Second International Conference on
Fuel Cell Science, Engineering and Technology
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FuelCell2004 – 2457

TECHNOLOGY STATUS AND DESIGN OVERVIEW OF A HYBRID FUEL CELL ENGINE FOR A MOTORCYCLE

Nathan J. English[1] **and Ramesh K. Shah**[2]
[1]Rochester Institute of Technology, Rochester, NY, USA; E-mail: nje4319@rit.edu
[2]Rochester Institute of Technology, Rochester, NY, USA; E-mail: rkseme@rit.edu

ABSTRACT

The global development of fuel cell based propulsion has emphasized larger vehicles, with most manufacturers demonstrating a car, van or truck. However, the transportation market in many countries is dominated by smaller two and three wheeled vehicles. A fuel cell motorcycle could replace two stroke scooters that proliferate emissions, as well as, their electric counterparts that require long recharges for short ranges, and also four stroke motorcycles. This paper is a review and assessment of literature relating to the design and analysis of hybrid electric fuel cell motorcycle engines. The engine design is intended for a specific demonstration motorcycle, but should be able to scale down to a scooter size, or be adapted to work in other small vehicles. The proton exchange membrane fuel cell system utilizes an ambient air blower, pure hydrogen storage in metal hydrides, a control system, active liquid cooling, a radiator, power conditioning and water management systems.

INTRODUCTION

The turn of the century has seen a global push by automotive manufacturers to research, develop, and market environmentally friendly, efficient vehicles. Initial efforts emphasized the reduction of emissions from Internal Combustion Engines (ICEs) and have been met with much success. Still, environmental and health concerns dictate that more emissions reduction is needed and alternative energy sources such as bio fuels, clean electricity, hydrogen, solar energy and other renewable energy sources are being looked at. There is also concern about the longevity of the oil supply and the tremulous politics that often accompanies it. A major trend in the industry is toward commercialization of fuel cell powered electric vehicles, which are more energy efficient than ICEs. Currently, the hydrogen fueled Proton Exchange Membrane (PEM) fuel cell is popular, as it operates within a range of relatively low temperatures, has a good power density, is relatively robust, responds promptly to demand, starts quickly and produces no local emissions.

Industry has focused on the larger and more profitable vehicles, and there has been relatively little development of fuel cell systems for motorcycles. Most existing work has been done on smaller scooters. Here, a motorcycle is considered to be capable of adequate highway and city driving, whereas a scooter is only capable of city driving, and a moped is a scooter that requires power input from the rider. It is logical that motorcycles will follow suite if there is a large paradigm shift toward hydrogen in the automotive industry. However, the technology might not be easily scaled down. Studies by Tso and Chang (2003) and Wang et al. (2000) indicate that motorcycles would be a suitable application for fuel cells, and also one with an easier to implement infrastructure transition.

An excellent thesis written by Lin (1999) explores most every design feature of a fuel cell powered scooter on a theoretically basis. The paper considers both hybrid and pure fuel cell designs, but only in the under 6 kW of peak power range. There is an in-depth discussion about application in Taiwan, as well as, cost projections for advancing technology and economy of scale cost reductions. The design would be similar in many aspects; however, the present work focuses on the Western driving conditions, which require larger vehicles. The significant increase in peak power means that a motorcycle designed for the West would perform equally well in a crowded Asian city, while a scooter designed for city driving in Taiwan would not be accepted for highway driving in the US. The paper will not look at the powerful racing motorcycles that are popular, but at motorcycles used for commuting.

The key motivator for fuel cell powered motorcycles is the emissions problem. Small ICEs come in both two and four stroke varieties. The four stroke engines are used in larger vehicles and although they can be engineered for smaller systems, they are more complex and expensive. The majority of Western motorcycles use four stroke engines. However, the two stroke engines are very common in scooters and smaller motorcycles, as they provide a good power density with a simple system. As there are only two strokes, the engine must draw in fresh fuel while it is exhausting and this leads to unburnt hydrocarbons being released to the atmosphere. Also, in order to lubricate the mechanical parts, an oil fuel mix is used and this leads to burning of the oil, as well as, atomized oil being exhausted. The net effect is to produce a large volume of pollutants from a relatively small engine. Small four stroke engines are not as polluting as the two strokes, but the net pollution is still unavoidable and significant. Furthermore, in developing countries, it is not uncommon to use kerosene as a cheap fuel, which produces even more pollution. Countries such as Taiwan have had to tighten pollution regulations to the point that adequate two stroke systems are a challenge to produce and are no longer as simple and cheap. Some companies are developing small four stroke engines as a replacement, but many others are changing to battery-powered electric motors. In the fuel cycle of a PEM motorcycle, the emissions are produced at a central location where the fuel is processed into hydrogen. This centralization increases efficiency and gives more control over the product emissions.

The long term goal is to research and construct a fuel cell engine capable of powering a motorcycle, perform testing on this engine for optimization, and prepare it for installment in an appropriate vehicle for demonstration purposes. The present work is a preliminary look at what will need to be considered for that engine and a review of published information on similar systems. The desire is to promote the development of fuel cell powered motorcycles in coincidence with the industrial development of fuel cell automobiles. This paper will consider a full sized, though not large, motorcycle with a maximum gross power production of 25 kW (5 kW fuel cell power and 20 kW of peaking power for acceleration), although economics might necessitate scaling the prototype down. This power range exceeds that of most previous prototypes and relates to gasoline (petrol) powered motorcycles with engine displacements in the 250 cc size range.

TECHNOLOGY STATUS

The automotive industry has focused on vehicles with large power requirements such as cars, trucks, boats and buses, using fuel cells with 50 kW of power or greater. To meet varying power demands, the dynamic ability of the cell is used by controlling fuel and air supply to the stack. There has been some interest in the 10-50 kW range for hybrid vehicles using auxiliary electrical storage. For example, Fuel Cells 2000 [1] reports that the Mazda Demio, a concept passenger car, uses only 20 kW of fuel cell power in conjunction with a bank of supercapacitors. Other industries such as consumer electronics, medical equipment and the military have worked on the lower than 1 kW range, but less has been done in the 1-10 kW range.

The 1-10 kW range includes a diverse selection of small vehicles such as motorcycles, scooters, wheel chairs, forklifts, all terrain vehicles (ATVs), leisure watercraft and utility vehicles. Specifically, two and three wheel transports are globally pervasive, accounting for a quarter of all vehicles in some European countries, and up to three quarters in some Asian countries such as Taiwan, Indonesia, Thailand and India. The current movement is toward purely electric systems powered by batteries. However, with some development and mass production, fuel cell systems should be an excellent fit for these vehicles. Of course, different vehicles will have different geometric constraints, but the components of the motorcycle engine should be modular enough to re-configure. The key adjustment would be for the different drive cycle of each vehicle, in which case, the fuel cell components can remain constant while the peak power handling devices are modified.

It is worthwhile to note that fuel cell engines have already been constructed, within a similar power range, both for two-wheeled vehicles and otherwise. Also, although purely electric vehicles use a different power source, they share the same drive train, and shed light on fuel cell configurations in general. There are many small all-electric vehicles of similar power specifications that are already available or are in development.

Electric scooters and mopeds are certainly widespread, though perhaps not especially popular, with a movement toward 48 V systems in larger units. Unfortunately, the majority of them are not built for more than a few kWs of power. Individuals and racing teams have made powerful electric drag racing motorcycles [2], but they are not produced commercially or practical for long distances. One notable exception is the Electric Motorbike Inc. (EMB) Lectra [3, 4]. Production of the Lectra ended in 2000, but it is capable of 80 km/h (50 mph) and distances of up to 56 km (35 mi) before recharging, depending on load. The 104 Ah, 24 V battery pack consists of four Optima D750 lead acid automotive batteries. Another company, eCycle Inc. [5], made a prototype electric motorcycle, but the project was terminated and they have focused recent efforts on a diesel electric hybrid.

The first fuel cell motorcycle was built by Karl Kordesch in 1967 [19]. It implemented an alkakaline fuel cell system fueled by a hydrazine solution. On one gallon of fuel, the motorcycle could travel 322 km (200 mi) at a speed of 40 km/h (25 mph). The prototype was built for research purposes only and was not duplicated.

A joint effort between Parker Hannifin and Vectrix [6] has patented, with hopes of commercialization, a scooter styled vehicle with power comparable to a small motorcycle. The system is a PEM and Ni-MH battery hybrid using direct methanol fuel. Published specifications are limited, but they claim quick acceleration to a maximum speed of 100 km/h (62 mph) and a range of 250 km (156 mi).

A smaller scooter that is moving toward marketable production is the Asia Pacific Fuel Cell Technologies' (APFCT) ZES series [7]. The hydrogen is stored in metal hydrides and the stack operates up to 5.5 kW with no peak power device. The scooter can attain a max speed of 58 km/h (36 mph) with a range of 120 km (75 mi) before refueling.

One fully sized and powered concept is the hydrogen fuel cell powered Bombardier EMBRIO [8]. This unique system is controlled by gyroscopes so that the EMBRIO begins on three wheels, but relies on only one larger wheel at higher speeds. For most driving conditions, it is operating as a unicycle. The EMBRIO is only a design exercise and no prototypes have been made.

Parallel to the work of Lin (1999), Arne Laven at the Desert Research Institute [9] built a prototype scooter with a 3 kW PEM using hydrogen stored in metal hydrides and ultracapacitors providing peaking power.

Geiger (2003) reports the design of an urban moped, "Hunter", by Peter Jaensch. The vehicle uses a 3 kW stack at 48 V. The moped is only a concept vehicle, but should be capable of a 100 km (62 mi) distance at top speeds of 45 km/h (28 mph) before refueling. Compressed H_2 in a six liter canister is used for fuel and the work suggests that an infrastructure could be developed in which empty canisters are exchanged for full ones at retail sites such as supermarkets and convenience stores.

Yamaha [10] has been promising fuel cell motorcycle development, but the current extent is the FC06 scooter that is comparable to a 50 cc ICE scooter and runs on a 500 W PEM using direct methanol fuel.

Several companies, such as Manhattan Scientifics, Aprilia [11] and Palcan Fuel Cells, have worked on fuel cell assisted bicycles. These were very small units that provide extra cycling power on the order of less than 1 kW. Cardinali et al. (2002) describe the system used for a 300 W power assisting unit for a bicycle, using compressed hydrogen and a PEM. A good analysis of this type of system has been done by Colella (2000), who has also constructed a prototype. The bike's design was geared toward countries in which a lower standard of living and road congestion has led to smaller vehicles and slower road speeds (16 km/h, 10 mph average). Not only would this bike be a good match for these markets, but it would also be more effective in a transition to alternative fuels due to the difference in capital costs between scooters and full scale automobiles, as well as, the population concentration (one H_2 station could service many people). Her prototype uses a small compressed hydrogen cylinder.

Astris Energi [12] has made an alkaline fuel cell powered golf cart that runs on compressed hydrogen. It has a hybrid system designed for a 3.6 kW fuel cell providing base power along with a battery for peaking power. The Astris stack is capable of quick startups, uses ambient air, and operates within a similar temperature range as a PEM. The cart is capable of 40 km/h (25 mph) and 7 hours of driving between refills.

Schatz Energy Research Center [13] has produced a fuel cell golf car, as well as, a four wheel Neighborhood Electric Vehicle (NEV). Both platforms use compressed hydrogen and do not mention peak power devices. The golf cart uses a 4 kW fuel cell and is capable of traveling 24 km (15 mi) at 20 km/h (12.5 mph). The NEV uses a 9 kW fuel cell and is capable of traveling 48 km (30 mi) at 56 km/h (35 mph).

Table 1. Comparison of Published Data on Current Technology. [Compiled from Geiger (2003) and the data of Refs. (3-13)].

	Stack Power (kW)	Fuel or H_2 storage	Max Speed (km/h)	Range (km)	Status
EMB Lectra (electric)	n/a	2,500 Wh lead acid battery	80	56	production ended
Parker scooter	n/a hybrid	methanol	100	250	production planned
APFCT scooter	5.5	metal hydrides	58	120	production planned
Hunter moped	3.0	compression cylinder	45	100	on paper
Yamaha scooter	0.50	methanol	n/a	n/a	prototype
Astris golf cart	3.6	compression cylinder	40	280	prototype
Schatz golf cart	4.0	compression cylinder	20	24	prototype
Schatz NEV	9.0	compression cylinder	56	48	prototype
Aprilia bicycle	3.0	compression cylinder	56	193	prototype

Table 1 provides a comparison of the today's technologies. Most companies have only produced a prototype and do not plan on mass production. The two most important challenges for commercial production are: (1) The development of the hydrogen infrastructure, whether in the form of hydrogen storage in metal hydride canisters, pressurized hydrogen tanks, or even in a carrier fuel such as methanol; the choice will depend on the cost, driving range and fuel cell system efficiency. (2) The high initial cost, with government incentives being essential for the development of the H_2 infrastructure and providing subsidies to make the fuel cell motorcycle reasonably competitive with the current technology at the onset. Certainly, the progress on the commercialization of fuel cell powered motorcycles/scooters is not taking place due to the foregoing reasons. However, companies such as Parker Hannifin and APFCT are currently poised to begin production now, or as soon as the greater automotive industry begins to transition.

DESIGN OVERVIEW

Basic Calculations

The power P_w in W, needed for driving a motorcycle, is given by,

$$P_w = mVa + C_{rr}mVg + \tfrac{1}{2}C_d A_f \rho_{air} V^3 \qquad (1)$$

where m is the mass of the fully-loaded motorcycle, kg; V is the driving speed, m/s; a is the acceleration, m/s^2; C_{rr} is the coefficient of rolling resistance, dimensionless; g is the gravitational acceleration, m/s^2; C_d is the drag coefficient, dimensionless; A_f is the projected frontal area of the motorcycle, m^2; and ρ_{air} is the density of air, kg/m^3. This type of analysis has been conducted by Wong (2001), with the equation resulting from a balance of the main forces acting on the motorcycle.

The electrochemical reaction between hydrogen and oxygen (from air) in the presence of catalysts in a PEM fuel cell governs the production of electricity along with heat and water/steam as byproducts. The relationships can be generalized to a whole stack, and also be put in terms of the stack operating power P_e, W; individual cell voltage V_c, V. The PEM air and hydrogen usage, and water and heat production rates in terms of P_e and V_c, are given by Larminie and Dicks (2003) for the air stoichiometric value λ as follows,

$$\text{Air usage} = 3.57\times10^{-7}\,\lambda\,(P_e/V_c)\ \text{kg/s} \qquad (2)$$

$$\text{Hydrogen usage} = 1.05\times10^{-8}\,(P_e/V_c)\ \text{kg/s} \qquad (3)$$

$$\text{Water Produced} = 9.3410^{-8}\,(P_e/V_c)\ \text{kg/s} \qquad (4)$$

$$\text{Heat Produced} = P_e(1.25/V_c - 1)\ \text{W} \qquad (5)$$

As dictated by physics, the desired power output can be given by the following,

$$\text{Desired Power Pe} = (nV_c)(miA_c)\ \text{W} \qquad (6)$$

where n is the number of cells per stack, m is the number of stacks used, i is the current, and A_c is the active area of a cell. The operational voltage is given by the first term in parenthesis and the total current is given by the second. Of course, during operation the cell voltages will drop as the current draw is increased.

Power Production and Drive Cycle

The fuel cell motorcycle would ideally replace or compete with ICE motorcycles having 250 cc displacement engines. These are small motorcycles that are capable of handling Western driving conditions, and though they might not set any speed or power records, they are competitive in the low end market. Also, they closely match vehicles that are popular in developing countries, where markets for such vehicles are much larger. Some examples of comparable ICE motorcycles are the Kawasaki Ninja 250R, Honda Nighthawk 250, and Yamaha Virago 250. Dynamometer testing of these models by Bartels et al. (1997) show a maximum power at the wheel between 15-27 hp (11-20 kW). A system capable of producing a gross power of 25 kW should be able to handle similar peak power requirements after net losses.

One important point from the work of Lin (1999) is that for scooters, as for most road vehicles, the difference between average power and peak power is significant. In the case of scooters, the power that is needed for acceleration on a grade is on the order of ten times that needed for cruising. The difference is particularly high for scooters due to rapid acceleration and deceleration changes during a usual drive cycle. Designing for average power consumption on a larger motorcycle, a more conservative difference of five times is used, or an average power of 5 kW for this system. Due to the cost of fuel cell technology, the necessity of complex subsystems for larger stacks, and size and weight considerations, it is preferable to use a smaller stack. Lin analyzed both pure and hybrid fuel cell systems, and concluded that for all practical purposes a hybrid system is sufficient, so long as the fuel cell can meet the average power requirements. Therefore, a hybrid system is considered that uses a fuel cell capable of operating at 5 kW and 20 kW of additional peaking power. Note that this is four times larger than Lin’s system.

The internal processes of any specific stack will not be considered. The fuel cell will be taken as a given device that is capable of continuously producing the specified power at an acceptable efficiency. The fuel cell output will generally be kept continuous, though there will be transients in startup and shutdown. Also, if the peak power device is satisfactorily charged and less power is needed, the fuel cell will be throttled down. An example of an acceptable unit would be one with 80 cells and a 250 cm^2 active area per cell. With an average cell voltage of 0.6 V the stack would operate at 48 V and 104 A. This would be a 50% efficiency at 0.42 A/cm^2. Of course, availability is another issue. It might be necessary to use a larger stack or combine several smaller stacks. Several retail options are currently available within this range [17,18].

To ensure that 5 kW will be adequate for average power, some fundamental power calculations are performed. Using the US standard federal drive cycle (FTP75), with the modified cycle for aggressive driving (US06) [14], the acceleration requirements of the motorcycle can be calculated and then used to analyze power consumption with Eq. (1). The plot of the standard drive cycle is given in Fig. 1, and the plot of power needed at the wheel is given in Fig. 2. One can see that there are large spikes for power (peaking just over 20 kW) needed to accelerate, but that the average power is significantly lower.

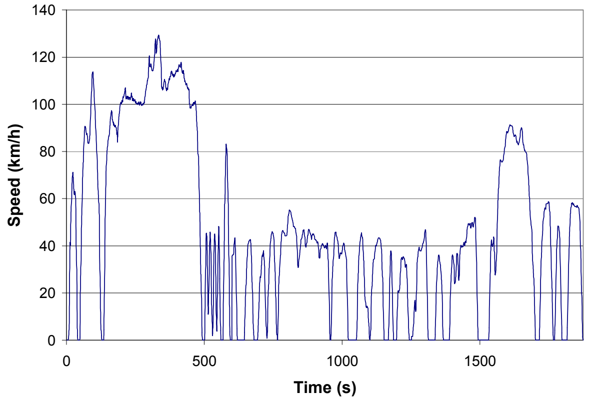

Fig. 1. US Standard Drive Cycle Modified with ftp us06.

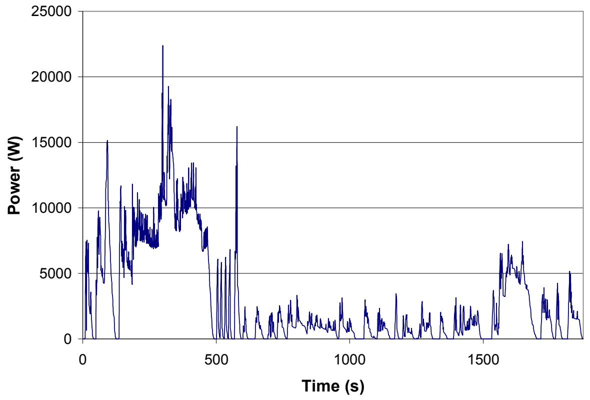

Fig. 2. Power Required to Accelerate the Motorcycle.

A fuel cell is not an energy storage device, but if it is supplied fuel in appropriate conditions, it can produce power indefinitely. Therefore, the fuel cell is said to possess a very good specific energy and be a good source for average power. However, at any given time the output power of the stack is not very great, yielding a lower power density. For a peak power device, it is preferable to have a high power density. An important advantage of the hybrid system is that it allows for regenerative braking, with the motor essentially acting as an electric generator during deceleration. Some of the power going out of the batteries is then returned to them and an increase in system efficiency results.

Specific power and energy for Ni-MH and Li-Ion batteries are compared in Table 2 along with an ultracapacitor (aka. supercapacitor) and a PEM fuel cell. The battery information is of current Saft Battery Company batteries [15]. There are some advanced lead acid batteries that approach the specific power of Ni-MH, but they generally fall around 600 W/kg. The ultracapacitor is a Maxwell Technologies BOOSTCAP® [16]. The fuel cell is a 1.5 kW Anuvu Power-X^{TM} [17] and is only included to demonstrate its converse properties from the storage devices. Realistically the balance of plant, fuel, and fuel storage would reduce both numbers.

Table 2. Specific Power and Energy of Power Sources. [Compiled from the data of Refs. (15, 16, 17)].

	Ni-MH	Li-Ion	UltraCap	Fuel Cell
Specific Power (W/kg)	900	1,350	4,300	220
Specific Energy (Wh/kg)	47	85	4.3	735

A schematic of the fuel cell system developed by APFCT for their commercial scooter is shown in Fig. 3. The fuel cell itself is comparable in size to the system presently discussed. However, there is no peak power device, and so the maximum output is only the 5.5 kW from the stack. The present system discussed would similar, but both more powerful and complex.

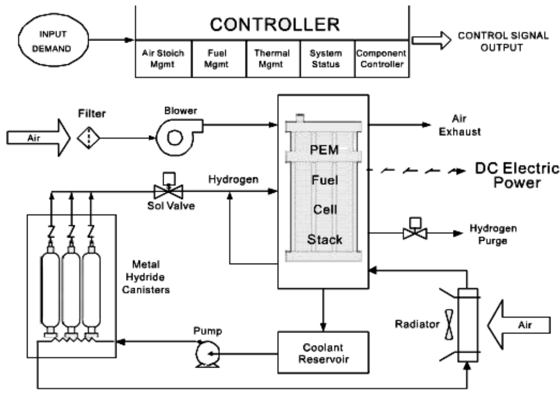

Fig. 3 Schematic of APFCT's ZES IV Scooter Engine [7].

RESULTS AND DISCUSSION

The following summarizes the results of preliminary calculations for power requirement during the drive cycle, airflow and blower design, weight of components, hydrogen supply, hydration, and an overview of various balance of plant components.

Equation (1) is utilized by taking typical values, for a motorcycle, of $A_f = 0.8$ m^2, $C_d = 0.6$, $C_{rr} = 0.01$, and $\rho_{air} = 1.23$ kg/m^3. The mass is taken as 250 kg, that of a similar gasoline motorcycle that is well loaded. Integrating Eq. (1) over the drive cycle, the motorcycle would require an average power at the wheel of 2.97 kW. If the drive train efficiency is 75%, then that would require 4 kW of power, leaving 1 kW for auxiliaries and to stay ahead of the battery charging. Therefore, the 5 kW chosen for the stack power appears to be a reasonable value. Note that a grade is not taken into consideration, as the drive cycle does not include that type of information. It is possible to manipulate Eq. (1) to include a grade over all or part of the cycle. Of course, more power would be required on a grade, potentially exhausting the peak power device and diminishing acceleration.

For a cell operating at 5 kW and with an average cell voltage of 0.6 V (a reasonable value for available operational stacks), a 2.98×10^{-3} kg/s inlet mass flow rate of air is obtained from Eq. (2). However, this is a stoichiometric value and implies that all of the O_2 is consumed before exiting the cell. Realistically, two to four times that amount would be blown through, and with a stoichiometry of four, the volumetric flow rate would be 38.3 m^3/hr (22.6 cfm) if operating at atmospheric pressure and an ambient temperature of 40°C. The blower must be capable of this flow rate at a minimum, as well as, be able to overcome the 15 kPa (stack dependant) pressure drop across the stack and any drop in the rest of the path. One must keep in mind that a pressure differential across the membrane should be avoided, as a large difference might rupture it.

The hydrogen flow is either dead ended within the stack or re-circulated with a small pump, so as not to waste the expensive fuel. With either method, if one uses Eq. (3) under the same conditions as for the air, 4.31 m^3/hr of hydrogen is consumed by the stack. Although metal hydrides are considered low pressure vessels, as the hydride is heated, to release the hydrogen, back pressure is built up and the flow can be established. With four, quickly refillable, H Power CL-720 [18] canisters that would be almost an hour of operation at full power. The range is shorter than for a ICE motorcycle, but comparable to common electric scooters, and without the long recharge time of the pure electric systems.

From Eq. (4), the stack produces water at the rate of 2400 cm^3/hr if operated continuously at 5 kW. At the typical operating temperatures, the water produced by the stack is quickly evaporated into the exit air flow, even given a range of ambient humidities. Indeed, usually there is more of a problem with the membrane drying out and slowing the electrochemical reactions. Hydrating the reactant flows adds cost, complexity and weight to the system. One way to avert this is to adjust the air stoichiometry so that the air exiting the cell is near saturation. For practical stoichiometry, the stack could not be operated at more than 60°C to meet this condition, and that would result in a lower power. However, the loss might be worth the trade for a simpler and smaller system. Stack design is very important for the water management issue. For example, according to Burch (2004) of The Fuel Cell Store, there is no external humidification of the reactants needed for their 4.2 kW PEM over the operational range of ambient humidities and with temperatures from ambient to 70°C.

The implications of Eq. (5) are that as much or more heat is produced by the stack as electricity. With a 5 kW cell, the cooling system should be able to remove at least that much heat, although there will be heat loss by natural convection and conduction, as well as, the latent heat in evaporation of product water. The waste heat is actively removed from the PEM stack by circulating coolant through integrated channels. Air could be used as the coolant, but for a stack of this size either it would not remove adequate amounts of heat, or the stack would have to increase undesirably in volume to accommodate the extra flow. A liquid coolant would be more effective and would also provide a means of heating the metal hydrides. Deionized water is commonly used as it does not conduct away any of the stack's current, is easy to use, and is readily available. A mix of ethylene glycol and water could be used if the engine is to be started at lower temperatures.

The coolant would be pumped through the stack, past the metal hydrides, and through a radiator. Both the metal hydrides and the radiator would dissipate heat. The metal hydrides require heat as the release of H_2 is an endothermic reaction. Sandrock (2003) reports that the hydrides will absorb between 1-1.5 kW of the waste heat produced by the 5 kW stack. The electric power lost to the pump and radiator fan would be a parasitic loss on the stack power.

When considering the metal hydride H_2 storage, it is noted that the motorcycle will not have the range of its gasoline counterpart. A greater range could be achieved by adding more hydride canisters, but this would continue to add weight and cost. However, the range is competitive with most electric scooters, and is better than the EMB electric motorcycle. Furthermore, the hydrides can be replaced with full canisters very quickly, or recharged with H_2 in a short time. Onboard storage of H_2, or other fuel, is a challenge for all fuel cell vehicles. H_2 is particularly problematic because of the large containers required by its low density. Outside of the very high pressure tanks used in automobiles, the hydrides are not uncompetitive with compressed H_2 when it comes to the ratio between the mass of fuel stored and the mass of the container. Also, the hydride canisters are smaller in size than equivalent compression cylinders. The hydride's other key characteristics are their innate safety as low pressure devices, and their tendency to cool, which prevents H_2 release, if ruptured in an accident.

Table 3. Fuel Cell Engine Components. [Compiled from calculations, Lin (1999), and the data of Refs. (15, 16, 18)].

Component	Characteristics	Comment
FC Stack	5.0 kW	Operated at peak or stack oversized and under peak.
Blower	38.3 m^3/hr air.	320 W consumption
Coolant Pump[†]	1.0 cm^3/s coolant	25 W consumption
Metal Hydride H_2 Storage	4×720 std. liters	Peak stack operation for almost an hour.
Radiator[†]	10.6 m^3/min coolant flow.	5 kW dissipation 14 W fan consumption
Air filter	0.1μm	Air particulate could clog flow channels.
Ultracapacitors	25.2 kW	15×2.8V×600A (42V)
Batteries (Li-ion)	21.7 kW	24×3.6V×250A (42V)
DC-DC converter	12-48 V range	Condition power from inputs and to outputs.
Solenoid Valve	H_2 compatable	Cuts off flow to stack.
Controller	Takes acceleration, sensor and environmental inputs and manages engine output.	
Sensors	Monitor the system temperature, pressure, charge, etc..	

[†] The specifications of the coolant system are dependant on the cooling geometry integrated in the stack, and so information for some existing stacks is used from Lin (1999).

Table 3 provides a list of components for the motorcycle engine. It should be noted that the system would also include various plumbing, wiring and support structures necessary for an operational unit. Some defining characteristics are given from a first order analysis. Both types of peak power sources are listed.

DC-AC power conditioning could be used in order to utilize an AC motor and higher voltages. However, it would be simpler to use a DC motor. The motor should be able to handle the peak power of 20-25 kW. Brushless DC motors (BLDC) are available within this power range and offer a good efficiency, power density and durability. BLDCs are widely used in the electric scooter business. A motor of such a size will generate a noticeable amount of heat, and might require some external heat removal, depending on how it is engineered by the manufacturer. Air flow is not a problem for a motorcycle moving at speed. Therefore, an air intake with a fin array could be used for cooling. Alternatively, the coolant loop for the fuel cell could be extended to the motor.

The fuel cell itself will be on the order of 30-35 kg excluding auxiliaries. The metal hydride storage will add 23 kg. In order to produce the necessary peak power the Ni-MH, Li-Ion and ultracapacitor will add 22.2, 14.8 and 4.65 kg respectively. An electric motor, capable of the specified power, will also add another 15 kg. The weight is quickly adding up and does not include the blower, heat exchanger system, smaller peripherals and the motorcycle frame.

The weight of the motorcycle is an unavoidable issue. There are both very large and quite small ICE powered motorcycles, but years of refinement have led to very good specific power over the spectrum of engine models. Fuel cell and battery technology have not reached that stage of sophistication, and thus the system described here will certainly be heavier than a similarly powered ICE version. Motorcycles of the 250 cc range are usually very light in both frame and engine in comparison to larger motorcycles, and to some degree this compensates somewhat for their lack in power. The fuel cell system will lose that edge, and extra power will be consumed to overcome the additional inertia, resulting in a slightly more sluggish acceleration. As with all fuel cell vehicles, it is expected that development will push the systems to meet and then exceed the performance of their ICE counterparts.

In a study by Wang et al. (2000), it is noted that cost and weight are the largest obstacles to overcome in designing a specific motorcycle. Also, it is pointed out that motorcycles serve as the cheapest mode of quick, personal, transportation. For fuel cell technology to compete in the long term, it must be brought to the customer's economic level for both the initial purchase and the life cycle costs. Life cycle costs are difficult to predict because of the lack of infrastructure, but that infrastructure should be easier to establish in the densely populated areas where motorcycles are most popular. The initial cost is primarily due to the stack, peak power device, air blower, and fuel storage. With development, and the economics of scale, it is reasonable to think that costs will become competitive, particularly with stricter emissions policies being enforced.

The choice between the peak power devices is complex. With weight being a significant issue, the ultracapacitors are a very attractive option as they posses the usual rugged characteristics of a capacitor, and there is little loss in efficiency after many rapid discharges and recharges. However, the cost is high enough ($160 per unit) that they are currently impractical for commercial systems. The ultracapacitors are an excellent choice for prototypes, but batteries are more cost effective for mass production. Also, with multiple power sources (i.e. battery, fuel cell, and regenerative braking), the electrical system begins to get complex. A DC-DC converter will be necessary to make sure power is properly conditioned. This will introduce some inefficiency, particularly for devices with high fluctuation in voltage, such as the ultracapacitors.

In constructing this motorcycle, cost and refueling are not being considered, because it is only a prototype. However, if design for mass production is considered, then cost and infrastructure become the two key obstacles. The prototype costs are orders of magnitude greater than the consumer market would bear. Particularly, the cost to the manufacturer of the stack itself, the peak power device, and the hydrogen storage systems is far too high. Mass production will bring those costs down, but in order to make the products competitive, government incentives will be needed. Furthermore, if cheap PEM motorcycles are available, but no mass retail sales of hydrogen are established, then few people will buy them. The distribution could come in the form of pressurized tanks or metal hydride canisters that are sold at retail, or refueling stations similar to those for gasoline. Once again, industrial pioneering or government direction will be needed to make way for the new technology.

CONCLUSIONS

The current technology status and salient design considerations for a motorcycle engine using a PEM fuel cell stack is summarized. The fuel cell power is designed for steady cruising load while the transients are taken care of by an ultracapacitor and/or batteries. Currently, pure hydrogen is supplied by metal hydride canisters, although high pressure hydrogen bottles are an alternative option. Several manufacturers have developed fuel cell powered scooters and some are ready to commercialize. However, the major challenges to address are the development of a hydrogen supply infrastructure and the high cost of the fuel cell system.

REFERENCES

B. Bartels, M. Hammond, and G. McClure, 1997. *0.25 Caliber Shootout*. Motorcycles Online. Available: http://www.motorcycle.com/mo/mccompare/250shootout.html, [2004, January 17].

J. Burch, 2004, Fuel Cell Store, Personal communication, February.

L. Cardinali, S. Santomassimo, and M. Stefanoni, 2002, Design and realization of a 300 W fuel cell generator on an electric bicycle. *J. of Power Sources,* Vol. 106, No. 1-2, pp. 384-387.

W. Colella, 2000, Market prospects, design features, and performance of a fuel cell-powered scooter. *J. Power Sources*, Vol. 86, No. 1-2, pp. 255-260.

S. Geiger, 2003, Fuel Cell-Powered Moped-Urban Transport 2005? *Fuel Cell Today* [Online]. Available: http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_562_Hunter0303.pdf [December 17, 2003].

J. Larminie, and A. Dicks, 2003, *Fuel Cell Systems Explained*, Second Edition, Wiley, Chichester, UK.

B. Lin, 1999, *Conceptual design and modeling of a fuel cell scooter for urban Asia*, M.S. Thesis, Princeton University, Princeton, New Jersey, USA.

G. Sandrock, 2003, Hydride Storage. *Handbook of Fuel Cells – Fundamentals, Technology, and Applications*, W. Vielstich, A. Lamm, and H. Gasteiger (Eds), Wiley, Chichester, UK, Vol. III, pp. 101-112.

C. Tso, and S. Chang, 2003, A viable niche market - Fuel cell scooters in Taiwan. *Int. J. Hydrogen Energy*, Vol. 28, No. 7, pp. 757-762.

J. Wong, 2001. *Theory of Ground Vehicles*. Third Edition, Wiley, New York, USA.

J. Wang, W. Chiang, and J. Shu, 2000, Prospects - fuel cell motorcycle in Taiwan. *J. Power Sources,* Vol. 86, No. 1-2, pp. 151-157.

1. http://www.nedra.com
2. http://www.fuelcells.org/fct/carchart.pdf [February 15, 2004].
3. http://www.ebike.net/Motorbike/ [February 15, 2004].
4. http://www.motobykz.co.uk/Bike_tests/Lectra.htm [February 15, 2004].
5. http://www.ecycle.com/powersports/electricmotorcycle.htm [February 15, 2004].
6. http://www.parker.com/markets/FuelCells/Parker-Vectrix%20Scooter%20Brochure%2010-13-03.pdf [February 15, 2004].
7. http://www.apfct.com [February 15, 2004].
8. http://www.brp.com/en-CA/Media.Center/Press.Releases/2003/1/2003.07.09.htm [2004, February 15].
9. http://www.spinglass.net/scooters/arne.html [February 15, 2004].
10. http://www.fuelcelltoday.com/FuelCellToday/EducationCentre/EducationCentreExternal/EduCentreImageArchive/0,1760,Order%253Ddesc%2526SortBy%253DTitle%2526CategoryID%253D1,00.html [February 15, 2004].
11. http://www.mhtx.com/media_center/pressrelease41.htm [2004, February 15].
12. http://www.astris.ca/golf/index.php [February 15, 2004].
13. http://www.humboldt.edu/~serc/vehiclefactsheet.html [February 15, 2004].
14. http://www.epa.gov/otaq/sftp.htm [March 5, 2004].
15. http://www.saftbatteries.com [February 15, 2004].
16. http://www.maxwell.com [February 15, 2004].
17. http://www.anuvu.com/stack.html [February 15, 2004].
18. http://www.fuelcellstore.com/cgi-bin/fuelweb/view=item/cat=4/subcat=5/product=132 [February 15, 2004].
19. http://chem.ch.huji.ac.il/~eugeniik/history/kordesch.html [April 9, 2004].