CHAPTER 3
METHODOLOGY

To achieve the objectives of the present investigations, experiments were conducted on an experimental setup, which was designed, assembled, fabricated and made available to test the engine with conventional diesel, pre-heated Jatropa based straight vegetable oil at $90^{o}C$ (PHSVO 90), PHSVO 90 with different gaseous hydrogen (GH_2) supplementation and PHSVO 90 with optimized GH_2 band with different injection timings and injection pressures, in Engine Research Laboratory (ERL) of University of Petroleum & Energy Studies, (UPES), Dehradun. A schematic diagram along with its photograph of the experimental setup is shown in Figures 3.1 and 3.2.

3.1. SELECTION OF FUELS FOR ENGINE

Jatropa curcas, generally known as Jatropa was selected as pilot fuel for the proposed experimental investigation because of its availability, renewable, almost same power output as compared to diesel. The Jatropa seeds were supplied by Uttarnchal Vanopaj Sahkari Sharam Savid-Dehradun. And these seeds were crushed and filtered in biofuels laboratory at UPES, Dehradun.

Further, **Hydrogen**, is the lightest element on the earth and being major energy resource of the of the present and future, renewable, clean, high flame velocity, low minimum ignition energy, high calorific value, zero GHGs .. For experimentation, gaseous hydrogen was made available from M/s. INOx Air Products, Delhi and M/s. Gupta Gas Agencies, Dehradun for the present investigation. The present work is a major step forward in the direction of eradicating the problems imposed by the present fossil fuel crisis.

The physico-chemical properties of selected fuels like conventional diesel, Jatropa based straight vegetable oil, and gaseous hydrogen showed in Table 3.1.

3.2. PHYSICO & CHEMICAL PROPERTIES OF DIESEL, JATROPA'S STRAIGHT VEGETABLE OIL (SVO) AND HYDROGEN

Table 3.1 Physico- Chemical properties of different fuels

Sl.No	Description	Diesel	Jatropa SVO	H_2	Test method
1	Specific gravity	0.824	0.935	0.081	IS: 1448 (P-32) 1992
2	Self-Ignition temp. ^{o}C	210-256	315-340	500-568	literature
3	Kinematic Viscosity, cSt at 40^{o} C	2.33 – 2.77	34.33-36	-	lS: 1448 (P-25) 1976
4	Kinematic Viscosity, cst at 90^{o} – 100^{o}C	-	4.73	-	lS: 1448 (P-25) 1976
5	Calorific value, MJ/kG	44.5	41.2	119	IS: 1448 (P-6) 1984
6	Flash Point, ^{o}C	78	235	-	IS: 1448 (P-21) 1992
7	Fire Point, ^{o}C	93	262	-	lS: 1448 (P-69) 1969
8	Pour Point, ^{o} C	0.5	-10	-	IS: 1448 (P-10) 1970
9	Water content, mg/kg	115	186	-	ISO: 12937
10	Sediment, % by mass	Nil	Nil	-	IS: 1448 (P-30) 1970
11	Conradson carbon residual, % by mass	0.01	0.53		ASTM D-189
12	Total acid number, mg KOH/gm	0.1	18.8		IS: 1448 (P-2) 2007
13	Total base number, mg KOH/gm	Nil	0.52		IS: 1448 (P-86) I977

3.3. EXPERIMENTAL SETUP

Experimental set up comprises agricultural stationary, lister, 4 stroke, IDI, single cylinder diesel engine and eddy current dynamometer with all necessary allied equipment and associated instrumentation. A properly designed and fabricated gaseous hydrogen handling system was used to supplement the gaseous hydrogen for a given duration at pre-determined injection timing. To ensure the repeatability of the results, at least three times experiments were conducted and its average was considered for calculations. All the safety related issues in handling and storage of gaseous hydrogen were designed and adopted in Engine Research Laboratory (ERL) for present investigation, as per Class I, Division 2, Group B of National Fire Protection Association (NFPA), Massachusetts, USA as shown in **Appendix-A**. Standards emission measurement equipment along with properly designed exhaust gas flow system was used to authenticate the engine emissions data. The detailed description about experimental set up was described in further sections of the this chapter.

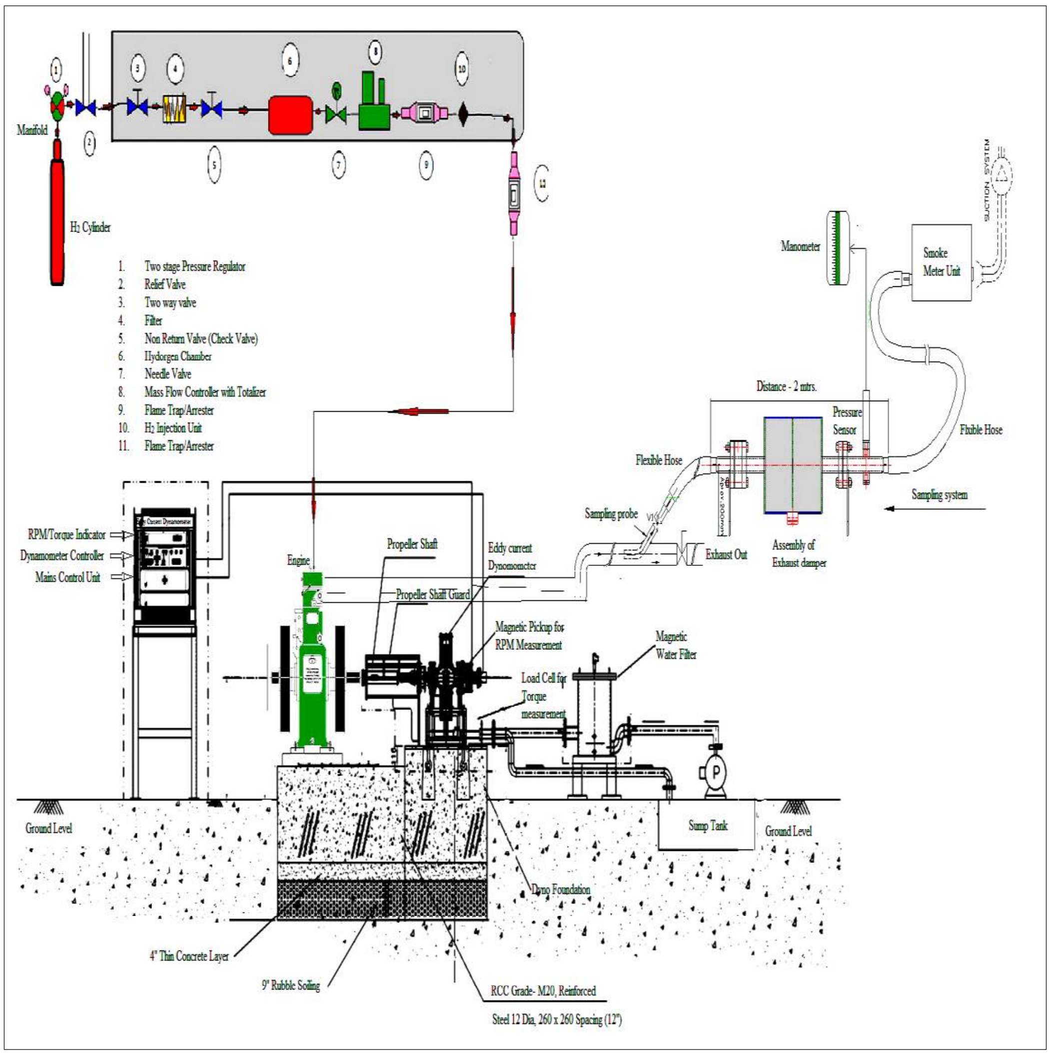

Figure 3.1 Schematic diagram of Experimental Set Up

Figure 3.2 Photographic view of Experimental Set Up

3.3.1. Engine

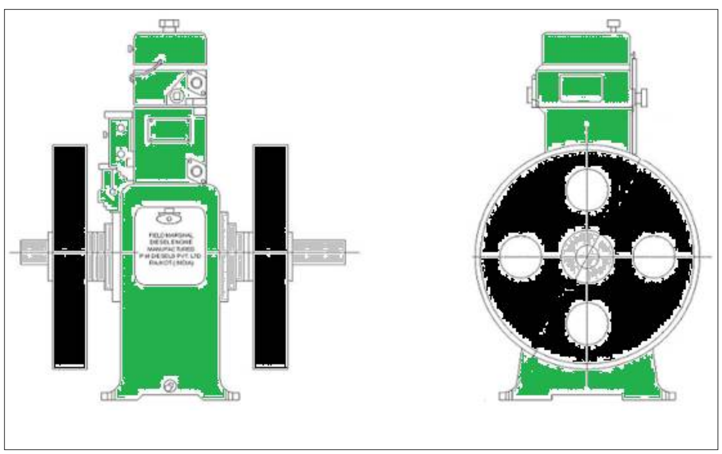

Figure 3.3 Pictorial representation of selected engine

Table 3.2 Technical specifications of the selected engine for experimentation

Description	Technical Details
Make	Field Marshal
Model	FMS 10
General details	4S, Single cylinder, Water cooled, Lister, Vertical engine
Bore	120 mm
Stroke	139.7 mm
Compression ratio	17:1
Fuel Injection Opening Pressure	175 bar
Static Fuel Injection timing	20^{o} bTDC

As the engine was initially manual cranked (specifications as listed in Table 3.2), both ends of the engine had crank angle encoder at one end and eddy current and eddy current dynamometer on the other hand. Hence to start the engine, a separate cantilever based ring gear along with cranking motor was developed to self-start the engine as shown in Figure 3.4.

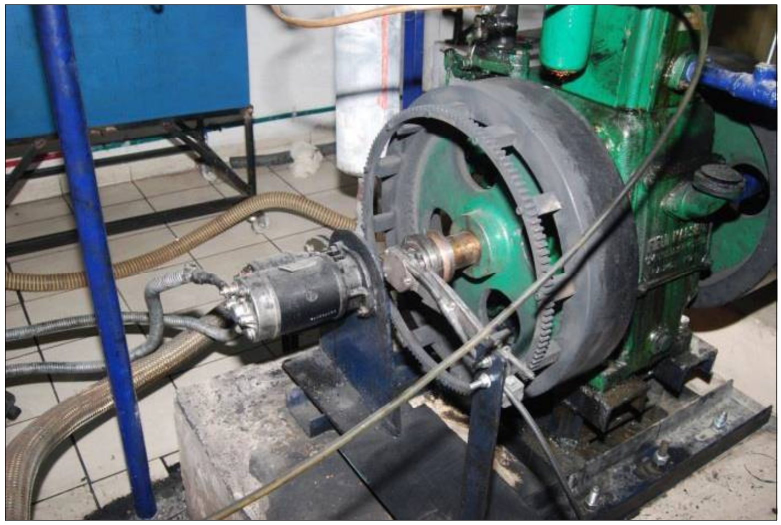

Figure 3.4 Cantilever based self-starting system

3.3.2. Eddy Current Dynamometer

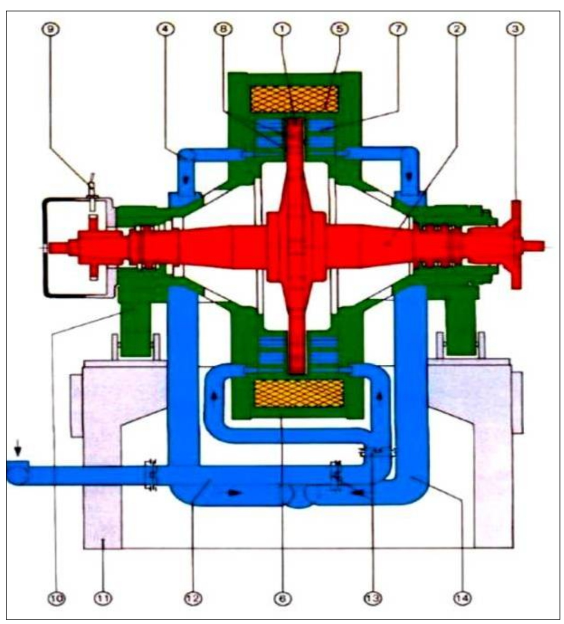

Figure 3.5 The cut sectional view of eddy-current dynamometer, where: 1) rotor, 2) rotor shaft, 3) coupling flange, 4) water outlet with thermostat, 5) excitation coil, 6) dynamometer housing, 7) cooling chamber, 8) air gap, 9) speed pick-up, 10) flexure support, 11) base, 12) water inlet, 13) joint, 14) water outlet pipe.

Table 3.3 Technical specifications of eddy current dynamometer

Description	Technical Details
Make	Dynomerk Controls
Model	EC 70
Maximum Power	70 HP at 5000 to 10,000 RPM
Maximum Speed	10,000 RPM
Maximum Torque	91 N-m
Direction of Rotation	Bi-directional
Torque Radius	509.84 mm
DC Excitation	60 V 6 Amp.
Maximum Weight in Pan	20 kg

An eddy current dynamometer (specification as listed in Table 3.3) [139] was able to control the engine in three modes as; constant speed, constant load and variable speed and load. Further, being a governor based engine, constant load mode of the eddy current dynamometer was selected by disconnecting the governor from the fuel supply system of the engine. By varying the rack position, as shown below Figure 3.6 the engine speed was maintained at a constant speed of 1000 rpm at various loads.

Figure 3.6 Rack control mechanism to run the engine at constant speed

3.3.3. 5 Gas Analyzer & Smoke Meter

An AVL Digas 4000 model Five gas analyzer was used to measure the exhaust emissions like NO_x, HC, CO, CO_2 and O_2. Smoke opacity was measured with AVL 437 Smoke meter [140, 141]. A detailed technical specifications of the both equipment are given in Tables 3.4 3.5 and 3.6.

Table 3.4 Measurement Parameters for Smoke Meter [85]

Description	Opacity	Absorption
Measuring range	0 – 100%	0 – 99.99 m^{-1}
Accuracy	$\pm$ 1% of full scale	Better than $\pm$ 0.1m^{-1}
Resolution	0.1%	0.01 m^{-1}

Table 3.5 Smoke Meter operational details [85]

Description	Range of operation
Smoke temperature at entrance	250^o C maximum
Measuring Chamber length	430 $\pm$ 5 mm
Heating	Thermostatically controlled
Heating time	20 min. (max) at 220 V supply
Operating temperature	90^o C
Light Source	Halogen Lamp, 12V / 5W
Sensor	Selenium Photocell
Ambient operating temperature	0 – 50^o C
Ambient operating humidity	90% at 50^o C (non- condensing)

A Non-Dispersive Infrared (NDIR) method is used to measure CO, CO_2 and HC. Whereas electrochemical method was used to trap the NO_x and O_2 by using 5 gas analyzer. To measure the smoke using AVL Smoke meter 437 is working on light absorption principle is also called Opacimeters.

Table 3.6 Measurement Parameters for 5 Gas Analyzer [86]

Description	Measurement range	Resolution
Engine Speed	250 – 8000 rpm	10 rpm
Oil temperature	0 – 120^o C	1^o C
CO	0 – 10% by vol.	0.01% by vol.
CO_2	0 -20 % by vol.	0.1% by vol.
HC	0 – 20000 ppm vol.	1 ppm vol.
O_2	0 – 4 % by vol. 4 – 22% by vol.	0.01% by vol. 0.1% by vol.
NO	0 – 4000 ppm vol.	1 ppm vol.

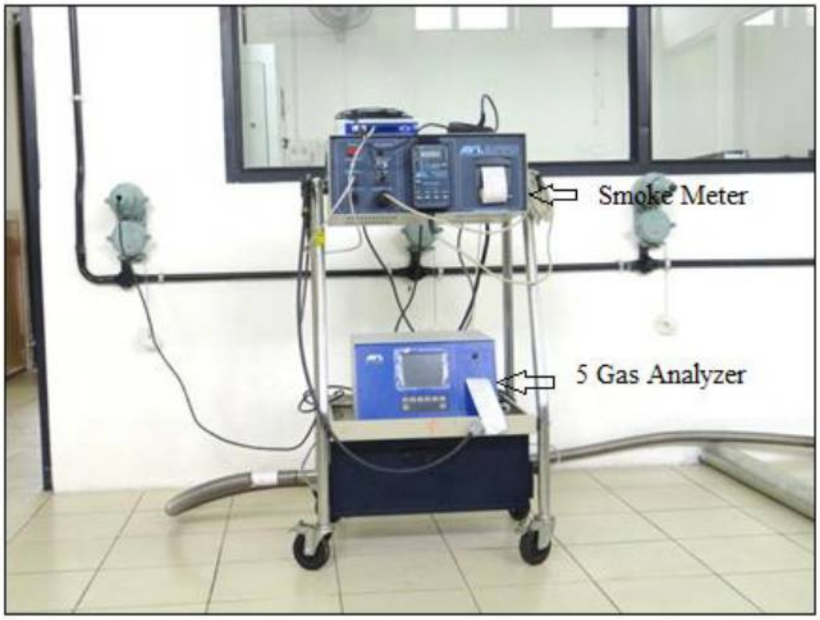

Figure 3.7 Smoke Meter and 5 Gas Analyzer

3.3.3.1. Sampling Unit

For emission measurements a representative sample is required for smoke meter and five gas analyzer. But, being a single cylinder, 4 stroke engine to fade the fluctuations from the exhaust, a sampling unit as shown in Figures 3.8 and 3.9 was designed and incorporated in the exhaust line to ensure proper representative sample to authenticate the exhaust emission measurements.

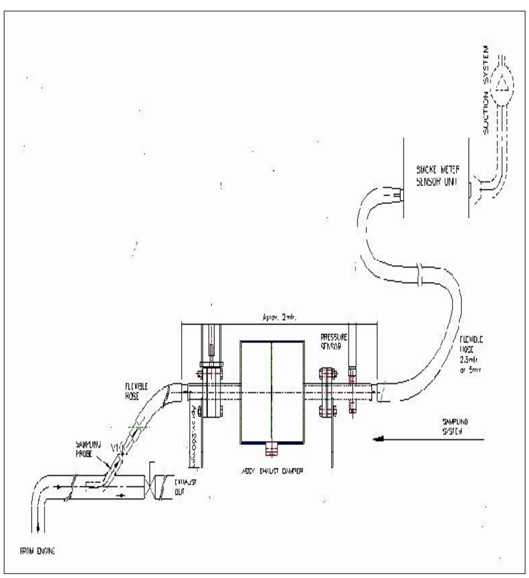

Figure 3.8 Schematic diagram of sampling system

Figure 3.9 Photographic view of sampling system

3.3.4. Fuel Measurement and Fuel lines

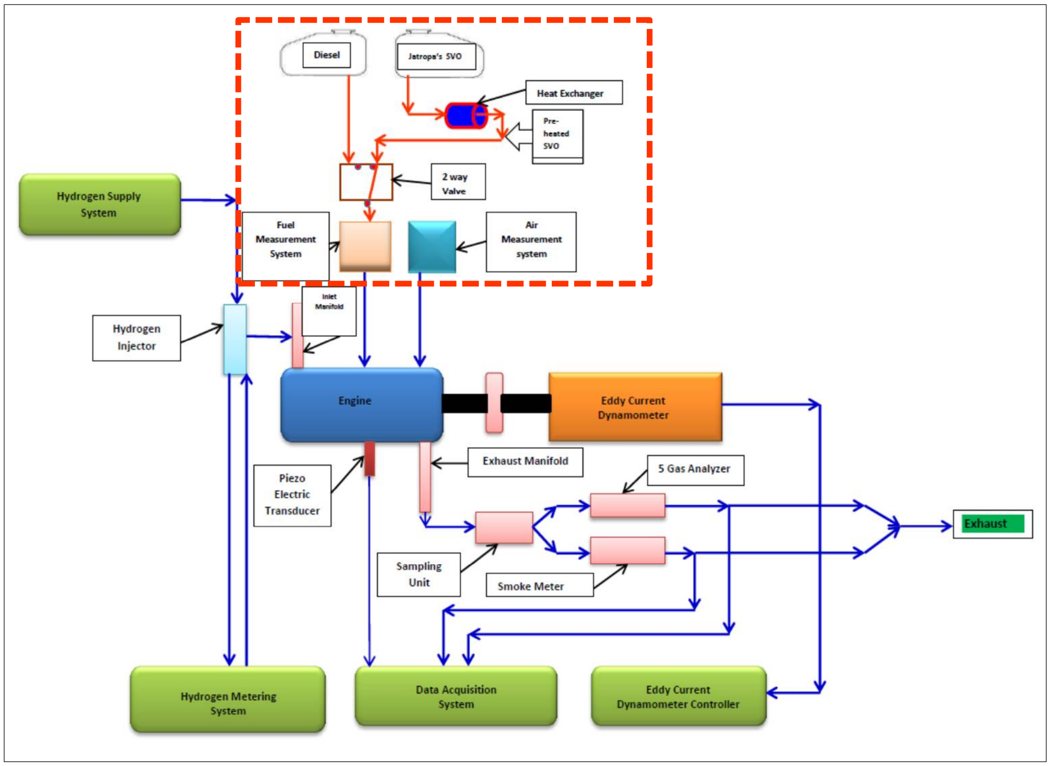

Figure 3.10 Fuel line Modifications

A gravimetric fuel measurement system was adopted to measure the fuel consumption measurements. However, at peak loads in order to reduce the flow fluctuations due to thirsty engine, a separate burette as a reservoir was made available to ensure proper flow of the fuel without affecting the fluctuations in fuel consumption measurements. A two-way valve was provided as shown in Figure 3.10, to ensure the supply of diesel during starting and stopping of the engine in addition to pre-heated straight vegetable oil. In order to overcome the problem of high fuel viscosity and cold start, the engine was always started with diesel fuel and then switched to vegetable oil. The engine was allowed to run for approximately 45 to 50 minutes to make sure that all diesel fuel was flushed out by the vegetable oil before the actual start of the measurements. Similarly, while shutting down, the engine was switched back from vegetable oil to diesel fuel and run for another 45 minutes to ensure that only diesel fuel was left inside the fuel system to avoid problems associated with cold start.

3.3.5. In-Cylinder Pressure Data Acquisition System

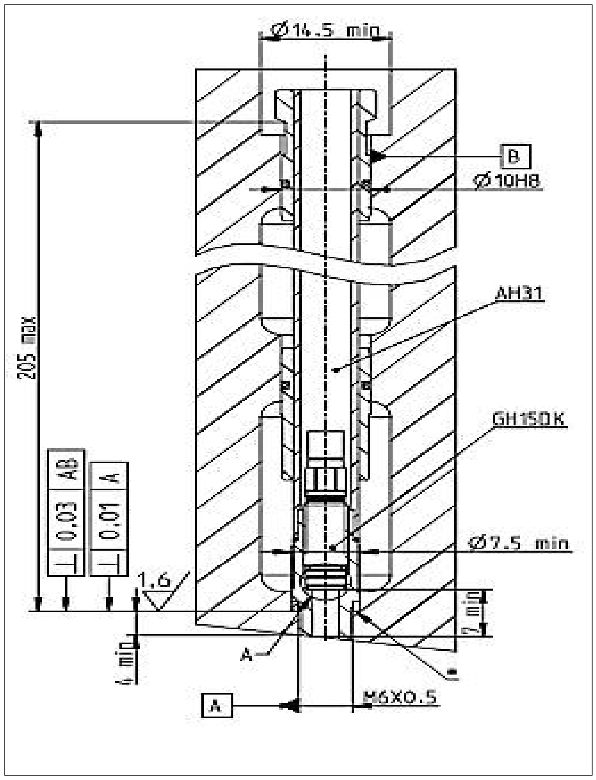

Figure 3.11 GH15DK Pressure Transducer

In-cylinder thermodynamic measurements were measured with AVL make $GaPO_4$ element based GH15DK model, double shell design, pressure transducer as shown in Figure 3.11 was used [142].

Table 3.7 Technical Specifications of Pressure Transducer

Description	Measurement range
Pressure measurement	0 to 300 bar
Overload	350 bar
Operating Temperature	- 40^o to 400^o C

This pressure transducer was provided perpendicular to the linear motion of the piston to ensure the proper exposing of burned products by the sensor during the combustion. Positioning of pressure transducer was shown below in Figures 3.12 and 3.13.

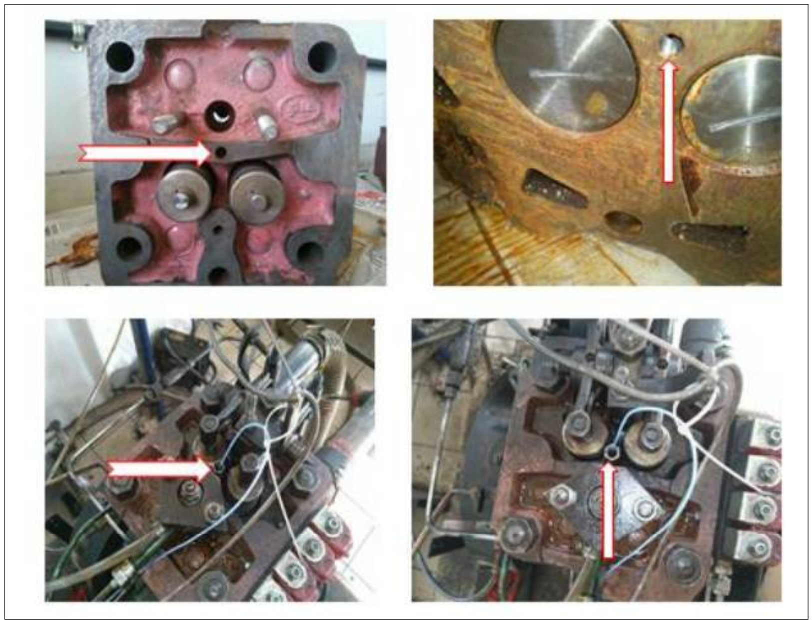

Figure 3.12 Photographic view of the Pressure Transducer mounting position on the cylinder head of the engine

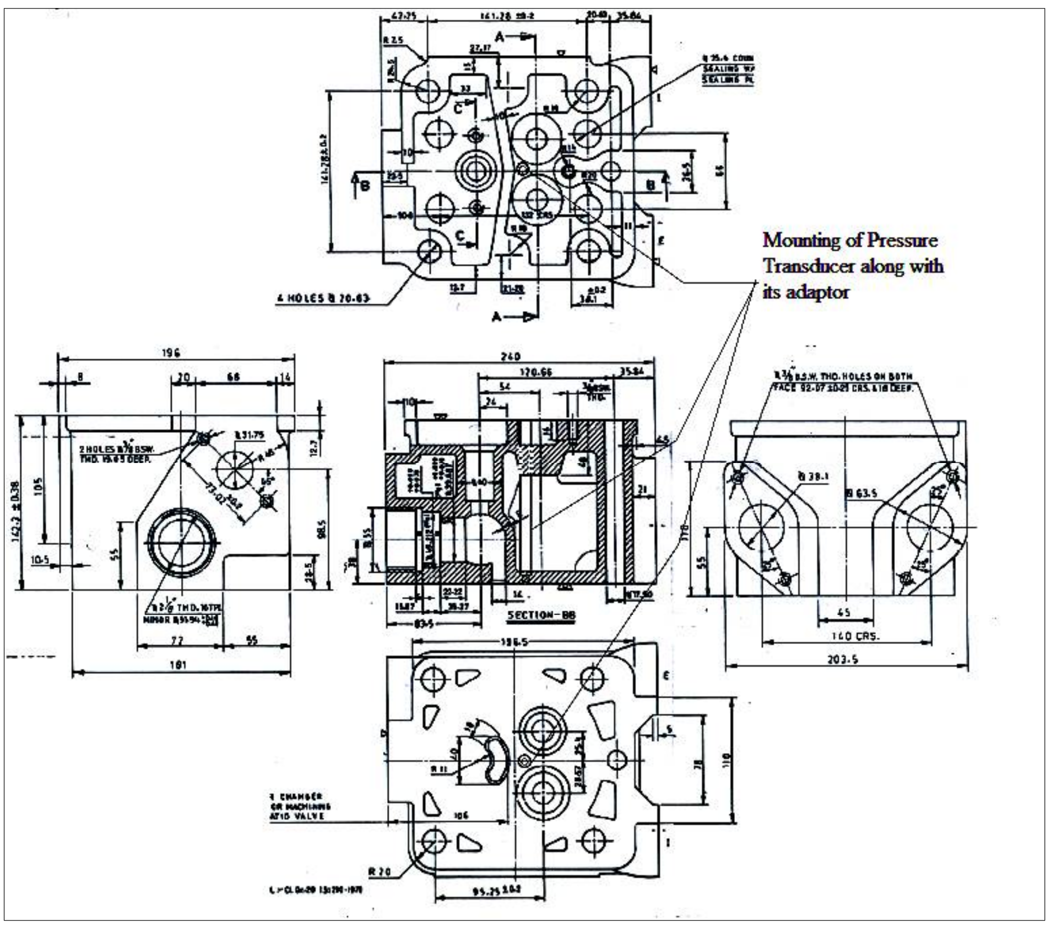

Figure 3.13 Cut –Sectional view of Pressure Transducer mounting position on the cylinder head of the engine

AVL 365 cc model, 720 pulses crank angle (CA) encoder [143] was mounted on one side of the engine as shown in Figure 3.14 & 3.15 and synchronized with TDC of the engine for accurate measurement of the cylinder pressure with respect to CA position. This CA encoder converts the analog momentum 'angle' of the crank shaft to digital signal and transfers same to advanced combustion analyzer, AVL Indi smart 612 [144].

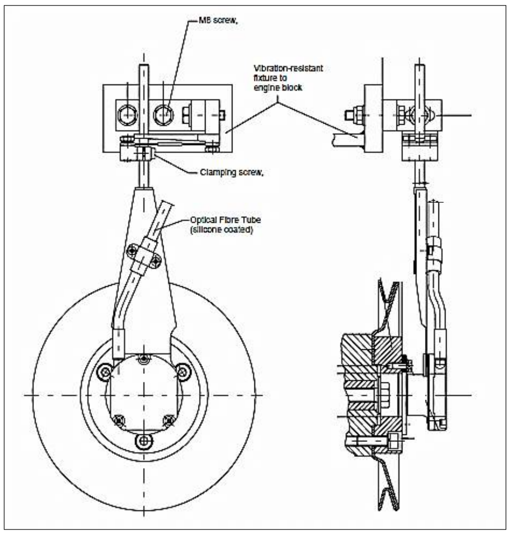

Figure 3.14 Crank Angle Encoder

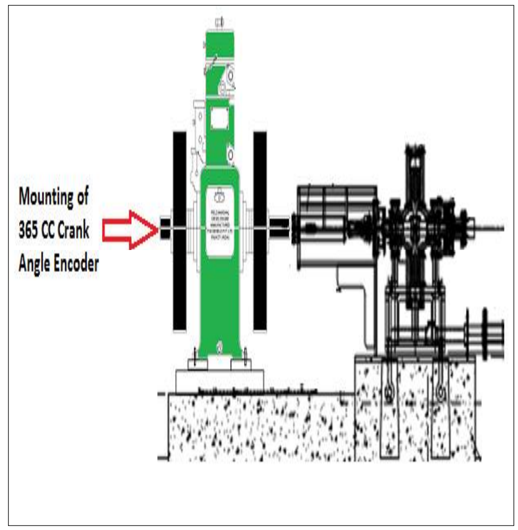

Figure 3.15 Mounting of AVL CA Encoder on Engine

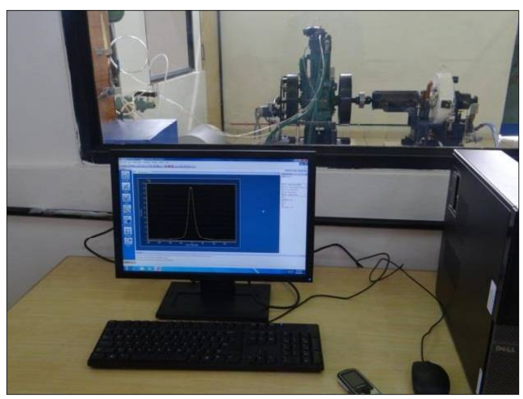

Figure 3.16 AVL Indi smart 612 advanced combustion analyzer

Further, TDC of the cylinder was determined by peak position of the piston during motoring time and transferred to advanced combustion analysis software, Indicom Mobile, will store the signal and using for further thermodynamic calculations which will be supported by hardware, AVL Indismart 612, is a multi-channel indicating system for the acquisition and processing of fast crank angle and time based signals typical for combustion engines as shown in Figure 3.16.

3.3.6. Design and Development of Gaseous Hydrogen Supply System

A gaseous hydrogen supply system was designed and developed as shown in Figures 3.17 and 3.18. To supply the gaseous hydrogen, commercially available 140 bar pressure, 47 liter water capacity with 99.99% pure hydrogen cylinder/ bottle was used. Further, hydrogen supply system consists of SS 316 Tubing of Sandvik make, Two stage Pressure regulator, Relief valve, Two way valve, Filter, Non Return Valve (Check valve), Hydrogen Chamber, Needle Valve of Swagelok make, Mass Flow controller along with Totalizer of Bronkhorst make, Flame Arrester, Hydrogen Injection Unit along with metering software and Flame Traps.

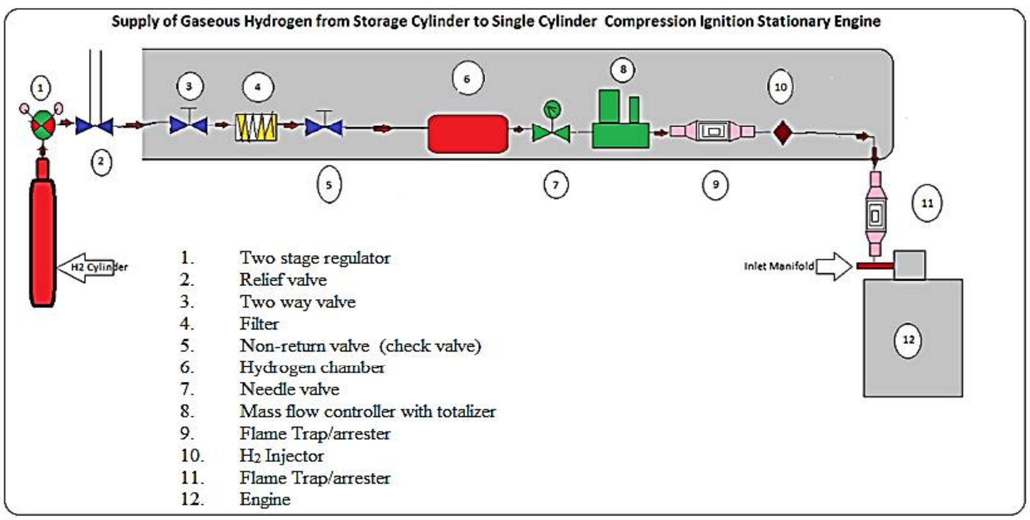

Figure 3.17 Schematic diagram of gaseous hydrogen supply system

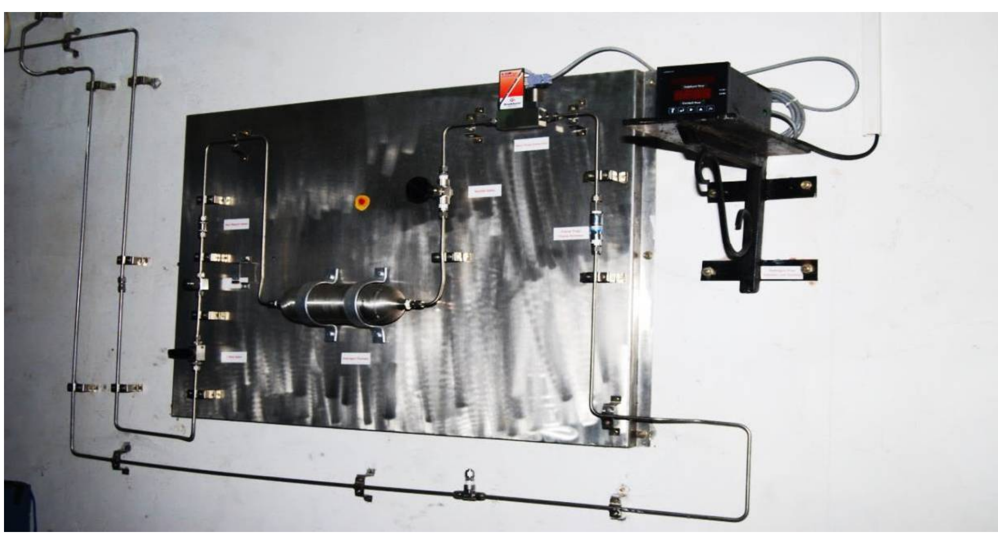

Figure 3.18 Pictorial representation of gaseous hydrogen supply system

High pressure hydrogen cylinder along with two stage Pressure regulator mounted on the manifold and relief valve were kept outside the engine test cell to ensure the safety. A relief valve bye- passes hydrogen gas beyond set value, when pressure regulator fails to reduce, and releases the same in to open climate to avoid the damage of the components. Remaining were kept inside the engine test cell. Two stage pressure regulator , reduces the cylinder pressure from 140 bar to 2.5 bar and the same was supplied to the engine through 2- way valve which acts as a ON/OFF valve to allow the fluid to move ahead. After hydrogen passing through the 2-way valve, it enters the filter, which filters the hydrogen gas and further sending through the Check valve (Non- return valve) which allows the fluid to flow when the cracking pressure reaches at least 1 psi. Further, if the both ends of the check valve difference in pressure, releasing pressure, more than 6 psi, then forward movement of the gaseous hydrogen will be stopped by this valve. Once the hydrogen was moved from the check valve it enters the hydrogen chamber, acts as a reservoir to compensate the pulsation during suction of the hydrogen injector. Needle valve was provided to control the flow. Further, to control and to maintain the constant flow rate of gaseous hydrogen in gm/min thermal mass flow controller along with totalizer were installed. Thermal mass flow controller along with totalizer, calibrated for hydrogen, will help to meter the hydrogen in the range of 0.3 gm/min to 1.8 gm/min. To avoid the abnormal anomalies like backfire problems, two flame arresters were provided, one before the hydrogen injector and another after the injector which is nearer to inlet manifold of the engine. It has two functions: first, will help to block the forward movement of hydrogen, when backfire exists and secondly it will not allow the fire to enter into the system. Hydrogen injection unit along with computer data acquisition system will help to meter the quantity of hydrogen for supplying to engine. Further, software was able to meter the quantity of hydrogen as per requirement like; it can vary the injection duration and time of injection. It receives the signal from proximity sensor provided nearer to tappet of the valve and accordingly supply the given quantity of gaseous hydrogen to injector for given duration.

In detail discussion of design and selection of these components of hydrogen supply system was given in **Appendix-B.** For reliable and compatible for hydrogen supply, SS 316 tubing was preferred comparing to piping [145] and all necessary standards were considered in selection of tubing. Further details were discussed in

Appendix-C. Flare less tube was selected along with mechanical grip type fitting, consisting of body, nut front ferrule and back ferrule. For the same, hinging and colleting type tube fittings were used with a chromium and nickel content not less than 17% and 12% by weight in order to avoid the hydrogen embrittlement of the tubing and its fittings. Further, SAT 12 heat treatment process of low temperature hardening process was selected/adopted to maintain the corrosion resistance [146, 147]. For detailed understanding of selection of tube, tube grips and respective heat treatments were discussed in **Appendix-C**.

3.4 PLANNING OF ENGINE EXPERIMENTATION WITH DIESEL, PHSVO 90 AND PHSVO 90 WITH GASEOUS HYDROGEN SUPPLEMENTATION INCLUDING VARYING OF INJECTION TIMING AND INJECTION PRESSURES OF GH_2 SUPPLEMENTED PHSVO 90

First and foremost, before a set of measurements is commenced, the selected engine was run for 20 minutes at idling to reach the lubricating oil temperature of 70^oC, recommended by the manufacturer in order to reach the stable operating temperature and also ensured the limits of accuracy with respect to engine speed (rpm) ,maximum pressure (bar) inside the cylinder, fuel consumption (ml or cc) through gravimetric method, Hartridge Smoke value (HSU), and exhaust gas opacity [148].

In addition to these measures, as discussed in the section 3.3.4, fuel measurements and fuel lines and shown in Figure 3.10, a two way valve was used in order to operate the engine with diesel during starting and stopping conditions of the engine to avoid cold starting. Further during switching over from diesel to PHSVO 90 and vice versa engine was run at least for 45 to 50 minutes to drain out the existing fuel.

Further, at an identified load, engine was run for minimum 10 minutes before measuring/recording the different performance, emissions and combustion parameters, and the process was repeated at least three times for repeatability and consistency of the measuring performance and emission parameters, whereas for recording the combustion data,100 cycles average was taken into consideration.

In order to achieve the identified objectives of the present investigation, the following sequence of experimentation was planned on the experimental set up:

1. Generation of base line data on the selected engine with conventional diesel, and pre-heated Jatropa based straight vegetable oil at 90^o C (PHSVO 90) with respect

to performance, emissions and combustion characteristics and compared these results with each other and identified the deteriorated performance of PHSVO 90 when compared to conventional diesel. Further, understood the best efficiency load for the both fuels.

A matrix of measured parameters in order to achieve the point number 1 is showed below in Table 3.8.

Table 3.8 Matrix of measured parameters for diesel & PHSVO 90 fuel mode operated engine

Performance Parameters				Exhaust Emissions					Combustion Parameters	
Load (%)	Speed (rpm)	Fuel consumption (ml or cc)	Time taken for fuel consumption (sec.)	Smoke (HSU)	CO (% by vol.)	CO_2 (% by vol.)	HC (ppm)	NO_x (ppm)	Pmax (bar)	ID (^oCA)
20										
40										
60										
80										
100										

2. In order to augment the deteriorated performance of PHSVO 90, GH_2 was supplemented in the range of 0.3 gm/min to 1.0 gm/min through Timed Manifold Induction (TMI) Technique. Further, understood the best efficiency load and best efficiency band of GH_2 out of selected range (0.3 gm/min to1.0 gm/min) with respect to performance parameters, exhaust emissions and combustion characteristics.

A matrix of measured parameters in order to achieve the point number 2 is showed below in Table 3.9.

Table 3.9 Matrix of measured parameters for PHSVO 90 with GH_2 supplementation (0.3- 1.0 gm/min) fuel mode operated engine

Performance Parameters					Exhaust Emissions					Combustion Parameters	
Load (%)	Speed (rpm)	Fuel consumption (ml or cc)	Time taken for fuel consumption (sec.)	GH_2 consumption in gm/min	Smoke (HSU)	CO (% by vol.)	CO_2 (% by vol.)	HC (ppm)	NO_x (ppm)	Pmax (bar)	ID (^oCA)
20											
40											
60											
80											
100											

3. As self-ignition temperature of inducted GH_2 is very high, heat liberated by the pilot fuel is not sufficient to initiate the proper combustion of inducted GH_2 from the manufacturer recommended injection timing and injection pressure at best efficiency load. Hence the injection time got varied (being SVO denser and high viscous, injection advancement was considered) by maintaining the same injection pressure recommended by the manufacturer at optimized load and optimized supplemented GH_2 band with PHSVO 90. Later on from this selected GH_2 band, further identified the best GH_2 supplemented dosage with PHSVO 90 with respect to performance parameters, exhaust emissions and combustion characteristics at optimized load and manufacturer recommended injection pressure.

   A matrix of measured parameters in order to achieve the point number 3 is showed below in Table 3.10.

Table 3.10 Matrix of measured parameters for PHSVO 90 with optimized GH_2 supplementation band mode operated engine at different Injection timings ranging from 20^o to 26^o bTDC with an increment of 2^obTDC

	Performance Parameters				
Inj. Timg. bTDC	Load (%)	Speed (rpm)	Fuel consumption (ml or cc)	Time taken for fuel consumption (Sec.)	GH_2 consumption in gm/min
20, 22, 24 & 26	20				
	40				
	60				
	80				
	100				

Inj. Timg. bTDC		Exhaust Emissions					Combustion Parameters	
	Load (%)	Smoke (HSU)	CO (% by vol.)	CO_2 (% by vol.)	HC (ppm)	NO_x (ppm)	Pmax (bar)	ID (^{o}CA)
20	at best efficiency load							
22								
24								
26								

4. Once optimized the injection timing and GH_2 dosage at optimized load, influence of variation of injection pressure (being SVO viscous injection pressure increased) was seen with respect to performance parameters, exhaust emissions and combustion characteristics of PHSVO 90 and identified the best injection pressure at optimized injection timing, optimized GH_2 dosage at optimized load.

A matrix of measured parameters in order to achieve the point number 4 is showed below in Table 3.11.

Table 3.11 Matrix of measured parameters for PHSVO 90 with optimized GH_2 supplementation dosage operated engine at Optimized Injection timing, optimized load with different injection pressures ranging from 175 bar to 265 bar with an increment of 30 bar.

	Performance Parameters					Exhaust Emissions					Combustion Parameters	
Inj. Pre. (bar)	Load (%)	Speed (rpm)	Fuel consumption (ml or cc)	Time taken for fuel consumption (Sec.)	GH_2 consumption in gm/min	Smoke (HSU)	CO (% by vol.)	CO_2 (% by vol.)	HC (ppm)	NO_x (ppm)	Pmax (bar)	ID (°CA)
175	at best efficiency load											
205												
235												
265												

Further calculations of Performance parameters like; Mass of fuel consumed, BSEC, Power and brake thermal efficiency along with combustion parameter like; Differential heat release rate from measured data were discussed in **Appendix-D.**

5. In order to understand the improved performance and reduction in emissions, optimized injection timing, injection pressure, GH_2 supplemented dosage at optimized load was compared with baseline pre-heated straight vegetable oil and conventional diesel with respect to performance, emissions and combustion characteristics.

Further, the sequence of experimentation in a Flow chart showed in **Appendix-D**.