DOE Advanced Alkaline Water Electrolysis Meeting: Cell-Level Challenges

Steven Kloos, CEO

26 Jan 2022

AQUAHYDREX

AquaHydrex Overview

- Founded in late 2012 by True North Venture Partners
  - Invests in and builds businesses that help the world transition to a clean and sustainable future
  - PE-like playbook for early-stage ventures, focused solely on disruptive innovations
  - Makes long term commitments to their businesses through a perpetual holding company, which is capitalized in excess of $700 million
- Based in Louisville, Colorado (near Boulder)
  - Originally founded in Wollongong, Australia
- Singular company focus has been to develop an idealized electrolysis platform for Green Hydrogen at scale
  - Not pushing a technology but trying to solve for the ideal
  - “Right to left” thinking
  - Clean-sheet redesign of alkaline water electrolysis to design-out the problems and achieve the requirements
- Strong team, equipment and lab capabilities, engineering design, prototyping, and testing
- Company is in the early stages of commercialization

AQUAHYDREX

Core Requirements of an Idealized Electrolysis Technology

1) Safe

2) Efficient conversion of $/unit electricity to $/unit hydrogen (ie, making the lowest cost of hydrogen possible)

- High electrochemical performance over a broad range
- Low *system* capex
- Low operating & maintenance cost

3) Directly tie to variable renewable energy

4) Fast & easy to deploy in projects with minimal plant-level BOP, EPC time & expense

5) Achieves necessary quality hydrogen regardless of situation: high purity & ability to make at high pressure

6) For grid-connected cases, grid-friendly and grid-supporting

Alkaline Water Electrolysis Position

- Alkaline water electrolysis (AWE)'s heritage dates to invention of the diaphragm cell by Charles Watt in 1851 and commercialization of the chlor-alkali electrolysis process in about 1888
- With demand for hydrogen to feed Haber Bosch, in 1928 Norsk Hydro (now NEL) commercialized water electrolysis, based on the chloralkali platform, to produce hydrogen from hydroelectric
- AWE scaled nicely – to levels well beyond the total running electrolyzer plants today (< 300 MW)
  - Over 100 MW in the 1930s
  - Peaked at ~600 MW by about 1960
- Excellent fundamental and exploratory work in the early-mid 1900's
- Today's AWE leaders look a lot like those from 100 yrs ago
  - The chlor-alkali players are leading the charge in AWE, with chlor-alkali like AWE offerings
  - NEL's technology still is pretty similar to their original offering
- Some interesting work by a few players to create pressurized technology
- But not a lot has changed in in AWE in the past ~75 yrs

Alkaline Water Electrolysis Characteristics

- Poor J-V curves; current densities around 2-6 kA/m2 (200-600 mA/cm2), recently as high as 9 kA/m2
  - PEM is at 15-25 kA/m2, at similar voltages (and moving to higher current densities @ higher voltages)
- Terrible cell-level pressure management that results in unsafe crossover upon rapid changes in current density
  - Means that AWE can't be directly tied to variable renewable energy without mitigation
- Large & complex balance of plant, including flowing electrolyte loops filled with high concentration caustic
  - Also, external gas-electrolyte separators and mist eliminators
  - On-site caustic management
- Parasitic shunt currents results in:
  - Reverse currents if the system is turned off, damaging catalysts (consequently, AWE systems shouldn't be powered-off and tend not to use advanced catalysts)
  - Corrosion (eg, in steel electrolyte piping or electrolyte-gas separation tanks)

Current Position of AWE

- Because of the mature nature of AWE and its poor characteristics, the US Department of Energy has largely ignored AWE as a viable future electrolysis platform and instead has bet on sexier PEM & SOEC (and now also AEM)
  - Essentially no AWE work funded by DOE or reported on at the Annual Merit Reviews
- Little research on AWE in the past ~50+ yrs
  - Little work on advanced AWE catalysts (thankfully, AEM now driving some activity)
  - Little recent work to address stack & system issues
- But, because of the ability for the chlor-alkali value chain to pivot to AWE, and because of the proven nature of AWE and it's fundamentally low cost position, AWE is actually leading the charge in Green Hydrogen
  - And because PEM really isn't proven yet (at scale) and doesn't have a built-up supply chain
  - And because many don't see PEM scaling due to its dependency on iridium

What has the DOE Been Excited About?

PEM

- PEM's cell environment is highly acidic, resulting in foundational problems:
  - Most metals corrode in acid, so need to use expensive machined titanium, making PEM fundamentally high capex
  - In the acidic environment, catalyst choices are severely limited, and iridium is the only high performance choice
  - PEM uses a cation exchange membrane that turns from a conductor to a resistor if (when?) fouled with hardness

SOEC

- Solid Oxide requires high temperature operation (> 750 C), resulting in foundational problems:
  - Solid oxide systems require about 35% of the input energy to be heat
  - Solid oxide systems don't like to be turned on & off – they are best used 24x7
  - The high temp environment has been tough on performance stability in SOFC, should we expect the same in SOEC?

AQUAHYDREX

[At Least Some of] Alkaline's Problems Are Addressable

- The alkaline environment is suitable for a wide range of metals and an accessible amount of elastomers and polymers
  - Can use nickel in the cell
  - Many metals and catalyst materials are stable in the alkaline environment
- Some, if not all, of alkaline's problems are addressable
  - And, even if they aren't, alkaline is in the lead position today and is widely viewed by analysts to command a considerable market share going forward
- If AEM is able to be commercialized, it probably will need a conductive electrolyte, at which point it becomes alkaline water electrolysis, and will have similar problems
- DOE needs to jump on board and, ideally, lead

Opportunity: High-Electrochemical Performance

- Target achieving high current densities, ie 20+ kA/m2, at good voltages
  - Has to be in zero-gap cells
  - Most AWE electrolyzers do not use an applied catalyst (other than the base Ni metal) and give low current densities, around 2-4-ish kA/m2
  - Some AWE use applied catalysts, possibly with PGMs (for robustness), and run up to ~6-9 kA/m2
- Target stable, long-life, advanced electrodes (ie, those with a catalyst)
- Achieving voltage excellence
  - Understanding all impedances and working to make them as low as their practical entitlement
- Related, need to reduce the ‘slope’ of the J-V curve
- Pressurized systems
- Shunt current management

AQUAHYDREX

Need: High Electrochemical Performance Cells

- Only one known supplier in the world of proven advanced AWE anode & cathode
  - No US-based production of advanced AWE electrodes
- There is a debate of what AWE technology will win out
  - Low cost (classic NEL, Chinese) AWE electrolyzers that don't use advanced electrodes
  - More expensive AWE electrolyzers that use high-cost, higher-performance advanced electrodes
- The current reversal issue in AWE has hampered the development and deployment of non-PGM advanced electrodes
  - Can current reversal be avoided or managed?
  - Alkaline is a great environment for many possible catalyst choices – this is a white space – huge opportunity for DOE & academics
- Need to understand bussing and substrates and their affect on performance
- Need to understand bubbles
  - Including at elevated pressure
- Need to advance to higher temperatures over time
  - From ~60-80 C to 100-140 C
  - Will need to address the membrane separator

Need: Testing at Industrially Relevant Conditions

- The literature contains little to no info on AWE performance & lifetime at target conditions, for example at:
  - Higher temps (90 C – 140 C)
  - Higher pressures (30 bar, 100 bar)
  - Higher current densities (10 kA/m2 to 30+ kA/m2)
- Need to understand degradation mechanisms & rates, especially at these advanced operating conditions
  - Electrode degradation is a key driver of stack change-out and O&M costs, so important
- Need test methods to accelerate degradation and identify failure modes
  - Effect of on/off, higher voltage, material loading & surface area, bubbles (ablation), temperature, …
- Need to accurately measure impedances through the cell, from bipolar plate to bipolar plate, and compare to individual components
  - The membrane separator tends to show a much higher impedance in operation than when tested separately as a component – why?
- Need to understand upper current density limit due to hydroxide diffusion limits, and effect of temperature
- Need to develop and understand separator membrane performance at higher temperatures (100 – 140 C)
  - Crossover will increase but electrochemical performance and hydroxide diffusivity increase, too

Need: Understand & Improve Crossover

- Three types of crossover in AWE
  - Crossover due to diffusive transport of dissolved H2 and O2 to the wrong side of the cell
    - This type of crossover defines the lower turn-down current density
    - Is it true that a ‘better’ membrane in terms of impedance will always result in more crossover?
  - Crossover due to cell internals
    - Cell compression on the membrane
    - Trapped bubbles between an electrode and the membrane
  - Crossover due to pressure fluctuations in the cell caused by current density changes
    - This is what limits AWE’s ability to directly tie to renewables, which is a huge limitation, but the literature has little to no data on this problem
    - Can this be somehow mitigated?

Summary

- PEM & solid oxide aren’t a great fit with the requirements of an idealized electrochemical platform
- AWE, despite being considered ‘mature’ and low-tech, is playing a key role at the start of the green hydrogen revolution and is projected to have staying power
- The DOE and academics have largely ignored AWE
- There are considerable areas of opportunity to improve AWE and the DOE should play a key leading role in driving the development and fundamental understandings in AWE
- Improved AWE is the likely winning choice for long-term production of Green Hydrogen @ Scale

AQUAHYDREX