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What Are Regenerative Fuel Cells?

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11-14 minutes

Scientists, researchers, and engineers are on a quest for the holy grail of energy technologies, and a key component of any energy system is figuring out new and innovative ways to store energy. One of the most popular visions for a renewable energy future is the hydrogen economy, but the question as to where one gets the hydrogen required to sustain it is as old as the idea itself. The regenerative fuel cell might be the answer that hydrogen economists are looking for.

What are regenerative fuel cells?

Ever wonder what would happen if you could run a fuel cell in reverse? You get a reverse fuel cell (RFC) or regenerative fuel cell. If a fuel cell is a device that takes a chemical fuel and consumes it to produce electricity and a waste product, an RFC can be thought of as a device that takes that waste product and electricity to return the original chemical fuel. Indeed any fuel cell chemistry can be run in reverse, as is the nature of oxidation reduction reactions, but a fuel cell that isn't designed to do so may not be very efficient at running in reverse.

In fact many fuel cells are designed to prevent the reverse reaction from occurring at all, for why would you want to consume the energy you just produced? Instead you might design a separate cell for the express purpose of taking energy generated from another source and storing it as a fuel for conversion back into energy when you need it via fuel cell. Enter, the RFC, also known as an electrolyser, which in the hydrogen economy is how you take electricity and split water back into hydrogen and oxygen.

How does an RFC work?

When you run a fuel cell in reverse, the anode becomes the cathode and the cathode becomes the anode. The mechanics of an electrolyser are best understood using the hydrogen fuel cell as an example.

Hydrogen Fuel Cell

In a hydrogen fuel cell, the goal is to consume hydrogen and oxygen to generate water and an electric current that can be used to perform work. The oxidation reaction occurs at the anode, breaking down hydrogen H2 gas into positive hydrogen ions and negative electrons. The reduction reaction occurs at the cathode combining hydrogen and oxygen and electrons into water. An external wire between the anode and the cathode completes the circuit, allowing electrons to flow from the anode to the cathode. This current can be used to supply useful work.

Regenerative Mode

By contrast, supplying a current and reversing the polarities of the electrodes in the hydrogen fuel cell results in a regenerative hydrogen fuel cell. The electrode that was once the cathode is now the anode, it oxidizes water decomposing it into oxygen gas O2, hydrogen ions and electrons. The electrode that was once the anode is now the cathode, it reduces hydrogen and electrons into hydrogen gas. The external current will have to be supplied from a power source, like a solar cell.

Unitized Regenerative Fuel Cell

Now you may have noticed, that the process of running a fuel cell in reverse sounds very similar to another chemical cell that can run in reverse, a rechargeable battery. For the most part while the chemistries are similar fuel cells are not batteries because they require a chemical fuel, you would have to pair a fuel cell with an electrolyser to get the same effect. However there is a type of fuel cell designed to run both forwards and backwards, the unitized regenerative fuel cell (URFC).

The URFC is a fuel cell and electrolyzer system based on the hydrogen proton exchange membrane fuel cell (PEMFC). Both the fuel cell and electrolyser stacks can be said to consist of the same major parts: membrane, catalyst, bipolar plates and end plates. The key is to use bifunctional electrodes that are capable of switching roles during charge and discharge without losing efficiency, similar to a rechargeable battery. The major design hurdle in a URFC is managing liquid water. Water formed in the cathode chamber during the fuel cell mode needs to be circulated out of the system, but at the same time allow water to be fed back into the electrode chamber to perform electrolysis during the regenerative mode. Historically this has been accomplished using a series of pipes, pumps, and canisters to manage the different feedstocks.

Research in recent years has led to the development of a new type of URFC, one that avoids the liquid phase altogether. In this system, you still have a hydrogen gas tank, oxygen tank, and water reservoir connected to the URFC stack. The design is however simplified by incorporating static feeds of water, oxygen, and hydrogen in their vapor phase by operating under a vacuum and using the storage tanks as heat sinks and sources.

How a URFC works

The URFC can be considered analogous to a battery that has a discharge phase and a recharge phase. The "discharge" phase for a URFC is when the fuel stack takes in hydrogen and oxygen gas and converts it into electricity and water. The "charge" phase is when the URFC fuel stack splits water back into the reactants hydrogen and oxygen. Let's see what is happening at each component of the fuel cell stack during discharge and charge modes.

"Charge" - Regenerative Fuel Cell Mode

An external power source, like the photovoltaic cell on a solar airplane, provides an electrical current to the URFC stack powering electrolysis of water into oxygen and hydrogen gas. As water is used up during electrolysis, the fuel stack draws in water from an expandable water reservoir that consists of a bellows within a pressure dome. Between the bellows and the dome is a layer of pressurized oxygen that keeps the water pressure below the pressure of oxygen flowing in the system. Maintaining this pressure differential is critical towards keeping liquid water separate from oxygen and hydrogen gas within the URFC stack

A bidirectional pressure control system orchestrates the pressure differentials that control flow into and out of the oxygen and hydrogen tanks, and the water bellows. The other control variable used to manage the various flows within the stack is a series of thermal heat pipes. The small amount of heat produced during electrolysis is transferred to a system of heat pipes to bring the URFC up to optimum operating temperature. Heat pipes wrapped around each of the storage tanks transfer the heat to the tanks which then act as cooling fins radiating thermal energy into the URFC's surroundings. Temperature of the tanks effectively drops below 0 C due to because the tiny amount of heat produced from electrolysis is not enough to heat the system and instead produces a gradient whereby heat is flowing out of the system and into the ambient environment.

Inside the URFC stack, oxygen and water vapor in equilibrium with the pressure and temperature of the stack exit through a pipe leads to a gas dryer that separates the two chemicals into an oxygen storage tank and an expandable water vapor reservoir. The oxygen storage tank, which is in direct contact with the dryer, acts as a heat sink, cooling the gas mixture and condensing or freezing the water vapor along the walls of the dryer. The dried oxygen gas stream continues to the oxygen tank to be stored until it is needed for the discharge phase, while the water remains condensed within the dryer's pipes.

On the hydrogen side of the equation, temperature and pressure is used to channel a gas mixture of hydrogen and water vapor through a hydrogen regenerative dryer in contact with the hydrogen gas tank. Once again heat is transferred from the gas stream into the hydrogen tank effectively condensing or freezing the remaining water vapor onto the walls of the dryer. In this manner, hydrogen fuel is stored in the hydrogen tank, ready to be consumed during discharge.

"Discharge" - Fuel Cell Mode

When a current is drawn from the URFC, it operates in fuel cell mode, taking hydrogen and oxygen gas from their respective storage tanks and recombining them to form water. Consuming oxygen gas lowers the pressure of oxygen in the storage tank and the layer between the water reservoir and pressure dome. As oxygen gas flows back through the dryer it picks up heat and water vapor as it re-enters the URFC stack. In fact as more waste heat energy is generated during the fuel cell operation, enough thermal energy is generated to heat the surface of the tank and in turn the dryer walls evaporating all the water that previously condensed during electrolysis. The heat reaches the storage tanks via the same heat pipe system that cooled them during electrolysis. A similar process is repeated on the hydrogen side of the equation, where temperature and pressure differentials are used to effectively evaporating all the water trapped within the dryer effectively regenerating it for the next electrolysis step.

Inside the URFC stack hydrogen and oxygen are combined to form water and channeled out the electrodes into cavities within the stack. The water is siphoned out of the stack and back into the reservoir bellows. Once again the layer of oxygen surrounding the bellows ensures that the pressure of oxygen gas in the system is just high enough to prevent cell flooding during operation.

RFC Applications

Solar planes, spacecraft, military UAVs, and cars are just some examples of potential applications of RFC's. They are most often combined with PEM fuel cells and solar power in remote area power supply systems (RAPS) or as a backup for wind or solar power systems. In such a configuration, photovoltaic panels, a PEM electrolyser and PEM fuel cell are used as a renewable replacement for conventional diesel generator with chemical battery backup.

Hydrogen Storage Systems for RAPS

The cost of transporting diesel fuel to RAPS can be too high to be economically feasible. If you had a rover on mars, it would make more sense to use a combination of solar power with a battery as a back up. While batteries have historically worked well for NASA in the past, fuel cells have the potential for even greater energy storage in the form of hydrogen fuels. In a hydrogen storage system, coupled with an on-site renewable energy source like solar, hydrogen fuel can be produced on site, eliminating the need for a supply chain

Exploring another planet.

The NASA All Terrain Hex Limbed Extra Terrestrial Explorer (ATHLETE) is a six legged concept rover designed to be able to navigate the surface of an asteroid and perform routine analysis and experiments. To test the feasibility of using fuel cells for RAPS, the ATHLETE was outfitted with an PEMFC system that could recharge its batteries while the rover was standing still to perform diagnostics, and supply support power during locomotion. When the rover needs to recharge, it returns to a hydrogen fueling station that converts solar energy into hydrogen via a regenerative fuel cell.

Hydrogen Cars

One potential application for the URFC is to incorporate it into a hydrogen vehicle. Normally a hydrogen fuel cell car would have to refuel at a hydrogen fueling station. The disadvantage here would be providing the infrastructure for hydrogen to be transported to fueling stations. A URFC could be incorporated into an electric vehicle and serve as a battery. The car could recharge the URFC by plugging into the electrical power grid at a charging station or personal garage. A highly efficient URFC vehicle would probably still need to be refueled at a hydrogen fueling station periodically, but not as often as a conventional fuel cell car or gas powered vehicle.

Future of RFC's

It will be some time before RFC systems can replace the role of diesel generators on the commercial scene. However as solar and wind generators grow in popularity and commercial vehicles begin switching to renewable energy sources, the RFC will play an increasingly more critical role in sustainable energy storage.