Light Traction: Fuel Cells

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Introduction

As a proton-exchange membrane fuel cell (PEMFC) can be started instantly at ambient temperatures and can work with air as oxidant without carbon dioxide problems, it is so far the most viable fuel cell (FC) system that has the potential to replace internal combustion engines (ICEs) and batteries for transportation applications to power cars, buses, and personal electric vehicles (PEVs). This article focuses on the application of this technology for light traction vehicles, such as scooters, bicycles, forklifts, wheelchairs, and tour carts.

Fuel Cell Systems

There is no doubt that a vehicle should be able to start instantly regardless of the powering technology used. Because onboard hydrocarbon reforming takes too much time to generate hydrogen, an FC that powers a vehicle has to use either hydrogen or liquid fuels directly. For light traction applications, it is also desirable that the FC system is simple, compact, and cost-effective.

Hydrogen–Air Systems

Figure 1 depicts a hydrogen–air FC system. Basically, an FC stack receives hydrogen from a storage tank and oxygen from air through a fan, a blower, or a pump. The direct current (DC) electrical power generated by the FC is used to power an electrical motor that drives a vehicle.

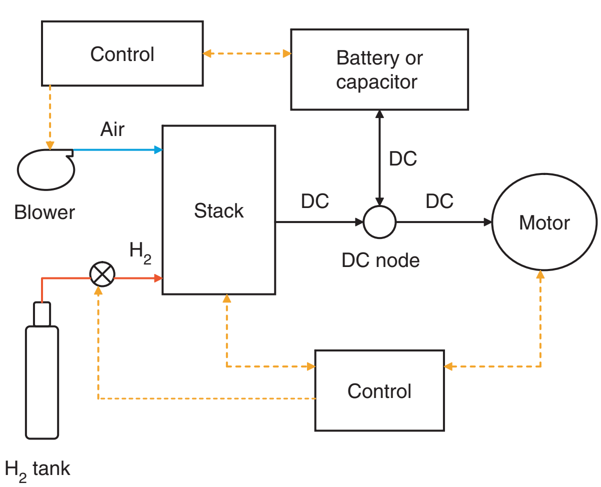

Figure 1 Function block diagram of a hydrogen–air fuel cell (FC) system. DC, direct current.

The motor is preferred to be one that can operate with a wide voltage range so that a DC–DC converter does not need to be used, thereby reducing cost and increasing system efficiency. In addition, in-wheel (or wheel-hub) motor configurations where an electrical motor is located in the wheel should be considered in order to save space and to eliminate freewheeling. A microprocessor can be used to control the system operation.

In order to reduce the size and weight of the FC stack and to meet acceleration and hill climbing demands, it is helpful to include either a battery or a capacitor in the system. A battery or a capacitor can provide burst power needed during acceleration and hill climbing. In addition, they can store waste energy through regenerative braking, where the momentum of the wheels during braking drives the electric motor to run in reverse so that the latter becomes a generator that produces electricity to charge the battery or the capacitor. When the vehicle is under cruise operation, the battery or the capacitor is recharged by the FC. Another FC/battery configuration, not shown here, is to use the battery only to drive the motor while the FC is just for charging the battery, i.e., the FC acts as a range extender. In either case, because the battery is frequently charged by the FC, the deep charge/discharge cycles that normally shorten battery lifetime can be avoided. A supercapacitor has lower internal resistance, more charging/discharging cycles and less efficiency loss during cycles, and requires lower maintenance than a battery. Moreover, because a supercapacitor stores and provides electricity in response to the fluctuations of the FC output, it does not require a converter for voltage regulation.

The amount of hydrogen stored in a storage tank determines how long a vehicle can operate before the tank needs to be refilled or replaced. Presently, the most viable ways of storing hydrogen are using either metal hydrides or high-pressure bottles. The former, where hydrogen is absorbed in the intermetal lattices of a solid, often stores hydrogen at no more than 1 MPa, whereas the latter can have hydrogen compressed to about 35 MPa. These bottles are often designed to be able to handle several times higher pressure in order to store hydrogen safely. Due to the weights of both the metal hydride and the bottles (typically made of stainless steel), the mass of hydrogen stored is normally $<1.5\%$, which is quite low. Aluminum bottles that are reinforced by carbon fibers and glass fibers are much lighter than stainless-steel bottles, but they cost much more. An overpressure relief valve that will open when the hydrogen pressure inside the bottle becomes higher than a predetermined value is normally used for enhanced safety. A hydrogen sensor may be used to detect hydrogen leakage. If a hydrogen leak is detected, ventilation should be activated automatically and the hydrogen supply line should be shut down. Contrary to public perception, hydrogen is safer than other fuels when there is a leakage because hydrogen dissipates upward quickly due to its extremely low density.

It should be understood that not all the hydrogen stored in a metal hydride can be released. It is an endothermic process where hydrogen is released, and the bottle can become quite cold, which also limits the amount of hydrogen that can be released. Air passing by the bottle can be cooled down and then used for FC stack and system cooling. In contrast, fueling a metal hydride bottle with hydrogen is an exothermic process and the bottle becomes quite hot. This can limit the hydrogen fueling rate, and cooling the bottle is often necessary during the fueling process. Metal hydrides can be very reactive with water, so it is important to prevent any water from entering the bottle. In addition, the hydrogen storage capacity of a metal hydride goes down with the number of charging/discharging cycles, and it needs to be replaced with new ones after its capacity becomes lower than a desired value.

It is well known that hydrogen can cause brittleness of many metals because it can diffuse into the structures of these metals. So selecting the right cylinder material is crucial for safe hydrogen storage. During a hydrogen fueling process, a hydrogen dispenser that transfers hydrogen from a storage tank to a vehicle includes a hose and a nozzle, and the nozzle must be sealed onto the vehicle fuel tank opening. A control system automatically stops hydrogen dispensing when the tank is full.

A control unit (e.g., a microprocessor) coordinates the operation of the entire system. It regulates the reactant flow rates to the stack according to the load demand from the FC. It monitors the condition of the FC stack and the battery or capacitor, and displays it on a panel that can be easily seen by a driver. It will shut down the FC system when it detects problems such as stack overheating or hydrogen leakage.

Hydrogen flow to the stack should be either dead-ended or recirculated in order to minimize waste and avoid contaminating the environment. In a dead-ended configuration where the hydrogen outlet port is closed for most of the time, hydrogen cannot be humidified, and periodic opening of the hydrogen outlet port is often necessary to vent out accumulated water and any inert gases, such as nitrogen, that accumulate in the anode compartment. Accumulation of water and inert gases in the anode compartment can seriously lower an FC's performance in a dead-ended hydrogen configuration. This venting process is often called purging, because the input hydrogen flow rate is normally increased in order to purge water and inert gas out of the anode compartment in a short time (e.g., a fraction of a second). Some hydrogen also rushes out of the stack during purging to cause waste of fuel and contamination of the environment. Ideally, this hydrogen should be collected for the FC to use, or it should be converted into water in an anode tail gas oxidizer or burner, but these processes may make the system more complicated and bulkier. The purging frequency can be either programmed to occur at predetermined time intervals or based on need. The former requires a thorough study and understanding of the FC behavior, and the FC behavior is predictable. The latter can be performed through the control algorithm when the stack voltage reaches a predetermined low value.

A PEMFC can run longer and performs better when the membrane–electrode assemblies (MEAs) are properly hydrated. Generally, reactants are humidified by humidifiers before they enter the stack in order to hydrate the MEAs. For an FC stack that generates 1 kW or greater power, reactant humidification normally cannot be avoided, which will in turn make the FC system more complicated, costly, and bulkier. For a stack generating <1 kW of power, eliminating reactant humidification is feasible. For example, the flow-field channels, shown in **Figure 2**, that were used at H Power (acquired by Plug Power Inc. in 2002) for nonhumidification stack operation consist of dual inlets and outlets in an arrangement of one channel's inlet being placed near the other channel's outlet so that the wet reactant in one channel shares its moisture with the drier reactant in the neighboring channel to achieve better water uniformity in the entire active area.

Related to MEA hydration is stack cooling. Besides electricity, heat is also generated by an FC reaction, and this heat needs to be removed in order to avoid MEA overheating. A higher temperature will evaporate more water from the MEA to make it drier. For a stack generating a power of 1 kW or higher, a liquid coolant is often needed. The coolant flows along the coolant flow fields made on the surface of coolant plates to remove the heat generated by the FC. Every cell or every several cells can have a coolant plate. When a liquid coolant is used, a coolant tank, pump, meter, and valve will be needed, in turn making the FC system more complicated. In addition, the coolant needs to be of negligible ionic conductivity, otherwise it will short the stack to cause severe damage; thus, a coolant purifier may also be needed.

For a stack generating <1 kW power, air cooling may be adequate. Air can be driven by fans or blowers. For effective heat removal, it is necessary to increase the stack's surface-to-volume ratio. The ratio can be increased by either having transverse channels between

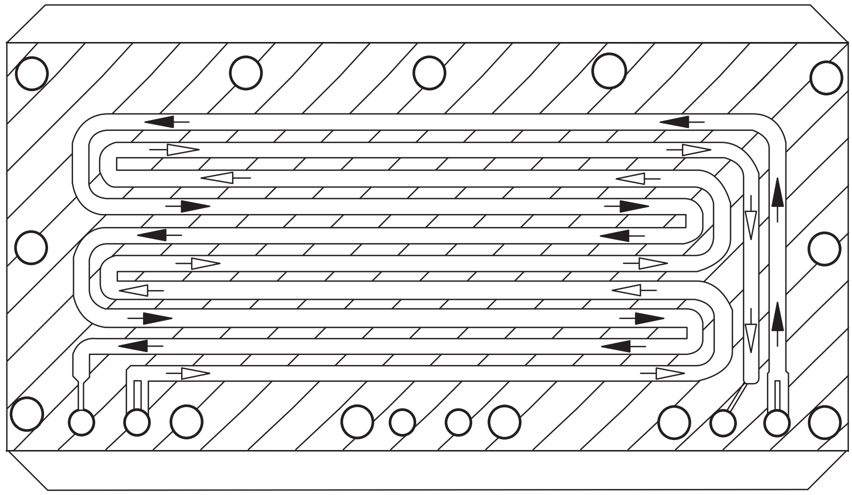

Figure 2 Dual-inlet and dual-outlet flow-field design. Reprinted from *Journal of Power Sources* 109, Qi Z and Kaufman A, PEM fuel cell stacks operated under dry-reactant conditions, 469–476, Copyright (2002), with permission from Elsevier.

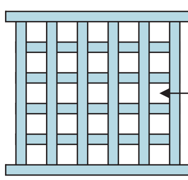

Figure 3 Illustration of air-cooled stacks with transverse channels.

Figure 4 Illustration of air-cooled stacks with fins.

cells (**Figure 3**) or having fins at the edge of the plates (**Figure 4**). For very low power stacks, blowing air over the outside surface of the entire stack may be satisfactory.

Direct-Feed Liquid Systems

Due to the low hydrogen storage capacity and the lack of hydrogen infrastructure, FCs using direct-feed liquid fuels are very attractive for light traction applications owing to their high volumetric energy density and ease of storage and transportation. The most widely investigated system is the direct methanol fuel cell (DMFC). Methanol has an energy density of $6.3\,\mathrm{kWh\,kg^{-1}}$ or $5.0\,\mathrm{kWh\,L^{-1}}$ based on the high heating value, but it often needs to be highly diluted before it is fed to a stack.

Figure 5 shows a schematic functional diagram of a DMFC system. Methanol stored in a fuel tank is mixed with water and the resulting mixture is sent to an FC stack. The methanol concentration in the mixing tank is monitored by a methanol sensor. Dilute methanol and air undergo oxidation and reduction at the FC anode and cathode, respectively, to produce DC electrical power. The unreacted methanol mixture is circulated back to the fuel mixing tank and carbon dioxide is vented out. Air exhaust is normally fully saturated with water, because a lot of water transports through the membrane from the anode to the cathode. The water is condensed and collected into either a water tank or the fuel mixing tank.

For a DMFC system, the methanol concentration can hardly be $>3\,\mathrm{mol\,L^{-1}}$ ($\sim$10wt%) for the following reasons. First, because methanol has a relatively high permeation rate through a membrane such as Nafion, and methanol oxidation at the cathode can significantly lower the cathode potential, a higher methanol concentration results in a larger amount of methanol transporting to the cathode side and leads to higher cathode overpotential loss and more waste of fuel. Second, the oxidation of each methanol molecule produces six protons, and each proton can drag up to three water molecules from the anode to the cathode. This means that 3 mol of methanol requires the presence of 54 mol of water, which translates to a maximum methanol concentration of about $3\,\mathrm{mol\,L^{-1}}$. The best FC performance is often achieved when about $1\,\mathrm{mol\,L^{-1}}$ methanol solution is used.

Due to the permeation of methanol and its subsequent oxidation at the cathode, a DMFC often has an open-circuit voltage of only around 0.7 V. Because of the significant overpotentials suffered by both the anode and the cathode, it will be good performance if the cell voltage reaches 0.4 V at a current density of $0.2\,\mathrm{A\,cm^{-2}}$ at 60 °C cell temperature. So, the power density of a DMFC stack is much lower than that of a PEMFC stack. Also, due to

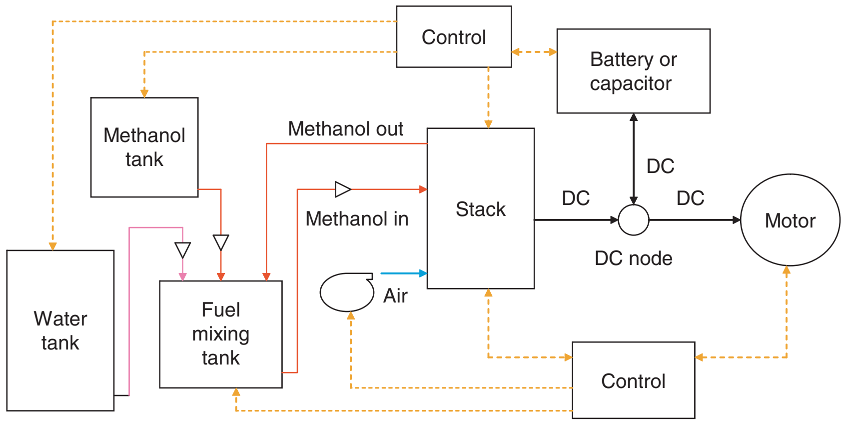

Figure 5 Function block diagram of a methanol/air fuel cell (FC) system. DC, direct current.

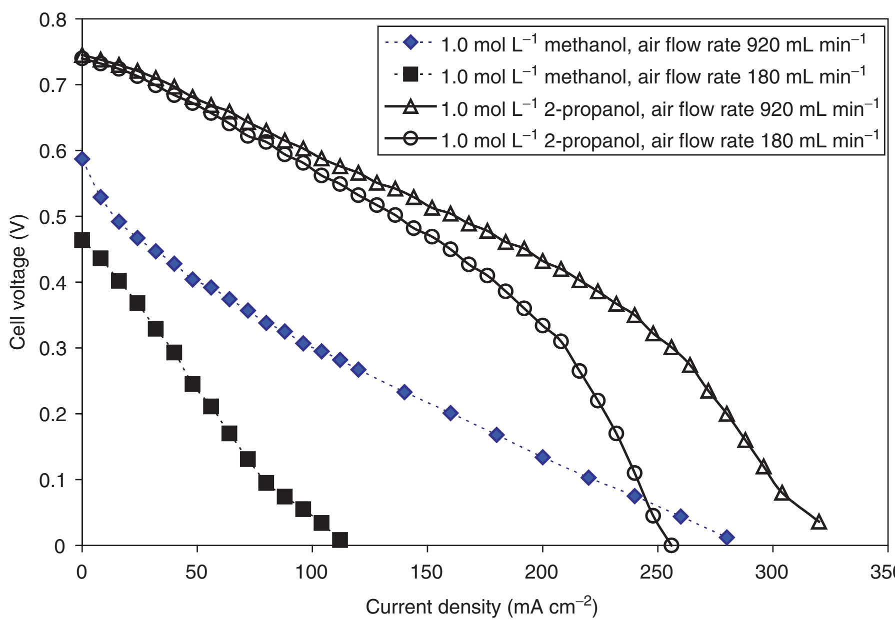

Figure 6 Performance of 2-propanol vs methanol. Reprinted from *Journal of Power Sources* 112, Qi Z and Kaufman A Performance of 2-propanol in direct-oxidation fuel cells, 121–129; Copyright (2002) with permission from Elsevier.

the high methanol crossover rate, a significant portion of the fuel is wasted. Hydrocarbon membranes may have better ability to block methanol crossover than perfluorinated membranes.

The MEAs in a DMFC are always fully hydrated because of the presence of a large quantity of water in the anode fuel mixture. Therefore, cathode reactant humidification is rarely required. Instead, dry air is preferred in order to reduce the severity of cathode flooding. Very often a quite high stoichiometric air flow rate is needed to minimize cathode flooding, but higher air flow rates make water balance more difficult. Cooling of the cell is also not necessary due to the presence of the liquid fuel mixture.

Although methanol is the most widely investigated liquid fuel for direct oxidation, its slow reaction kinetics, high crossover rate, and toxicity limit its applications. It has been shown that some other liquid fuels such as 2-propanol can perform better (**Figure 6**) before the anode is seriously poisoned by the reaction intermediates.

Methanol can also be fed to an FC anode as vapor. The vapor can be formed through either a natural evaporation of methanol at the cell temperature or boiling of methanol with a heat supply. This system, however, may be more complicated and may encounter higher engineering challenges.

Light Traction Vehicles Powered By Fuel Cells

The research and development activity in this area is much lower than that for automobiles such as passenger cars and commercial buses. One of the largest cooperative efforts so far is probably the HYCHAIN MINI-TRANS project that will deploy several fleets of innovative FC vehicles in four regions of Europe operating on hydrogen as an alternative fuel. It is expected that light traction vehicles such as scooters and electric-assisted bicycles will become more popular as oil prices continue to increase and possibly remain high, and as the environmental regulations become tougher. Most automobile trips are <15 km and such a distance can be easily handled by scooters and bicycles. Also, it is really a waste of energy when considering that about half of the trips involve only a driver.

The major components of a conventional PEV are throttle, battery, battery charger, motor speed controller, and electric DC motor. The throttle sends an electronic signal to the motor controller to allow the rider to change and control the speed. The battery provides the electric power to the motor, and the battery charger is for charging the battery. The motor speed controller controls the power to send to the motor based on inputs from the throttle and the motor speed.

For an FC system-powered personal vehicle, the battery and battery charger are replaced by an FC system. Because there is very limited knowledge in the public domain about FC-powered light traction vehicles, the following discussion is based on a generic study and some examples.

Scooters

Scooters are two-wheel vehicles with a power requirement somewhere between that of motorcycles and electric bicycles. The driver rests his/her feet on a platform directly in front of him/her. The curb weight, which is the vehicle weight without driver and cargo, should be <130 kg for off-power maneuverability. Highly polluting two-stroke 50-cc ICE scooters are popular in Asian countries. Scooters with four-stroke ICEs that can offer significant pollution reduction should be adopted. Some countries have mandated the adoption of zero-emission electric scooters. These electric scooters are powered by batteries that need to be recharged every day for several hours to overnight, and the range of travel after each recharging is very limited. The inconvenience of frequent recharging and short travel distance makes them less attractive to consumers than the ICE-powered counterparts. This situation provides a good opportunity for developing FC-powered scooters.

In 2000, Lin published an insightful comparison study between battery-powered and PEMFC-powered scooters based on a standard road load model that is governed by eqns [1] and [2]:

$$P_{\text{wheels}} = mav + mgv\sin\theta + mgvC_{\text{RR}}\cos\theta + 0.5p_{\text{air}}C_{\text{D}}A_{\text{F}}v \quad [1]$$

$$P_{\text{output}} = P_{\text{wheels}}/\eta_{\text{drivetrain}} + P_{\text{auxiliary}} + P_{\text{parasitic}} \quad [2]$$

where P_{wheels} is the mechanical power demand at wheels; m the combined mass of vehicle, driver, and cargo; a the acceleration rate; v the velocity of vehicle; g the gravitational acceleration rate; C_{RR} the coefficient of the rolling resistance; p_{air} the density of air ($1.23\,\text{kg m}^{-3}$); C_{D} the drag coefficient; A_{F} the vehicle frontal area; P_{output} the engine power output; $\eta_{\text{drivetrain}}$ the efficiency of electric motor and controller subsystem (Lin used 77%); $P_{\text{auxiliary}}$ the auxiliary power; and $P_{\text{parasitic}}$ the parasitic power needs. Auxiliary power units consist of data acquisition and panel display for parameters such as battery/capacitor/FC voltage and current, scooter speed, elapsed time, fuel pressure (or amount), and temperatures. Equation [1] shows that heavier vehicles, higher velocity, higher acceleration rate, steeper slope, and larger vehicle frontal area will result in higher power demand and shorter driving distance. **Table 1** lists the performance requirements for a mid-range power scooter. The values in the brackets are Lin's modeling results for engine power output needs assuming a driver of 75 kg and an average auxiliary power of 60 W.

Lin used the Taipei Motorcycle Driving Cycle (TMDC) to calculate maximum power and average power needs for urban driving, and the results are summarized in **Table 2**. Clearly, due to the unavoidable need for acceleration and hill climbing during routine driving, the maximum power required from the engine becomes about nine times as large as that required for steady-state cruising (5.6 kW vs 615 W). Also, the largest portion of power is consumed by acceleration. Further, the 5.6 kWh energy requirements for 200 km is about four times the energy amount stored by regular scooter batteries in 2000.

It is necessary to know that, in contrast to ICEs, if an electric motor is not powerful enough to move a scooter when the throttle is turned to the maximum, the motor or controller will often burn out. Therefore, any FC system that is considered for powering the scooter must be able to generate a maximum power of 5.6 kW.

With this information, Lin then modeled PEMFC-powered scooters in three configurations: pure FC (5.9 kW), hybrid 1 with 3.2 kW FC and 2.6 kW battery, and hybrid 2 with 1.1 kW FC and 4.6 kW battery. A basic rule was that the battery provided supplemental power whenever the FC maximum power was insufficient for

Table 1 Performance requirements for a mid-range power scooter

Specification	*Requirement*
Maximum motor power output	4–6 kW
Travel range per refueling	200 km at 30 km h^{-1} cruising velocity
Fuel efficiency	>100 mpge
Acceleration	0–30 km h^{-1} in less than 5 s
Speed on 15° slope	10 km h^{-1} (requires 2050 W)
Speed on 12° slope	18 km h^{-1} (requires 3020 W)
Maximum speed	60 km h^{-1} (requires 2600 W)
Curb weight	<130 kg

mpge, mile per gallon equivalent.
Source: Reprinted from *Journal of Power Sources* 86, Lin B, Conceptual design and modeling of a fuel cell scooter for urban Asia, 202–213, Copyright (2002), with permission from Elsevier.

Table 2 Modeled power requirement for TMDC and steady-state driving

Specification	*TMDC*	*30 km h^{-1} cruising*
Total drive time	950 s	950 s
Average speed	19.3 km h^{-1}	30 km h^{-1}
Maximum speed	46 km h^{-1}	30 km h^{-1}
Maximum acceleration	6.4 km h^{-1} s^{-1}	NA
Maximum deceleration	–8.6 km h^{-1} s^{-1}	NA
Maximum power from engine	5.6 kW	615 W
Average power from engine (exclude parasitic)	566 W	615 W
Average acceleration power	215 W	NA
Average rolling resistance power	151 W	305 W
Average aerodynamic drag power	117 W	250 W
Mileage per kilowatt-hour	35.5 km	48.8 km
Total energy requirement for 200 km	5.6 kWh	4.1 kWh

NA, not applicable; TMDC, Taipei Motorcycle Driving Cycle.
Source: Reprinted from *Journal of Power Sources* 86, Lin B, Conceptual design and modeling of a fuel cell scooter for urban Asia, 202–213, Copyright (2002), with permission from Elsevier.

the driving requirements; 300 W was added on top of the 5.6 kW due to the parasitic power requirements of an FC for powering pumps, fans, and blowers. In all three cases, hydrogen was supplied in a dead-ended configuration, air was provided at a 2.5 times stoichiometric flow rate, liquid cooling was employed, FeTiH1.9 metal hydride that could store hydrogen at 1.75 wt% and 101 g L^{-1} was used, and state-of–the-art FC performance was assumed (0.82, 0.71, and 0.61 V cell voltage at 200, 600, and 1000 mA cm^{-2} current densities, respectively). **Table 3** summarizes the FC design specifications and the scooter performance under TMDC. The model results indicated that, in all the three cases, the FC vehicles offered more than three times the range of Taiwan ZES-200 electric scooters. The FC systems were only slightly heavier but required a lot more space due to the bulky auxiliaries, liquid cooling, and hydrogen storage canisters. The pure FC configuration had slightly higher fuel efficiency and better performance with respect to maximum power endurance and 3.2 kW hill climbing endurance than the hybrid configurations. The inferior performance of the hybrid configurations was due to the use of the power complementary batteries. In addition, the FC-powered scooters can have more than three times the fuel efficiency of gasoline-powered two-stroke ICE scooters.

Since 2000, tremendous progress has been made in the area of FC technologies. For example, a prototype motorbike developed by Intelligent Energy (London, England) used a 1-kW PEMFC stack with a power density of 2.5 kW L^{-1}. The stack did not require either liquid cooling or reactant humidification. The FC achieved full power almost instantaneously at room temperatures and in less than 60 s at –25 °C. Combined with a 720-Wh battery pack (4 × 12 V × 15 Ah), the motorbike accelerated from zero to the top speed of 80 km h^{-1} in 12.1 s using a 6-kW, 48-VDC brushed motor. With 2.4 kWh hydrogen stored onboard in high pressure and lightweight reinforced aluminum cylinders, the motorbike that weighed 80 kg could travel at least 160 km before refueling. The refueling took <5 min.

Figure 7 shows an FC-powered scooter developed by Palcan Power Systems Inc. (Canada) in 2003. The scooter used a 700-W electric motor powered by a 1.5-kW PEMFC. The FC stack contained 40 cells and was cooled by liquid water. Two batteries rated at 12 V and 12 Ah were used to assist the FC during acceleration and hill climbing. Regenerative breaking was used to recharge the battery during breaking. Three metal hydride canisters with a total weight of 10.5 kg were used to store hydrogen at a pressure of 690 kPa. Hydrogen was fed to the stack in a dead-ended configuration. The scooter could travel for 70 km after each refueling of 0.9 m^3 hydrogen, whereas a battery-powered counterpart could only travel for about half of that distance. It had a maximum speed of 50 km h^{-1} and could climb slopes up to 25° with a 70-kg rider.

When considering where to install an FC system on a scooter, the center of gravity and weight distribution should be considered along with the availability of space. Because a lower center of gravity makes a scooter more stable, heavy components of an FC system should be arranged as low as possible. Also, the components should be arranged in such a way that a proper weight distribution is achieved to avoid instability over bumps if the weight is too far forward and improper front wheel tracking if the weight is too far backward. Further, the hydrogen storage bottles should be put in a strong protective case for enhanced safety.

Table 3 Fuel cell (FC) system design specifications and scooter performance under TMDC

Specification	*Fuel cell*	*Hybrid 1*	*Hybrid 2*
Maximum fuel cell gross power	5.9	3.2	1.1
Current at maximum power (A)	172	89	31
Efficiency at maximum power (%)	41.2	43.2	43.6
Electrode active area (cm^2)	170	100	35
Total active area needed (cm^2)	9600	5600	2000
Maximum heat generation (kW)	7.0	3.5	1.2
Maximum fuel cell net power (kW)	5.9	3.0	1.0
Assisting battery power (kW)	0	2.6	4.6
Cooling fan power need at steady 3020 W (W)	14	28	4
Coolant pump power need at steady 3020 W (W)	25	38	21
Average total power output (W)	674	709	726
Average fuel cell power (W)	674	698	577
On-vehicle fuel economy (mpge)	344	316	343
Fuel cell conversion efficiency (%)	56	53	47
Average power regenerated through braking (W)	0	65	86
Braking energy recovered/maximum braking loss	0	0.51	0.68
Fuel cell stack weight (kg)/volume (L)	7.6/7.8	5.4/5.3	4.1/3.2
Auxiliary weight (kg)/volume (L)	17.5/22.0	15.6/21.3	10.5/8.4
Battery weight (kg)/volume (L)	0/0	3.1/3.0	5.6/5.4
Stack and combined auxiliary weight (kg)/volume (L)	25.1/29.8	24.6/29.6	20.2/17.0
Motor and controller weight (kg)/volume (L)	15.5/9.1	15.5/9.1	15.5/9.1
Hydride canister for 200 km weight (kg)/volume (L)	21.4/3.7	22.8/4.0	24.3/4.2
H_2 mass for 200 km range (g)	250	266	285
Total drive system weight (kg)/volume (L)	61/43	63/43	60/30
Duration to sustain maximum power (s)	Unlimited	~10	~10
Duration to sustain 3.2 kW hill climbing (min)	Unlimited	Unlimited	<3

mpge, mile per gallon equivalent; TMDC, Taipei Motorcycle Driving Cycle.
Source: Reprinted from *Journal of Power Sources* 86, Lin B, Conceptual design and modeling of a fuel cell scooter for urban Asia, 202–213, Copyright (2002), with permission from Elsevier.

Figure 7 Picture of a scooter. Courtesy of Palcan Power Systems Inc.

Bicycles

Bicycles are the most popular commuting vehicles for a travel distance <10 km in many Asian countries. In recent years, electric-assisted bicycles powered by batteries have started picking up popularity. For an electric-assisted bicycle, the US Federal Government regulates that the vehicle must have operable pedals, a motor of no more than 750 W, and cannot be operated under power >32 km h^{-1}. Because the rider can still pedal during acceleration and hill climbing, electric bicycles normally do not need motor power >400 W. This makes their design much easier and their cost more affordable than scooters that need about nine times as power output during acceleration and hill climbing as steady-state cruising. Lead–acid and nickel–cadmium batteries are widely used to provide the electric power. Similar to scooters, due to the inconvenience of frequent recharging and the low energy storage capacity of batteries, a PEMFC-powered bicycle could be more advantageous.

Hwang and coworkers installed a 40-cell air-cooled stack that provided a nominal power of 303 W at 0.7 V and a peak power of 378 W onto a 30-kg bicycle. Hydrogen stored in a metal hydride canister was supplied to the stack at 48 kPa in a dead-ended configuration. In combination with a pressure regulator, the hydrogen canister provided a passive and simple load-following mechanism: a solenoid valve opened as the pressure in the fuel feeding line decreased to a predetermined value due to the consumption of hydrogen at the anode. An anode purging valve opened when the stack voltage dropped to a predetermined value of 22 V. Cooling fans were turned on when the stack temperature was $>40\,^{\circ}C$. Neither hydrogen nor air was humidified. During a 1-h roller-stand test, the bicycle reached a maximum speed of $25.2\ km\ h^{-1}$ with reliable operation. During a road test with a 70-kg rider but without pedaling, the bicycle reached a maximum speed of $16.8\ km\ h^{-1}$, and 6.8 g hydrogen was sufficient for a driving distance of 9.2 km, i.e., the bicycle had a distance-to-fuel ratio of 1.35 km per gram of hydrogen. The system efficiency varied from about 24% at 100 W power output to 34% at 315 W power output. In 2004, an FC-powered bicycle jointly developed by US and Italian inventors reached a top speed of $32\ km\ h^{-1}$ with no pedaling and traveled 100 km with a small tank of hydrogen.

Forklifts

Battery-powered forklifts are used in warehouses worldwide. It is estimated that there are about 2.5 million forklifts in North America and Europe. The battery has to be either replaced or recharged after running for <8 h, and the lifting may become sluggish even before the battery replacement or recharging. Fuel cell/battery (or supercapacitor) powered forklifts developed and tested by several companies have shown much better performance, and the total package can be much smaller and lighter than a pure battery system. For example, a 2300-kg forklift that was powered by a 12-kW HyPm 12-FC stack in conjunction with a supercapacitor developed by General Motors (GM) of Canada and Hydrogenics Corp. ran 12 h before the hydrogen tank (containing 1.8 kg H_2) was refilled, and the refueling only took 2 min. In addition, without any modification of current forklifts, there is more than enough space to host an FC system if the batteries are replaced. One of GM's onsite electrolyzers, which generated 65 kg of hydrogen at 34.5 MPa per day, could serve 25 forklifts for three shifts daily. It took up less floor space than the charger and battery system, which could only supply three to four batteries daily.

Other Light Traction Vehicles

FCs are expected to be in a more advantageous position than batteries to power other light traction vehicles that travel in the sky, on the ground or water, or in the ocean. For example, in June 2004, Asia Pacific Fuel Cell Technologies, Ltd (Taiwan) completed a second-generation wheelchair that was powered by a PEMFC and nickel–metal hydride (Ni–MH) battery with a combined maximum power of 1000 W. The wheelchair reached a maximum speed of $6\ km\ h^{-1}$, and it could continuously operate for 12 h for 60 km. An AB5-type metal hydride was used to store hydrogen in extruded aluminum alloy bottles. A bottle with a diameter of 76.2 mm and length of 365 mm stored $0.54\ m^3$ hydrogen at $30\,^{\circ}C$, and the total canister weighed about 4.5 kg. **Figure 8** shows a wheelchair-type personal mobility vehicle developed by Beijing Fuyuan Century Fuel Cell (China).

FCs have also been demonstrated for powering golf carts and tour carts. **Figure 9** shows an FC engine–powered four-seat tour cart developed by Shanghai Shen-Li High Tech Co., Ltd (China) in 2004. The FC engine weighed 100 kg and had a power output of 5 kW, with an electrical efficiency $>50\%$. The cart demonstrated a travel range of 200 km with the amount of hydrogen stored in a reinforced aluminum bottle. The bottle had a volume of $0.07\ m^3$, weight of 40 kg, and the hydrogen was pressurized at 20 MPa. The cart could

Figure 8 Picture of a wheelchair. Courtesy of Beijing Fuyuan Century Fuel Cell.

Figure 9 Picture of a tour cart. Courtesy of Shanghai Shen-Li High Tech.

reach a top speed of 20 km h^{-1} in 30 s. The cart was exclusively powered by the FC while a very small battery was used to start the system. This cart achieved a total of 20 000 km driving distance as of July 2006.

Illustrated in **Figure 10** is a mini scooter on which an operator will stand that was developed by GasHub Technology (Singapore). The scooter was powered by a 200-W air-cooled PEMFC in conjunction with two ultracapacitors (58 F, 15 V each) that assisted acceleration and hill climbing, and it reached a top speed of 20 km h^{-1} with a travel range between 50 and 80 km. The net weight of the scooter was 23 kg, its load-carrying capacity was 100 kg, and it had four speed levels and could climb a slope up to 10°. The two metal hydride cylinders weighed 6 kg and contained a total of 0.6 m^3 of hydrogen. In comparison, a similar scooter powered by batteries traveled for only 20–30 km.

Challenges

There are still many hurdles to overcome before FC-powered light traction vehicles are widely accepted by the general public. First, the cost of FC systems has to come down so that they are affordable and their life cycle cost is comparable to conventional power sources. Second, the reliability and durability of FC systems have to improve to be as good as current power sources. Third, a hydrogen infrastructure that includes hydrogen production, transportation, storage, and fueling needs to be established, and the hydrogen mass storage capacity must be increased. As of August 2006, there were about 140 hydrogen fueling stations worldwide, which is too few to be of any significance. **Figure 11** shows China's first hydrogen generation and fueling station of its type that was built by Beijing LN Power Sources Co. Ltd in 2006. This station could produce 300 $Nm^3 h^{-1}$ hydrogen through electrolysis of water (**Figure 12**), and the hydrogen is compressed to 40 MPa. The station is used to refuel not only automobiles but also hydrogen bottles and oxygen bottles. Fourth, as conventional power sources become cleaner and more efficient, it will be even tougher for FCs to compete. Fifth, the misperception that hydrogen is more dangerous than other fuels must be corrected through public education so that the general public realizes that hydrogen is just as safe as other gaseous or liquid fuels when handled properly.

Figure 10 Picture of a mini scooter. Courtesy of GasHub Technology.

Figure 11 Picture of a hydrogen generation and refueling station. Courtesy of Beijing LN Power Sources.

Figure 12 Picture of an electrolysis system. Courtesy of Beijing LN Power Sources.

Conclusions

The feasibility of FC-powered light traction vehicles has been demonstrated by a number of companies worldwide. Fuel cell or FC/battery (or supercapacitor) hybrid systems enable such vehicles to operate several times longer than a battery system. The FC or its hybrid system can also be several times more efficient than ICEs. Hydrogen stored in either metal hydride cylinders or high-pressure bottles is almost exclusively used.

Nomenclature

Symbols and Units

a	acceleration rate
A_F	vechicle frontal area
C_D	drag coefficient
C_{RR}	coefficient of rolling resistance
g	gravitational acceleration rate
m	combined mass of vehicle, driver, and cargo
p_{air}	density of air
$P_{auxiliary}$	auxiliary power
P_{output}	engine power output
$P_{parasite}$	parasitic power needs
P_{wheels}	mechanical power demand at wheels
v	velocity of vehicle
$\eta_{drivetrain}$	efficiency of electric motor and controller subsystem

Abbreviations and Acronyms

DC	direct current
DMFC	direct methanol fuel cell
FC	fuel cell
GM	General Motors
ICE	internal combustion engine
MEA	membrane-electrode assembly
mpge	mile per gallon equivalent
PEMFC	proton-exchange membrane fuel cell
PEV	personal electric vehicle
TMDC	Taipei Motorcycle Driving Cycle

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