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OVONIC METAL HYDRIDE BASED HYDROGEN ICE SCOOTER

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Abstract

Metal hydrides are solid-state, compact, and reversible means of hydrogen storage at low pressure; ideal for on-board hydrogen storage on two- and three-wheelers. Of the nearly 200 million gasoline ICE two-wheelers on the streets of the world, most of them are in the developing nations like India and China. Major cities in these countries have air pollution that has reached alarming levels. The merits of hydrogen as the ultimate clean fuel is well-accepted. Even as various means of hydrogen production and distribution are being debated, it is crucial to promote hydrogen-fuelled vehicle and metal hydride technology that can help achieve this goal. We report on the use of ECD's metal hydride storage modules for ICE scooter applications and also on the work undertaken by ECD to convert a gasoline ICE scooter to run on hydrogen.

Introduction

Globally two-wheelers create as much air pollution as the passenger cars over their lifetime. There are approximately 200 million two-wheelers on the streets of the world. This has resulted in extremely poor air quality in many of the cities in Asia. New Delhi has one of the worst air qualities in the world and hence stricter emission controls were mandated. Commendable measures are being undertaken to convert all public transport vehicles (buses, taxis and three-wheelers) to CNG. As a result the air quality has improved in a relatively short time. However, this is not a long-term solution since CNG is a limited resource. For a long-term solution non-depletable and sustainable energy sources are being considered [1,2].

As a part of the program partially funded by the U.S. DOE Hydrogen Energy Program, ECD is involved in converting a gasoline ICE scooter to run on hydrogen, in addition to developing metal hydrides and on-board metal hydride storage system for the scooter and determining the cost and availability of renewable hydrogen.

This paper will report some of the properties of ECD's low-temperature metal hydrides and hydrogen storage modules. Preliminary results on the conversion of a Honda Elite 80 gasoline scooter will also be discussed.

Metal Hydride Storage Systems for H-ICE Scooters

ECD has developed metal hydrides with suitable thermodynamic and kinetic properties for use in the H-ICE scooters [3]. The cycle life (hydriding – dehydriding) of the alloys in the presence of pure hydrogen and in the presence of hydrogen with trace contaminants (CO and moisture) was determined. The alloy that was chosen for use in the storage system has 1.5 wt% reversible storage capacity at 30°C, above 1 atm pressure. The alloy was cycled 1080 times in pure hydrogen without any measurable loss in reversible storage capacity. The alloy has good cycle life in hydrogen containing 0.1 vol% CO (over 320 cycles), and slightly modified alloy composition shows improved moisture resistance, as indicated by a test of 532 cycles with hydrogen containing 100 ppmv moisture. Large quantity of the alloy was manufactured in ECD's production facility by induction melting. The material is reduced in size and packaged to optimize the heat and mass transfer characteristics. An ideal metal hydride (MH) storage module design for hydrogen ICE scooter will depend on the several considerations such as:

1. Desired driving range
2. Drive cycle
3. Thermodynamic and kinetic properties of the alloy
4. Geometrical considerations

Two types of MH modules were tested their hydrogen charge/discharge characteristics. They are air heat exchange modules (OAC) and liquid heat exchange (OTP) modules, as shown in Figure 1. The air heat exchange modules are suitable for smaller scooters like Honda Elite 80, which has an air-cooled engine. The liquid heat exchange modules could be conveniently integrated into larger scooters such as Honda Helix, which are equipped with liquid-cooled ICE engine. Their technical specifications are summarized and listed in Table 1.

Hydrogen discharge characteristic from OAC-1 are shown in Figure 2. In the ambient air, OAC-1 module delivers hydrogen up to 30 minutes at a constant rate of 25 SLM (standard liter per minute), the estimated rate of hydrogen consumption by Honda Elite. No sophisticated thermal management is necessary for achieving a good reversible desorption of the stored hydrogen.

Figure 1: Ovonic prototype OAC-1 and OTP-1 metal hydride hydrogen storage modules.

Table 1: Specifications of OAC-1 and OTP-1 storage modules

Modules	Total Weight (kg)	Foot Print (inxinxin)	Charging Pressure (psig)	Charging Duration (hour)	Hydrogen Stored (gram)
OAC-1	20	5×18×12	150	1.5	120
OTP-1	35	5×18×9	150	3.5	300

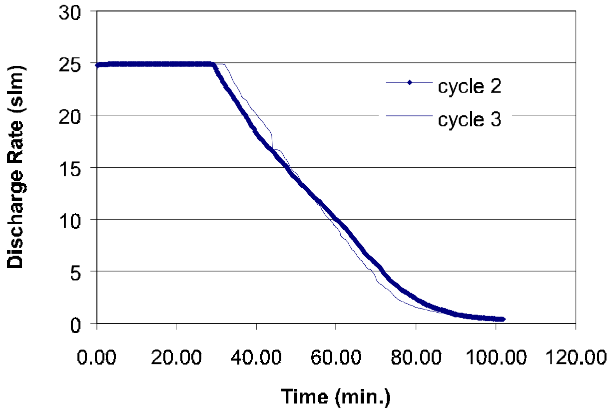

Figure 2: Hydrogen discharge rate of OAC-1 storage module in ambient air

Metal Hydride – Electrolyzer System

Availability of hydrogen to meet the refueling needs of the H-ICE two-wheelers is very important for the long-term field testing and evaluation of the hydrogen ICE with on-board metal hydride. The hydrogen produced in the short-term may be derived from fossil fuel but would ultimately be derived from renewable sources and processes. ECD is addressing renewable means to produce hydrogen via water electrolysis using either PV power or using bagasse cogeneration power. The cost comparison of these two approaches is being evaluated.

ECD has negotiated an agreement to integrate metal hydride storage systems with an alkaline electrolyzer (IMET® 10) manufactured by Hydrogen Systems (Montreal, Quebec, Canada). The electrolyzer delivers hydrogen at a rate of 180 slpm at 150 psig. The moisture and oxygen from the product hydrogen will be removed using an external dryer and deoxygenation system. The pressure and purity of the product electrolytic hydrogen has been found suitable to charge the metal hydride. Estimates show that the IMET® 10 can feed hydrogen to either 50 OTP storage systems or to 120 OAC storage systems.

Specifications and Performance of Gasoline Scooter Engine

Scooter engine specification/vehicle description

The Honda Elite CH 80, 2000-year model, four-stroke scooter with a 79 cc engine, was screened for oil control and was found to be satisfactory. Good oil control minimizes the problem of unwanted combustion by the carbon residual deposits from the oil.

Some of the salient features are given below, and with more details in the scooter manual [4].

The engine is an air-cooled, 4 –stroke single cylinder engine with overhead cam.

Bore x stroke		49.5x41.4mm
Displacement		79.7 cc
Compression ratio		9.3:1
Cylinder compression		199 psig
Intake valve	Opens	0 deg BTDC (before top dead center) at 1mm lift
	Closes	20 deg ABDC (after bottom dead center) at 1 mm lift
Exhaust valve	Opens	-2.5 deg BBDC (before bottom dead center) at 1 mm lift
	Closes	30 deg ATDC (after top dead center) at 1 mm lift
Idle speed		1800 +/- 100 rpm
Ignition timing		18 deg BTDC at 1800 rpm (idle), advance starts at 2400 rpm and full advance to 27 deg at 3000 rpm.
Vehicle capacity load		152 Kg
Transmission		V-belt drive, CVT
Gear ratio		2.8 – 1.08
Final reduction		8.382:1
Carburetion		16 mm venturi diameter

Instrumentation and data acquisition

A magnetic pick-up is located on the stator assembly (mounted on the crank shaft) that provides the pulse that triggers the spark plug. The spark plug is fired twice in an engine cycle; once during the power stroke and once during the exhaust stroke. The vehicle was fitted with an on-board data acquisition unit (Advantage Motor Sports, Flemington, New Jersey). Initially the unit was configured to measure the engine RPM and the front wheel speed. Later the cylinder head temperature (CHT, type J or type K) and the exhaust gas temperature (EGT, type K) were included. The CHT is measured at the spark plug. The data can be exported into an Excel spreadsheet.

Baseline performance with gasoline

The performance of the scooter with gasoline was studied. A water brake engine dynamometer (Go Power Corp, Palo Alto, California) was mounted to the crankshaft of the engine. A 50 lb load cell (model LC101-50, Omegadyne) was connected to a 6" load-arm to read the load. The load value could be directly read from a display/power supply unit – Omega DP-25 S. Additionally, the DC voltage output from the load cell could be measured with a voltmeter and the load value determined from a calibration chart. RPM was measured with an inductively coupled pick-up that was part of the Advantage Motorsports' data acquisition unit. The transmission between the crankshaft and the rear wheel was decoupled.

With the engine idling, the exhaust temperature, the temperature of the air around the engine, the engine body and the exhaust skin temperatures were measured with a type K thermocouple after warming the engine for approximately 10 –15 minutes. The readings are listed below:

Engine body	200 –225 F
Exhaust	170 F
Air around the engine	135 F – 150 F
Exhaust skin	225 F (measured at the end of the exhaust tail pipe)

A digital tachometer (MHT 96 meter, Track Master, Inc, Taylor, Michigan) that works on the principle of inductive pick-up was included to get a direct display of the engine rpm.

The baseline performance of gasoline powered Elite was determined. Load is applied at WOT by controlling the water inlet valve to the dynamometer. A constant rpm was maintained for 2 minutes before moving to the next data point and measurements were done in the rpm range of 2000-6000. A plot of power, and torque versus rpm is shown in Figure 3. We see that the engine is capable of producing 3.8 hp at 6000 rpm and the torque changes by 28 %, from 3.5 N-m to 4.5 N-m as the rpm changes from 2000 – 6000. The exhaust temperature ranged between 380 – 600 deg C.

Conversion to Run on Hydrogen

Three different methods were adopted to introduce hydrogen to the engine, viz:

a. Modify the carburetor, admit hydrogen continuously at the throat of the carburetor
b. Admit hydrogen continuously into the intake manifold
c. Timed-fuel injection into the intake manifold

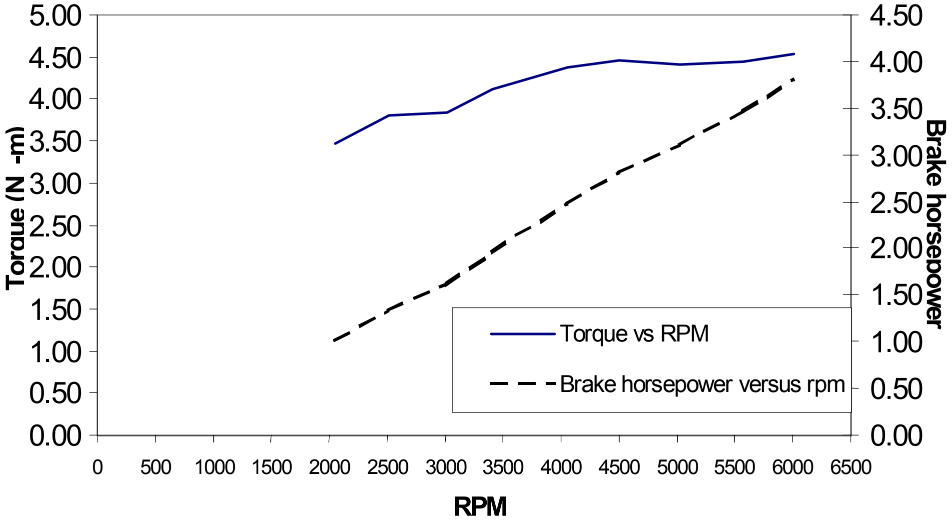

Figure 3: Torque and EGT versus rpm for a gasoline Honda Elite 80 cc scooter engine, ignition at 18 deg BTDC.

Instrumentation

For preliminary testing, hydrogen was supplied from a compressed gas cylinder (UHP grade, AGA size 049, 2400 psig pressure) regulated to operating pressure of 20 psig or lower. Hydrogen flow was measured using a correlated rotameter (Porter Instruments), 150 mm in length with a 1/4" stainless steel float (density: 8.03 gm/cc, 1.063 grams). Correlation charts and correction factors for pressure and temperature were obtained from the manufacturer. An orifice plate (Lambda Square, Inc, Bay shore, New York) will be used to determine the hydrogen flow rate. The upstream pressure (Omega PX 176), the differential pressure drop (Sensotec, Columbus, Ohio) across the orifice plate and the gas temperature (type K thermocouple) will be required to calculate the hydrogen flow rate. In addition to the Advantage Motorsports' D/A unit, a portable data logger from Omega (Omega 3000) was used to log up to three voltage and three temperature readings. A double barrier flash arrester (Kemp, Florida) was installed close to the carburetor/intake manifold to prevent the flame from reaching the hydrogen source. A 5-gas exhaust emission analyzer (TIF, Florida) was used to measure and log the concentration of oxygen and NOx in the exhaust gas. A portable hydrogen leak analyzer (A Ti technologies, Pennsylvania) was also used to measure the hydrogen concentration in the exhaust and to detect hydrogen leaks elsewhere in the test station.

Ignition system modification

The spark plug was triggered off the cam rather than the crankshaft. This eliminates the spark in the exhaust stroke and minimizes the possibility of backfiring. The spark trigger from the cam was used in all the runs with hydrogen gas.

Carburetor modifications and hydrogen induction into carburetor

Hydrogen was delivered into the throat of the carburetor at 8 – 10 psig. Stock timing (18° BTDC) was used. The measured load, hydrogen flow and RPM are given below in Table 2. The modifications carried out are as follows:

- Removed the float bowl chamber, closed the float chamber with a flat aluminum plate with a 1/8” NPT port to admit hydrogen
- Opened up the metering (main) jet from 0.032” to 0.04” to allow more hydrogen flow.

Table 2: Performance characteristics of Elite 80 with hydrogen into carburetor

Run #	Avg RPM	Engine Temperature (deg C)				EGT deg C	Torque (N-m)	Power (hP)	H_2 flow rate (l/min @ Pr. psig)
		T1	T2	T3	Avg. CHT				
1	2317	56		67	95	235	1.36	0.44	17.6 @ 6 psi
2	2417	62	66		103	232	1.56	0.55	18.5 @ 8 psi
3	2822	61	64	74	128	224	1.39	0.59	36.9 @ 8 psi
4	3269	67	72	89	144	277	1.19	0.55	23 @ 8 psi
5	3891	74			133	270	1.02	0.56	23 @ 8 psi
6	4258	76	79		144	318	0.92	0.54	21.2 @ 8 psi
7	3720	84	92		157	294	1.36	0.67	23 @ 8 psi

Figure 4 shows the torque and power curve versus rpm for the run described above. The exhaust gas temperature ranges between 200 – 350 deg C and increases with engine speed. The peak torque of 1.5 N-m is generated at ~ 2400 rpm and the peak power of 0.7 hP at 3700 rpm. The NOx and oxygen concentration in the exhaust were monitored and the NOx level was low (less than 10 ppm) when the engine was running lean ($\lambda > 4$). However, on occasions when more load was applied on the dynamometer, the rpm decreased and to keep the rpm high, more hydrogen was admitted. This resulted in the NOx level increasing steadily from 200 ppm (λ =3) to as high as 3000 ppm (λ=1). The engine quits running when the mix got rich. The engine was backfiring. The spark plug (NGK, 10 mm) shows grayish blue appearance suggestive of very high temperature at the spark plug and may promote preignition. It was felt that the constant presence of hydrogen-oxygen (air) mix in the carburetor was a probable cause for unwanted combustion. Hence it was decided to admit the hydrogen into the inlet manifold. It should also be noted that the fuel-air mix is lean and that may partially explain the low power output.

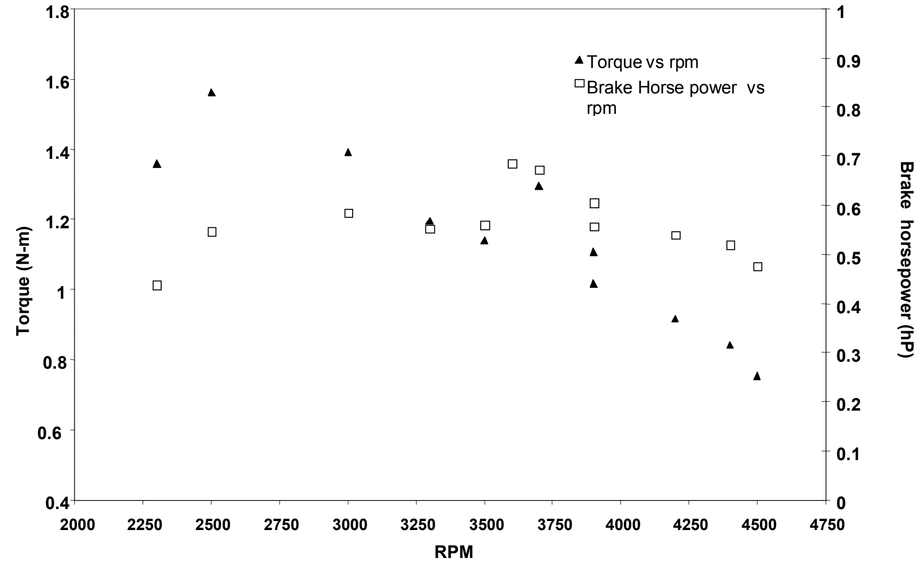

Figure 4: Torque and power versus rpm for hydrogen ICE Honda Elite 80 cc scooter at WOT (wide open throttle), lambda = 3 - 5

Hydrogen induction into the inlet manifold

The NGK spark plug was replaced with a BOSCH surface gap spark plug (10mm) that is known to run cooler. The hydrogen port in the carburetor was closed and instead hydrogen was fed into the inlet manifold, downstream of the carburetor. The carburetor was otherwise intact and the throttle valve was still being used to control the airflow. Several experiments were conducted by varying the spark timing to the following values:

The ignition was timed to occur at 45°, 21° and 18° BTDC. The spark occurs at 18° BTDC (at < 2400 rpm) and the CDI advances it to 27° BTDC at 3000 rpm. A type K thermocouple was used to measure the CHT at the spark plug. The scooter engine attained temperature of 138 deg C (280 F) after 40 min. A maximum torque of 1.3 N-m was generated at 3600 rpm. At higher RPM increasing the load on the engine resulted in the engine stalling. Compared to the other runs, the engine temperature did not rise sharply. With the spark timing fixed at 18 deg BTDC, the scooter was tested once again to determine the torque and power curve versus rpm (Figure 5).

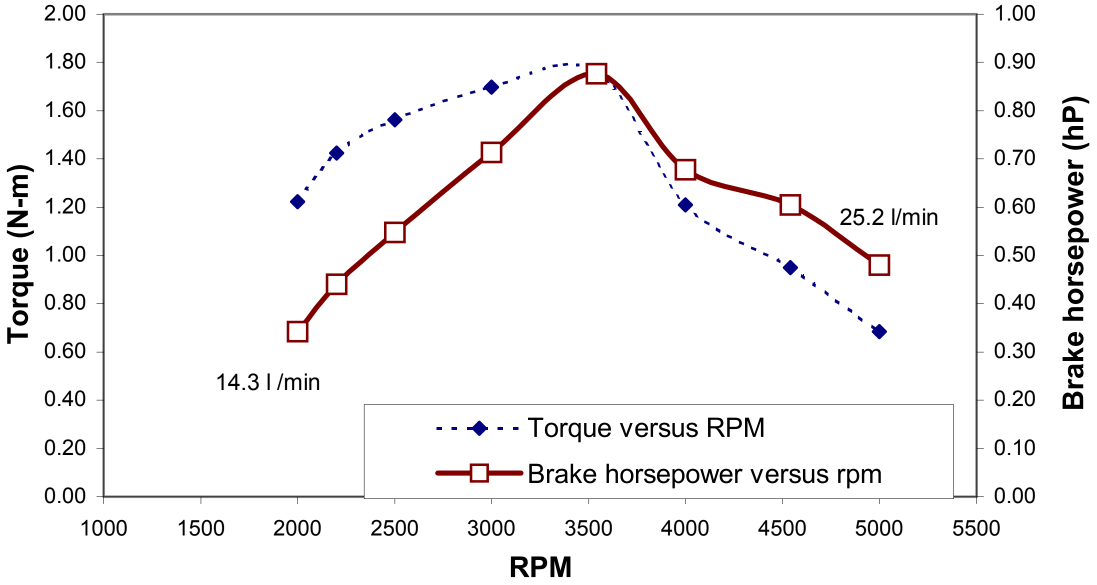

Figure 5: Performance characteristics of a Honda Elite 80 cc, hydrogen admitted into intake manifold at WOT, lambda = 2

We see that the engine develops peak torque of 1.8 N-m at 3500 rpm and falls rather rapidly at higher speeds. The ignition timing undergoes an advance to 27° BTDC at 3000 rpm. This may be a reason why the torque drops very sharply at higher speed.

Timed manifold induction of hydrogen

Continuous hydrogen induction into the intake manifold still results in frequent back-firing of the engine. In order to minimize this, fuel injection was timed using an ECU (Electronics Control Unit, Velcam Consulting, Detroit, MI). The ECU uses for input the signals from a Manifold Absolute Pressure (MAP) sensor, a Throttle Position Sensor (TPS) and the Top Dead Center (TDC) signal from a Variable Reluctance sensor. The fuel injector pulse width is determined based on these input and varies between 3 ms and 10 ms depending on the MAP and throttle position. Two fuel injectors were used to obtain high enough flow at low supply pressure (10 psig or lower) so that lambda values close to 2 or lower could be achieved at Wide Open Throttle (WOT.) The fuel injectors open after the exhaust valve has closed during the intake stroke following the valve overlap period. This is likely to help in two ways,

- dilute and cool the exhaust gas in the residual volume
- minimize back-firing by not mixing hydrogen with hot exhaust gas

No significant gain in power was observed by using timed injection of hydrogen; however there was significant reduction in backfiring as lambda values approached 2 or lower.

Having succeeded in minimizing the occurrence of backfiring using Timed-Manifold Injection, it was decided to use hydrogen from a metal hydride instead of a compressed gas cylinder.

The objective of the next run was to establish the driving range of the scooter with on-board metal hydride. OAC-1 was used for on-board hydrogen storage and exchanged heat passively with the hot exhaust. The storage system was placed in close contact with the hot-exhaust tubing and the heat-exchange between the storage system and the exhaust tube was realized using natural convection or forced convection of ambient air. The RPM was fixed around 3000 –3200 rpm where the peak power is produced. The parameters and the performance results are summarized below:

On-board hydrogen storage	120 grams
Total duration of the run	77 minutes
RPM range	2990-3200
Brake Horsepower	0.3 – 0.6 hP
Estimated vehicle speed at 3000 rpm	16 mph (26 kph, at high gear)
Range	22 miles (33 km)
Approximate hydrogen consumption	3.6 grams/km (120 grams of H_2 was used)

Table 3 below shows the performance in a different run at WOT with hydrogen supplied from a metal hydride pack (OAC -1) with 120 grams of reversible hydrogen storage capacity.

Table 3: Performance of Honda Elite 80 supplied with hydrogen from metal hydride pack

RPM	EGT (^{O}C)	Lambda	Torque (N-m)	Power (hP)	H_2 flow (L/min)	H_2 pressure (psig)
2500	124	3	1.8	0.62	23.7	14
3000	201	2.4	1.6	0.66	24	8
3500	221	2.3	1.4	0.67	27.9	10

Discussion

Conversion of a gasoline ICE to hydrogen ICE is on-going at ECD. We have converted a Honda Elite 80 cc scooter to run on hydrogen. Due to the wide flammability range of hydrogen and the low ignition energy required, the problem of back-firing is common. The ignition timing that results in the maximum torque with hydrogen has to be determined. For most of the tests spark timing of 18° BTDC (up to 2400 rpm) was used. The stock CDI (capacitive discharge unit) progressively advances the timing to 27° BTDC at 3000 rpm. The present spark trigger configuration allows changing the spark timing only on the advanced side. In fact, retarded ignition is recommended for hydrogen since it burns faster than gasoline.

Preliminary tests have been carried out with on-board hydrogen storage in a metal hydride. Hydrogen desorption is an endothermic reaction and the metal hydride exchanges heat with the exhaust gas passively. The equilibrium plateau pressure increases with increase in temperature at a given hydrogen concentration in the alloy. It is important to have a good exchange of heat so that the supply pressure is high enough at the injector to allow for sufficient hydrogen injection. Rapidly dropping hydrogen supply pressure due to insufficient heat exchange appears to affect the hydrogen flow. This results in a fuel-air ratio that progressively becomes leaner and the power output decreases at a given throttle position.

An orifice plate is being used to measure the hydrogen flow rate, in addition to a rotameter. If this is found to be acceptable (in terms of accuracy and repeatability) it will be considered for on-board fuel measurement. A ‘fuel gauge’ built around this orifice plate would determine the state of charge of the metal hydride bed.

Conclusions

In this paper, we have evaluated the suitability of an Ovonic Metal Hydride for on-board hydrogen storage for a near-term application of hydrogen technology, namely hydrogen ICE scooter. The metal hydride storage system used (OAC –1) stores 120 grams of hydrogen (reversible capacity). The storage system supplied hydrogen for 77 min to the engine that is unoptimized. This translates to a range of approx 33 km at a speed of 26 kph.

Future Work

Tests are on-going with hydrogen induction timed into the intake manifold with an electronic fuel injection controller. An electronic spark ignition system purchased from MSD Ignition would enable us to change the spark ignition timing to obtain the maximum torque. In addition to engine dynamometer testing, chassis dyno testing under typical driving cycles will be carried out to evaluate the performance of the scooter. In addition to completing the tests on Honda Elite 80, we will also convert a Honda Helix, which has a 250-cc, water-cooled, four-stroke engine. Further alloy development and storage system development work will be carried out to improve the driving range of the vehicle and to reduce the system weight.

Acknowledgement

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