Hydrogen-fueled Power Generator using Nanogalvanic Aluminum Alloy to Produce Hydrogen

Girish Srinivas, Brady Clapsaddle, Joe Fredrickson, Jackson Brandstaetter, Jeff Martin*
TDA Research, Inc.
Wheat Ridge, Colorado, U.S.A., 80033
gsrinivas@tda.com / 1-303-422-7819

Abstract

Hydrogen gas (H_2) has many benefits as an alternative energy source, including environmental and energy supply benefits. Hydrogen can be used to produce electricity in fuel cells and hydrogen internal combustion engines. Producing H_2 at the point-of-need is especially attractive, as storing and transporting pressurized tanks of hydrogen is hazardous due to the high pressure and flammability of the gas involved. There are several solids that can produce H_2 when reacted with water that have far higher energy densities than hydrocarbon-based fuels and are safer to transport than pressurized hydrogen. One material is a novel nanogalvanic aluminum alloy developed by the Army that has the highest volumetric energy density of any solid hydrogen fuel. However, equipment for safely generating hydrogen from fuels at the point-of-need does not exist. To realize the potential of solid hydrogen fuels, hazardous, pressurized fuel tanks must be eliminated and replaced with an on-demand hydrogen generation capability at the point-of-need. TDA has developed a novel, portable, 900-Watt power generator that relies on hydrogen gas produced from the chemical reaction of the alloy and water to produce hydrogen as power is needed from the generator. The DC generator is portable, does not require high pressure sources of hydrogen, and only produces hydrogen as it is needed at the point of operation. The power generator is ideal for operating portable electronics (laptops, mobile phones, etc.) and charging batteries.

Keywords

Alternative Energy, Aluminum, Clean Energy, Fuel Cell, Gas generation, Hydrogen, Portable, Power Source

Introduction

The use of hydrogen to fuel power sources in mobile Military operations is very attractive as a replacement for hydrocarbon fuels. Producing hydrogen (H_2) at remote, mobile Military installations, however, can be difficult. Several solid chemical compounds exist that produce H_2 when reacted with water, including hydrides and metals, to name a few, but these compounds are difficult to transport and react violently and can ignite when they react with water.

Aluminum (Al) metal, in contrast, is easily handled, has a favorable H_2 production reaction with water and is controllable. However, *pure* Al contains a passivating oxide layer that is extremely stable in water, preventing the reaction of the underlying metal from forming hydrogen. As a result, pure aluminum will only produce hydrogen in water at high pH's (> 9) that first dissolve the passivating oxide layer, thus alkali solutions containing caustic, strong bases during reaction are required for full H_2 recovery from Reaction 1. Disposal and/or storage of this waste stream is

$$\text{Reaction 1. } Al + 3H_2O = Al(OH)_3 + 1.5\ H_2(g) \quad \Delta H \approx 100\text{kcal/mol}$$

not practical for mobile Military operations.

Recently, researchers at the Army Research Laboratory (ARL) have developed a novel, nanogalvanic aluminum alloy powder (Al-alloy; Figure 1) that can produce hydrogen upon direct contact with water without the oxide-passivation that typically hinders Al/water reactions during H_2 production (Figure 1). The novel Al-alloy has the fastest H_2 generation rate ever reported for an Al-water based H_2-production reaction, and 100% of the hydrogen yield is obtained within 3 minutes.[1]

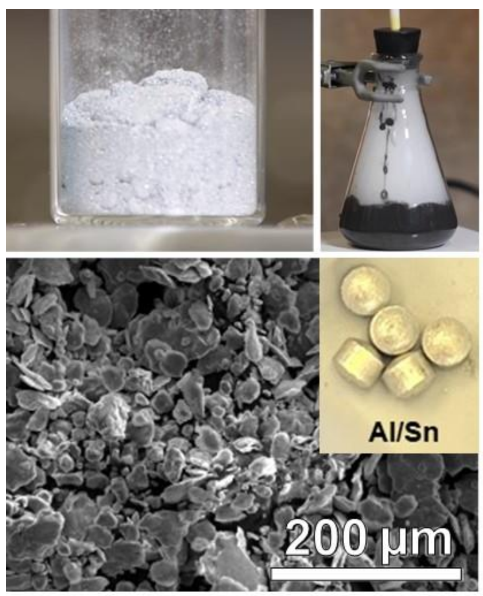

Figure 1. ARL's nanogalvanic aluminum powder. *Upper left*: powder. *Upper right*: water-powder reaction producing H_2. *Bottom*: SEM of the powder. *Bottom right*: TDA's pelletized Al-alloy powder (1/4" pellets).

While having great potential as a new power source for Military and commercial applications, ARL's powder suffers from the same problem as all solid H_2 producing fuels; *equipment for safely generating H_2 gas from solid fuels at the point-of-need does not exist.* To solve this problem, TDA Research, Inc. (TDA), has been developing a first of its kind, point-of-use hydrogen gas production system that is integrated with a PEM fuel cell in a portable power generator. The power generator uses pellets made from the ARL's nanogalvanic aluminum powder to generate hydrogen gas in a water-filled reactor in a design based on previous gas generators built at TDA.[2] The hydrogen produced *via* Reaction 1 is directly fed to a fuel cell and converted to power. The novel, hydrogen-powered generator currently produces enough hydrogen (~0.7 g/min.) for *c.a.* 1 kW of power and is designed to run continuously for 4 hours before refilling with Al-alloy pellets. Most importantly, the generation of the hydrogen gas that fuels the generator is self-regulating; hydrogen is produced *on-demand* as power is drawn from the generator and will stop once no power is needed. Currently, TDA's gas production system is integrated with the power generator (Figure 2) and is 4.5 ft^3, ~40 lbs., and has 12/24 V DC and 120 V AC output.

Design and Fabrication

The hydrogen-fueled power generator is a self-contained machine consisting of 2 independent subsystems: the hydrogen production reactor, and the electrical energy generation/storage system.

Figure 2. Design rendering of TDA's hydrogen-fueled portable power generator. The gas production unit with a spherical reactor is located at the front of the generator, and the fuel cell and power outputs are housed in the casing. An aluminum frame protects the generator.

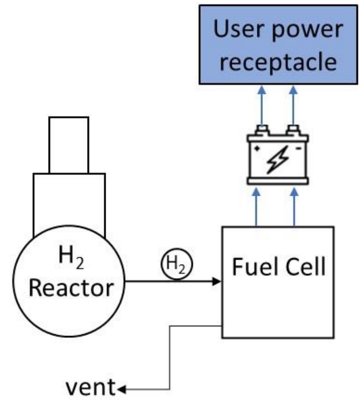

Figure 3. Schematic for TDA's H_2-fueled power generator.

The Hydrogen Production Reactor. The hydrogen production reactor is composed of a pellet dosing mechanism and a water reactor. The pellet dosing mechanism is a simple feeding mechanism that feeds Al-alloy "fuel" pellets into the water-containing reactor until an operable pressure (~30 psi) is obtained. The dosing mechanism provides Al-alloy to the reactor when hydrogen is demanded by the fuel cell to produce electricity. When power is needed, Al-alloy is fed to the water reactor, where it reacts with water to produce hydrogen for the fuel cell, which then produces electricity. When the power from the generator is no longer required, the Al-alloy dosing mechanism shuts down and halts hydrogen production *via* an electronically controlled feedback loop. In this manner, hydrogen is only produced as power is needed, and no fuel is wasted while power is not being drawn from the generator (compare this to a hydrocarbon-fueled generator that still idles when no power is being drawn).

A major part of the hydrogen production reactor is heat management, as the hydrogen production reaction (Reaction 1) is very exothermic. Removing the heat from the system is important in order to ensure that Rection 1 remains controlled and does not affect the reaction kinetics of hydrogen generation. Therefore, a custom heat removal system has been integrated into the reactor to ensure that the system does not exceed an operating temperature of 80-100 °C.

Energy Generation and Storage System. When power is demanded from the generator, hydrogen gas is fed to an on-board fuel cell, which produces direct current (DC) electricity that can be used directly, or be stored in a battery. When large loads are demanded from the system, the battery will take stress off the fuel cell when large current spikes are demanded and will allow the power generator to deliver continuous electricity if the hydrogen generation system fails to produce sufficient hydrogen for short periods of time.

Figure 3 Shows a schematic for the power generation system. To fabricate the hydrogen-fueled power generator, we have used a combination of off-the-shelf (OTS) parts and electronics, as well as custom-built parts, and the entire generator was built in TDA's machine and electronics shop.

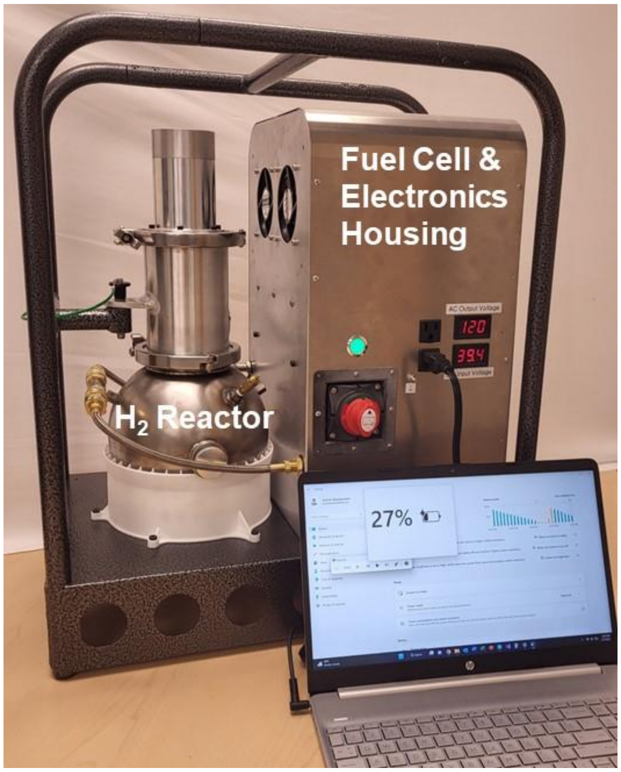

Figure 4. TDA's 900-Watt, on-demand H_2 fueled power generator.

The current hydrogen-fueled power generator with the hydrogen production reactor and the energy production/storage system can be seen in Figure 4.

The specifications of our current 900-Watt, H_2-fueled power generator are summarized in Table 1 and compared to a gasoline-powered generator with a similar power output. TDA's 900 W generator is built to run continuously for four hours using 3.3 lbs. (1.5 kg or 0.6 L) of Al-alloy pellets before needing to be refilled with pelletized fuel and water. A hydrocarbon (gasoline) fueled generator needs 1.5 gallons (9 lbs. or 6 L) of fuel to produce the same amount of electricity. Our H_2/fuel cell system weighs 40 lbs., while a 1.2 kW gas-fueled power generator weighs ~58 lbs. with no fuel (45% more). TDA's H_2-fueled power generator produces *no carbon emissions*, compared ~8 lbs. of CO_2 for the 1.2 kW gasoline power generator (EPA, 2022).[3] Further, unlike a standard gasoline generator, TDA's generator system can stay turned-on for long periods of time without wasting any fuel should the power demand drop to zero, since the fuel cell stops consuming (and producing) hydrogen when the output current drops to zero. In contrast, a hydrocarbon fueled generator continues to consume fuel as it idles, even if there is no current draw.

Table 1. Specifications for TDA's H_2-fueled power generator vs. a commercial gasoline powered generator.

Specification	Fuel	
	H_2 (TDA)	Gasoline
Size	4.5 ft^3	2.5 ft^3
Weight	40 lbs.	58 lbs.
Power output	900 W	1,200 W
Fuel (wt)	3.3 lbs	9 lbs.
Fuel (vol.)	0.6 L	5.7 L
Water	2 liters	--
Operation time	4 hours	5 hours
Noise	45 dB	65-75 dB

Operation

TDA demonstrated its hydrogen fueled power generation system system: an H_2 gas generator with H_2 produced from Reaction 1 and electricity generation in a PEM fuel cell. The entire system self-regulates to meet the H_2 demand required by the electrical load placed on the fuel cell. A custom-designed hydrogen gas regulation and flow system was implemented between the H_2 reactor and the fuel cell in order to ensure that H_2 was provided to the fuel cell at a flow rate of 200 mL/minute, resulting in the production of ~2.6 A of current and a voltage of 0.7 V. (Note, in actual practice, the flow rate can be much higher depending on the power demand; the system is designed to be self-regulating to produce and supply the fuel cell with the amount of hydrogen needed to keep up with the power demand.) The H_2 flow rate and reactor pressure, as well as the current and voltage of the fuel cell during operation are shown in Figure 5. In our test, changing the current draw from the fuel did not affect the delivery of hydrogen to the cell, which operated independently of the fuel cell and continued to provide steady H_2 flow to the fuel cell. Finally, the fuel cell was also operated using pure hydrogen from a pressurized cylinder of H_2 gas (Figure 5 top; dashed lines). When hydrogen from the cylinder was supplied at 200 mL/minute, the fuel cell produced identical power, thus demonstrating that there is no difference between the hydrogen produced chemically in our generator and pure H_2 from a high-pressure gas cylinder.

Conclusions

TDA has developed a first of its kind hydrogen fueled power generator. The generator is designed to be portable, produce hydrogen on-demand and at the point of use, and mitigates many of the hazards associated with transporting pressurized hydrogen tanks. The key to on-demand hydrogen generation is the use of a novel, aluminum alloy powder produced by the Army Research Laboratory that reacts with water to produce hydrogen gas. The power generator prototype is designed to operate for four hours using 3.3 lbs. of Al-alloy and two liters of water. The power generator produces no carbon emissions and does not consume fuel when power is not needed from the generator.

Acknowledgements

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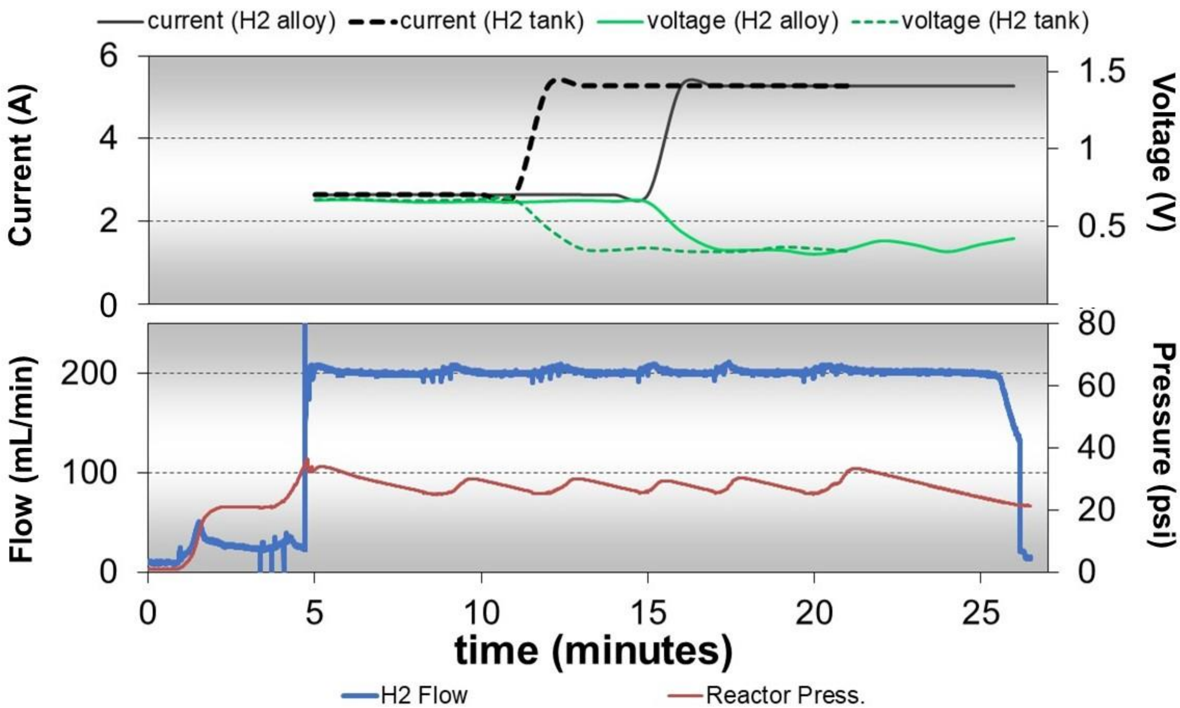

Figure 5. Hydrogen production reactor pressure and hydrogen flowrate with concurrent fuel cell current and voltage vs. time for operation of TDA's power generation system. The fuel cell was operated with a hydrogen flow of 200 mL/minute using both hydrogen produced from Reaction 1 (Al-alloy; solid lines) and from a pressurized tank of H_2 gas (dashed lines). For the chemically produced hydrogen run, the generator was allowed to "start-up" (*i.e.*, pressurize to its operating pressure of ~30 psi) before the fuel cell was started at 5 minutes. For the chemically generated hydrogen run, current draw from the fuel cell was increased at ~15 minutes to demonstrate the continued operation of the H_2 generator as power demand was increased.

References

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