International Journal
of
Automobile Engineering

E-ISSN: 2707-8213
P-ISSN: 2707-8205
www.mechanicaljournals.com/ijae
IJAE 2024; 5(1): 16-27
Received: 13-11-2023
Accepted: 20-12-2023

H2 ice-hydrogen internal combustion engine

Ankit Mehta, Bivas Bhattacharyya, Arnab Dasgupta and Rahul Kumar

Ankit Mehta
Team Lead - Design, ER&D
TML, Tata Technologies, Pune
Maharashtra, India

Bivas Bhattacharyya
Seinor Team Lead-
Engineering, ER&D TML,
Tata Technologies, Pune
Maharashtra, India

Arnab Dasgupta
Project Manager, ER&D TML,
Tata Technologies, Pune
Maharashtra, India

Rahul Kumar
Program Manager, ER&D
TML, Tata Technologies, Pune
Maharashtra, India

Corresponding Author:
Ankit Mehta
Team Lead - Design, ER&D
TML, Tata Technologies, Pune
Maharashtra, India

Abstract

Today we are facing two major challenges, first is global climate change and second is that of energy security concerns. Since we are entirely dependent on crude oil imports it has been one of the biggest challenge for our country. Volatility in crude oil prices adversely impacts global economy. In order to meet these challenges alternative solutions are required which can run on renewable and clean source of energy. Battery Electric Vehicle and Fuel Cell Electric Vehicles are solutions but which require complete design change and change of technology. Battery operated vehicles makes use of electricity stored in rechargeable high voltage battery that powers electric motor and power train for movement of vehicle. Fuel Cell Electric Vehicles also runs on similar concept, but battery is powered by hydrogen. Both these solution result in vehicles with zero CO_2 emissions, these requires considerable design change in current vehicle architecture which will required large investment for new technology and also infrastructure for its production and after sales service. Electrification of Commercial vehicles is not viable solution as it requires large batteries thereby reducing capacity to carry goods. Application of hydrogen as fuel in Internal Combustion Engines is one of best options which requires no major changes in current technology and infrastructure. This paper includes detailed literature on properties of hydrogen as fuel, H2ICE Engine Design requirements, H2ICE Fuel Injection Systems, improving efficiency of H2ICE, conversion of conventional engines, challenges, advantages and current developments in field of hydrogen based internal combustion engines.

Keywords: Hydrogen, internal combustion engine, combustion, H2 ICE, zero CO_2 emission

Introduction

Climate Change is one of biggest challenge in today's world. It has become quintessential that every country takes this crisis seriously otherwise it may cause havoc in near future. Automobiles are one of the major contributor towards environment pollution. Additionally there is an increased concern of energy security due to reliance for its imports from unstable regions of the world. In order to address aforementioned concerns automobile sector has come up with electrification of vehicles thereby reducing direct greenhouse gas emissions and reduction of dependency on fossil fuels.

But electrification has its limitations in terms range, increase in weight and lack of charging infrastructures. These are some of the shortcomings which makes its implementation in Medium and Heavy Commercial vehicles further difficult. Since commercial vehicles finds it application in various sectors such as construction, agriculture, e-commerce, etc. therefore technology to run these vehicles needs to be more robust and flexible. Other alternative is to use Fuel Cell Electric Vehicle technology where pure hydrogen is used to power the batteries which in turn drives electric motor to propel the Vehicle forward. Hydrogen Fuel Cell technology is expensive and large batteries will be required to store the electricity generated. In heavy commercial vehicles where we have near zero emission alternative solutions such as Battery Electric Vehicle, Fuel Cell Electric Vehicle, Biofuel based Engines etc., hydrogen based ICE engines is best suitable technology to meet current challenges.

Application of Hydrogen in vehicle is also supported by Indian Government initiative like - The National Green Hydrogen Mission, which was approved on 4th January 2022, with intended objective of making India a leading producer and supplier of Green Hydrogen (carbon emissions is minimal as it utilizes renewable source of energy for hydrogen extraction when compared to Grey and Blue Hydrogen) in the world.

Application of H2 ICE in commercial vehicle [4, 5] releases trace amounts of NOx during combustion, along with minimal particulate matter as air pollutants, this can be reduced by selecting a suitable after treatment system. Application of advanced SCR (Selective Catalytic Reduction) [6] catalysts and particulate filters in exhaust system will result in zero emissions from vehicles.

On board availability of hydrogen as reducing agent can also be utilized to reduce oxides of nitrogen to nitrogen and water.

Properties of hydrogen: Fuel

The properties of hydrogen that makes it an ideal alternative fuel [7] are as given below: Wide Range of Flammability Hydrogen, in comparison to all other fuels, has a wide flammability range thereby providing wide range of fuel-air mixture in internal combustion engines for combustion. It means hydrogen powered IC engines can run on lean mixture, *viz*. a mixture in which the amount of fuel is less than the theoretical, stoichiometric or chemically ideal amount required for combustion with a given amount of air. Engine running on lean mix has an added advantage of fuel economy as it enable complete combustion of the fuel. The final combustion temperature is considerably lower, reducing the amount of pollutants being emitted from exhaust [8]. This is also raises concerns about handling and storage of hydrogen. Output power limits the amount of lean mixture that can be used in engine.

Low Ignition Energy

Hydrogen requires very less amount of energy for ignition. This enables use of lean mixtures and prompt ignition in hydrogen powered engines [9-11]. It can adversely cause premature ignition and flashback as hydrogen may get ignited through hot spots and hot gases present in the cylinder.

Small Quenching Distance

The perpendicular distance from wall where flame gets extinguished, or the gap between two parallel plates, or diameter of tube in which the flame is just able to propagate under given charge conditions, is called quench distance. Hydrogen has small quenching distance thereby making it difficult to extinguish hydrogen flame. It also the reason why hydrogen flames travels closer to cylinder walls in comparison to other fuels. This has an adverse impact of backfire because flame from a hydrogen-air mixture can more readily pass through a nearly closed air intake valves.

High Auto Ignition Temperatures

Auto ignition temperature is a temperature at which the fuel spontaneously ignites in a normal atmosphere without requirement of any external source of ignition such as spark or flame.

Auto Ignition Temperature of hydrogen is relatively very high. Auto ignition temperature is an important factor for determining compression ratio to be used in engine.

The relationship between temperatures - compression ratio is given by equation considering adiabatic process as shown in below formula:

$$T_2 = T_1 \left(\frac{\boldsymbol{V}_1}{\boldsymbol{V}_2}\right)^{\boldsymbol{\gamma-1}}$$

Where

V1/V2 = the compression ratio, The compression ratio is defined as the ratio between the volume of the cylinder with the piston in the bottom position, V1 (largest volume), and in the top position, V2 (smallest volume).

T1 = absolute initial temperature T2 = absolute final temperature.

γ = ratio of specific heats, defined as the ratio of the specific heat of the gas at a constant pressure (Cp) to its specific heat at a constant volume (Cv).

Hence in order to prevent premature ignition, it is achieved by limiting the compression ratio. This also shows that hydrogen cannot be used in Compression Ignition arrangement as temperature required for this type of ignition is relatively high.

High Flame Speed

Hydrogen flame speed is quite faster in comparison to other fuels. This makes hydrogen ideal fuel as it can easily approach ideal engine cycle. Although lean mixtures of fuel decreases the flame velocity significantly.

High Diffusivity

Hydrogen is an ideal fuel as it has diffusivity rate [12]. It has the ability to disperse and form a uniform mixture with air. Ensuring safety of vehicle during leakage is easy as it completely and quickly spreads and mixes into the atmosphere.

Low density

Hydrogen has very low density which makes it difficult for storage and reduces its energy density. Due to its low density large amounts of hydrogen storage is required for providing vehicle with adequate driving ranges. This further impacts vehicle output for each unit of fuel burnt [13].

Table 1: Hydrogen properties compared with compressed petrol and diesel [14-18]

Properties	Hydrogen	Petrol	Diesel
Carbon content (mass %)	0	84	86
Lower heating Value (MJ/kg)	119.7	44.8	42.5
Density (at 1bar, 273K) (kg/m3)	0.089	730-780	830
Volumetric Energy Content (at 1bar, 273K) (MJ/m3)	10.7	33X103	35X103
Molecular Weight	2.016	~110	~170
Boiling Point (at 1 bar) (in K)	20	298–488	453–633
Auto-ignition temperature (in K)	858	~623	~523
Minimum ignition energy in air (at 1 bar, at stoichiometry) (in mJ)	0.02	0.24	0.24
Stoichiometric air/fuel mass ratio	34.5	14.7	14.5
Quenching distance (at 1 bar, at 298K, at stoichiometry) (mm)	0.64	~2	-
Laminar flame speed in air (at 1 bar, at 298K, at stoichiometry) (m/s)	1.85	0.37–0.43	0.37–0.43
Diffusion coefficient in air (at 1bar, 273K) (m2/s)	8.5 × 10−6	-	-
Flammability limits in air (vol %)	4–76	1–7.6	0.6–5.5

Hydrogen as Fuel: Engine Design

Study on properties of hydrogen shows major areas of concerns in choosing the design of engine for use of hydrogen as a fuel. To overcome this we require certain solutions and decision whether to use a SI Engine design (Spark-Ignition) or CI Engine design (Compression Ignition). In CI engines, during intake air enters into combustion chamber and it is compressed up to auto ignition temperature of the fuel, post which fuel is injected which immediately ignites and burns rapidly resulting in power stroke. In SI engines, during intake stroke air –fuel mixture enters combustion chamber and it is compressed up to a much lower temperature and pressure as it is ignited using an ignition system that sends spark through high voltage spark plug and leads to ignition of air –fuel mixture.

SI engines are less expensive and have lower emissions of pollutants [10, 14, 22-23]. Some advantages of using hydrogen as fuel in SI engines are optimized and improved combustion process due to its high flame speed, low ignition energy and wide flammability range. Methods of employing hydrogen as fuel in SI engines:

- **Manifold induction:** Hydrogen at low temperature is injected into the manifold through valve controlled duct.
- **Direct Introduction:** Hydrogen is stored in liquid form in cryogenic tanks. Liquid hydrogen is vaporized by passing it through heat exchanger and then cold hydrogen is injected into the engine. Cold hydrogen reduces formation of oxides of nitrogen and pre-ignition is avoided.
- **Hydrogen addition to petrol:** In this method hydrogen is added to petrol and mixture is introduced into combustion chamber. Then mixture is ignited using a spark from spark plug.

Due to its wide flammability range lean mixture of hydrogen can be used and it results in combustion at low temperatures. This results in lower heat transfer to walls, higher engine efficiency and lower of oxides of nitrogen emissions. This is an important benefit of hydrogen fueled SI engines.

However there may be chances of pre-mature ignition and back firing in engines when using hydrogen as a fuel due to its low ignition energy. This can be solved using a non-platinum cold rated spark plug. This is because platinum results in unwanted catalytic response with hydrogen and air mixture. Also, cold rated spark plug will ensure that there is no pre-ignition or backfiring due to hotspots [19].

CI engines may be an ideal approach as it eliminates the requirement for ignition system that is spark plug. But since quenching distance of hydrogen is small and laminar flame speed is high there is increased propensity of flame backfiring into intake manifold. This can eliminated by optimizing design of engine geometry thereby reducing heat losses from combustion chamber and pre-mature ignition cases [20, 21].

There are also advantages of unique physical and thermo-physical properties of hydrogen which facilitates in design of highly efficient Internal Combustion Engines. Hydrogen has high diffusivity which makes dispersion of hydrogen faster compared to other fuels and also promote in-cylinder mixing of air-fuel. Wide flammability and high flame speed makes it ideal to be used as lean mixture thereby improving thermal efficiency. Wide flammability limits also supports the use of exhaust gas recirculation for reduction in oxides of nitrogen which may be result of engine running at lean mixtures.

Additional measures that can be taken in engine design is to use effective scavenging system meaning complete replacement of exhaust gas from combustion chamber with fresh air. Hence it can be concluded that CI Engine design with optimized geometry and certain additional measures can be applied for hydrogen based engine development.

Hydrogen as fuel: fuel injection systems

The primary problem of application of hydrogen as fuel in engines is that of premature ignition because of its lower ignition energy, wider flammability range and shorter quenching distance. Premature ignition is a condition in which fuel in combustion chamber is ignited abnormally resulting in inefficient and rough running of engines.

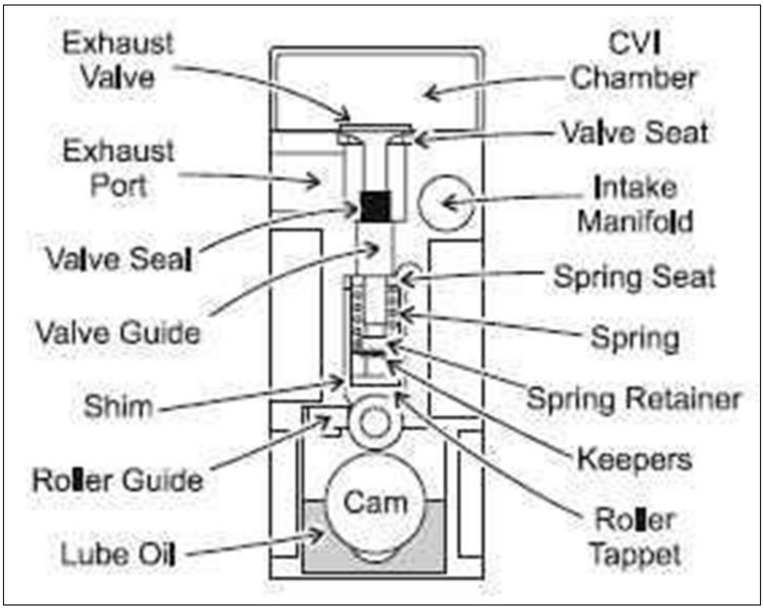
Pre-ignition is caused due to several reasons in hydrogen engines. Some of the studies shows that premature ignition are results of hot spots developed in combustion chamber, such as on spark plug or on exhaust valve. Also backfires can happen when there is overlap of intake and exhaust valve opening. Pre-ignition can also happen due to thermal decomposition (pyrolysis) of oil present in suspended form in combustion chamber or in the crevices above the piston ring. The thermally decomposed oil can pass into combustion chamber through blow-by from crank case.

Effective design of fuel delivery system can help in reducing or eliminating the cases of pre-ignition. The structure of hydrogen fueled engines is almost similar to conventional internal combustion engines. In order to avoid problems of abnormal combustion, low power or high NOx emissions it requires use appropriate fuel injection system.

Use of carburetor to mix hydrogen with air is one such method, which has an added advantage of not requiring pressure as high that is required in other methods. With this it easy to convert convention engine to hydrogen powered engines. The disadvantage of using central hydrogen injection system the amount of fuel in mixture is quite low which results in power losses. But with higher hydrogen-air mixture and intake valve open, if ignition occurs during this time it may result in spreading of flame or may cause backfire in intake manifold. This may result in major damage to engine.

Port Fuel Injection uses electric or mechanical injector to inject hydrogen at the beginning of every inlet stroke. At the same time air is supplied separately at the intake stroke and further reduces temperature in the engine combustion chamber [24-26]. Furthermore this reduces chance of premature ignition in combustion chamber. Intake pressure required is higher in this system when compared to carbureted or central injection methods but less when compared to direct injection method.

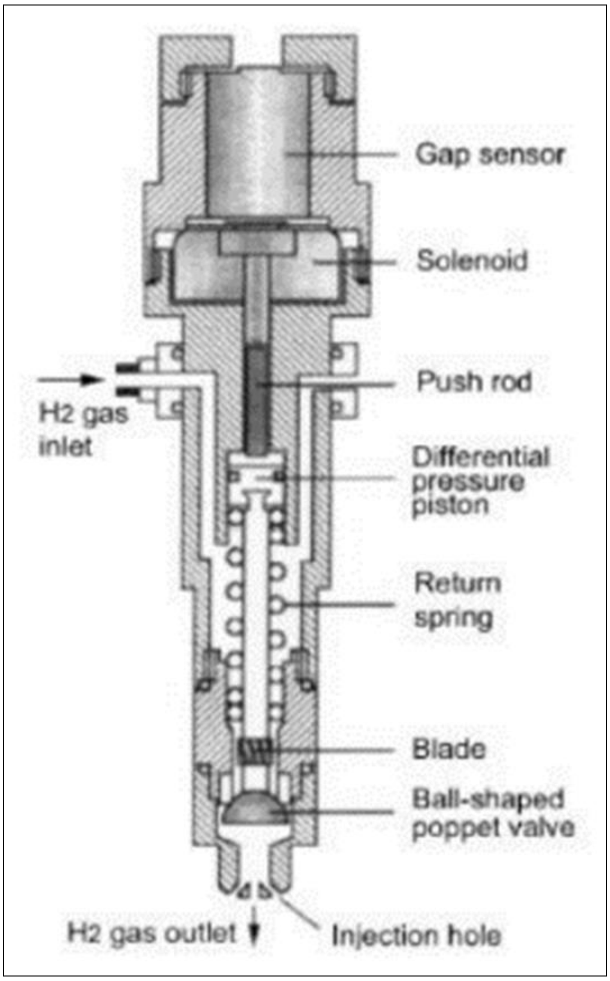
The constant volume fuel injection (CVI) system uses mechanically cam controlled device to determine the timing of hydrogen injection into each cylinder.



(***Source***: https://www.ijraset.com/fileserve.php?FID=15997)

Fig 1: Constant Volume injector model

The electronic fuel injection (EFI) system makes use of individual electronic fuel injectors (solenoid valves) to send metered hydrogen to each cylinder. These injector are connected to a common rail containing fuel.



(***Source***: https://www.researchgate.net/profile/Ir-Ts-Dr-Mohd-Faizal-Fauzan/publication/332413579/figure/fig6/AS: 747828339044353 @1555307578369/Hydrogen- Injector-15.ppm)

Fig 2: Electric Fuel Injector

Constant Fuel injection system uses constant injection timing and variable rail pressure whereas Electric Fuel injection system make use of variable timing and constant rail pressure [27- 29].

In Direct Injection, hydrogen is directly injected into the combustion chamber during completion of compression stroke. Compared to other inductive methods this is the most efficient. Using this method, engine power output achieved is 20% more compared to petrol driven engine. Also, power output achieved is 42% more when compared to hydrogen engine using carburetion system. This system has its challenges due to unique properties of hydrogen. The main challenges include high self-ignition temperature, long auto ignition delay and fast rate of pressure increase. Use of direct injection system solves the problem of premature ignition in intake manifold but is unable to control same in engine combustion chamber. The mixture formed is not homogenous which results in higher NOx emissions compared to other methods.

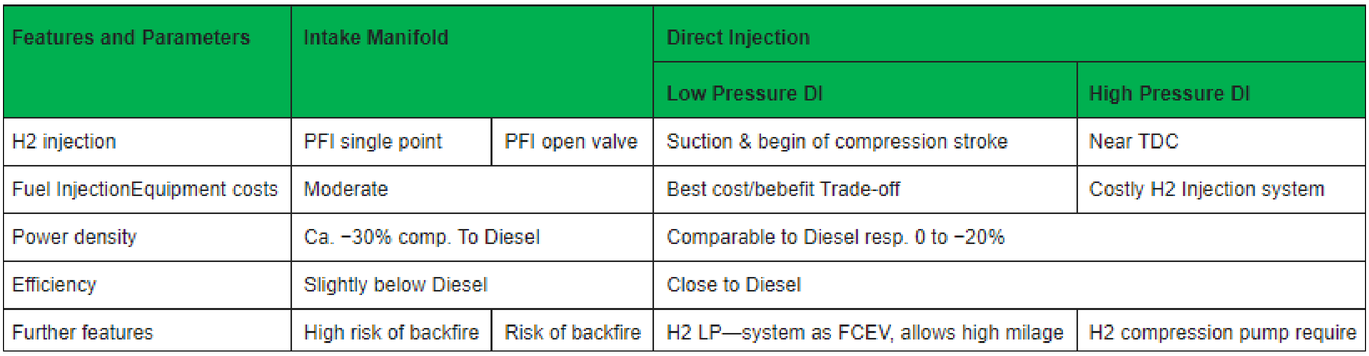
The primary task of fuel injection system is fuel metering and fuel delivery. Since gaseous fuel are compressed outside fuel injection system therefore only metering system is required. The quantity of hydrogen injected into system is precisely measured and controlled actively by varying duration of injection. The basic function requirements of hydrogen injection system can identified by following characteristics:

- **Time of full opening of injector is to be kept short:** This time is defined as time required for injector to move from one extreme position to other. It required that injection time to be kept minimum and also low flow rates to be maintained while opening and closing of valves. This ensures maximum average mass flow rate during injection. This ensures improvement in mixture formation.
- **Response of injection to impulse activating its operation to be rapid:** This is the time from impulse controlling the initial needle movement to the actual movement of the needle. A delayed time between needle movement and its control impulse prevents injector operation from adapting to high engine speeds.

- **Duration of Fuel Injection:** In order to achieve required air – fuel mixture, duration fuel injection needs to closely monitored and controlled. This can be made possible only by the use electronic injector system with efficient controllers to optimize the engine performance [28, 29].
- **Fuel Leakage to be kept minimum:** Leakages may result in premature ignition during induction stage. In case of leakage during exhaust stroke it result to loss of hydrogen and hence reducing volumetric efficiency.
- **Application of durable injectors:** Frequency of injector need is 50 Hertz and also its high dynamic movement result in high impact load on the surfaces restricting tis movement, hence injector valves should be resistant to damage.

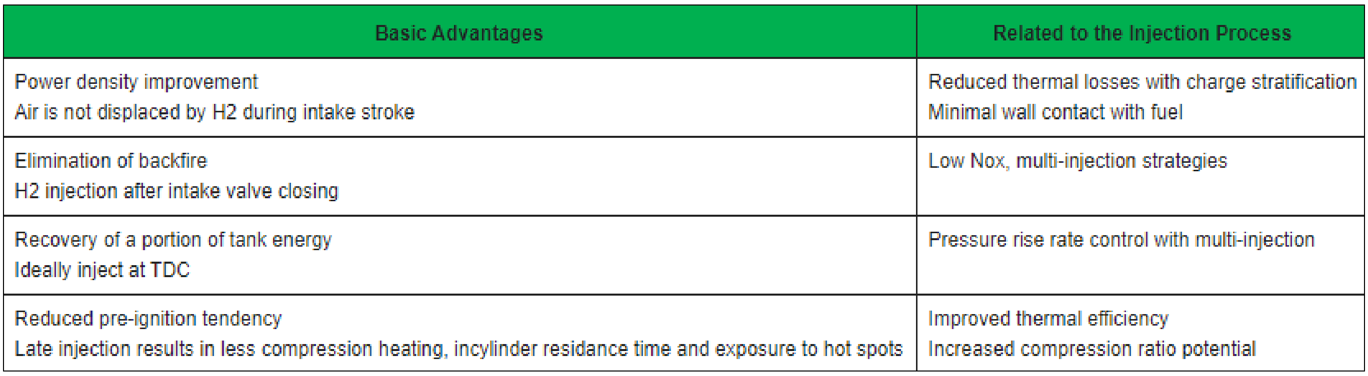
Aforementioned characteristic can be met with following two types of injection – Low pressure direct injection (LDPI) and high pressure direct injection (HDPI). LDPI can occur when intake is closed and cylinder pressure is low, whereas HDPI is based on fuel injection on completion of compression stroke.

In current application it is found that injection concepts for hydrogen engines are mainly concerned with port fuel injection and direct injection. Port fuel injection requires high rail pressure in comparison to direct injection system for same air –fuel ratio. Port fuel injection system is widely being used because its development is easy as its injector is placed outside cylinder (hence also known as external mixture formation) just before intake valve and resultant mixture of air – fuel is uniform. Direct injection provides high power density and reduced erratic behavior. For given air-fuel ratio direct injection provides higher torque and higher efficiency as compared to Port fuel injection system. In direct injection, injector is mounted on cylinder head (hence also known as internal mixture formation), homogenization of mixture is difficult but volumetric efficiency is high. In case of direct injection system we need to distinguish between high pressure and low pressure systems. For high pressure system more effort, cost, and complexity is involved.



Features and Parameters	Intake Manifold		Direct Injection	
			Low Pressure DI	High Pressure DI
H2 injection	PFI single point	PFI open valve	Suction & begin of compression stroke	Near TDC
Fuel InjectionEquipment costs	Moderate		Best cost/bebefit Trade-off	Costly H2 Injection system
Power density	Ca. −30% comp. To Diesel		Comparable to Diesel resp. 0 to −20%	
Efficiency	Slightly below Diesel		Close to Diesel	
Further features	High risk of backfire	Risk of backfire	H2 LP—system as FCEV, allows high milage	H2 compression pump require

Fig 3: Comparison between PFI & DI [26]



Basic Advantages	Related to the Injection Process
Power density improvement Air is not displaced by H2 during intake stroke	Reduced thermal losses with charge stratification Minimal wall contact with fuel
Elimination of backfire H2 injection after intake valve closing	Low Nox, multi-injection strategies
Recovery of a portion of tank energy Ideally inject at TDC	Pressure rise rate control with multi-injection
Reduced pre-ignition tendency Late injection results in less compression heating, incylinder residance time and exposure to hot spots	Improved thermal efficiency Increased compression ratio potential

Fig 4: Advantages of DI Vs PFI [30]

Strategies for optimizing Ignition & Injection System

Internal Combustion Engines can be divided into two on basis of fuel injection system as Port Fuel Injection and Direct Injection Systems. These groups can be further divided on the basis of their ignition system. Port fuel injection system based engines are further classified into homogenous charge compression ignition, spark ignition & ignition with pilot diesel. Direct Injected Engines as further classified as – ignited by glow plug, spark ignition or a pilot diesel [31-33].

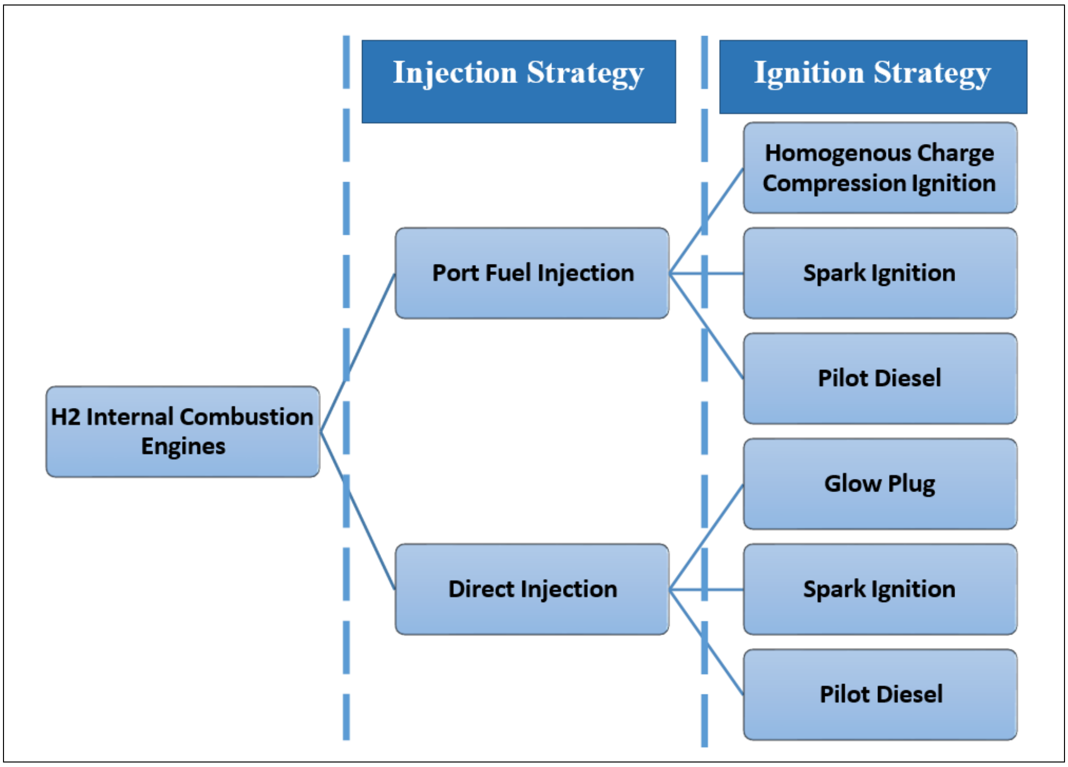


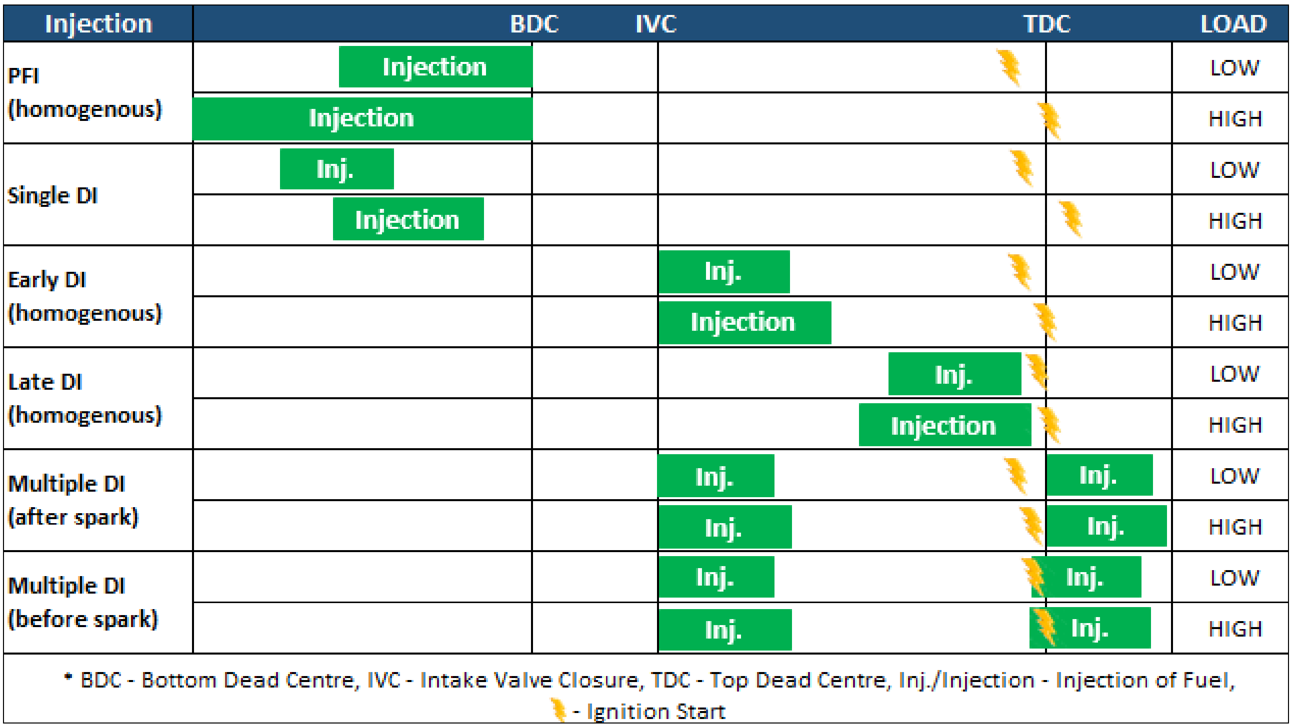
Fig 5: Categorization of Hydrogen Internal Combustion Engines based on typical Injection and Ignition Strategies

For developing injection and ignition strategies are dependent on engine load (which is related to air/fuel ratio for un-throttled operation), injection timing and nitrogen oxide emissions.

At low engine loads, low air/fuel ratio, early direct injection (resulting in a lean homogenous mixture) results in low NOx emissions. Beyond a certain load or air/fuel ratio (~0.5), the NOx emission increases rapidly which peaks at about ~0.8 and decreasing slightly as it reaches a stoichiometric mixture. This is applicable for both Port Fuel Injection and early Direct Injection system due to resulting combustion mixture being fairly homogenous.

Late Direct injection, i.e. just before ignition phase, generally results in opposite trends of NOx emissions [30-31].

A figure below shows the six basic ignition and injection strategies considering both high and low load conditions.



* BDC - Bottom Dead Centre, IVC - Intake Valve Closure, TDC - Top Dead Centre, Inj./Injection - Injection of Fuel,
⚡ - Ignition Start

Fig 6: Six strategies with varying Injection and Ignition timings [30, 31].

In case of Port Fuel Injection, availability of homogenous mixture at the inlet port may result in backfire in intake manifold. To avoid this timing of injection need to happen only during portion of suction stroke which will reduce the chances of backfire. But injection of fuel during suction stroke will replace the fresh air thereby worsening volumetric efficiency and power density of engine. Application Direct Injection helps in improving performance of engine and reduce NOx emissions. But it results increase of particulate emissions.

Multiple injections in engine helps to create lean and homogenous mixture. NOx emissions can be further reduced by controlled timing of additional hydrogen injection during combustion process. This can be further differentiate by controlling ignition timing relative to second injection timing depending on whether the mixture is already ignited or not at the start of second injection. Stratification (an internal-combustion engine in whose cylinders the combustion of fuel in a layer of rich fuel-air mixture promotes ignition in a greater volume of lean mixture) enables to improve combustion rate and also reduce heat losses through chamber walls. The design of nozzle is an important aspect for optimizing this stratification.

Increasing efficiency of H2 Ice

Application of a combination of pre-mixed combustion of an SI engine with non premixed CI engine to control the combustion process, where we typically a partial amount of hydrogen is injected early and ignited by spark plug, the remaining amount of charge required to reach the desired load is achieved by injecting it into the flame for subsequent diffusion type combustion. At low load conditions may result in knocking which can be overcome at high loads. Hydrogen combustion technology is basically into various groups of spark ignition concepts with homogenous premix and compression ignition concepts.

SI Engines considerably reduce harmful emissions, achievable power density is widely dependent on air ratio at full load conditions. The greatest challenge of SI H2ICE are that of power density, fuel efficiency and performance during transition. Power density that can be achieved in SI engine is completely dependent on excess air ratio at full load conditions and amount of NOx emissions. The difficulties in terms SI engine performance is that of power density, fuel efficiency and transient performance. Moderate injection pressure is required in case low pressure hydrogen combustion process thereby eliminating need for an additional compression system, hydrogen can be directly supplied from tanks. High pressure combustion process require higher injection pressure, therefore an additional compression system is required so that maximum amount of hydrogen from tank can be used.

Therefore, it supports use of high pressure injection of hydrogen during combustion whereas diffusive combustion can be used to overcome all the shortcomings of pre-inflammation and knocking. The premixed low pressure combustion process can be used by resolving conflicts between efficiency, power density, time to market and costs for development and operation of engine.

Application of DI engines has following shortcomings which need to be addressed for its implementation:

- The mass flow rate of hydrogen injected into small bore engines is dependent on injector size and at relatively low injection pressures. The injection timings and duration are related to each other, thus making late injection in system difficult.
- The highly diffusive nature makes it idle for mixture homogenization but on the other hand it makes it difficult to control stratification and spread to cylinder liner walls and piston crevices.
- High velocity spray of hydrogen into under expanded supersonic conditions results Mach Discs formation and hydrogen sprayed tends to follow the path cylinder walls. This creates difficulty in homogenization of mixture which can be overcome by optimized design cylinder geometries and cylinder walls.

For small loads, in order to increase brake thermal efficiency following strategies can be implemented:

- Operating engine on a stoichiometric mixture, with throttling (and/or EGR) and exhaust gases after treatment system.
- Running engine at fixed lean mixture with throttling and without after treatment system.
- The operation of engine at variable air/fuel ratio, with throttle body open, at medium loads, without an after treatment system.
- Operating engine at a lean mixture ratio with supercharging and without after treatment
- Operating engine at a variable equivalence ratio, which is operation between stoichiometric conditions and the NOx threshold at wide open throttle, with lean NOx after treatment.

At the highest loads the strategies include

- Application of DI engine operating at stoichiometric mixture with after treatment system.
- Application of PFI engine operating at stoichiometric mixture with supercharging and after treatment.
- Application of PFI engine operating at stoichiometric mixture with cryogenic fuel injection and after treatment.
- Operating at a fixed lean equivalence ratio (NOx threshold deviation) with (high) supercharging and without after treatment.

Conversion of conventional engines

The major changes required in conventional engines to be run on hydrogen are hardware changes, layout of combustion system, turbocharging system, fuel injection system, ignition system and exhaust after treatment system. The most important changes that required are as mentioned below:

- **Combustion systems:** Cylinder head–spark plug, piston and piston rings, compression ratio, valve, valve seats and valve guides materials, and control system–knock and ignition need to be changed application of hydrogen as fuel. Cylinder head need to be of optimum design to avoid hot spots in combustion chamber. New material for cylinder head, valve seats and guides to avoid risk caused by hydrogen embrittlement and lack of lubrication. Piston and piston rings design to be change to avoid blow-by and hydrogen leak to the sump.
- ECU, crankcase ventilation system, and engine lubricating oil.
- **Turbocharging system (turbocharger):** Specialized turbocharging system for hydrogen engine which cater lower boost pressure demands.

- **Fuel injection system:** Hydrogen injectors and relevant rails and pipes, hydrogen fuel supply according to the pressure level of PFI or DI, and gas pressure regulator is to be ensured. Also injection timing is a pre-requisite and high flow rate design injectors are required for hydrogen based engines.
- **Ignition system:** Cold rated spark plugs and ignition coils are required. Ignition system need to be properly grounded to prevent occurrence of uncontrolled and unwanted ignition due to low ignition energy of hydrogen.
- **Exhaust after treatment system:** Optimized for hydrogen combustion and reduction NOx emissions.

Reason for changes in hydrogen engines is basically irregular combustion processes and unique properties of hydrogen on iron and steel. Crank case ventilation is much more important as hydrogen has low ignition energy and its passage to crank case may result in ignition. Hence hydrogen accumulation should be should be prevented using suitable crank case ventilation system. In case of ignition in crank case may also to an engine fire. Hotspots formation in combustion chamber should be avoided by the use of cooled exhaust valves, multi valve engine heads and use of small exhaust valves (two in place of one is recommended). In addition lubrication system needs to be modified for coolant passages around valves and adequate exhaust venting system.

Due to low lubricity property of hydrogen, valve seat material should be of suitable choice and low temperature spark plugs to be used to prevent backfire in engine.

Challenges for h2ice technology

Technical challenges of application of hydrogen is mainly due to its unique properties, that have already been discussed earlier and described, results in engine damage, also may result in damage of fuel injection systems. Injection technology is affected due to:

- Degradation of piezoelectric material used in fuel injectors caused by hydrogen poisoning and high pressure of hydrogen uptake.
- Sliding friction and wear of injectors due to motion between needle guide part and nozzle body.
- Epoxy breakdown due to high temperatures and pressure of hydrogen.

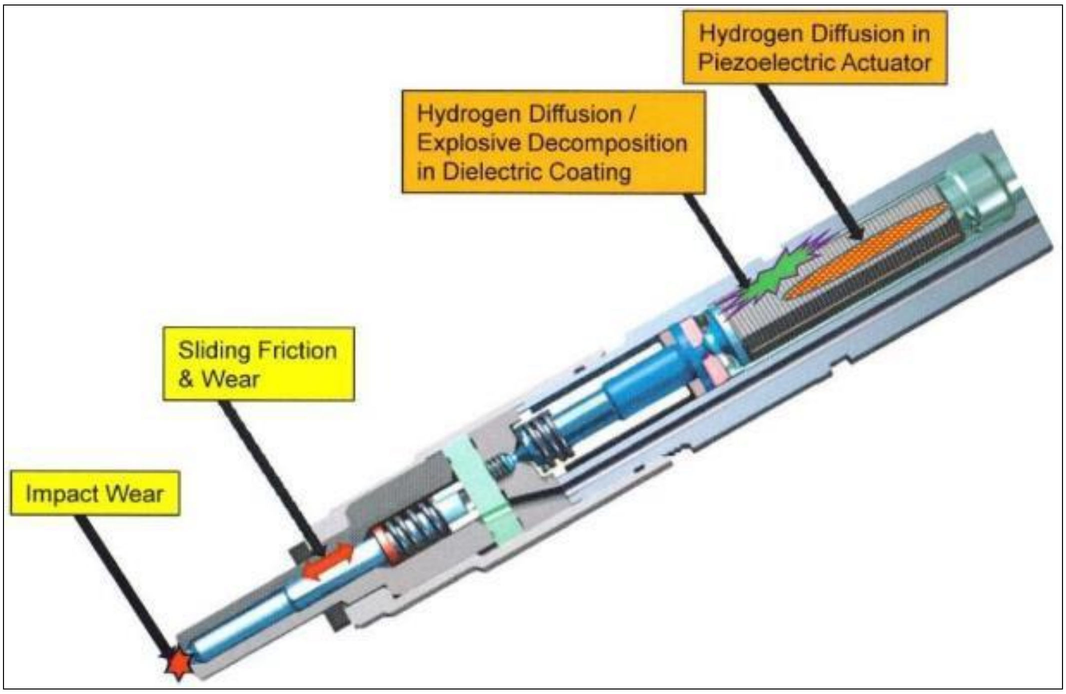


Fig 7: Type of wearing in Injectors

The interaction of needle with nozzle seat is that of sliding contact which results in impact wear of needle during its opening and closing operation. This causes a slight plastic deformation at contact surface of needle and nozzle. The factors affecting impact wear is mechanical and thermochemical properties of material, working environment, lubrication and formation of surface oxide layers. In reducing environment of hydrogen, the wear induced loss of surface oxides may result in bar surface contact which in turn increases friction and wear between the parts. Further to damage of epoxy material results in voids formation and micro arcing and carbon tracks from the damaged epoxy. This can lead to electric short circuits between adjacent electrodes in stack. Formation of hydroxide bonds results in deterioration electric properties caused by changes in dipole moments in crystal.

Due to low lubricating properties hydrogen, it may leak into the engine combustion chamber due to injector damage resulting in abnormal combustion in engine.

In addition to technical challenges for conversion and modification of present conventional engines we need to address below key challenges and barriers for development. Below are certain challenges mentioned:

- Involves high initial investment cost in R&D for development and mass deployment of the technology. R&D Investment involves development of advanced predictive 3D Simulation processes for optimized design.

- Customer acceptance and market sustenance to break-even and profit from investment in technology development.
- Risks of bans on all Internal Combustion Engines. Standard guidelines required for hydrogen based internal combustion engines.
- Production, storage, handling and supply infrastructure is required for hydrogen to be used as commercial transportation fuel. Cost of production for hydrogen fuel.
- Ensure Vehicle safety and standards for application of hydrogen as fuel. Vehicle packaging constraints for development of H2ICE.
- Market competition with already developed Electric Vehicles.
- Development of technology for studying advance diagnostics for hydrogen injection and combustion.
- Experimental facilities to study the performance of hydrogen based engine.
- Requires increased customer awareness about H2ICE technology.

It further requires support from Government for incentives in development of infrastructure for production and validation of hydrogen based engines. Separate standard guidelines and safety regulations for vehicle to run on H2ICE. Platform to demonstrate the performance of the technology and to encourage it as a clean alternative for conventional engines.

Developments in storage systems

Numerous studies have been conducted in terms of material and methods for hydrogen storage systems [34, 35]. To cater to the current market requirements certain technologies are being developed.

As hydrogen has very low density at atmospheric conditions, the current applications require ultra-high pressurized gas bottles or low temperature liquid bottles for liquid hydrogen. Pressure of approximately 25-70 MPa require 11-13% of hydrogen energy content to reach these pressure levels. The complexity and cost involved • in hydrogen storage and transport has prevented wider application of hydrogen as fuel.

An alternative is chemical reaction processes to produce low carbon synthetic fuel from hydrogen. These hydrogen based low carbon liquid fuel generated from hydrogen using renewable resources can be used in existing combustion engines for long-distance vehicles and vessels. For example, methanol and ethanol production from renewable sources and used in ICE with zero life cycle carbon emissions. Storing hydrogen in in dense-hydrogen liquid fuel form has benefits of compatibility and synergy with present grid storage and transportation of renewable energy around the world, for example production of methanol production in solar powered plants in part of the world can be transported to another part to meets it energy demands. Therefore new methods of storing hydrogen in liquid fuels would provide benefits of wider application and improved engine performance supported by lower emissions of engines. An alternative emerging approach is to storing hydrogen in bubble form in liquid fuels. This approach is being studied for its wider range application in vehicles. It has been found that bubbles remain stable in liquid for months and have high internal gas density. These high stability, internal density and concentration makes storage of considerable amount of hydrogen in liquid fuels. The increased concentration of hydrogen bubbles can further increase hydrogen storage capacity in liquid fuels. Since hydrogen has higher calorific value (heating value) in comparison to petrol and diesel for example hydrogen fuel blend will have higher energy density compared to base liquid fuel, which makes it appealing for improving engine performance and reducing carbo dioxide emissions.

Hydrogen: A prime choice for heavy vehicles' sustainable future

In heavy commercial vehicles, option of electrification is constrained due to weight of large battery pack requirement and charging time considerations. Also the amount modification required in current natural gas engines. H2ICE plays a critical role ensuring decarbonization of this segment. Following are the options which makes hydrogen a viable choice for Heavy Commercial Vehicle Segment -:

- High energy density of hydrogen makes it preferable choice by reducing the payload capacity of the vehicle.
- Refueling time required for hydrogen based vehicles is considerably lower when compared to other choices available in the market.
- Total cost of ownership for H2ICE vehicle is also reduced as it reduces idle time of the vehicle due to recharging time when compared Battery Electric Vehicle.
- Since modification required for changing current heavy vehicles from conventional engines to hydrogen based engines is minimal when compared to other alternatives, thereby providing quicker migration to clean energy technology at lower delta cost.
- Tail pipe emission are almost zero when compared to other alternatives – CNG & LNG.

Current developments & trends

Below are the list of certain notable organizations working on H2ICE development [36]:

Ashok Leyland

First H2ICE Truck is developed by Ashok Leyland & Reliance Industries Limited (RIL) at India Energy Week in Bangalore. Ashok Leyland developed the H2ICE heavy duty truck (19-35 tonnes) in collaboration with RIL which is based on conventional engine. The truck makes use two large tanks of hydrogen to power the truck. RIL has further plans to use a fleet of approximately 45,000 truck with retro fitment for its refining and marketing operations.

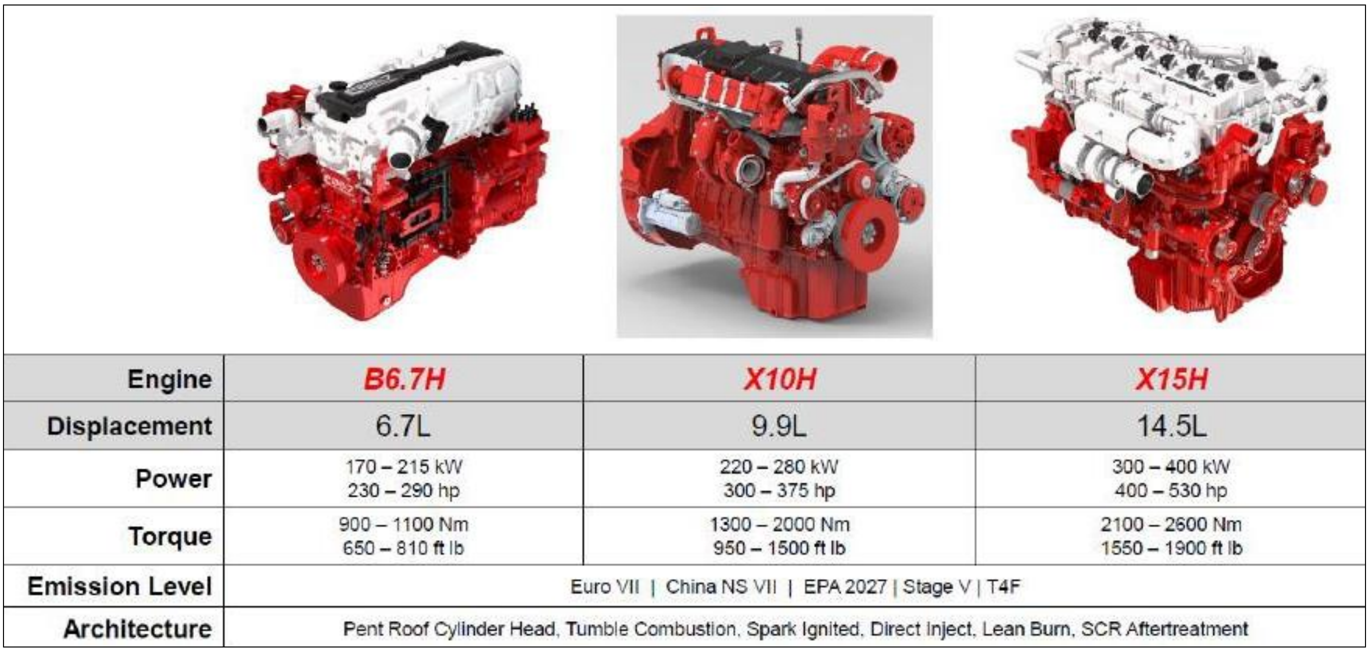
Fig 8: First H2ICE Heavy Duty Truck [37]

Cummins & Tata Motors

As an organization they are working towards find best alternatives for cleaner technology development. Working in collaboration with Tata Motors for development of vehicles which has set-up two state of the art R&D Facilities for developing hydrogen propulsion technologies at Pune.

Fig 9: Cummins B6.7H H2ICE

Cummins also showcased its B6.7H H2ICE engines at CII EXCON 2023 with zero well to wheel CO_2 emissions. It is further working on developing more solutions for heavy commercial vehicle applications.



Engine	B6.7H	X10H	X15H
Displacement	6.7L	9.9L	14.5L
Power	170 – 215 kW 230 – 290 hp	220 – 280 kW 300 – 375 hp	300 – 400 kW 400 – 530 hp
Torque	900 – 1100 Nm 650 – 810 ft lb	1300 – 2000 Nm 950 – 1500 ft lb	2100 – 2600 Nm 1550 – 1900 ft lb
Emission Level	Euro VII | China NS VII | EPA 2027 | Stage V | T4F		
Architecture	Pent Roof Cylinder Head, Tumble Combustion, Spark Ignited, Direct Inject, Lean Burn, SCR Aftertreatment		

Fig 10: Cummins Higher Load Applications

Tata Motors and Cummins showcased Industry-first H2 ICE truck for eco-friendly goods transport at Bharat Mobility Global Expo 2024, held from 1-3 February 2024 [38].

Fig 11: Prima H.55 S [38]

- **MAN Trucks**

MAN showcase its in house developed prototype test in 2021. It has developed a demo vehicle which runs on hydrogen as fuel which provides same output as diesel trucks. Also target to complete test vehicle trial in collaboration with customers by 2024 and move forward with mass production by 2025.

Fig 12: MAN Truck and Bus is developing H2ICE

Conclusion

The wide preface of hydrogen combustion engine into mass product has not yet begun, primarily because the hydrogen infrastructure that's needed for all hydrogen- fueled vehicles (i.e., energy cell electric motors as well as hydrogen- fueled internal combustion machines) is underdeveloped. With the construction of H2 infrastructure planned and formerly underway in some requests, whether and how hydrogen-powered internal combustion engines can compete with fuel cells to contribute to CO_2-free propulsion systems are presently being discussed. Examples of arguments in favor of hydrogen- fueled internal combustion engines include low investment due to expansive use of being product capacity and vehicle structuring to date as well as long service life. Further, hydrogen- fueled ICEs can be integrated with electric motors in electrified powertrain. In addition to the advantages in terms of effectiveness and driving range, this leads to attractive opportunity for functional synergy and fresh degrees of freedom in terms of design and operating strategies to be considered.

References

1. Desantes JM, Molina S, Novella R, *et al*. Comparative global warming impact and NOx emissions of conventional and hydrogen automotive propulsion systems. Energy Conversion and Management. 2020;221:113137.
2. Reitz RD, Ogawa H, Payri R, *et al*. IJER editorial: the future of the internal combustion engine. International Journal of Engine Research. 2020;21(1):3–10.
3. Kansu S, Kahraman N, Ceper B. Experimental study on a spark ignition engine fueled by methane-hydrogen mixtures. International Journal of Hydrogen Energy. 2007;32(17):4279–4284.
4. Simon JM. Heavy duty hydrogen ICE: Production realization by 2025 and system operation efficiency assessment in Powertrain Systems for Net-Zero Transport. London: CRC Press; c2021.
5. Klepatz K, Konradt S, Tempelhagen R, Rottengruber H. Systemvergleich CO_2- freier Nutzfahrzeugantriebe [System comparison CO_2-free commercial vehicle drives]. In: Berns K, Dressler K, Kalmar R, Stephan N, Teutsch R, Thul M, editors. Commercial vehicle technology 2020/2021. Wiesbaden: Springer Viewer; [cited 2023 Mar 21]. DOI: 10.1007/978-3-658-29717-6_13.
6. Koch D, Eßer E, Kureti S, *et al*. H2-DeNOx-Katalysator für H2- Verbrennungsmotoren. MTZ Motortech Z. 2020;81:32–39.
7. Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Progress in Energy and Combustion Science. 2009;35:490–527.

8. Subash GP, Das LM. An experimental investigation on the performance and emission characteristics of a hydrogen fueled spark ignition engine. International Journal of Science and Technology Management. 2011;8:197–208.
9. Karim GA. Hydrogen as a spark ignition engine fuel. Chemical Industry. 2002;6:256–263.
10. Ono R, Nifuku M, Fujiwara S, Horiguchi S, Oda T. Minimum ignition energy of hydrogen-air mixture: Effects of humidity and spark duration. Journal of Electrostatics. 2007;65:87–93.
11. Gandhi RD. Use of hydrogen in internal combustion engine. International Journal of Engineering Management Science (IJEMS). 2015;3:207–216.
12. Iafrate N, Matrat M, Zaccardi JM. Numerical investigations on hydrogen-enhanced combustion in ultra-lean gasoline spark-ignition engines. International Journal of Engine Research. 2021;22(2):375–389.
13. Verhelst S, Maesschalck P, Rombaut N, *et al.* Increasing the power output of hydrogen internal combustion engines by means of supercharging and exhaust gas recirculation. International Journal of Hydrogen Energy. 2009;34(10):4406–4412.
14. Das LM. Hydrogen engines: A view of the past and a look into the future. International Journal of Hydrogen Energy. 1990;15:425–443.
15. White CM, Steeper RR, Lutz AE. The hydrogen-fueled internal combustion engine: A technical review. International Journal of Hydrogen Energy. 2006;31:1292–1305.
16. Wimmer A, Wallner T, Ringler J, Gerbig F. H2-Direct Injection—A Highly Promising Combustion Concept; SAE Paper 2005-01-0108; SAE International: Warrendale, PA, USA; c2005.
17. Glaude PA, Fournet R, Bounaceur R, Molière M. Adiabatic flame temperature from biofuels and fossil fuels and derived effect on NOx emissions. *Fuel Processing Technology*. 2010;91:229–235.
18. Chong CT, Hochgreb S. Measurements of laminar flame speeds of liquid fuels: Jet-A1, diesel, palm methyl esters and blends using particle imaging velocimetry (PIV). Proceedings of the Combustion Institute. 2011;33:979–986.
19. Huyskens P, Van Oost S, Goemaere PJ, Bertels K, Pecqueur M. The Technical Implementation of a Retrofit Hydrogen PFI System on a Passenger Car; SAE Paper 2011-01-2004; SAE International: Warrendale, PA, USA; c2011.
20. Kondo T, Iio S, Hiruma M. A study on the Mechanism of Backfire in External Mixture Formation Hydrogen Engines—About Backfire Occurred by Cause of the Spark-Plug; SAE Paper 971704; SAE International: Warrendale, PA, USA; c1997.
21. Lee JT, Kim YY, Lee CW, Caton JA. An investigation of a cause of backfire and its control due to crevice volumes in a hydrogen fueled engine. Journal of Engineering for Gas Turbines and Power. 2001;123:204–210.
22. Verhelst S, Sierens R, Verstraeten S. A Critical Review of Experimental Research on Hydrogen-Fueled SI Engines; SAE International: Warrendale, PA, USA; c2006.
23. Srinivasana CB, Subramanian R. Hydrogen as a spark ignition engine fuel technical review. International Journal of Mechanical Mechatronics Engineering (IJMME-IJENS). 2014;14:111–117.
24. Ikegami M, Miwa K, Shioji M. A study of hydrogen-fueled compression ignition engines. International Journal of Hydrogen Energy. 1982;7:341–353.
25. Maccarley CA, Van Vorst WD. Electronic fuel injection techniques for hydrogen-powered I.C. engines. International Journal of Hydrogen Energy. 1980;5:179–203.
26. Kufferath A, Schünemann E, Krüger M, Jianye S, Eichlseder H, Koch T. H2 ICE Powertrains for future on-road mobility. In Proceedings of the 42nd International Vienna Motor Symposium, Vienna, Austria, 29–30 April 2021.
27. Faizal M, Chuah LS, Lee C, Hameed A, Shankar M. Review of hydrogen fuel for internal combustion engines. Journal of Mechanical Engineering Research and Developmen (JMERD). 2019;42:35–46.
28. Lucas GG, Emtage AL. Microprocessor control of the hydrogen/petrol engine. IMechE. 1987:231–240, paper no. C08/87.
29. Maccarley CA, Van Vorst WD. Electronic fuel injection techniques for hydrogen-powered I.C. engines. International Journal of Hydrogen Energy. 1980;5:179–203.
30. Pauer T, Weller H, Schünemann E, Eichlseder H, Grabner P, Schaffer K. H2 ICE for future passenger cars and light commercial vehicles. In Proceedings of the 41st International Vienna Motor Symposium, Vienna, Austria, 22–24 April 2020.
31. Wallner T, Ciatti S, Bihari B, Stockhausen W, Boyer B. Endoscopic investigations in a hydrogen internal combustion engine. In Proceedings of the 1st International Symposium on Hydrogen Internal Combustion Engines, Graz, Austria; c2006.
32. Boretti A, Watson H, Tempia A. Computational analysis of the lean-burn direct-injection jet ignition hydrogen engine. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2010;224:261–269.
33. Eichlseder H, Grabner P, Gerbig F, Heller K. Advanced combustion concepts and development methods for hydrogen IC engines. In: FISITA World Automotive Congress; GWV Fachverlage GmbH: Munich, Germany; c2008.
34. Beduneau JL, Kawahara N, Nakayama T, *et al*. Laser induced radical generation and evolution to a self-sustaining flame. Combustion and Flame. 2009;156:642–656.
35. Zheng J, Liu X, Xu P, *et al*. Development of high pressure gaseous hydrogen storage technologies. International Journal of Hydrogen Energy. 2012;37:1048–1057.
36. Web: [Online]. Available from: https://www.energy.gov/sites/default/files/2023-03/h2iqhour-02222023.pdf
37. Web: [Online]. Available from: https://timesofindia.indiatimes.com/auto/commercial-vehicles/reliance-industries-ashok-leyland-unveil-indias-first-hydrogen-powered-heavy-duty-truck-at-india-energy-week/articleshow/97694334.cms?from=mdr
38. Press Release - “Tata Motors Presents ‘Future of Mobility’ portfolio at Bharat Mobility Global Expo 2024”, dated 31 January 2024.