



SURFACE VEHICLE INFORMATION REPORT

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Fuel Cell Vehicle Thermal Management

RATIONALE

Fuel cells (FCs) have been used in vehicles with special air quality needs, such as warehouse forklifts, and in space applications. For general transportation, fuel cell vehicles (FCVs) offer the following advantages:

- As the most abundant element on earth, hydrogen can be generated from a variety of sources, including natural gas, nuclear, coal, and renewable sources (e.g., solar, wind, biomass, hydro, and geothermal).
- Ultra-low to zero tailpipe emissions.
- Good ride experiences including smooth and quiet operation of electrical motors and good acceleration.
- Longer ranges, comparable to vehicles with internal combustion engines (ICEs).
- Shorter fueling times, in minutes, comparable to vehicles with ICEs.
- A good backup electrical power supply in case of an emergency.

As of February 1, 2019, about 3000 FCVs and 6000 FCVs had been sold and leased in Japan and U.S., respectively [1]. Chinese OEMs produced 629, 1272, 1527, and 3000 commercial FCVs in 2016, 2017, 2018, and 2019, respectively [2, 3, 4]. More FCVs of various kinds are being developed worldwide. A good reference is needed for the industry to understand the special requirements and practices in fuel cell vehicle thermal management.

1. SCOPE

The purpose of this SAE Information Report is to provide an overview of special requirements and practices in fuel cell vehicle thermal management. This document is primarily directed to fuel cell applications in motor vehicles.

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Documents

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2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

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3. FUEL CELL VEHICLE ARCHITECTURE AND REQUIREMENTS

3.1 Vehicle Architecture

The duty cycle of the fuel cell in an FCV depends on the degree to which the vehicle relies upon the fuel cell. This, in turn, is a function of both the size or output capacity of the fuel cell stack, and the environmental operating capabilities of the fuel cell stack. Where the capacity of the fuel cell stack falls short of the maximum vehicle demand, or where the fuel cell stack is not capable of operating in an expected environmental condition, such as extreme cold, an additional power delivery or energy storage device, i.e., high voltage battery, is needed. The propulsion power architecture of the FCV may be classified by the degree to which additional or secondary power devices are utilized [5, 6, 7].

Fuel cell only: As mentioned, the limiting case on one end of the spectrum is the one where the fuel cell by itself is capable of meeting all of the vehicle's power demands and will operate in all anticipated environmental conditions. In this case, no additional power devices are strictly required, and it is possible to architect a vehicle powered exclusively by the fuel cell. This configuration avoids weight/cost/complexity of high voltage battery packs and ultracapacitors, but sacrifices significant energy efficiency because without battery or ultracapacitor there is no way to capture regenerative braking power in an energy storage device [8].

Paired with energy storage: A logical step from the first limiting case is to add electrical energy storage, usually in the form of a high voltage battery pack, slaved to the fuel cell stack through a DC/DC converter as in Figure 1. This provides a supplemental power source which may enable the use of a fuel cell stack with a rated output below the peak power needs of the vehicle's mission profile. Perhaps even more importantly, it allows for regenerative braking power to be captured and stored, significantly increasing the vehicle's efficiency. For these reasons, this architecture is the most common FCV configuration, and therefore is the focus of this informational report. This configuration may be further subcategorized by the type and degree of energy storage added. Supercapacitors or ultracapacitors alone may be used, with improvements in power output but limited energy storage. Supercapacitors or ultracapacitors may also be combined with a high voltage battery pack to reap the power benefits of the capacitor and the energy benefits of the battery, which has been studied in an electrical hybrid vehicle by Snoussi et al. [9]. While most of this report's discussion and analysis will focus on a road vehicle execution, this architecture also lends itself to off-highway vehicles with lighter duty cycles such as in fork lift trucks, where power and environmental demands will be lower than in the road vehicles [10]. In rail transport, hydrogen fuel cell rail transport is commonly called hydrail. The typical architecture for hydrail is similar to the passenger vehicle case examined in this report, a proton-exchange membrane (PEM) fuel cell stack augmented with high voltage battery and/or capacitors. The reduced uncertainty in duty cycle and longer amortization of rail power make the fuel cell a reasonable proposition. The fuel cell has an additional advantage for rail applications where new routes or emissions driven diesel conversions are required, as the fuel cell system costs can compete favorably with the investment of running new electrical overhead lines.

Paired with rechargeable (i.e., plug-in) energy storage: The next step in terms of increasing additional power outside of the fuel cell is to have plug-in capability for the high voltage battery pack. In this configuration, the vehicle is essentially a battery-electric vehicle with a fuel cell range extender, enabling some flexibility in terms of fueling from either the electrical grid or hydrogen stations. Because the high voltage battery pack is now the primary power source, the fuel cell output may be further reduced or optimized against the range extending duty cycle. As more power is drawn from the battery pack, however, thermal management of that system becomes more demanding.

Paired with conventional ICE propulsion: FCs may be added to an ICE vehicle as an auxiliary power unit for applications where a substantial electrical supply is needed during use cases where using the ICE's alternator is not desired. Semi tractor-trailers are one such example, where fuel cells are used to provide cabin electrical power during extended "idling" or for container refrigeration units.

In summary, among all possible architectures, this information report is to focus on the most common FCV configuration: the fuel cell stack being supplemented with an electrical energy storage through a DC/DC converter as in Figure 1. This configuration has been adopted by every major series production FC passenger vehicle [11, 12].

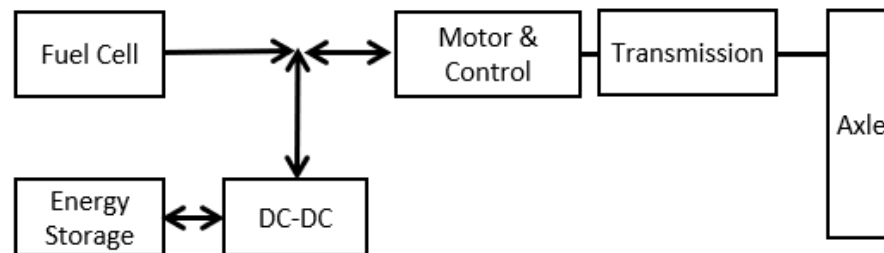


Figure 1 - Fuel cell propulsion configuration with a supplemental electrical energy storage

3.2 Power and Thermal Load

3.2.1 Power, Heat Sources, and Heat Sinks - Passenger Vehicles

Managing FCV thermal loads involves the dealing with waste heat generated by the fuel cell itself, electric powertrain and passenger comfort systems, including air conditioning (A/C). Waste heat is the direct result of inefficiencies in energy conversion processes; for example, the fuel cell stack and FC air compressor have an efficiency on the order of 60% resulting in high waste heat rejection. Therefore, raising efficiency through improved design is important for certain components like the FC air compressor [13, 14]. Accessory loads can be significant with A/C compressor and heater peak power requirements over 6 kW in high or low ambient temperature conditions (e.g., $\leq -7^\circ\text{C}$ or $\geq +35^\circ\text{C}$). Average heating and cooling loads after cabin temperature stabilization are in the 2 kW range [15].

Examples of primary components which generate heat are characterized in Table 1. This characterization is for a hybrid application of a fuel cell stack coupled with a small-capacity high voltage battery as shown in Figure 1. An example of energy flows can be found in [16]. Note that waste heat recovery from these sources is a primary design consideration for passenger comfort use and secondary for battery thermal conditioning.

Maximum power is a typical component design value for a light-duty vehicle. Maximum heat is the estimated thermal rejection at maximum power. Typical heat is the average heat rejection over a drive cycle. Note that specific vehicle implementations will vary depending on vehicle configuration, size and other system design choices.

Table 1 shows the power and heat sources in which power and heat are generated.

Table 1 - Power and heat sources for FC passenger vehicles

Power/Heat Sources	Max Power [kW]	Max Heat [kW]	Typical Heat [kW]
FC stack	100+	45	3
FC boost converter	100+	4	0.3
E-machine (motor/generator)	100+	8	0.4
Power electronics	100+	7	0.5
Electrical battery	50	5	0.15
FC air compressor	15+	5	4
Auxiliary electric heater at 20 °F	4	4	1
A/C Compressor at 35 °C and 850 W solar load	6	0.5	0.2

Table 2 shows primary heat sinks, with power varying by vehicle size, for C-segment (compact), D-segment (mid-size), and E-segment (full-size) vehicles, respectively.

Table 2 - Heat sinks for FC passenger vehicles

Power/Heat Sources	C-Segment		D-Segment		E-Segment	
	Max Heat [kW]	Typical Heat [kW]	Max Heat [kW]	Typical Heat [kW]	Max Heat [kW]	Typical Heat [kW]
Stack exhaust	<70	<20	70	~20	>70	>20
Radiator(s)	<70	<20	70	~20	>70	>20
Heater core	<3	<1.5	3~5	1.5-3	>5	>3
Condenser (air or water cooled)	<10	<5	10~14	5-8	>14	>8
Evaporator	<5	<3	5~7	3-5	>7	>5
Chiller (for liquid cooled battery)	<5	<1.5	5	~1.5	>5	>1.5
Battery (per cooling topology)	<5	<1.5	5	~1.5	>5	>1.5

3.2.2 Power, Heat Sources, and Heat Sinks - Commercial Vehicles

Commercial vehicles vary widely in their applications and thus in their power, with 32 kW and 228 kW stack maximum power for delivery truck and utility truck, respectively, as shown in Table 3. Their thermal loads will be impacted by their individual applications or drive cycles in addition to the variation in the peak power level. The cabin thermal design for a bus load of passengers is vastly different from that for one or two semi-truck drivers. This SAE Information Report therefore does not cover various thermal system design details of diverse commercial FCVs.

Table 3 - Power variation of fuel cell commercial vehicles

Vehicle Type	Stack Max Power	Battery Capacity	Reference
Bus, 10.5 m long	46 kW	100 kWh	4
Bus, 11 m long	90 kW	39 kWh	19
Delivery truck	32 kW		10
Parcel delivery battery electric vehicle (BEV): FC range extender	32 kW	45 kWh	20
Utility truck for port application	228 kW	12 kWh	21
Semi-truck	190 kW	73.2 kWh	22

3.3 Fuel Cell Stacks

A fuel cell stack consists of individual fuel cells stacked together to produce the required amount of power. The main components of a fuel cell stack as shown in Figure 2 are:

- Fuel cells, the number of which depends on total power required.
- Bipolar plates, to channel oxygen and hydrogen to the anode and cathode catalyst layer of the PEM. As indicated by its name, a bipolar plate serves as a cathode to one cell and an anode to its neighbor, enabling the fuel cells to operate in series.
- Membrane electrode assembly (MEA).
- Gaskets at the perimeter of the MEAs.
- Cooling plates, to transport coolant fluid to fuel cell stack for temperature control.
- Terminal plates or bus plates, located at each end of the stack with electrical connections.
- Endplates, one at each end of the stack, with fluid connections.
- Tie-rods, to maintain the whole stack together.

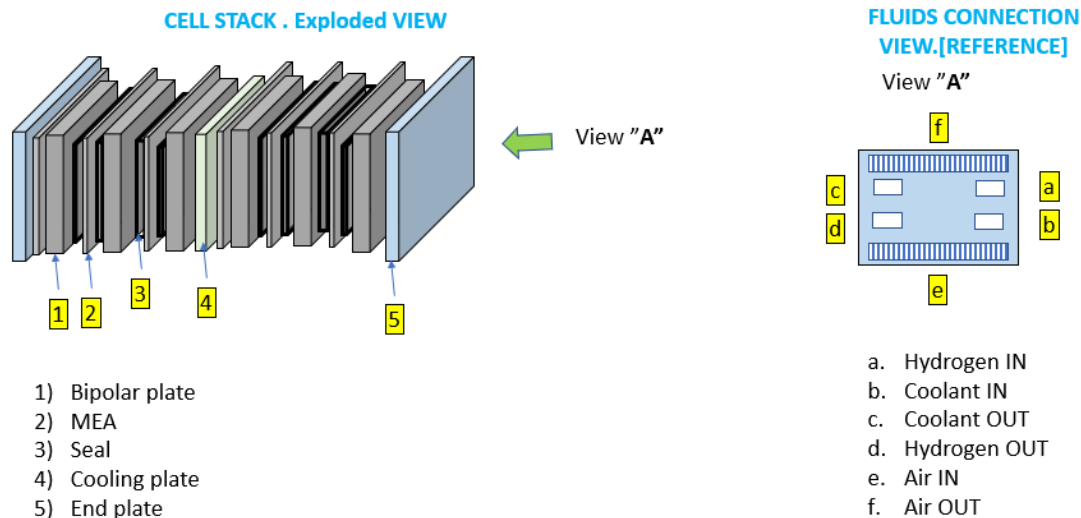


Figure 2 - A fuel cell stack

Depending on the stack design, there are two principle orientations possible: bipolar plates in either horizontal or vertical orientation.

3.3.1 Stack Sizing

An overall reference on how to size a fuel cell stack is provided in the following set of equations [17]:

The stack power output (W) is equal to the product of overall stack voltage (V_{st}) and the stack current:

$$W = V_{st} \times I \quad (\text{Eq. 1})$$

Stack voltage (V_{st}) is equal to the product of cell voltage (V_{cell}) and the number of cells (n_{cell}):

$$V_{st} = V_{cell} \times n_{cell} \quad (\text{Eq. 2})$$

Stack current (I) is equal to the product of current density (i) and the cell active area (A_{cell}):

$$I = i \times A_{cell} \quad (\text{Eq. 3})$$

The stack efficiency (η), in a decimal, is equal to the cell voltage (V_{cell}) divided by the thermoneutral potential, 1.482 V:

$$\eta = V_{cell} / 1.482 \quad (\text{Eq. 4})$$

3.3.2 Fuel Cell Stack Main Requirements for Passenger Vehicles

To achieve the power output required for a typical passenger vehicle, the size of FC stack and suitable operating parameters may be approximately characterized as shown in Table 4.