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# On-board Hydrogen Storage and its Performance in a Three Wheeler

**Janardan Sharma, M.A. Siddiqui**
Corporate R&D Center, Bharat Petroleum Corporation Ltd. Greater Noida – 201306, India



## ABSTRACT

A CNG three wheeler was developed for hydrogen use with an objective to gain experience of hydrogen storage, refueling and performance in a vehicle. Two CNG 3-wheelers were used in the study. One of these was converted for hydrogen operation retaining option of CNG/gasoline operation as and when needed. Another remained on standard CNG/gasoline operation for comparative study. An experimental prototype metal hydride canisters system was identified and installed on-board for hydrogen storage with provisions for convenient refueling, and systems for cooling during refueling and heating during gas release. The necessary modifications and tuning of the engine were carried out for smooth operation on hydrogen with adequate safety and without incidence of backfire. This involved provision of flame trap in the gas-air mixer, vacuum lock in the secondary pressure regulator, retarded spark timing and lean mixture operation. Field tests were carried out for acceleration, range and fuel efficiency of the vehicle with hydrogen vis-à-vis standard CNG/gasoline operations. The results show hydrogen refueling in metal-hydrides though slow, provide adequate range in comparison to steel cylinders, which can be further improved with advanced materials. The three-wheeler started easily and ran smooth on hydrogen with substantial improvement in fuel efficiency. However, acceleration was slower in relation to CNG/gasoline operation, due to power loss which is characteristic of carbureted engines converted for hydrogen operation. Power loss would be an issue for small engines found typically in two and three-wheelers and may require redesign with gas injection system for hydrogen operation.

## INTRODUCTION

Hydrogen as fuel for transport has been exciting since early development of internal combustion (IC) engines. Hydrogen is considered as the ultimate clean fuel due to benign nature of the product of combustion which is water. However, hydrogen is an energy carrier like electricity and not a fuel by itself, and has to be produced from other energy sources. It has remained as a potential long term option with diverse resource base-natural gas, heavy oil residues, bio-mass, solar and nuclear, etc. As a short term option, it has to be produced from oil, natural gas and coal. Ultimately it has to be produced using either solar energy for water electrolysis or bio-mass co-generation. Its popularity as auto fuel would depend upon the expected breakthrough in its economic production and storage, and also on economic development of fuel cells. Till economic deployment of fuel cells, hydrogen application in IC engines is being considered either as an admixture with compressed natural gas (CNG) or as neat fuel.

In India, interest in use of hydrogen as an alternate fuel started in 1976 by setting up a task force under Dept. of Science & Technology (DST) which received a fresh boost in 1983 under Dept. of Non-conventional Energy Sources, when thrust areas were decided for a 15 year period 1985-2000, and small research projects were initiated to look into production (BARC, IIT-M, BHU, Univ. of Madras), storage (ISRO, NPL, IIT-Kh, BHU) and utilization(IIT-M, BHU) [1]. However momentum was lost due to stabilization of oil prices. Interest was revived in 2003 by the Planning Commission, by forming a Committee under the chairmanship of its Member (Energy), to prepare plan for various aspects of development of hydrogen energy. Under this Committee, Four Sub-Committees have been formed to look into Production- headed by Secretary, DST, Storage & Distribution- headed by Secretary, Ministry of Petroleum & Natural Gas (MoP&NG), Applications- headed by Secretary, Ministry of Non-conventional & Renewable Energy Sources (MNRES), and Safety Standards, Security & Policy Issues- headed by Director General, The Energy Resource Institute (TERI). Various deliberations took place based on it and programs & projects were announced including establishment of a Hydrogen Corpus Fund of Rs 100 Crore by MoPNG [2-4].

The National Hydrogen Energy Board (NHEB) set up a in 2003 by MNRES, recently announced 'National Hydrogen Energy Road Map: Hydrogen Vision 2020' under Green Initiative for Future Transport (GIFT) and Green Initiative for Power Generation (GIP) which envisage [5]:

*Numbers in the parentheses designate references at the end of paper

- 1 million vehicle ~ 0.75 million 2&3 wheelers, ~ 0.15 million cars/taxis & ~ 0.1 million buses
- 1000 MW power generation ~ 50 MW stand alone IC engine generators, ~ 50 MW stand alone Fuel Cell generators & ~ 900 MW centralized plants
- Hydrogen cost at delivery point @ Rs 60-70/kg
- Hydrogen storage capacity 9 w%
- Adequate support infrastructure including dispensing stations
- Safety, regulations, legislation, codes & standards

Hydrogen has low mass density per unit volume, an order less compared to CNG or other gaseous fuels. This poses storage challenge on-board a vehicle for sufficient range. It has to be either stored in metal-hydrides at moderate pressures or compressed to very high pressure for storage in specially designed high pressure gas cylinders (made of carbon fiber wrapped high density polymer). Its cryogenic storage in liquefied form is also possible but is expensive and impractical. When used in automobiles, its low volumetric energy density is compensated to some extent by its high energy density which is 2.7 times than natural gas or gasoline. Being free of carbon, hydrogen is a clean burning fuel, emitting only water when used in fuel cells and some nitrogen oxides when used in IC engines. However, if sourced from fossil fuels is not carbon neutral as CO2 is emitted during its generation.

With the expected wide use of hydrogen as auto fuel, many aspects related to its application in vehicles need to be known. The purpose of this study was to develop a hydrogen three wheeler to gain first hand experience of hydrogen storage on-board and refueling in a metal hydride hydrogen storage system, and also performance of vehicle with hydrogen as fuel. Both metal-hydride and compressed storage of hydrogen was attempted in this study and field trials were conducted for vehicle performance, reliability of operation and safety. The results of refueling experience, range, fuel consumption, and acceleration in comparison to standard CNG/ gasoline 3-wheeler are presented and discussed along with a review of other's findings on hydrogen storage and performance as auto-fuel.

## EXPERIMENTAL

TEST VEHICLES - The test vehicles used in the study were are two nos. three wheeler CNG auto rickshaws of a popular make, powered by a single cylinder, air cooled, 173.5 cc, 4-stroke, CNG/petrol engine specified to develop 4.4 kW @ 5500 rpm on CNG, and 6 kW @ 5000 rpm on gasoline. Fuel tanks: 29 liter WC steel cylinder rated to store 4.6 kg of CNG at 200 bar, and a gasoline tank of 3 liters for limp back.

One test vehicle remained on standard CNG/ gasoline operation while the other vehicles was converted and tuned for smooth hydrogen operation with adequate performance (Fig.1). The existing CNG kit was modified for hydrogen service with adequate safety. The gas air mixer was provided with a flame arrestor upstream to back flash when engine is running. Additionally, a vacuum lock was provided downstream the secondary pressure regulator to avoid flooding of the intake manifold when engine was not running. To avoid back-fire, spark timing was retarded and gas power valve was adjusted for lean mixture operation. The vehicle retained its capability to operate on CNG/ gasoline with performance levels similar to standard CNG/gasoline operation through some optimizations for their fuel strength.

ON-BOARD HYDROGEN STORAGE - For hydrogen storage on-board, a metal hydride (MH) system was identified and installed on-board the vehicle (Fig. 1b). It consists of 10 nos. canisters of 1.38 liter WC (6 kg) each, containing calcium, nickel, lanthanum rich mischmetal with capacity to store 0.7 kg hydrogen (99.99% purity) at 35 bar. Manifold canisters were enclosed in an external casing to facilitate cooling/heating and charging/withdrawal of gas. System was engineered for chilled water circulation during refueling and engine exhaust circulation for adequate gas release during vehicle running. Chilled water was from an external source.

TEST FUELS - Hydrogen used in the study is standard industrial grade-II (>99.99% purity), supplied by a local vendor. CNG is from IGL. Gasoline, regular grade, is from local retail outlets. Auto fuel properties of the test fuels are compared in Table-1.

FIELD TRIALS - The acceleration performance was evaluated by measurement of time taken from standstill to max speed in best possible manner on a 1 km flat stretch. Acceleration is primarily a function of power and inertia of the vehicle. Hence, acceleration time and max speed achieved was considered as a good indication of power developed by the hydrogen engine in relation to standard CNG/ gasoline operation.

The fuel consumption of the vehicles on hydrogen, CNG and gasoline fuels was measured for regular driving from tank fill to tank fill, and also under uniform test conditions (pay load 150 kg, route length 25 km). Amount of hydrogen refueled was measured from measurement of initial and final pressures and temperatures during refueling and also checked by weighing the hydrogen cylinder from which gas was transferred. During vehicle operation, gas (hydrogen/CNG) consumption was calculated from measurement of gas tank pressure and ambient temperature, using PVT-Z relations and gas constants (R) for respective gases.

## RESULTS AND DISCUSSION

HYDROGEN STORAGE AND REFUELING - The metal hydride canister was refueled from industrial cylinder of 47 liter WC storing hydrogen at 150 bar. Refueling was carried out till cylinder pressure dropped and stabilized at the lowest value which was observed to vary from 10-30 bar depending on circulated cold water temperature which could be controlled at 10+5 C. The time taken for refueling varied between 30-45 minutes. The maximum hydrogen quantity that could be stored was 0.47 kg, which is only 1.04 w% against the claimed capacity of 1.56 w%.

At statutory pressure of 150 bar for storing hydrogen in steel cylinders, calculations show that on-board CNG tank can store 0.34 kg of hydrogen under normal site conditions. Since refueling could be carried up to 75 bar only as source cylinder stored hydrogen at 150 bar, as expected only 0.17 kg hydrogen could be stored. If hydrogen refueling could be carried out at 250 bar or more in similar capacity, specially designed high pressure cylinders (carbon fiber wrapped polymer), hydrogen storage would be 0.54 kg and higher that would be comparable to metal hydride storage.

Several metal hydrides for storage of hydrogen are known from an early date and have been reviewed for vehicular use. Hoffman K.C., et. al. [6] attempted to find potential hydrides for mobile and stationary applications and were of the view that iron-titanium hydride ($FeTiH_{1.74}$ – $FeTiH_{0.14}$) with 1.52 w% $H_2$ capacity is promising for stationary applications while magnesium-nickel hydride ($Mg_2NiH_{4.2}$) with 3.8 w% $H_2$ capacities is promising for mobile applications but more research is required to evaluate latter's safety. To achieve longer range, Buchner H. & Povel R. [7] suggest use of high temperature Mg-Ni hydride for running in conjunction with low temperature hydrides based on titanium-chromium-manganese alloys with 2 w% $H_2$ for starting. Deluchi M.A. [8] takes note of shortcomings of hydrides, i.e., low mass & volumetric energy density, bulky storage when complete with housing for cooling/ heating, and susceptibility to contamination of magnesium and vanadium alloys in presence of impurities.

Schlapbach L. & Zuettel A. [9-10] reviewed various storage options for automobile applications, i.e., compressed, liquefied, carbon nanostructures and metal hydride, etc., and concluded that metal hydrides are an effective, safe and compact way of hydrogen storage. They found that no comparable economic effort on hydrogen storage in carbon nanostructures exists. The two well known metal hydrides; magnesium nickel hydride ($Mg_2NiH_4$) and lanthanum nickel hydride ($LaNi_5H_6$), have hydrogen storage capacity of 3.59 and 1.37 mass percent respectively. However, like many other known metal hydrides, such as $Li_3Be_2H_7$ & $BaReH_9$ which can store hydrogen up to 9 mass%, $Mg_2Ni$ hydride's pressure and temperature range are not attractive for mobile storage which requires reversible storage at room temperatures. Alloys derived from $LaNi_5$ are more promising due to fast and reversible sorption with small hysteresis but still below 2 mass% of hydrogen while requirement for mobile application is 4-5 mass% [US DOE targets are 6.5 mass% and 62 kg hydrogen per cubic meter].

VEHICLE PERFORMANCE - The engine was observed to start much easily on hydrogen but was somewhat sluggish in operation in relation to CNG or gasoline due to an under powered engine on hydrogen. Reasons for it are discussed in the subsequent section.

Furuhama S., et. al. [11] studied problems of hydrogen operation and to control abnormal combustion, used lean mixture operation, retarded spark timing and colder spark plug. The other measures suggested were use of higher compression ratio, EGR and in-cylider hydrogen injection. Bindon J., et. al [12] reviewed lean burning performance of hydrogen engines and used lean burning hydrogen carburettor adapted from a readily available LPG system. They observed that carburetor proved more driveable in the lean burning mode than the throttled hydrogen supply, mainly due to lower propensity of back flashing. Das L.M. [13] has discussed undesirable combustion vis-à-vis hydrogen fuel properties and possible fuel induction techniques-carburetion, inlet manifold injection, inlet port injection and direct in-cylinder injection. He concluded that mixture formation method and also mode of hydrogen storage & supply system, play a decisive role in emergence of a future hydrogen specific engine. He found late fuel injection very promising in precluding possibility of back fire and developed and demonstrated an appropriate timed manifold injection (TMI) system to ensure smooth engine operational characteristics without any undesirable combustion phenomena.

FUEL EFFICIENCY - Results of the field trials for range and fuel efficiency under uniform test conditions is presented in Table-2, while that for normal driving is presented in Table-3. Under uniform test condition, hydrogen 3-wheeler showed a fuel efficiency of 138 km/kg in comparison to 38 km/kg on CNG and 25 km/l on gasoline. Results were similar for normal driving. The hydrogen 3-wheeler showed an average range of 57 km on a single fill of the metal hydride storage system which stored on an avg. 0.43 kg of hydrogen. Under normal driving, the standard CNG 3-wheeler has an average range of 150 km on 4 kg of CNG. Thus for a competitive range, hydrogen 3-wheeler would require 1.14 kg of hydrogen. This calls for either advanced materials for storage or larger capacity MH storage system; almost double the present one.

As can be observed from fuel efficiency expressed in terms of gasoline liter equivalent (GLE) on net energy basis (Table-2), hydrogen operation has substantially higher energy efficiency (36.4 k/GLE), 1.3 times the CNG (28.7 km/GLE) and 1.4 times the gasoline operations (25.3 km/l). This is due to hydrogen's low ignition energy, high flame velocity and wider flammability, resulting into completeness of combustion of lean mixtures, while CNG or gasoline has a tendency of quenched combustion at part loads.

A similar prototype hydrogen 3-wheeler developed by Energy Conversion Devices of Troy, Michigan, and Bajaj Auto Limited, Pune [17], used a hydrogen fuelled IC engine (H2ICE) and a metal hydride storage system in place of the existing fueling tank. Initial trial runs, in the cold climatic conditions of Michigan, yielded a range of 130 km per 900 gm of hydrogen (38.2 km/GLE), i.e. 144.4 km/kg of hydrogen which is almost same as that achieved on the hydrogen three wheeler developed by BPCL.

ACCELERATION AND POWER - The time taken for the hydrogen 3-wheeler in comparison to standard CNG/ gasoline 3-wheeler, to accelerate to max speed on a 1 km level stretch is given in Table-4. The acceleration performance of the hydrogen vehicle is slower by 30-40% and also the max speed achieved is substantially lower in comparison to standard CNG/ gasoline 3-wheeler. Sluggish operation is primarily due to under powered hydrogen engine; developing only approximately 60% of the maximum power compared to standard CNG/ gasoline engine, and also due to the added weight of the MH storage system.

Davidson D., et. al [14] converted a gasoline powered farm tractor engine for hydrogen operation using a LPG carburettor system and mish-metal alloy $MNi_{4.5}Al_{0.5}$ which had a storage density of 0.65 w% and observed that maximum power developed on hydrogen is only 67% of that obtained on gasoline. They explained that difference observed in peak power between the two fuels is primarily due to two factors: the reduced volumetric efficiency of the H2/air mixture (hydrogen displaces air in the cylinder) and the difference in chemical heats of combustion per unit mass of fuel, and suggested that to achieve equivalent power, turbo-charging or fuel injection would be necessary. Petkov T., et.al. [15] in their review of hydrogen as an automotive fuel explained the reasons for low power on hydrogen; in a unit volume (1 liter) of engine cylinder, when engine burns gasoline, its vapors occupy only 17 cc of the cylinder, while hydrogen occupies 300 cc. The small density of hydrogen and lower amount of air in the cylinder, results into amount of heat release from a unit volume of stoichiometric mixture of hydrogen-air to be only 0.85 times that of gasoline-air. If hydrogen is directly fed into the engine cylinder, the heat released is about 20% greater.

## CONCLUSIONS

To gain first hand experience of hydrogen application in vehicles, a standard CNG/gasoline 3-wheeler was successfully converted for hydrogen operation using a MH system for on-board hydrogen storage with provisions for convenient refueling and discharge.

Fuel efficiency of the hydrogen engine is significantly higher; due to completeness of combustion of the H2/air mixture; 30-40% more than the CNG/gasoline engine. But due to limited storage of hydrogen on-board, the range of the present hydrogen 3-wheeler is limited to 57 km compared to 150 km of the standard CNG 3-wheeler. The range can be enhanced to 150 km using advanced storage materials or higher capacity of the present MH storage system, capable of storing 1 kg or more of hydrogen. The compressed storage of hydrogen in specially developed very high pressure cylinders would also be competitive.

An inferior acceleration performance of the hydrogen 3-wheeler is seen in comparison to standard CNG/gasoline operation, primarily due to power loss on hydrogen which is an inherent feature of converted hydrogen engines using gas carburetion and lean burning. The performance of the hydrogen engine can be enhanced substantially using gas injection and redesigning the engine specifically for hydrogen use.

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Fig. 1a) MH Canisters

Fig.1b) Engine and Gas Kit

Fig.1 Test Vehicle

Table-1 Auto Fuel Properties of the Test Fuels

| Properties | Hydrogen | CNG | Gasoline |
|---|---|---|---|
| Lower heating value, MJ/kg | 120 | 43.5 | 43.1 (31.5 MJ/m3) |
| Density (gas) at STP (1 atm, 15 C), kg/m3 | 0.084 | 0.81 | ~4.4 |
| Density (liquid), kg/l | 0.071 | 0.42 | 0.73 |
| Octane rating, RON | 130 | 120 | 88 |
| Auto ignition temperature, C | 585 | 540 | 390 |
| Air/Fuel ratio (stoichiometric) by mass | 34.3 | 15.1 | 14.7 |
| Energy of stoichiometric mixture, MJ/m3 | 3.6 | 3.5 | 3.9 |
| Flammability limits in air, v% | 4-75 | 5.3-15 | 1-7.8 |
| Minimum ignition energy in air, MJ | 0.02 | 0.29 | 0.24 |
| Maximum flame speed in NTP air, cm/s | 265 | 33.5 | 39.6 |
| Diffusion co-efficient in air, cm/s | 0.61 | 0.16 | 0.05 |

Table-2  Fuel Efficiency of the Three Wheelers under Uniform Test Conditions

| Fuel | | Dist. traveled on test route, km | Fuel consumed | Fuel Efficiency | Fuel Efficiency km/l of GLE* |
|---|---|---|---|---|---|
| Hydrogen | Metal Hydride storage at 35 bar | 25 | 0.18 kg | 138.8 km/kg | 36.4 |
| | Compr. storage at 75 bar in 29 lit. WC cylinder | 24.8 | 0.17 kg | 145.8 km/kg | 38.3 |
| CNG | At 180 bar in 29 l WC cylinder | 26.3 | 0.66 kg | 39.6 km/kg | 28.7 |
| Gasoline | Limp back tank 3 liter | 25.3 | 1.0 liter | 25.3 km/liter | 25.3 |

* Gasoline liter equivalent (GLE) on energy basis

Table-3  Fuel Efficiency of the Three Wheelers under Normal Duty Cycle

| Fuel | | Range in one fill, km | Fuel consumed | Fuel Efficiency | Fuel Efficiency km/l of GLE* |
|---|---|---|---|---|---|
| Hydrogen | Metal Hydride storage at 35 bar | 56.8 | 0.43 kg | 132.1 km/kg | 34.7 |
| | Compr. storage at 75 bar in 29 lit. WC cylinder | 24.4 | 0.17 kg | 143.5 km/kg | 37.7 |
| CNG | At 180 bar in 29 l WC cylinder | 154.4 | 4.13 kg | 37.4 km/kg | 27.1 |
| Gasoline | Limp back tank 3 liter | 75.3 | 3.0 liter | 25.1 km/liter | 25.1 |

* Gasoline liter equivalent (GLE) on energy basis

Table-4  Acceleration Performance of the Three Wheelers

| Fuel | Time taken to cover 1 km in best possible manner, s | | Max speed achieved, km/h |
|---|---|---|---|
| | With pay load | Without payload | |
| Hydrogen | 155 | 142.5 | 35 |
| CNG | 123.5 | 108.5 | 55 |
| Gasoline | 102 | 99 | 60 |