrogen supply system, crank angle encoder, mounting of pressure transducer, and usage of advanced combustion analyzer. And this chapter also describes the experimental procedure in order to conduct the various experiments staring from base line data with conventional diesel, pre- heated straight vegetable oil (Jatropa) at 90^oC (PHSVO 90) and extended to gaseous hydrogen (GH_2) supplementation with PHSVO 90 at manufacturer recommended engine variables, varied injection timings and injection pressures for engine optimization and its comparison with base line data.

CHAPTER 4: Analysis and discussion of results as per identified objectives were presented. Results of baseline conventional diesel and PHSVO 90 were discussed individually and compared with each other in order to understand the best efficiency load on the basis of performance, emissions and combustion characteristics. Also discussed the influence of GH_2 supplementation with PHSVO 90 along with different injection advancements and injection pressures were discussed. Finally, compared the optimized results with baseline diesel and as well as PHSVO 90 results.

CHAPTER 5: Summarizes the major conclusions of the present investigation and offers future scope of the work.