

Using DCOV Methodology for Virtual Hydrogen Concentration Sensor Development (for use in the fuel cell electric vehicle)

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ABSTRACT

Accounting for more than 90% of the molecules and more than 75% of the mass [1], hydrogen is the most abundant element in the universe. Due to the small molecule size and high buoyancy, it is not available in its free form on Earth. In recent years, hydrogen has gained the attention of the automotive industry [2–12] as an environmentally friendly alternative fuel.

As a fuel, hydrogen is unique - it is odorless, colorless, tasteless, and burns invisibly in sunlight. Detection solutions such as the odorants used in natural gas are not yet feasible for automotive hydrogen because the available additives can poison the fuel cell catalyst. Additionally, the lower flammability limit of hydrogen is lower, and the flammability range wider, than fuels such as gasoline [13]. Hydrogen detection and

its concentration measurement is usually done using hydrogen concentration sensors [13]. For special purposes alternate methods are being developed to overcome the deficiencies of hydrogen sensors operating in harsh environments [14], such as inside of a fuel cell system.

In this paper, we present a method for estimating the composition of the anode gas in the fuel cell system. This method is based on indirect measurements and usage of already available signals inside the fuel cell system. Successful implementation of this method makes direct hydrogen concentration measurement unnecessary yielding significant savings in cost ($\approx$ \$100 per unit) and increase in reliability and robustness.

INTRODUCTION

High material and manufacturing costs have made fuel cells uncompetitive with existing energy technologies [15], limiting applications to specialty areas such as spaceflight. In the past decade, due to increased environmental concerns [16], rising oil prices [17, 18], and the uncertainty caused by geo-political factors [19–21], the automotive industry has accelerated efforts to develop more fuel efficient and environmentally friendly vehicles. This has resulted in a number of prototype fuel cell powered vehicles such as Ford P-2000 [5–7], Ford FCV Focus [9, 22], Daimler NECAR and F-Cell, Mazda Premacy [8], Honda FCX [11] and Clarity, and Toyota FCHV [10], to name a few. A number of cities around the world (Amsterdam, Barcelona, Hamburg, London [2], Luxembourg, Beijing [3], Madrid, Porto, Reykjavik, Stockholm, Stuttgart, Perth [4] e.t.c.) have introduced fuel cell bus fleets as a part of their mass transit system, while other areas are gearing toward custom designed fuel cell based transportation solutions [23]. As the number of fuel cell vehicles increase and plans emerge for FCV sales to the public [24, 25], the focus of development shifts from proof-of-concept to practical implementation that can be put into production in high volumes. Among the other things, this means a shift from prototype and lab sensors to automotive sensors and other alternatives that can be implemented robustly and inexpensively. One such cost reduction and reliability improvement efforts is elimination of expensive and unreliable sensors.

Initially, due to the limited operational experience with hydrogen, vehicles like Ford P-2000 [5–7] or Ford FCV Focus [9, 22] were heavily instrumented with some specially developed sensors such as sensors for monitoring the fuel cell stack voltages¹ or hydrogen detection. The most appropriate initial solution was the use of flammable gas detectors and direct hydrogen concentration sensors, either as safety sensors [14] or control sensors. The reliability of hydrogen sensors is location sensitive. Packaging of hydrogen sensors in the vehicle must take into consideration the buoyancy and diffusion characteristics of hydrogen, as well as the limitations of the sensor itself. If the sensing technology is sensitive to liquid water or high humidity, it must be taken into consideration, or the result may not be accurate.

¹CVM - cell voltage monitor

In this paper we present a method for hydrogen concentration detection using an indirect measurement method.

DEFINE - PROBLEM STATEMENT

Automotive fuel cell system consists of fuel cell stack and "balance of plant" for air and fuel delivery to the fuel cell stack, such as shown in [10] or [5]. During the operation of a fuel cell, nitrogen from the cathode (air) side of the fuel cell diffuses through the cell membranes into the anode (hydrogen) circuit. Additionally, water that is created as a byproduct on the cathode side diffuses to the anode. Therefore, the gas composition on the anode side of the fuel cell varies greatly and has significant impact on fuel cell stack lifetime. Also, this fuel (hydrogen) dilution by presence of nitrogen and water results in need for a "purge" - to open up the anode circuit and discharge accumulated nitrogen and water. In order to determine when to purge, a number of strategies have been proposed, like ones presented in [26–28]. Those purge strategies use some predetermined levels that are developed apriori, such as look-up tables, thresholds and maps. Although very effective, practical and simple, these methods tend to be rather conservative leading to higher hydrogen consumption.

Another method to initiate the purge of the anode loop is to utilize a hydrogen concentration sensor and purge when the read concentration falls below a predetermined level. Although this approach can yield minimal fuel waste, it suffers from high sensor cost and lack of robustness of available sensing technologies.

From the above arguments, we can state our problem as: *"Can we determine the anode gas composition without the hydrogen concentration sensor?"*. Answer, in theory, should be - yes. However, inferring the composition of the anode gas based on nitrogen and water transport models is very cumbersome [29, 30], and for a real time application in an embedded controllers very unpractical. For that reason, we ventured on development of an indirect measurement method utilizing the hydrogen pump like shown in [10, 31] as a "measurement device".

In an electro-mechanical device, consumption of the electrical power is directly dependent on the mechanical power delivered to the pumped fluid. The heavier the fluid, more mechanical power is needed to main-

tain the flow, leading to increased electrical consumption. On the other side, lighter anode fluid would require less blower power at the same motor speed. The functional cascade is shown in Figure 1.

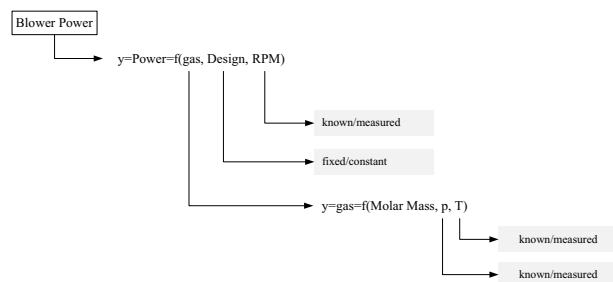


Figure 1: Functional cascade $y=f(x)$

CHARACTERIZE - TESTING & TRANSFER FUNCTION DERIVATION

In order to develop the method, a suitable hydrogen recirculation blower has to be identified. Although several hydrogen recirculation blowers were tested, only the most prominent designs' test results are presented here. This design, in further text referred as "blower"² was tested several years ago, and is slated to be used in upcoming fuel cell vehicles.

Testing

The molar mass of gas was determined by use of cal-gas mixtures and pure gasses, as shown in Table 1. Although performance testing was also done using pure nitrogen (28 g/mol), it is perceived that a fuel cells cannot operate without hydrogen, and therefore that data has been disregarded in this study.

Gas Mixture (% by volume)	Molar Mass $\frac{g}{mol}$
100 %H ₂	2
78.06%H ₂ -17.86%N ₂ -4.08%CO ₂	8.4
51.27%H ₂ -44.65%N ₂ -4.08%CO ₂	15.3

Table 1: Gases and gas mixtures and their molar masses (dry gases)

Characterization testing on hydrogen recirculation blower was carried out at supplier's site with the in-

²Due to the confidentiality agreements the manufacturer and model can not be disclosed

tent of verifying pressure and performance of the unit. Three units were characterized against several parameters. The testing can be summarized in Design of Experiments form, as shown in Table 2. The Electrical Power consumption is used as a metric.

Molar Mass (g/mol)	Speed (% RPM_{max})	Inlet Pressure p_{in} (barg)
2	17	1
8.4	35	2
15.3	53	3
	70	
	88	
	100	

Table 2: Blower Characterization Matrix (factors and levels)

It should be pointed out that this data was extracted from recirculation blower pressure/flow characterization which was aimed toward generation of blower performance maps. Using electrical power consumed as a metric, with the goal of deriving a preliminary regression model, we generated the main effect plots and interaction plots, shown in Figure 2. From those plots we can see, as expected, that electrical power has a non-linear dependency on rotational speed of the blower.

Transfer Function Derivation

Now, based on these results we can derive a regression equation to link molar mass and power consumed. Although strictly speaking, we could perform a regression to determine Molar Mass = $f(\text{Power, Speed, } p_{in})$, procedurally correct way is to determine Power = $f(\text{Molar Mass, Speed, } p_{in})$. After several iterations removing terms with high P-value, with $R^2_{adj} = 98.6\%$ we determined regression equation as:

$$\begin{aligned} \text{Power} = & 122 - 3.13 * \text{Speed} + 0.0542 * \text{Speed}^2 + \\ & + 0.0263 * \text{Molar Mass} * \text{Speed} - \\ & - 6.22 * \text{Molar Mass} * p_{in} + \\ & + 0.218 * \text{Molar Mass} * p_{in} * \text{Speed}. \quad (1) \end{aligned}$$

The residual plots are shown in Figure 3.