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Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications

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ABSTRACT

The fuel cell hybrid bus (FCHB) program was initiated at the University of Delaware in 2005 to demonstrate the viability of fuel cell vehicles for transit applications and to conduct research and development to facilitate the path towards their eventual commercialization. Unlike other fuel cell bus programs, the University of Delaware's FCHB design features a battery-heavy hybrid which offers multiple advantages in terms of cost, performance and durability. The current fuel cell hybrid bus is driven on a regular transit route at the University of Delaware. The paper describes the baseline specifications of the bus with a focus on the fuel cell and the balance of plant. The fuel cell/battery series-hybrid design is well suited for urban transit routes and provides key operational advantages such as hydrogen fuel economy, efficient use of the fuel cell for battery recharging, and regenerative braking. The bus is equipped with a variety of sensors including a custom-designed cell voltage monitoring system which provide a good understanding of bus performance under normal operation. Real-time data collection and analysis have yielded key insights for fuel cell bus design optimization. Results presented here illustrate the complex flow of energy within the various subsystems of the fuel cell hybrid bus. A description of maintenance events has been included to highlight the issues that arise during general operation. The paper also describes several modifications that will facilitate design improvements in future versions of the bus. Overall, the fuel cell hybrid bus demonstrates the viability of fuel cells for urban transit applications in real world conditions.

1. Introduction

Fuel cell buses are ideally suited for urban transit applications. The zero-emission feature of fuel cells is attractive for mitigating urban air pollution, they are relatively quiet compared to diesel buses, and the hydrogen refueling and maintenance infrastructure is greatly simplified because buses can be refueled and maintained at a single centralized location by the fleet operator. Equally important, the high cost of fuel cells can be greatly offset by employing series-hybrid designs which are particularly advantageous in urban transit applications which comprise a start-and-stop driving pattern at low average speeds. Apart from demonstrating and evaluating fuel cell powerplant systems, prototype fuel cell buses can also serve as an ideal platform to test and improve hybrid power trains. Buses offer greater latitude than cars in terms of weight and volume while designing the hybrid power train because they can more easily accommodate the fuel cell stack, balance of plant, fuel storage system, and electrical energy storage devices such as batteries or ultracapacitors [1–3]. Another major objective of fuel cell bus programs is to spread awareness and educate the public about the benefits of hydrogen and fuel cells. Highly visible bus demonstrations in densely populated areas are an effective means for public outreach.

Several fuel cell vehicle projects have been completed and are still active all over the world. United States itself has 11 fuel cell buses in active demonstration and there are about 29 more under development [3]. The operation and experiences from many such fuel cell bus programs have been reported. Haraldsson et al. [1] have reported the first experiences of the Stockholm CUTE project from a climate perspective, followed by reports on the attitude towards hydrogen fuel cell buses [4,5] and energy system analysis of the operated buses [6]. SunLine Transit Agency has been operating one fuel cell bus in revenue service in Palm Springs, California, since January 2006. The operation of this bus has been documented in a series of evaluation reports [7–12] from the National Renewable Energy Laboratory (NREL). NREL has evaluated and reported many such hydrogen powered buses at different demonstration sites within the United States [13–20].

The University of Delaware initiated its fuel cell hybrid bus (FCHB) program in 2005, with the goal to develop and demonstrate fuel cell buses and hydrogen refueling stations in the state of Delaware. The main objective of the program is to demonstrate

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Table 1
UD fuel cell bus program.

University of Delaware bus fleet				
Bus #	Length	Stack	Batteries	Delivery
1	22 ft	20 kW	60 kWh of Ni–Cadminum batteries	February 2007
2	22 ft	40 kW	60 kWh of Ni–Cadmium batteries	May 2009
3	30 ft	40 kW	33 kWh of Li–Ti batteries	2010
4	30 ft	40 kW	33 kWh of Li–Ti batteries	2011

H_2 refueling stations	
1. Newark, DE	In operation since 2007
2. Wilmington, DE	In the planning stage
3. Dover, DE	In the planning stage

Table 2
Fuel cell hybrid bus specification.

Parameter	Value
Length	6.7 m
Width	2.3 m
Gross weight	9300 kg
Curb weight	7450 kg
Maximum speed	72 km h^{-1}
Traction motor	130 kW AC Induction
Transmission	1-Speed chain drive
Batteries	300 V 200 Ah Nominal NiCd
Fuel cell	Ballard Mark9 SSL 19.4 kW
Hydrogen storage	12.8 kg at 350 bar
Range	290 km (180 miles)
Fuel economy	15.7 l/100 km (gasoline equivalent)

the viability of fuel cell vehicles for transit applications and conduct research and development to facilitate the path towards their eventual commercialization. A total of four fuel cell hybrid buses will be deployed in the state of Delaware with a focus on design improvements for performance and reliability, and the identification and resolution of technical and operational issues. As shown in Table 1, our program involves the systematic development and demonstration of four buses and three hydrogen refueling stations. Each new bus design incorporates lessons learned from its predecessors as well as the latest improvements in fuel cell technology, balance of plant, and batteries to produce more efficient, reliable, and cost-effective fuel cell bus systems. The wide distribution of hydrogen refueling stations across the state is aimed at facilitating bus demonstrations in several population centers in order to maximize public outreach.

The first bus was delivered to the University of Delaware in February 2007 and has been in service on campus for the past two years. It is the subject of this paper. Data have been collected with a variety of sensors on all subsystems including the fuel cell stack, balance of plant, hydrogen storage system, and batteries for real-time monitoring and analysis. This paper focuses mainly on the description, advantages, and energy analysis of the series-hybrid power train employed on the bus, our experience with the operation and maintenance of the vehicle, and improvements and developments made during the current period of operation both to the bus and the refueling station.

2. Description of the fuel cell hybrid bus

The 22 ft bus was designed and built by EBus, Inc. and can hold 22 seated and 10 standing passengers (Fig. 1). The specifications of the hybrid bus are provided in Table 2. It is powered by a Ballard Mark 9 SSL 110-cell stack, rated for 19.4 kW gross power. The bus is driven by a single three-phase AC induction motor that is rated for 130 kW peak and 75 kW continuous power and speeds up to 5000 rpm. The motor is coupled to the rear drive wheels through a single-speed chain drive and a differential, with gear ratio selected to allow speeds of up to 45 mph while providing enough torque to climb a 20% grade fully loaded. The bus incorporates a series-hybrid powertrain that employs SAFT Nickel–Cadmium (NiCd) liquid-cooled batteries in two 300 V strings. The strings are connected in parallel because of the traction inverter voltage limitation, and the two together are capable of meeting high power demands (~120 kW). Each string consists of 50 monoblocks, each containing 5 cells. The cells are rated for a nominal charge capacity of 100 Ah and total energy capacity of 60 kWh. This typically gives the vehicle an all-electric range of 40 miles. The bus uses compressed hydrogen stored in twin composite high-pressure tanks mounted on the roof of the bus. The tanks are rated for 350 bar and have a total storage capacity of approximately 12.8 kg. This amount of hydrogen yields an average range of about 140 miles. The plug-in feature of the bus permits the initial portion of each route to be driven solely on battery power with the fuel cell switching on when the battery state-of-charge falls below the chosen threshold value.

Fig. 1. University of Delaware fuel cell hybrid bus #1.

The fuel cell stack is fed with air by a scroll-type compressor at pressures of 83–124 kPa, depending on load, which is humidified by moisture from the cathode exhaust air using membrane humidifiers. Hydrogen is supplied at a slightly higher pressure, and hydrogen is recirculated from the stack outlet to the inlet using a rotary single-vane pump, to ensure clearance of water from all parts of the anode. The stack is liquid-cooled, using a low-conductivity ethylene glycol/water mixture and a fan-cooled radiator. After subtracting the power requirements of the balance of plant, the fuel cell stack delivers a maximum net power output of 14 kW.

Since the stack's operating voltage is typically between 65 and 75 V, a boost converter is used to deliver power to the main DC bus at a nominal battery voltage of 300 V (which can range from 250 to 370 V during normal vehicle operation), controlling the amount of power drawn from the fuel cell. The schematic of the hybrid drivetrain for this bus is shown in Fig. 2. The fuel cell system is controlled by a programmable logic controller (PLC), which coordinates the functions of all parts of the fuel cell system according to the amount of power requested by the vehicle control computer.

The bus was equipped at UD with a data acquisition system installed in a laptop computer, currently running custom software within LabVIEW. It monitors the vehicle control computer, the fuel cell system's PLC, and the traction inverter. In addition, it has a GPS receiver and a UD-designed Cell Voltage Monitoring (CVM) system for monitoring the voltages of individual cells within the fuel cell stack. Real-time data are collected from a variety of other on-board sensors monitoring

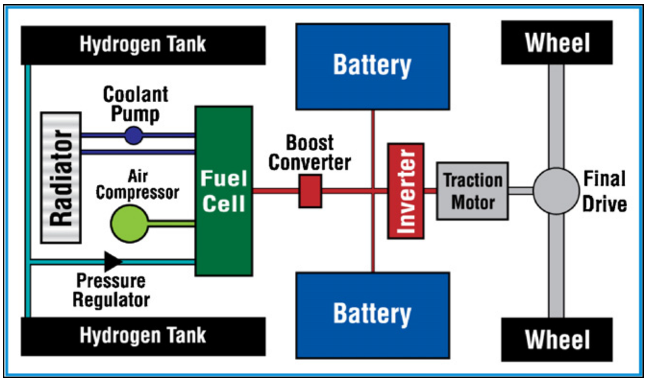

Fig. 2. Simplified schematic of the hybrid power train.

fluid temperature, flowrate, and humidity within the fuel cell system.

3. The hydrogen refueling station

The bus is refueled at a station operated by Air Liquide at their Delaware Research and Technology Center, where the bus is housed. The current station is a “slow fill” type; it compresses hydrogen from a tube trailer into the bus’s tanks while the bus is connected to the station. This process usually requires 2–4 h to refill the vehicle. The station is currently being upgraded with a high-pressure buffer tank that will be filled by the compressor to approximately 41,370 kPa while the station is not in use. When the vehicle is connected, hydrogen will flow from this tank to the vehicle and complete the refill in approximately 15 min.

4. Demonstration route

The first fuel cell bus has been deployed for transit service on one of the University of Delaware campus routes, called the Express Route (Fig. 3), since May 2007 in order to demonstrate the technology and evaluate the performance of the series-hybrid power train. The drive cycle is typical of urban routes and is characterized by a low average speed of 4.8 m s^{-1} (10.7 mph) and an idling period of 27% of the driving duration. Details of the Express Route are provided in Table 3. During a typical driving duration of 2.5 h, the bus completes four to five loops of the Express Route and achieves a ridership of approximately 100 passengers per day. A large amount of data and experiences relating to performance, efficiency, reliability and availability are being collected and analyzed.

5. Advantages of the series-hybrid design and operation

Critical to the commercialization of fuel cell powered buses are cost-effective and energy-efficient designs. Although vehicles powered by fuel cells alone can serve as a good platform to evaluate the performance and reliability of fuel cells, the implementation of fuel cell/battery hybrid drivetrain designs has the potential to greatly lower costs especially in urban transit applications and is therefore more practical for current and near-term systems. This section explains the advantages of the design and operation of our first bus which is also the first fuel cell hybrid design produced by EBus, Inc.

The average power demand of urban drive cycles is usually 10–20% of the maximum power demand. The choice of a 14 kW (net) fuel cell system, which is capable of delivering slightly over 10% of the maximum load despite its small size, significantly reduces the cost of the vehicle. This is an important design consideration and makes the bus more affordable for transit agencies wishing to incorporate new fuel cell technology into their fleet.

Besides cost benefits, a series-hybrid design that combines a small stack with a large battery bank has several additional advantages. A battery-heavy hybrid can significantly improve the transient performance of the fuel cell stack by avoiding rapid fluctuations in power demand and thus prolong its life. Furthermore, frequent exposure of the cells to high voltages typical of open circuit conditions can accelerate catalyst degradation. Therefore it is desirable to operate the stack towards the higher end of its power rating which is quite possible when smaller stacks are used. In our vehicle, the NiCd batteries are capable of supplying and accepting approximately 120 kW of peak power (Fig. 4) and are therefore solely responsible for meeting any fluctuations in power demand. Urban driving conditions, specifically transit routes, involve frequent starts and stops which provide an opportunity to recover appreciable energy through regenerative braking by the induction motor. By virtue of its battery-heavy hybrid configuration, the vehi-

Table 3
Drive cycle characteristics of express route (UD Campus).

Drive cycle characteristics	Value
Mean velocity (m s^{-1})	4.8
Stop ratio	0.27
Mean positive acceleration (m s^{-2})	0.73
Mean negative acceleration (m s^{-2})	0.78
Maximum speed (m s^{-1})	15.7

Fig. 3. Aerial view of the University of Delaware Express Route traced by the fuel cell hybrid bus.

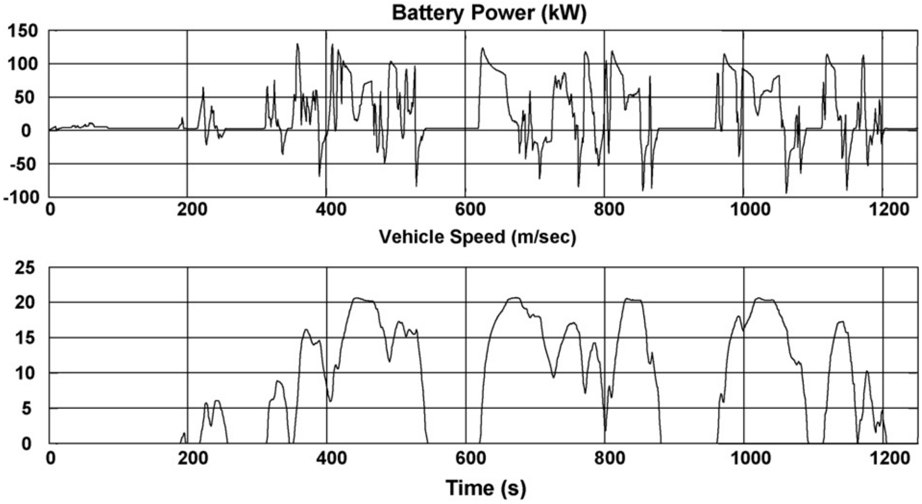

Fig. 4. Correlation between battery power profile and velocity profile for first 1250 s of a drive cycle driven solely on battery power.

cle can recover approximately one-third of gross energy drawn by the traction motor. This is a significant amount of savings which would otherwise be lost as heat in dump resistors in a vehicle powered by fuel cells alone.

The overall design of our bus features a battery-heavy hybrid which uses the fuel cell as a range extender. The basic control strategy is to run the bus in battery-only mode until the state-of-charge (SOC) reaches a threshold value. This value can be reprogrammed, but defaults to 0.65. Once the SOC reaches 0.65, the fuel cell turns on with a power request governed by

$$\text{FC power request} = \frac{V_{\text{nom}}Q_{\text{nom}}(\text{SOC}_{\text{d}} - \text{SOC}_{\text{c}})}{t_{\text{recharge}}} + P_{\text{one hour moving avg}}$$

where SOC_{d} is the threshold value, SOC_{c} is the current calculated SOC, V_{nom} is the nominal voltage of the batteries (300 V), Q_{nom} is the nominal charge capacity (200 Ah), t_{recharge} is the desired amount of time (in s) to recharge the batteries to the threshold SOC (45 min or 2700 s), and $P_{\text{one hour moving avg}}$ is the moving average power use of the bus over the last hour.

Fig. 5 shows the outcome of this control strategy during a 3.5 h period of bus operation. The vehicle runs solely on the battery at the start of the drive cycle resulting in a steady drop in SOC. As soon as the SOC reaches the threshold value of 0.65 the fuel cell stack is turned on and after ramping up at a desired rate, it delivers an average power to sustain the battery SOC at 0.6. The stack is turned off after the completion of the route and the bus returns to its garage on batteries alone to deplete it further. This mode of operation, known as charge depletion, not only reduces hydrogen consumption but also allows the NiCd batteries to be cycled over a large fraction of their capacity, which helps to avoid the effect known as “voltage depression” and thus maintain usable capacity [21]. While the existing design and operation offers multiple advantages in terms of cost, performance and durability, it presents additional opportunities to improve the design and control strategy which are currently being pursued.

6. System energy data and analysis

It is crucial to study the energy flow in the power train in order to identify possible ways to improve system efficiency. The Sankey diagram is commonly used to represent power flow in hybrid systems [1,6]. Accordingly, the power consumption and losses in our fuel cell bus system have been calculated and reported using a Sankey diagram (Fig. 6). The diagram is

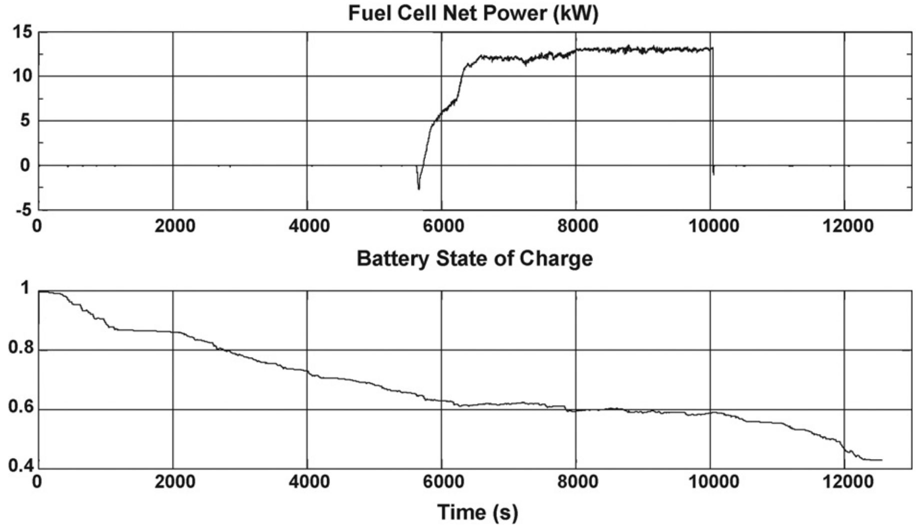

Fig. 5. Correlation between fuel cell power and battery SOC during a typical run of the bus.

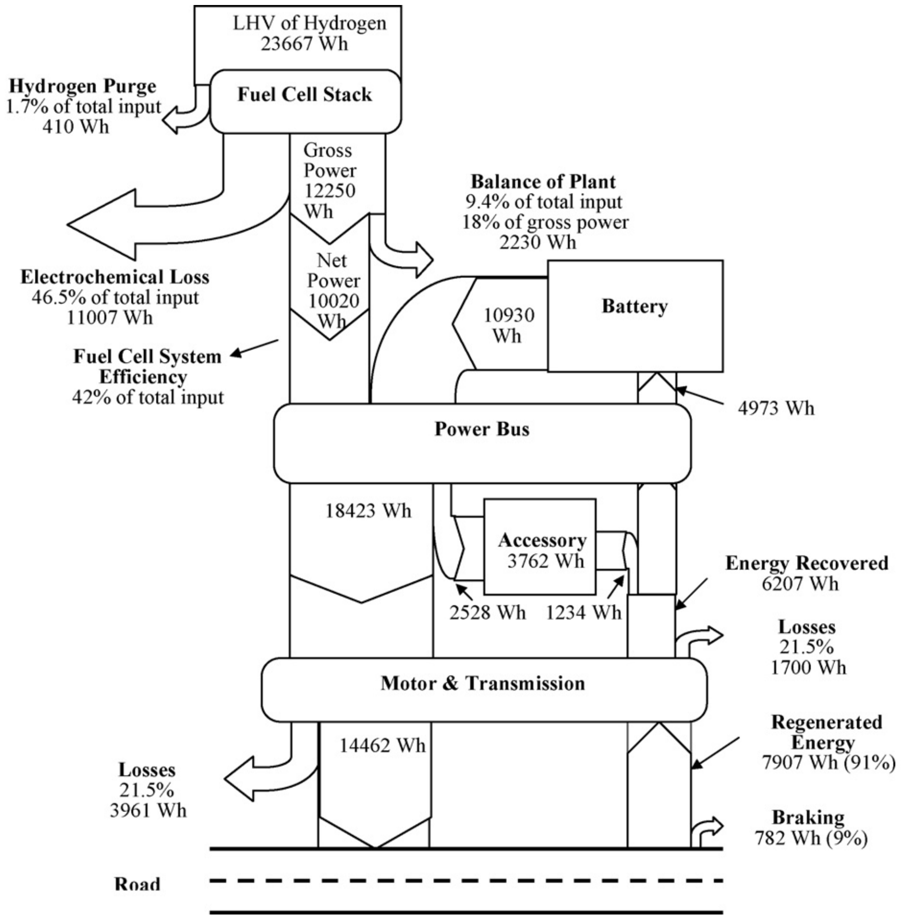

Fig. 6. Sankey diagram showing energy flow and losses in the hybrid power train for a typical drive cycle.

based on data that were logged during a randomly chosen drive cycle.

Hydrogen is one of the energy sources that drives the vehicle and its corresponding energy input is given by the lower heating value (LHV) of hydrogen. As shown in Fig. 6, approximately 1.7% of hydrogen is lost due to purging which is required to remove moisture and inert gases from the anode side; the precise amount of hydrogen lost depends upon the flooding condition of stack during the purging process. The fuel cell gross power is computed by taking the product of stack voltage and stack current. The electrochemical efficiency of the stack is calculated as the ratio of the gross energy produced by the stack and the LHV of the hydrogen that was reacted in the stack without accounting for the amount of hydrogen that was purged during operation. Fig. 6 shows that the average electrochemical efficiency during a 3.5 h period is 52.7%. Some of this produced energy is utilized to run the balance of plant which comprises of hydrogen humidifiers, hydrogen pump, air compressor, and radiator. The compressor consumes the bulk of balance of plant power. The remaining fuel cell net energy is available to the traction system. The net fuel cell system efficiency is the fraction of energy contained in the consumed hydrogen that is finally available to the traction system. The average fuel cell system efficiency (%) is given by

$$\eta_{\mathrm{fc,avg}}(\%) = 100 \times \frac{E_{\mathrm{fc,net}}(\mathrm{Wh})}{m_{\mathrm{H_2}}(\mathrm{kg})\mathrm{LHV}_{\mathrm{H_2}}(\mathrm{Wh\,kg^{-1}})}$$

where $E_{\mathrm{fc,net}}$ is the net energy delivered by the fuel cell over the duration of the drive cycle, and $m_{\mathrm{H_2}}$ is the corresponding total fuel consumption. The Sankey diagram indicates an average efficiency of 42% which shows that the stack performed very well during the chosen drive cycle. However it should be noted that average efficiency is not expected to be the same on every day. Fluctuations in average efficiency are mainly due to stack operation at either low or high load which requires a greater fraction of its energy to feed the balance of plant, or flooding conditions at the anode side resulting in fuel starvation and a drop in stack efficiency. This latter problem is usually overcome by hydrogen purging which adds to system losses.

During the 26.2 km (16.3 miles) Express Route drive on the University of Delaware campus, the traction motor required 18,423 Wh of gross energy (702 Wh km^{-1}, or 1130 Wh miles^{-1}) which is met by the fuel cell stack and battery combined. The traction energy requirement is expected to vary due to variations in the amount of ridership and random traffic patterns on different days. Approximately 21.5% of this energy is lost in the motor and transmission and the remaining 14,462 Wh goes into driving the vehicle. Ordinarily, deceleration in non-hybrid vehicles is assisted by friction and air drag and the remaining kinetic energy is dissipated by normal braking. However, since our bus is equipped with regenerative braking and a large bank of batteries to absorb the recovered energy, approximately 91% of kinetic energy is regenerated back to the traction motor and only 9% is lost due to braking. This value was obtained from simulation software based on speed data [22]. The fraction of regenerated energy depends upon the size of the energy storage system and driving style. After undergoing losses in the motor and transmission a total of 6207 Wh (237 Wh km^{-1}, or 381 Wh miles^{-1}) of energy is recovered which is 33.7% of the gross traction energy consumption.

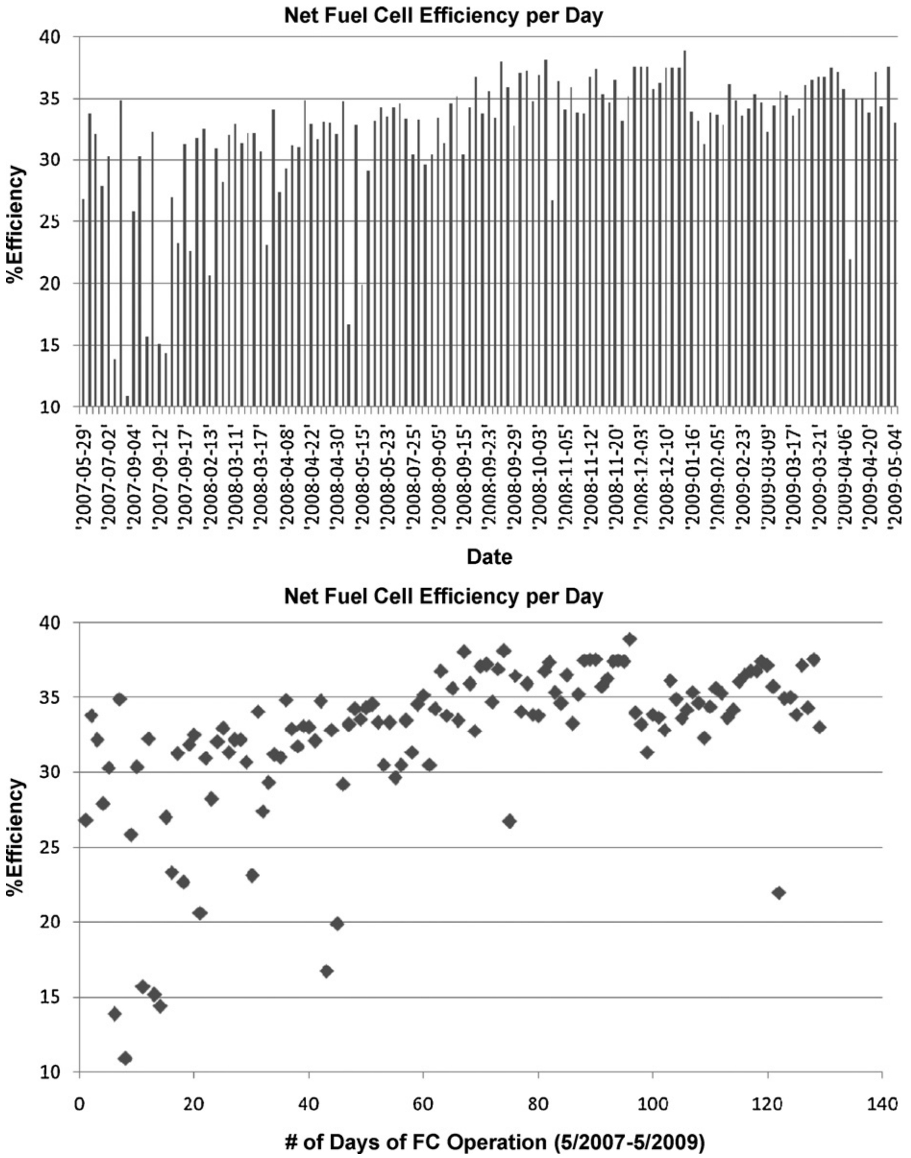

Fig. 7. Average efficiency of warmed-up fuel cell system on different days. Top figure shows dates of operation.

A small portion of energy is consumed by accessory components which include the vehicle air compressor (for non-stack related needs such as operating air brakes, air bag suspension, and pneumatic accessories), power steering hydraulic pump, battery chiller pump and compressor, 12 V accessories such as headlights, and air conditioning.

Analysis of the flow of energy through the power train also reveals further avenues for design improvements to make the system more efficient. In particular, the fuel cell balance of plant can be modified to remove liquid water more effectively from the anode using improved recirculation devices and water separators, and the control system can be reprogrammed to reduce delivery of air at low loads. The use of higher power density batteries such as those based on advanced lithium technology for onboard energy storage is another possible way to reduce vehicle energy consumption. Our simulation results indicate that the replacing NiCd batteries with an advanced Lithium Titanate battery pack of the same power capability in our bus can reduce the net traction motor energy requirement by approximately 13% as the battery mass would be reduced from 1800 kg to approximately 360 kg. Hence, buses #3 and #4 in the UD fuel cell bus program will use Lithium Titanate batteries (see Table 1).

While the Sankey diagram summarizes the overall energy flow and losses in the power train, it is also useful to examine the variation of key metrics such as the net fuel cell efficiency and fuel cell average power on different days of vehicle operation to evaluate the performance of the fuel cell stack in real world transit applications. The net efficiency is plotted in Fig. 7 after the fuel cell is warmed up and running at steady state. The average efficiency value over all days weighted by the hours of operation per day was 32.4%. The average fuel cell power (Fig. 8) was calculated each day by integrating the recorded fuel cell stack power and dividing it by the total time when the fuel cell was running at steady state. The total net average power value over all days was found to be 10 kW. Figs. 7 and 8 depict chronological plots of the net fuel cell efficiency and average power ranging from May 2007 to May 2009.

From the efficiency plot of Fig. 7, one can observe a rising trend with a leveling off, indicating an initial period of improvement followed by stabilization of fuel cell system efficiency. The efficiency plot depicts that the net fuel cell efficiency was char-

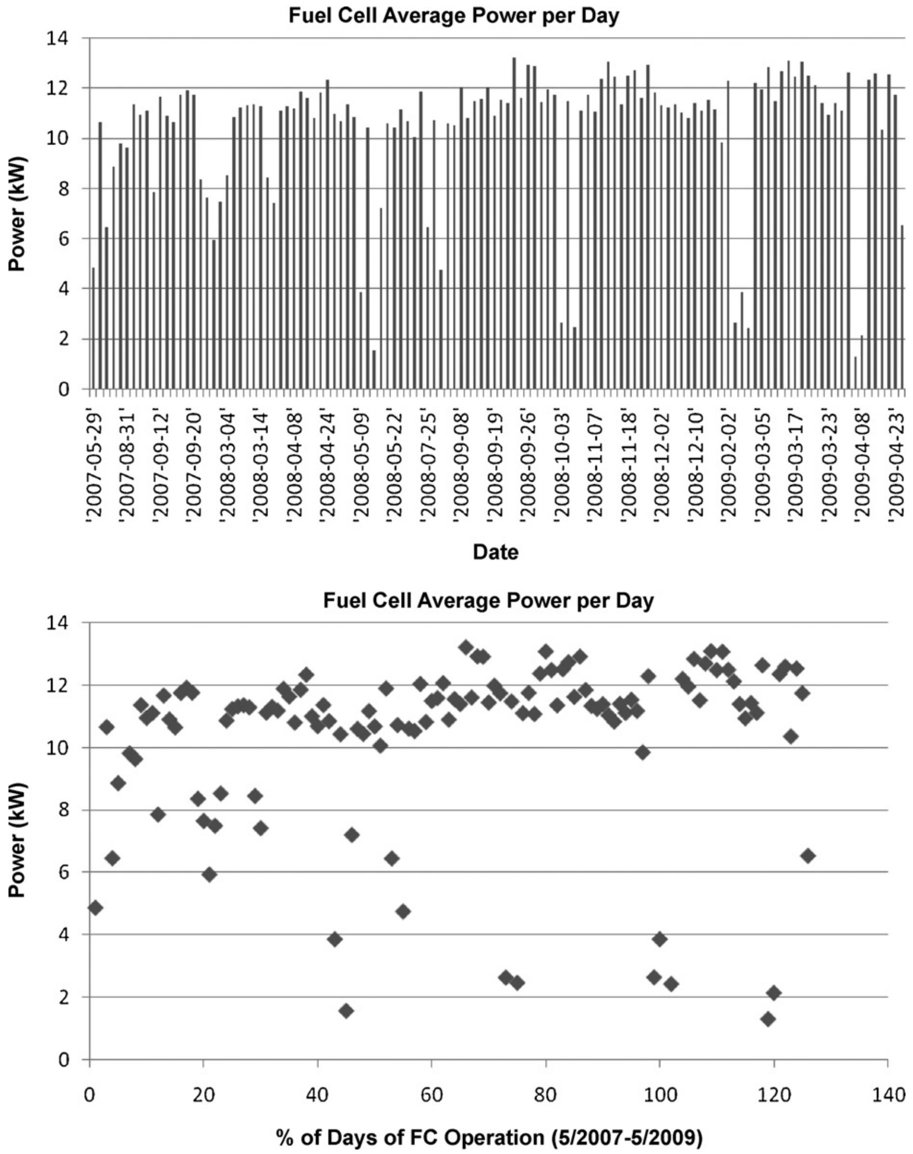

Fig. 8. Average net power delivered by the fuel cell system on different days. Top figure shows dates of operation.

acterized by noticeable variations in late 2007 and early 2008, followed by a reduction of scatter up to May 2009. Low efficiency days were investigated and were found to result from fuel cell system problems which were subsequently fixed. The average power plot displays a flattening trend with some outliers. The flattening trend is indicative of steady average fuel cell power use; again, outliers mainly correspond to low power events resulting from fuel cell system problems, similar to the net efficiency plots.

For example, our records indicate that the fuel cell experienced problems in Q4 2007 and Q1 2008 due to the lingering effects of freeze damage sustained during shipment of the bus to UD. This issue is evident by the low values and scatter in the efficiency data in Q4 2007. Additional low efficiency dates have been investigated and attributed to similar maintenance events. In essence, outliers in the generated metric data can be used to monitor and track issues with the fuel cell stack and conduct fault diagnosis. Steady improvements to the bus were instrumental in reducing scatter in the data and stabilizing performance.

Another important metric is the ratio of regenerative braking energy delivered by the traction motor to the gross energy consumed by the same. This ratio is important because it quantifies the energy savings achieved by regenerative braking and validates the use of hybrid technology. Fig. 9 depicts the variation of this ratio for 121 days of bus operation when motor current data were available. The plot shows that this ratio varies from 0.2 to 0.4. These variations are attributed to changing ridership, and hence mass, of the bus during operation on any given day, as well as random variations in the drive cycles due to changing driving conditions or slight detours from the prescribed route.

Hydrogen consumption is another important metric for evaluating the effectiveness of the fuel cell hybrid bus system in real world transit applications and depends upon the manner of fuel cell utilization in a hybrid power train. For our analysis, we have considered hydrogen consumption per unit distance that the vehicle covers while stack generates power. Fig. 10 displays a daily record of hydrogen consumption per mile by the UD fuel cell bus from Q4 2007 to Q1 2009. During a normal operation when the stack turns on and sustains the battery SOC, the average per mile consumption has been observed to be approximately 0.053 kg km^{-1}, or 0.085 kg miles^{-1}. This average value corresponds to normal operation when the vehicle is driven with no net energy being drawn from the battery, such that the battery SOC remains constant. Variations in power demand and drive cycle can influence hydrogen consumption and explain the small fluctuations

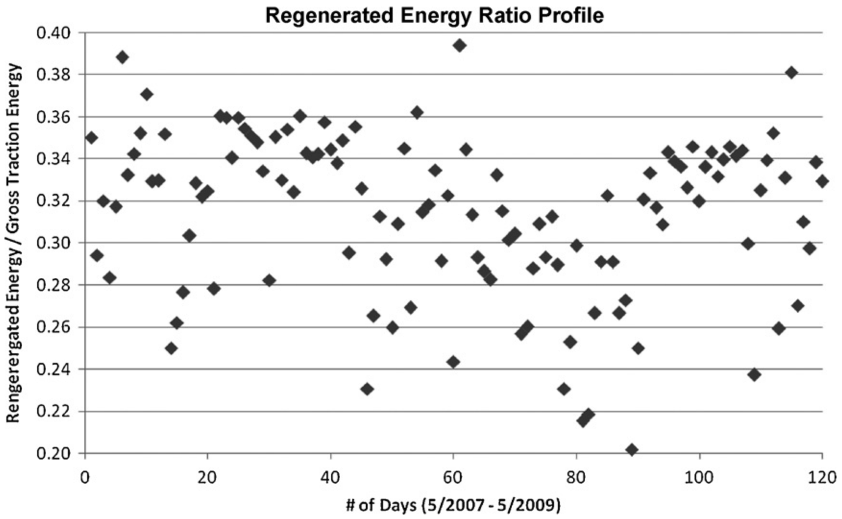

Fig. 9. Ratio of regenerative braking energy delivered and gross energy consumed by the traction motor.

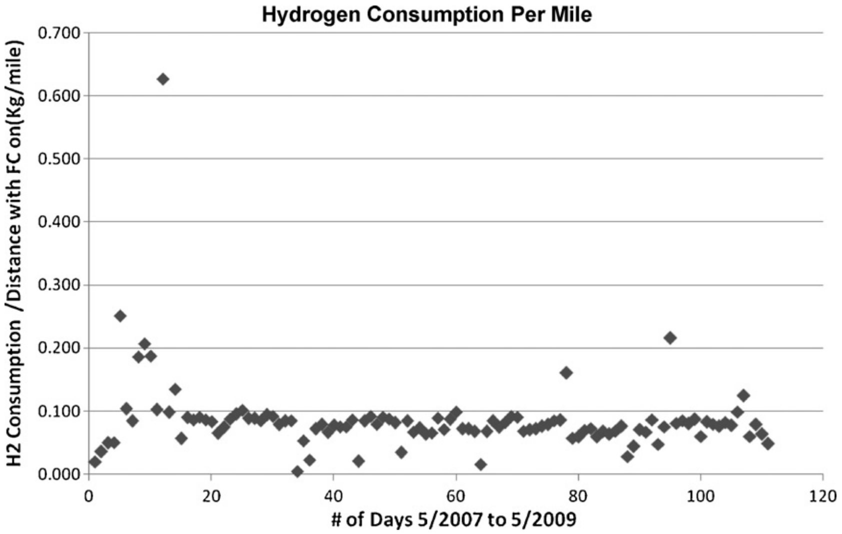

Fig. 10. Variation in hydrogen consumption on different days of bus operation.

in Fig. 10. However, some outliers are caused by deviations from normal hybrid operation. For example, values greater than 0.1 are attributed to additional hydrogen consumption for charging the battery while the vehicle is idling. Conversely, small consumption values result from the stack's inability to generate the required power for certain durations due to flooding conditions. Such outliers are useful in tracking deviations from normal fuel cell utilization.

A key issue with the implementation of fuel cell vehicles is hydrogen management. Due to the low gravimetric and volumetric storage efficiency of hydrogen, reducing the overall hydrogen demand will pay dividends in terms of system efficiency and cost-effectiveness. Apart from the benefits of regenerative braking to fuel economy, the plug-in hybrid configuration of our bus significantly lowers hydrogen consumption because the bus operates solely on battery power replenished by grid electricity for the initial portion of each drive cycle.

7. Maintenance

The bulk of the issues with the vehicle were related to debugging of the fuel cell system, which was the first ever built by EBus. This included issues with fuel cell freeze protection, the hydrogen delivery system, the boost converter, and the hydrogen recirculating pump, all of which have been resolved sufficiently well to ensure reliable vehicle operation. The hydrogen pump's issues were due to excessive friction within the pump caused by a combination of internal corrosion and thermal contraction of the stainless steel housing relative to the graphite rotor; these have been mitigated by changing the pump's mounting orientation and preheating the housing. In addition, there were minor design issues with the vehicle's chain drive and rear brakes, which were also fixed by UD. The vehicle's only road call was due to a failure of an internal monitoring component in the power steering inverter, which was easily replaced.

Regular maintenance of the vehicle is similar to maintenance of a similarly-sized diesel transit vehicle with air-over-hydraulic brakes, with the obvious exception that the engine is replaced with fuel cell and battery systems. The fuel cell system requires only periodic cleaning of the air intake filter and replacement of the fuel cell stack when its performance drops unacceptably low (which has not yet occurred in our bus). The NiCd batteries require watering at roughly three-month intervals, which consists of fully charging and then overcharging the batteries, waiting 30 min, and then watering

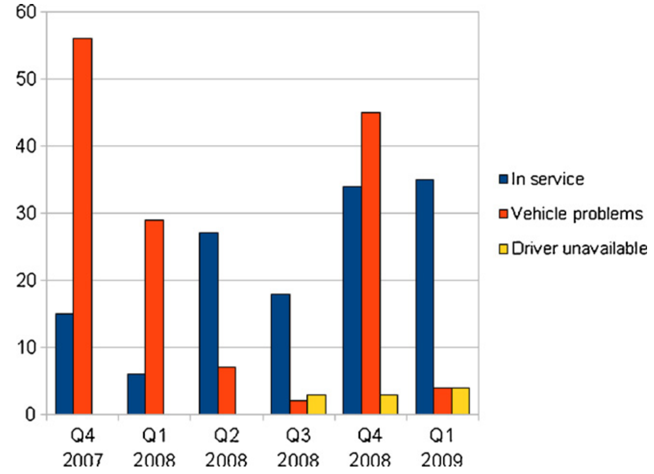

Fig. 11. Frequency of vehicle issues and availability in successive quarters.

using a gravity-fed tank feeding a siphon system that automatically tops up each cell correctly. In addition, to maintain full performance of the batteries, it is necessary to deep cycle individual battery blocks roughly every year; this is accomplished *en masse* using a device built by EBus called a "battery analyzer". With the addition of connectors to allow the batteries to remain in the vehicle during this process, it requires approximately 10 days out of service with minimal supervision.

Counting only the days of operation of the UD transit system during the past two years, our bus has operated for a total of 135 days, and was out of service for 143 days. As can be seen from Fig. 11, these out of service days are concentrated in three quarters. The first two, Q4 2007 and Q1 2008, were when the fuel cell system was inoperable due to stack damage (first from freezing during shipment and then from overpressure due to hydrogen delivery system problems). As a result of the limited range of the vehicle due to stack damage in Q4 2007, the distance covered was less than the following quarters (Fig. 12). Once the stack was replaced, the vehicle's service record improved and satisfactory fuel cell utilization was observed starting from Q1 2008. As expected, the fuel cell utilization trend was correlated with hydrogen consumption from Q1 2008 to Q1 2009 (Fig. 13) during which the average quarterly consumption was 19.1 kg. The only other period of vehicle unavailability was during Q4 2008, when it was out of service for deep cycling of the batteries. At that time, the procedure involved removing the batteries from the vehicle and setting up a separate cooling system, which took the vehicle out of service for most of October 2008. As mentioned earlier, the procedure has now been greatly simplified and deep cycling can be accomplished in 10 days. Despite these issues, the vehicle was in service for more than 30 days Q4 2008 and covered a substantial distance, Q4 being a busy period for the university transit system. Also, the increasing trend of vehicle utilization depicted by Fig. 12 is encouraging and is expected to continue with the support of dedicated maintenance and development efforts.

8. Developments and improvements

Cell voltage monitoring (CVM) is important in fuel cell and high performance battery systems in general, because it can detect damagingly low or high individual cell voltages that would not be appar-

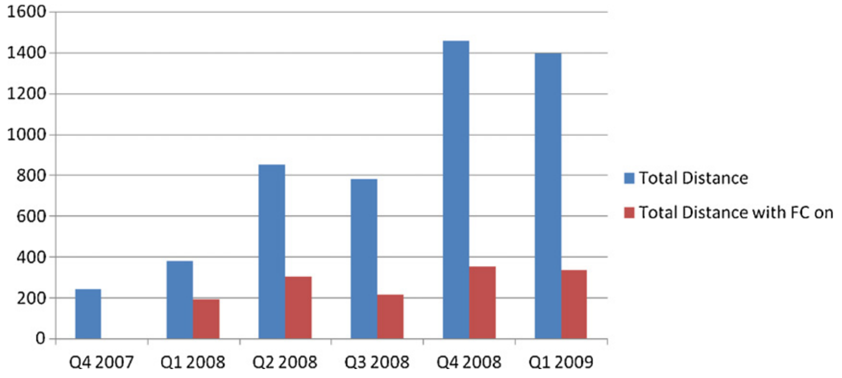

Fig. 12. Total distance covered by the vehicle during successive quarters.

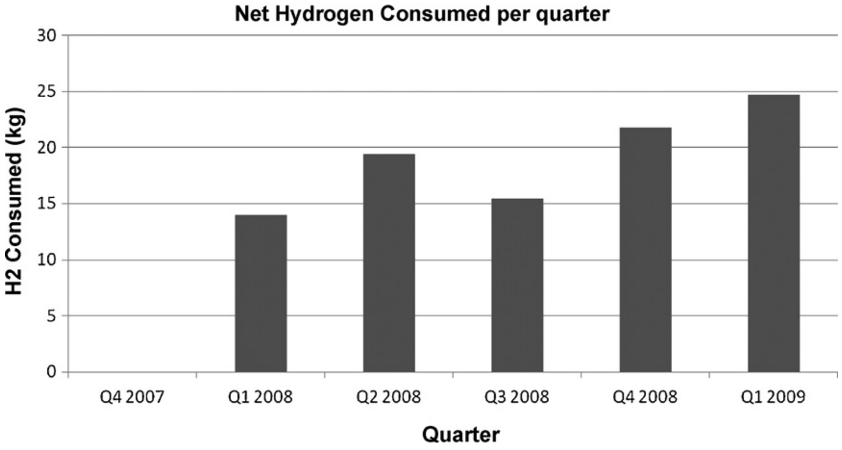

Fig. 13. Hydrogen consumption of the fuel cell stack during successive quarters.

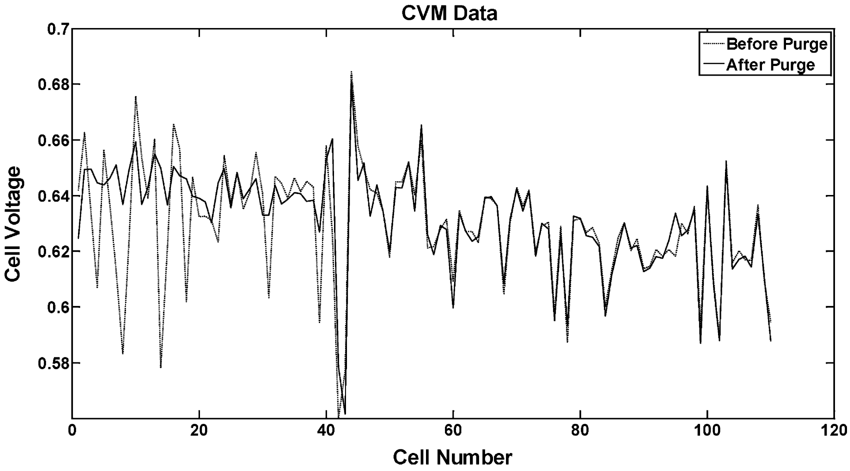

Fig. 14. Recovery of cell voltage after CVM-triggered purging.

ent from the voltage of the entire stack (or battery string); however, the large number of cells and the high voltage of the overall system compared to the voltage of an individual cell make it nontrivial to implement. Many cell voltage monitoring systems use semiconductor switches to connect each cell in turn to an analog-to-digital converter (ADC), so that the entire stack can be scanned. The drawback of this approach is that semiconductor switches have a considerable leakage current (up to the microampere range, dependent on temperature, and inconsistent between devices), and therefore the connections to the stack must be low-resistance, so that the leakage current from the connections that are switched off does not impact measurement accuracy. This means that, in the event of a component failure (especially a switch that fails shorted), large currents can flow; therefore, these designs can be hazardous if not protected by a bulky set of individual per-cell fuses.UD's patent-pending CVM system employs electromechanical relays, in conjunction with resistors connected between every tap point and the monitoring unit. Reed relays have far lower leakage current than semiconductor devices, and are available with a service life of 10^9 cycles or more. This ensures that a component failure on the monitoring board will not result in dangerous fault currents, while avoiding the large measurement errors caused by the leakage current through semiconductor switches. A full description of the design and implementation of the CVM will be covered in a separate manuscript.

The UD CVM system is used as part of the fuel cell control system on the bus. It is used to avoid damage to the stack caused by operating cells with low voltage; cells in this condition are operating at low efficiency, and can consequently overheat and be damaged or destroyed. This can occur due to a temporary water blockage, low system temperature, or many other factors; the CVM detects low cells and reduces stack current as needed to maintain acceptable voltage.

The CVM is also used to detect the cause of low cell voltages. In our system, the most common cause has been water blockage of the anode channels, resulting in fuel starvation. This produces a characteristic pattern of cell voltages, which is detected by the data acquisition system and signaled to the PLC, triggering more frequent purges of the hydrogen recirculation loop to eliminate excess water. Fig. 14 shows the cell voltages measured before and after a hydrogen purge, numbered from 0 at the end of the stack closest to the gas ports to 109 at the opposite end. The low cells in the region of the stack close to the gas ports (low cell numbers) had cleared during the purge, whereas the cells far away from the gas ports had not cleared as effectively. The low voltage on cells 42–43 is due to a small internal short circuit due to earlier overpressure damage to the stack.

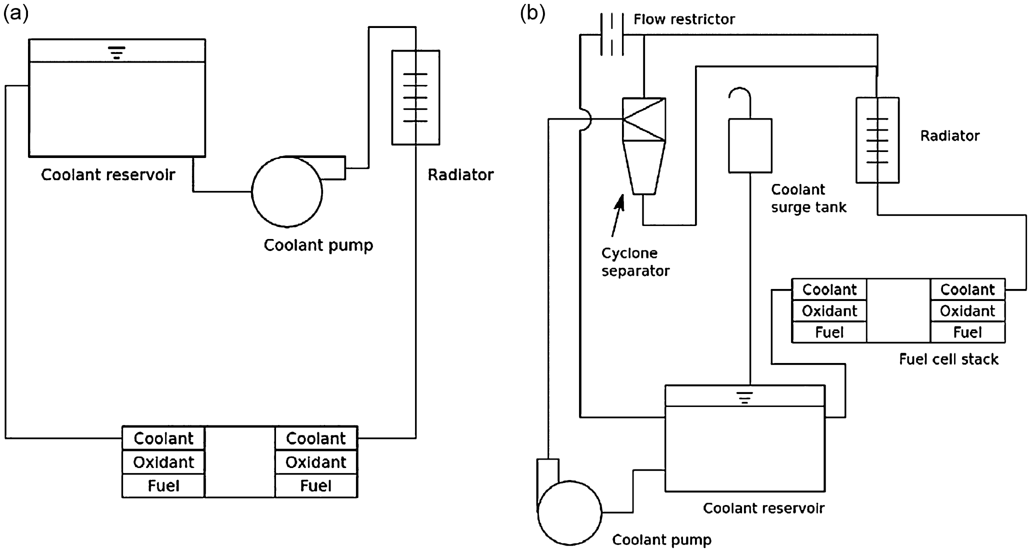

Fig. 15. Fuel cell cooling system (a) original, (b) reconfigured.

To mitigate the problem of liquid water in the anode channels, an improved hydrogen heat exchanger was added to preheat hydrogen coming from the fuel tanks. The heat exchanger is a parallel plate design, using nickel foam as a high performance heat exchange medium on the hydrogen side, and taking heat from the hot coolant leaving the coolant pump. This warms the dry hydrogen to near the temperature of the coolant, so that the hydrogen entering the stack is warmer than with no heat exchanger, and more of the water mixed with the hydrogen is in a vapor state.

The fuel cell cooling system was reconfigured to reduce pressure on the stack, as shown in Fig. 15a and b, since the vehicle as delivered could not meet the stack manufacturer's specification for maximum temperature differential from stack inlet to outlet without violating the specification for maximum coolant pressure with respect to gas pressure, and vice versa. This was accomplished by relocating the coolant reservoir and pump from the roof of the vehicle to the rear, below the fuel cell stack, so that the coolant only has to flow through a 1 m long hose from the stack to the reservoir, which is at atmospheric pressure, while dropping 0.5 m. In the original configuration, the coolant had to flow through a 5 m long hose to reach the reservoir, while rising 1.5 m. Since the coolant reservoir was no longer the highest point in the cooling system, a cyclone type air separator ("swirl pot") was added on the roof before the radiator, with an air purge line returning directly to the reservoir via a flow restrictor, as well as a surge tank connected to the reservoir. When the system is off, coolant rises to partially fill the surge tank; when it is on, coolant is drawn from the surge tank until it is emptied and there is air at atmospheric pressure in the top of the coolant reservoir, as shown in the diagram.

When the vehicle was first delivered, it used the amount of gross power being produced as the basis for its control of power ramp rates and air delivery to the fuel cell. This was found to be unstable, because adverse operating conditions could cause the fuel cell to operate in the portion of its polarization curve where power decreases with increasing current; therefore, the algorithm rapidly increased current (which was not subjected to ramp rate limiting) until the minimum allowable voltage was reached and current was cut back to protect the fuel cell. Changing the system to one based on current damped these oscillations to an acceptable level, and reduced the excessive delivery of air at low power levels.

The vehicle was also delivered with a control algorithm that simply stopped current draw from the stack as soon as the system was commanded to shut down, so that the stack remained at open circuit voltage for an extended period after shutdown. This is widely recognized as a cause of catalyst degradation, so the shutdown routine was revised to shut off air, continue to supply hydrogen at low pressure, and draw a small current from the stack to pull down the voltage by air starvation.

9. Summary and conclusions

A fuel cell hybrid bus program has been initiated at the University of Delaware to demonstrate the viability of fuel cell hybrid vehicles for transit applications. The current bus has been rigorously tested by running regular transit routes on campus with passengers, and valuable experience has been gained in the operation of fuel cell hybrid buses. The bus has undergone various maintenance events to improve overall performance. Developments such as the CVM, improved fuel cell cooling system, and improved hydrogen heat exchanger have yielded significant benefits in reliability and durability. Extensive data collection and reduction from a variety of on-board sensors has generated critical insights into fuel cell bus operation. System energy data analysis has revealed high-efficiency performance due to features such as regenerative braking and the plug-in configuration. Ongoing efforts include improvements to the bus hardware and software, troubleshooting, cataloging maintenance events, and reducing energy losses with improved design. Overall, the fuel cell hybrid bus program has successfully demonstrated the viability and cost-effectiveness of series-hybrid fuel cell/battery buses for urban transit applications.

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