Water Balance in Fuel Cells Systems*

J. P. Kopasz, S. Ahmed, R. Kumar, M. Krumpelt

Electrochemical Technology Program
Chemical Technology Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

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J. Kopasz, S. Ahmed, R. Kumar, M. Krumpelt
Argonne National Laboratory, Argonne, IL 60439
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Introduction

Fuel cell systems are attractive for their high efficiency (i.e., electric power generated per weight/volume of fuel,) and lower emissions. These systems are being developed for applications that include transportation (propulsion and auxiliary), remote stationary, and portable. Where these systems use on-board fuel processing of available fuels, the fuel processor requires high-purity water. For utility applications, this water may be available on-site, but for most applications, the process water must be recovered from the fuel cell system exhaust gas. For such applications, it is critically important that the fuel cell system be a net water-producing device. A variety of environmental conditions (e.g.,ambient temperature, pressure), fuel cell system design, and operating conditions determine whether the fuel cell system is water-producing or water-consuming. This paper will review and discuss the conditions that determine the net-water balance of a generic fuel cell system and identify some options that will help meet the water needs of the fuel processor

The Problem

Fuel cell systems such as those for transportation are being designed to operate with petroleum-derived hydrocarbon fuels that can be supplied through existing infrastructure. This design would greatly facilitate the transition to fuel cell vehicles.

Table 1 shows the water balance results of operating a fuel cell system with gasoline. Column 1 shows the input parameters used to simulate the fuel cell system operation, and column 2 shows the computed results. Let us consider that the steam-to-carbon ratio in the feed is 1.5, a typical value used for autothermal reforming. This ratio corresponds to a water feed rate of 11 gmol/min into the fuel processor. The system is considered to be thermally integrated (reformer feeds are preheated), such that the autothermal reforming products exit the reformer 200°C hotter than the reactants. The heat for this temperature rise is generated by the autothermal reforming reaction.

The idealized reforming reaction (as shown in Eq. 1) produces a reformate gas that contains 44.6% hydrogen (dry basis) and has a lower heating value of 62.8 kW(t): the fuel processor then is said to operate at 84.8% efficiency. This equation is as follows:

$$C_nH_mO_p + x\ O_2 + (2n-2x-p)H_2O = nCO_2 + (2n-2x-p+m/2)H_2 \qquad \text{eq. 1}$$

The reformate gas should contain 2.8 gmol/min of water at a concentration of 7.5% (wet basis).

In the fuel cell anode, 80% of the hydrogen coming from the fuel processor is used. On the cathode side, the air is supplied at a rate of 73.9 gmol/min such that 40% of the oxygen reacts electrochemically with the hydrogen on the anode side. The 40% oxygen utilization corresponds to an air stoichiometry of 2.5. The unreacted hydrogen from the anode is then combusted with the unreacted oxygen from the cathode in the burner. The products from the burner then contain 18.4 gmol/min of steam at a concentration level of 17.7% (wet basis).

Table 1. Water Balance of a Fuel Cell System Operating on Gasoline

Input/Assumptions		*Calculated Parameters*	
H_2O/C Ratio into FP	1.5		
Temp. Rise in Reformer, °C	200	O_2/Fuel Molar Ratio into FP	3.19
		Air Feed into FP, gmol/min	15.2
		O_{Air}/C Ratio	0.9
		Water Feed into Fuel Proc., gmol/min	11
		Idealized FP Products	
		H_2, gmol/min	15.5
		H_2 Conc. in Reformate, %-dry	44.6
		LHV of H_2, kW(t)	63
		Fuel Processor Efficiency, %	85
		H_2O in Reformate, gmol/min	2.8
		H_2O Conc. in Reformate, %-wet	7.5
Fuel (H_2) Used in FC, %	80		
O_2 Used in Cathode, %	40	Air Stoichiometry in FC	2.5
		Air into Cathode, gmol/min	73.9
		H_2O in Burner Product, gmol/min	18.4
		H_2O Conc. in Burner Product, %-wet	17.7
Ambient Pressure, mm. Hg	760		
Exhaust Gas Temperature, °C (°F)	46.4 (115)	Saturated Moisture Content in Exhaust Gas, %-wet	10
		Recoverable Water, gmol/min	8.9
		Net Water Produced, gmol/min	-2.1
		Net Water Produced, mL/min	-38
		Exhaust T Needed for Water Balance °C (°F)	42.0 (107)
Radiator/Condenser Approach T °C (°F)	11.1 (20)	Ambient Temperature Needed for Water Self-Sufficency °C (°F)	30.9 (87)

The burner products are cooled in the radiator/condenser and leave the system as exhaust at a temperature of 46.4°C (115°F). Since the exhaust will leave saturated (8.5% wet) at that temperature, the amount of water that is recoverable from the system through condensation is 8.9 gmol/min. Comparing this with the water fed into the fuel processor (11 gmol/min), the system has a net shortage of 2.1 gmol/min (38 mL/min) of water which must be replenished.

In order to recover the 11 gmol/min water that was fed to the fuel processor, the exhaust gas temperature would have to be less than 42.0°C (107°F). If the radiator/condenser is designed for an approach temperature of 11.1°C (20°F), then the ambient temperature would have to be less than 30.9°C (87°F) to ensure the system's water self-sufficiency. The water balance position of a fuel cell system will also be affected by ambient pressure because that affects the saturated partial pressure of moisture in the exhaust gas. Thus, fuel cell systems located in Denver, CO, or Los Alamos, NM, where the ambient pressure is much lower than at sea level, will not be able to condense (and recover) as much water in the radiator/condenser. Consequently, the exhaust gas will need to be at a lower temperature than that shown in Table 1, where 760 mm of Hg was assumed to be the atmospheric pressure, to compensate for the difference in saturated partial pressure of water. Similarly, Table 1 does not account for moisture contained in the air fed to the fuel cell system. This moisture level will alleviate the water balance scenario somewhat (1-10%).

Solution Options

For many applications of fuel cell power, a consumable water supply is not available or feasible. Thus, it is very important to recognize the conditions which may lead to a net-water-consuming fuel cell system and design the system to operate as a net-water-producing system. This section reviews the system operating conditions to identify the options that can contribute to a net-water-producing system.

Higher Oxygen Utilization

The exhaust gas, which is moisture saturated, carries a significant portion of the water from the system. It follows, therefore, that reducing the exhaust-gas flow rate will reduce the amount of water exiting the system. One way to achieve this is by operating the fuel cell stack at higher oxygen utilization (cathode air stoichiometry). The effect of the cathode air stoichiometry on the water balance is shown for gasoline in Fig. 1. All other conditions are identical as described in Table 1. Lower air stoichiometry (higher oxygen utilization) improves the net water balance. For gasoline, the system becomes water-sufficient at a stoichiometry of 1.9.

Operating the fuel cell at higher oxygen utilizations is not an easy option, since it would lower the oxygen concentration in the downstream cells in the fuel cell stack. At low oxygen concentrations, the cell generating potential is adversely affected due to diffusional limitations. This reduces the overall energy conversion efficiency and is therefore undesirable.

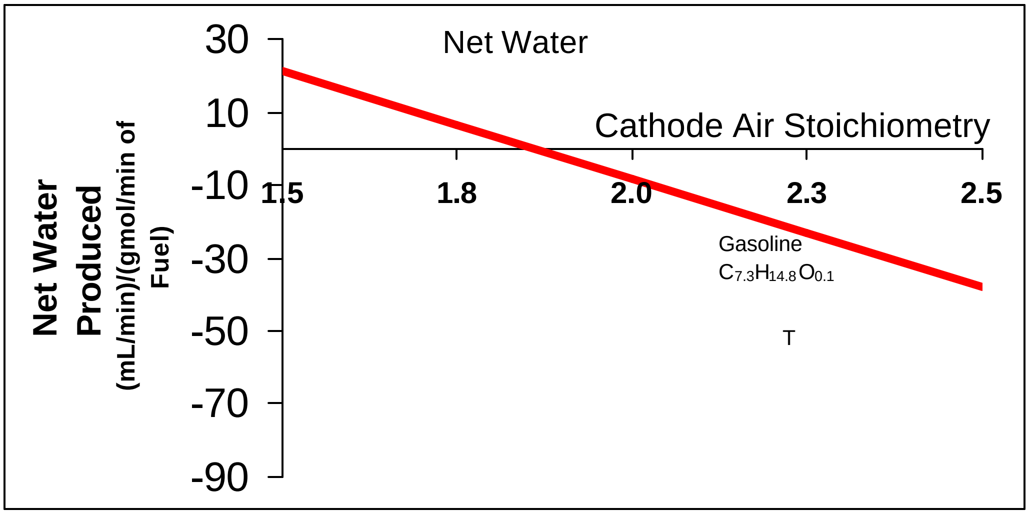

Figure 1. Effect of Cathode Air Stoichiometry on the Net Water Production (Consumption) from a Fuel Cell System. Basis = 1 gmol/min of fuel.

Pressurized Operation

Raising the fuel cell system pressure to higher than ambient pressures has the effect of lowering the mole fraction of water vapor at which the exhaust gas is saturated. Consequently, at a given exhaust gas temperature, more water condenses out and is therefore recovered. The effect of operating the fuel cell system at 1.5 atm is shown in Fig. 2. It is quite evident that elevating the operating pressure has a significant impact on the system's water balance.

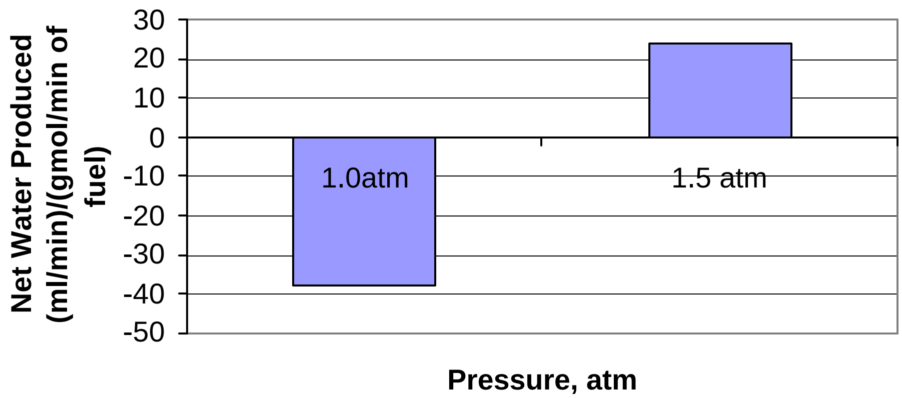

Figure 2. Effect of Fuel Cell System Pressure on the Net Water Production (Consumption) from a Fuel Cell System. Basis = 1 gmol/min of fuel.

Raising the system pressure is quite costly. Air feeds into the system must be compressed and compressors tend to be heavy and inefficient. The electric power consumed by the compressor represents a significant parasitic loss, which reduces the overall efficiency of the fuel cell system. Furthermore, the added cost of fabricating and maintaining a pressurized system is unlikely to make this an attractive option.

Less Thermal Integration

If the fuel cell system is designed for a high level of thermal integration, it can lead to significant preheating of the feed streams into the fuel processor. This is beneficial for the efficiency of the fuel processor and, therefore, the fuel cell system. In Table 1, a high degree of thermal integration was assumed, as reflected by the parameter "Temperature Rise in Reformer," which was considered to be a reasonably low value of 200°C. Relaxing that parameter such that the feeds are not preheated as much would require more heat generation in the fuel processor. Table 2 shows the effect of lesser thermal integration on water balance. It compares the two scenarios where the temperature rise in the reformer is 500°C and 200°C, using gasoline as the fuel.

With less thermal integration (500°C), more air feed is necessary into the reformer. This results in lower hydrogen concentration (38.4%) in the reformate, lower fuel processing efficiency (75.7%), and a smaller water deficit (30 mL/min).

Although reducing the thermal integration of the fuel processor alleviates the water deficit, it leads to lower hydrogen concentrations in the reformate gas. Since this reduces the rate of the electrochemical reaction in the fuel cells, it compromises two key performance parameters: the power density (kW/L) and the specific power (kW/kg) of the fuel cell system. The lower efficiency of the system also detracts from the attractiveness of the fuel cell system, which is being developed to increase the fuel efficiency of power generation.

Table 2. Comparison of Water Balance with Varying Degrees of Thermal Integration (Temperature Rise Needed in Reformer) with Gasoline as Fuel

Fuel	Gasoline	
Temperature Rise in Reformer, °C	200	500
O_{Air}/C Ratio	0.87	1.1
H_2 Conc. in Reformate, %-dry	44.6	38.4
LHV of H_2 from FP, kW(t)	63	56
Fuel Processor Efficiency, %	84.6	75.7
Net Water Produced, mL/min	-38	-30
Exhaust T Needed for Water Balance, °C (°F)	42.0 (107)	42.9 (109)
Ambient Temperature Needed for Water Self-Sufficency, °C (°F)	30.9 (87)	31.8 (89)

(Other input parameters and assumptions are identical to Table 1)

Lower Fuel Utilization: Reducing the fuel utilization of the fuel cell stack has a favorable effect on the water balance, since less oxygen and cathode air is required in the fuel cell stack. As shown in Table 3, lowering the fuel utilization from 80% to 60% reduces the cathode air feed from 74 to 55 gmol/min. The lower cathode air (less nitrogen) translates to higher moisture content in the burner products, (e.g. 22% at 60% utilization versus 18% at 80% utilization). For a given exhaust temperature (95°C, 115°F), the higher moisture concentration enables more water to be recovered in the radiator/condenser. Thus, with 60% fuel utilization, the net water deficit is reduced to ~1 mL/min. Lowering the fuel utilization reduces the electric power generated by the fuel cell stack (from 25 to 19 kWe). The overall system efficiency is also reduced from 34% to 25%. The loss in power density, specific power, and efficiency make this option an unattractive path to alleviate the water deficit issue.

Conclusions

For some applications, water balance in the fuel processing systems is critical. In these systems, running under standard conditions can lead to a water deficit. Several operating options can alleviate the water balance, but these options reduce efficiency.

Table 3. Effect of Fuel Utilization on the FC System's Water Balance

Fuel	Gasoline	
Fuel Utilization, %	80	60
Cathode Air Required, gmol/min	74	55
Electric Power from Fuel Cell, kWe	25	19
Fuel Cell System Efficiency, %	33.8	25.4
Moisture Concentration in Burner Product, %-wet	18	22
Net Water Produced, mL/min	-38	-0.7
Exhaust T Needed for Water Balance, °C (°F)	42.0 (107)	46.4 (114.8)
Ambient Temperature Needed for Water Self-Sufficency, °C(°F)	30.9 (87)	35.2 (94.8)

(Other input parameters and assumptions are identical to Table 1)

Reference

1. S. Ahmed and M. Krumpelt, “Hydrogen from hydrocarbon fuels for fuel cells,” International Journal of Hydrogen Energy, Vol. 26, pp-291-301, 2001.