

Demonstration of a Prototype Unit Producing Green Hydrogen, Heat and Alumina by Catalytic Water Decomposition With Recycled Aluminum Metals

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Abstract. Hydrogen gas is the cleanest fuel for electricity production by using H₂/Fuel Cells as well as for other applications. The objective of the present study is the greening of circular economy by innovative transformation of reuse of recycled Aluminum into green H₂ gas (potentially to be used for electricity production), thermal energy and other value-added by-products, such as Aluminum Hydroxide (Al(OH)₃) powder for the Aluminum production companies and/or for other uses such as, polishing pastes, abrasive detergents, abrasive particles for water jets cutting, etc. Specifically, Hystore Tech Ltd, a leading technology Cypriot SME, contacted different studies in order to investigate the behavior of different kind of recycled Aluminum metals such as, Shavings (Chips), Cans (Flatten/Cut) and Slabs (Chunks) in terms of producing Green H₂ by catalytic decomposition of water in the presence of NaOH at different concentrations. The ultimate goal of the present study is the design, construction, operation and demonstration of a final Prototype Unit utilizing recycled Aluminum reaching TRL6. The design capacity of the Prototype Unit is expected to be about 50kg of Al metal per day. Experiments performed at different bath-temperatures showed that the H₂ production rate is higher for higher temperatures, as expected. Also, the H₂ production rate is higher as the NaOH wt% concentration increases. At the same time, high NaOH wt% concentrations favor the initially produced NaAl(OH)₄ to remain in solution, whereas for low NaOH wt% concentrations the reaction favors the further decomposition of NaAl(OH)₄ into Al(OH)₃ precipitates and regenerated NaOH catalyst. The overall water decomposition with Al reaction is exothermic exhibiting an enthalpy of the reaction of -415 kJ/moleAl, indicating that as the reaction progresses, the H₂ production rate is expected to rapidly increase. Future demonstration experiments on the final prototype unit will take into account the expected heat-production and efficiently store the heat in the form of useful hot water. The use of an experimental prototype unit (10-50g of recycled Aluminum) revealed that the H₂ production rates are higher when using Aluminum Shavings, Cans and Slabs, respectively, due to their higher specific area exposed to the water solution of NaOH. Experiments performed by using the experimental prototype unit revealed that it is possible to produce nearly the theoretical amount of 1246 NLH₂ ±10% (0.112 kgH₂) per kg of recycled Aluminum depending on its purity and taking into account the experimental error involved.

1. Introduction

The global transition toward sustainable energy systems has heightened the demand for clean hydrogen production technologies. Hydrogen, with its high gravimetric energy density and zero-emission profile, is a vital component of the future decarbonized energy landscape [1]. However, its large-scale deployment is constrained by the limitations of current production, storage, and distribution methods, many of which remain carbon-intensive or economically unviable [1-3].

Among alternative hydrogen production pathways, the hydrolysis of aluminum (Al) stands out as a promising option. Aluminum reacts exothermically with water to produce hydrogen gas and aluminates and/or hydroxides. However, this reaction is hindered by the formation of a passivating oxide layer on the metal surface, which inhibits further reaction unless removed or disrupted through activation processes [4], [5]. Recent innovations have focused on overcoming this barrier using alloying, mechanical activation, and catalytic techniques to promote consistent and efficient hydrogen generation [1], [3], [6]. A growing body of research has shown that combining recycled aluminum with water in the presence of alkalis (e.g., NaOH) or eutectic-forming elements (e.g., Ga, In, Bi) significantly enhances the kinetics of hydrogen evolution [4-6]. For example, aluminum-bismuth and aluminum-gallium-indium alloys have demonstrated rapid hydrogen generation in various aqueous salt solutions [4], while aluminum hydroxide ($\text{Al}(\text{OH})_3$), when properly synthesized, shows high catalytic efficiency at near-neutral pH levels [5]. To render aluminum hydrolysis viable at scale, researchers have explored various alloy systems, feedstock formats (e.g., powders, wires), and reactor designs. Mutlu et al. [3] designed a continuous-flow hydrogen generator that feeds commercially available aluminum wire into a NaOH solution, optimizing parameters such as wire diameter, temperature, and catalyst concentration to produce stable hydrogen flows capable of powering a 5–30 W fuel cell. This type of controlled aluminum feeding addresses critical safety concerns, such as thermal runaway and agglomeration, especially when working with nano- or micro-sized aluminum particles. The use of Sn-free Al-based alloys has recently gained attraction due to their recyclability and improved purity of by-products. Wang et al. [6] demonstrated that removing tin from aluminum-gallium-indium alloys not only maintained high hydrogen yields (97.3% conversion) but also simplified the recovery of valuable elements post-reaction via vacuum distillation. This innovation supports the circular economy by minimizing contamination of alumina and enabling re-use of alloying elements—challenges often overlooked in traditional systems using Sn-containing materials.

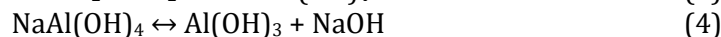
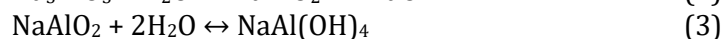
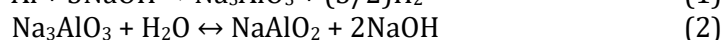
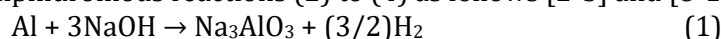
Hydrogen generation by aluminum hydrolysis has also been recognized for its compatibility with broader green energy strategies. As pointed out by Zhdaneev et al. [7], integrating such systems with renewable energy waste recycling, particularly from photovoltaics and wind turbine components can help close the material loop in hydrogen supply chains. Given the growing volumes of renewable energy waste expected by 2050, such synergies could offer dual environmental and economic benefits through resource recovery and carbon mitigation [7]. Optimizing catalysts also remains a crucial factor. Chen et al. [5] studied different aluminum hydroxide catalysts and demonstrated that nano-sized, self-synthesized variants could catalyze near-complete hydrogen release within 60 seconds at mildly alkaline pH, outperforming reactions conducted at even higher pH without a catalyst. These results underscore the need to balance catalyst performance, recyclability, and reaction conditions to develop efficient, scalable aluminum-water hydrogen production systems.

Overall, aluminum-water systems represent a technically viable and environmentally sustainable path to decentralized and on-demand hydrogen production. Whether used in portable fuel cell applications, stationary power systems, or integrated with industrial recycling processes, these systems align well with climate goals and circular economy principles. Much more work will

need to refine alloy compositions, optimize catalyst performance, and engineer reactors that can operate safely and reliably under a range of conditions, while ensuring cost-effectiveness and scalability.

Presently recycled Aluminum metal is collected in different locations, accumulated by an authorized company which compacts them and delivers them for melting then into Aluminum ingots. Such a process is energy consuming and causes CO₂ emissions due to the transportation of recycled Aluminum for long distances, especially when marine transportation is used.

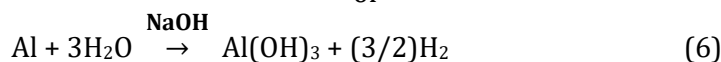
Aluminum, according to the exothermic reaction (1), produces H₂ gas and different intermediate and/or final products such as, Na₃AlO₃ (Sodium Aluminate), NaAlO₂ (Sodium meta-Aluminate), NaAl(OH)₄ (Hydrated Sodium meta-Aluminate) and Al(OH)₃ (Aluminum Hydroxide) according to the amphidromous reactions (2) to (4) as follows [2-3] and [8-11]:



leading to two overall reactions:



or



According to the overall reaction (5), a molecular NaOH/Al (mol/mol) ratio of $\geq 1/1$ is needed to promote the complete reaction to the right. According to the overall reaction (6), Aluminum decomposes water (H₂O) catalytically through the existence of NaOH as a catalyst which nearly totally regenerates according to reactions (2)-(4). The catalytic nature of the reaction (6) even at NaOH wt% concentrations as low as 1wt% and molecular NaOH/Al (mol/mol) ratio as low as 0.25 was recently supported experimentally D. Hadjipetrou et. al., [12-14].

The present study deals with the reuse of recycled Aluminium metal collected in neighbourhoods, industrial areas, hospitals and elsewhere, to, in-situ, produce green Hydrogen and other value-added useful products. The general objective of the present study is to design, construct, operate and demonstrate a simple, final prototype unit utilizing directly recycled Aluminium metal (Shavings, Cans and Slabs) **without any pre-alloying, melting, pre-treatments, etc.**, in order to produce:

- Pure green hydrogen gas (potentially to be used for electricity production)
- Thermal energy (hot water for central heating and other uses)
- Value-added by-products, such as NaAl(OH)₄ and/or Al(OH)₃ powder for the Aluminium production companies and/or for other uses (polishing pastes, abrasive detergents, abrasive particles for water jets cutting, etc.)

2. Experimental

Recycled Slabs and Shavings of Aluminum Alloy 6063 with an approximate composition of about 98.5wt% Aluminum and 0.8wt% Magnesium, 0.4wt% Silicon and 0.3wt% Iron and recycled Aluminum Cans of an approximate composition of about 97.5wt% Aluminum, 1wt% Magnesium, 1wt% Manganese and 0.5wt% Iron were used for all the experiments.

In order to examine the H₂ production under different NaOH wt% concentrations water solutions and NaOH/Al molecular ratios (mol/mol) at different temperatures, the experimental set-up shown in **Figure 1** was used, where the reactor was placed in a constant temperature water-bath in order to stabilize the desired temperature. Usually, Aluminum slabs of 0.4-1g, about

9.5mm width, 1.5mm in thickness and variable length were used. The H_2 production was measured by the water-displacement method. At the same time, the ambient and solution temperatures were monitored as a function of time. At the end of each experiment, the Aluminum slab was directly observed as to whether was fully or partially dissolved.

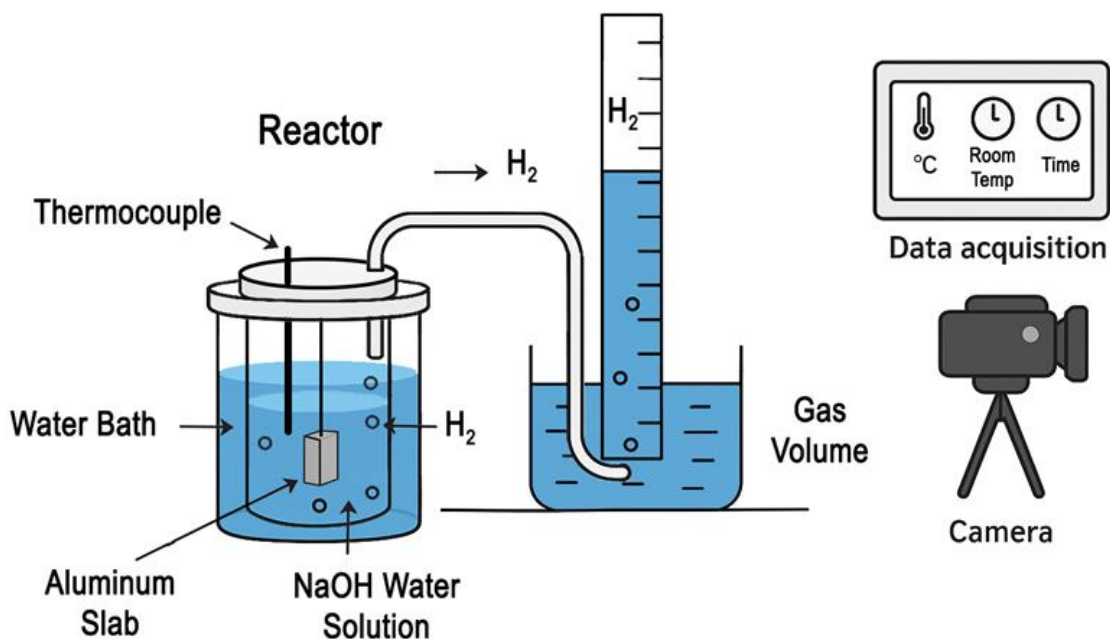


Figure 1. Experimental set-up for determination of the H_2 production under different NaOH wt% concentrations and different NaOH/Al molecular ratios (mol/mol) under stagnant conditions (no agitation), at constant bath-temperatures

For scale-up, using Aluminum Shavings, Cans and Slabs of 10-50g, an experimental prototype unit was set-up as shown in **Figure 2**. The bottom container is the reactor containing the recycled Aluminum subjected to reaction, which was filled-up with a water solution of a given NaOH wt% concentration through the top plastic container and with the assistance of a water-pump, constantly pumping the liquid into the reactor. On the top of the reactor a plastic mesh (<0.5mm openings) was placed in order to capture any plastics and/or particles moving in the liquid stream. The generated H_2 gas was filtered from any possible H_2O /NaOH spray and measured by the water-displacement method. At the same time the ambient and solution temperatures were monitored as a function of time. At the end of each experiment, the Aluminum Shavings, Cans and Slabs were directly observed as to whether were fully or partially dissolved. Furthermore, there was an observation with respect to the clearness and colour of the reacting solution. In the case of Aluminum Cans, the remaining plastics (Bisphenol clear coating and paints) were collected and measured. The Aluminum Cans have a Bisphenol coating on all surfaces except the outside bottom of the can. On the outside surface they also contain paints. The Aluminum Cans were found to contain about 2.5wt% coating and paints. Similarly, the Aluminum Shavings coming from painted Aluminum profiles subjected to cuts and lath-shaping were found to contain about 3wt% plastics and paints. On the other hand, the Aluminum Slabs contained no plastics and were 100% metallic. In all measurements, there was an experimental error of $\pm 5\%$. Taking into account the purity of each type of recycled Aluminum, the total error in NLH_2 per kgAl was estimated to be less than $\pm 10\%$.

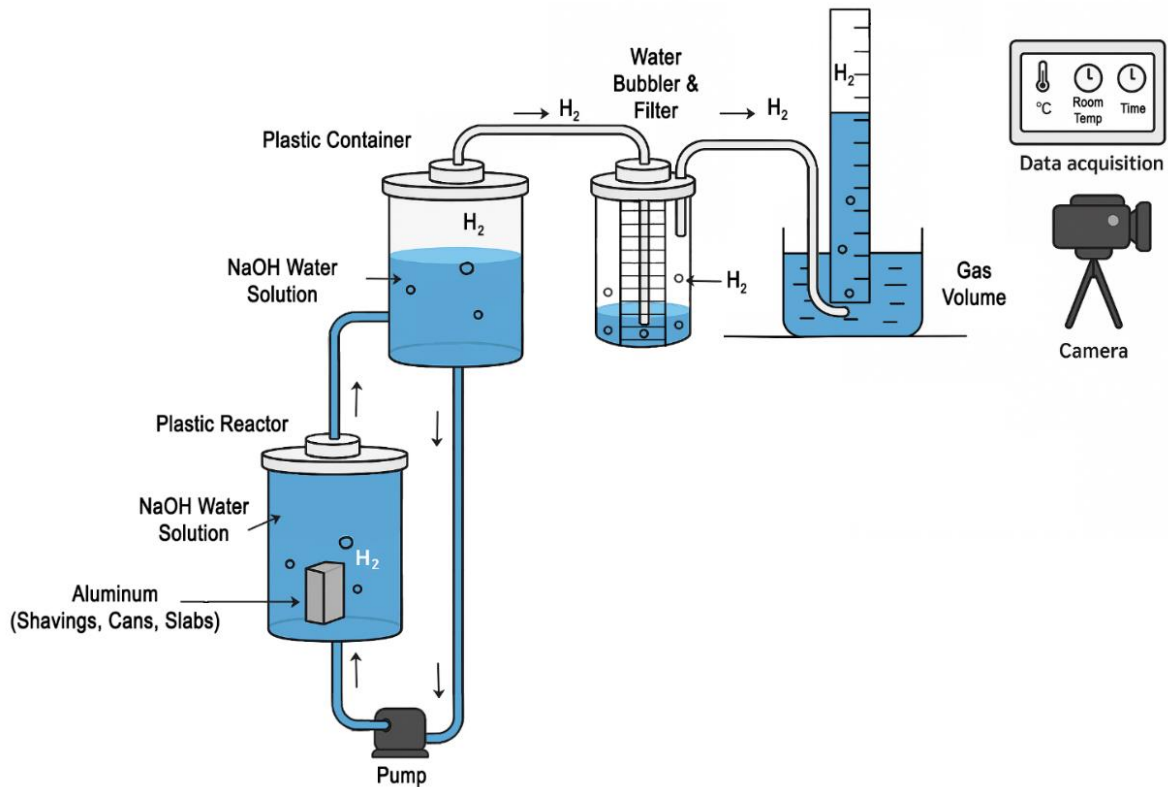


Figure 2: Experimental prototype unit (10-50g) for determination of the H₂ production of Aluminum Shavings, Cans and Slabs, under different NaOH wt% concentrations under constant solution agitation

3. Experimental results - Discussion

3.1 Hydrogen production rate as a function of NaOH wt% concentrations at the constant temperature of 40°C.

The H₂ production as a function of time under different NaOH wt% concentrations and NaOH/Al molecular ratios (mol/mol) of >1/1, based on overall reaction (5), under stagnant conditions (no agitation), at the constant temperature of 40°C were performed in the experimental set-up shown in **Figure 1**. The corresponding diagrams are shown in **Figure 3**. It is obvious that the H₂ production rate (initial slope of the line of H₂ production as a function of time) increases as the NaOH wt% concentration increases. It is worth noting that for NaOH concentrations above 5wt% the H₂ production rates are similarly quite high. For NaOH wt% concentrations below 5wt% the H₂ production rate decreases considerably. It is expected that, in case of agitation, the H₂ production rate could increase significantly, even at concentrations of below 5wt%NaOH. Under constant agitation the reaction product which is stagnant Hydrated Sodium Aluminate (NaAl(OH)₄), according to the overall reaction (5), will be forced away for the reaction-zone around the Aluminum surface. At the same time, stagnant NaOH away from the reaction-zone moves into the reaction-zone becoming available to contact with the Aluminum surface, thus promoting the H₂ generation reaction according to the overall reaction (5). Therefore, the reaction under stagnant conditions is expected to be slow and diffusion-limited, whereas under agitation the reaction becomes faster and concentration-limited process, which it was very important to consider for the design of the experimental (**Figure 2**) and final Prototype Units (see Paragraph 5).

3.2 Hydrogen production rate as a function temperature for different NaOH wt% Concentrations

The diagrams in **Figures 4-5** show, as expected, that by increasing the temperature the H₂ production rate increases significantly. This is very important for the design of the large-scale prototype unit where the temperatures, due to the huge exothermic enthalpy (-415 kJ/moleAl) of the reaction [15], could rich the water boiling temperature of 100°C, and that must be considered in order to remove and store such a huge thermal energy in the form of useful hot water.

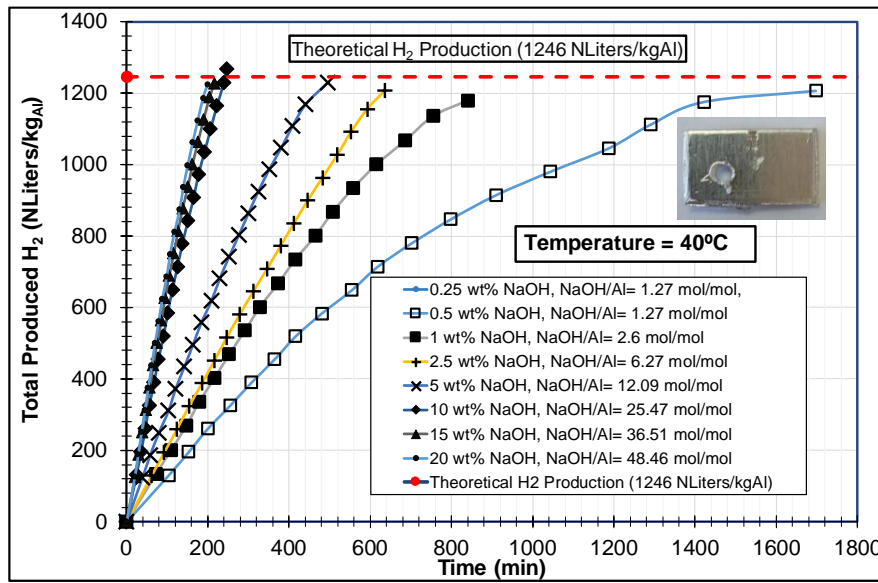


Figure 3: H₂ production as a function of time under different NaOH wt% concentrations and molecular NaOH/Al (mol/mol) ratios >1, at 40°C (Slab as shown in the picture inside the Figure 3)

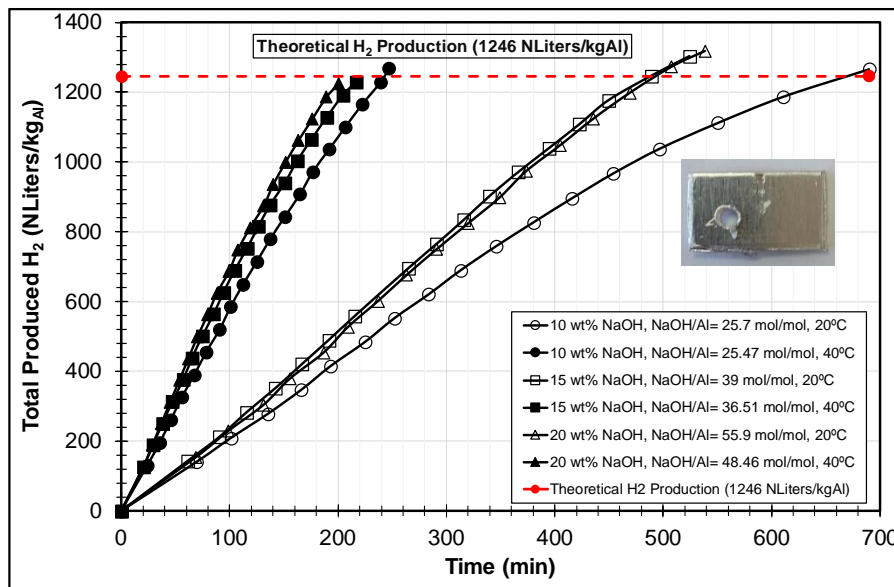


Figure 4: H₂ production rates under different (10-20wt%) NaOH wt% concentrations at 20°C and 40°C, for comparison (Slab as shown in the picture inside the Figure 4)

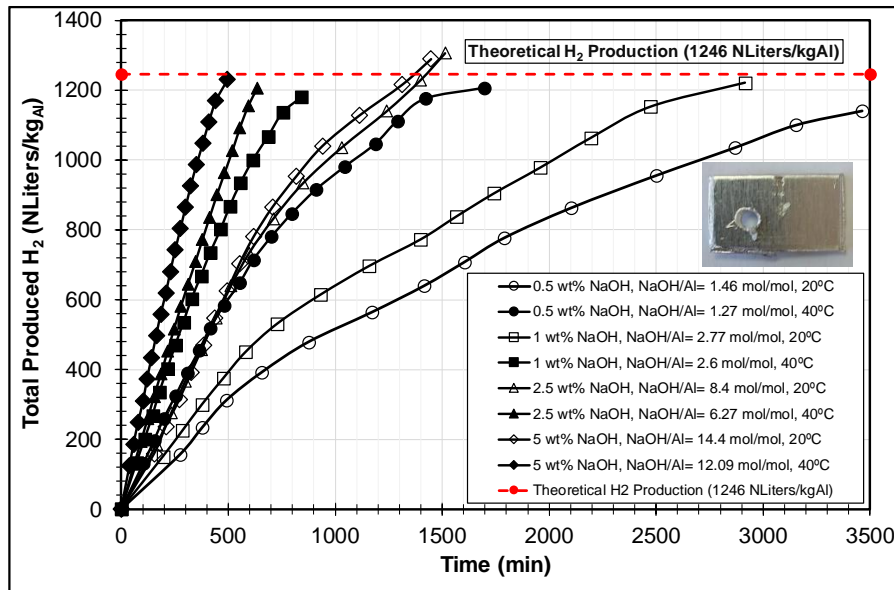


Figure 5: H₂ production rates under different (0.5-5wt%) NaOH wt% concentrations at 20°C and 40°C, for comparison (Slab as shown in the picture inside the Figure 5)

3.3 Hydrogen production rate for different type of recycled Aluminum metals under different NaOH wt% Concentrations

The investigation of Hydrogen production rate of different type of recycled Aluminum metals (Shavings, Cans and Slabs) were performed in the experimental prototype shown in Figure 2.

3.3.1 Aluminum Shavings (Chips)

Figure 6 shows the H₂ production rate of recycled Aluminum Shavings (Shaving as shown in the picture inside the Figure 6) for different NaOH wt% concentrations and molecular NaOH/Al ratios (mol/mol) of >1/1. As the NaOH wt% concentration increases the H₂ production rate increases.

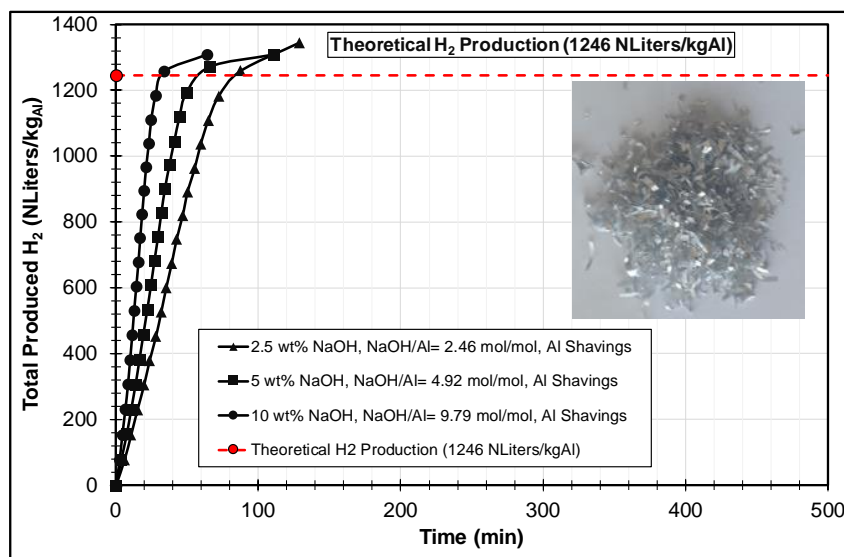


Figure 6: H₂ production rate of recycled Aluminum Shavings (Shaving as shown in the picture inside the Figure 6) for different NaOH wt% concentrations and molecular NaOH/Al ratios (mol/mol) of >1/1

3.3.2 Aluminum Cans

Figure 7 shows the H₂ production rate of recycled Aluminum Cans (Flatten Cans cut symmetrically in 4 pieces as shown in the picture inside the Figure 7) for different NaOH wt% concentrations and molecular NaOH/Al ratios (mol/mol) of >1/1. As the NaOH wt% concentration increases the H₂ production rate increases.

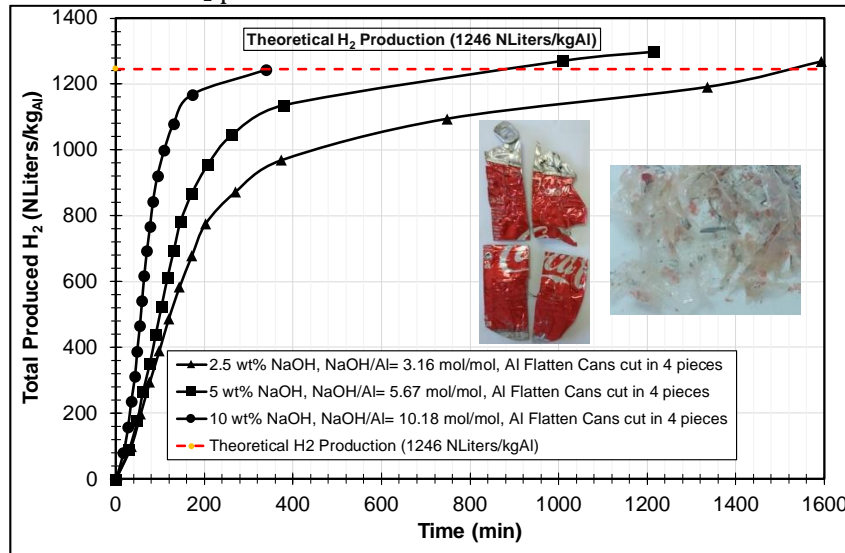


Figure 7: H₂ production rate of recycled Aluminum Cans (Flatten Cans cut symmetrically in 4 pieces as shown in the picture inside the Figure 7) for different NaOH wt% concentrations and molecular NaOH/Al ratios (mol/mol) of >1/1. Inside the Figure 7, there is a picture of the remaining Bisphenol coating and paints

3.3.3 Aluminum Slabs (Chunks)

Figure 8 shows the H₂ production rate of recycled Aluminum Slabs (Slab as shown in the picture inside the Figure 8) for different NaOH wt% concentrations and molecular NaOH/Al ratios (mol/mol) of >1/1. As the NaOH wt% concentration increases the H₂ production rate increases.

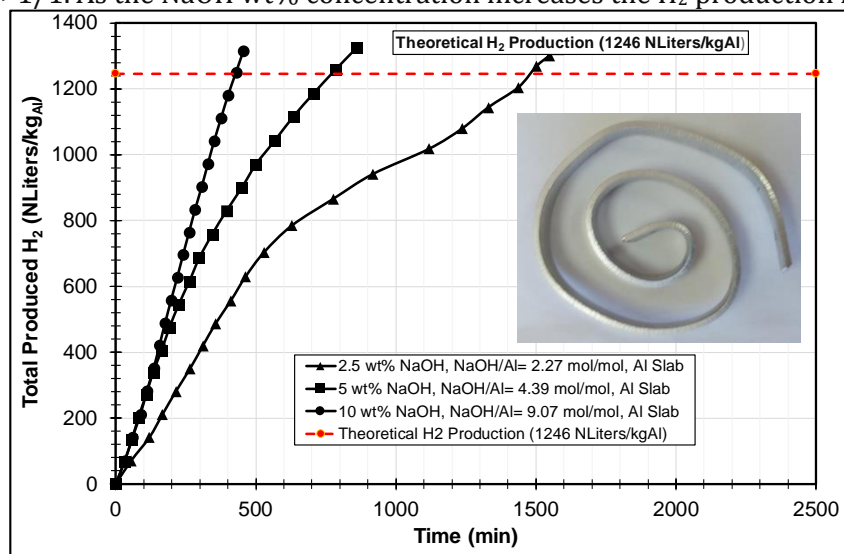


Figure 8: H₂ production rate of recycled Aluminum Slabs (Slab as shown in the picture inside the Figure 8) for different NaOH wt% concentrations and molecular NaOH/Al ratios (mol/mol) of >1/1

4. Comparison of H₂ production rate of recycled Aluminum Shavings, Cans and Slabs for different NaOH wt% concentrations

Figure 9-11 show the H₂ production rate of recycled Aluminum Shavings, Cans and Slabs for different NaOH wt% concentrations for comparison. The H₂ production rate increases as one uses recycled Aluminum Shavings, Cans and Slabs, respectively, due to their corresponding higher specific surface (m²/kg).

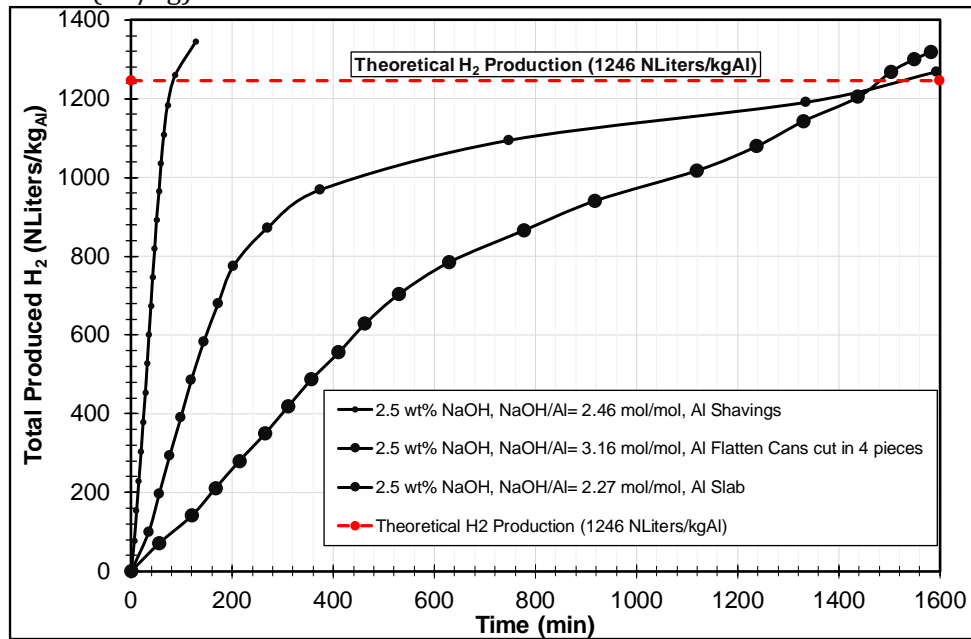


Figure 9: H₂ production rate of recycled Aluminum Shavings, Cans and Slabs under 2.5wt% NaOH solution

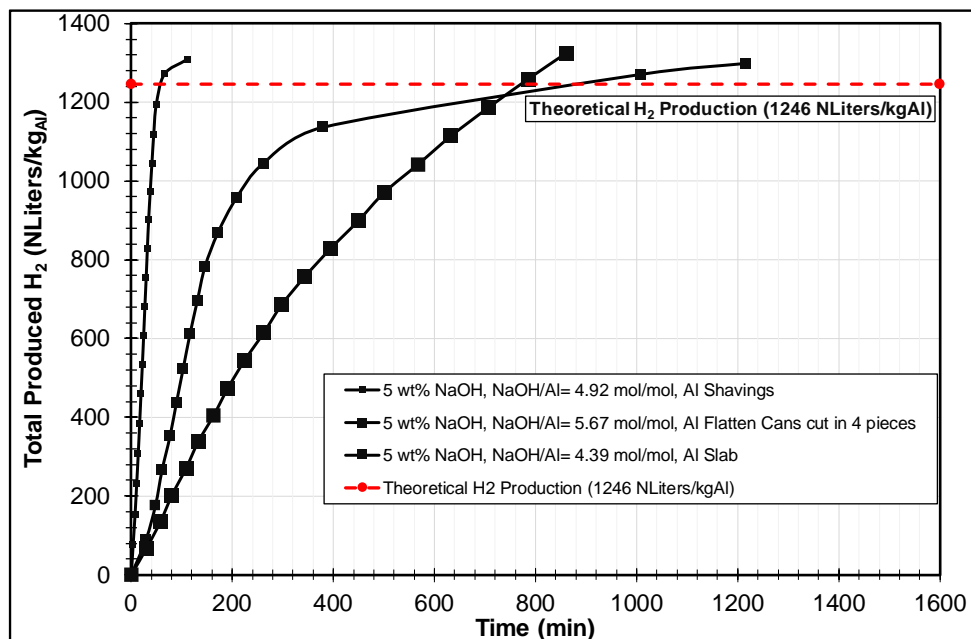


Figure 10: H₂ production rate of recycled Aluminum Shavings, Cans and Slabs under 5wt% NaOH solution

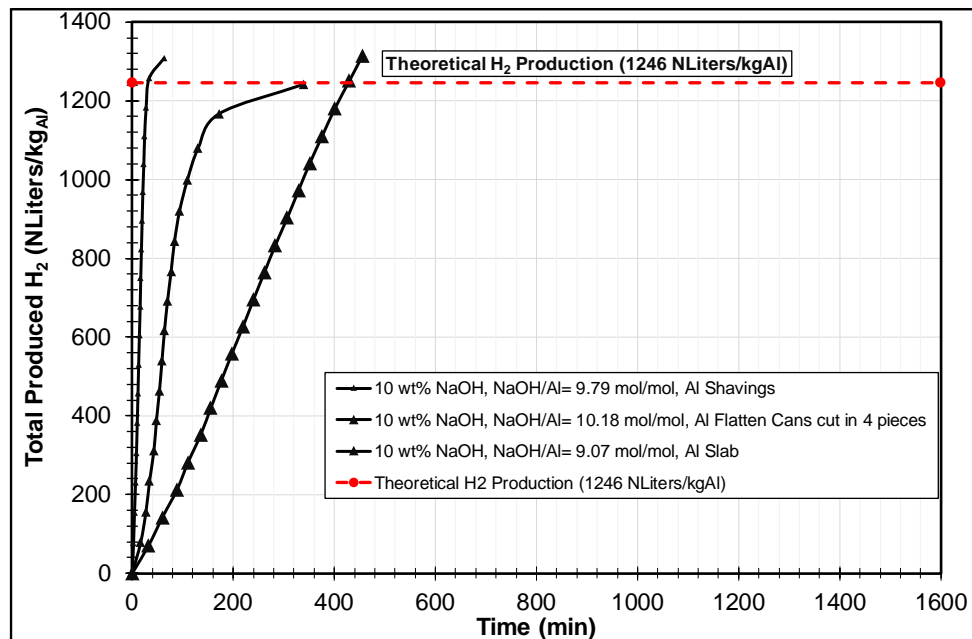


Figure 11: H₂ production rate of recycled Aluminum Shavings, Cans and Slabs under 10wt% NaOH solution

5. Preliminary design of a large-scale final prototype unit

Based on the results obtained during the described experimental results, a preliminary flow-diagram of the final prototype unit has been developed, as show in **Figure 12**.

The design takes into account the following:

- a) All parts of the Unit will be Stainless Steel (SUS304) and/or High Temperature Plastic in order to withstand alkaline corrosive environment.
- b) 50kg of recycled Aluminum should fit into the Reactor Tank
- c) The total mass of the NaOH water solution should be such that the initial molecular NaOH/Al ratio is $\geq 1/1$.
- d) In order to avoid any precipitation of solids ($Al(OH)_3$), it is expected that a 10wt% NaOH water solution will be used.
- e) A pump should recirculate the liquid constantly in order to ensure homogeneity of the NaOH water solution, fast reaction kinetics and assist the heat-exchange through the radiator in the Hot Water Tank
- f) The heat produced in the Unit ($415 \text{ kJ/moleAl} = 15.37 \text{ MJ/kgAl}$) should be removed through a radiator Hot Water-Tank, containing enough water to keep the system under 90°C .
- g) The volume of the H₂ Separator Tank should be large enough to store, if needed, all the available liquid.
- h) A water bubbler and water/NaOH spay filter will be placed in the output of the H₂ Separator Tank in order to supply pure H₂ gas.
- i) The Unit, especially the Reactor Tank, should be easily disassembled in order to remove any expected plastics/paints/Solids, for proper disposal.
- j) The liquid should be able to be easily discharged and stored for further use.
- k) Safety measure should be taken for the safe operation of the final Prototype Unit: A pressure relief valve in the H₂ Separator Tank and a H₂ Detector will be placed on the top of the unit in order to give a sound signal for possible leaks.

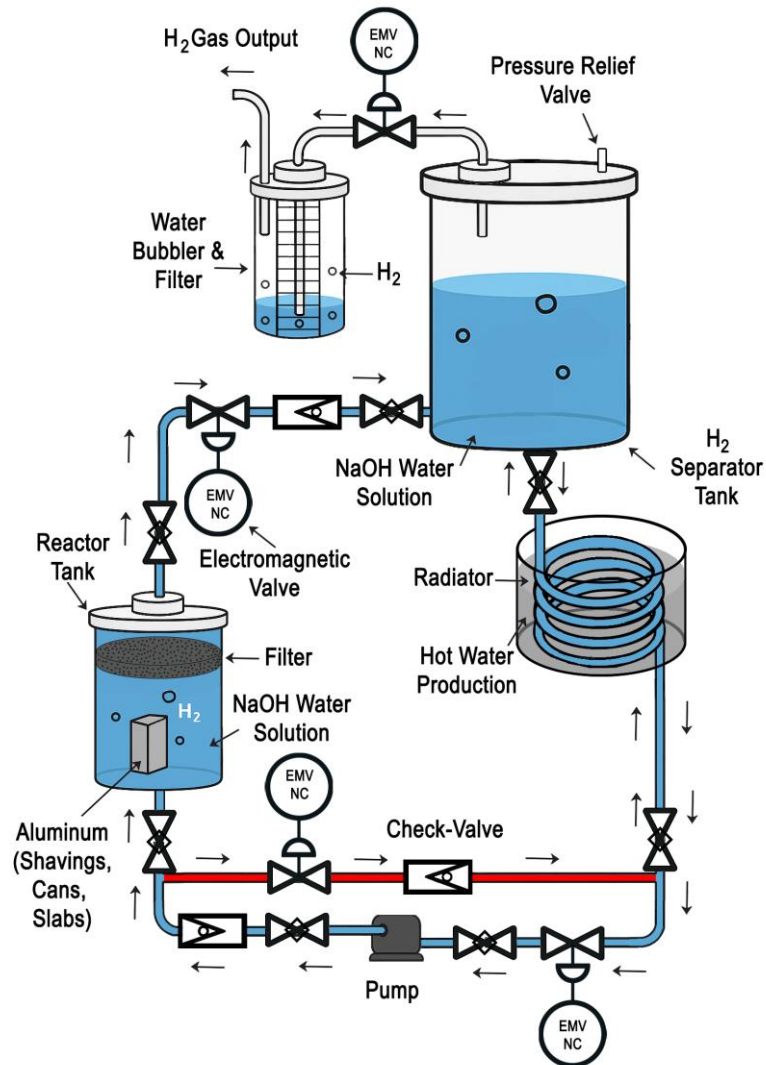


Figure 12: Preliminary flow-diagram of the final prototype unit for H₂ production by water decomposition with recycled Aluminum Shavings, Cans and Slabs in the presence of NaOH solution, as a catalyst

6. Conclusions

An experimental prototype unit was constructed and operated smoothly obtaining results on the production of green H₂ gas by using recycled Aluminum Shavings, Cans and Slab.

The H₂ production rate is higher by using Recycled Aluminum Shavings, Can and Slabs, respectively, due to its higher specific surface area.

The H₂ production was found to be very close to the theoretical 1246NLH₂ per kgAl (3H/Al atom/atom ratio), within ±10% depending on the purity of the recycled Aluminum and taking into consideration the experimental error involved.

It was found that As the NaOH wt% concentration increases the reaction rate increases.

For high NaOH wt% concentrations, the produced NaAl(OH)₄ remains in solution whereas for low NaOH wt% concentrations, it further decomposes into Al(OH)₃ precipitates (white precipitate) and regenerated NaOH catalyst.

A preliminary design (flow-diagram) was developed to be used as a basis for the Design and Construction of the Final Prototype Unit of 50kg recycled Aluminium per day.

Acknowledgments:

The present study was partially funded by Research & Innovation Foundation (RIF) “Greening Circular Economy by Innovative transformation of Reuse Recycled Aluminium into Green Hydrogen”, COM-CONCEPT ENERGY/0624/0004/HY-CIRCULAR, Hystore Tech Ltd, April 1, 2025 to March 31, 2026.

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