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Design and Fabrication of Low Cost and Efficient Hydrogen Reactors

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Abstract: **Hydrogen reactors (also called hydrogen electrolysers) available today are mostly focused on the large-scale industrial level production of hydrogen requiring huge capital expenditure to setup and operate. No such viable reactors are present for small scale use that everyday people can incorporate into their use cases efficiently and at low costs. In this paper the design and fabrication work of two low cost and efficient reactors is studied, reviewed and discussed. Low share of hydrogen production for everyday applications is due to cost ineffectiveness, high maintenance, low durability and stability of the reactors produced at such low-price points. This research paper researches and reviews all the design parameters to be kept in mind towards achieving the goal of fabricating hydrogen reactors for everyday applications and at the same time keeping the costs as low as possible.**

Keywords—Alkaline Electrolysis, Hydrogen Reactor, Efficient Electrolyser, Green Energy, Green Fuel.

I. INTRODUCTION

A. Current Scenario:

Why is there a need for green energy? Why do we need this type of energy? Can't we stay on fossil fuel for our electrical needs? These were the question that crops up wherever research is done in the green energy production field.

As of the year 2021, a report from Global Carbon Project shows that we are emitting a total of 36.4 Gt of carbon dioxide which is almost 60% more compared to 30 years back in 1990. For reference, the following graph is provided,

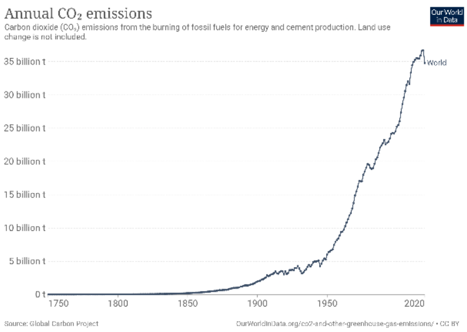

Fig. 1 – Increment of CO_2 emission for past years.

The atmosphere is polluted with plenty of greenhouse gases such as SOx, NOx, CO_2, and CO majority of these gases' productions are due to the burning of fossil fuels such as petrol, diesel, CNG, LPG, etc. And in today's day and age majority of our vehicles and cutting or wielding tools run on fossil fuels and natural gas which contribute to the production of greenhouse gases and directly affect the ecosystem. The production of a clean and safer energy/fuel has led to hydrogen gas production and a substitute because when hydrogen gas is combusted/consume the by-product is nothing but harmless water (H_2O).

Hydrogen was taken into consideration in this research paper because Hydrogen is the most promising energy source for future technologies. Hydrogen energy density is one of the highest in the Universe - 142 MJ / kg. For comparison, gasoline has 45 MJ / kg, and lithium-ion batteries have 6 MJ / kg. The only fuel with a higher energy density than hydrogen is plutonium and uranium.

The best and most efficient way to produce hydrogen gas is through a process called 'electrolysis'. This term was introduced by English scientists William Nicholson and Sir Anthony Carlisle in the 1800s.

The atmosphere is polluted in a number of ways. One of which being the emissions of flue gases released after combustion of fossil fuels…

B. Water Electrolysis as a method for Hydrogen Production:

There are many important non-fossil fuel-based processes like Water electrolysis, photocatalysis processes and thermochemical cycles for hydrogen productions in practice. The use of solar energy and wind energy are sustainable methods for hydrogen production by water electrolysis with high purity, simple and green process [1].

For hydrogen production, water electrolysis has its various merits like pollution free process if renewable energy sources use purity of high degree, very simple process and plenty of resources. Water electrolysis is an around 200-year-old technology; around 1800 AD the principle demonstrated by experiment by J. W. Ritter in Germany. In the same year William Nicholson and Anthony Carlisle decompose water into hydrogen and oxygen in England. The application of this technology started to use after tens of year. The French military in 1890 AD constructed a water electrolysis unit to generate hydrogen for use in airships by Charles Renard. Around 1900 AD more than 400 industrial electrolysers were operating worldwide. Around 1930 AD different types of alkaline electrolysers were developed.

From 1970s onwards different methods for hydrogen production like PEM water electrolysis and high temperature electrolysis were developed. Although these methods were revealed to be more efficient than alkaline water electrolysis [1], the capital expenditure required to set them up and the complexity of the system make them unfit for use in the context of everyday applications and portable design. Therefore, alkaline water electrolysis was selected as a suitable method for hydrogen production whilst designing the reactors.

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C. Applications of hydrogen fuel:

Hydrogen is said to be the cleanest fuel because when consumed in a fuel cell the resultant product are water, heat, and much-needed electricity. Hydrogen and fuel cells play an important role in a broad range of applications, across virtually all sectors—transportation, commercial, industrial, residential, and portable.

Hydrogen and fuel cells can provide energy for use in diverse applications, including distributed or combined-heat-and-power; backup power; systems for storing and enabling renewable energy; portable power; auxiliary power for trucks, aircraft, rail, and ships; specialty vehicles such as forklifts; and passenger and freight vehicles including cars, trucks, and buses.[3]

Due to their high efficiency and zero-or near-zero-emissions operation, hydrogen and fuel cells have the potential to reduce greenhouse gas emissions in many applications. Energy Department-funded analysis has shown that hydrogen and fuel cells have the potential to achieve the following reductions in emissions:

- Light-duty highway vehicles: more than 50% to more than 90% reduction in emissions over today's gasoline vehicles.
- Specialty vehicles: more than 35% reduction in emissions over current diesel and battery-powered lift trucks.
- Transit buses: demonstrated fuel economies of approximately 1.5 times greater than diesel internal combustion engine (ICE) buses and approximately 2 times higher than natural gas ICE buses.
- Auxiliary power units (APUs): more than 60% reduction in emissions compared to truck engine idling.
- Combined heat and power (CHP) systems: 35% to more than 50% reduction in emissions over conventional heat and power sources (with much greater reductions—more than 80%—if biogas or hydrogen from low- or zero-carbon sources is used in the fuel cell) [3]

Depending upon the rate of gas generation, this gas is used in a wide array of applications ranging from fuel for laboratory work to boosting IC engines, powering impulse devices, making a cutting/welding torch, fuel in pulse jet engines, generating clean energy through hydrogen fuel cell, etc. with novel methods of using this gas being discovered each day.

II. PRIOR EXPERIMENTATIONS

In order to determine functional parameters necessary to be incorporated in the design, preliminary experimentations were carried out to collect data from which inferences were drawn. With the help of two pieces of iron, a glass of water and a power supply, absolutely all the parameters that are needed to build the most modern electrolyser were computed. A low-power Laboratory Power Supply of 150W (30V, 5A) was used in order to clearly see how the current, voltage and power depend on each other.

When two pieces of iron with opposite charges are immersed in water, the electrolysis reaction starts. Bubbles will start to appear on the contacts. Thus, in very simple terms, environmentally friendly fuel from the most common substance on Earth was received.

Now as the plates were moved towards and then away from each other, the current and voltage readings on the power supply changed. At a distance of about 2- 3 mm, the voltage remains unchanged, and the intensity of the reaction is maximum. At a greater distance, the reaction weakens & at a smaller distance, the bubbles on the plates begin to stick together and interfere with the reaction. Therefore, a distance of 2-3 mm between the plates was considered optimal.

The plates were continued to be moved and the voltage readings on the power supply were followed. If the plates are spread further apart, the voltage on the plates increases and the current decreases. If the plates are brought closer, then the voltage decreases, because the charge begins to move from the negative plate to the positive one more intensively. One important observation made was that by fixing the plates at a distance of 2-3 mm from each other, one is not be able to raise the voltage on the power supply more than 2-3 volts. It will fall. Hence, this voltage was concluded as the optimum voltage between the electrolyser plates.

Thus, the optimal distance between the plates was taken 2mm, and the optimal voltage between them as 2 volts. It was also noticed that the more area is involved in the process, the more gas is released. This can be referred to as the active area. As the plates are lowered deeper into the water, more of their area is used. In this case, the current increases. And when the plates are taken out of the water, that is, we drain the active area, less gas is produced and the current decreases.

Next, it was tried to increase the current without increasing the active area and it was observed that by turning the current control to maximum, the reaction will go stronger, but after a while the water will start to heat up. This means that if the current is too large in relation to the active area, then the reactor becomes more of a heater than an electrolyser. This means that there must be a certain ratio between the area of the plates and the current that passes through them.

The question was then raised, "What should be done to increase the gas generation rate after the maximum active area possible as per dimensional constraints is achieved?". And the solution agreed upon was to add more plates. Therefore, more plates were connected to the circuit according to the scheme - + - or + - +, no difference. Thus, you can add as many pieces of irons as you like. The problem is that each will need to be connected. And if we continue experiments in a glass, jar or other container, where the plates are simply immersed in water, we will need to connect all of them. The supply current will increase with an increase in the number of plates, but the voltage is still the same between two plates: 2-3 volts. In this situation, we may need a power supply with a huge current and tiny voltage, which is very inconvenient. But this is not the only problem with "wet" electrolysers, that is, electrolysers with a common bath of all plates.

In an electrolyser with a common bath, all contacts are in one container and have the only possible connection method - connect each plate. This means that the common bath must be divided into several, that is, to make sure that the water between the first and second plates does not contact (or almost does not contact) with water between the second and third plates. One of the ways is to separate the plates with rubber spacers. Then each two plates will form a separate cell. In such a scheme, it is no longer necessary to connect each plate. One can connect the first and third. So, 3 plates form two separate cells. Each cell, regardless of size, needs a voltage of 2 volts. Now one can easily calculate the supply voltage of any electrolyser. One needs to take the number of cells and multiply this number by 2. But in practice, if we can make absolutely any number of cells, then it is more convenient to adjust their number to standard power supplies.

A connection diagram in which current is applied to each plate, as in a wet cell with a common bath, is called "parallel connection". When the first and last plate are connected, this is a "daisy chain" or in-series connection. It is easy to remember, because virtually all cells are connected one after the other, in series. All that needs to kept in mind is that there are about 2 volts per cell. The most common situation is when there is a 12-volt battery and an electrolyser with a large number of plates. For example, let's say an electrolyser in a hydrogen accelerator for a motorcycle has 18 cells (19 plates). We connect negative wire to 1 and 13 plates, and positive to 7 and 19 plates. Or vice versa, polarity is not important. The main thing is that there is a voltage of 2 volts on each cell.

Standard Voltage in V	Number of cells and (plates)	Power Supply
2	1 (2)	Lithium Ion 18650 Battery
9	4 (5)	9V battery
12	6 (7)	Standard on-board power supplies, motorcycle and car batteries
30-36	18 (19)	Assemblies of lithium-ion batteries for electric vehicles, batteries from scooters. etc.
110	55 (56)	US Standard Voltage
220	110 (111)	Standard voltage for non-US outlets

Table 1 – No. of cells and plates corresponding to standard power supplies

III. DESIGN OF THE REACTORS

Keeping all the inferences from previous experimentations and as per the applications described earlier in mind, two reactors/electrolysers were designed to suit specific needs, namely Mk_1 and Mk_2 respectively.

The important parameters considered for the design calculations were as follows:

1. Task to be performed.
2. Plates and the electrolyser shape.
3. Gas generation rate.
4. Power.
5. Active area.
6. The number of active zones.
7. The proportions of the active zones.
8. The area and size of the active zones.
9. The dimensions of the plates.
10. Spacers and distance between plates.
11. Body and dimensions.
12. Bottom circulation holes.
13. Upper vent holes.
14. Fittings.
15. Hoses.
16. Circulation tank.

Many parameters were similar or even same in designing both the reactor models, the same has been mentioned wherever applicable.

3.1. Mk_1:

Mk_1 model consists of 12 electrolytic cells connected in a combined way (in parallel and in series). Each cell is a container with electrolyte, bounded by metal plates (electrodes) and an insulator.

The rate of fuel gas generation in the model Mark I – 300 ml / min with a power consumption of 30 watts. It should be noted that the gas generation rate of the reactor can be accelerated by increasing the current (ampere) and provisions for the same have been made in the design. The reactor is designed to be powered from 12 – 24 volts, current around 5 amps, temperature up to 60 degrees. Maximum pressure 4 atmospheres.

Plates and the electrolyser shape: In 90% of cases, electrolysers are rectangular, and very rarely round. The main difference is that round cells withstand more pressure due to its uniform distribution along the walls. Hence, circular shape was selected for the design. Same was done for Mk_2 reactor as well.

Gas generation rate: For this model, 300 ml of gas generation rate per minute was set with provisions included to generate a higher rate of gas under specific conditions.

Power: From experimentation, it was found that on average, 1 kW gives a gas generation rate of 10 litres per minute. It is clear that there are a lot of factors that affect the efficiency, and from the findings of prior experimentations if one tries to take them all into account, then 1 kW = 10 l/min. This means that if this model only needs 300 ml per minute, then the power supply = around 0.03 kW.

Active area: As it was found from experiments that the more power and generation rate desired, the more area is needed. In order for the electrolyser to work without overheating, an active area of 1 m^2 is needed for every 1 kW of power. the active area means all metal surfaces that participate in the reaction. The outer sides of the external plates, parts of the plates that are overlapped by spacers & parts of the plates that are not immersed in water - are not active surfaces. In short, all the metal that is bubbling is the active zone. This means that if it's desired to pump in around 30W into the

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reactor / electrolyser, a total active area of 0.03 m^2 will be needed which gives each plate an active area of 0.01476 m^2 for 12 cells, which means total plates (electrodes) equal to 13.

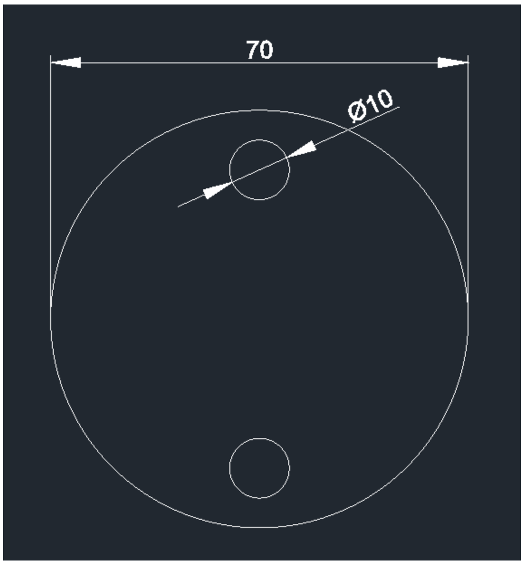

Fig 2: Electrode (without contact pin) of Mk_1 reactor

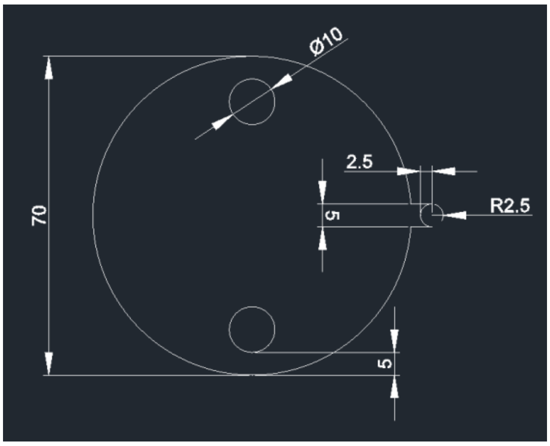

Fig 3: Electrode (with contact pin) of Mk_1 reactor

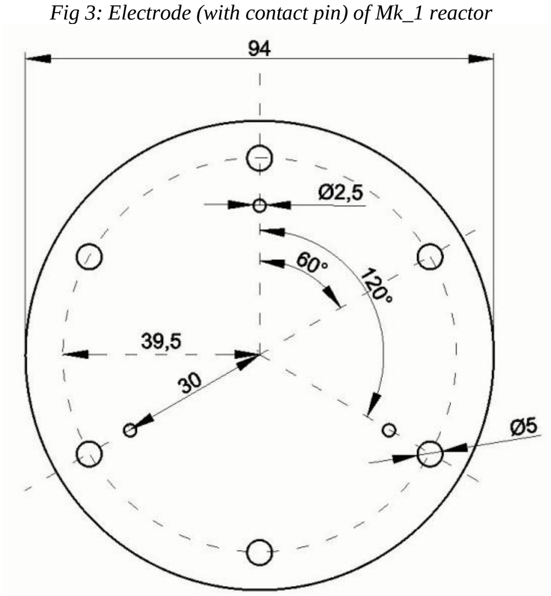

Fig 4: Front Wall of Mk_1 reactor

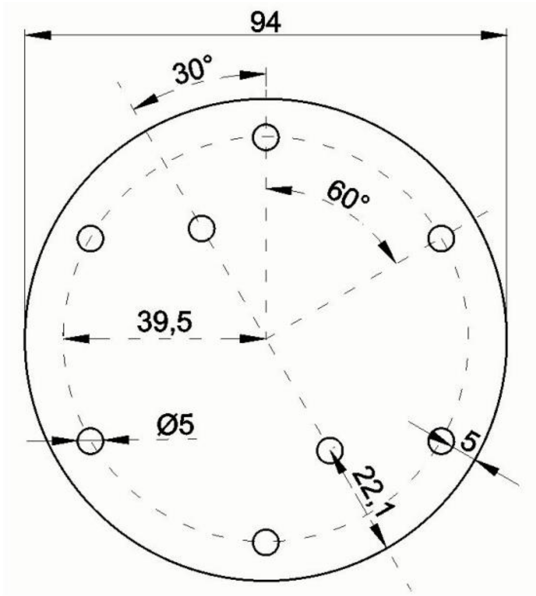

Fig 5*: Back Wall of Mk_1 reactor*

The number of active zones: The total active area is now known - 0.03 m^2. How many plates is it better to divide the electrolyser into for a given area? If one can take any quantity, then it is better to adjust the number of cells to the power source. to power the electrolyser from a 12V motorcycle battery or from a 30V, 5A laboratory power supply. For 12 volts, 6 cells (7 plates) are needed, for 30V - 15 cells (16 plates). To make it convenient to power the electrolyser, 12 cells (13 plates) can be made from both the block and the battery. When powered by a battery, we connect negative wire to 1st and 13th plate & positive wire to 7th plate - so we get 2 volts on each cell. When powered from the power supply, we connect negative to 1st plate, and positive to 13th plate. And either we tighten the voltage settings by 24 volts, then there will be exactly 2 volts on the cell. Or we leave 30 volts and there will be a slight overvoltage of 2.5 volts on each cell.

The area and size of the active zones: If there is a total active area (0.03 m^2) and the number of plates is 13 (13 pcs), then calculating their dimensions is pure arithmetic. This model is a 13-plate sandwich and each plate participates in the reaction on both sides, except for the outer two plates: 13 x 2 - 2 = 24. That is, 13 plates give 24 active surfaces. The total active area is 0.03 m^2, it must be divided into 24 surfaces: 0.03 / 24 = 0.00125 m^2 or 1250 mm^2 is the active area of each plate. For practical purposes and to give more potential for gas generation when more current is supplied an area of 2670.353 mm^2 was concluded as the final active area for each active surface.

Spacers (Gaskets) and distance between plates: The distance between the plates of 2-3 mm is the same for all electrolysers. For this model, Silicone rubber with a thickness of 2 mm was selected as it can withstand temperatures up to 60°C and from it were cut 14 spacers with an external diameter of 70 mm and internal hole of 60 mm.

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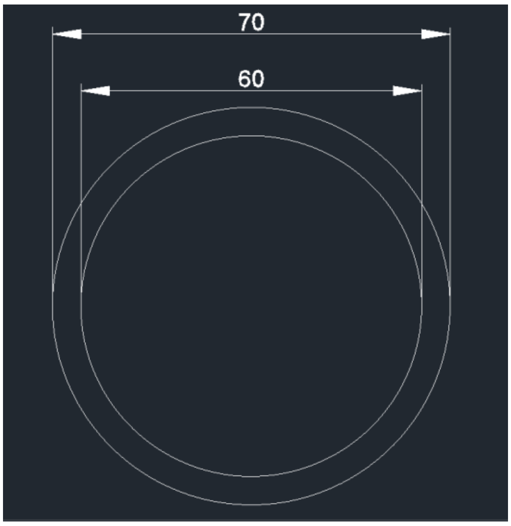

***Fig 6**: Separator pads / Gaskets of Mk_1 reactor*

Body: The body plates, by means of screws and nuts, compress the plates and gaskets of the electrolyser. In this model, the body parts do not participate in the reaction, which means they should not conduct current. The exact dimensions of the case will depend on the strength of the material from which they are made. In this design, 5 mm thick plexiglass was used for the front and back wall of the case. Additionally, a 10 mm plexiglass component having a washer like appearance was also used to mount LEDs and improve the aesthetics of the product.

Bottom circulation holes: In order for the water in each cell to be completely separated from the others, there must be no electrical connection between them. That is, the cells with water must be completely separated by plates. In practice, this is difficult to achieve, because then it would be necessary to make a separate supply of water to each cell with a thickness of only 2 mm. In order not to suffer with such a system, a small hole is made at the bottom of each plate for water circulation. Advantage: the water that is supplied to the electrolyser through the lower fittings in the walls is evenly distributed over all cells without additional technical complications. Disadvantage: because of these holes, the cells cannot be considered completely separated, which means that the current from the power source goes not only through the plates, but also through these holes. This is what gives the voltage drop, which becomes especially noticeable with a large number of plates. And in fact, in order to maintain a voltage of 2 volts on each of the 12 cells, the first and last plate must be supplied with a voltage not of 24 volts, but of 26-30 volts, depending on the conductivity of the water. Therefore, it is important to make these holes not too large. 3 - 5mm hole is enough for circulation. Also, to further reduce the voltage drop, these holes can be made not in the middle, but closer to the lower corners. Fig. 2 and Fig 3. show the arrangement of the bottom circulation holes made in the design of Mk_1.

Upper vent holes: In addition to the lower holes, the upper holes are also needed in the plates. They are needed to efficiently remove HHO gas and foam. Each cell of the electrolyser generates gas and foam as a by-product. It is very important that gas and foam leave each cell as soon as possible. Otherwise, the gas will push out the liquid, which will leave through the lower holes. This leads to dehydration of the core, that is, its reduction. This instantly reduces the gas exit rate, accelerates the heating of the electrolyser and, in very rare cases, can lead to arcing, which is highly undesirable given what gas is generated in the device. The rate of gas and foam formation depends on the rate of gas generation and on the input power. The higher the power and rate of gas generation, the larger the upper holes should be. For a generation rate of 1 - 2 litres, 6 - 8mm holes are sufficient. For speeds 2-5 litres, holes 10mm. We provided 5 mm holes for Mk_1. At higher generation rates, it is better to make not one, but several holes, or flat horizontal slots as high as possible, so as not to reduce the active area. Later, with more experimentation, it was found that the holes need not necessarily be circular, that is included and covered in the design part of Mk_2.

Fittings: Nipples or fittings are parts that connect the cell to the hoses. The threaded part of the fitting is screwed into the wall of the electrolyser, and a hose is put on the "herringbone". It is important that the inner diameter of the fittings allows the generated gas to be removed as quickly as possible. Gas and foam are discharged through the upper fittings, water enters the electrolyser through the lower ones. The best option for placing fittings is at least two fittings on each wall. If the electrolyser has fittings on only one wall, then the gas will be removed more slowly in the cells that are closer to the opposite wall. At high gas generation rates, this greatly affects efficiency. If one uses the preferred connection scheme, 2 pieces on each side, then a fitting with an inner diameter of 3.5 - 4mm is suitable for our model. In the model that gives 20 litres per minute, we can use 4 fittings on each side, with an inner diameter of 10 mm. You can navigate by these dimensions. Most air and hydraulic fittings are inch threads. But it is best to look for fittings with a metric, because they have more turns per centimetre. That is, the fitting will be more reliable to screw into a thin wall and will not leak.

Hoses: Hoses, pipes, reinforced hoses and high-pressure hoses are matched to the outer diameter of the fittings. Rigid plastic tubing is preferable. They withstand alkali and pressure and do not break, unlike rubber or silicone. Considering the size of our fittings, these can be standard plastic tubes with a diameter suitable to fit on the selected fittings.

Circulation tank: The main task of the circulation tank is to solve the foam problem. When the electrolyser enters the operating mode, then through the upper fittings, in addition to the fuel gas, foam begins to actively come out. It does not need to be filtered with sponges or filters, because if the liquid from this foam is not returned back to the electrolyser, this again leads to dehumidification of the core. The tank has as many openings for the circulation of foam, gas and water as the electrolyser has, plus two more for filling with water and gas outlet, which are located from the very top. The fluid level in the tank should be between the bottom and top holes. Then the foam and generated gas will easily escape through the upper openings, and through the lower - the liquid will return back to the electrolyser in order to prevent the core from drying out. It is better to make the minimum volume of the circulation tank not less than the volume of the

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electrolyser. Since the circulation tank can also be used as a supply with water, the maximum volume of the tank depends on how many hours the electrolyser is desired to work without refuelling. The circulation tank can be located above or next to the electrolyser. The main thing is that the gas outlet openings of the circulation tank are higher in level than the gas outlet openings of the electrolyser and the liquid flows through them only in one direction.

3.2: Mk_2:

The design points to be considerations are mostly similar to the ones discussed in the design of Mk_1 model with a few exceptions. This model has higher output capacity and is designed for high pressure. Thereby besides the obvious increase in dimensions, all the design factors are as follows:
Choosing the shape of the reactor is simple as before,
round plates and gaskets withstand more pressure due to
the uniform distribution of it.

We needed to get a minimum gas generation rate of 3 litres per minute. From prior experimentations, we know that for a generation rate of one litre per minute 100 Watts is needed, so for 3 litres 300 Watts is needed. Obviously, the more power is inserted into the cell the larger it should be so there must be some optimal ratio of size and power but what is it like? Due to a lack of information available on this topic even after a lot of research, we conducted our own tests to come to a conclusion. The tests have shown that for every 100W an active plate area of one tenth of a square meter ($0.1m^2$) is needed. If it is active area is larger than that, then the electrolyser doesn't work at the full power, remains cold for a long time and the usable area is just useless and if the area is smaller, then the cell quickly fills the gas and overheats. Thus, we come to the clear conclusion that for every kilowatt of power, one square meter of active area is needed.

The number of plates needed depends on supply voltage. Each pair of plates forms one cell. From prior experimentation it is known that the electrolysis starts at a voltage about two volts per cell. Thus, we conclude we need 19 plates for a standard power supply of 32 volts. Knowing the total active area needed of $0.3m^2$, we divide it by the total number of plates and subtract the area of the holes thus we get the area of the plates and also their diameter.

Slots were provided as shown in Fig 5. And Fig 6. This shape of slot instead of holes helps to get more active area from the electrodes while taking care not to hamper the outflow of produced gas. Thus, more output can be generated from the reactor.

The front and back wall were made slightly larger to accommodate the plates/electrodes and gaskets/separator pads within. Also, to withstand the pressure they were made of 5mm thickness 304 Stainless Steel.

There are 2 types of plates in this model - with contact pins and without contact pins. Both types are cut from 1.5 mm stainless sheet. Plates with contacts - 2 pcs. Plates without contacts - 15 pcs. The number of plates is important because the voltage on each cell depends on this. 17 inner plates + outer plates of the body form 19 plates, i.e., 18 cells with the required voltage of 2 volts each.

The Separator pads were made out of 2mm Silicone rubber sheet with outer diameter of 135 mm and inner diameter of 115 mm.

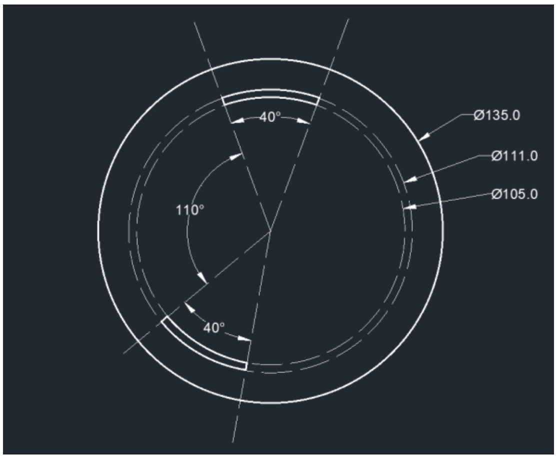

Fig 7: Mk_2 electrode without contact pin

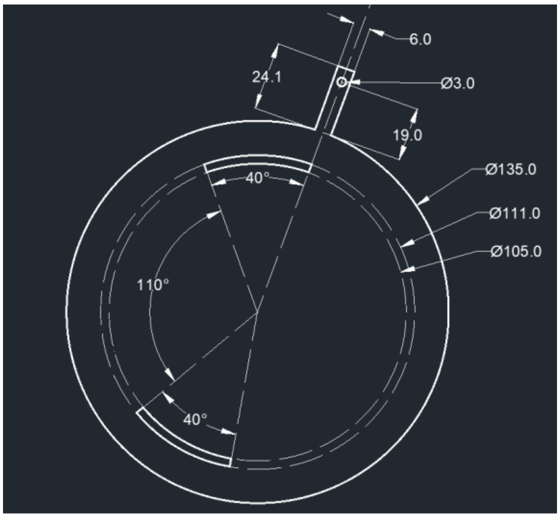

Fig 8: Mk_2 electrode with contact pin

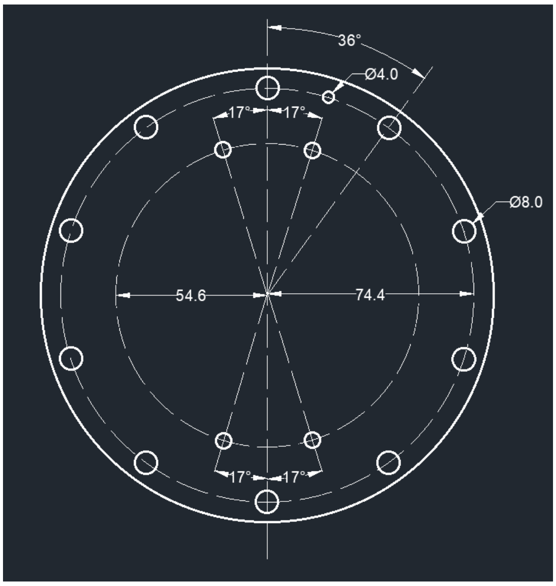

Fig 9: Front Wall of Mk_2 reactor

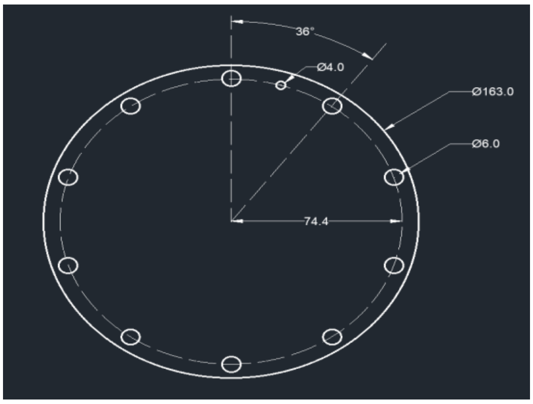

Fig 10: Back wall of Mk_2 reactor

Fabrication and Additional points to note:

All the plates / electrodes and the front and back walls of the reactors need to be laser cut to ensure high precision and improve the stability of the reactors thereby increasing efficiency. It is essential to remove all the burrs from the plates after all the machining operations have been performed on it.

During electrolysis, when Hydrogen bubbles are formed, they tend to stick to the surface of the electrodes/plates if they have a smooth finish, this reduces the efficiency of the reactor. In order to overcome this, all the active surfaces participating in electrolysis reaction need to be processed with a sandpaper of 150 grit firstly in vertical manner and then in a horizontal manner as shown in figures 11 & 12.

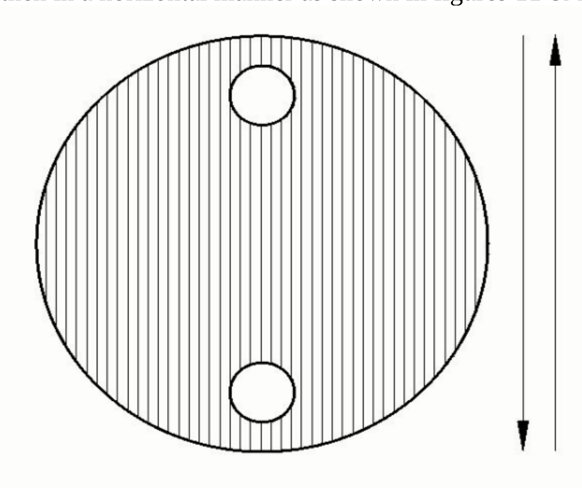

Fig 11: Grinding electrodes with sandpaper in a vertical manner

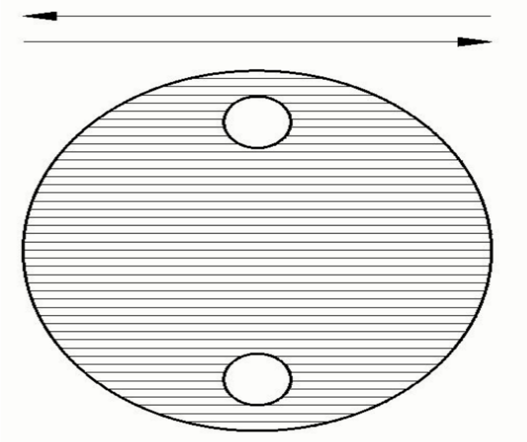

Fig 12: Grinding electrodes with sandpaper in a horizontal manner

Bolts of suitable sizes have to be used to assemble the reactor assemblies. For Mk_1: M5x60 & for Mk_2: M8x90.

For fire tests or for using the generated gas in applications like welding torch or any other explosive applications, it is recommended to install a flashback arrestor to arrest any flashes of sparks that might return through the supply tube because if for any reason a spark reaches the inside of the reactor where the process of electrolysis is actively taking place, there is a very high risk of explosion. Of course, to mitigate that risk a bubbler and a circulation tank is installed, the circulation tank serves a dual purpose: one it acts as a foam separator delivering clean HHO gas and also prevents any sparks from reaching the reactor thereby making it safe, the latter function is the same for bubbler. For the circulation tanks coolant reservoirs were used and for bubbler any suitable size plastic bottle is feasible. The bubbler makes it absolutely certain that no sparks reach the insides of the reactor. Along with it, a flashback arrestor was also included for additional safety.

RESULTS:

The proposed output of 300 mL/min from Mk_1 and that of 3 L/min from Mk_2 was obtained while applying the specified power. As provisions were made in design, more output was possible to be generated from the reactors by supplying more amps.

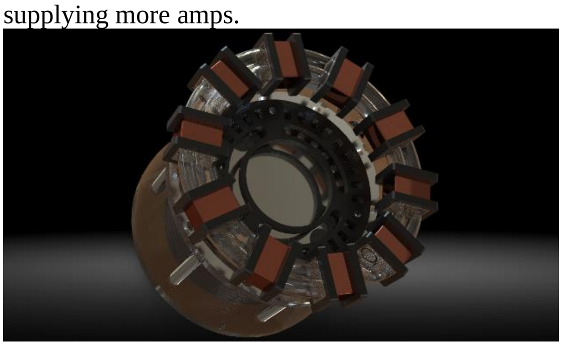

Fig 13: Mk_1

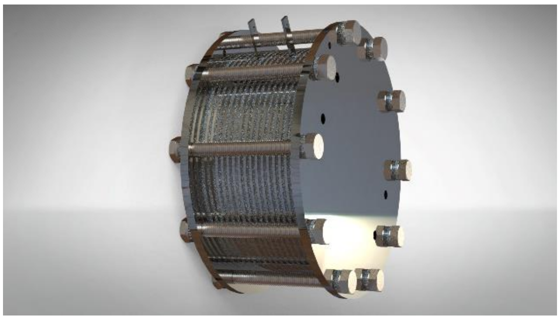

Fig 14: Mk_2

CONCLUSION:

The most suitable and efficient design of reactors for small scale applications using alkaline electrolysis was thus achieved.

FUTURE SCOPE OF WORK:

Along with the prevailing existence of many methods of hydrogen production, further research is warranted to find out ways of reducing their costs along with their efficiency.

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