Achieving Separation with Membraneless Water Electrolysers

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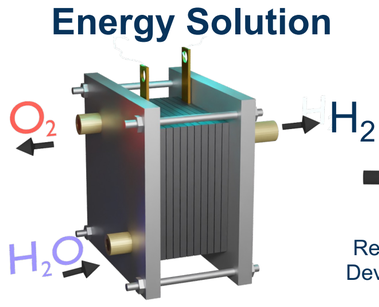
Motivation

Energy Problem

UK Wind energy curtailment predicted cost at 3.5bn £ a^{-1} (2030) [1]

AC to DC Power

Energy Solution



Research & Development

Store energy as H_2 by splitting water in electrolysis

Electrolyser Challenges

Mining Supply of Iridium (PEM) ~ 7 t a^{-1} [2]

High Cost due to low throughput (current density) (2000 $ kW^{-1}) [3]

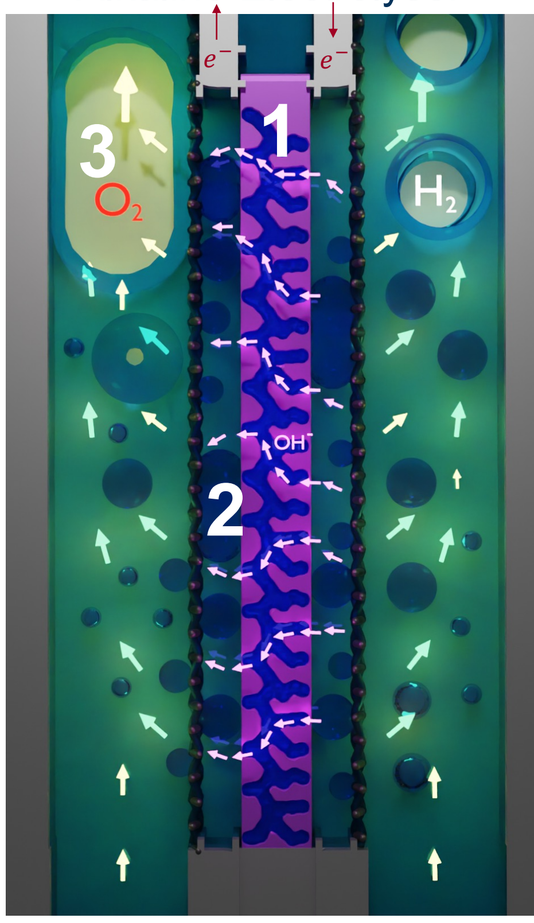
Alkaline Challenges

Nickel Catalyst

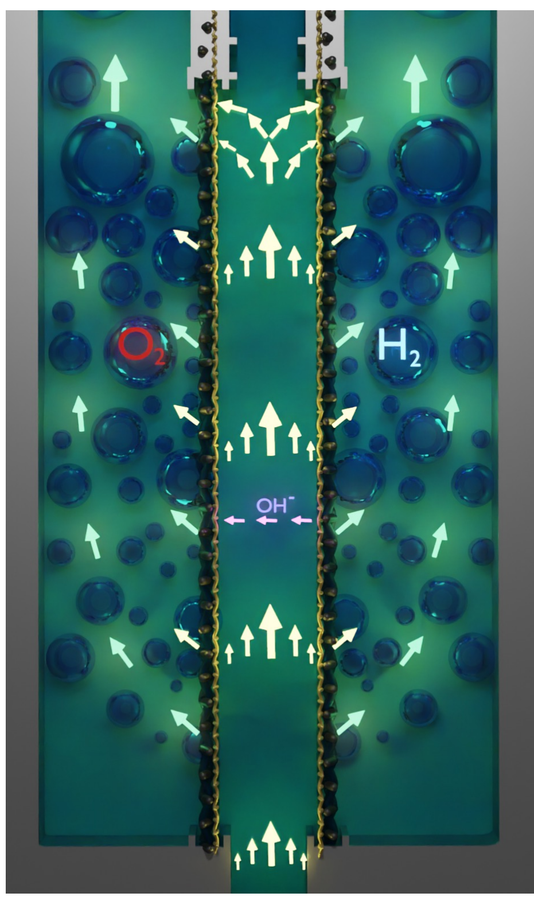
Reduce resistances

1. Thick Porous Separator
2. Gas bubbles blocking Ion conduction
3. High gas crossover H_2 in O_2 stream

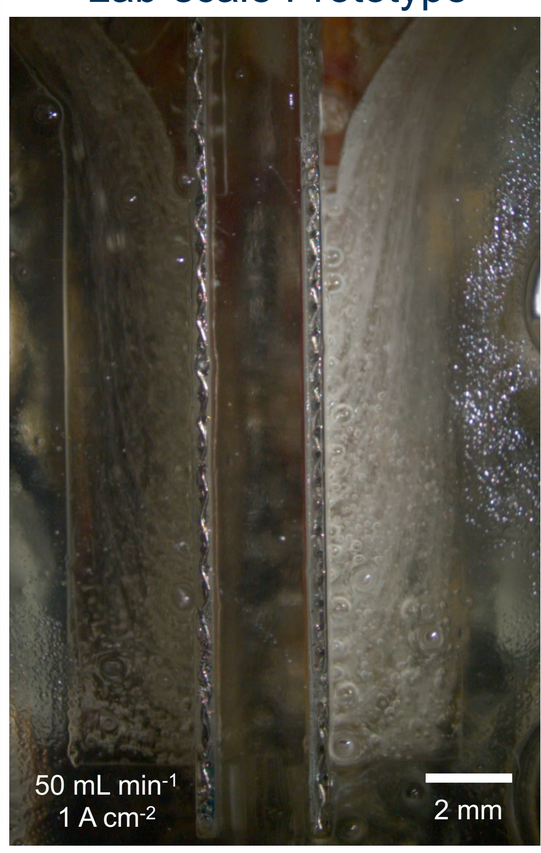
Alkaline Electrolyser



Membraneless



Lab-scale Prototype



How to separate products & improve efficiency by removing the membrane separator ?

Methodology

Simulation – Building a Virtual Laboratory

Computational Fluid Dynamics for Momentum Transport

$$\rho\frac{\partial u}{\partial t}+\rho\nabla\cdot(uu)=-\nabla \mathrm{P}+\nabla\cdot\left(\mu(\nabla u+\nabla u^{T})\right)+\sigma\kappa\nabla\alpha+\rho g$$

Volume Fraction Advection (VOF)

$$\frac{\partial\alpha}{\partial t}+\nabla\cdot(\alpha u)=0$$

Electrolyte-Electrode Energy Balance (Charge)

$$\nabla\cdot(-k_e\nabla\phi_e)=\alpha j_0\exp\left(\frac{\phi_s-\phi_e-E_0}{b}\right)\Big|_{\text{electrode}}$$

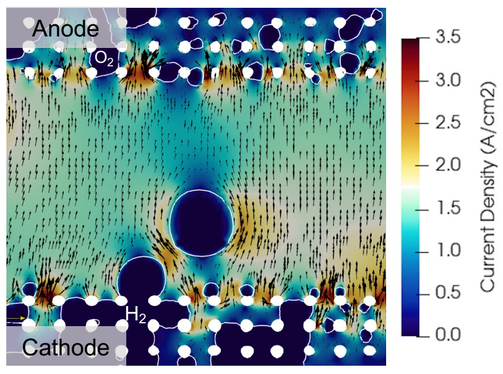
Ion Conduction

Electrochemical reaction

OpenFOAM

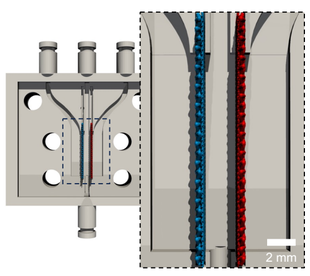
Coupling:

1. Two-phase flow
2. Electrochemistry

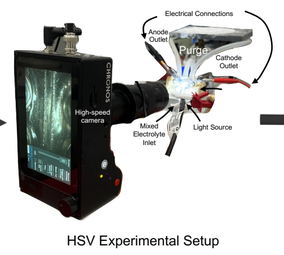


Ionic current distribution and blocking effect of bubbles

Experimental – Validating Model and Verifying Membraneless Operation

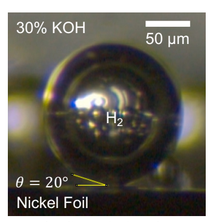


3D Printing of Electrolyser Body



HSV Experimental Setup

High-speed-magnification videography (Chronos 1.4)

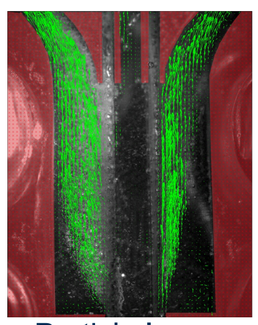


In-situ contact angle

In-situ nickel-H_2-electrolyte wettability

Original Frame

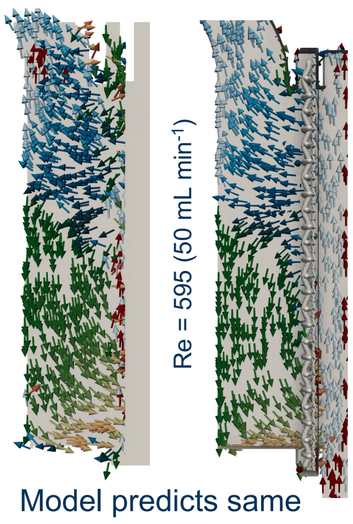
Mean Image Subtraction



Particle Image Velocimetry (PIV)

Fluid Flow Vectors

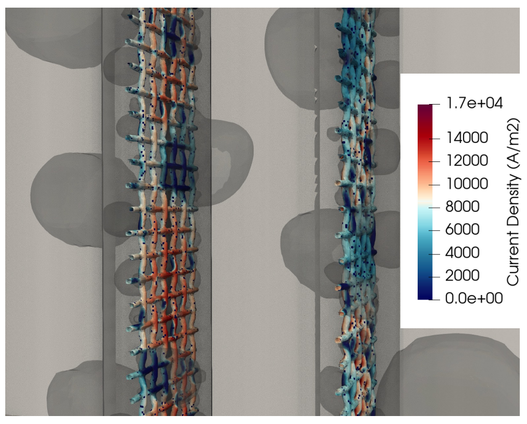
Experiment Simulation



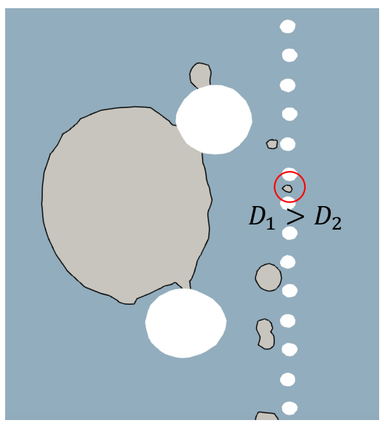
Model predicts same recirculation pattern

Two-phase (gas-electrolyte) flow models

Electrode Only

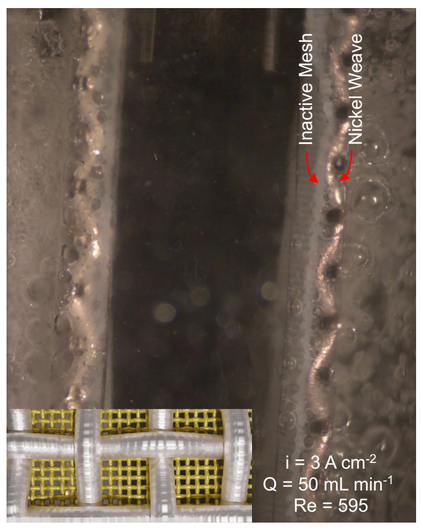


With Barrier Layer



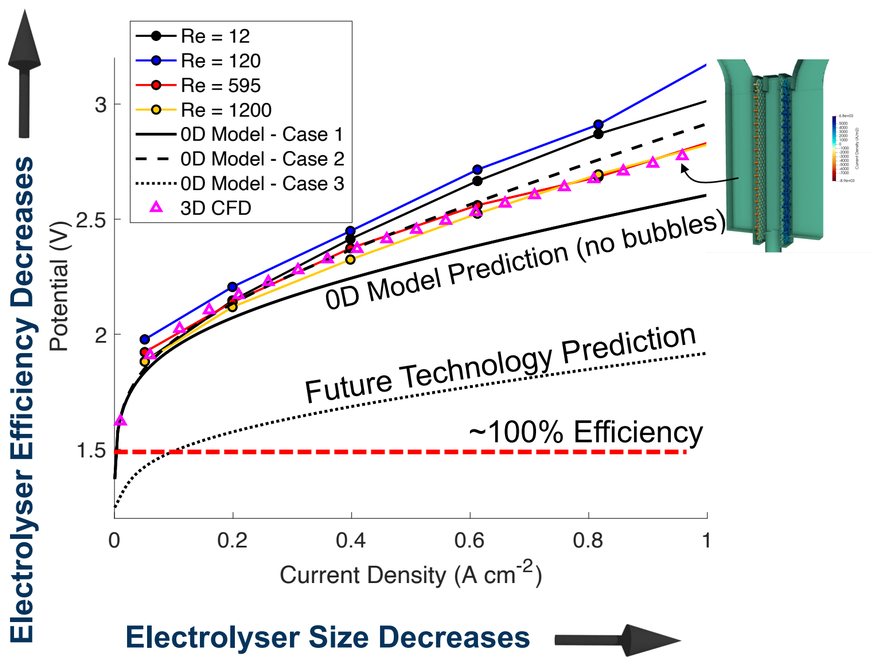
1. Bubble dependent local reaction rate is higher towards electrode gap.
2. Electrolyte flow is not enough for separation.
3. Porous barrier layer with specific properties can achieve separation.

Working Prototype

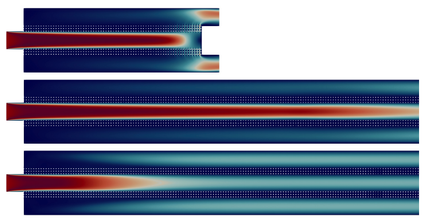


Results

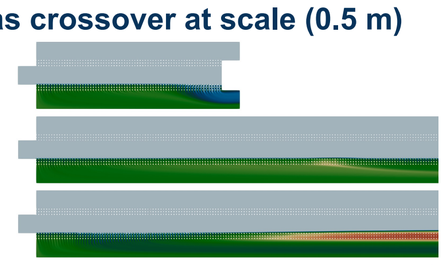
Experimental and Simulation Electrolyser Current-Voltage



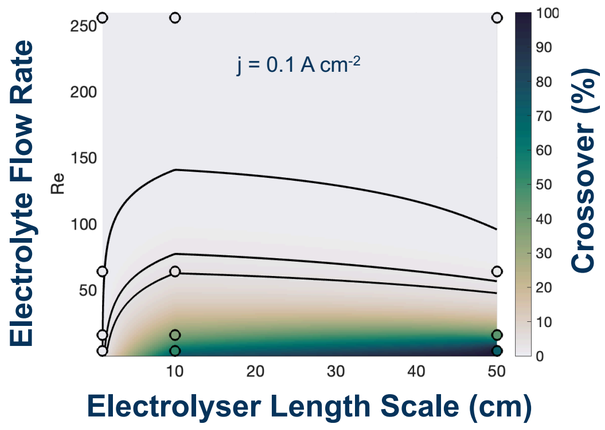
Prediction of dissolved gas crossover at scale (0.5 m)



Fluid Flow Velocity (m s^{-1})



Dissolved Hydrogen Concentration (mol m^{-3})



To scale flow simulation (0.5 m)

Conclusion

1. Achieved separation of bubbles in both model and lab-scale prototype using designed porous electrode and flow properties up to 7 A cm^{-2}
2. Minimum electrolyte flow rate (Reynolds number of 50) required for <2% crossover.
3. Future membraneless electrolyser should minimise electrode gap while ensuring uniform flow distribution through porous electrode at scale

References:
[1] - Carbon Tracker, "Britain Wastes Enough Wind Generation to Power 1 Million Homes," 2024
[2] - Minke et al., Int. J. Hydrogen Energy, 2021
[3] - Niblett et al., J. Power Sources, 2024.

Engineering and Physical Sciences Research Council

This work was funded by the EPSRC as part of the Ocean-REFuel (Ocean Renewable Energy Fuels) Programme Grant EP/W005204/1

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