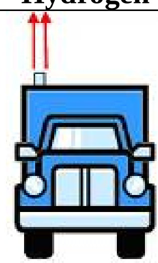
Appendix-A

SAFETY RELATED ISSUES IN HANDLING AND STORAGE OF GASEOUS HYDROGEN

As hydrogen molecule is smallest and lightest, if leaking this gas will accumulate at the roof of the enclosed area. The diffusivity rate of hydrogen is 10 times more than petrol and other fuel vapors [1].

Table AA.1 Leak Profile of Hydrogen and conventional Diesel Fuel

Sl.No	Description	Gaseous Hydrogen	Liquid Hydrogen	Diesel Fuel
1	Pictorial Representation			
2	Rising into atmosphere	Quickly disperses in the form of Gas	Puddles appeared at leaked location. Later vaporizes	Puddles appeared. Vaporization is very less.
3	Visual detection	Not Visible	Visible in the form of Fog and frost	Visible in the liquid form
4	Smell/Odour	None	None	Yes
5	Flammability	Very very rapidly catches the Fire/Ignition	Very very rapidly catches the Fire/Ignition	Rapidly catches the Fire/Ignition
6	Flame	Invisible at day light.	Invisible at day light	Visible in the form smoke

As it posses the high diffusivity property, the burning velocity of hydrogen air mixture will take care at equivalence ratio Φ=1.8, whereas for the same burning velocity with hydrocarbon-air mixture takes place at Φ=1.1 [2]

In this context, researchers has to consider the all necessary safety related issues in handling the high pressure gaseous hydrogen. Glimpse on different issues are considered below:

Storage area safety aspects
Handling area safety aspects
Engine specific systems
Health related safety issues

1.0 STORAGE AREA SAFETY ASPECTS:

Maximum Allowable Quantity (MAQ): Maximum Allowable Quantity is the total quantity of hydrogen combined available in storage and usage areas.

The storage areas are classified into Gas cabinets, exhausted enclosures along with sprinkler and without sprinkler systems. If the gas storage is up to $28m^3$ by volume, there is no requirement of gas cabinet, exhaust enclosures under sprinkled area.

Table AA.2 Storage area requirements as per the MAQ

Sl. No	MAQ of Hydrogen storage	Requirement		
		Sprinkled area	Gas Cabinet	Exhaust enclosure
1	$< 28\ m^3$	No	No	No
2	$>28< 56\ m^3$	No	Yes	Yes
3	$>56<112\ m^3$	Yes	Yes	Yes

If the storage area is covered with sprinkler facility, then up to volume of $56\ m^3$ MAQ of Hydrogen can be stored there is no requirement of gas cabinet and exhaust enclosures[3].

1.1.Storage and Usage Area Construction

As per ASTM E 136 standards approved 'Non Combustible' material has to use to construct the storage and handling areas [4, 5]. The accessibly and approaching road leads to these areas must have 20ft to 50ft width road with 13.6 ft. height clearance and having minimum radius of road width for the convenient of Fire safety vehicle to reach these places in an emergency [6].

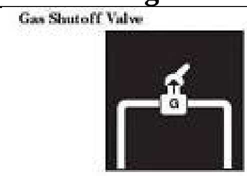
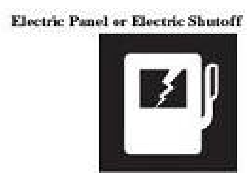
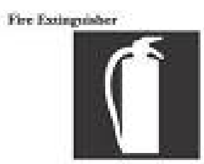
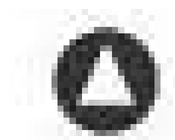
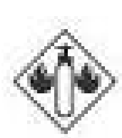
These buildings must be provided with an exhaust ventilation at a distance not more than 1 feet from the ceiling because this hydrogen gas is lighter than air, causes any leakage of hydrogen reaches the roof and leads to electric accidents. If mechanical ventilation is provided, then rate of mechanical ventilation is not less than 0.3048 $m^3/min/m^2$[7]. It is very essential to make use of Hazard identification signs in these areas all entrances where compressed gases stored, produced or utilized. And all these signs must be allowed to keep in a accessing mode to all people within range of 25ft distance from the storage space [8, 9].

WARNING: HYDROGEN –
FLAMMABLE GAS

NO SMOKING – NO OPEN FLAMES

Some such signs are given below [10].

Table AA.3 Different Signs which must be available at the Storage site

Sign	Indication	Sign	Indication
	The Identification of areas where smoking is prohibited		The location of gas shutoff valve
	The identification of areas where the open fires are not permitted		The identification and location of an electrical panel or other electric shutoff devices
	For everyday use in working places and public areas:		Gas detector
	For everyday use in working places and public areas: supplementary text can be used to increase comprehension		Fully sprinklered area
	Flammable gas		Partially sprinklered area

Further, these buildings must be provided with suitable gas leakage sensors and monitors on the basis of Lower Explosion Limit (LEL) along with hooter and alarm as shown below by that if is there any leakage, then hooter will give an alarm by that, one can pay attention to control the leakage as soon as possible by shutoff of gas and electrical power supply [11-15]. One such implemented Gas sensors with its monitor was shown below.

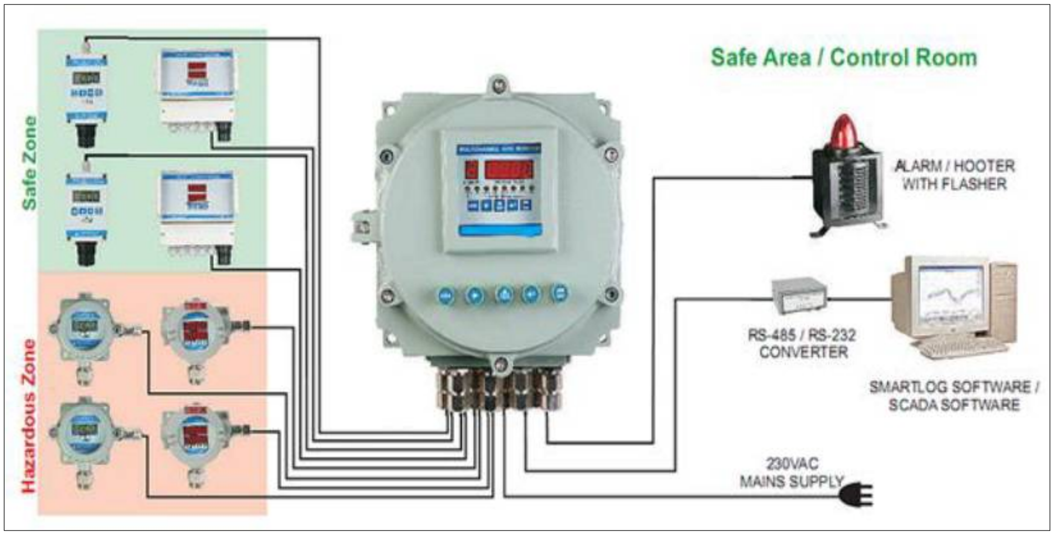


Figure AA.1 Complete pictorial representation of Hydrogen Gas Leakage Monitoring system

1.2. Fire Extinguishers

Fire: Fire is a chemical reaction in which a substance undergoes process of oxidation in presence of heat. The reaction is exothermic in nature, making this reaction is a chain reaction.

For gases, it is essential to keep class B type fire extinguisher but one has to keep class A for solid fire like wood, paper cloth etc. and Class E for Electrically energized equipment [10].

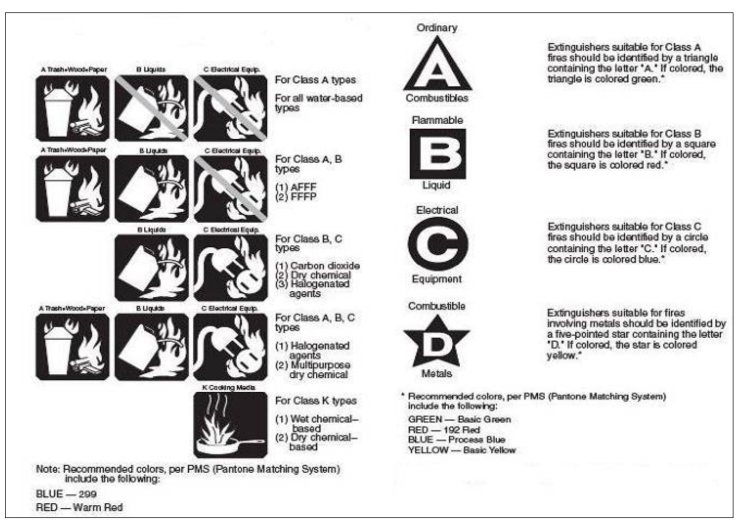


Figure AA.2 Fire Extinguishers

1.3. Electrification

As per the requirement of usage of high pressure gaseous hydrogen different applicable standards are available. The scope of this paper is limited to minimum quantity of hydrogen storage i.e., less than the MAQ and the storage is confined to standard 47 Ltr water storage capacity with a pressure not exceeding 140 Bar. Hence Class I, Division2, Group B standard of NFPA is applicable to provide electrification in this area[16].

Class I represents that, Flammable gases are present in sufficient quantity in the air are responsible to ignite or explosive.

Division 2 represents that, flammable gases which are stored in a confined small cylinders and

Group B represents that, Flammable gases, which are present in sufficient quantity in the air having an experimental safe gap with less than or equal to 0.45mm. Hydrogen will be considered under this category.

1.3.1. Wiring

Rigid metal or Steel intermediate Conduit will be used with Zero Halogen Fire Retardant (ZHFR) / Halogen Free Fire Retardant (HFFR) wire [17].

1.3.2. Luminaries

Luminaries and other heat-producing apparatus, switches, circuit breakers and plugs are potential sources of ignition are must be provided with suitable metal enclosures in classified locations as per the Class I, Division 2 Group B standards.. Further, Luminaries are protected from Physical damage by suitable guards or by location. Where there is a danger that falling sparks or hot metal from lamps or luminaries might ignite localized concentrations of flammable vapours or gases, suitable enclosures or other effective protective means shall be provided [18].

1.3.3. Protection Concepts

There are varying types of equipment that can be used within these zones to ensure that the potential for an explosion is removed or greatly reduced. This equipment must be designed and manufactured in accordance with particular construction parameters known as protection concepts.

Table AA.4 Details of Protection Concepts

Type of Protection Method	Equipment Code	Description	International Standard	Suitable for Zones
Intended to prevent an ignition from escaping outside the equipment	Ex d	Flameproof protection	IEC 60079-1	1, 2

1.3.3.1. Ex d Flameproof

The equipment that may cause an explosion is contained within an enclosure which can withstand the force of an explosion and prevent transmission to the outside hazardous atmosphere. This method of protection also prevents the hazardous atmosphere from entering the enclosure and coming into contact with equipment.

1.3.3.2. Ingress Protection

Another consideration in the protection of equipment in hazardous areas is the safeguarding against the ingress of solid foreign objects and water. This is known as the degree of ingress protection and is commonly referred to as the IP Code. The relevant standard for the degree of ingress protection is IEC 60529. And the preferable one is IP 65.

Table AA.5 Details Ingress Progression 65

1st Numeral	Degree of Protection	2nd Numeral	Degree of Protection
6	Total protection against the ingress of any dust	5	Protected against water jets from any direction

Some such electrical equipment are given below:

Figure AA.3 Class I, Division 2, Group B Electrical Equipment

This storage of compressed gaseous hydrogen must be separated with lot lines, public streets, open flames etc.

Table AA.6 Explosives Distance Maintained

Sl.No	Description	Minimum distance maintained from storage space in feet
1	Lot Lines	45
2	Exposed persons other than those involved in servicing of the system	25
3	Air Intakes – Compressors	45
4	Unclassified Electrical Equipment	15
5	Utilities (overhead) including electrical power building services, Hazardous materials, piping	20
6	Ignition sources such as open flames and welding	45
7	Parked cars	25
8	Flammable Gas storage systems including other Hydrogen systems above the ground	20
9	Ordinary combustible including fast burning solids such as Ordinary lumber, excelsior, paper and vegetation other than found in maintained land scraped areas	20
10	Heavy Timber, Coal or other than slow burning combustible solids	20
11	Smoking	25

Table AA.7 Separation of Cylinders by Hazard Class Gases

Sl. No	Gas Category	Minimum distance maintained from storage space in feet
1	Toxic or High Toxic	20
2	Pyrophoric	20
3	Oxidizing	20
4	Corrosive	20
5	Unstable Reactive class 2, 3 and 4	20
6	Other Gases	No separation required

2.0 HYDROGEN HANDLING SYSTEM ISSUES

This stored hydrogen as in confined cylinders must be designed, fabricated, tested and marked as per the standard testing procedures like ASME Boiler and Pressure vessel [19-24]. One has to ensure that under any circumstances these cylinders should not expose to a temperature not more than 52^0 C. And these cylinders must be protected from physical damage and falling from its position. These cylinders should be secured through standard securing procedures like guard posts, chains belts etc.

Use Cylinder caps whether the cylinders stored empty or fill. And these empty and full cylinders must be separated. Never allow the cylinder to fall down. If the cylinder fall down without cap, there is a possibility of turning this full pressurized cylinder into a rocket. One such incident shown below [25].

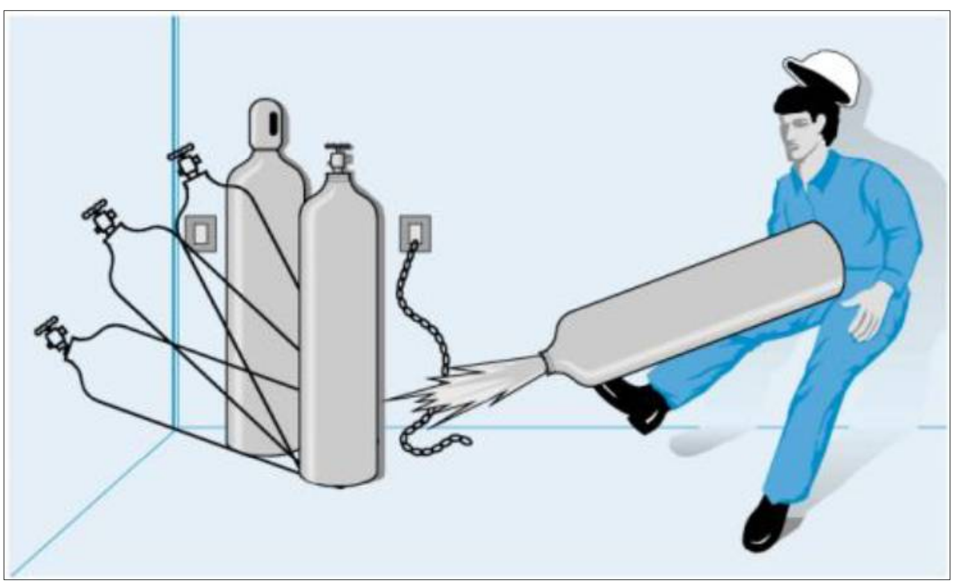


Figure AA.4 How Compressed gas Cylinder will turn into a Rocket

Cylinders are not supposed to drag even for small distances also. For smaller distances transportation also one has to use hand operated cylinder trucks [26]. Never allow the cylinders are subjected to mechanical shocks also. Cylinders must be positioned as per ISO Standard 11625 or Compressed Gas Association (CGA) Pamphlet Part-1.

Figure AA.5 Cylinders carrying Trolleys

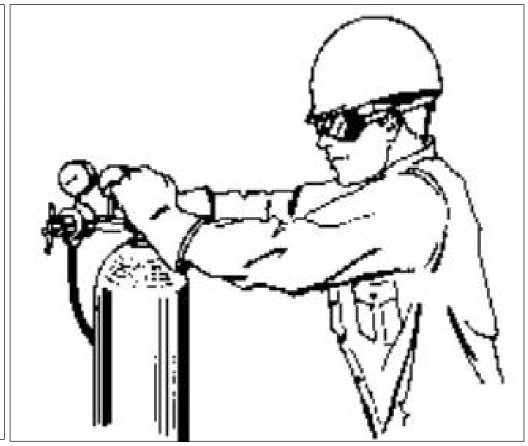


Figure AA. 6 Safe method to operate with Pressure Regulator

While transporting the gas from the high pressure to low pressure at the working place like at engine test bench, one of the important component which is playing crucial role in bringing the high pressure to low pressure is the Pressure Regulator. Use standard SS316 material customizely designed and fabricated double stage regulators has to use. This double stage and single stage pressure regulator depends on the gas pressure requirement at the usage area. While safety checking of the regulator the operator has to take of the safety aspects as shown below [27].

And second most important is the Relief valve. If the pressure regulator is failed to sent the gaseous hydrogen at given low pressure, then there is a possibility of damage the hydrogen flow components in the flow line and great risk will be there if this gas leaked from these damaged components. Hence one has to use this relief valve and its outlet has to keep to the atmosphere by that any damage to regulator, this leaked high pressure gas will be entered into climate. This discharge procedure and the pressure relief valves must be in accordance with Compressed Gas Association (CGA) G 5.5, S 1.1 and NFPA standards [20, 21, 28].

It is very essential that other systems like tubing , valves and fittings must be designed and installed as per the standard procedures of NFPA and IFGC codes [22, 29, 30]. It is always preferable to join the tube and different systems/components/devices with tube fittings only. Better to avoid BSP and NTP threads as much as possible when handling with gaseous hydrogen. Further, it is advisable to go for annual maintenance by a qualified engineers as per the standard maintenance protocol mentioned in NFPA standards. These maintenance records has to kept for at least 3years. Never use Cast Iron material components for Hydrogen storage and transportations. It is always preferable to go for SS 316 material for this gas. All these components along with tubing installation must be inspected under pressure test at a pressure not less than $1\frac{1}{2}$ times of working pressure as per recommended standard procedures of NFPA, IFGC and ASME codes [31].

3.0 ENGINE SPECIFIC SYSTEMS

While introducing this hydrogen into the engine, there is generally two modes most of the researchers adopted. Those are Manifold injection and the direct injection i.e., induction and injection modes.. This paper is mainly focused at the manifold injection. In this manifold injection, the delivery pressure of the hydrogen in the inlet manifold is nearer and just above the atmospheric pressure. Because this gas will be inducted by the pressure difference between the in and outside of the engine during suction stroke. Main problem of this induction technique is the backfire due to pre ignition and the hot spots of the combustion chamber. A lot of research was taken place in Indian Institute of Technology (IIT) Delhi under the guidance of Dr. L.M. Das. There are so many induction techniques like carburetion, port injection, Timed manifold Injection (TMI) available. With detailed investigation it is advised that through Timed Manifold Injection is the best induction techniques to control these undesirable combustion phenomena. Further, engine operation should preferably be carried out with well dispersed water sprays in the exhaust system by which this cooled exhaust will suppress the detonation. Even CO_2 is also some times can be sent into this exhaust system by that also this undesirable phenomena can be controlled. In the engine test cell, better have to some sort of Inertizer gases like Nitrogen, CO_2, and Helium and fire extinguisher powders like Ammonium Phosphate or Potassium Chloride can be used inert the inside atmosphere by that if is there any leakage of hydrogen can be get inertized though the Hydrogen is mixed with air in the combustible range [32-34]. Sometimes even delayed Port admission is also equally helpful like Timed Manifold Injection (TMI) and is very safe method of introducing the hydrogen in the engine[35].

4.0 HEALTH HAZARDS

The potential health hazard of the this hydrogen is much effecting when a victim had inhaled that, during leaking of this lightest gas immediately mix with the Air inside the confined area and replaces the oxygen causes the asphyxiation. Victim is unable to experience this situation also that he undergone to asphyxiation. Because of this oxygen deficient atmosphere the victim may experience symptoms like dizziness, nausea, vomiting and loss of mobility and unconsciousness. And there is no adverse effect on the skin. If this hydrogen is exposed to eyes, then eyes start irritation, at this situation, the victim must rinse his/her eyes immediately and has to continue for 15 minutes time.

Leaked hydrogen replaces the oxygen causes, asphyxiation in that particular area and predicting this situation is also very difficult. Because of this asphyxiation the victim will lose their consciousness without his/her knowledge. As victims exposed to this type oxygen deficient atmosphere experience symptoms like dizziness, salivation, vomiting and nausea etc. However exposed to skin will not have any type of adverse effect [36].

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Appendix-B

DETAILS OF GASEOUS HYDROGEN EQUIPMENT

1.0. TWO STAGE PRESSURE REGULATOR [1]

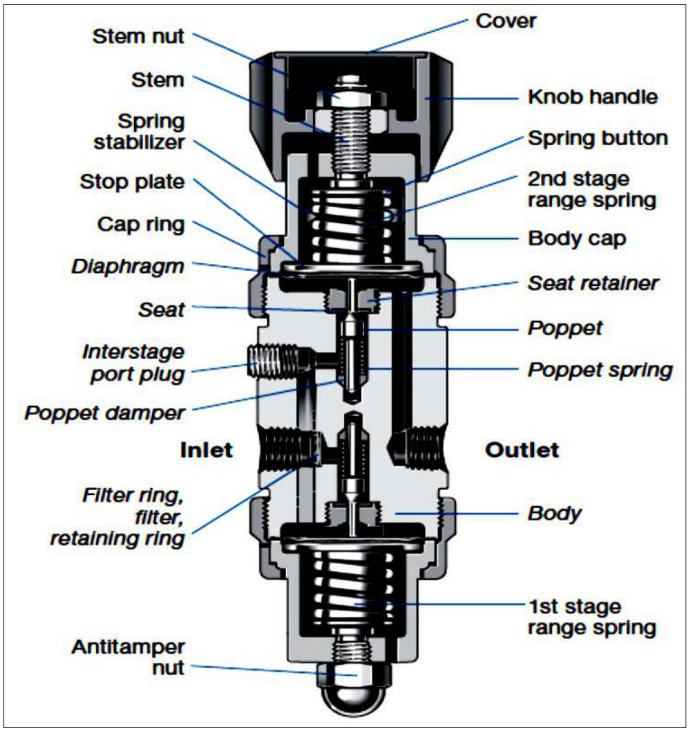

Figure AB.1 Two stage Pressure regulator

Table AB.1 Technical Specifications of Two-stage pressure regulator [1]

Description	Technical details
Body	SS 316
Inlet Pressure	248 bar
Outlet Pressure	0 to 6.8 bar
Weight	1.9 kG
Make	Swagelok
Model	KCY1FRF412A90020
Accessories	provided with Inlet & Outlet pressure indicating gauges

Pressure regulators reduce the pressure of a gas from the source to a lower pressure. A Pressure regulator provides better resolution and control when its inlet and control range pressures closely match the pressure requirement of the fluid handling system. Resolution is the number of turns needed to adjust a regulator from its lowest to highest outlet pressure setting. Control is the ability of the regulator to hold a given outlet pressure set point.

2.0. RELIEF VALVE [2]

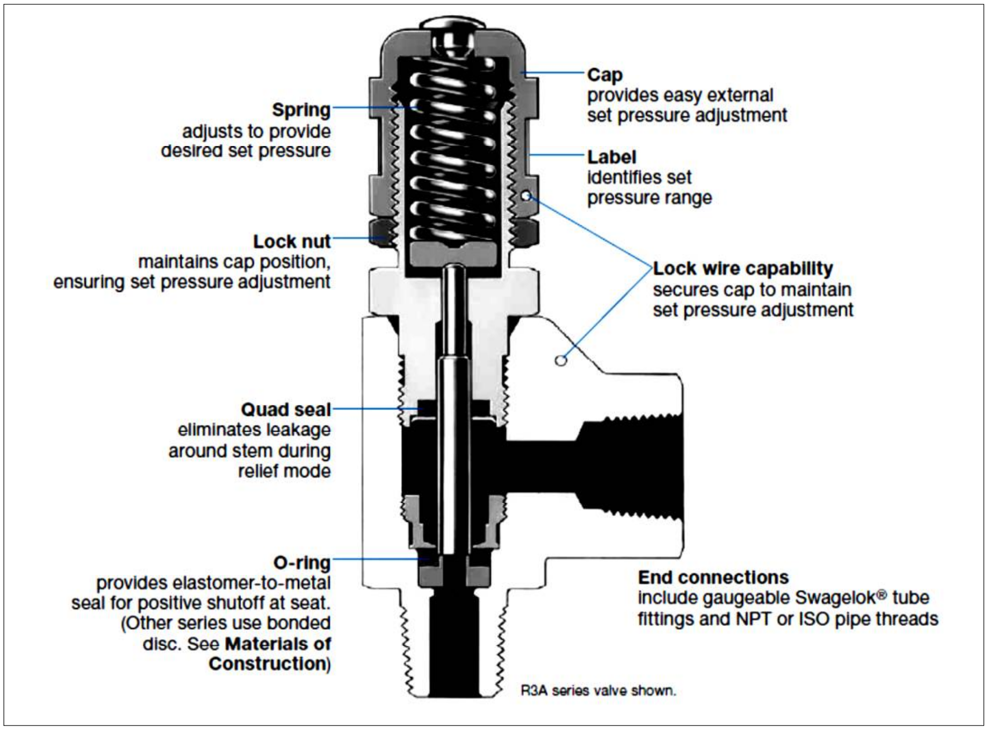

Figure AB.2 Relief Valve

Table AB.2 Technical Specifications of Relief Valve [2]

Description	Technical Details
Body	SS 316
End Connection	¼" OD Compression Fittings
Make	Swagelok
Model	SS 4R3A

These relief valve opens when system pressure reaches the set pressure. And close when system pressure falls below the set pressure.

3.0. TWO- WAY VALVE [3]

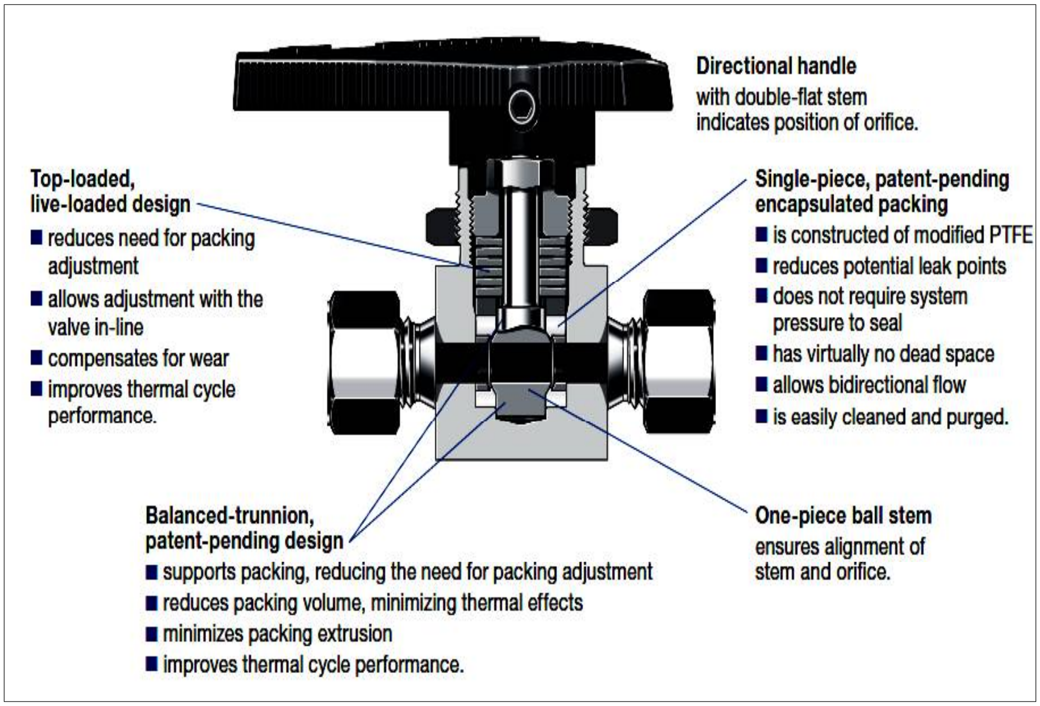

Figure AB.3 Two- way valve

Table AB.3 Technical Specifications of Two-way valve [3]

Description	Technical Details
Body	SS 316
Pressure Holding	up to 413 bar (temp range: 0 to 250^{o} C)
End Connection	¼" OD Compression Fittings
Make	Swagelok
On/Off	Quarter Turn
Model	SS-4SKPS4

These two-way valves are used to On/Off the flowing fluid. Quarter turn of the handle is sufficient to either On or Off the flowing fluid.

4.0. FILTER [4]

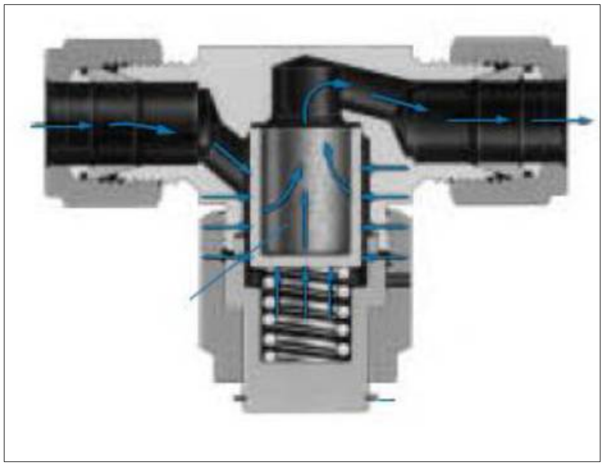

Figure AB.4 Tee- Filter

Table AB.4 Technical Specifications of Tee- Filter [4]

Description	Technical Details
Body	SS 316
Filter	Sinter element
End Connection	¼" OD Compression Fittings
Make	Swagelok
Model	SS -4TF-7

Three filters are available like: All welded inline filters, Inline Filters and Tee- type Filters. Out of three, Tee- Type filter was used because of its advantages over others is that, filter element can be replaced without removing body from system.

5.0. NON- RETURN VALVE OR CHECK VALVE [5]

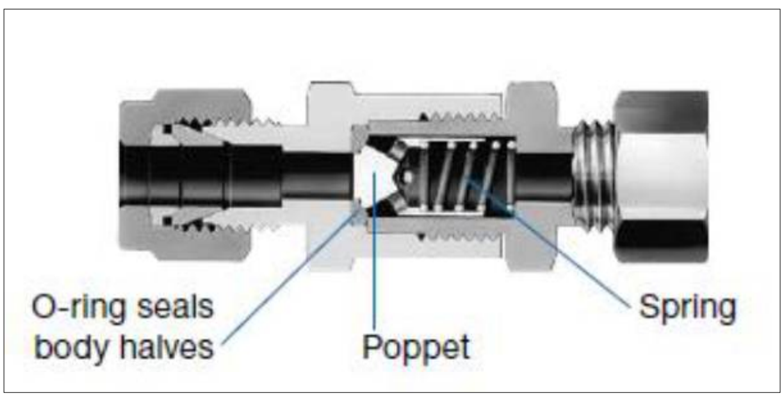

Figure AB.5 Non - Return valve or Check valve

Table AB.5 Technical Specification of Non-return or check valve [5]

Description	Technical Details
Body	SS 316
Downstream Pressure	68.9 bar at 20^{o} C
End Connection	¼" OD Compression Fittings
Make	Swagelok
Model	SS-4C-1

These are used to arrest the back flow of the gases.

6.0. HYDROGEN CHAMBER [6]

Figure AB.6 Hydrogen chamber

Table AB.6 Technical Specifications of Hydrogen Chamber [6]

Description	Technical Details
Body	SS 304
Pressure rating	124 bar
Type	Double ended open
End Connection	¼" OD Compression Fittings
Make	Swagelok
Model	304L-HDF4-1000

Hydrogen chamber will act as a reservoir of Hydrogen to avoid the pulsation during suction of the hydrogen Injector.

7.0. NEEDLE VALVE [7]

Figure AB.7 Needle Valve

Table AB.7 Technical Specifications of Needle Valve [7]

Description	Technical Details
Body	SS 316
Make	Swagelok
Model	SS-1RS4
End Connection	¼" OD Compression Fittings

These needle valves are used to control the flow of gas as well as shut off the flow

8.0. MASS FLOW CONTROLLER [8]

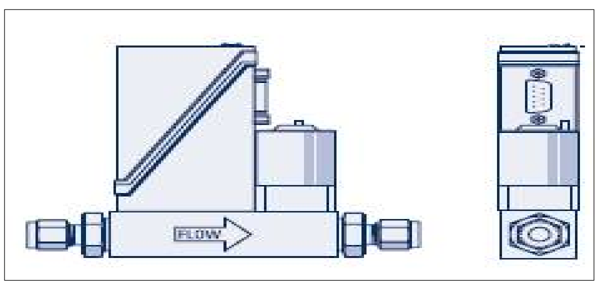

Figure AB.8 Mass Flow Controller (MFC)

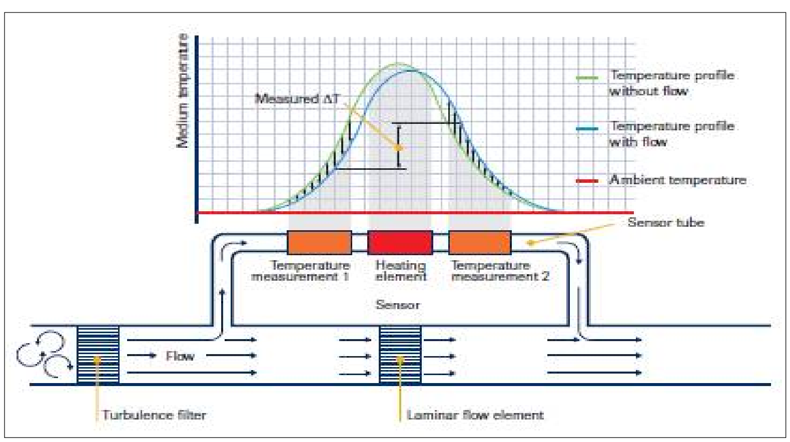

Figure AB.9 Working principle of Mass Flow Controller

Table AB.8 Technical Specifications of Mass flow controller [8]

Description	Technical Details
Gas	Hydrogen
Operating temperature	25 – 45° C
In let Pressure	2- 6 bar
Outlet pressure	1- 4 bar
Flow	0.16 – 8 gm/min
Pressure Drop	2 bar
Body	SS 316
End Connection	¼" OD Compression Fittings

Table AB.9 Totalizer Specifications [8]

Description	Technical Details
Flow Indication	4 digit, 0.5", 7 segment, LED Display
Set point	Through Key Board
Totalizer	8 digit, 0.5", 7 segment, LED Display

8.1.Constructional details and working principle of Thermal mass flow Controller [8]

In a given path of flowing gas, there are two elements provided namely turbulence filter and a laminar flow element is made up of SS capillary tubes. Further, in by pass tube there are two temperatures measuring sensors along with heater provided. The gas which is passing through the turbulence filter will filter the turbulence and send it to laminar flow element. In the mean- while, some part of gas was passing through the sensor tube heating element. Then the temperature difference between before and after heating element is directly proportional to mass of gas flowing through the sensor.

9.0.FLAME ARRESTER

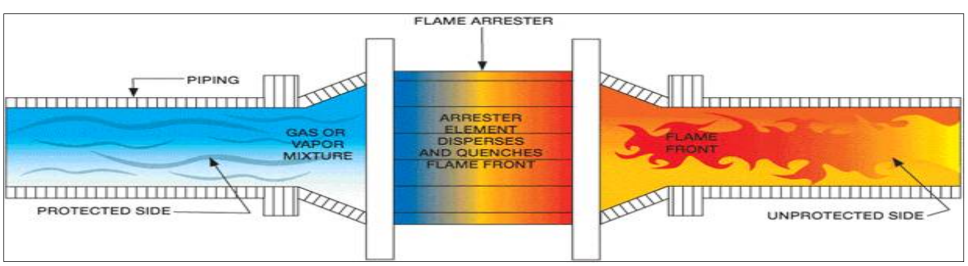

Figure AB.10 Working Principle of Flame Arrestor

These are used to control and arrest the back fire. Further, during backfire it stops the forward movement of the hydrogen in the line.

10.0. HYDROGEN INJECTOR AND GAS SUPPLY PORT SYSTEM

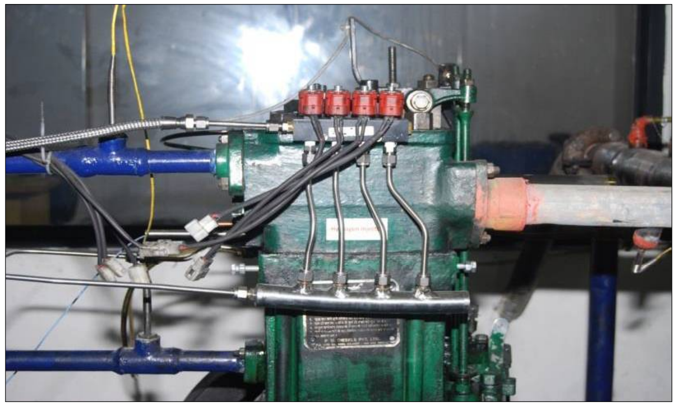

Figure AB.11 Gaseous Hydrogen Injector

10.1. Gas supply Port system

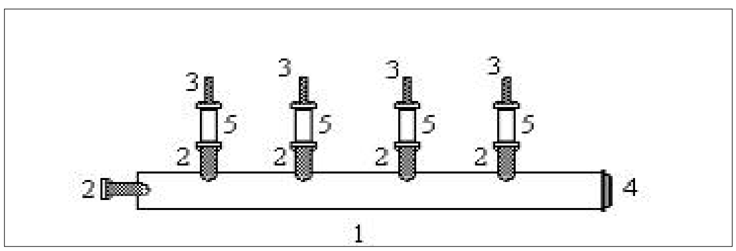

Figure AB.12 Gas supply port system

Where	1	-	SS 316 Pipe ¾”
	2	-	SS 316 Male Connector ¼” OD x ¼” MNPT
	3	-	SS 316 Male Connector ¼” OD x 1/8”MNPT
	4	-	SS 316 welded Cap ¾”
	5	-	SS 316 ¼” OD

10.2. Hydrogen Injector control module Software

10.2.1. Electronic Control Unit (ECU)

The electronic control unit is a pre-programmed micro controller. The ECU is used to control the start of injection and duration of injection. The Electronic Control unit is provided with two variable controls:-

a. **Start of Iinjection** : Electronic Control unit receives the signal from the crankshaft position sensor and detects the engine crank angle.. The user can change the start of injection (Advance or retard) by using a graduated potentiometer knob. The potentiometer is connected to the ECU.

b. **Injection Duration (Throttle)** : The injection duration can be also be controlled by using a graduated potentiometer knob provided on the ECU.

c. **Software:** The injector Control Module is interfaced to the computer through windows based software by which, one can vary the start of injection and duration of injection with the help of software. The screen shot of the software was shown in Figure AI.13

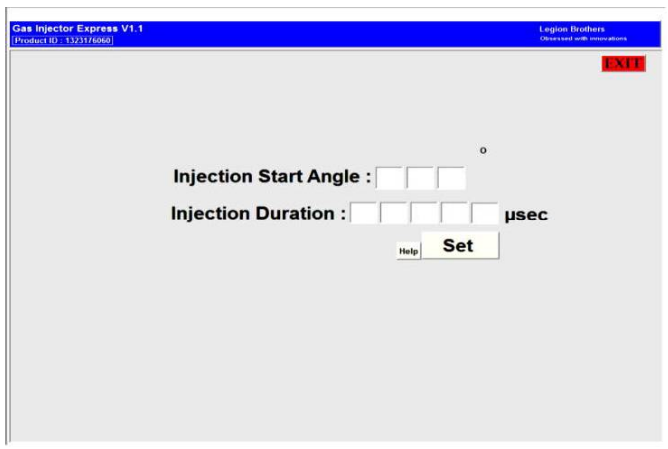

Figure AB.13 Gaseous Hydrogen metering software

10.2.2. Hydrogen Injector

Based on the signal received from the Injector control module, the hydrogen injector will supply the hydrogen at a maximum pressure of 3.5 bar, and operating temperature range is in between - 20^o C to 125^o C; for this experimentation pressure and temperature of hydrogen injection were kept equal to NTP conditions.

Table AB.10 Technical Specifications of the Hydrogen Injector

Description	Range
Operating Temperature, ^{o}C	-20 to 125
Operating Pressure, bar	Atmospheric to 3.5
Maximum Peak current, Amp	6.4
Inductance	4mH at 120 Hz
Flow rate, LPM	175

References- Appendix -B

1. Swagelok, *Pressure Regulators*, March 2010.
2. Swagelok, *Proportional Relief Valves*, December 2010,.
3. Swagelok, *Trunnion Ball Valves*, May 2011.
4. Swagelok, *Filters,* July 2002.
5. Swagelok, *Check Valves,* April 2010.
6. Swagelok, *Sample Cylinders, Accessories, and Outage Tubes*, October 2007.
7. Swagelok, *Integral - Bonnet Needle Valve*, May 2005.
8. Bronkhorst, *Digital Mass Flow Controllers*.

Appendix- C

TUBING & TUBE FITTINGS

1.0. SELECTION OF TUBING

For reliable and compatible for hydrogen supply, tubing is very essential rather than piping [1] to avoid the leakage of low density hydrogen. Refer the following Figure AC.1

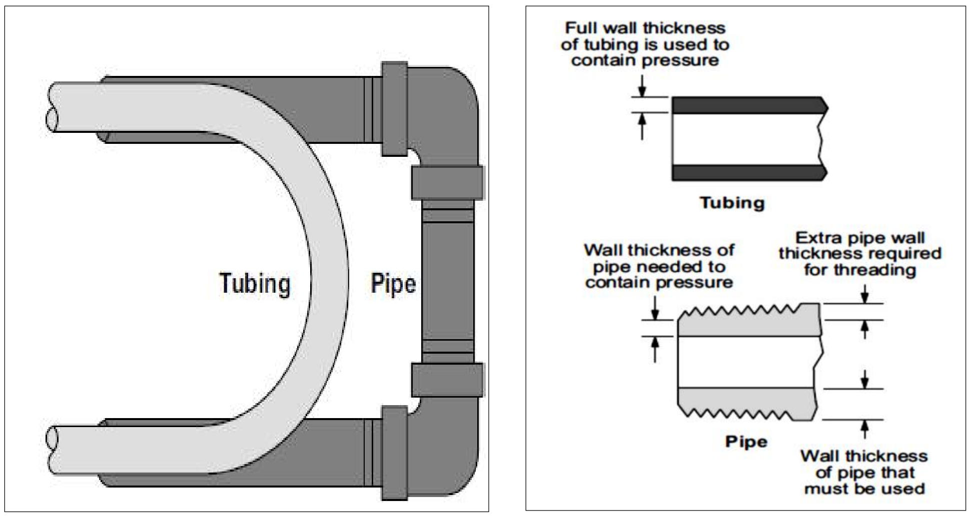

Figure AC.1 Advantages of Tubing over piping

Further, advantages of using tubing

a. Better strength to weight ratio.
b. Thinner tube can be used for same pressure rating
c. Tubing is lighter and making it less expensive to transport and easier to assemble and fabricate.

Hence, it is very essential to select the proper material for supply of gaseous hydrogen. There are wide variety of materials like Carbon steel, Stainless steel, Aluminium, Alloy 400, Alloy C-276, Alloy 20, Alloy 600, Grade 2 Titanium , Alloy 625. In which, Stainless Steel 316 is best compatible for hydrogen to avoid the hydrogen embrittlement problems.

In addition to compatible material following variables are very important in selecting and installing the tubing.

1. Surface finish and
2. Wall Thickness.

a. Surface finish: As per ASTM A 450 a general tubing specifications recommending the Straightness and Finish. i.e., selected tubes must be reasonably straight and have smooth ends free of burrs.

b. Tubing wall Thickness: All tubes must be specified by ASME B 31.3 process piping.

Table AC.1 Suggested Allowable pressure table for Stainless Steel Tubing (fractional)

Tube OD (in.)	TUBE WALL THICKNESS (in.)															
	0.010	0.012	0.014	0.016	0.020	0.028	0.035	0.049	0.065	0.083	0.095	0.109	0.120	0.134	0.156	0.188
1/16	5600	6800	8100	9400	12 000											
1/8						8500	10 900									
3/16						5400	7000	10 200								
1/4						4000	5100	7500	10 200							
5/16							4000	5800	8000							
3/8							3300	4800	6500							
1/2							2600	3700	5100	6700						
5/8								2900	4000	5200	6000					
3/4								2400	3300	4200	4900	5800				
7/8								2000	2800	3600	4200	4800				
1									2400	3100	3600	4200	4700			
1 1/4										2400	2800	3300	3600	4100	4900	
1 1/2											2300	2700	3000	3400	4000	4900
2												2000	2200	2500	2900	3600

Working Pressure (psig)

NOTE: For tubing for gas service, use only tube wall thickness outside screened area.

Table AC.2 Factors used to determine the tubing Pressure ratings at elevated temperatures

FACTORS							
°F	°C	Aluminum	Copper	Carbon Steel	304SS	316SS	Alloy 400
200	93	1.00	0.80	0.95	1.00	1.00	0.87
375	190	----	----	0.87	----	----	----
400	204	0.40	0.50	----	0.93	0.96	0.79
600	315	----	----	----	0.82	0.85	0.79
800	426	----	----	----	0.76	0.79	0.75
1000	537	----	----	----	0.69	0.76	----
1200	648	----	----	----	0.30	0.37	----

c. Tube handling: To avoid scratches and unwanted damages, good handling practices are greatly influenced. Some of such practices are:

1. Tubing should never be dragged out of tubing rack or from storage across the rough surface

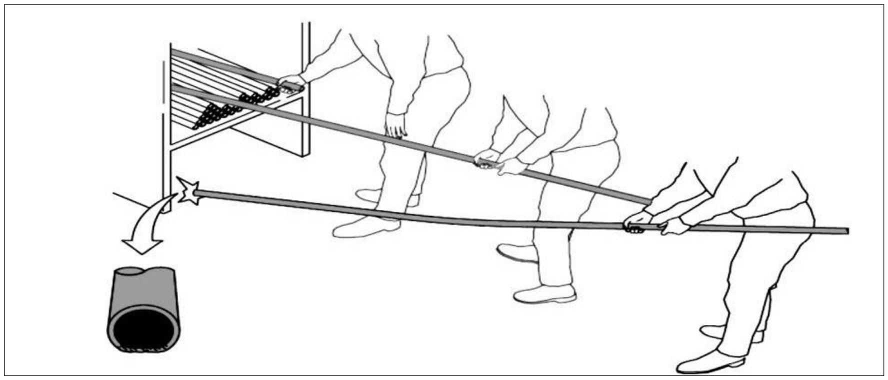

Figure AC.2 Tube handling

2. Tube cutters or hacksaws should be sharp. Don't go for deep cuts with each turn by cutter or stroke of the saw.
3. Tube ends must be deburred. This helps to ensure that te tubing will go all the way through the ferrules without damage the ferrule sealing edge.
4. Always arrange the tube in vertical instead of horizontally

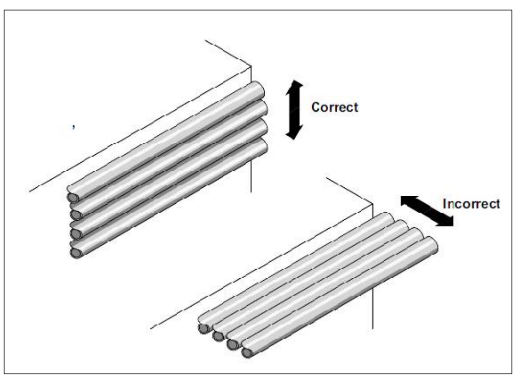

Figure AC.3 Mounting of Tubes

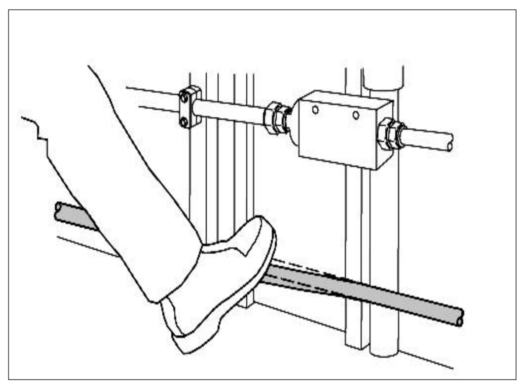

Figure AC.4 Foot rail tubing

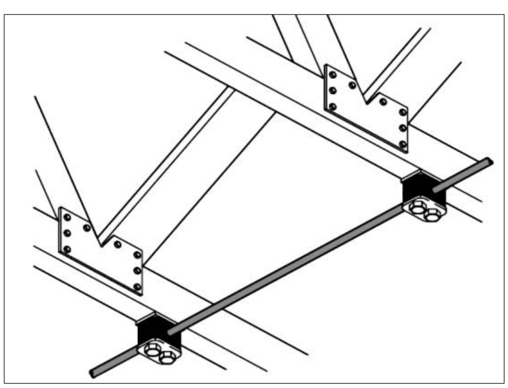

Figure AC. 5 Tubing support

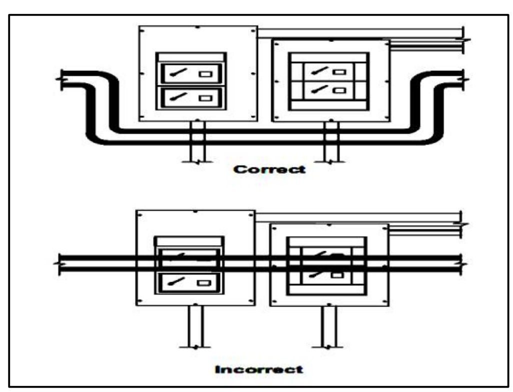

Figure AC.6 Placement of Tubing

5. Avoid foot rail tubing
6. Proper tubing support is most important
7. Better to avoid to placement of tubes directly in front of the equipment
8. Properly plan the layout of the tubing for easy installation and maintenance

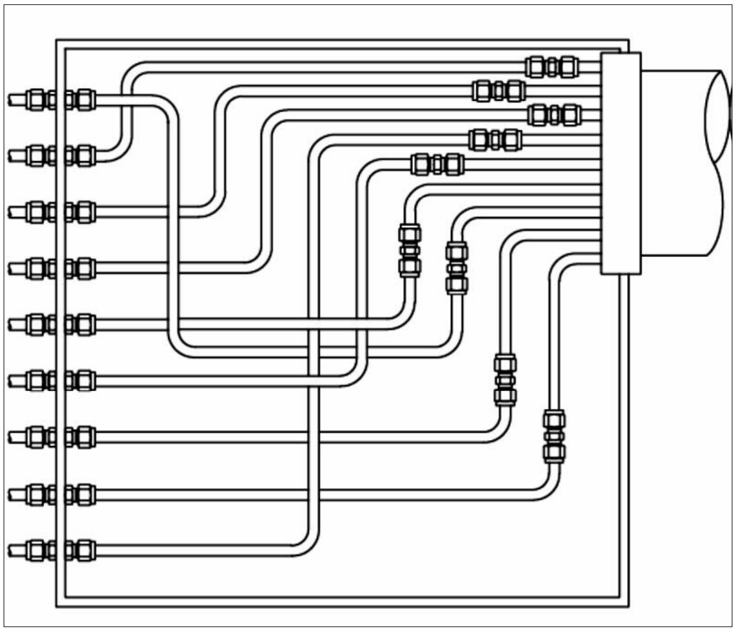

Figure AC.7 Proper planning of tubing

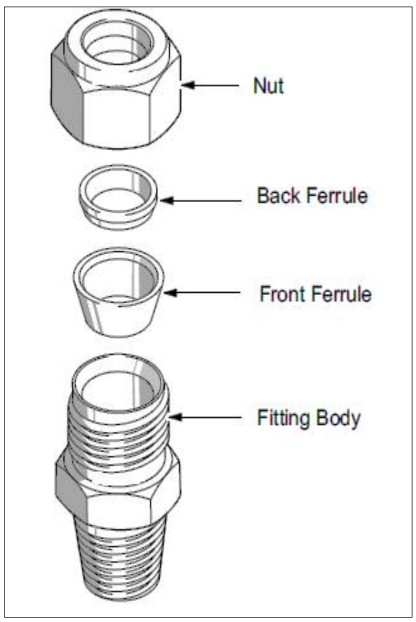

Figure AC.8 Compression fitting model

1.1. Selection of Tube Fittings [2]

Tube fitting must be flare less, mechanical grip type fitting, consisting of body, nut front ferrule and back ferrule. The fitting must be leak free after proper installation.

In the design, installation and maintenance of fluid systems there are wide variety of choices available in the selection processes for tubing connections.

Some of those selection procedures are discussed below:

1.1.1. Metallurgical Aspects [3]

In general generic 316 stainless steel tubings at harsh climatic applications get corrode due to less Chromium and Nickel quantity available in the selected material below the ASTM 316/316L stainless steel standards. Hence, it is very essential that all components/equipment using for gaseous hydrogen must follow the ASTM standards.

ASTM standards for maintain the minimum quantity of Chromium and Nickel in 316/316L stainless steel materials are as follows.

Chromium	-	16 - 18%
Nickel	-	10 – 14%

It was ensured that, all the components/ equipment using for gaseous hydrogen handling and storage were selected tested with spectroscopy and the Chromium and Nickel content was not less than 17% and 12%.

12% content of Nickel in 316 stainless steel, stabilizes the austenitic structure. Further helps to avoid the second phase contaminants, ferrite and stain induced martensite maintaining:

1. Corrosion resistance
2. **Avoid the Embrittlement due to flow of hydrogen**
3. Provides a ductile, non-brittle alloy over a wide range of temperatures and media.

Of course, Molybdenum is key to stainless steel corrosion resistance. Definitely Molybdenum helps in improving the corrosion resistance. But, if the alloy stability of Nickel and passivity of Chromium are minimized, added Molybdenum will not compensate. Maintaining the Nickel and Chromium above 12% and 17% respectively provides a robust stainless steel. Further, adding of Chromium provides corrosion resistance, which forms a passive oxide surface layer that makes stainless steel. And added Molybdenum adds corrosion resistance in certain Chlorine media.

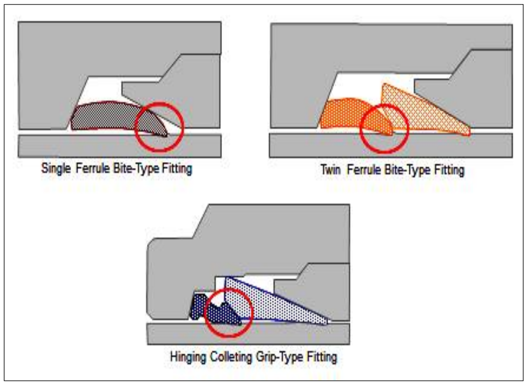

Figure AC.9 Different designs of tube fittings

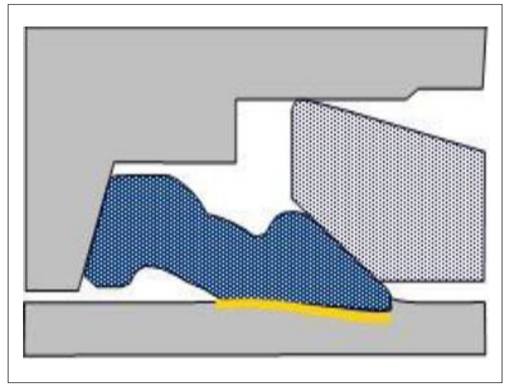

Figure AC.10 Hinging and colleting action type tube fitting

Further, selected tube fitting must be fulfill the following

1. Robust tube grip
2. Leak tight gas seal
3. Minimum Stress raiser and Excellent vibration resistance

1.1.2. Tube Grip

By nature of their design as shown in Figure 3.28, all tube fittings generate a sharp indent and stress raiser on the surface of the tube during the gripping part of the assembly. This sharp disruption or intent from the grip on the tube. The reliability of the tube grip is related to how well the gripping ferrule performs this function.

Generally two types of designs generally available for compression tube fittings. Those are:

1. Bite type ferrule and
2. Hinging and colleting action type ferrule compression tube fittings

A bite type ferrule, as illustrated in Figure 3.28, both single and double ferrule design bows when assembly occurs. This bowing action drives the leading edge of the biting ferrule into the tube to grip or indent the tube surface. The leading edge of these bite type ferrules are intended to bite for proper tube grip. If there is vibration, pulsation, thermal shock or side load exerted on the fitting, the minimal contact of the gripping ferrule offers little support behind the bite, i.e., in a dynamic system, the potential for either damage to tube or pull out may exist. Whereas with hinging and colleting action type tube fitting, available back ferrule enhances the grip of the tube. The hinging and colleting action moves more back ferrule material in close contact with the tube adjacent to the tube gripping indent. This added material provides both direct axial support of the tube gripping indent and additional colleting squeeze grip of the tube.

1.1.3. Gas Seal:

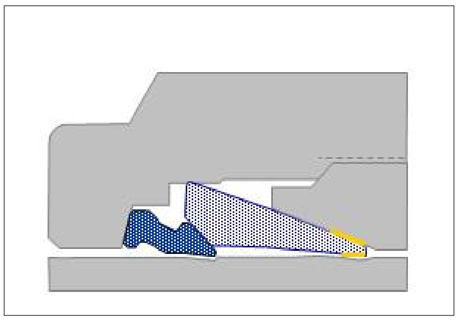

Figure AC.11 Gas Seal

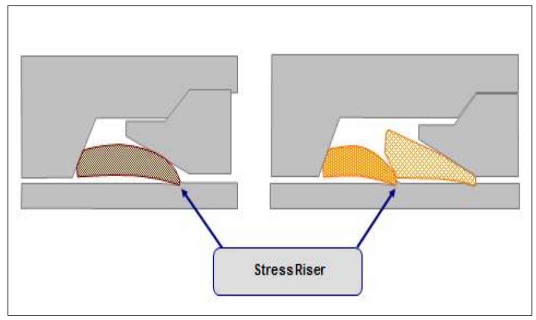

Figure AC.12 Stress risers in bite type fittings

A gas seal is achieved by the burnishing or polishing that occurs between the front ferrule and the tube fitting body and the front ferrule and the tubing. This burnishing action accompanies concentrated zones of contact as shown in yellow in Figure AC.11. The back ferrule drives the front ferrule to a sufficient distance to achieve the gas seal. Once this is accomplished, the back ferrule will no longer progress against the front ferrule. By controlling the movement of the back ferrule just enough to ensure a leak-tight seal, this tube fitting limits the stroke and deformation on the front ferrule. This means that the front ferrule retains an enhanced remarkability in the fitting. This refers to this controlled movement of our back ferrule as compensating action. Compensating action allows the tube fitting to overcome tubing variables such as materials, hardness, wall thickness, and dimensions, and achieves a leak-tight seal.

1.1.4. Stress Risers and Vibration Resistance

Bending, deflection, and vibration impart stresses on the tubing, which can become concentrated and amplified at the stress riser and cause tube fractures. To reduce the effects of bending, deflection, and vibration, the mid portion of the back ferrule adjacent to the tube gripping nose collets and applies a compressive stress against the tube that isolates, dampens, and protects the stress riser at the nose of the back ferrule. The live-loading, spring action, and residual elasticity of the front and back ferrules compensate for thermal cycling, thermal and mechanical transients [rapid changes]. The elasticity of the ferrules respond and maintain a seal through these transients. This design has a protected stress riser through back ferrule geometry, which reduces the damaging effects of system dynamics.

1.2. Heat Treatment

In addition to geometry of the back ferrule and how it relates to the performance in tube grip, gas seal and vibration resistance robust performance will also improve by heat treatment process essential in producing back ferrules with very good hardness, corrosion resistance and ductility that ensures consistent hinging and colleting action.

1.2.1. Carburization:

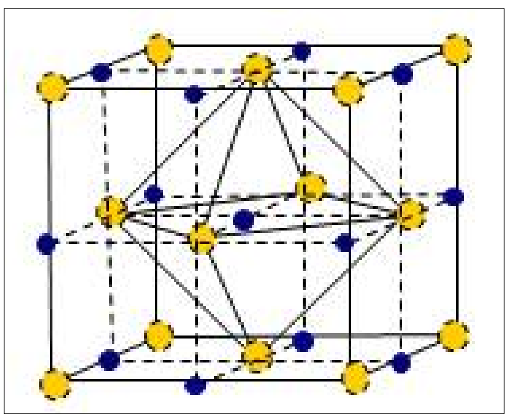

Figure AC.13 Carburization

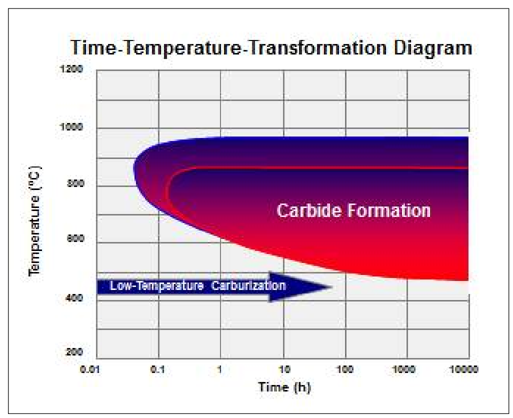

Figure AC.14 Time – Temperature- Transformation (TTT) diagram

Taking a microscopic look at stainless steel, this is a face centered cubic structure. And those blue spots there are the zones where carbon can diffuse into what are called interstitial sites of the cell structure of stainless steel. Stainless steel is made up of four primary elements… chromium, nickel, molybdenum and iron. During the SAT12 treating process of the material, included are two stages in this three-day process, activation and carburization. During the activation cycle, hydrogen chloride strips away the chromium oxide passive layer of the stainless steel, activating the surface and enabling the material to absorb carbon. During the treatment or carburization cycle, the carbon source gas and hydrogen gas mixture combined with heat, provide carbon at the surface that diffuses into the material.

By interstitial site, what we mean is the vacant zones between the chromium and iron and nickel that make up the face center cubic of the stainless steel, the austenite structure. The spaces between all those atoms of the metal, is where the carbon takes up residence in incredible abundance. This incredible percentage of the stainless steel now made up of carbon defusing in from surface.

1.2.1.1. Low-Temperature Carburization

These tube fitting low temperature carburization process works so well. Figure AC.14, illustrated here, in a Time-Temperature-Transformation Diagram. Temperature running along the Y axis, time along the X axis, and then the red and the blue zones here are zones where carbide would form. And the importance of low temperature carburization is that, do this at a low enough temperature that we stay below those zones, this is why it works. We avoid carbide precipitation. Heat treaters, when they want to harden stainless steel, typically operate at those upper temperatures, get those carbides to form, those carbides are hard, they think they're achieving the hardness that they're trying to get at the surface of the stainless steel. It is better to go to the lower temperature, by which one can avoid the formation of carbides and counter intuitively, this actually makes the stainless steel much harder than would be achieved by the formation of carbides, as well as very corrosion resistance and avoids carbide precipitation [which would result in embrittlement and loss of corrosion resistance].

1.2.1.2. Hardness Depth Profile

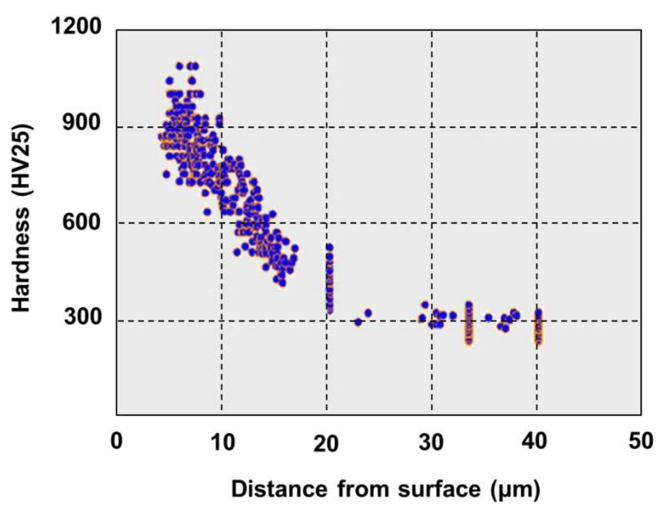

Figure AC.15 Hardness Depth profile

This hardness depth profile shows the hardness that is achieved by the SAT12 process. The hardness indents, depicted as tiny blue circles are part of our in-process inspection showing that at the surface of the stainless steel material, we are achieving hardness's up to 1200 Vickers, which is equivalent to greater than RC 70. The depth of this hardening process is approximately 25 to 30 microns into the surface of the material. 300 Vickers is the typical hardness of untreated stainless steel.

References- Appendix-C

1. Swagelok, *Tube versus Pipe—An Offshore Success Story*.
2. Swagelok, *Gaugeable Tube Fittings and Adapter Fittings*, March 2010.
3. Swagelok, *Tubing Data*, January 2010.

Appendix-D

CALCULATIONS OF PERFORMANCE PARAMETERS, EXHAUST EMISSION AND COMBUSTION CHARACTERISTICS

1.0. CALCULATION OF PERFORMANCE PARAMETERS

Engine performance is an indication of the degree of success with which it is doing the conversion of chemical energy contained in the fuel into useful mechanical work. The degree of success is compared on the basis of the following.

1. Power, Watt
2. Mass of fuel consumed, kg/hr.
3. Brake specific fuel consumption, kg/kW-hr.
4. Brake specific energy consumption, kJ/kW-hr
5. Brake thermal efficiency, %

According to first law of thermodynamics, energy can be neither be created or nor destroyed. It can only be converted from one form to other. In reciprocating internal combustion engines fuel is fed in the combustion chamber where it burn in air, converting its chemical energy into heat. The whole of this energy cannot be utilized for driving the piston as there are losses to the exhaust, to the coolant, and to radiation. The remaining energy, converted to power is called indicated power. This is utilized to drive the piston. The energy applied to the piston passes through the connecting rod to the crankshaft. In this transmission there are energy losses due to friction, pumping etc. The sum of all these losses converted to power, is termed as friction power. The remaining energy is the useful mechanical energy, it is termed as brake power.

Brake Power, bp =

$$\frac{2\Pi\ \mathrm{N\ (rpm)\ T\ (N-m)}}{60}\text{, Watt} \qquad \text{(A D-1)}$$

Mass of fuel consumed =

$$\frac{\text{Fuel consumed in the burette (cc or ml) x } 10^{-6} \text{ x sp. gravity of fuel x sp. weight of stanadard fluid x 3600}}{\text{60 (Sec)}}$$

, kg/hr., (AD-2)

Brake specific fuel consumption, abbreviated as bsfc is the specific fuel consumption on the basis brake power.

Bsfc =

$$\frac{\text{mass of fuel consumed in kg/hr}}{\text{Brake Power ,kW}}, \text{ kg/kw-hr.} \qquad \text{(AD-3)}$$

Brake specific energy consumption is used, when two fuels used in different states. In the present investigation, Jatropa based straight vegetable oil in liquid state and hydrogen was used in gaseous state. Hence, rather than using brake specific fuel consumption (bsfc), brake specific energy consumption (BSEC) was considered.

Brake specific energy consumption (BSEC) =

$$\frac{\text{Total Enetrgy in put } (\frac{\text{kJ}}{\text{hr}})}{\text{Brake Power (kW)}}, \text{ kJ/kW-hr.,} \qquad \text{(AD-4)}$$

Energy input of Jatropa straight vegetable oil (SVO) is = Mass of SVO consumed in kg/hr. x Lower calorific value in kJ/kg.

Energy input of Hydrogen (H_2), = Mass of H_2 consumed in kg/hr. x Lower calorific value in kJ/kg.

Total Energy in (kJ/hr.) = Energy input of SVO in (kJ/hr.) + Energy input of H_2 (kJ/hr.)

Brake thermal efficiency is the ratio of energy in the brake power to the fuel energy =

$$\frac{\text{Brake Power (kW)}}{\text{Fuel Energy}, \frac{\text{kJ}}{\text{Sec}}}, \text{ i.e.,}$$

$$\frac{Brake\ Power\ (kW)}{\frac{Fuel\ consumed\ in\ (cc\ or\ ml)\ x\ 10^{-6}\ x\ sp.gravity\ of\ fuel\ x\ sp.\ weight\ of\ stanadrd\ fluid\ x\ lower\ calorific\ value\ of\ fuel\ x\ 10^{-6}}{t\ (\text{Sec})}}, \frac{kJ}{Sec}.$$

(AD-5)

2.0. EMISSION PARAMETERS

As previously mentioned, NO_x emissions are one of the major pollutants emitted from diesel engines. Generally, NO_x consist mainly Nitrogen Monoxide (NO) and Nitrogen Dioxide (NO_2). It has been reported [1] that 10 to 30 percent of total NO_x is represented by NO_2 emission. The well-known Zeldovich mechanism (1946) clearly describes the NO formation by the following reactions [2, 3].

$$O + N_2 = NO + N \quad \text{(AD-6)}$$

$$N + O_2 = NO + O \quad \text{(AD-7)}$$

$$N + OH = NO + H \quad \text{(AD-8)}$$

The formation of the NO emissions mainly occurs at high temperatures, in excess oxygen regions through reaction (AD-6), leaving one free atom of nitrogen. It can be later combined with oxygen (reaction AD-7) or OH (reaction AD-8), already present in the combustion process, to form nitrogen monoxides. The already formed NO during combustion can be further converted to NO_2 by reaction (AD-9). Afterwards, it can be also converted back to the form of NO by reaction (AD-10) [2, 3].

$$NO + HO_2 = NO_2 + OH \quad \text{(AD-9)}$$

$$NO_2 + O = NO + O_2 \quad \text{(AD-10)}$$

Together with NO_x, particulate matter emissions are major pollutants from combustion in compression ignition engines. There are three definitions of particles emissions can be found regarding traffic regulations, the workplace and environment. Traffic regulations define particles as everything that can be filtered and weighted at temperature of 325 K. In the workspace, the overall mass of elementary carbon less than 5 μm is counted. In the environmental law, it is an overall mass detected with high volume samplers of less than 10 μm (PM10) and less than 2.5 μm (PM2.5) independent of their chemical composition. In the compression ignition engines, the soot is formed by cracking the complex hydrocarbons from the fuel composition and then producing solid carbon particles. The model of soot formation in diesel spray has been proposed Dec J.E[4] and it is illustrated in Figure AD.1

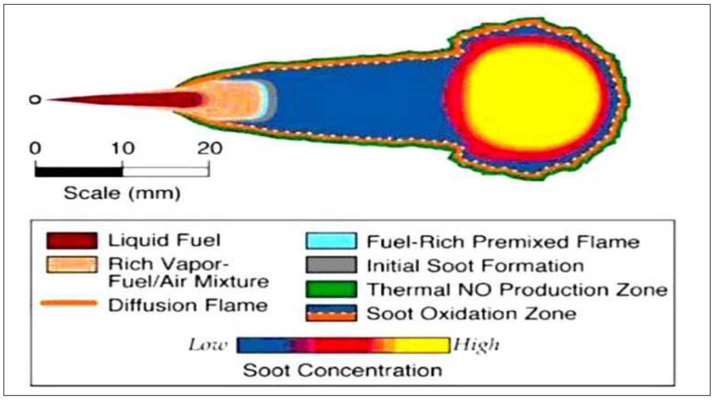

Figure AD.1 Conceptual model of the soot formation process in diesel spray, proposed by Dec [4]

Generally, the single carbon particles are formed during the breakdown of the complex structure of fuel compounds. Additionally, it can be seen that the soot emission is formed in rich fuel/air mixture, preferably in the flame zone, during the diffusion combustion. On the periphery of the spray, soot particles start to oxidize. A higher rate of oxidation would produce less particles in the tail pipe. During the combustion and oxidizing processes, single solid carbon particles start to accumulate and agglomerate with each other to form aggregates. Generally, the particles from diesel combustion can be divided as carbonaceous (soot particles), sulphate particles and soluble materials (mainly hydrocarbons) known as Soluble Organic Fraction or Volatile Organic Fraction (SOF/VOF). In the later stage of combustion, sulfur usually reacts with water vapour to form sulphuric acid and together with SOF/VOF may start to condense on the solid carbon particles at lower temperatures. In Figure AD.2, a detailed diagram of particulate matter composition is presented accordingly to the work done by Kittelson [5].

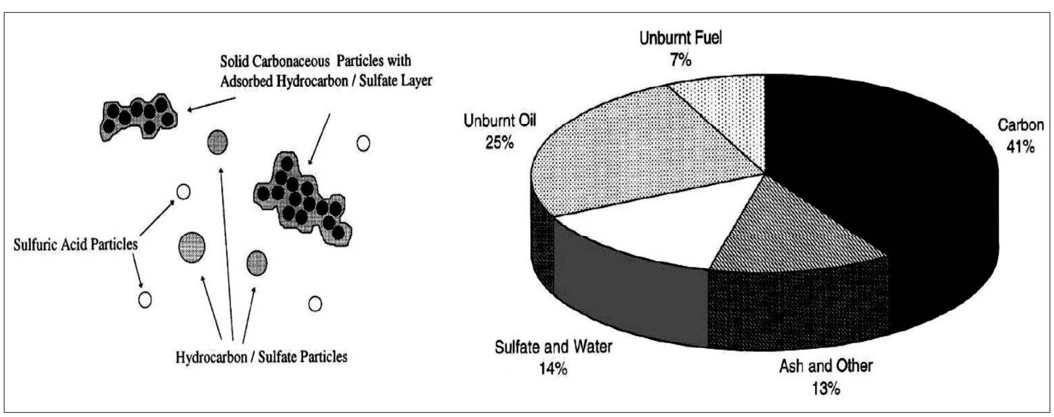

Figure AD.2 Soot particles composition from compression ignition engine [73]

Particulate matters affect human health and the environment. The adverse effect of soot particles (PM2.5 and PM10) has been reported [6, 7], while the influence of ultrafine particles (below 100nm) has not been fully understood but still generates interest. Generally, inhaling particles affects the human body and may cause diseases such as asthma, lung cancer, cardiovascular issues, and in extreme cases premature death. From the environmental point of view, soot particles in the atmosphere may scatter and absorb solar and infrared radiation which can influence climate change.

In the case of combustion products, NO_x and soot emissions become a major problem in conventional engines as they can be described by a well-known NO_x – soot trade off. A reduction in NO_x emissions always results in higher soot emissions and vice versa. Generally less NO_x in the exhaust tile pipe can be achieved by decreasing the in-cylinder temperature either by using exhaust gas recirculation (EGR) or by retarding the injection timing. However, unfortunately, a reduced temperature environment is favourable for high soot emission. An exception from this conventional diesel trade-off is Low Temperature Combustion (LTC) where simultaneous reduction of NO_x and soot can be achieved usually at very late injection parameters and high EGR rates.

The emissions of unburned hydrocarbons and carbon monoxide from compression ignition engines are usually much lower than those from spark ignition. They are both products of incomplete combustion, usually from engine operation at very rich A/F mixtures. Generally, the CO emission strongly depends on the stoichiometry of combustion. Usually, spark ignition engines operate at stoichiometry or a richer mixture, where the CO emission is very high. Under these conditions, a three-way catalyst has the highest possible efficiency (around 95%) of reduction of NO and oxidizing of CO and THC. However, in the case of conventional compression ignition engines, which are usually operated at lean mixtures, CO and THC are low enough to be considered minor pollutants [2, 3]. Nevertheless, recent combustion techniques (LTC) provide a considerably high amount of these pollutants and they have to be taken in to consideration. Hydrocarbon emissions appear as total hydrocarbons which are usually measured as a concentration of carbon atoms in the exhaust gases. They are different in composition for various engines and operating conditions, especially for diesel combustion where the formation process is more complex. The major causes of THC emissions are summarized as follows

Overmixing – local zones of mixtures leaner than combustion limit

Undermixing – overfueling, rich mixtures from trapped fuel in the injector sac volume

Wall quenching and misfires – low temperature of cylinder walls, very high cyclic variability in the combustion process

Carbon monoxide is colorless, odourless and tasteless gas which is lighter than air. It is highly toxic to humans and animals in higher quantities. As a result of incomplete combustion, humans can breathe CO without knowing of its presence in the ambient air causing breathing difficulties at a first stage, unconsciousness, deep poisoning or death in extreme situations. This is one of the most dangerous gases which humans can have contact with even in a household. Hydrocarbon vapour in high concentrations, especially benzene, toluene or xylene (BTX) is highly poisonous causing cancer, neurological diseases and death in extreme situations. As a product of combustion, carbon dioxide emission is a dominant composition of exhaust gases from both spark ignition and compression ignition engines. As long as the fuel for these engines is a form of hydrocarbons, the main combustion process and production of CO_2 will be preceded by following the basic reaction

$$\mathrm{C} + \mathrm{O_2} = \mathrm{CO_2} + \mathrm{Energy} \qquad \text{(AD-11)}$$

The carbon atoms are derived by the hydrocarbons from fuel composition. The combustion of fuel delivers a high amount of CO_2 into the atmosphere and eventually has a huge effect on the climate change.

Different Emissions like smoke, CO, HC and NO_x from the exhaust tail pipe were considered form the available literature to understand the impact of hydrogen supplementation/substitution in dual fuel mode to understand the tail pipe emissions.

2.1. After Treatment Processes

In the case of compression ignition engines, after treatment systems reduce emissions such as: carbon monoxide, unburned hydrocarbons, nitrogen oxides and also soot particulates. Oxidising catalysts are commonly used in both spark and compression ignition engines. Basically, they oxidise unburned hydrocarbons and carbon monoxide in the presence of catalytic materials which can be precious metals such as platinium (Pt), palladium (Pd) or Rhodium (Rh). The monolith substrate consists of small canals which in total give a cross-section area equal to the original tail pipe. The monolith can be made as an inorganic material (Al_2O_3, SiO_2, TiO_2), ceramic or metal with dispersed Pt, Pd or Rh on its surface. It allows a large reaction surface within a small space. The reactions of the oxidation of THC and CO are as follows:

$$C_yH_n + \left(1 + \frac{n}{4}\right) O_2 \rightarrow y\, CO_2 + \frac{n}{2} H_2O \qquad \text{(AD-12)}$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \qquad \text{(AD-13)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(AD-14)}$$

The efficiency of oxidizing catalysts is about 80 – 90% for lean mixture combustion (mostly compression ignition combustion). When the engine is operated at gradually richer mixtures, the efficiency of catalyst decreases. However, such a high efficiency is possible only at high temperatures of catalytic converter, around 300^{o}C (activation temperature). In the case of spark ignition engines, the NO_x emissions are easily reduced in three-way catalysts. It consists of the previously described oxidizing catalyst together with precious metal coating for NO_x reduction. When a very efficient oxidation of CO and THC proceeds at lean mixtures, with availability of oxygen in the exhaust composition, efficient reduction reactions of NO_x take place at rich mixture conditions. Thus, only a small window of engine fuel/air ratio regulation can be used in gasoline engines due to the highest possible three-way catalyst efficiency. Generally, NO/NO_2 reduction reactions are as follows

$$NO\ (\text{or } NO_2) + CO \rightarrow \frac{1}{2} N_2 + CO_2 \qquad \text{(AD-15)}$$

$$NO\ (\text{or } NO_2) + H_2 \rightarrow \frac{1}{2} N_2 + H_2O \qquad \text{(AD-16)}$$

$$\left(2 + \frac{n}{2}\right) NO\ (\text{or } NO_2) + C_yH_n \rightarrow \left(1 + \frac{n}{4}\right) N_2 + yCO_2 + \frac{n}{2} H_2O \qquad \text{(AD-17)}$$

As compression ignition engines mostly operate at lean mixtures new techniques are required to reduce NO_x emissions. In this case, the below methods can be used in diesel engines [4].

(a) Active selective catalytic reduction (SCR) (active DENOx)

The method is based on the addition of ammonia (NH_3) or urea ($CO(NH_2)_2$) into the exhaust tail pipe. Conversion efficiencies reach even 80% and proceed at the following reactions:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \qquad \text{(AD-18)}$$

$$2NO_2 + 4\,NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \qquad \text{(AD-19)}$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \qquad \text{(AD-20)}$$

$$4NO + 2\,(NH_2)_2CO + O_2 \rightarrow 4N_2 + 4\,H_2O + 2CO_2 \qquad \text{(AD-21)}$$

(b) Passive SCR (passive DENO$_x$)

This passive method (nothing added into the exhaust tail pipe) is based on utilizing hydrocarbons emissions to reduce NO$_x$ emissions in the presence of catalysts. A major problem is a very narrow temperature window (160^o – 220^o C) for platinum catalysts where these reactions occur [8, 9] . However, with copper base zeolite it could be possible to reduce NO$_x$ even up to 40%.

(c) NO$_x$ traps

This technique can be described by four fundamental reactions. At the presence of a catalytic converter, NO is transformed into NO_2 (reaction AD -22).

$$NO + \frac{1}{2}\,O_2 \rightarrow NO_2 \qquad \text{(AD-22)}$$

Then, NO_2 reacts with metal oxides dispersed on the catalytic converter and forms storage material nitrate (reaction AD-23).

$$NO_2 + Me\,O \rightarrow Me - NO_3 \qquad \text{(AD-23)}$$

As stored NO_2 increases the efficiency of nitrate formation is reduced, so in this case the storage materials have to be periodically regenerated. For this reason the engine must be briefly switched to rich mixture operation. Afterwards, at higher temperature, the storage material releases trapped NO_2 by using the following (reaction AD-24)

$$Me - NO_3 \rightarrow NO + \frac{1}{2}\,O_2 \qquad \text{(AD-24)}$$

The NO then reacts with THC and CO presented in the exhaust gases during rich engine operation (reaction AD-25).

$$NO + HC\ (\text{or } CO) \rightarrow \frac{1}{2}\,N_2 + H_2O\ (\text{or } CO_2) \qquad \text{(AD-25)}$$

This method requires short periods of operation on a rich mixture which are easier to obtain by spark ignition engines rather than compression ignition engines where operation on rich mixtures provides maximum engine power. To reduce soot particles emitted from compression ignition engines, diesel particulates filter (DPF) or soot traps have been proposed. Generally, soot particles are collected (filtered) on the monolith material. Different types of materials, such as ceramic monoliths, alumina-coated wire mesh, ceramic foam, ceramic fiber mat, woven silica-fiber rope wound on a porous tube are used to manufacture these filters [1]. Figure AD.3 presents DPF filters and the soot filtration process in ceramic monolith (commonly used).

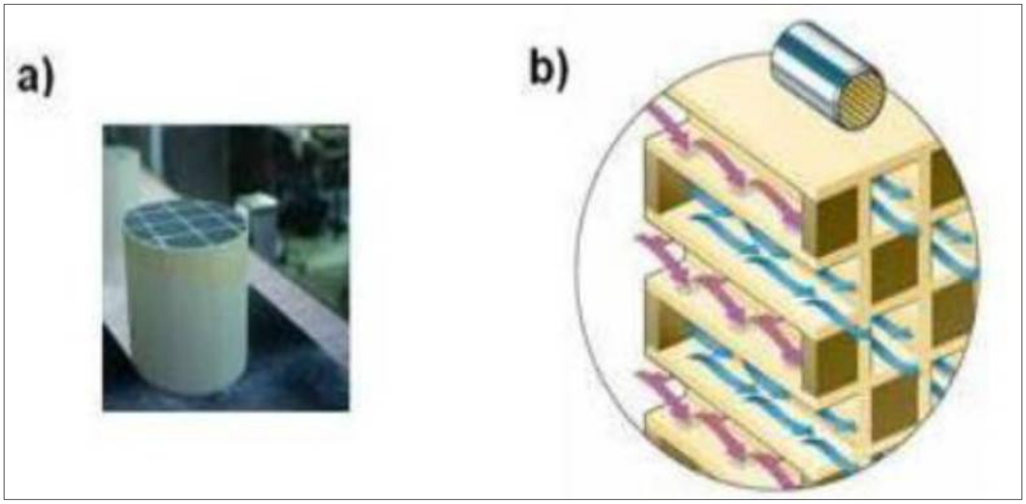

Figure AD.3 DPF filter: a) size and design, b) ceramic monolith filtration method

Raw exhaust gases, with soot particles, enter cells which are closed at the end and pass through walls. A major problem in this method is a back pressure build up when soot is gradually collected on the filtrating material. In this case, DPFs need to be periodically regenerated. The best way is to burn deposited soot by increasing exhaust gases temperature to that range where diesel soot particles start to ignite (about 50^o to 600^{o}C). It can be done in two ways: positive regeneration (external heaters or fuel injection before DPF) or catalytic regeneration (addition of catalytic material which can decrease soot ignition temperature by up to 200^o C) [2, 3]. The well-known continuously regenerating trap (CRT) method effectively filtrates soot particles. It consists of two sections, where the first is a platinum catalyst which generates more NO_2 from the exhaust's NO and the second is a soot trap. A high amount of NO_2 would oxidize soot continuously. Usually, this method is used in heavy duty diesel engines and is required to use a low sulfur fuel.

3.0. CALCULATION OF COMBUSTION PARAMETERS

Combustion inside the engine will influence the performance and emissions of the same engine. In order to understand the degree of conversion of chemical energy into mechanical energy was reflected in the form of heat release rate from the selected fuels during combustion. Further, heat release rate is directly proportional to maximum cylinder pressure inside the engine. Hence, in this direction different combustion parameters were studied like: P- theta, Differential Heat Release Rate(DHRR), Ignition delay were considered in this present investigation. Out of these selected parameters, P- theta was the measured one by the sensor provided on the cylinder head and the remaining data were calculated from the measured P-theta data.

3.1. Heat Release Rate

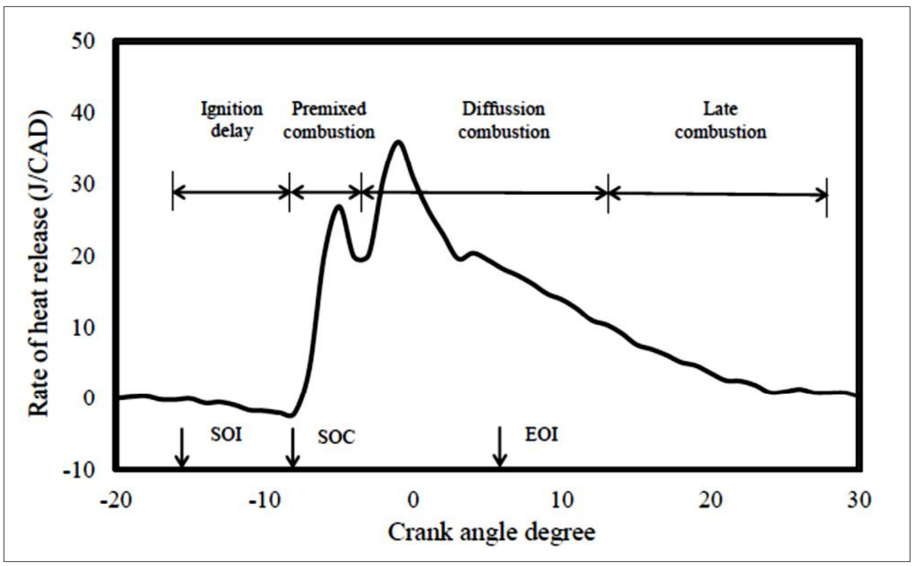

Figure AD.4 Typical Heat Release Rate analysis of a diesel engine

Ignition delay

The period between the start of injection of fuel in the combustion chamber to the start of the combustion. No heat release occurs up to the point at which fuel injection starts. Soon after the start of fuel injection a small dip is observed showing a negative heat release rate due to heating and vaporization of fuel. Then owing to pre-combustion reactions heat release rate slowly begins and combustion starts, marking the end of ignition delay when heat release rate suddenly rises.

Pre-mixed or rapid or un-controlled combustion

Combustion of the fuel- air mixture formed during the ignition delay period in their flammable limit is being ignited rapidly in few crank angle degrees. This burned mixture initiates the burning of unburned /left over charge of the chamber.

Mixing or controlled combustion

The burning rate in this phase will be controlled by the mixture available during this time. Though so many factors influenced for the heat release rate like fuel atomization, vaporization, mixing and pre-flame chemical reactions. However, the heat release is depending primarily on vapour –air mixing processes. The heat release rate of second phase may or may not be the maximum of first peak. Further, in dual fuel operation, it was observed that second peak may rise due to the difference in self-ignition temperature of different fuels. This is main heat release rate period and its duration is about 30- 40° CA. Nearly 80% or more of total heat is released during premixed and mixed or controlled combustion phases. After this heat release rate is gradually decreased.

Late combustion Phase

Late combustion phase is the last phase of combustion and is not so distinct as the other phases proceeding it. At the end of the mixing controlled combustion phase some fuel might have remained unburned and some partially burned products like soot from fuel rich regions are also present. Mixing of leftover unburned fuel and incomplete combustion products with high temperature air leads to complete of combustion. Combustion continues almost throughout the expansion stroke. As the expansion stroke progresses combustion reaction slow down and eventually get extinguished.

3.2. Cylinder Pressure Data Analysis

Cylinder Pressure versus Crank Angle was measured with GH15DK model AVL make Piezo Transducer mounted on the cylinder head as shown Figure AD.5.

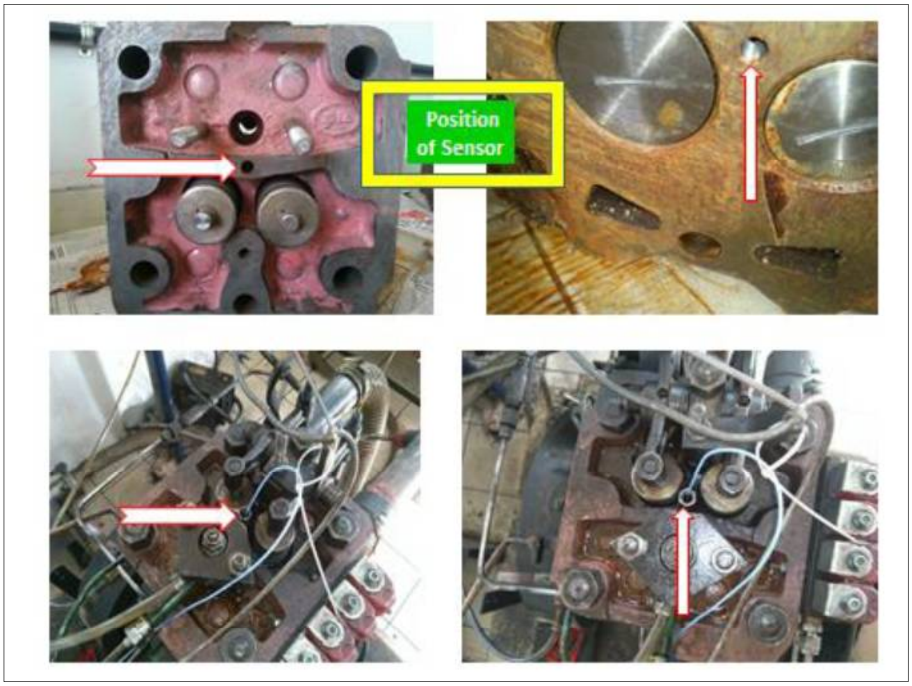

Figure AD.5 Position of Piezo-Transducer along with its adaptor to measure the thermodynamic data

Usually, pressure transducers require a separate cooling system but selected version was able to resist to thermal shocks. The quartz crystal provides the proportional charge to the level of the cylinder pressure. Then, a charge signal (16 pC/bar) is amplified by the charge amplifier and captured by the PC with the installed Indi smart 612 software. This measured cylinder pressure data was synchronized with angular momentum of 365CC, 720 pulses Crank Angle Encoder attached to the engine crank shaft.

3.3. Consideration of Geometrical Properties of the Selected Engine for calculation of combustion surface area and thermodynamic calculations

Cylinder Bore (d)	:	The nominal diameter (inner) of the working cylinder is called the cylinder bore and is designated by ‘d’ and is usually expressed in ‘mm’ Cylinder Bore (d) of the selected engine is = 120 mm
Piston Area (A_p)	:	The area of the circle of diameter equal to the cylinder bore is called Piston area and is designated by the letter ‘A’ and is expressed in cm^2

Stroke (L) : The nominal distance through which a working piston moves between two successive reversals of its direction of motion is called the stroke and is designated by the letter 'L' and is expressed in 'mm'

Stroke (L) of the selected engine is = 139.7 mm

Stroke to Bore Ratio (L/d) : It is important in classifying the size of the engine. If

$d < L$ - under square engine

$d = L$ - square engine

$d > L$ - over square engine

For the selected engine Stroke (L) is greater than Bore (d).

Displacement or Swept Volume (Vs) : The nominal volume swept by the working piston when travelling from one dead center to other is called displacement volume and is designated by 'cc'

i.e., Vs = A x L = 1580 cc

Clearance Volume (Vc) : The nominal volume of the combustion chamber above the piston when it is at Top Dead Center (TDC)

Vc = 92.94 cc

Compression Ratio : It is the ratio of the total cylinder volume when the piston is at the Bottom Dead Center (BDC) , V_T , to the clearance volume (Vc)

Compression Ration of the selected engine is = 17:1

3.4. Calculation of Combustion Chamber Surface Area

Ratio of Connecting Rod length to Crank Radius, $R_{cc} = l/a$

Cylinder volume 'V' at any crank position, 'θ' is

$$V = Vc + \frac{\Pi}{4} d^2 (l + a - S) \qquad \text{(AD-26)}$$

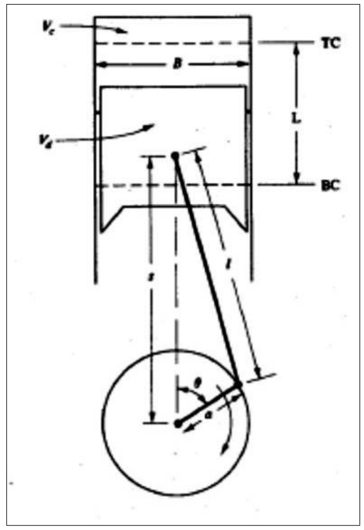

Figure AD.6 Geometry of the Engine

Where ‘S’ is the distance between crank axis and piston pin axis and is given by

$$S = a\,\mathrm{Cos}\theta + (l^2 - a^2\,\mathrm{Sin}^2\,\theta)^{1/2} \qquad \text{(AD-27)}$$

The angle ‘θ’ is the crank angle, and equation (AD-26) can be re write with the help of equation (AD-27) is,

$$\frac{V}{V_c} = 1 + \frac{1}{2}(r-1)\,[R_{cc} + 1 - \mathrm{Cos}\theta - (R^2_{cc} - \mathrm{Sin}^2\theta)^{½}] \qquad \text{(AD-28)}$$

Then the combustion chamber surface area at any crank position, θ, is

$$A = A_{ch} + A_p + \Pi B\,(l + a - S) \qquad \text{(AD-29)}$$

Where,

A_{ch} = Cylinder head surface area

A_p = Piston Crown area

Being a Flat piston area, for this selected engine, $A_p = \frac{\Pi}{4}\,d^2$ (AD-30)

From the equations (AD-28) and (AD-29), equation (AD-28) can be rewrite as

Then the combustion chamber surface area at any crank position is given by,

$$A = A_{ch} + A_p + \frac{\Pi}{2}\,dl\,[R_{cc} + 1 - \mathrm{Cos}\theta - (R^2_{cc} - \mathrm{Sin}^2\,\theta)^{½}] \qquad \text{(AD-31)}$$

3.5. Calculation of Heat Release Rate

Cylinder pressure versus crank angle data over the compression and expansion strokes of the engine operating cycle can be used to obtain quantitative information on the progress of combustion. The rate the fuel's heat release rate or rate of fuel burning through the diesel engine combustion process can be described by the methods of quasi static (i.e., i=uniform in pressure and temperature) analysis start with the first law of thermodynamics for an open system.

We know that,

$$\Sigma m_i h_i = \frac{du}{dt} - \frac{dQ}{dt} + p.\frac{dv}{dt} \qquad \text{(AD-32)}$$

Where $\frac{dQ}{dt}$ is the heat transfer rate across the system boundary, $p.\frac{dv}{dt}$ is the rate of work done transfer by the system due to system boundary displacement. m_i and h_i are the mass and enthalpy of the flow in to the system. p and v are the pressure and volume of the cylinder and U is the internal energy of the cylinder contents.

$$\frac{dQ}{dt} = m.c_{v.}\, dT + p.\frac{dv}{dt} \qquad \text{(AD-33)}$$

Where, $dT = \frac{T}{P}\, dp + \frac{T}{V}\, dv$

$$dQ = dU + pdV$$

$$\frac{du}{dT} = Cv$$

$$\frac{dQ}{dt} = \frac{du}{dt} + p.\frac{dv}{dt}$$

We know that, $dU = m\, c_v\, dT$

$$= p.\frac{dv}{dt} + \frac{m\, c_v\, dT}{dt}$$

$$= p.\frac{dv}{dt} + \frac{c_v}{R}\, p.\frac{dv}{dt} + \frac{c_v}{R}\, .v.\frac{dp}{dt} \qquad \text{(AD-34)}$$

$$\frac{dQ_n}{dt} = p.\frac{dv}{dt}\left(1 + \frac{c_v}{R}\right) + \frac{c_v}{R}\, v.\frac{dp}{dt}$$

We know that, $c_p - c_v = R$

$$\frac{c_v}{R} = \left\{\frac{1}{\gamma - 1}\right\}$$

$$\frac{dQ_n}{dt} = \left\{\frac{\gamma}{\gamma-1}\right\} p.\frac{dv}{dt} + \left\{\frac{1}{\gamma-1}\right\} v.\frac{dp}{dt} \qquad \text{(AD-35)}$$

Where, γ	=	adiabatic index , taken as 1.35.
p	=	cylinder pressure
v	=	cylinder volume

The net (apparent) heat release rate calculations apply to the first two terms and represent a sensible energy change and work transfer to the piston (equation AD-35)

It is well known that a specific heat ratio has a strong influence on the peak of the heat release rate [10, 11] The value of adiabatic index normally varies between 1.3 and 1.35 [2]. Since this work is focused on comparing the effects of various fuels and different engine operating conditions, a constant adiabatic exponent of 1.35 was used.

4. HYDROGEN INJECTION DURATION CALCULATION

Engine speed	=	1000 rpm
Revolution per second	=	1000/60 = 16.67 rps
Time taken for one revolution	=	1/16.67 = 0.0599 Sec..
One revolution	=	360^o
Equivalent time for crank angle for 360^0	=	0.0599 Sec.
For 1^0 Crank angle duration	=	0.0599/360 = 1.666 x 10^{-4} Sec.
Then for 25^0 crank angle	=	1.666 x 10^{-4} Sec. x 25
	=	4165 μ Sec.

5.0 FLOW CHART OF ENGINE EXPERIMENTATION

Identification of physico-chemical properties of selected fuels

Experimentation with conventional diesel

Experimentation with Jatropa based pre-heated straight vegetable oil (PHSVO 90)

Comparison of PHSVO 90 data with conventional diesel data and identification of best efficiency load with respect to performance parameters exhaust emissions and combustion characteristics

Experimentation on gaseous hydrogen (GH_2) supplementation in the range of 0.3 to 1.0 gm/min with PHSVO 90 and identification of best band of GH_2 supplementation and best efficiency load with respect to performance parameters exhaust emissions and combustion

Experimentation on identified best GH_2 band with PHSVO 90 with varying the injection timings (advancements) and optimization of injection timing and best GH_2 dosage at best efficiency load with respect to performance parameters exhaust emissions and combustion characteristics

Experimentation on optimized injection timing, optimized GH2 dosage with PHSVO 90 at best efficiency load with varying injection pressures (increasing mode) and optimization of injection pressure with respect to performance parameters exhaust emissions and combustion characteristics

Comparison of optimized GH2 dosage, optimized injection timing and optimized injection pressure data with baseline conventional diesel and PHSVO 90 at best efficiency load

6.0 DATA SHEETS

6.1 Performance Parameters and Exhaust Emissions

Table AD.1 PHSVO at 90˚C with 0.5 gm/min GH_2 supplementation at injection timing 20^o bTDC , injection pressure 175 Bar Performance parameters & Exhaust emissions

Date : P= t=

S.no.		Load	Speed (RPM)	Power (kW)	Fuel consumed (ml)	Time Taken(sec)	mass of fuel consumed in kg/hr	mass of fuel consumed in gm/min	H_2 consumption (gm/min)	H_2 Mass Share %
1	0.5 gm/min	20%	1000	1.5	15	60	0.8	13.8	0.5	3.5
2	0.5 gm/min	40%	1000	3.0	21	60	1.2	19.3	0.5	2.5
3	0.5 gm/min	60%	1000	4.4	25	60	1.4	23.0	0.5	2.1
4	0.5 gm/min	80%	1000	5.9	30	60	1.7	27.5	0.5	1.8
5	0.5 gm/min	100%	996	7.4	42	60	2.3	38.6	0.5	1.3

Energy input of SVO (KJ/hr) (A)	Energy input of H2 (KJ/Hr) (B)	Total Energy input (A) + (B) (KJ/Hr)	Total Energy input (KJ/Sec)	% of H2 Energy Share	BSEC (kJ/kW-hr)	Thermal Efficiency (%)	Smoke opacity, (HSU)	CO (% by Vol.)	HC (ppm)	NOx (ppm)
34039.4	3570	37609.4	10.4	9.5	25411.8	14.2	13.0	0.04	5	155
47655.2	3570	51225.2	14.2	7.0	17305.8	20.8	16.0	0.06	5	250
56732.4	3570	60302.4	16.8	5.9	13581.6	26.5	28.2	0.08	7	361
68078.9	3570	71648.9	19.9	5.0	12102.9	29.6	60.0	0.09	8	396
95310.4	3570	98880.4	27.5	3.6	13362.2	26.9	92.0	0.93	23	340

6.2 Combustion Data

6.2.1 Pmax Vs. CA

Table AD.2 Pmax Vs. CA of 20^{o}bTDC injection timing, 175 bar injection pressure at 80% load of conventional diesel, PHSVO 90 and GH2 supplemented PHSVO 90 fuels

CA	PHSVO 90	Diesel	0.3H2	0.4 H2	0.5 H2	0.6 H2	0.7 H2	0.8 H2	0.9 H2	1.0 H2
-90	0.909	1.7758	0.389	0.358	0.317	0.369	0.36	0.389	0.35	0.403
-89.5	0.917	1.7946	0.393	0.36	0.322	0.371	0.367	0.391	0.35	0.412
-89	0.928	1.8136	0.396	0.364	0.325	0.375	0.366	0.396	0.357	0.413
-88.5	0.934	1.832	0.402	0.371	0.329	0.384	0.374	0.399	0.363	0.415
-88	0.941	1.852	0.403	0.368	0.332	0.383	0.379	0.401	0.363	0.415
-87.5	0.948	1.8728	0.404	0.375	0.335	0.388	0.378	0.4	0.369	0.42
-87	0.953	1.894	0.41	0.376	0.337	0.392	0.383	0.405	0.369	0.427
-86.5	0.957	1.9134	0.413	0.384	0.342	0.402	0.388	0.409	0.383	0.429
-86	0.969	1.9316	0.418	0.384	0.344	0.399	0.392	0.407	0.38	0.432
-85.5	0.974	1.955	0.42	0.387	0.348	0.403	0.396	0.42	0.387	0.436
-85	0.976	1.9762	0.432	0.394	0.351	0.404	0.399	0.421	0.389	0.443
-84.5	0.985	1.9986	0.429	0.395	0.353	0.411	0.402	0.431	0.394	0.443
-84	0.997	2.0194	0.435	0.403	0.363	0.415	0.41	0.429	0.393	0.45
-83.5	1.003	2.0452	0.44	0.411	0.359	0.421	0.412	0.433	0.398	0.452
-83	1.017	2.0704	0.451	0.415	0.364	0.427	0.414	0.443	0.402	0.461
-82.5	1.02	2.0946	0.453	0.415	0.368	0.43	0.424	0.446	0.404	0.464
-82	1.029	2.1182	0.454	0.419	0.376	0.438	0.429	0.446	0.412	0.472
-81.5	1.038	2.1434	0.461	0.426	0.377	0.437	0.433	0.454	0.42	0.476
-81	1.048	2.1662	0.469	0.429	0.382	0.449	0.434	0.46	0.424	0.485
-80.5	1.065	2.192	0.475	0.435	0.382	0.45	0.435	0.467	0.428	0.488
-80	1.071	2.219	0.472	0.441	0.393	0.456	0.447	0.469	0.433	0.487
-79.5	1.08	2.2476	0.489	0.443	0.396	0.46	0.447	0.475	0.434	0.497
-79	1.093	2.2792	0.488	0.45	0.4	0.464	0.459	0.479	0.445	0.497
-78.5	1.106	2.3038	0.499	0.454	0.404	0.475	0.465	0.484	0.451	0.503
-78	1.115	2.3326	0.504	0.462	0.412	0.478	0.468	0.491	0.452	0.512
-77.5	1.128	2.359	0.51	0.472	0.411	0.485	0.474	0.494	0.459	0.514
-77	1.141	2.3916	0.508	0.476	0.422	0.493	0.476	0.507	0.464	0.528
-76.5	1.158	2.4212	0.522	0.48	0.427	0.495	0.489	0.508	0.472	0.531
-76	1.168	2.4532	0.525	0.491	0.435	0.504	0.496	0.518	0.475	0.539
-75.5	1.188	2.4852	0.531	0.495	0.435	0.515	0.495	0.525	0.484	0.546
-75	1.204	2.5162	0.539	0.502	0.443	0.514	0.505	0.533	0.492	0.554
-74.5	1.22	2.5488	0.548	0.507	0.448	0.523	0.514	0.542	0.499	0.558
-74	1.238	2.5842	0.558	0.512	0.453	0.531	0.52	0.548	0.498	0.572
-73.5	1.254	2.6212	0.566	0.519	0.46	0.542	0.523	0.56	0.507	0.577
-73	1.278	2.66	0.571	0.527	0.463	0.549	0.536	0.565	0.512	0.585
-72.5	1.3	2.6926	0.58	0.533	0.47	0.556	0.538	0.57	0.52	0.594

-72	1.317	2.7294	0.59	0.544	0.474	0.563	0.554	0.579	0.53	0.602
-71.5	1.344	2.7666	0.599	0.553	0.485	0.575	0.554	0.59	0.54	0.61
-71	1.37	2.8034	0.608	0.561	0.495	0.578	0.568	0.598	0.542	0.617
-70.5	1.396	2.8482	0.612	0.573	0.493	0.591	0.575	0.607	0.549	0.631
-70	1.419	2.8892	0.621	0.58	0.507	0.595	0.585	0.616	0.562	0.644
-69.5	1.442	2.9308	0.632	0.588	0.514	0.603	0.597	0.62	0.57	0.649
-69	1.472	2.971	0.643	0.594	0.522	0.612	0.608	0.634	0.581	0.663
-68.5	1.492	3.0106	0.653	0.602	0.531	0.622	0.611	0.64	0.588	0.666
-68	1.522	3.0548	0.663	0.612	0.534	0.631	0.619	0.654	0.598	0.679
-67.5	1.559	3.102	0.67	0.628	0.542	0.644	0.634	0.662	0.609	0.688
-67	1.585	3.1484	0.683	0.632	0.552	0.654	0.643	0.671	0.617	0.704
-66.5	1.618	3.198	0.691	0.638	0.554	0.663	0.657	0.685	0.629	0.713
-66	1.647	3.2436	0.701	0.654	0.573	0.676	0.657	0.696	0.637	0.723
-65.5	1.683	3.2968	0.717	0.664	0.577	0.685	0.674	0.707	0.645	0.739
-65	1.712	3.3436	0.724	0.677	0.586	0.695	0.683	0.72	0.654	0.749
-64.5	1.747	3.398	0.736	0.689	0.594	0.708	0.688	0.732	0.664	0.759
-64	1.782	3.4502	0.751	0.701	0.61	0.715	0.711	0.742	0.678	0.77
-63.5	1.819	3.506	0.762	0.708	0.615	0.732	0.718	0.756	0.688	0.787
-63	1.859	3.5626	0.78	0.725	0.627	0.744	0.732	0.769	0.698	0.798
-62.5	1.899	3.62	0.786	0.738	0.64	0.758	0.745	0.785	0.713	0.809
-62	1.939	3.6822	0.801	0.753	0.644	0.767	0.759	0.798	0.724	0.833
-61.5	1.982	3.7396	0.819	0.768	0.663	0.781	0.773	0.813	0.739	0.838
-61	2.027	3.7992	0.834	0.774	0.671	0.799	0.783	0.828	0.745	0.855
-60.5	2.075	3.863	0.847	0.79	0.682	0.811	0.797	0.84	0.761	0.872
-60	2.127	3.9298	0.864	0.815	0.703	0.828	0.813	0.856	0.774	0.88
-59.5	2.177	3.9972	0.876	0.821	0.716	0.843	0.829	0.871	0.786	0.897
-59	2.229	4.0666	0.89	0.836	0.725	0.858	0.843	0.894	0.795	0.919
-58.5	2.284	4.1374	0.915	0.85	0.739	0.871	0.856	0.91	0.815	0.941
-58	2.341	4.2142	0.93	0.865	0.75	0.89	0.872	0.93	0.827	0.96
-57.5	2.396	4.2908	0.946	0.884	0.767	0.907	0.89	0.946	0.845	0.981
-57	2.457	4.367	0.964	0.906	0.783	0.927	0.906	0.963	0.859	0.999
-56.5	2.52	4.4456	0.987	0.926	0.801	0.947	0.925	0.984	0.875	1.019
-56	2.583	4.5228	1.001	0.949	0.815	0.968	0.943	1	0.893	1.035
-55.5	2.65	4.608	1.02	0.97	0.833	0.987	0.96	1.016	0.91	1.056
-55	2.717	4.6906	1.044	0.984	0.851	1.004	0.984	1.041	0.928	1.084
-54.5	2.788	4.7786	1.061	1.014	0.869	1.021	1	1.061	0.95	1.102
-54	2.863	4.8688	1.084	1.032	0.902	1.041	1.019	1.084	0.974	1.131
-53.5	2.94	4.9586	1.103	1.055	0.925	1.062	1.042	1.103	0.988	1.147
-53	3.012	5.054	1.126	1.085	0.95	1.082	1.065	1.123	1.016	1.17
-52.5	3.091	5.1486	1.151	1.106	0.977	1.104	1.088	1.151	1.039	1.199
-52	3.173	5.2542	1.176	1.127	1.001	1.125	1.105	1.173	1.054	1.231
-51.5	3.253	5.3494	1.202	1.152	1.029	1.152	1.134	1.199	1.084	1.257
-51	3.336	5.457	1.223	1.184	1.058	1.172	1.16	1.227	1.101	1.281

-50.5	3.425	5.5644	1.252	1.214	1.089	1.205	1.183	1.253	1.13	1.308
-50	3.507	5.6758	1.282	1.241	1.122	1.235	1.213	1.276	1.153	1.336
-49.5	3.599	5.7936	1.31	1.268	1.153	1.262	1.239	1.311	1.181	1.365
-49	3.687	5.9098	1.339	1.298	1.189	1.29	1.269	1.34	1.207	1.395
-48.5	3.782	6.0302	1.373	1.338	1.217	1.326	1.3	1.372	1.239	1.43
-48	3.878	6.1492	1.406	1.367	1.256	1.35	1.331	1.407	1.262	1.465
-47.5	3.979	6.2778	1.44	1.403	1.292	1.383	1.362	1.44	1.297	1.5
-47	4.077	6.4094	1.465	1.444	1.332	1.418	1.396	1.471	1.327	1.54
-46.5	4.184	6.5416	1.502	1.485	1.371	1.457	1.433	1.511	1.364	1.573
-46	4.3	6.6826	1.542	1.523	1.409	1.492	1.473	1.551	1.397	1.614
-45.5	4.402	6.8258	1.579	1.568	1.46	1.535	1.517	1.588	1.439	1.65
-45	4.515	6.973	1.622	1.613	1.502	1.572	1.561	1.633	1.481	1.699
-44.5	4.64	7.123	1.666	1.658	1.561	1.614	1.604	1.672	1.524	1.748
-44	4.76	7.2752	1.707	1.712	1.6	1.664	1.658	1.722	1.568	1.795
-43.5	4.879	7.4322	1.752	1.76	1.656	1.706	1.709	1.765	1.617	1.844
-43	5.01	7.5968	1.797	1.822	1.708	1.753	1.762	1.819	1.661	1.888
-42.5	5.144	7.7684	1.853	1.869	1.769	1.805	1.821	1.872	1.71	1.939
-42	5.278	7.942	1.899	1.933	1.825	1.865	1.876	1.923	1.765	1.997
-41.5	5.416	8.1224	1.954	1.993	1.888	1.913	1.939	1.981	1.817	2.05
-41	5.562	8.3064	2.013	2.057	1.953	1.971	2.004	2.038	1.87	2.112
-40.5	5.715	8.4942	2.072	2.126	2.022	2.03	2.07	2.101	1.929	2.174
-40	5.875	8.6926	2.135	2.201	2.095	2.092	2.138	2.162	1.995	2.237
-39.5	6.042	8.8934	2.2	2.272	2.174	2.16	2.216	2.221	2.067	2.315
-39	6.216	9.1008	2.27	2.358	2.256	2.22	2.299	2.29	2.127	2.377
-38.5	6.403	9.314	2.349	2.443	2.333	2.291	2.375	2.362	2.206	2.462
-38	6.589	9.5334	2.425	2.534	2.423	2.367	2.46	2.437	2.284	2.538
-37.5	6.797	9.7598	2.507	2.632	2.517	2.449	2.556	2.509	2.368	2.621
-37	7.001	9.991	2.596	2.736	2.617	2.528	2.655	2.587	2.451	2.716
-36.5	7.213	10.2308	2.684	2.841	2.722	2.61	2.764	2.669	2.543	2.812
-36	7.426	10.4746	2.787	2.965	2.826	2.703	2.876	2.751	2.64	2.91
-35.5	7.641	10.7262	2.894	3.094	2.941	2.801	3.002	2.845	2.752	3.019
-35	7.857	10.9906	3.01	3.224	3.067	2.899	3.139	2.937	2.859	3.126
-34.5	8.077	11.262	3.138	3.371	3.203	3.012	3.29	3.036	2.982	3.249
-34	8.309	11.5396	3.27	3.519	3.347	3.129	3.452	3.14	3.122	3.377
-33.5	8.547	11.8232	3.405	3.683	3.519	3.255	3.633	3.255	3.268	3.516
-33	8.794	12.1202	3.56	3.858	3.693	3.388	3.823	3.378	3.423	3.66
-32.5	9.051	12.4184	3.723	4.045	3.872	3.538	4.036	3.513	3.607	3.831
-32	9.314	12.7258	3.899	4.238	4.057	3.709	4.246	3.666	3.799	4.009
-31.5	9.585	13.0468	4.077	4.457	4.266	3.896	4.472	3.831	3.992	4.204
-31	9.873	13.3732	4.275	4.684	4.48	4.081	4.717	4.014	4.197	4.417
-30.5	10.162	13.713	4.489	4.939	4.715	4.275	4.978	4.213	4.419	4.652
-30	10.459	14.0554	4.738	5.211	4.967	4.493	5.245	4.428	4.658	4.885
-29.5	10.769	14.4118	5.014	5.501	5.248	4.723	5.535	4.656	4.902	5.15

-29	11.096	14.775	5.338	5.803	5.555	4.978	5.837	4.889	5.169	5.428
-28.5	11.437	15.1522	5.676	6.129	5.899	5.252	6.153	5.125	5.457	5.716
-28	11.785	15.5414	6.045	6.466	6.266	5.556	6.481	5.376	5.774	6.015
-27.5	12.144	15.9398	6.422	6.819	6.65	5.869	6.826	5.652	6.098	6.326
-27	12.53	16.344	6.809	7.2	7.053	6.215	7.204	5.954	6.43	6.64
-26.5	12.909	16.759	7.206	7.595	7.473	6.591	7.591	6.27	6.78	6.974
-26	13.302	17.1916	7.589	8	7.911	6.977	7.983	6.599	7.15	7.309
-25.5	13.695	17.627	7.986	8.419	8.349	7.394	8.398	6.942	7.531	7.638
-25	14.096	18.0728	8.385	8.854	8.798	7.823	8.828	7.311	7.939	7.969
-24.5	14.503	18.5304	8.801	9.302	9.246	8.275	9.277	7.708	8.362	8.319
-24	14.916	18.9984	9.218	9.755	9.717	8.718	9.747	8.142	8.803	8.696
-23.5	15.336	19.4724	9.658	10.215	10.183	9.19	10.227	8.618	9.258	9.1
-23	15.766	19.9668	10.094	10.686	10.69	9.674	10.729	9.12	9.728	9.53
-22.5	16.203	20.4606	10.538	11.17	11.224	10.181	11.254	9.648	10.209	9.993
-22	16.653	20.9686	10.984	11.663	11.738	10.703	11.779	10.221	10.708	10.483
-21.5	17.117	21.487	11.437	12.163	12.255	11.235	12.325	10.815	11.223	11.002
-21	17.578	22.0124	11.9	12.684	12.774	11.78	12.88	11.425	11.759	11.557
-20.5	18.057	22.5504	12.378	13.216	13.29	12.337	13.461	12.043	12.303	12.12
-20	18.542	23.0886	12.884	13.741	13.812	12.908	14.046	12.678	12.865	12.702
-19.5	19.033	23.6386	13.433	14.275	14.339	13.489	14.631	13.319	13.44	13.302
-19	19.537	24.1904	14.01	14.815	14.879	14.089	15.218	13.969	14.032	13.924
-18.5	20.046	24.7594	14.626	15.36	15.424	14.71	15.804	14.615	14.647	14.54
-18	20.562	25.3288	15.276	15.907	15.973	15.353	16.395	15.268	15.288	15.146
-17.5	21.086	25.9064	15.934	16.472	16.537	15.995	16.996	15.944	15.93	15.76
-17	21.62	26.4832	16.607	17.042	17.115	16.644	17.589	16.634	16.598	16.372
-16.5	22.154	27.0626	17.277	17.615	17.691	17.297	18.207	17.319	17.254	16.995
-16	22.695	27.6432	17.953	18.211	18.281	17.956	18.831	17.996	17.921	17.628
-15.5	23.247	28.2306	18.619	18.805	18.883	18.62	19.459	18.667	18.581	18.276
-15	23.795	28.8052	19.295	19.416	19.503	19.286	20.089	19.328	19.24	18.928
-14.5	24.355	29.3848	19.961	20.041	20.124	19.943	20.717	19.986	19.892	19.592
-14	24.919	29.96	20.622	20.666	20.759	20.599	21.353	20.631	20.548	20.237
-13.5	25.481	30.5314	21.302	21.299	21.397	21.254	21.987	21.28	21.209	20.878
-13	26.043	31.0948	21.971	21.941	22.044	21.908	22.625	21.937	21.883	21.545
-12.5	26.613	31.6462	22.63	22.581	22.684	22.567	23.265	22.596	22.528	22.209
-12	27.172	32.1876	23.292	23.213	23.317	23.216	23.911	23.247	23.175	22.878
-11.5	27.737	32.7176	23.95	23.854	23.962	23.866	24.552	23.896	23.824	23.554
-11	28.293	33.2396	24.613	24.495	24.611	24.509	25.189	24.551	24.475	24.233
-10.5	28.843	33.7354	25.271	25.13	25.264	25.15	25.826	25.205	25.122	24.91
-10	29.376	34.2142	25.917	25.759	25.919	25.774	26.458	25.843	25.759	25.575
-9.5	29.905	34.6656	26.578	26.386	26.571	26.407	27.082	26.485	26.402	26.239
-9	30.425	35.0894	27.234	27.005	27.206	27.034	27.699	27.119	27.027	26.897
-8.5	30.935	35.4872	27.88	27.614	27.823	27.636	28.305	27.734	27.653	27.562
-8	31.422	35.8528	28.496	28.209	28.425	28.23	28.903	28.335	28.258	28.202

-7.5	31.891	36.1936	29.108	28.801	29.018	28.81	29.485	28.931	28.843	28.822
-7	32.344	36.4984	29.701	29.376	29.604	29.375	30.059	29.503	29.411	29.441
-6.5	32.768	36.7846	30.283	29.935	30.175	29.926	30.611	30.066	29.97	30.038
-6	33.171	37.055	30.827	30.474	30.71	30.443	31.15	30.599	30.499	30.602
-5.5	33.552	37.335	31.359	30.989	31.228	30.94	31.654	31.12	31.018	31.142
-5	33.908	37.6352	31.88	31.472	31.719	31.426	32.142	31.617	31.497	31.667
-4.5	34.221	38.0222	32.373	31.95	32.197	31.901	32.621	32.102	31.97	32.176
-4	34.513	38.4984	32.865	32.431	32.673	32.376	33.105	32.587	32.43	32.66
-3.5	34.766	39.0796	33.353	32.896	33.126	32.856	33.594	33.06	32.874	33.122
-3	34.997	39.7058	33.852	33.362	33.558	33.333	34.09	33.53	33.306	33.592
-2.5	35.208	40.2874	34.354	33.866	34.041	33.824	34.607	34.015	33.747	34.085
-2	35.402	40.7458	34.875	34.398	34.558	34.35	35.133	34.508	34.208	34.581
-1.5	35.608	41.0772	35.394	34.94	35.074	34.892	35.652	35.029	34.691	35.114
-1	35.869	41.3334	35.891	35.466	35.674	35.455	36.184	35.562	35.222	35.653
-0.5	36.199	41.5332	36.375	36	36.258	36.016	36.728	36.097	35.772	36.182
0	36.618	41.6966	36.88	36.528	36.806	36.525	37.189	36.599	36.28	36.69
0.5	37.131	41.8518	37.33	36.997	37.332	37.021	37.624	37.088	36.74	37.161
1	37.691	41.9838	37.73	37.427	37.844	37.507	38.082	37.548	37.212	37.614
1.5	38.207	42.1208	38.159	37.833	38.297	37.919	38.403	37.963	37.677	37.988
2	38.663	42.257	38.514	38.177	38.699	38.29	38.72	38.332	38.065	38.344
2.5	39.007	42.3784	38.794	38.494	39.088	38.655	39.066	38.667	38.386	38.674
3	39.263	42.52	39.096	38.814	39.453	38.982	39.361	38.981	38.747	39.028
3.5	39.456	42.6664	39.41	39.119	39.766	39.265	39.594	39.284	39.04	39.345
4	39.651	42.806	39.643	39.377	40.076	39.558	39.87	39.574	39.3	39.651
4.5	39.823	42.9532	39.87	39.648	40.371	39.84	40.16	39.852	39.589	39.947
5	39.999	43.0866	40.125	39.914	40.625	40.087	40.36	40.101	39.854	40.214
5.5	40.157	43.2226	40.335	40.146	40.887	40.334	40.572	40.358	40.104	40.439
6	40.251	43.3672	40.489	40.391	41.159	40.593	40.814	40.573	40.341	40.655
6.5	40.374	43.4822	40.684	40.617	41.374	40.813	40.986	40.785	40.601	40.874
7	40.475	43.55	40.86	40.814	41.593	41.023	41.144	40.98	40.811	41.017
7.5	40.588	43.5846	40.965	41.039	41.79	41.254	41.36	41.159	40.991	41.174
8	40.694	43.5998	41.101	41.238	41.949	41.438	41.504	41.333	41.198	41.321
8.5	40.783	43.615	41.228	41.411	42.109	41.587	41.631	41.467	41.36	41.408
9	40.86	43.59	41.296	41.581	42.25	41.761	41.776	41.583	41.497	41.49
9.5	40.91	43.5136	41.366	41.714	42.352	41.861	41.857	41.68	41.601	41.563
10	40.957	43.3898	41.409	41.812	42.41	41.929	41.936	41.712	41.687	41.566
10.5	40.982	43.2482	41.411	41.913	42.457	42.037	41.997	41.771	41.762	41.567
11	40.984	43.097	41.382	41.916	42.447	42.026	41.984	41.726	41.743	41.545
11.5	40.96	42.9044	41.288	41.918	42.389	42.003	41.969	41.631	41.752	41.433
12	40.929	42.624	41.183	41.889	42.32	41.988	41.925	41.571	41.694	41.364
12.5	40.875	42.3398	41.026	41.784	42.178	41.848	41.809	41.412	41.58	41.208
13	40.781	42.0464	40.861	41.701	42.031	41.755	41.702	41.251	41.494	41.02
13.5	40.648	41.717	40.67	41.525	41.821	41.582	41.516	41.082	41.314	40.845

14	40.506	41.328	40.458	41.343	41.596	41.376	41.314	40.875	41.132	40.595
14.5	40.35	40.9	40.214	41.132	41.35	41.151	41.074	40.634	40.938	40.334
15	40.171	40.4848	39.944	40.844	41.053	40.879	40.795	40.357	40.659	40.037
15.5	39.941	40.0678	39.651	40.572	40.718	40.585	40.497	40.054	40.362	39.693
16	39.711	39.5914	39.344	40.242	40.36	40.241	40.164	39.739	40.048	39.347
16.5	39.454	39.0766	38.972	39.873	39.956	39.857	39.781	39.336	39.678	38.95
17	39.165	38.575	38.589	39.507	39.529	39.463	39.398	38.949	39.281	38.507
17.5	38.838	38.0798	38.196	39.118	39.11	39.05	38.977	38.552	38.892	38.072
18	38.482	37.548	37.756	38.696	38.618	38.593	38.559	38.06	38.449	37.625
18.5	38.135	36.9878	37.287	38.251	38.129	38.117	38.074	37.612	37.994	37.112
19	37.757	36.4288	36.835	37.805	37.64	37.642	37.601	37.134	37.546	36.614
19.5	37.346	35.8948	36.315	37.323	37.1	37.121	37.115	36.593	37.044	36.101
20	36.927	35.3474	35.794	36.847	36.599	36.611	36.613	36.096	36.545	35.54
20.5	36.517	34.7818	35.288	36.368	36.069	36.102	36.135	35.565	36.065	35.017
21	36.101	34.2144	34.743	35.836	35.503	35.548	35.618	34.986	35.523	34.469
21.5	35.651	33.6702	34.193	35.332	34.959	35.009	35.067	34.448	34.986	33.885
22	35.195	33.127	33.66	34.802	34.407	34.453	34.544	33.892	34.468	33.354
22.5	34.749	32.573	33.096	34.263	33.84	33.891	34.005	33.316	33.914	32.797
23	34.297	32.0198	32.542	33.741	33.268	33.336	33.472	32.753	33.376	32.216
23.5	33.833	31.482	32.004	33.208	32.711	32.775	32.938	32.187	32.826	31.661
24	33.359	30.9568	31.445	32.678	32.149	32.22	32.395	31.63	32.275	31.103
24.5	32.896	30.4246	30.91	32.136	31.585	31.67	31.865	31.056	31.738	30.564
25	32.426	29.894	30.37	31.606	31.038	31.111	31.326	30.493	31.194	30.019
25.5	31.959	29.3694	29.828	31.075	30.496	30.57	30.8	29.944	30.669	29.479
26	31.488	28.8668	29.297	30.55	29.958	30.04	30.28	29.396	30.135	28.947
26.5	31.013	28.3676	28.775	30.039	29.438	29.512	29.752	28.858	29.607	28.423
27	30.556	27.8706	28.253	29.518	28.912	28.991	29.238	28.322	29.087	27.934
27.5	30.093	27.3814	27.738	28.999	28.395	28.478	28.73	27.793	28.574	27.438
28	29.632	26.9048	27.235	28.495	27.881	27.98	28.228	27.275	28.071	26.932
28.5	29.163	26.44	26.736	28	27.384	27.473	27.73	26.768	27.569	26.446
29	28.696	25.977	26.247	27.502	26.881	26.98	27.243	26.268	27.075	25.98
29.5	28.248	25.5182	25.767	27.005	26.387	26.486	26.753	25.777	26.581	25.524
30	27.797	25.0662	25.293	26.515	25.906	26.006	26.272	25.296	26.09	25.056
30.5	27.349	24.6374	24.827	26.042	25.442	25.539	25.804	24.828	25.619	24.615
31	26.908	24.2158	24.379	25.567	24.974	25.082	25.338	24.362	25.147	24.199
31.5	26.48	23.7962	23.942	25.108	24.514	24.635	24.877	23.922	24.685	23.783
32	26.059	23.3848	23.513	24.657	24.068	24.19	24.434	23.488	24.235	23.372
32.5	25.646	22.987	23.095	24.214	23.648	23.766	23.999	23.067	23.806	22.986
33	25.239	22.597	22.697	23.786	23.22	23.358	23.579	22.654	23.38	22.608
33.5	24.827	22.2102	22.315	23.365	22.803	22.961	23.173	22.266	22.961	22.232
34	24.424	21.8292	21.931	22.951	22.409	22.567	22.775	21.879	22.565	21.88
34.5	24.029	21.4538	21.56	22.555	22.01	22.183	22.381	21.504	22.159	21.539
35	23.637	21.0914	21.209	22.16	21.626	21.816	21.999	21.141	21.781	21.204

35.5	23.252	20.7322	20.86	21.776	21.249	21.446	21.626	20.788	21.393	20.869
36	22.862	20.379	20.525	21.404	20.887	21.091	21.255	20.44	21.033	20.561
36.5	22.493	20.0278	20.198	21.029	20.527	20.742	20.902	20.102	20.67	20.249
37	22.127	19.6882	19.879	20.683	20.172	20.416	20.554	19.772	20.328	19.944
37.5	21.768	19.3538	19.569	20.336	19.831	20.087	20.214	19.454	19.981	19.652
38	21.417	19.03	19.273	19.999	19.503	19.761	19.888	19.147	19.653	19.372
38.5	21.082	18.7088	18.982	19.669	19.183	19.457	19.577	18.849	19.331	19.107
39	20.752	18.3978	18.707	19.349	18.87	19.163	19.262	18.562	19.02	18.835
39.5	20.437	18.0908	18.439	19.04	18.573	18.87	18.958	18.283	18.712	18.571
40	20.123	17.7928	18.187	18.738	18.286	18.595	18.673	18.011	18.425	18.324
40.5	19.821	17.5006	17.939	18.448	18.003	18.322	18.398	17.753	18.146	18.081
41	19.522	17.2136	17.697	18.175	17.729	18.064	18.121	17.503	17.871	17.836
41.5	19.234	16.9316	17.46	17.901	17.466	17.797	17.851	17.259	17.604	17.604
42	18.95	16.656	17.23	17.633	17.21	17.549	17.602	17.02	17.351	17.37
42.5	18.674	16.3872	17.01	17.377	16.957	17.308	17.353	16.788	17.101	17.15
43	18.407	16.1264	16.798	17.128	16.719	17.076	17.109	16.567	16.858	16.935
43.5	18.152	15.8638	16.591	16.877	16.481	16.841	16.867	16.346	16.624	16.716
44	17.907	15.6124	16.384	16.652	16.255	16.621	16.644	16.134	16.393	16.512
44.5	17.665	15.361	16.182	16.429	16.033	16.404	16.418	15.933	16.164	16.298
45	17.436	15.114	15.996	16.207	15.819	16.177	16.199	15.73	15.946	16.097
45.5	17.213	14.8778	15.804	15.991	15.612	15.973	15.988	15.537	15.738	15.901
46	16.994	14.6424	15.619	15.787	15.403	15.771	15.786	15.353	15.539	15.715
46.5	16.781	14.4138	15.447	15.591	15.209	15.579	15.584	15.17	15.342	15.532
47	16.574	14.1902	15.27	15.394	15.021	15.379	15.39	14.994	15.15	15.342
47.5	16.376	13.9716	15.098	15.199	14.835	15.194	15.2	14.82	14.965	15.163
48	16.179	13.7578	14.928	15.015	14.651	15.014	15.015	14.648	14.778	14.985
48.5	15.983	13.55	14.762	14.828	14.474	14.837	14.829	14.487	14.6	14.807
49	15.793	13.3428	14.601	14.655	14.305	14.659	14.646	14.328	14.423	14.636
49.5	15.611	13.1432	14.444	14.48	14.138	14.491	14.471	14.17	14.246	14.467
50	15.424	12.9486	14.286	14.309	13.975	14.326	14.304	14.018	14.087	14.306
50.5	15.249	12.7592	14.138	14.144	13.816	14.155	14.135	13.871	13.927	14.14
51	15.074	12.572	13.988	13.981	13.662	13.997	13.974	13.728	13.771	13.983
51.5	14.902	12.3892	13.845	13.823	13.512	13.838	13.809	13.585	13.613	13.828
52	14.732	12.2094	13.694	13.664	13.369	13.683	13.656	13.453	13.465	13.671
52.5	14.574	12.0314	13.562	13.514	13.22	13.53	13.501	13.318	13.317	13.521
53	14.408	11.8592	13.426	13.364	13.075	13.384	13.352	13.184	13.168	13.378
53.5	14.255	11.6924	13.295	13.222	12.944	13.237	13.205	13.055	13.025	13.234
54	14.099	11.5252	13.16	13.076	12.807	13.094	13.062	12.93	12.893	13.094
54.5	13.949	11.3646	13.038	12.938	12.672	12.956	12.917	12.807	12.751	12.958
55	13.801	11.2036	12.907	12.801	12.541	12.821	12.781	12.689	12.615	12.82
55.5	13.651	11.0474	12.782	12.675	12.419	12.686	12.65	12.572	12.492	12.689
56	13.512	10.8976	12.664	12.543	12.296	12.552	12.515	12.455	12.358	12.558
56.5	13.374	10.7466	12.544	12.416	12.173	12.425	12.386	12.343	12.23	12.431

57	13.232	10.6008	12.423	12.289	12.056	12.298	12.264	12.235	12.112	12.307
57.5	13.101	10.459	12.309	12.16	11.938	12.173	12.14	12.127	11.993	12.182
58	12.966	10.3162	12.193	12.044	11.815	12.054	12.023	12.023	11.874	12.062
58.5	12.835	10.175	12.086	11.925	11.712	11.928	11.903	11.917	11.754	11.94
59	12.705	10.0444	11.973	11.812	11.598	11.816	11.792	11.811	11.647	11.823
59.5	12.585	9.9114	11.864	11.696	11.489	11.701	11.673	11.709	11.528	11.708
60	12.459	9.7804	11.76	11.577	11.384	11.584	11.564	11.609	11.424	11.598
60.5	12.339	9.6564	11.65	11.471	11.273	11.476	11.449	11.513	11.313	11.493
61	12.221	9.5316	11.552	11.361	11.175	11.37	11.339	11.416	11.209	11.378
61.5	12.101	9.4076	11.456	11.256	11.065	11.261	11.231	11.32	11.107	11.274
62	11.989	9.288	11.35	11.146	10.97	11.164	11.128	11.228	11.002	11.173
62.5	11.871	9.17	11.249	11.047	10.864	11.055	11.023	11.137	10.902	11.07
63	11.761	9.0552	11.155	10.952	10.765	10.955	10.92	11.044	10.804	10.966
63.5	11.644	8.9432	11.06	10.843	10.676	10.85	10.821	10.958	10.706	10.869
64	11.535	8.8324	10.968	10.746	10.579	10.762	10.726	10.866	10.617	10.771
64.5	11.426	8.7246	10.872	10.652	10.489	10.66	10.635	10.778	10.52	10.679
65	11.325	8.6174	10.785	10.546	10.394	10.571	10.54	10.691	10.43	10.582
65.5	11.22	8.5152	10.693	10.466	10.305	10.475	10.447	10.609	10.343	10.493
66	11.118	8.4128	10.612	10.368	10.217	10.383	10.356	10.523	10.252	10.403
66.5	11.017	8.3104	10.526	10.281	10.129	10.295	10.266	10.442	10.167	10.315
67	10.917	8.2126	10.437	10.194	10.049	10.205	10.177	10.358	10.087	10.233
67.5	10.826	8.1154	10.356	10.108	9.97	10.121	10.096	10.28	9.996	10.149
68	10.727	8.0182	10.277	10.023	9.878	10.037	10.006	10.2	9.92	10.064
68.5	10.638	7.9254	10.194	9.936	9.803	9.954	9.921	10.127	9.84	9.979
69	10.545	7.8394	10.12	9.854	9.723	9.871	9.846	10.041	9.754	9.898
69.5	10.453	7.7482	10.038	9.767	9.641	9.789	9.76	9.963	9.68	9.813
70	10.367	7.661	9.966	9.687	9.563	9.71	9.683	9.889	9.6	9.738
70.5	10.281	7.5776	9.885	9.616	9.489	9.628	9.605	9.811	9.527	9.658
71	10.188	7.4916	9.816	9.539	9.409	9.549	9.527	9.739	9.45	9.595
71.5	10.105	7.411	9.743	9.464	9.34	9.476	9.453	9.671	9.38	9.52
72	10.018	7.333	9.67	9.382	9.267	9.402	9.378	9.592	9.307	9.45
72.5	9.932	7.2496	9.601	9.31	9.194	9.328	9.306	9.524	9.24	9.374
73	9.848	7.1764	9.527	9.246	9.119	9.256	9.236	9.452	9.17	9.3
73.5	9.766	7.1032	9.467	9.167	9.053	9.183	9.165	9.384	9.096	9.235
74	9.691	7.0248	9.401	9.095	8.984	9.111	9.094	9.314	9.028	9.163
74.5	9.611	6.9554	9.336	9.026	8.914	9.043	9.03	9.249	8.958	9.098
75	9.53	6.8808	9.272	8.959	8.846	8.974	8.956	9.189	8.891	9.034
75.5	9.455	6.8098	9.206	8.888	8.787	8.906	8.89	9.114	8.824	8.967
76	9.383	6.7422	9.145	8.822	8.719	8.843	8.822	9.049	8.761	8.904
76.5	9.309	6.6714	9.089	8.753	8.656	8.774	8.763	8.987	8.698	8.837
77	9.237	6.6072	9.028	8.692	8.59	8.708	8.693	8.923	8.634	8.775
77.5	9.16	6.5414	8.966	8.627	8.529	8.656	8.641	8.862	8.574	8.714
78	9.091	6.476	8.903	8.565	8.465	8.591	8.573	8.797	8.516	8.646

78.5	9.018	6.4136	8.843	8.501	8.397	8.529	8.515	8.741	8.452	8.587
79	8.948	6.3492	8.794	8.443	8.34	8.466	8.454	8.684	8.4	8.528
79.5	8.885	6.2868	8.73	8.375	8.283	8.4	8.393	8.62	8.332	8.47
80	8.812	6.2278	8.674	8.315	8.223	8.348	8.334	8.561	8.271	8.407
80.5	8.743	6.1718	8.615	8.255	8.162	8.288	8.278	8.504	8.214	8.349
81	8.679	6.1134	8.568	8.2	8.107	8.228	8.217	8.445	8.158	8.298
81.5	8.613	6.056	8.506	8.144	8.053	8.172	8.162	8.388	8.105	8.236
82	8.547	6.0018	8.453	8.083	7.992	8.118	8.105	8.332	8.047	8.187
82.5	8.487	5.9448	8.401	8.029	7.944	8.061	8.048	8.277	8.001	8.13
83	8.42	5.8916	8.35	7.975	7.881	8.014	7.997	8.219	7.94	8.08
83.5	8.359	5.8398	8.298	7.921	7.83	7.957	7.944	8.17	7.885	8.027
84	8.298	5.7894	8.242	7.865	7.778	7.9	7.888	8.115	7.833	7.975
84.5	8.235	5.7346	8.194	7.813	7.723	7.852	7.837	8.066	7.781	7.92
85	8.17	5.684	8.142	7.764	7.673	7.801	7.784	8.012	7.727	7.866

6.2.2 Differential Heat Release Rate (DHRR)

Table AD.3 DHHR for Diesel, PHSVO 90 and PHSVO 90 with Different Hydrogen Supplementations

CA	PHSVO 90	Diesel	0.3 H2	0.4 H2	0.5 H2	0.6 H2	0.7 H2	0.8 H2	0.9 H2	1.0 H2
-19	0.383	3.5	2.721	3.96	2.148	2.132	3.383	3.219	2.675	3.572
-18	0.194	2.996	2.362	3.858	2.019	2.071	3.21	2.905	2.755	3.675
-17	0.056	2.607	2.17	3.718	1.889	1.984	3.025	2.56	2.391	3.901
-16	-0.358	2.044	2.004	3.25	1.476	1.606	2.563	1.974	2.226	3.504
-15	-0.805	1.453	1.583	2.722	1.044	1.21	2.083	1.36	2.088	3.286
-14	-1.022	1.061	1.104	2.433	0.862	1.023	1.802	1.008	1.697	3.07
-13	-0.916	1.014	0.837	2.406	0.984	1.123	1.803	1.047	1.326	2.559
-12	-1.465	0.347	0.896	1.78	0.587	0.627	1.236	0.572	1.179	1.979
-11	-1.759	-0.087	0.387	1.426	0.483	0.362	0.899	0.352	1.306	1.594
-10	-2.048	-0.532	0.134	1.019	0.305	0.071	0.523	0.106	0.833	1.546
-9	-2.349	-1.004	-0.164	0.539	0.031	-0.256	0.138	-0.199	0.567	0.946
-8	-2.656	-1.395	-0.506	0.113	-0.232	-0.579	-0.101	-0.474	0.242	0.55
-7	-3.302	-1.771	-0.801	-0.481	-0.878	-1.225	-0.475	-0.902	-0.128	0.148
-6	-2.925	-0.328	-1.404	0.204	-0.594	-0.908	0.316	-0.114	-0.456	-0.222
-5	-2.14	2.462	-0.922	1.593	0.087	-0.352	1.557	1.335	-0.986	-0.512
-4	0.061	6.363	0.065	4.077	1.912	1.231	3.858	3.908	-0.386	-0.992
-3	3.597	9.865	2.276	7.017	4.757	4.028	6.836	6.733	0.512	-0.252
-2	7.356	12.537	5.53	9.628	8.051	7.559	9.426	9.07	2.337	1.049
-1	10.418	14.347	8.936	11.713	11.316	11.065	11.364	11.034	5.114	3.464
0	15.566	17.448	11.674	16.197	17.268	17.151	16.044	15.124	8.267	6.5
1	16.955	17.581	16.776	16.93	19.175	19.296	17.364	15.391	11.155	9.24
2	17.126	18.816	17.961	17.537	19.978	20.298	18.055	15.827	16.407	11.407
3	17.382	21.329	18.08	18.834	20.693	20.864	19.29	17.197	17.873	16.021
4	18.923	24.16	18.306	20.539	21.777	21.715	21.357	18.795	18.676	16.88
5	21.222	26.9	19.594	22.205	23.273	23.217	23.232	20.522	19.396	17.261
6	23.502	29.055	21.324	23.744	25.28	25.208	24.609	22.437	20.432	18.28
7	26.31	31.085	22.946	25.526	28.061	27.634	26.323	24.516	22.183	19.869
8	27.919	31.617	25.151	25.974	29.519	28.67	26.84	25.179	24.463	21.574
9	29.564	32.46	26.068	26.754	31.134	30.093	27.576	26.109	27.063	23.292
10	30.771	33.051	27.041	27.335	32.422	31.166	28.027	26.681	28.245	25.292
11	31.649	33.469	27.84	27.774	33.311	31.852	28.407	27.032	29.773	25.883
12	32.181	33.912	28.578	28.035	33.969	32.4	28.539	27.124	30.885	26.794
13	31.775	33.178	28.948	27.436	33.72	32.091	27.779	26.246	31.556	27.489
14	32.061	33.214	28.495	27.558	34.132	32.292	27.639	26.029	31.885	27.954
15	31.538	32.313	28.769	26.967	33.623	31.559	26.828	25.159	31.282	28.283
16	30.262	30.568	28.157	25.664	32.146	30.147	25.279	23.483	31.306	27.934
17	28.908	28.713	26.767	24.248	30.422	28.56	23.706	21.722	30.477	28.287
18	28.069	27.394	25.314	23.354	29.153	27.43	22.846	20.659	28.909	27.851

19	27.347	26.121	24.383	22.527	27.838	26.39	22.198	19.842	27.214	26.733
20	26.266	24.45	23.493	21.352	26.076	25.015	21.317	18.703	26.107	25.548
21	25.701	23.56	22.276	20.731	25	24.164	20.959	18.103	25.034	24.807
22	25.079	22.556	21.52	20.282	23.917	23.333	20.882	17.769	23.662	24.126
23	24.078	21.462	20.904	19.658	22.519	22.188	20.497	17.057	22.788	23.031
24	22.709	20.002	20.023	18.812	20.93	20.653	19.897	16.115	21.954	22.305
25	22.168	19.669	18.957	18.924	20.308	20.079	20.227	16.073	20.815	21.74
26	21.631	19.156	18.916	19.133	19.676	19.537	20.743	16.098	19.346	20.906
27	20.408	17.947	18.952	18.779	18.325	18.512	20.635	15.591	18.804	19.955
28	19.698	17.171	18.501	18.925	17.532	18.224	20.994	15.759	18.228	20.062
29	19.425	16.966	18.675	19.561	17.183	18.493	21.728	16.571	17.069	20.393
30	18.873	16.608	19.434	19.985	16.72	18.73	22.072	17.301	16.365	20.203
31	18.015	15.994	19.977	20.059	16.3	18.895	22.084	17.95	16.251	20.492
32	17.47	15.803	20.334	20.345	16.545	19.524	22.359	18.978	16.162	21.179
33	16.838	15.515	21.125	20.541	17.037	20.121	22.51	19.929	16.131	21.558
34	16.021	14.912	21.827	20.38	17.632	20.514	22.314	20.493	16.72	21.569
35	15.798	14.517	22.15	20.524	18.948	21.266	22.428	21.312	17.521	21.737
36	15.788	14.045	22.807	20.754	20.332	21.956	22.5	22.085	18.179	21.852
37	15.426	13.834	23.444	20.489	21.199	22.041	21.998	22.284	19.103	21.639
38	15.522	13.653	23.366	20.532	22.283	22.332	21.817	22.656	19.978	21.704
39	15.954	13.615	23.55	20.863	23.326	22.762	21.923	23.158	20.281	21.783
40	16.209	13.872	23.929	20.853	23.775	22.782	21.782	23.298	20.848	21.382
41	16.609	14.175	23.942	20.802	23.934	22.81	21.609	23.262	21.563	21.292
42	17.152	14.611	23.922	20.767	23.957	22.865	21.418	23.125	21.81	21.418
43	17.788	15.157	23.903	20.665	23.971	22.934	21.251	22.982	22.008	21.285
44	18.121	15.634	23.893	20.592	23.934	23.036	21.103	22.82	22.114	21.135
45	18.445	16.092	23.778	20.37	23.604	22.998	20.682	22.443	22.086	20.969
46	18.622	16.439	23.354	20.062	23.384	22.958	20.284	22.215	22.115	20.806
47	18.583	16.558	23.015	19.904	23.417	23.068	20.23	21.933	22.022	20.697
48	18.566	16.656	22.989	19.585	23.17	22.927	19.954	21.772	21.902	20.32
49	18.53	16.658	22.643	19.391	23.128	22.94	19.786	21.639	21.987	19.949
50	18.379	16.555	22.504	19.15	23.028	22.851	19.548	21.473	22.065	19.888
51	18.269	16.397	22.265	18.929	23.029	22.763	19.351	21.378	22.244	19.563
52	18.147	16.247	22.099	18.774	23.055	22.786	19.172	21.34	22.304	19.417
53	17.954	15.997	21.974	18.565	23.037	22.8	18.936	21.344	22.392	19.156
54	17.794	15.725	21.774	18.369	23.096	22.927	18.758	21.514	22.593	18.935
55	17.61	15.393	21.66	18.176	23.22	23.249	18.628	21.855	22.801	18.766
56	17.418	15.153	21.625	18.051	23.435	23.68	18.527	22.457	23.157	18.501
57	17.235	14.887	21.613	17.948	23.771	24.204	18.498	23.288	23.698	18.302
58	16.923	14.509	21.676	17.786	24.022	24.684	18.365	24.126	24.376	18.177
59	16.637	14.294	21.735	17.745	24.366	25.18	18.4	25.058	25.102	18.061
60	16.334	13.97	21.962	17.679	24.597	25.465	18.429	25.784	25.725	18.04
61	15.947	13.558	22.273	17.617	24.625	25.523	18.452	26.189	26.287	17.981

62	15.692	13.274	22.608	17.772	24.68	25.53	18.688	26.462	26.623	18.027
63	15.54	13.083	23.13	18.13	24.718	25.51	19.043	26.608	26.743	18.083
64	15.247	12.792	23.677	18.507	24.552	25.268	19.362	26.44	26.815	18.129
65	15.151	12.664	23.982	19.219	24.515	25.156	19.94	26.411	26.836	18.321
66	14.961	12.47	24.354	19.963	24.418	25.015	20.497	26.268	26.652	18.683
67	14.54	12.178	24.457	20.554	24.081	24.584	20.853	25.894	26.58	19.023
68	14.296	12.015	24.297	21.274	23.891	24.366	21.412	25.774	26.397	19.548
69	13.855	11.696	24.311	21.689	23.444	23.979	21.603	25.445	26.025	20.064
70	13.442	11.487	24.034	21.952	23.05	23.628	21.747	25.237	25.91	20.355
71	13.158	11.281	23.808	22.101	22.598	23.341	21.798	25.032	25.49	20.696
72	12.86	11.022	23.658	22.083	22.188	23.058	21.723	24.805	25.183	20.797
73	12.629	10.902	23.375	22.083	21.88	22.807	21.617	24.613	24.931	20.851
74	12.415	10.599	23.159	21.953	21.449	22.44	21.43	24.331	24.545	20.831
75	12.123	10.335	22.915	21.845	21.132	22.101	21.225	23.992	24.275	20.79
76	11.744	10.059	22.553	21.627	20.724	21.587	20.879	23.616	23.997	20.758
77	11.395	9.754	22.152	21.341	20.221	21.079	20.588	23.144	23.666	20.608
78	11.012	9.562	21.729	21.047	19.82	20.602	20.268	22.666	23.214	20.431
79	10.63	9.257	21.29	20.69	19.421	20.111	19.964	22.276	22.861	20.188
80	10.319	8.964	20.863	20.413	18.937	19.671	19.717	21.86	22.415	19.879
81	9.925	8.654	20.519	20.143	18.575	19.278	19.516	21.565	21.978	19.664
82	9.537	8.305	20.186	19.861	18.183	18.942	19.297	21.336	21.616	19.406
83	9.208	7.932	19.927	19.552	17.702	18.554	19.069	21.014	21.212	19.136
84	8.88	7.728	19.617	19.248	17.318	18.216	18.725	20.679	20.806	18.852
85	8.621	7.463	19.231	18.8	16.85	17.799	18.226	20.272	20.38	18.57

References- Appendix-D

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Appendix-E

PHOTOGRAPHS OF EXPERIMENTAL SET UP

Figure AE.1 Experimental Test Bench

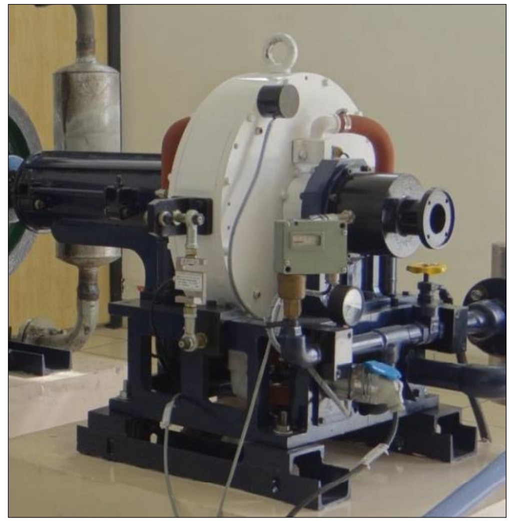

Figure AE.2 IDI diesel engine **Figure AE.3 Eddy current dynamometer**

Figure AE.4 Heat exchanger **Figure AE.5 Rack control mechanism**

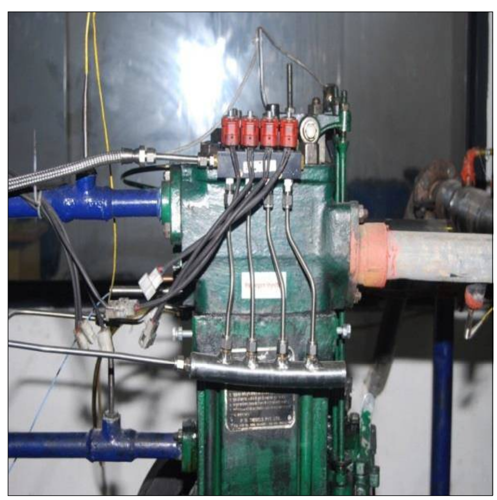

Figure AE.6 Development of self starting system **Figure AE.7 Gaseous hydrogen injector**

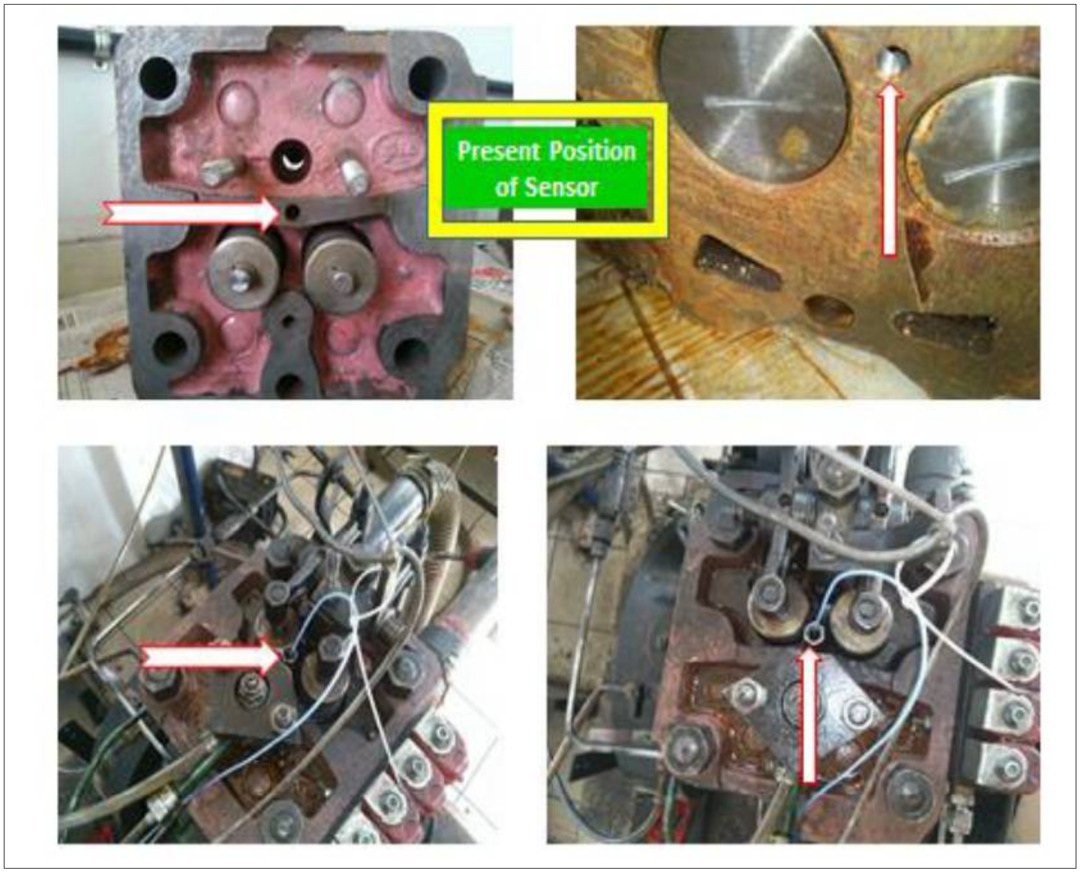

Figure AE.8 Position of piezo electric transducer

Figure AE.9 Fuel characterization laboratory

As per Class 1, Division 2, Group B of NFPA Standards

Figure AE.10 Luminaries

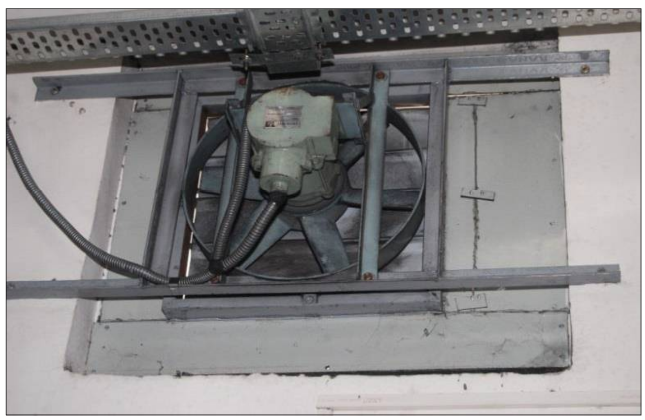

Figure AE.11 Exhaust fan

Figure AE.11 Switches

As per Class 1, Division 2, Group B of NFPA Standards

Figure AE.12 Hydrogen gas detecting sensor

Figure AE.13 Hydrogen gas monitoring system

Figure AE.14 Alarm cum Hooter

As per Class 1, Division 2, Group B of NFPA Standards

Figure AE.15 Hydrogen storage area