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Article

The impact of pulse width modulation (PWM) on the generation of hydroxy gas (HHO)

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Abstract: Alkaline water electrolysis is the most practical method for producing large amounts of hydrogen using renewable energy sources. However, water electrolyzers perform poorly at low load conditions, thereby restricting their operational capacity. The main reason for poor efficiency under low loads is power loss due to current. The article explains the inefficiency and proposes an improved water transformer model based on the electrolyzer's internal construction. PWM electrolysis significantly enhances hydrogen generation efficiency at low loads compared to cells supplied with direct current. This study examines the effects of duty ratio and pulse width modulation (PWM) on efficiency enhancement. It is feasible to regulate them under different operating conditions. You may also change the efficiency trend by adjusting the electrolyzer's parameters. Finally, employing pulse width modulation (PWM) for electrolysis to generate hydroxyl gas helps maintain lower cell temperatures and enhances productivity compared to a system linked to direct current.

Keywords: PWM; pulse width modulation; Modulation of pulse width in the production of hydroxy gas (HHO)

1. Introduction and Literature Review

Environmental problems, including air pollution and ecological degradation, have persisted since the turn of the century due to the ever-increasing use of fossil fuels. According to scientists, burning fossil fuels releases carbon dioxide into the atmosphere, which is the primary culprit in most environmental problems [1]. I strongly recommend replacing traditional fossil fuels to combat the escalating environmental crisis. Hydrogen, a plentiful and environmentally friendly energy carrier, has recently emerged as a prominent contender in the global debate over fossil fuel scarcity [2, 3]. As a percentage of mass, this fuel is the most energetic. Hydrogen has three times the energy of methane and gasoline, with a peak heating value of around 3.54 KWh/Nm^3 [4].

Furthermore, no harmful components are released into the environment because the byproduct of burning hydrogen is just water [5]. Hydrogen generation technologies like steam methane reforming and coal gasification are less efficient than water electrolysis from renewable energy sources [6–8]. water electrolysis does not contribute to global

warming or dangerous pollution because it uses water as its sole input and only emits hydrogen and oxygen. Because of its potential to combine with renewable energy sources, hydrogen generation by water electrolysis has gained promise in light of the recent rapid development of solar and wind turbines [9, 10]. It can work as a flexible resource with the friendly energy grid, offset the power system strain from renewables, and make up for their intermittent and fluctuating character [11, 12].

There are still unsolved issues with using renewable energy for the electrolysis of acidic water [14, 13]. Reducing energy usage, electrode disintegration, and gas pollutants are some obstacles water electrolysis faces in its broad implementation. Particularly pressing is the issue of rising energy consumption costs as a result of inefficient hydrogen generation. Due to its low efficiency of about 56%–73 % in large-scale operations, alkaline water electrolysis is not viable for producing hydrogen on a large scale [15, 16]. However, their output power is uncertain because renewable energy sources cross and oscillate. The opposite is true for electrolyzers, which cannot run constantly at full power. They have to work over a broader range and deal with frequent starting and stopping to keep up with the power flow. When electrolyzers cannot operate continuously, inefficiency and contaminants will manifest, challenging renewable energy sources [17].

Stable and cost-effective operation of alkaline water electrolyzers requires more research. According to future research, alkaline water electrolysis has shown enhanced hydrogen generation in recent years.

1.1. Hydrolysis of water and the laws of thermodynamics

Water undergoes electrolysis to produce hydrogen gas and its ions. An electrode potential difference is required, proportional to the gas production during a given time. Below is a list of procedures performed on the electrodes [18, 19].

$$\text{At cathode: } 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (\mathbf{R1})$$

$$\text{At anode: } 4OH^- \rightarrow O_2 + 2H_2O + 4e^- \quad (\mathbf{R2})$$

$$\text{Overall reaction: } 2H_2O \rightarrow 2H_2 + O_2 \quad (\mathbf{R3})$$

An external voltage EΔG of one volt (i.e., E° anode minus E° cathode) is required to overcome the potential difference between the electrodes. They refer to this VoltageVoltage as the reversible or equilibrium cell voltage. Here is the equation for the open cell's equilibrium voltage, EΔG, at 25 °C and 1 atm:

$$E_{\Delta G} = \frac{-\Delta G^o}{nF} \quad (\mathbf{1})$$

When ΔG^o= 237.2 KJ/mol.k, F = 96485 °C/mol. Conversely, we provide the equilibrium cell voltage for a closed-cell EA operating at a steady temperature with minimal volume change. The Helmholtz free energy ΔA fluctuates, and EΔA represents this fluctuation as follows:

$$E_{\Delta A} = \frac{-\Delta A^o}{nF} \quad (\mathbf{2})$$

This means that $\Delta A^o = -\Delta H^o$ - TRΔN. The absolute temperature, N number of moles of gas, universal gas constant, H entropy, and δ heating know that the standard enthalpy of electrolysis with one mole of liquid water is 2285.8 kJ/mol.K. This is because ($\Delta S^o H_2$ = 130.6 J/mol.K), ($\Delta S^o O_2$ = 205.1 J/mol.K), ($\Delta S^o H_2O$ = 70 J/mol.K), (ΔS^ototal = 163.14 J/mol.K), and (ΔA^o = 233.1 kJ/mol.K).

Based on the calculations, the minimum voltage needed for electrolysis in a closed cell is 1.23 V. In contrast, 1.21 V. Additional voltage is required in an open cell to sustain the electrochemical process. Cell overpotential occurs when the applied voltage exceeds its equilibrium potential. Tables [18–20]. Low overpotential levels are necessary for endothermic electrolysis.

There is a limiting voltage, sometimes called the thermoneutral voltage. Exothermic electrolysis occurs when the overpotential is raised. As the electrolyte temperature increases, the equilibrium voltage falls, and the thermoneutral voltage marginally rises, as seen in Fig. 1. Most of the time, the partial molar enthalpies of the individual variables can represent the thermoneutral voltage. According to [21], the components' partial molar enthalpies ($\breve{H}$) can represent the thermoneutral voltage under normal circumstances.

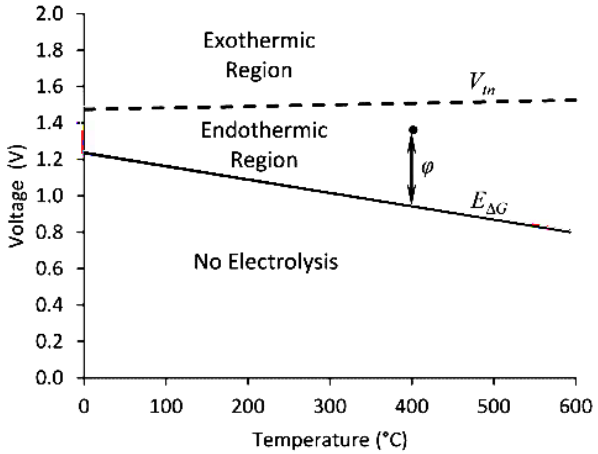

Figure 1. Electrolysis zones and temperature-dependent changes in cell potential [20].

Fig. 2 shows that the total cell overpotential and the number of different types rise with increasing current density [22]. This shows that overpotentials (HER) and (OER) are identified as the main obstacles to the electrochemical process. Aside from bubble, membrane, and ion resistance, ohmic losses also play a significant role in the overpotential.

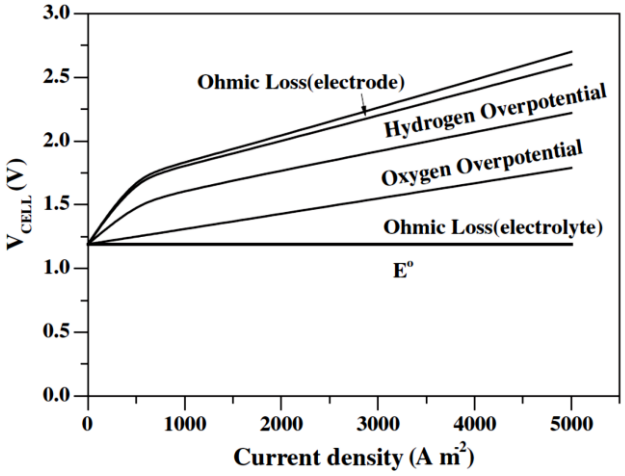

Figure 2. Variation of Overpotential with Current Density [20]

$$\boldsymbol{V_{tn} = \frac{1}{nF}\left[\left(\tilde{H}^{o}{}_{H2} + 0.5\tilde{H}^{o}{}_{O2} - \tilde{H}_{H2O(l)}\right) + \emptyset\left(\tilde{H}_{H2O(g)} - \tilde{H}_{H2O(l)}\right) + (1+\emptyset)(\tilde{H}_{t} - \tilde{H}_{25})_{H2O(l)}\right]} \quad \textbf{(3)}$$

Where p is the pressure, t is the temperature in degrees Celsius, l is the liquid, g is the gas, and ∅= 1:5p_w/(ppw). The following section includes additional voltage levels that help illuminate the thermodynamics of electrolysis: The enthalpic voltage is abbreviated as Vt,p [21]—the voltage changes as the electrolyzed water's molar enthalpy changes.

$$V_{t.p} = \frac{\Delta\tilde{H}_{t.p}}{nF} \quad \textbf{(4)}$$

The negative of the enthalpy of the production of liquid water at time t and pressure p is denoted as ΔH ٹ.p. Voltage Voltage with a higher heating value (VHHV) [20, 21, 23] indicates: Another way to put it is as the voltage needed to heat the reaction water from 25 °C to t °C in order to generate one mole of hydrogen.

$$V_{HHV} = \{\Delta\widetilde{H}_{t.p} - [H^{o}{}_{25}]_{w(l)}/nF\} \ (\mathbf{5})$$

Where

$$V_{HHV} = V^{O}{}_{t.p} + (\widetilde{H}^{O}{}_{t} - \widetilde{H}^{O}{}_{25})/nF \ (\mathbf{6})$$

It is common for the thermoneutral voltage and the voltage associated with the more excellent heating value to converge at high working pressures because the electrolyzer maintains a constant temperature. Vacuum is required to maintain thermal equilibrium (Vtb) [21]. The electrolyzer maintains a constant temperature (t °C) by applying a voltage equal to its thermal balancing voltage. When added to the thermos neutral voltage, the thermal balancing (V) voltage compensates for heat losses caused by convection and radiation.

$$V_{tb} = V_{tn} + V_{rad} + V_{conv} \quad (\mathbf{7})$$

1.1.2. The following illustrates how convection and radiation cause heat transfer:

$$P_{rad} = A_{\varepsilon\sigma}(T^4 - T^4{}_a) \quad (\mathbf{8})$$

$$P_{conv} = 1.77A(T - T_a)^{1.25} \quad (\mathbf{9})$$

Because of radiation and convection, the thermal balancing voltage is not a state function like the thermoneutral, enthalpic, and more excellent heating value (V) voltages.

1.1.3. Cell efficiency

One can utilize one of several indices to characterize electrolysis efficiency. The percentage of the total applied voltage used for electrolysis is known as voltage efficiency [20, 24].

$$\boldsymbol{\mu_{Voltage}} = \frac{(\boldsymbol{E_{anode} - E_{cathode}})}{\boldsymbol{V_{cell}}} \quad (\mathbf{10})$$

The thermal and faradic efficiencies of electrolysis were calculated by adding up the energy losses from the process and the theoretical energy requirements, which we represented as changes in enthalpy and Gibbs free energy, respectively.

$$\boldsymbol{\mu_{Faradic}} = \frac{\Delta G}{\Delta G + Losses} = \frac{E_{\Delta G}}{V_{cell}} \quad \mathbf{(11)}$$

$$\boldsymbol{\mu_{Thermal}} = \frac{\Delta H}{\Delta G + Losses} = \frac{V_{tn}}{V_{cell}} \quad (\mathbf{12})$$

Using faradic efficiency, one can represent the theoretical voltage required to divide water molecules by a proportion of the supplied voltage. The requirement for extra energy to sustain the electrolyzer's thermal equilibrium is the foundation of thermal efficiency. One way to think about it is the input-to-output energy ratio. Endothermic electrolysis can absorb heat from its surroundings and generate more energy than it receives, demonstrating a thermal efficiency that approaches 100%. Nevertheless, Faradic efficiency is at most 100%. Equations (10) and (11), when applied to efficiencies at ambient temperature.

$$\boldsymbol{\mu_{Faradic}}(\mathbf{25^{o}c}) = \frac{\mathbf{1.23\ (V)}}{\boldsymbol{V_{cell}}} \quad (\mathbf{13})$$

$$\boldsymbol{\mu_{thermal}}(\mathbf{25^{o}c}) = \frac{\mathbf{1.48\ (V)}}{\boldsymbol{V_{cell}}} \quad (\mathbf{14})$$

Another option for determining the water electrolysis system's efficiency is to link the electrical energy input with the energy content of the created hydrogen.

$$\boldsymbol{\mu_{H_2}} = \frac{\dot{\boldsymbol{E}}_{\boldsymbol{H_2}}}{\dot{\boldsymbol{E}}_{\boldsymbol{el}}} = \frac{\dot{\boldsymbol{N}}_{\boldsymbol{H_2}} * \mathbf{2.84} * \mathbf{10^5}}{\boldsymbol{Vi}} \ (\mathbf{15})$$

Meanwhile, with 2.84 * 10^5J/mol, hydrogen has a higher heating value. Here is another popular energy-based definition of efficiency:

$$\mu_{net\ effciency} = 1 - \frac{E_{loss}}{E_{input}} \quad (16)$$

When energy losses are determined using an electrical analogy technique, bubbles, ions, membranes, the overpotential of H_2 and O_2, and an external circuit's resistance [28], as previously said, there are two approaches to improving electrolysis's efficiency: (a) reducing losses and (b) utilizing thermodynamic strategies to minimize the process energy requirements, such as raising pressure and temperature.

2.Properties of HHO

Figure. 3 illustrates several valuable hydrogen features, making it a potential alternative to traditional fuels [25, 26].

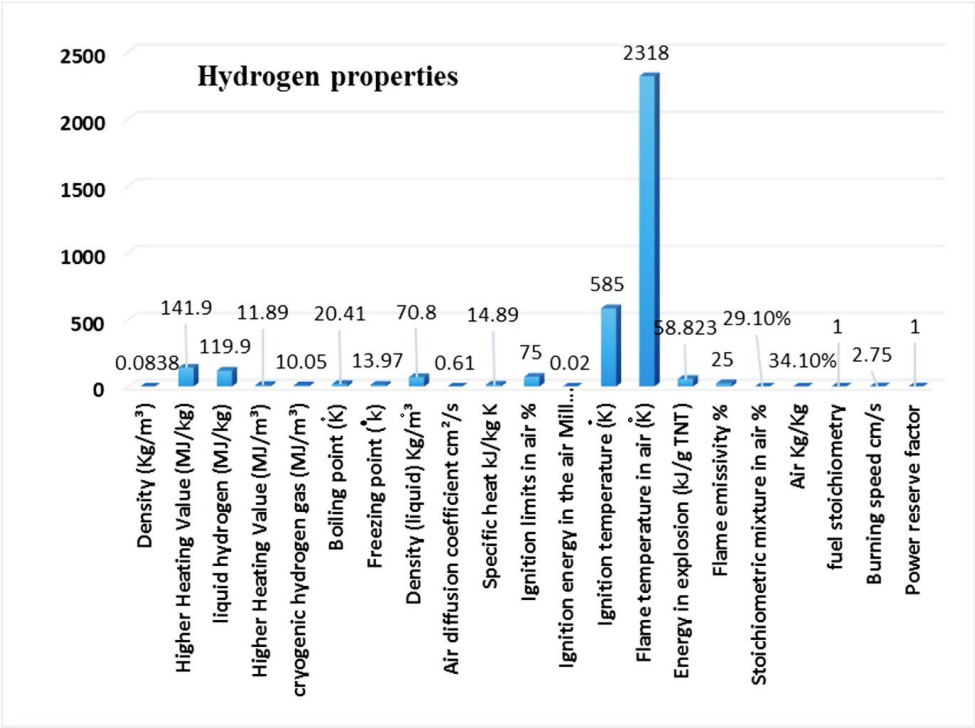

Figure 3. Hydrogen properties.

Electrolyzing a water-diluted electrolyte solution is a common method for producing HHO, as mentioned in Section Introduction [27]. Both the cathode and the anode contribute to producing gases containing HHO. Eqs. (R1-R3) show that the chemical reactions result in their production in stoichiometric proportions. Brown [29] covered hydrogen peroxide gas, an electrolysis byproduct, in welding. Here are two ideas on electrolytic cells. For the initial occurrence, two flat electrodes were immersed in a solution consisting of potassium hydroxide and water. Increasing the pH of water enhances its electrical conductivity. The stability and applicability of KOH make it a preferred metallic component over $NaHCO_3$. However, be careful when handling KOH because it is toxic and acidic [30].

The second concept used many electrodes to construct many series of cells [29]. The amount of power needed was lower than in the first plan. Brown also used a flashback arrester to prevent the burner flame from returning to the electrolytic cell. He suggested switching to direct current from alternating power because of its reduced electrical impedance. [29].

1- One, HHO, can be produced by the water electrolysis process either aboard or at the site using a wet or dry-cell electrolyzer.

2- The concentration of the electrolyte solution on the potential, the impact of temperature and time on the production rate, the quantity of energy required, the number of modules or units, and other factors all play a role in hydroxy gas generation.
3- As shown in Tables 1 and 2, potassium hydroxide and sodium hydroxide are three of the most common electrolytes for producing a large amount of HHO.
4- The selection of SS316L as the electrode material was based on its characteristics suitable for generating HHO.
5- More evidence suggests that current density affects the production of HHO.

Tables 1 and 2 below [31, 32, 33] list the critical findings from the aforementioned experimental studies.

2.1. Generating Device Type

2.1.1. Class of Dry Cell

The HHO dry cell generator utilizes a vacuum to segregate a series of electrodes, enabling the gas and water generated during electrolysis to flow through. Three types of HHO dry cells exist: alpha, beta, and omega.

2.1.2. Class of Wet Cells

The HHO generator produces hydrogen gas by immersing each electrode in an electrolyte solution within a water container in a wet cell. Fig. 4 illustrates the advantages and disadvantages of dry HHO fuel cells.

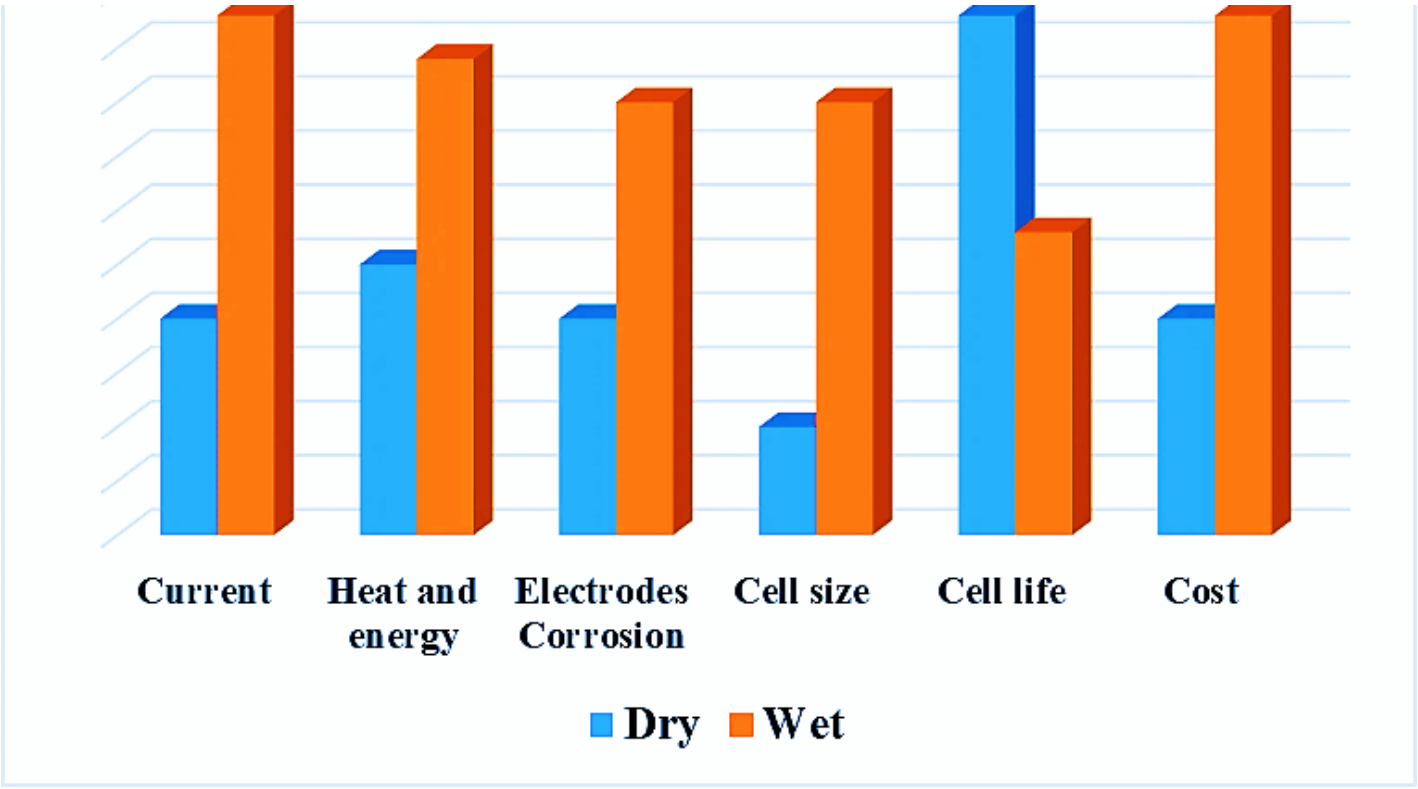

Figure 4. compares the benefits and drawbacks of dry HHO and wet HHO.

Table 1. Configuration of dry HHO gas generators

Gollei [40]	Mustafi et al. [39]		Baltacioglu [38]	Conker [37]	Yilmaz et al. [36]	Sakhrieh et al. [35]	Nabil et al. [34]			Ref.
Type of Dry										
SS 316L										Material
6	9	9	13	13	2-5- 8	4 3	19	13	5	Number Of Plates
5	8	8	NON	NON	NON	4 2	6	6	4	Number Of Cells
1	2	1	NON	NON	NON	NON	3	2	1	Number Of Stacks
NON	50mm	10mm	NON	NON	4mm	NON	3mm	3mm	3mm	Spacing
NON	150mm* 100mm* 1mm	150mm*100mm* 1mm	NON	NON	100mm* 100mm* 1mm	NON	140 mm * 100 mm * 1 mm	140mm * 100mm * 1mm	140mm* 100mm* 1mm	Dimensions
NON	NON	NON	NaOH	NaOH	Tap Water	KOH	NaOH	NaOH	NaOH	Salt
1-10 g/L	0.5%–1% by	0.5%–1% by mH_2O	10% by mH_2O	15% by mH_2O	NON	NON	0.125 M	0.125 M	0.125 M	Concentra-tion
5v-15v	12v	12v	5v	NON	NON	12v-14v	12 v	12 v	12 v	Voltage
5A-40A	15A-18A	07A-10A	2A-15A	60A	5.3A	40A-120A	5.6A-5.9A	4.8A-5.1A	4.2A-4.4A	Current
10.8w-103.2w	180w-216w	84w-120w	10w-75w	NON	NON	480w-1680w	67.2w-70.8w	57.6w-61.2w	50.4w-52.8w	Power
0.2-2.2	0.1	0.1	0.1-1.6	NON	NON	1.4 - 3	0.6	0.5	0.2	LPM

Manu et al. [47]	Badr et al.[46]	Ismail et al. [45]	U can et al. [44]	Kassaby et al. [43]	Barna and Lelea [42]	Essuman et al. [41]
N /A	21	10	24	16	11	26
NON	NON	NON	NON	3	5	5
NON	NON	NON	2	5	2	5
2mm,3mm	0.2mm	2mm	2mm	NON	3mm	2mm
NON	A150mm*70mm*0.8mm	90mm*90mm*1mm, 100mm*100mm*1mm, 110mm*110mm*1mm	165mm*165mm*1mm	160mm * 200mm * 20mm	140mm *185mm*1mm	100mm*100mm
NaOH KOH	NON	NaOH KOH	KOH	NaOH KOH	NaOH	NON
20–30% by mH_2O	NON	NON	NON	4 g/L Na OH	28% by mH_2O	NON
NON	NON	NON	35v	NON	13.6v	13v
NON	NON	NON	0A-60A	NON	15A	NON
NON	NON	NON	0w-2100w	NON	204w	NON
1	NON	NON	0-4.7	0.3 Max.	1	0.1-0.3

Table 2. Configuration of wet HHO gas generators.

Ismail et al. [25]	Thangaraj and Govindan [18]	Gohar and Hassan [55]	Mustafi et al. [54]	Bow et al. [53]	Prasetya [52]	Munther [51]	Karthik [50]	Choodum et al. [49]	Alam and Pandey [48]	Ref.
Type of Wet										
SS 316 L										Material
10	8	29	3	42	NON	10	2	2	NON	Number Of Plates
NON	NON	NON	1	NON	NON	1	NON	1	NON	Number Of Cells
NON	NON	1	2	6	NON	9	NON	1	NON	Number Of Stacks
2	NON	NON	NON	NON	NON	2, 3	NON	1,3,5,7,9	NON	Spacing
120 * 120 * 1	95.3 * 25.4 * 1.2	115 * 70 * 2	150 *100	110 * 60	150 * 150	170 * 150 * 1	115 * 70 * 2	30 * 20 * 2	155 * 50 * 1	Dimensions
NaOH	NaHCO3	KOH	KOH	NaOH	$Ba(OH)_2$	KOH	KOH	KOH	KOH	Salt
40 g/L	.2% by mH_2O	1% by mH_2O	1% by mH_2O	NON	1,3,5,7,9 g/L	0.7 g/L	1%	0.5%–1.5% by mH_2O	0.1 M	Concentration
13.8	12	12	12	12	NON	12	NON	52.9	03-10	Voltage
6	10	14.1	15-18	5-15	NON	13	NON	20-70	2	Current
NON	120	169.1	180-216	60-180	NON	156	NON	1050-3703	6-20	Power
705	NON	5	6-60	0.2-0.9	NON	0.2	NON	0.1	0.1	LPM

3.Electrolytic cell building and first electrode selection testing

The hydrogen production reactor is a square, dry-type acrylic electrolysis cell with a usable volume of approximately 49 cm^2. To provide continuous ionic contact between the anode and cathode areas, the height of the plate and electrodes is kept lower than the overall height of the reactor. Due to the open nature of the bottom and top of the reactor, ions and an electric current can move. Can flow between the electrodes. The lid had a small aperture to facilitate the ingress and egress of the gas produced in the anode and cathode regions. Fig. 5 depicts the analytical cell schematically.

Figure 5. The HHO dry cell generator

A plate with a length of 60 mm is employed to provide a physical barrier between the electrodes. A 60 mm long and 60 mm broad clearance was incorporated at the bottom and top of the separator plate to enhance ion exchange between the electrodes and facilitate the evacuation of ions from the top. When oxygen and hydrogen combine, they generate a mixture. The gaskets created a square region measuring 60*60 mm^2 between the positive, negative, and neutral plates, establishing a connection between the strips and the reactor wall. A portion of it remained outside the reactor to develop a connection with electrical cables. The electrode's prongs were circular. The process involves collecting hydrogen and oxygen gases from the electrolysis cell and placing them in a see-through measurement cylinder Fig. 6.

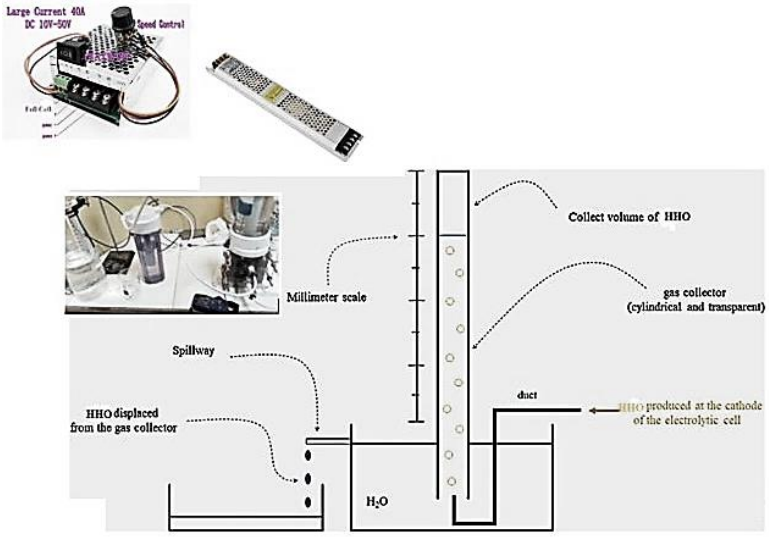

Figure 6. A schematic depicting the volumetric flow rate of HHO

The exterior of the glass cylinder is affixed with a 1mm precision-graded axial scale, which is used to monitor the quantity of water displaced. Measure the gas volume in the cylinder once the trials have concluded. The average volumetric flow rate of the gas was calculated by integrating the experimental volume and time measurements. It

generates hydrogen by utilizing corrosion-resistant 316 stainless steel. Potassium hydroxide solution is recommended as an electrolyte due to its low cost, high electrical conductivity, and absence of reactive ions at the electrode interface. It is effective at concentrations ranging from 5 to 25 g/L. The experimental setup directly connected the electrolytic cell to a DC voltage source and electrolyte. This setup allowed for manual voltage control, pulse width modulation (PWM), and voltage monitoring. The output range for current was 0-16 ± 0.01 A, while the output range for voltage was 0-12 ± 0.1 V. All experiments are conducted under standard room temperature and pressure conditions.

4. Experimental study

Two distinct methods of control were evaluated in this research. In the first method, a power supply of 12 volts is utilized. A constant voltage variation varies the amperage of the current. This method monitors the HHO generators' temperature to prevent overheating when a fixed load value is enabled. Manual control or operation suggests that the system shut down for cooling when an over-temperature is achieved. So, the system is run for a specific amount of time, which includes producing hydrogen and cooling it down as the temperature rises. Part two of the experiment involved controlling the HHO-generating system with pulse width modulation. This method runs the system at maximum capacity while taking all the precautions to prevent overheating. The PWM controller manages the HHO reactor's power input. Reactor temperature and produced hydrogen are the parameters defined as inputs to the pulse width modulation controller. A flow meter is used to measure the amount of hydrogen gas that is created. No matter whichever method is utilized to establish the control settings in the event of overheating, both control techniques utilize the same system setting. The second step was to cool the system down to stop heat from harming it. The HHO generator system, in contrast, runs without overheating because of the careful operation of the PWM-based controller. This means that the reactor never becomes hot enough to cause damage. Hydrogen is produced continually because the apparatus operates throughout the process. The system's operational temperature is maintained at T_{CO}.

5. Results and discussion.

5.1. The first- and second-case results from the HHO generator

Specifically, the KOH concentrations were changed at 5, 10, 15, 20, and 25 g/L to produce PWM. When the cell temperature remains at 50 °C, we often choose the optimal condition during the peak of HHO gas generation. The relationship between the electric current, cell temperature fluctuations, and HHO gas generation with and without PWM is depicted in Figures 9, 10, 13, and 14. Therefore, Case 2 is likely to improve compared with Case 1. The effect of time on temperature is shown in Figures 7 and 11, and the cell efficiency with applied amperage is shown in Figures 8 and 12. According to these results, the most effective amount of electrolyte is 15 g/L, and the optimum cell temperature is 48 °C, which is suitable for PWM. Case 1 also achieves its optimal results at a concentration of 15 g/L, as shown in Figures 9 and 10. The comparison of the system with and without PWM at a concentration of 15 g/L is shown in Figures 15, 16, 17, and 18. In all cases, the ideal cell voltage is about 2 volts, within the possible application range. If the cell converts the high voltage into thermal energy, it will generate excess heat and thus lose energy.

6. Plain Language Summary

Gas production optimization encompasses the various design and operational factors that increase the gas production rate. Two distinct HHO generator designs were evaluated and contrasted: one using PWM and the other without (cases 1 and 2, respectively).

- **not using pulse width modulation**

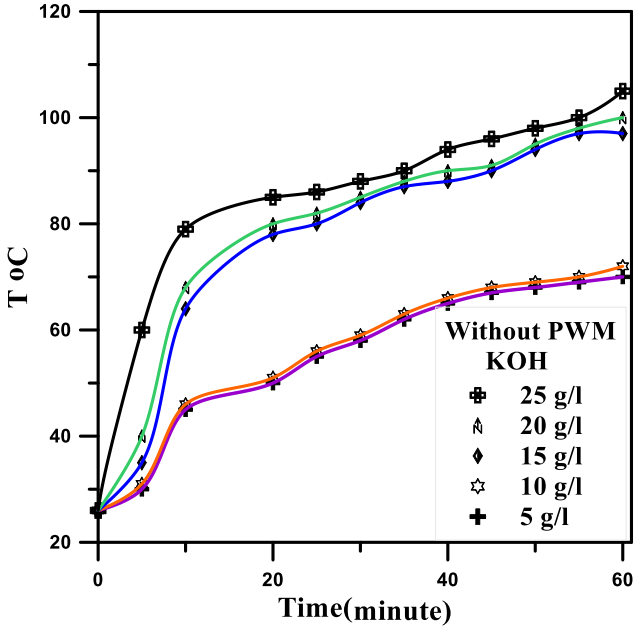

Figure 7. Influence of electrolyte temperature at different operating times and KOH concentrations on HHO gas production.

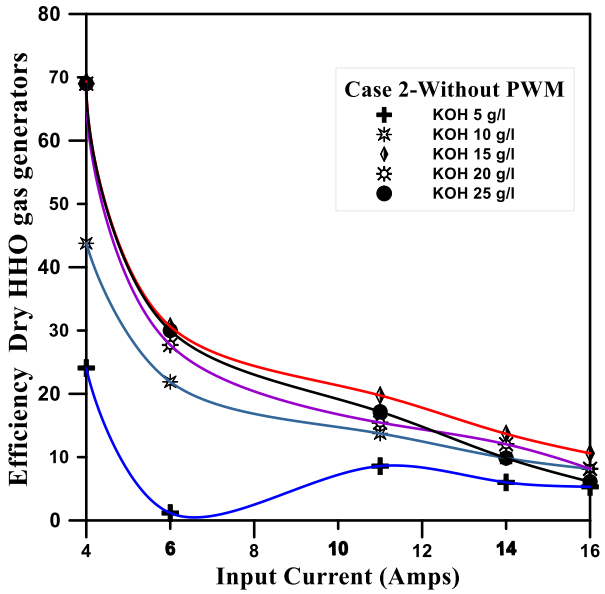

Figure 8. Efficiency as a function of current at varying KOH concentrations.

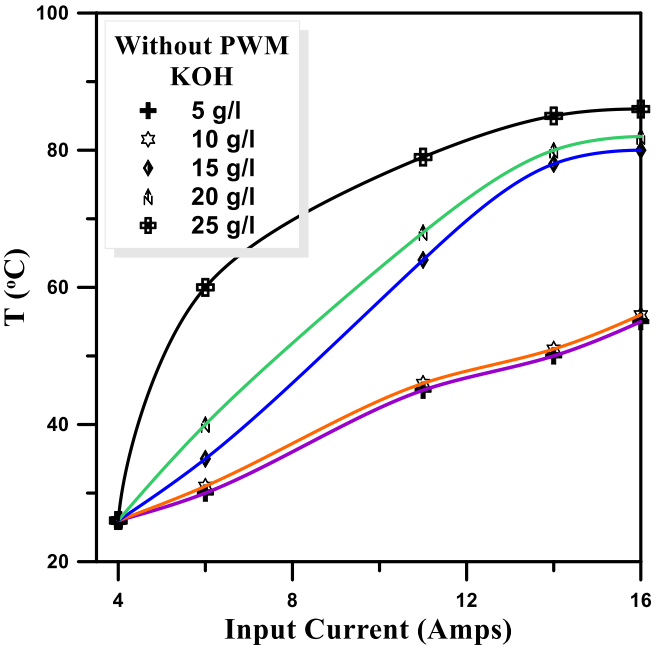

Figure 9. Influence of electrolyte temperature at different operating currents and KOH concentrations on HHO gas production.

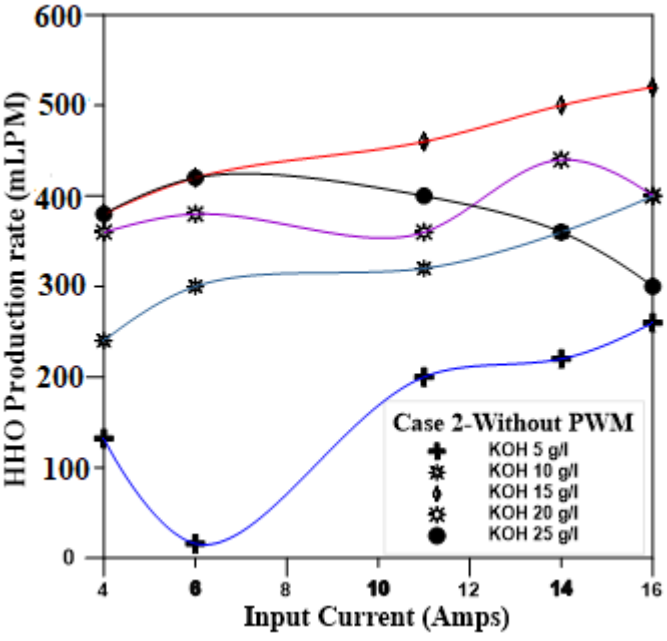

Figure 10. shows HHO gas productivity at different cell gaps, electrolyte currents, and KOH concentrations.

- **Using pulse width modulation**

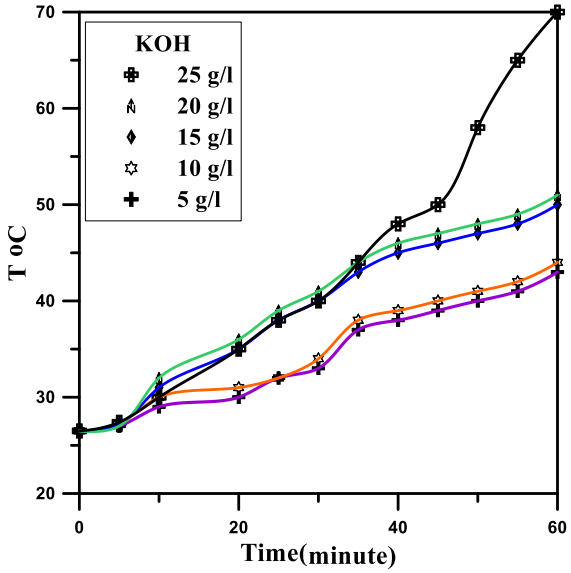

Figure 11. Influence of electrolyte temperature at different operating times and KOH concentrations on HHO gas production.

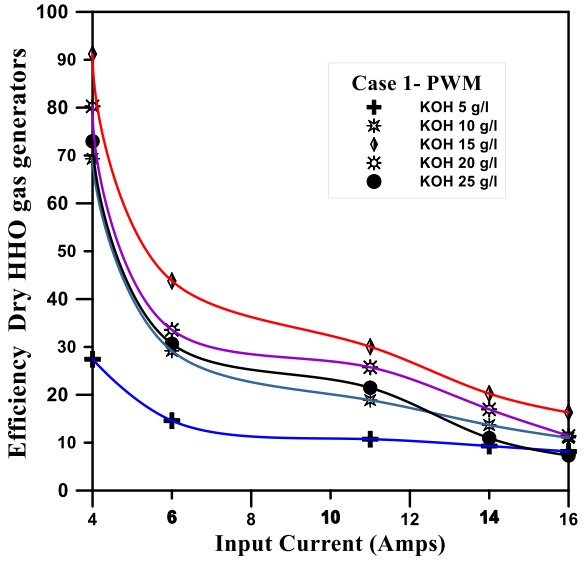

Figure 12. Efficiency as a function of current at varying KOH concentrations.

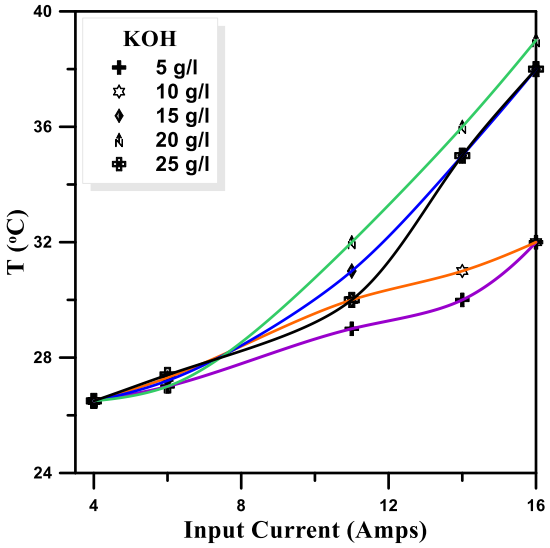

Figure 13. Influence of electrolyte temperature at different operating currents and KOH concentrations on HHO gas production.

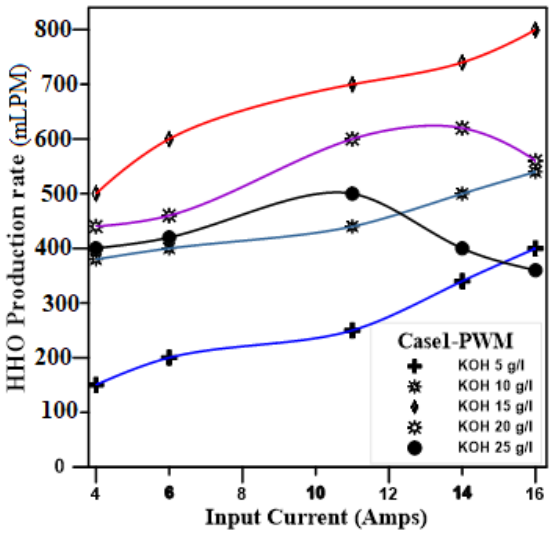

Figure 14. shows HHO gas productivity at different cell gaps, electrolyte currents, and KOH concentrations.

- **Comparison between the system incorporating additional pulse width modulation (PWM) and the system without additional PWM.**

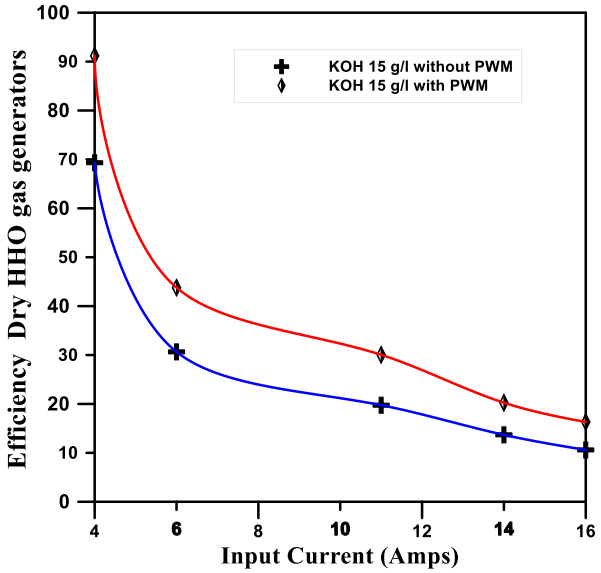

Figure 15. shows efficiency as a function of current at varying KOH concentrations.

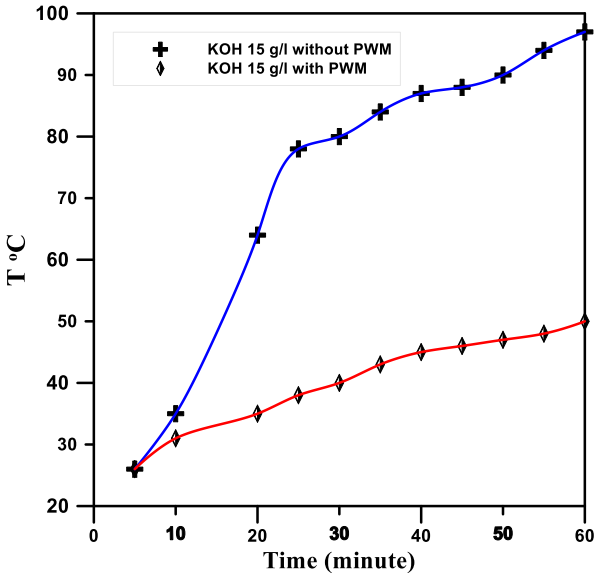

Figure 16. shows the influence of electrolyte temperature at different operating times and KOH concentrations on HHO gas production.

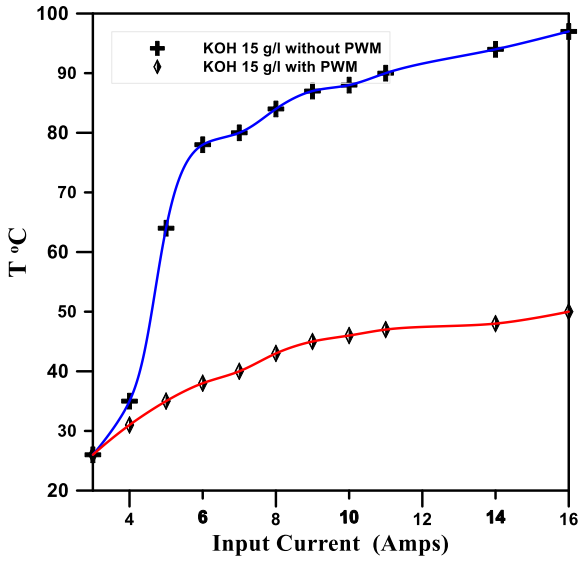

Figure 17. Influence of electrolyte temperature at different operating currents and KOH concentrations on HHO gas production.

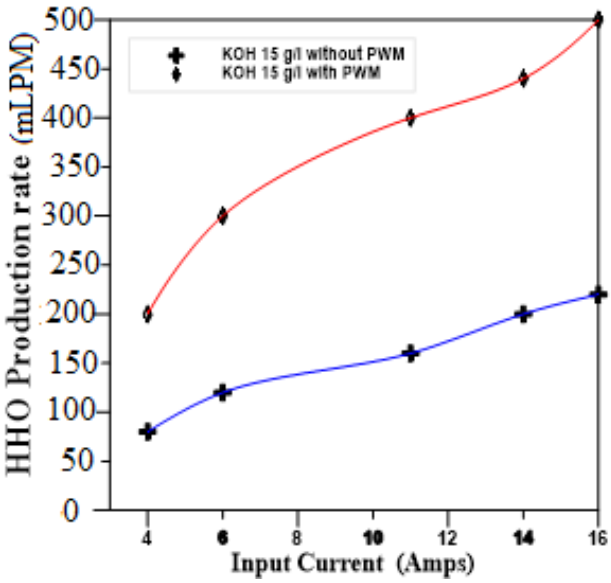

Figure 18. shows HHO gas productivity at different cell gaps, electrolyte currents, and KOH concentrations.

7. Conclusions

This study focuses on the controller's role in safeguarding the HHO generator against excessive temperatures while improving hydrogen production. Therefore, the system functions at its highest efficiency level while preserving the generator from thermal problems. Refers to the system that employs two separate control mecha-

nisms. The initial approach relies on predetermined control and load settings. When the system reaches its temperature limit, it automatically enters a cooling mode and shuts down under human control or operation. In the latter part of the experimental investigation, the PWM regulates the HHO-generating mechanism. This method optimizes system performance by operating at its highest capacity while maintaining the necessary parameters to prevent overheating. Employing PWM-based control to determine the continuous operating temperature improves the production capacity and resolves temperature issues. The proposed solution improves the system's functionality and mitigates thermal issues caused by existing control methods. Both conceptual and experimental support the proposed strategy. The results further demonstrate the efficacy of this strategy.

8. Nomenclature

Abbreviations		**N**	Number of gaseous moles
PWM	Pulse width modulation	ΔA^o	the absolute TemperatureTemperature
HHO	Hydroxy	**n**	No. of neutral plates per stack
Tco	Continuous operation temperature, °C	**NaOH**	Sodium hydroxide
H_2	Hydrogen	**H**	entropy, and enthalpy of the system.
DC	Direct current	**T**	Absolute temperature ^oC
KOH	Potassium hydroxide	$\mathbf{Q_{fuel}}$	Density of fuel (kg/m^2)
O_2	oxygen	**Symbols and Units**	
SS	Stainless steel	**KW**	Kilowatt
F	Faraday's constant	**kJ**	Kilojoule
V_{HHV}	enthalpic VoltageVoltage	**A**	Ampere (amp)
$\dot{N}_{H_2}$	The hydrogen generation rate (mol/s).	**I**	Electrical Current, A
ε	its emissivity	**V**	Electric Voltage
Ta	the ambient TemperatureTemperature	**Kg**	Kilogram
$E_{\Delta G}$	the variation in the electrochemical reaction's Gibbs free energy	**KWh**	Kilowatt-Hour
R	Universal gas constant	**HP**	Horsepower
		ºC	Degree Celsius
		L	Litter
		Cc	Cubic Centimetres

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❖ Author contributions

M. Gerwash, A. Alghonemy, M. A. Omara, Ibrahim Ahmed, and Gamal B. Abdelaziz contributed to proposing the research point, analyzing and discussing the results, and writing and reviewing the manuscript.

- Ethical Approval

  Not applicable.

- Competing interests, the authors declare that there is no conflict of interest relevant to the article.
- Data availability

  The datasets used and/or analysed during the current study available from the corresponding author on reasonable request

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