



# Scalable hydrogen production from a mono-circular filter press Divergent Electrode-Flow-Through alkaline electrolysis stack



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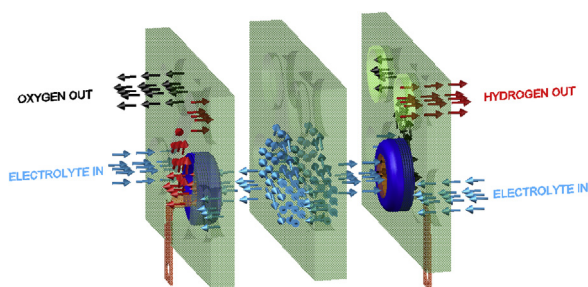
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## HIGHLIGHTS

- A MCFP DEFT™ membraneless alkaline electrolyser operates at high energy densities.
- H<sub>2</sub> and O<sub>2</sub> gas purities of 99.81 and 99.50 vol% are respectively obtained.
- A pure Ni anode and Ni cathode yields 1.14 A cm<sup>-2</sup> at a cell potential of 2.5 VDC.
- A double layer of Ni mesh yields 1.91 A cm<sup>-2</sup> at a cell potential of 2.5 VDC.
- Ideal for renewable energy sources as it can receive fluctuating energy loads.

## GRAPHICAL ABSTRACT



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## ABSTRACT

By incorporating all positive design criteria developed to date, to improve on performance and gas purities, a scalable and simplistic Mono-Circular Filter Press (MCFP) reactor has been developed and tested for the Divergent Electrode-Flow-Through (DEFT™) membraneless alkaline electrolysis technology. An improved gas/liquid separation methodology was utilised, which allows for hydrogen and oxygen gas purities of 99.81 and 99.50 vol% respectively, at the optimal flow velocity of 0.075 m s<sup>-1</sup> and an electrode gap of 2.5 mm. Circular 30 mm mesh electrodes were utilised, with each electrode pair having its own independent pressurised chamber, with a unique indirect injection mechanism for the electrolyte. By incorporating a gas purge ensures that gas purity is maintained for long operational periods. By utilising a Ni/Ni catalyst combination, a current density of 1.14 A cm<sup>-2</sup> at 2.5 VDC was obtained at a flow velocity of 0.075 m s<sup>-1</sup>, 60 °C, and an electrode gap of 2.5 mm. In utilising a double layer of mesh, with the same specification, and experimental conditions, a current density of 1.91 A cm<sup>-2</sup> at 2.5 VDC was realised, providing evidence for the effectiveness of multi-layered porous electrodes for the DEFT™ principle. Future improvements will focus on reducing the footprint and electrolytic flow velocity for the technology.

## 1. Introduction

Renewable energy sources, such as solar, wind, geothermal, and hydropower represent a promising alternative approach to energy

production and storage, amidst growing concerns pertaining to diminishing fossil fuel reserves and global warming, intensified through excessive greenhouse gas emissions [1]. Renewable power producers suffer in that the driving mechanism, for energy production and

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storage, is not always continuously available and hence cannot be relied upon to provide a reliable and stable base energy supply [2]. As a consequence either too much or too little power is available at some point in time. In the event of generating excess power it can be stored and utilised, when needed, in order to balance power grids, for example [3]. For this reason interest is growing in power-to-gas (PTG) and power-to-liquid (PTL) processes, as large capacity carbon neutral or carbon zero methods, of storing renewable energy [4]. Hydrogen, an energy carrier, can be generated from water electrolysis which represents a pollution free process of storing energy from a fluctuating renewable energy load. Despite this huge potential hydrogen production from water electrolysis remains economically uncompetitive with fossil fuel derived methods, such as steam methane reforming (SMR), due to the excessive OPEX costs associated and attributed largely to the cost of electricity [5].

Hydrogen can be produced from SMR for under US\$ 2/kg H<sub>2</sub>. The electricity cost contribution of a water electrolysis system, operating at 100% HHV efficiency, will need to be below 2–3 US cents/kWh. The average industrial electricity cost, as of August 2017 in the US, currently amounts to be 7.25 US cents/kWh [5,6]. The OPEX cost, of grid electricity alone, makes hydrogen production from water electrolysis not economically feasible. The cost of electricity (from renewables) is continuously decreasing, attributed to a number of factors such as efficiency, polysilicon price reductions, a reduction in the amount of raw materials used, and lastly an increase in the size of manufacturing plants [7]. In 2005, the cost of solar power amounted to be in the region of 4.1 US\$/watt. By 2012 the cost of solar power had reduced by more than 500% making solar power a viable renewable energy alternative [7]. It is foreseen that, with additional near term reductions in solar power, the OPEX costs (associated with the supply of electricity to electrolyzers) could reduce to below 3 US cents/kWh, that would place more importance on the CAPEX of these systems in order to make them cost competitive with SMR [5].

The large CAPEX costs, associated with proton exchange membrane electrolyzers (PEME's) and alkaline water electrolyzers (AWE's), is a well-documented impediment in the broad based industry uptake of water electrolysis technologies only being low enough at very large scales of production [8]. Neighbourhood scale systems (~10 kg H<sub>2</sub>/day), small forecourt systems (~100 kg H<sub>2</sub>/day), and forecourt systems (~1000 kg H<sub>2</sub>/day) have an electrolyser CAPEX cost of US\$ 5000/kW, US\$ 2000/kW, and US\$ 850/kW respectively, which clearly illustrates the cost reduction advantage of membrane systems producing hydrogen at large scale [9]. When utilising water electrolysis technologies to produce hydrogen from solar power the power is only available for a short duration during any day. The amount of hydrogen produced during the estimated lifespan of the plant is lower and the percentage contribution of CAPEX to the total cost to produce hydrogen becomes of even greater relevance [5].

AWE's are increasingly becoming more technologically relevant due to the scarcity and use of cost intensive materials for the production of PEME's, and consequently, alkaline electrolyzers are more probable for deployment in large scale applications [10]. Modern AWE systems are, however, limited by large plant scales as a consequence of limited operating current densities (< 500 mA cm<sup>-2</sup>) which results in a capital intensive approach despite being constructed from inexpensive materials [11]. The majority of research in water electrolysis deals with the incremental improvement of components in order to improve efficiencies and longevities of these systems, however, new disruptive technologies are needed in order to compete with hydrogen produced from SMR [5,12].

PEME's offer a more efficient technique of producing hydrogen in contrast to AWE's, yet they possess a number of mechanisms of membrane failure, which makes reliability and long term stable operation problematic. Both PEME's and AWE's are flexible in accepting an intermittent energy load (i.e. solar energy), however, they do remain restricted to operation below maximum current density thresholds, due

to elevated degradation of the polymer membrane [13]. It is found that Nafion, a common PTFE containing membrane material, used in both PEME's and AWE's, fails at current densities greater than 1.8 A cm<sup>-2</sup> due to the presence of 'hot spots' occurring on the electrode surface which is a result of an intensified uneven distributions of current lines across the electrode surface [13]. Though operation at greater current densities and temperatures is desirable, operational lifetimes due to component failures can be significantly inhibited, and hence operating temperatures of membrane systems remain low (< 100 °C) [4], [14].

In an attempt to overcome the issue of membrane durability, along with reducing the complexity and indirectly the CAPEX of water electrolysis technologies, membraneless electrolyzers have been developed that make use of an architecture that manipulates the flow of electrolyte in order to achieve gaseous separation. They represent a concept that has potential for enhanced reliability by being more tolerant toward contaminants and allowing for a wider material selection [5]. While a number of membraneless alternatives have surfaced reservations have been made on the ability of these technologies to be scaled for enhanced hydrogen production rates [15]. This is owing to the fact that most perceptible derivatives, of membraneless fuel cells and electrolyzers, have been developed as micro-fluidic devices [15,16].

Divergent Electrode-Flow-Through (DEFT™) membraneless alkaline electrolysis has been developed, to demonstrate scaled hydrogen production capabilities, with a simplistic design. High gas purities were previously demonstrated, achieving 99.83 vol% H<sub>2</sub>, at a current density of 3.5 A cm<sup>-2</sup> [17]. Similar performances were achieved employing a horizontal filter press (HFP) stack, when compared to previous findings from the concept optimisation stack, however, a reduction in gas purity was observed due to the inefficiency of the gas/liquid separation system to cope with the rapid throughput of bi-phase electrolyte [18]. A new approach in scaling the technology, communicated as part of this paper, will incorporate a culmination of positive design criteria from previously tested pilot plants.

## 2. Experimental apparatus and method

Divergent Electrode-Flow-Through (DEFT™) technology operates on the patented principle (US Patent: US9683298B2) of electrolytic solution flowing through porous electrodes, that are arranged parallel and opposing each other, in order to achieve high purity separation of the anodic and cathodic gases without the need for a membrane. A previous design that made use of the DEFT™ principle, which was a concept optimisation prototype to determine the relationship of electrode gap versus electrolytic fluid flow, made use of 30 mm circular electrodes arranged in a pressurised chamber to achieve equal fluid distribution between all electrode pairs [17]. This design was capable of achieving high gas purities (> 99 vol%) at high current densities (3.5 A cm<sup>-2</sup>), however, it had the impracticality in that it proved complex in achieving simplistic scaled hydrogen production. In an attempt to identify an alternate solution to scale-up, a Horizontal Filter Press (HFP) DEFT™ reactor was tested, utilising 20 mm × 400 mm rectangular electrodes for compact scale-up of the technology [18]. This design did not make use of circumferential injection of electrolytic fluid into the electrode gap, and consequently, uniform velocity distribution of fluid through the porous electrodes proved difficult. A drop in performance was yielded along with a reduction in gas purity that was intensified by an inefficient gas/liquid separation system [18].

The Mono-Circular Filter Press (MCFP) reactor serves to take advantage of all positive design elements, which were developed as part of prior test stacks and pilot plants, but still allows for a flexible electrode gap that ranges between 2.5 and 4.5 mm. By utilising 30 mm circular electrodes, with circumferential flow injection from an independent feed chamber, electrolytic flows are balanced to all electrode pairs while a filter press configuration provides a simplistic scalable design (Fig. 1). A filter press design is incorporated by multiple electrolyser designs in order to achieve a compact and scalable design. In a filter

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