Design and Characterisation of an Alkaline Electrolyser

Jorben Mus [a,*], Bram Vanhoutte [a], Sam Schotte [b], Steven Fevery [a], Steven K. Latré [a], Michael Kleemann [c], Frank Buysschaert [a]

[a] KU Leuven, Department of Mechanical Engineering, Div. TME, Bruges Campus
[b] VIVES University of Applied Sciences, Kortrijk Campus
[c] KU Leuven, Department of Electrical Engineering, ELECTA, Ghent Technology Campus
Spoorwegstraat 12, 8200 Bruges, Belgium
[*] jorben.mus@kuleuven.be

***Abstract*— Alkaline electrolysis has been gaining considerable attention lately as a viable method for producing green hydrogen from renewables. Researchers are currently focusing on improving electrolysers, for example, by trying to increase their dynamic performance and efficiency. New designs with improved components are introduced for this purpose. This paper proposes a simple and easy-to-manufacture electrolyser design made from readily available materials. The components are easy to disassemble and can be replaced by new or degraded components to assess their impact. Characterisation of the small single cell 10 W electrolyser gave consistent results, even after interchanging parts.**

Keywords—Electrolyser; Alkaline; Hydrogen; Design; Characterisation

I. Introduction

Recent global developments, such as climate change, confront humanity with its dependence on fossil fuels. As a method to become more independent from them and to enable a more global energy production, hydrogen as an energy carrier is a promising technology which has the potential to be less damaging to the climate [1]. European policymakers even expect hydrogen to be crucial in the future energy infrastructure [2]. However, in 2019 95% of the global demand for pure hydrogen was used in industry [3]. The most important applications are ammonia production for fertilisers and oil refinement [4].

Hydrogen is also expected to play a more prominent role in power generation, transportation, heating and buffering of renewables [2]. Currently, the majority (95%) of the hydrogen produced is so-called grey hydrogen. This means that greenhouse gases are released during production. Green hydrogen, on the other hand, is generated by splitting water with renewable energy [1]. Mueller-Langer et al. [5] performed a techno-economic assessment of hydrogen production and concluded that water electrolysis would play an important role in the near and mid-term. This is due to its ability to generate high-purity hydrogen and the fact that it is a well-established technique [6]. Currently, the market is dominated by polymer electrolyte membrane (PEM) and alkaline electrolysis. The latter is a robust and proven technology [7]. Alkaline electrolysis also differs from other forms in terms of price and its ease of use [8], in addition, earth-abundant materials can be used [7].

Disadvantages of alkaline electrolysis technology are lack of performance under dynamic operation and high ohmic resistance [7][9][10][11]. This is why research is being conducted into the next generation of systems. The focus is on zero-gap configurations, new membranes, high-temperature electrolysis and better electrodes [6][7][12].

A liquid electrolyte is used in alkaline electrolysers to lower the electrical resistance of water, which improves efficiency. Typically, this is an aqueous solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). KOH is typically favoured over NaOH due to higher conductivity [13]. There are two electrodes, one for the cathode and one for the anode, between which the electrolyte is contained. The contact surface between electrode and electrolyte is referred to as the reaction surface, or the area where the gases are formed when a DC voltage is applied across the electrodes. Electrical energy is used to split water and thus convert it into chemical energy. Hydrogen gas bubbles are formed at the cathode, while oxygen will be generated at the other electrode or anode. Between those electrodes, there is a separator, which is useful to avoid mixing output gases and to improve performance and safety [14].

The performance of new designs consisting of better components to counter the disadvantages should be evaluated. Therefore, a prototype should be built that, on the one hand, can be easily adapted with modular components due to its simple design and, on the other hand, is cheap and can be easily characterised.

This paper proposes the design of a 10 W modular alkaline electrolyser that is used to produce and store hydrogen. In addition, the objective is to evaluate the performance of components. First, the design of each component is examined separately based on the literature. Then, its function is also explained linked to the operating principle. After that, the design of the entire system is discussed. Two designs are considered with the aim of improving them. Finally, the characterisation is carried out, demonstrating that the design performs consistently. The intention is for this paper to serve as a starting point for creating a design that can be used to

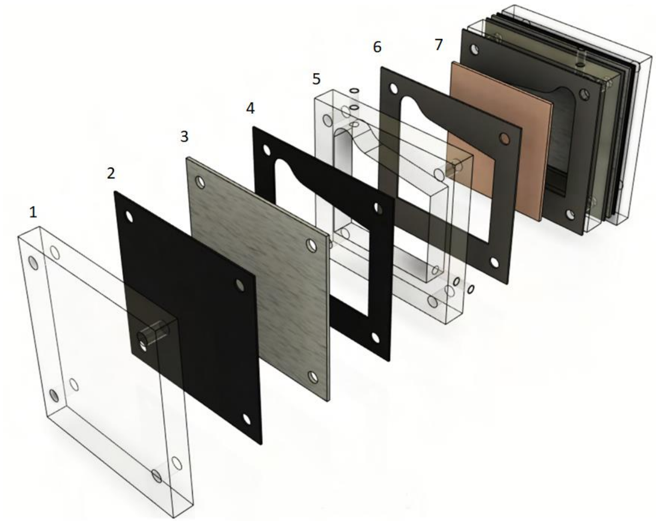

Fig. 1. CAD model of the first design. Based on [15]

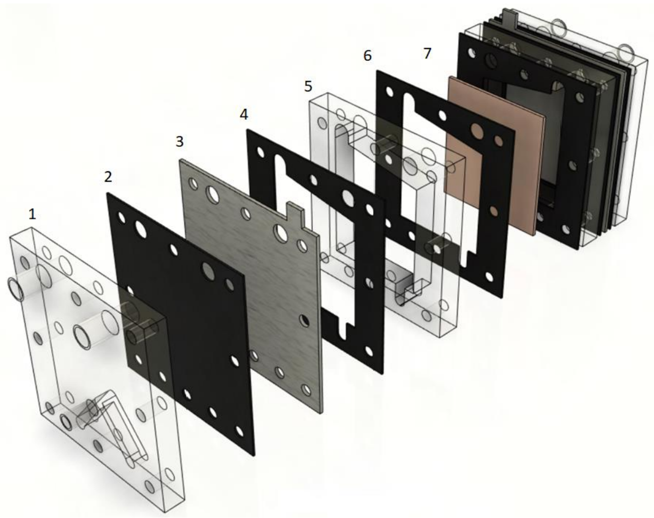

Fig. 2. CAD model of the second design. Based on [16]

quantify the increase or decrease in performance as a first test when using improved or degraded components.

II. Literature review

To achieve a working alkaline electrolyser for characterisation, existing designs in the literature are searched and analysed. The focus is on systems using a Zirfon separator made by Agfa, as it is the state-of-the-art separator and also the most commonly used [7][9][11]. Based on the advantages and disadvantages discussed in this section, choices were made for the new design. In order to carry out a better and clearer analysis, a CAD model was made of each useful design. The discussed designs are the relevant configurations. Findings from other sources were also taken into account in the design process. Several papers discuss the results of characterisation tests with different components and their influence on the performance. However, the design of the components and configuration of the electrolyser is rarely revealed.

A. First design

Dunnill [15] worked out the following alkaline electrolyser design to store renewable energy as hydrogen. A Zirfon separator was used. The electrolyser cell has a length and width of 100 mm. Figure 1 shows the design in a semi-exploded view. The design is symmetrical with respect to the central membrane and consists of the following components:

1. An endplate with a thickness of 12 mm made from plexiglass
2. Silicone seal of 1 mm
3. The electrode is made from stainless steel 316
4. Silicone seal of 1mm with cut-out
5. Spacer made of plexiglass of 12 mm thickness for the electrolyte bath. There is an inlet for the electrolyte at the right bottom and an outlet to capture generated gas at the top
6. Silicone seal of 1 mm with cut-out
7. Zirfon separator

A DC voltage is applied via the two electrodes. These make contact with the electrolyte in the spacers. The silicon seal with cut-out ensures gas and liquid tightness between the electrode and electrolyte chamber. The electrolyte is supplied through the lower inlet ports at the side of the spacer via a reservoir. The gas bubbles will rise and leave the electrolyser via the ports at the top of the spacers. A chamfered top of the electrolyte chamber improves gas removal. Overall, this is a simple design with components that are easy to manufacture from readily available materials. Bolts are used to make the electrolyser leakproof via compression. Disadvantages are:

- Susceptible to leaks, as there are only four compression points.
- Difficult to centre the membrane, which is essential for good performance and safety.
- The bolts go through all components and may cause a short circuit. They must be insulated, or nylon bolts must be used.
- A reasonably large chamber is provided for the electrolyte.

B. Second design

Rearden et al. [16] made an attempt to improve the previously discussed design. Figure 2 shows the semi-exploded CAD view of this electrolyser. The numbering and explanation of components related to the previous design also apply here. The electrolyser size and operating principle remained the same. However, components became more arduous to manufacture. The most important differences are discussed below.

Again, the electrolyte is supplied through a reservoir. A major difference from the previous design is the inlet port for the electrolyte. Instead of one port for each spacer, there is now only one port on one of the two end plates. The feed is split via an inverted V into two channels at that port. These run through the electrolyser, each leading to a spacer. In this case, only one electrolyte reservoir needs to be provided, and the feed takes place via just one port. In addition, eight bolts are used instead of four to compress. This ensures a more even distribution of forces, which improves leak tightness. However, there are still some disadvantages:

- The design is more complex, which is unfavourable for manufacturing and assembly.
- The channels to transport the electrolyte from the end plate to both chambers are prone to leakage as they pass through several components.
- Insulated bolts are needed.
- Difficult to centre the membrane.

III. METHODOLOGY

Starting from the existing designs found in the literature, an attempt was made to create a new design to improve the former. Figure 3 shows the exploded CAD model of the proposed configuration; the legend is below. Each component is discussed in detail with motivation for the choices made. Below is the legend, figure 4 shows a rendering of the fully assembled electrolyser:

Main components

1. 12 mm thick end plate (140x140 mm) from PMMA acrylic glass
2. 2 mm EPDM gasket (100x100 mm)
3. 1.5 mm 316 stainless steel electrode (100x100 mm)
4. 2 mm EPDM gasket (100x100 mm) with cut-out for the electrolyte
5. 2 mm PMMA plexiglass spacer (100x100 mm)
6. 1 mm Zirfon PERL UTP 500 separator (100x100 mm)
7. 30 cm^3 gas and electrolyte storage

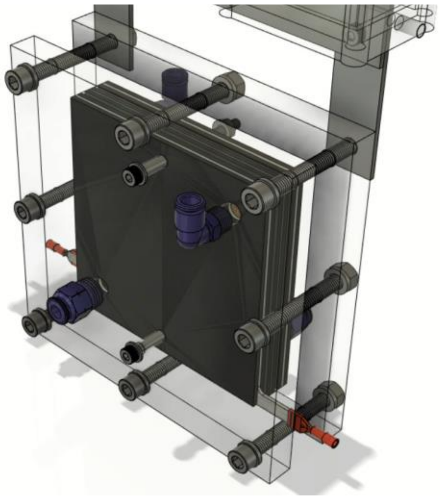

Fig. 4. Rendering of the fully assembled electrolyser

Additional tools

a) 8x M6x50 SS bolts with 16 washers and 8 nuts
b) 2x M4x55 SS bolts with 4 washers and 2 nuts
c) 2x M4x8 SS bolts with 4 washers and 2 nuts
d) 2x safety cable connector
e) 2x 6 mm push in quick connector knee
f) 2x 6 mm push in quick connector straight
g) Aluminium sheet metal to mount storage

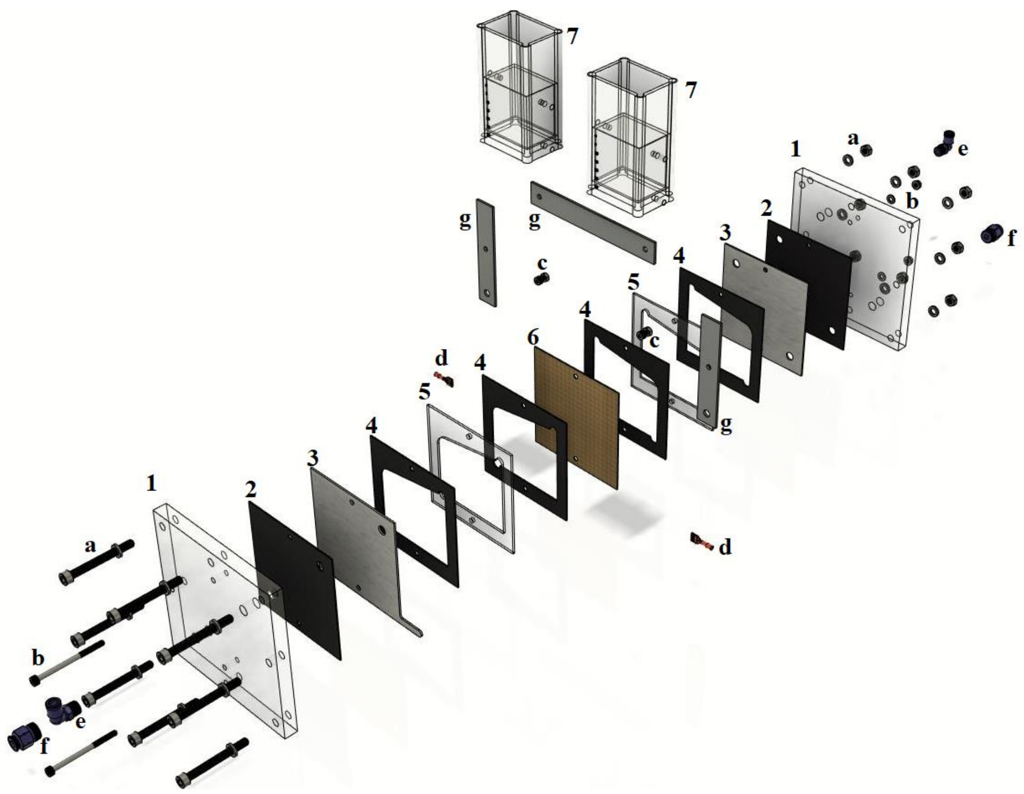

Fig. 3. Exploded CAD model of the proposed configuration

A. End plates

The end plates are the housing of the electrolyser and ensure a uniform distribution of the compression force. This improves performance as the electrodes make good contact with the electrolyte while also avoiding leaks. Polymethyl methacrylate (PMMA), also known as acrylic glass, is the material selection. It is easy to machine and has good resistance to KOH that will be used as electrolyte [17].

There are eight clearance holes for the M6 bolts used to compress the components and two M4 clearance holes for the bolts used to centre the components. The diameters are based on the DIN ISO 20273 standard [18]. The thread for the push-in quick connectors is the British Standard Pipe (BSP) because of its sealing characteristics. Figure 4 shows a rendering of the electrolyser. By making the end plates larger than the cell, the eight bolts for compression can be placed around the cell. This is advantageous because they don't go through the components and therefore do not have to be isolated, while also providing better compression. In addition, the use of more bolts for compression not passing through all components is also an improvement in leak tightness compared to the designs discussed in [15] and [16].

The electrolyser can easily be placed upright as the end plates also function as supports. Components are also more difficult to access thanks to the larger end plates, which enhances safety. Two M4 bolts ensure that each component is easily centred. This facilitates assembly and reduces the risk of leaks. In the previously discussed designs, the separator was difficult to centre. To prevent a short circuit, nylon bolts should be used, or metal bolts can be provided with a heat-shrinking tube.

B. Gaskets

Gaskets are essential to isolate the electrodes and prevent leaks. Therefore, a test was conducted to determine the best sealing material for the alkaline electrolyser. A total of 6 different seal materials were tested by clamping them between two acrylic plates. Each sample has the same size and thickness. In the middle, a hole was punched into which a piece of paper was placed. After the test, the paper was checked for wetness. Clamping the gasket between two acrylic glass plates with a torque of 0.5 Nm corresponds to the design of the complete electrolyser. After clamping, the sample is immersed in water for 20 minutes. In figure 5, the EPDM rubber sample is subjected to the test. Table 1 summarises the materials' most essential properties and shows the test results.

Table 1. Submerged gaskets test results

Gasket material	Shore A hardness	Time sub-merged (min)	Compression force (Nm)	Result
EPDM	65	20	0.5	OK
Silicone Rubber	60	20	0.5	NOK
Silicone Foam	10	20	0.5	NOK
Natural Rubber	45	20	0.5	NOK
Neoprene Rubber	65	20	0.5	NOK
NBR	65	20	0.5	OK

Only in the case of EPDM (ethylene propylene diene monomer rubber) and NBR (nitrile butadiene rubber), the paper remained completely dry. EPDM was ultimately chosen because of its better resistance to potassium hydroxide [19]. For the designs discussed in [15] and [16], silicon was used as the gasket material. However, this material failed the test that was performed in this paper.

As shown in figure 3, there are two types of seals in the configuration (numbers 2 and 4). Both are necessary to prevent leaks by compressing them. The complete seal ensures that the electrodes are isolated from the end plates. In the other seals, a cut-out is provided, allowing the electrolyte to come into contact with the electrode. This area is also called the reaction surface and corresponds to 50 cm^2 in this design.

The holes for centring bolts are taken 5% narrower than the DIN ISO 20273 standard. This way, the rubber tightens slightly around the bolt, making it more leakproof.

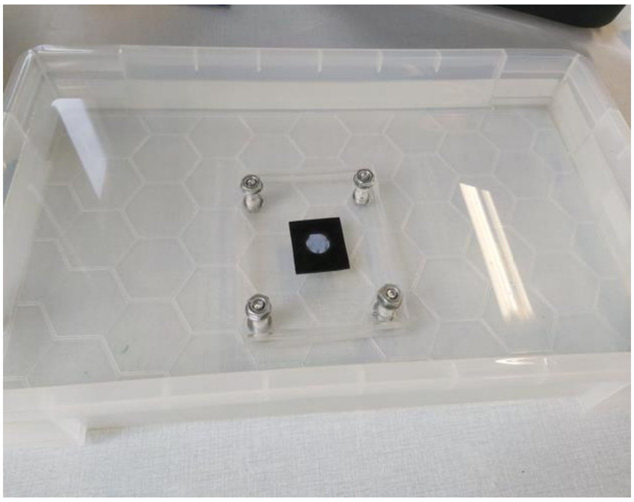

Fig. 5. Submerged gaskets test

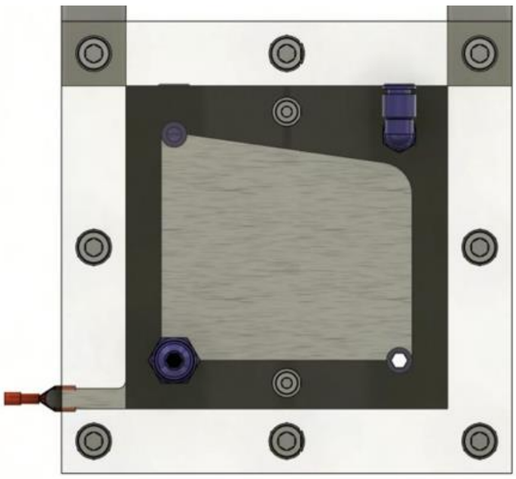

Fig. 6. Electrolyser cross-section at the spacer level

C. Electrodes

Electrochemical reactions occur at the electrode surface, where it contacts the electrolyte. As a result, hydrogen and oxygen are formed on the electrode surface. Stainless steel 316L is a widely used material, for example, in the food sector, because it has high corrosion resistance and is temperature resistant up to approximately 500°C [20]. In addition, the resistance to potassium hydroxide is excellent; the electrolyte does not affect the electrode [21]. Symes et al. [14] proved that SS 316L performs significantly better than conventional iron. Therefore, the electrodes are manufactured from SS 316L.

Figure 6 shows a cross-section of the electrolyser at the spacer level. The grey electrode is covered by the gasket with a cut-out; the visible part is the reaction surface. The spacer allows the gap to be filled with electrolyte, which is supplied through the hole in the bottom right-hand corner. Formed gas will rise and be more easily discharged through the upper hole due to the sloping side [15][16]. The supply and discharge channels run to the end plates, which are connected to the storage vessels by tubes. Bolts to compress the end plates to avoid leaks are also visible. The bolts in the middle ensure the centring of the components and are surrounded by a seal to improve leak-tightness. The cable connectors are attached to the tip of the electrode.

D. Spacers & Electrolyte

The spacer ensures enough electrolyte at the electrode to initiate the reactions. The electrolyte used in the alkaline electrolyser is a demineralised water solution with 30% potassium hydroxide (KOH). The amount of electrolyte has a significant influence on the ohmic resistance. To reduce ohmic losses, the thickness of the spacers, and thus the size of the chamber for the electrolyte should be as small as possible. Although there must be sufficient electrolyte to support the reactions [16][22][23]. Therefore, the thickness of the spacers is only 2 mm and again the selected material is PMMA.

E. Separator

Zirfon PERL UTP500, a state-of-the-art membrane made of zirconium oxide and polysulfone, fabricated by Agfa is chosen as the separator for the electrolyser [24]. The membrane has ideal characteristics to function as a gas separator, including strong conductivity, a high bubble point and good wettability [21]. The thickness is 1 mm as this is a compromise between low resistance and good durability.

F. Gas storage

Storage vessels with a capacity of 30cm³ are used to collect the produced hydrogen and oxygen. They also supply enough electrolyte to fill the spacers. The storage container's basic design is comparable to a high cup into which a smaller cup is inserted upside down. Figure 7 shows a schematic for clarification. The electrolyte is supplied to the lower connecting point on the electrolyser via a tube. Formed gas is discharged via the upper port and fills the inverted cup, which displaces the electrolyte to the upper chamber. All the gas can be released through the port on the left.

IV. RESULTS

Figure 8 shows the fully assembled electrolyser. Characterisation is used to prove that the electrolyser works and performs consistently. First, the polarisation curve, shown in figure 9, was obtained by increasing the voltage in a stepwise manner while monitoring the current. Doing this three times demonstrated consistent performance, resulting in an average polarisation curve shown in figure 10 (labelled as separator 1). Then, a second test was carried out to check whether the performance remained consistent after taking the system apart, for example, to examine a new component or to replace a degraded one. Therefore, the previous test was repeated three times, each time with a new separator of the same type Zirfon PERL UTP500. The results are summarised in figure 11 with the average polarisation curve for each separator.

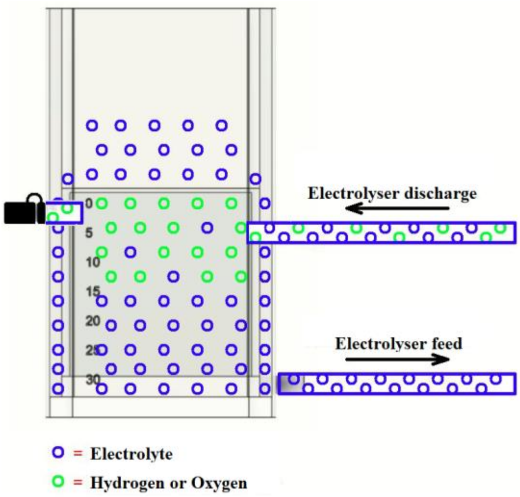

Fig. 7. Gas storage schematic

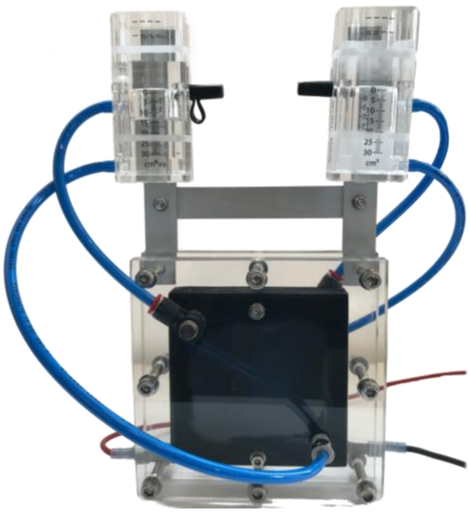

Fig. 8. Fully assembled electrolyser

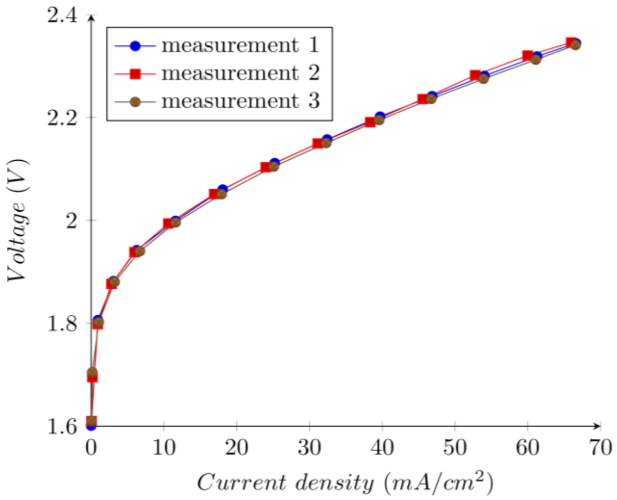

Fig. 9. Alkaline electrolyser polarisation curve

V. CONCLUSION

The proposed single cell 10 W alkaline electrolyser could easily be manufactured in the laboratory in a few days with readily available materials. Using characterisation, the polarisation curve was generated in various situations. The test was usually stopped at a current density of 70 mA/cm^2. In order to be able to carry out longer tests at higher currents, it is safer to have larger storage. Characterisation demonstrated that the electrolyser performs consistently, even after disassembling, and therefore satisfies the requirements. To the best knowledge of the authors, this paper is unique in describing the complete design of an alkaline electrolyser and showing the characterisation results. In the next step, the influence of a low-performing separator, better electrode or degraded component will be investigated. In addition, the impact of degradation or operating conditions will also be examined using a climate chamber. These results can be linked to the component properties by using more sophisticated characterisation techniques.

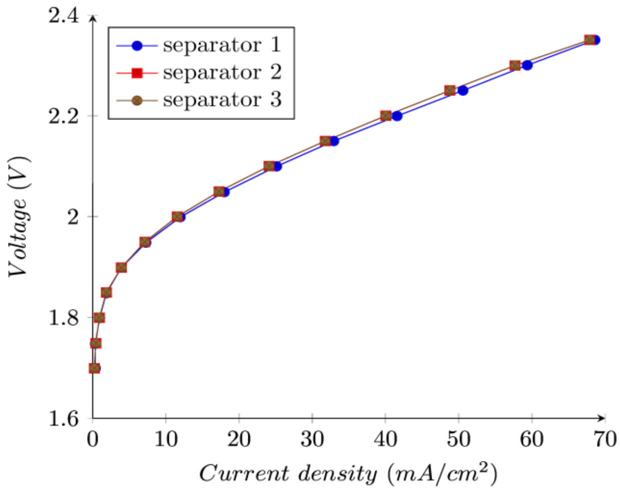

Fig. 10. Polarisation curve after interchanging the separator

ACKNOWLEDGEMENTS

This work has been established as part of a master thesis, which became possible thanks to the network opened to students by the VLAIO TETRA HBC.2020.2089 project. The authors also gratefully acknowledge Agfa for the given Zirfon PERL UTP500 separator sample.

REFERENCES

[1] R. L. Germscheidt, D. E. B. Moreira, R. G. Yoshimura, N. P. Gasbarro, E. Datti, P. L. dos Santos, J. A. Bonacin, Hydrogen environmental benefits depend on the way of production: An overview of the main processes production and challenges by 2050, Advanced Energy and Sustainability Research 2 (2021) 2100093. doi:https://doi.org/10.1002/aesr.202100093.

[2] Fuel Cells & Hydrogen 2 Joint Undertaking, Hydrogen Roadmap Europe: A Sustainable Pathway for the European Energy Transition. Publications Office of the European Union, 2019.

[3] EA, The future of hydrogen – analysis, 2019. URL: https://www.iea.org/reports/the-future-of-hydrogen.

[4] R. M. Navarro, R. Guil, J. L. G. Fierro, 2 - introduction to hydrogen production, 2015. doi:https://doi.org/10.1016/B978-1-78242-361-4.00002-9.

[5] F. Mueller-Langer, E. Tzimas, M. Kaltschmitt, S. Peteves, Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term, International Journal of Hydrogen Energy 32 (2007) 3797–3810. doi:10.1016/J.IJHYDENE.2007.05.027.

[6] M. David, C. Ocampo-Martinez, R. Sanchez-Pena, Advances in alkaline water electrolysers: A review, Journal of Energy Storage 23 (2019) 392–403. doi:10.1016/J.EST.2019.03.001.

[7] M. Holst, S. Aschbrenner, T. Smolinka, C. Voglst¨atter, G. Grimm, Cost Forecast for Low Temperature Electrolysis - Technology Driven Bottom- up Prognosis for PEM and Alkaline Water Electrolysis Systems, Fraunhofer Institute for Solar Energy Systems ISE, 2021.

[8] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, S. Few, Future cost and performance of water electrolysis: An expert elicitation study, International Journal of Hydrogen Energy 42 (2017) 30470–30492. doi:10.1016/J.IJHYDENE.2017.10.045.

[9] J. Brauns, J. Schönebeck, M. R. Kraglund, D. Aili, J. Hnát, J. Zitka, W. Mues, J. O. Jensen, K. Bouzek, T. Turek, Evaluation of diaphragms and membranes as separators for alkaline water electrolysis, Journal of The Electrochemical Society 168 (2021) doi:10.1149/1945-7111/ABDA57

[10] C. Karacan, F. P. Lohmann-Richters, G. P. Keeley, F. Scheepers, M. Shviro, M. Müller, M. Carmo, D. Stolten, Challenges and important considerations when benchmarking single-cell alkaline electrolysers, International Journal of Hydrogen Energy 47 (2022) 4294–4303.

[11] J. Brauns, T. Turek, Alkaline water electrolysis powered by re-newable energy: A review, Processes 2020, Vol. 8, Page 248 8 (2020) 248. URL: https://www.mdpi.com/2227-9717/8/2/248/htm https://www.mdpi.com/2227-9717/8/2/248. doi:10.3390/PR8020248.

[12] F. P. Lohmann-Richters, S. Renz, W. Lehnert, M. M¨uller, M. Carmo, Review—challenges and opportunities for increased current density in alkaline electrolysis by increasing the operating temperature, Journal of The Electrochemical Society 168 (2021) doi:10.1149/1945-7111/AC34CC.

[13] S. A. Grigoriev, V. N. Fateev, P. Millet, Alkaline electrolysers, Com-prehensive Renewable Energy (2022) 459–472. doi:10.1016/B978-0-12-819727-1.00024-8.

[14] D. Symes, B. Al-Duri, W. Bujalski, A. Dhir, Cost-effective design of the alkaline electrolyser for enhanced electrochemical performance and reduced electrode degradation, International Journal of Low-Carbon Technologies 10 (2015) 452–459. doi:10.1093/IJLCT/CTT034.

[15] G. P. C. W. Dunnill, Water splitting test cell for renewable energy storage as hydrogen gas, Journal of Fundamentals of Renewable Energy and Applications 05 (2015). doi:10.4172/2090-4541.1000188.

[16] A. Rearden, S. Mandale, K. Glover, R. Phillips, C. W. Dunnill, Optimizing the design of an alkaline water splitting device test cell for renewable energy storage as hydrogen., Archives of Chemistry and Chemical Engineering 2 (2020) 1–9. doi:10.5281/ZENODO.3964220

[17] ISM Industrial Specialities Mfg. and IS, Acrylic (pmma) chemical compatibility chart, 2019. URL: https://marketing.industrialspec.com/acton/attachment/30397/f-006b/1/a

[18] S. Wartzack, Technical Pocket Guide, 3 ed., Schaeffler Technologies AG Co. KG, 2021. URL: https://www.schaeffler.com/remotemedien/media/sharedmedia/08media library/01publications/schaeffler_2/catalogue_1/downloads_6.pdf

[19] Mykin Inc., Rubber chemical resistance. URL: https://mykin.com/rubber-chemical-resistance-chart-5.

[20] K. Saeidi, M. Neikter, J. Olsen, Z. J. Shen, F. Akhtar, 316l stainless steel designed to withstand intermediate temperature, Materials Design 135 (2017) 1–8. doi:10.1016/J.MATDES.2017.08.072.

[21] ISM Industrial Specialities Mfg. and IS, 316l stainless steel chemical compatibility chart industrial specialties mfg. and is med specialties (2020). URL: https://marketing.industrialspec.com/acton/attachment/30397/f-003a/1/-/-/-/-/3

[22] M. T. de Groot, A. W. Vreman, Ohmic resistance in zero gap alkaline electrolysis with a zirfon diaphragm, Electrochimica Acta 369 (2021) 137684. doi:10.1016/J.ELECTACTA.2020.137684.

[23] R. Phillips, A. Edwards, B. Rome, D. R. Jones, C. W. Dunnill, Minimising the ohmic resistance of an alkaline electrolysis cell through effective cell design, International Journal of Hydrogen Energy 42 (2017) 23986–23994. doi:10.1016/J.IJHYDENE.2017.07.184

[24] Agfa, Zirfon hydrogen separator membranes, 2022. URL:https://www.agfa.com/specialty products/solutions/membranes/separator-membrane