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Design of a Hydrogen Device for Cleaning Automotive Catalytic Converters

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Abstract

This project presents the design and development of an innovative hydrogen-based cleaning device for automotive catalytic converters. The system generates hydrogen gas through the electrolysis of distilled water and injects it into the engine's air intake, where it helps burn carbon deposits and restore catalytic efficiency.

The device operates safely at 12 V DC and is composed of titanium or stainless-steel plates separated by 3D-printed isolants. Several safety components, such as a bubbler, flame arrestor, temperature sensor, and cooling fan, ensure reliable operation. Prototype testing confirmed stable hydrogen production and safe performance, with only minor leakage due to fabrication tolerances.

This work demonstrates a clean, efficient, and cost-effective solution for reducing vehicle emissions and highlights the potential for green automotive technology development in Algeria.

Keywords: Cleaning, Cleaning automotive, Hydrogen cell, Hydrogen, engine, Catalytic converters

RÉSUMÉ

Ce projet présente la conception et le développement d'un dispositif innovant de nettoyage à base d'hydrogène destiné aux catalyseurs automobiles. Le système génère de l'hydrogène par électrolyse de l'eau distillée et l'injecte dans l'admission d'air du moteur, où il favorise la combustion des dépôts de carbone et restaure l'efficacité du catalyseur.

L'appareil fonctionne en toute sécurité sous 12 V CC, et se compose de plaques en titane ou en acier inoxydable, séparées par des isolants imprimés en 3D. Plusieurs dispositifs de sécurité, tels qu'un bubbler, un pare-flamme, un capteur de température et un ventilateur de refroidissement, garantissent un fonctionnement sûr et stable. Les tests du prototype ont confirmé une production d'hydrogène efficace et sécurisée, avec seulement de légères fuites dues aux tolérances de fabrication.

Ce travail démontre une solution propre, efficace et économique pour la réduction des émissions des véhicules, et souligne le potentiel de développement des technologies automobiles vertes en Algérie.

Mots-clés : Nettoyage, nettoyage automobile, cellule à hydrogène, hydrogène, moteur, convertisseurs catalytiques.

ملخص

يقدم هذا المشروع تصميم وتطوير جهاز مبتكر لتنظيف المحفزات في السيارات باستخدام الهيدروجين.
يعتمد النظام على تحليل الماء المقطر كهربائياً لإنتاج غاز الهيدروجين، ثم يحقن هذا الغاز في مدخل هواء المحرك حيث يساعد على حرق الترسبات الكربونية واستعادة كفاءة المحفز

يعمل الجهاز بأمان بجهد 12 فولت تيار مستمر، ويتكوّن من صفائح من التيتانيوم أو الفولاذ المقاوم للصدأ تفصل بينها عوازل مطبوعة ثلاثية الأبعاد بسماكة. كما يحتوي على عدة أنظمة أمان مثل مانع اللهب ومبخر الماء ومستشعر الحرارة ومروحة التبريد لضمان التشغيل المستقر والآمن

أظهرت اختبارات النموذج الأولي أداءً ثابتاً وإنتاجاً آمناً للهيدروجين مع تسربات بسيطة ناتجة عن تفاوت التصنيع. يبرهن هذا العمل على حل نظيف وفعال واقتصادي للحد من انبعاثات المركبات، ويبرز إمكانات تطوير التقنيات الخضراء في قطاع السيارات بالجزائر

الكلمات المفتاحية: التنظيف، تنظيف السيارات، خلية الهيدروجين، الهيدروجين، المحرك، المحولات الحفازة

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General Introduction

General Introduction

Over the past decades, the rapid growth of the global automotive fleet has profoundly transformed mobility and society. Yet, this progress has come at a significant environmental cost. Internal combustion engines (ICEs), which continue to dominate the transportation sector, are a major source of air pollutants such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx). These emissions contribute to urban smog, acid rain, and global warming, while also posing serious risks to human health [1], [2].

To mitigate these impacts, the automotive industry has progressively integrated catalytic converters into vehicle exhaust systems. These devices, based on precious metal catalysts such as platinum, palladium, and rhodium, enable the conversion of harmful gases into less toxic compounds, thus representing a cornerstone of emission-control strategies [3], [4]. However, catalytic converters are not immune to degradation. With time and use, they accumulate carbon residues and other deposits that block active catalytic sites. This fouling phenomenon leads to reduced efficiency, higher fuel consumption, and excessive pollutant emissions [5], [6]. In extreme cases, converters must be replaced, which represents a costly burden for vehicle owners and a sustainability challenge for the industry.

A range of cleaning and regeneration solutions has been developed in response. These include the use of chemical additives, ultrasonic cleaning, or mechanical regeneration. While each of these methods provides partial improvements, they are often limited by high cost, technical complexity, or environmental drawbacks [7], [8]. This context gives rise to a persistent question:

How can catalytic converters be cleaned efficiently, safely, and at a reasonable cost, without dismantling or replacing them?

Recent advances in hydrogen-based cleaning technologies offer a promising answer. Hydrogen, due to its low ignition energy and high flame velocity, improves combustion when introduced into the engine intake [9]. The presence of hydrogen promotes the oxidation of carbon deposits and soot, restoring the active surface of the catalytic converter and simultaneously improving engine performance [10], [11]. Unlike chemical additives, hydrogen cleaning does not rely on harmful substances, as the only required input is water for electrolysis [12].

This project is situated within this innovative framework. It aims to design and evaluate a compact hydrogen generator system capable of producing hydrogen on demand through water electrolysis. The system is conceived to be portable, safe, and cost-effective, making it particularly suitable for automotive workshops and garages. The approach integrates electrochemical design, mechanical conception, and safety engineering, while also considering the economic feasibility of deploying such devices on the local market.

The significance of this work is twofold. Scientifically, it contributes to the field of applied hydrogen technologies by demonstrating how controlled hydrogen injection can be adapted to catalytic converter regeneration. From an entrepreneurial perspective, it addresses a growing need in the automotive service sector for sustainable, low-cost maintenance solutions, and explores the potential for commercialization through a startup-oriented business model.

To meet these objectives, the report is structured as follows:

- Chapter I presents the scientific and technical background, reviewing the role and functioning of catalytic converters, the problem of fouling, existing regeneration methods, and the properties and applications of hydrogen.
- Chapter II describes the design of the hydrogen generator system, including electrolysis principles, component selection, safety measures, and control strategies.

- Chapter III focuses on prototyping and testing, with attention to the methodology, experimental validation, and performance evaluation.

Through this multidisciplinary approach, the project seeks to bridge scientific knowledge and practical innovation, with the dual ambition of advancing academic understanding and offering a tangible solution for cleaner, more sustainable vehicle maintenance.

Chapter I: Role and functioning of catalytic converters

Chapter I: Role and functioning of catalytic converters

1. **Function and Importance of the Automotive Catalytic Converter**

The catalytic converter is one of the most effective technologies developed to mitigate the environmental impact of internal combustion engines. It was first introduced commercially in the United States in the mid-1970s, following the enforcement of the Clean Air Act and the growing concern about air quality in urban centers [13], [2]. Since then, catalytic converters have become standard equipment in nearly all gasoline and diesel vehicles worldwide, forming the cornerstone of modern emission-control systems [5].



Figure 1.1 External View of a Catalytic Converter



Figure 1.2 Internal Structure of Catalytic Converter

The device is installed in the exhaust line, typically between the exhaust manifold and the muffler. Its role is to transform toxic combustion products into less harmful compounds before they are released into the atmosphere [3].

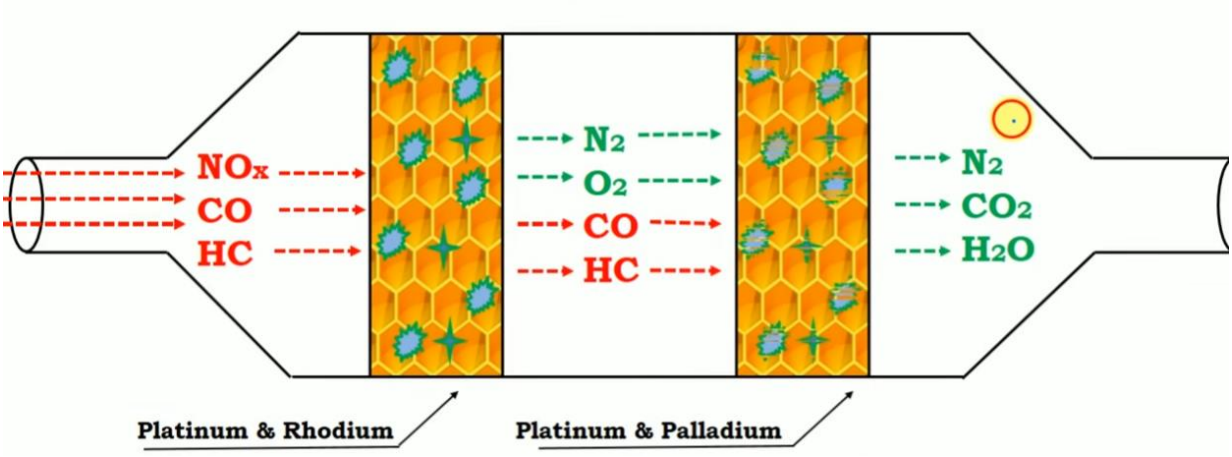


Figure 1.3 Schematic Representation of the Operation of a Three-Way Catalytic Converter

A modern catalytic converter consists of three essential elements:

- Substrate: a ceramic (cordierite) or metallic honeycomb structure with thousands of small channels, designed to maximize the contact area between the exhaust gases and the catalyst [14].

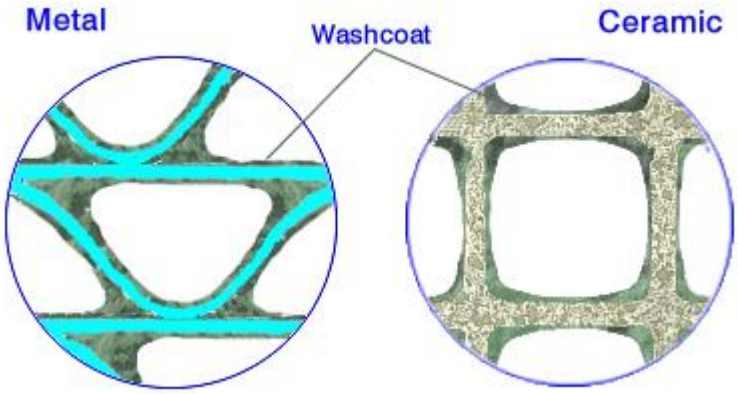


Figure 1.4 Metal Catalytic Converter Substdrate

- Wash coat: a porous layer (commonly γ-alumina) deposited on the substrate, which increases surface roughness and improves the dispersion of catalytic metals [15].

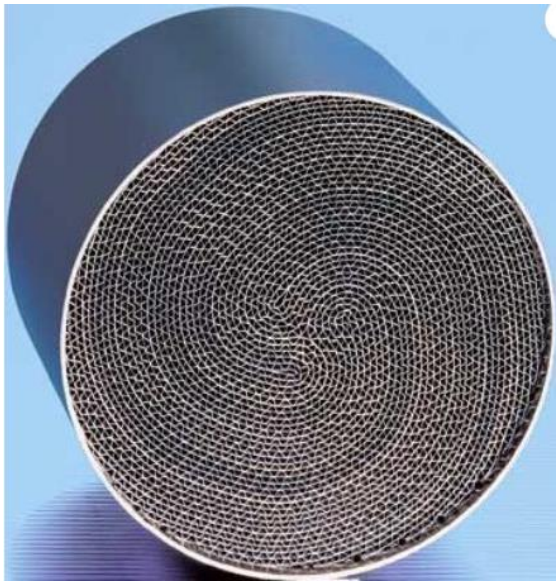


Figure 1.5 Wash coat in a Metal and Ceramic type

- Active catalytic materials: precious metals such as platinum (Pt), palladium (Pd), and rhodium (Rh), responsible for accelerating the conversion of pollutants through oxidation and reduction reactions [16].

When hot exhaust gases flow through this structure, three key reactions occur simultaneously:

- Oxidation of carbon monoxide (CO):

$$2CO + O_2 \rightarrow 2CO_2$$

Toxic carbon monoxide is converted into non-toxic carbon dioxide [17].

- Oxidation of hydrocarbons (HC):

$$C_xH_y + O_2 \rightarrow CO_2 + H_2O$$

Unburned hydrocarbons are oxidized into carbon dioxide and water vapor [18].

- Reduction of nitrogen oxides (NOx):

$$2NO_x \rightarrow N_2 + O_2$$

Harmful nitrogen oxides are reduced into nitrogen and oxygen [19].

This is why the modern automotive converter is called a three-way catalyst (TWC) [4].

2. Importance of the Catalytic Converter

The catalytic converter is a critical environmental technology for internal combustion engines. Under optimal operating conditions, it is capable of reducing up to 90% of CO, HC, and NOx emissions [6]. This significantly mitigates the negative environmental impact of vehicles, helping to reduce smog formation and acid rain.

From a public health perspective, catalytic converters reduce the concentration of toxic pollutants, lowering the incidence of respiratory and cardiovascular diseases linked to traffic emissions [20].

From a regulatory perspective, catalytic converters enable compliance with strict international standards such as the U.S. Environmental Protection Agency (EPA) regulations and the European Euro standards, without which conventional ICE vehicles could not legally operate [21], [2].

Finally, from a sustainability standpoint, catalytic converters extend the operational life of vehicles while allowing the automotive industry to balance technological and environmental goals [8].

In sum, the catalytic converter is not a simple exhaust component but a key enabling technology that ensures the continued use of internal combustion engines in line with environmental and public health objectives.

3. Causes of Fouling and Impacts on Engine/Environment

Catalytic converters are designed to operate effectively only when the active surface of the catalyst remains accessible to exhaust gases. Over time, however, they experience fouling and deactivation, which significantly reduces their efficiency [5].

Main Causes of Fouling:

1. Carbon Deposition (Soot Formation): Incomplete combustion of hydrocarbons in the engine produces soot particles, which accumulate on the surface of the catalyst and block active sites [8].
2. Oil-Derived Contaminants: Engine oil additives containing phosphorus, zinc, or calcium may enter the exhaust as combustion byproducts. These form stable compounds that chemically poison the catalyst [22].

3. Sulfur Compounds: Although modern fuels are low-sulfur, residual sulfur can still deactivate catalysts by forming sulfates on active metals such as platinum and palladium [18].
4. Thermal Aging: Prolonged exposure to high exhaust temperatures (>800 °C) leads to sintering of precious metal particles and collapse of the support surface area, reducing catalytic activity [23].
5. Fuel Additives and Impurities: Certain metal-containing additives (lead, manganese, iron) irreversibly poison catalysts, which was one of the main reasons for the global elimination of leaded gasoline [24].

Impacts on Engine and Environment:

- On Engine Performance: A fouled catalyst increases exhaust backpressure, reducing engine efficiency and increasing fuel consumption [6].
- On Emissions: Deactivated catalysts allow higher levels of CO, HC, and NOx emissions to escape into the atmosphere [2].
- On Durability and Cost: Persistent fouling often requires complete replacement of the catalytic converter, which is costly for consumers and contributes to resource consumption [21].

Thus, fouling not only reduces vehicle efficiency but also undermines the environmental role of the catalyst, making effective cleaning and regeneration strategies essential.

4. Existing Cleaning Technologies

To counter fouling, several cleaning and regeneration methods for catalytic converters have been developed. These can be grouped into chemical, mechanical, and physical approaches.

4.1 Chemical Cleaning

Chemical additives, typically poured into the fuel tank, are designed to pass through the engine and exhaust system to dissolve carbon and soot deposits [25].

- Advantages: Easy to apply, inexpensive, no disassembly required.
- Limitations: Efficiency is limited, especially for heavily fouled converters; some chemicals may leave harmful residues or damage the catalyst [26].

4.2 Mechanical Cleaning

This method involves removing the catalytic converter from the vehicle and cleaning it manually or by applying high-pressure air/water [27].

- Advantages: Effective in removing large soot deposits.
- Limitations: Labor-intensive, requires disassembly, risk of damaging fragile honeycomb structures.

4.3 Ultrasonic Cleaning

Catalysts are immersed in a liquid bath, and ultrasound waves are applied to generate cavitation bubbles that dislodge soot and deposits [28].

- Advantages: Non-destructive, highly effective in restoring flow through the honeycomb.
- Limitations: Requires specialized equipment and removal of the catalytic converter.

4.4 Thermal Regeneration

Also called "bake-out," this technique heats the catalytic converter to very high temperatures in controlled conditions to burn off carbon deposits [29].

- Advantages: Can restore catalyst activity if fouling is primarily carbon-based.
- Limitations: Risk of damaging the ceramic substrate; cannot remove chemical poisons (sulfur, phosphorus).

4.5 Hydrogen-Assisted Cleaning (Emerging)

More recently, hydrogen cleaning systems have been developed, where hydrogen gas is introduced into the engine intake, enhancing combustion and burning off deposits inside the engine and catalyst [10], [30].

- Advantages: No removal required, environmentally friendly (only water needed), effective for restoring catalytic activity.
- Limitations: Technology still emerging; long-term validation is ongoing.

Conventional methods (chemical, mechanical, ultrasonic, thermal) provide partial solutions but often require disassembly or have environmental drawbacks. Hydrogen-based cleaning appears as a promising alternative, combining efficiency, cost-effectiveness, and eco-friendliness and is the basis of the present project.

5. Introduction to Hydrogen

5.1 Properties

Hydrogen (H_2) is the lightest and most abundant element in the universe, representing nearly 75% of its elemental mass [31]. It exists naturally as a diatomic molecule and possesses unique physical and chemical properties that make it highly attractive as an energy carrier.

Physical and Chemical Properties:

- Atomic number: 1; Molecular weight: 2.016 g/mol.
- Density: 0.0899 g/L at standard temperature and pressure, making it the lightest gas [32].
- Ignition energy: ~0.02 mJ, significantly lower than gasoline (~0.24 mJ), which allows for easy ignition [9].
- Flame speed: Approximately 2.9 m/s, almost an order of magnitude higher than methane (0.4 m/s), enabling rapid combustion [33].

- Wide flammability range: 4–75% in air, compared to gasoline vapors (1–7%), making it versatile in combustion applications [34].
- Clean combustion: Produces only water vapor when burned in pure form.

These properties make hydrogen particularly suitable for enhancing combustion in internal combustion engines and for reducing carbon-based emissions.

5.2 Applications of Hydrogen

Hydrogen has been investigated and applied in a wide range of sectors:

- Energy Storage and Fuel Cells: Hydrogen is used in proton exchange membrane (PEM) fuel cells to generate electricity, as demonstrated in automotive applications like fuel cell electric vehicles (FCEVs) [35].
- Industrial Applications: It plays a central role in ammonia synthesis (Haber-Bosch process), petroleum refining, and methanol production [36].
- Aerospace and Mobility: NASA has used hydrogen fuel cells since the 1960s for electricity and drinking water supply during space missions [37].
- Automotive Internal Combustion Engines: Hydrogen enrichment in gasoline and diesel engines improves combustion stability, reduces emissions, and increases engine efficiency [11], [38].
- Environmental Technologies: More recently, hydrogen has been applied in engine cleaning and catalyst regeneration technologies as a safe and eco-friendly alternative to chemicals [30].

5.3 Advantages of Hydrogen for Cleaning (Decarbonization)

The use of hydrogen for engine and catalyst cleaning is based on its unique combustion characteristics and its ability to eliminate carbon deposits without damaging engine components.

Key Advantages:

- Enhanced Combustion Efficiency: The high flame speed and wide flammability range of hydrogen promote more complete combustion, which in turn reduces unburned hydrocarbons and soot formation [10].
- Decarbonization of Engine and Catalyst Surfaces: When hydrogen-enriched combustion occurs, localized high temperatures and reactive radicals oxidize existing carbon deposits in the combustion chamber, exhaust pipes, and catalytic converter [39].
- Environmentally Friendly Process: Hydrogen cleaning relies only on water electrolysis as a source of H_2 and O_2, avoiding toxic solvents or chemical additives. The only by-products are water vapor and small amounts of CO_2 from carbon oxidation [12].
- Restoration of Catalyst: Efficiency Hydrogen-assisted cleaning re-exposes catalytic active sites (Pt, Pd, Rh) blocked by soot, restoring their capacity to convert CO, HC, and NOx emissions [6].
- Cost-Effectiveness: Compared to replacing a catalytic converter, hydrogen cleaning provides a low-cost maintenance solution, extending the lifetime of engine and catalyst components [40].

Hydrogen is not only a potential clean fuel of the future, but also a practical maintenance tool for today's vehicles. Its properties allow for efficient combustion enhancement and effective decarbonization, making it a key enabler for environmentally friendly automotive technologies.

Chapter II: Design of the Hydrogen Device

Chapter II: Design of the Hydrogen Device

1. Choice of Principle: Water Electrolysis

Hydrogen can be produced through a variety of methods, including steam methane reforming, gasification of hydrocarbons, chemical hydrides, and electrolysis of water. While reforming processes are dominant in large-scale industrial hydrogen production, they are unsuitable for small-scale or mobile applications due to the complexity of equipment, CO_2 emissions, and safety concerns associated with handling hydrocarbons [41]. Similarly, the use of compressed hydrogen cylinders or metal hydrides introduces logistical challenges and risks related to high-pressure storage and transport [12].

For this project, water electrolysis was selected as the most appropriate principle of hydrogen generation. Electrolysis enables the on-demand production of hydrogen and oxygen gases (HHO) directly from distilled water with the assistance of an alkaline electrolyte. The fundamental reaction is:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

At the cathode, water is reduced to hydrogen gas:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

At the anode, water is oxidized to oxygen gas:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

This choice presents several key advantages:

- Safety: No hydrogen storage is required; gas is produced only when the system is powered, thus reducing explosion risks [9].
- Simplicity: Electrolysis cells can be compactly designed using readily available materials such as stainless steel or titanium plates.
- Eco-friendliness: The only resource required is water, making the process sustainable and clean [34].
- Adaptability: The gas flow rate can be tuned by adjusting current and voltage, enabling the device to match the needs of different engine sizes.

Therefore, electrolysis is not only scientifically robust but also practically suitable for a portable, workshop-ready hydrogen cleaning system.

2. Dimensioning of Components

The hydrogen cleaning device was designed with the dual objective of portability and efficiency, while ensuring robustness and safety. Dimensioning of the major subsystems was carried out to balance hydrogen output requirements, operational autonomy, and compactness of the overall unit.

2.1 Chassis (Housing)

The chassis serves as the structural frame holding the electrolysis cell, reservoir, safety systems, and control units. Its design must ensure stability, portability, and thermal resistance.

- Dimensions: Height 40–50 cm, Width 30–40 cm, Depth 20–30 cm.
- Weight: Approximately 5–10 kg, depending on material thickness and component integration.

- Material: Stainless steel or aluminum, chosen for corrosion resistance, heat tolerance, and mechanical durability [42].

These dimensions were selected to achieve compactness for garage/mobile use while maintaining sufficient internal space for integrating all components.

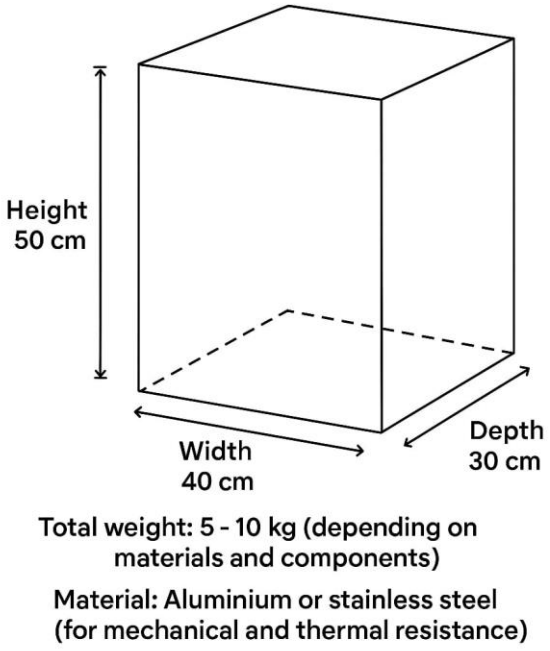


Figure 2.1 Chassis dimensions and expected look

2.2 Electrolysis System

At the heart of the device is the electrolysis stack, which determines hydrogen production capacity.

- **Electrodes:**
  - Material: Stainless steel 316L (common, affordable, corrosion-resistant) or Titanium (superior durability, but higher cost).
  - Dimensions: 15 cm × 15 cm each plate.
  - Plate spacing: 3 mm, optimized to minimize resistance and maximize surface area contact.
  - Number of plates: 9, depending on desired gas output (scalable design).
  - Hole families (Ø in cm): Ø = 0.6 (mounting/rods), Ø = 1.0 (process ports and main header)

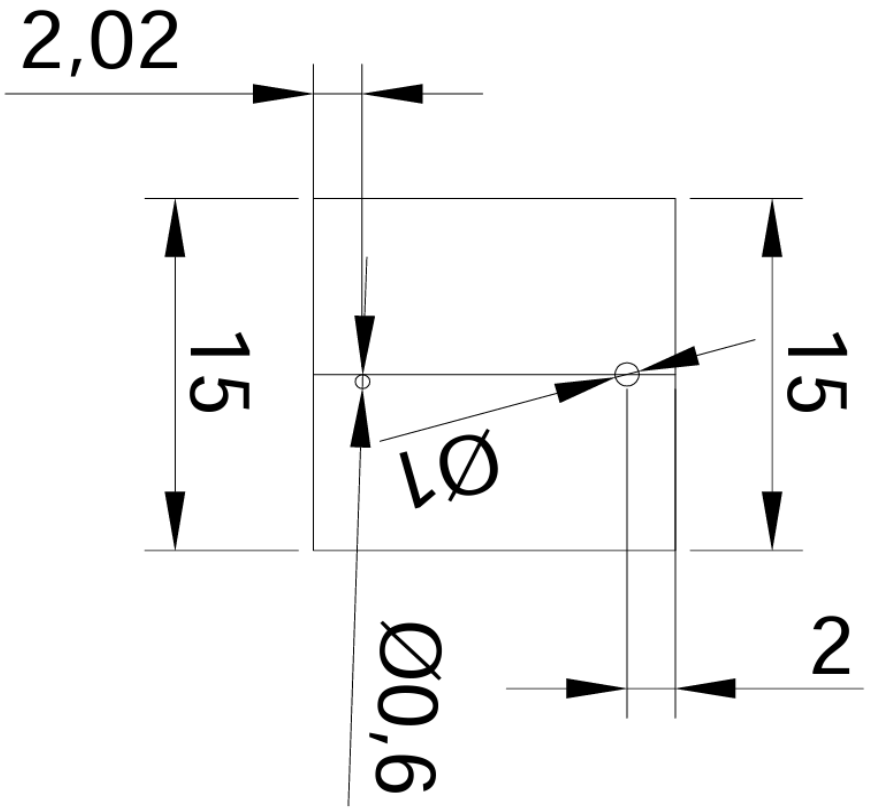


Figure 2.2 Neutral plate dimensions

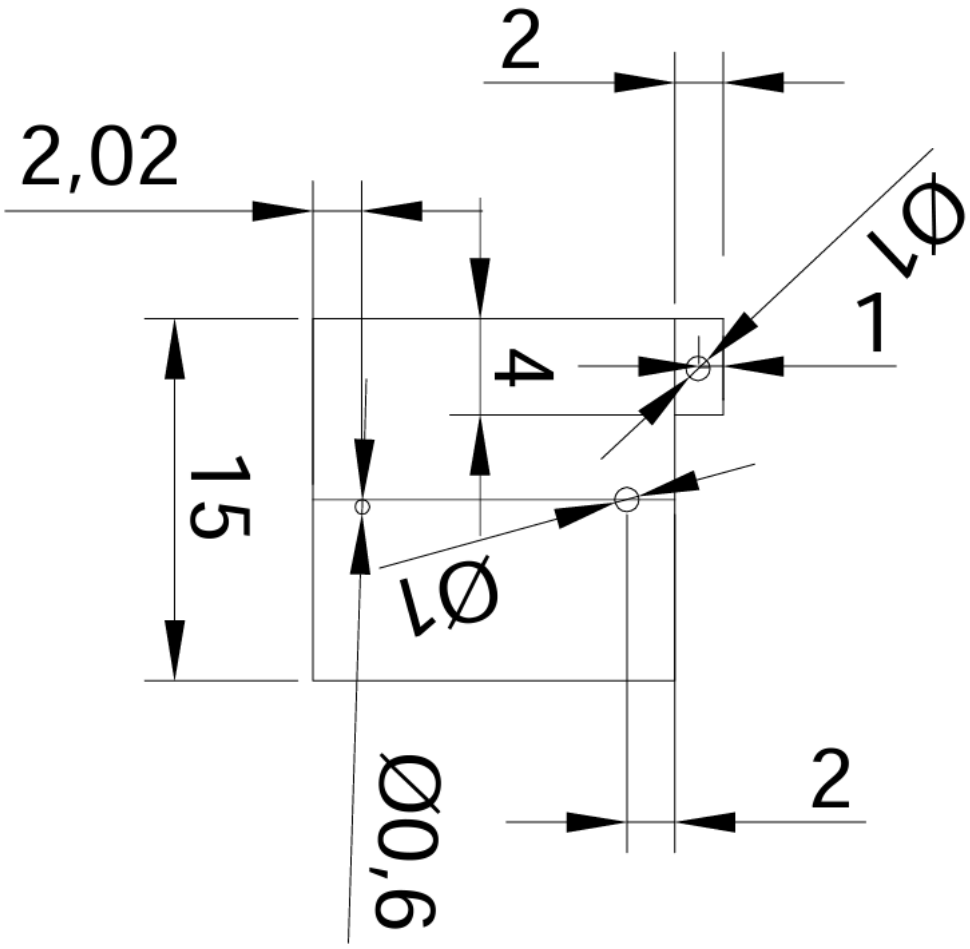


Figure 2.3 Negative plate (positive plate doesn't have holes in the middle) dimensions

- **Reservoir:**
  - Volume: 1–2 liters of distilled water.
  - Material: Heat-resistant plastic or stainless steel.
  - Function: Provides 30–60 minutes of continuous operation before refilling.
- **Electrical Input:**
  - Power source: 12 V DC from vehicle battery.
  - Consumption: 5–15 A depending on current density and required flow rate.
  - Protection: 15 A fuse and ON/OFF switch or digital timer for operational control.

This system is dimensioned to produce approximately 0.5–2.5 L/min of hydrogen gas, sufficient for cleaning engines ranging from 1.2 L to over 2.0 L in displacement [10].

2.3 Isolant:

The green isolant in Figure 8 is a square 3D-printed spacer/gasket and its shape and proportions confirm that:

- Outer dimensions: 13.5 cm × 13.5 cm
- Inner opening: 11.5 cm × 11.5 cm (the active reaction window)
- Thickness: 3 mm (in height, i.e., the plate-to-plate gap it defines)
- Material: polymer (3D-printed)

So the isolant forms a square frame with a uniform 2 cm border all around the inner cavity.



Figure 2.4 Form of the Isolant used in the prototype

2.4 Injection Circuit

The hydrogen produced is directed to the engine intake via a controlled injection circuit.

- Tubing: Internal diameter 6–10 mm, length 1–2 m.
    - Material: Silicone or PTFE, selected for resistance to hydrogen permeation and high temperatures [6].
- Flow Regulation:
    - Solenoid valve (2–5 V DC).
    - Flow capacity: 0.5–2 L/min.
    - Ensures precise metering of hydrogen into the intake system.

This dimensioning ensures a stable and safe gas supply without significant backpressure losses.

2.5 Safety System

Given hydrogen's high reactivity, multiple redundant safety features are integrated:

- Flame arrestor: Stainless steel, diameter 10–15 mm, prevents flashback from the engine.
- Bubbler: Water trap acting as a secondary flame barrier.
- Temperature sensor: Automatic cutoff above 60 °C to prevent overheating.
- Ventilation: 12 V cooling fan for continuous heat dissipation.
- Timer/display: LED/LCD timer with simple interface for operation control.

These measures collectively mitigate risks associated with explosion, backfire, or overheating [40].

2.6 Operating Autonomy

- Reservoir size (1 L): 30–60 minutes of continuous operation.
- Adjustability: Autonomy can be extended with larger tanks for cleaning larger vehicles.

This autonomy is sufficient for a complete catalytic converter cleaning session in garage conditions.

3. Justifications for Dimensioning Choices

3.1 Chassis (Housing)

- Dimensions: Height 40–50 cm, Width 30–40 cm, Depth 20–30 cm. These values ensure the device remains compact enough for portability (garage or mobile use) while still being large enough to contain all subsystems (electrolysis cell, reservoir, control electronics, safety systems). Smaller dimensions would make integration difficult and increase risk of overheating, while larger ones would reduce portability.
- Weight: 5–10 kg. This weight range strikes a balance between stability (heavy enough to avoid tipping during operation) and portability (light enough to be moved by one person). A unit lighter than 5 kg could be unstable during gas vibrations, while heavier than 10 kg would hinder mobility.
- Material: Aluminum or Stainless Steel.
    - Aluminum → lightweight, corrosion resistant, good thermal conductivity (helps with heat dissipation).
    - Stainless Steel → stronger, more durable, better resistance to high temperatures.

      These materials ensure mechanical robustness and thermal stability during prolonged operation.

3.2 Electrodes

- Dimensions: 15 × 15 cm. This surface area is sufficient to provide adequate contact area for electrolysis without requiring excessive current. Smaller plates would limit gas production, while much larger plates would increase power demand unnecessarily.
- Spacing: 3 mm.
    - Closer spacing (<3 mm) increases risk of short-circuiting due to bubble bridging.

  - Wider spacing (>3 mm) increases ohmic resistance, lowering efficiency. Thus, 3 mm is optimal to minimize resistance while allowing gas bubbles to escape efficiently [1].
- Number of Plates: 9.This range was chosen to balance gas output and current draw. Fewer than 9 plates → insufficient HHO flow; more than 9 plates → high electrical load on the car battery. This modular design also allows scalability depending on the application.
- Material: Stainless Steel 316L or Titanium.
  - SS316L → affordable, widely available, resistant to alkaline electrolyte corrosion.
  - Titanium → more expensive but offers superior resistance to corrosion and longer lifespan.

3.3 Isolant

Geometry and functional balance:

- The 1 cm frame border on all sides provides excellent mechanical rigidity and a wide enough sealing surface to prevent electrolyte leakage when the stack is compressed.
- The 11.5 × 11.5 cm inner window gives a large and symmetrical electrolyte chamber, centered on the 15 × 15 cm electrodes.
- This ensures uniform current distribution and symmetrical gas bubble release across the whole plate surface.

Thickness of 3 mm:

- Defines the electrolyte gap between two plates.
- 3 mm is thick enough to prevent electrical contact (short circuits) and allow good electrolyte circulation, but thin enough to keep internal resistance low and the stack compact.
- When compressed by the tie-rods, it slightly flexes (≈ 0.2 mm), producing a reliable, gas-tight seal without deforming.

3.4 Reservoir

- Volume: 1–2 liters.
    - 1 liter provides ~30 minutes of operation, sufficient for a standard decarbonization session in small cars.
    - 2 liters allows up to 60 minutes for larger engines or heavy-duty vehicles. Choosing this range avoids excessive size and weight while guaranteeing practical autonomy for workshops.
- Material: Plastic (heat-resistant) or Stainless Steel.
    - Plastic → lightweight, cheap, resistant to corrosion.
    - Stainless steel → durable, thermally stable. Either ensures safety against electrolyte heating during extended use.

3.5 Power Consumption

- Input: 12V DC (car battery). Chosen for compatibility with existing vehicle power systems. This avoids the need for external power sources.
- Current: 5–15 A.
    - <5 A → insufficient HHO production (too weak for catalytic cleaning).
    - 15 A → excessive strain on battery/alternator, overheating risk. This range ensures gas flow between 0.5–2.5 L/min, enough for most engines.
- Safety: 15 A Fuse + ON/OFF Switch or Timer. Protects the system against short circuits and allows controlled operation (avoiding excessive runtime or unattended use).

3.6 Tubing

- Diameter: 6–10 mm.
    - <6 mm → risk of backpressure, insufficient flow.
    - 10 mm → unnecessary gas volume, harder to control flow precisely. Thus, 6–10 mm ensures stable flow with manageable control.
- Length: 1–2 m.

Provides flexibility to connect from the generator to the engine intake, whether the system is placed near the car battery or further away in the garage.

- Material: Silicone/PTFE.
    - Silicone → flexible, heat-resistant.
    - PTFE → excellent chemical resistance to hydrogen and electrolyte vapors.

3.7 Solenoid Valve

- Operating Voltage: 2–5 V DC.
  Compatible with low-voltage control electronics, making it safe and easy to integrate with timers or microcontrollers.
- Flow Capacity: 0.5–2 L/min.
  Matches the optimal hydrogen flow rates for automotive cleaning:
    - 0.5–1.5 L/min → small engines (1.2–2.0 L).
    - 1.5–2.5 L/min → larger engines (>2.0 L).

  This ensures effective decarburization without flooding the engine with excess gas.

3.8 Safety System

- Flame Arrestor (10–15 mm, Stainless Steel): Prevents backfire propagation into the hydrogen generator. Stainless steel mesh dissipates heat and quenches flames.
- Bubbler: Secondary flame barrier that uses water to block flashback. Simple, cheap, and highly effective.
- Temperature Sensor (cutoff at 60 °C): Prevents overheating of the electrolyte, which could accelerate evaporation or damage seals. 60 °C is a conservative threshold for safety.
- Cooling Fan (12 V): Provides active thermal management to maintain cell efficiency and protect electronics.

- Timer/Display (LED/LCD with ↑ ↓ buttons): Allows operators to set operation duration, ensuring cleaning sessions stop automatically after the desired time. Prevents overuse and improves safety.

3.9 Operating Autonomy

- 1 Liter Reservoir = 30–60 Minutes.
  Typical cleaning sessions require no more than one hour, so this capacity was chosen as sufficient but not excessive.
- Scalability: Larger reservoirs could be used for heavy-duty vehicles, but would increase system size and weight unnecessarily for standard cars.

4. Risk Analysis and Safety Measures

Hydrogen is a highly reactive gas with a wide flammability range (4–75% in air) and a very low ignition energy (~0.02 mJ), making safety a critical design consideration [9]. While the hydrogen cleaning device is based on small-scale electrolysis and on-demand generation, potential risks must still be carefully analyzed and mitigated. The following subsections identify the main risks associated with the system and describe the safety measures integrated into the design.

4.1 Risk of Explosion and Fire

Hydrogen can easily ignite if mixed with air and exposed to a spark or hot surface. The greatest danger is a flashback from the engine intake propagating back into the hydrogen line and reaching the electrolysis cell.

Mitigation Measures:

- A flame arrestor (stainless steel, 10–15 mm, mesh-based) is installed in the gas line to quench any flame front before it enters the cell.
- A bubbler (water trap) provides a secondary protective barrier, absorbing backfire energy.

- All tubing is made of heat- and hydrogen-resistant materials (silicone/PTFE) to reduce permeation and leaks.

4.2 Risk of Overheating

Electrolysis cells generate heat as current passes through the electrolyte. Prolonged operation at high current (>15 A) can cause electrolyte evaporation, material degradation, or thermal runaway.

Mitigation Measures:

- A temperature sensor continuously monitors the cell. Automatic shutdown is triggered if the temperature exceeds 60 °C.
- A 12 V cooling fan ensures continuous airflow over the electrolysis chamber and control electronics.
- Operating current is limited to 5–15 A, preventing excessive heat generation while maintaining sufficient hydrogen output.

4.3 Risk of Electrical Faults

The system is powered by a 12 V vehicle battery. Faults such as short-circuits or overcurrent could damage the cell or create sparks, which are dangerous near hydrogen.

Mitigation Measures:

- A 15 A fuse protects the circuit against overcurrent.
- An ON/OFF switch or programmable digital timer ensures controlled activation and prevents unattended operation.
- All electrical connections are insulated and placed in sealed housings away from hydrogen tubing.

4.4 Risk of Gas Leaks

Hydrogen has a very small molecular size and can diffuse through weak joints. Even minor leaks may accumulate in confined spaces and create explosive mixtures.

Mitigation Measures:

- All tubing connections are sealed with hydrogen-resistant fittings.
- Periodic leak testing with soapy water or sensors is recommended in workshops.
- The compact housing design minimizes tubing length, reducing leak points.

4.5 Human and Operational Risks

Improper handling or misuse could compromise safety, such as leaving the system on for too long or operating it without proper ventilation.

Mitigation Measures:

- A user-friendly control interface (timer with LCD/LED display and ↑ ↓ buttons) allows operators to set precise cleaning durations.
- Labels and instructions guide operators to handle the device safely.
- Ventilation requirements ensure use only in open or well-ventilated garages.

4.6 Overall Safety Strategy

The system integrates multiple redundant safety layers, combining preventive measures (proper materials, electrical protection) with protective barriers (flame arrestor, bubbler, temperature cutoff). This approach aligns with general hydrogen safety recommendations issued by the U.S. Department of Energy (DOE) and the International Energy Agency (IEA) [40], [12].

By addressing explosion, overheating, electrical, and operational risks, the design ensures that the hydrogen cleaning device is safe for regular use in automotive workshops, without requiring specialized protective infrastructure.

5. Table of Components

N°	Component	Specification / Description	Quantity	Estimated Unit Price (DZD)	Total (DZD)
1	**Stainless Steel / Titanium Plates**	15 × 15 cm (electrodes – 10 plates: 2 negative, 1 positive, 7 neutral)	10	1,800	**18,000**
2	**3D-Printed Isolant Frames**	13.5 × 13.5 cm outer, 11.5 × 11.5 cm inner, 3 mm thick	10	600	**6,000**
3	**Reservoir for Distilled Water**	Heat-resistant plastic or stainless-steel, 1–2 L capacity	1	2,000	**2,000**
4	**Bubbler (Water Filter)**	Safety gas-water separator	1	1,500	**1,500**
5	**Flame Arrestor**	Stainless steel housing with mesh filter	1	2,500	**2,500**
6	**Silicone Tubing**	Ø 6–10 mm, heat and hydrogen resistant (2 m)	1 roll	1,000	**1,000**
7	**Electrolysis Container (Cell Housing)**	Stainless steel or acrylic frame, 40 × 30 × 20 cm	1	5,000	**5,000**
8	**Bolts, Nuts, and Tie-Rods (Stainless Steel)**	M6 threaded rods with washers and nuts	Set	2,500	**2,500**
9	**12V DC Power Supply (from Vehicle Battery)**	With fuse and switch protection	1	1,000	**1,000**
10	**Fuse 15A and Switch**	Safety circuit protection	1	500	**500**
11	**Temperature Sensor (Thermal Cutoff)**	60°C automatic shutoff sensor	1	700	**700**
12	**12V Cooling Fan**	80–120 mm, installed on chassis	1	1,200	**1,200**
13	**Digital Timer / Controller (Optional)**	For operation duration control	1	2,000	**2,000**
14	**Hydrogen Output Valves**	One-way check valve system	2	800	**1,600**
15	**Distilled Water (Electrolyte)**	5 L container	1	300	**300**
16	**KOH (Potassium Hydroxide)**	Electrolyte additive, 100 g	1	800	**800**
17	**Sealing Gaskets / Silicone Paste**	For leak prevention	1	500	**500**
18	**Display (LCD/LED)**	For monitoring temperature or current	1	1,500	**1,500**
19	**Miscellaneous Materials**	Wires, connectors, mounting brackets	Set	2,000	**2,000**

Table 2.1 Table of all the components needed to create our hydrogen cell

✓ **Notes:**

- Prices are based on 2025 Algerian market averages (Jumia DZ, MicroTech DZ, and Ouedkniss electronics sections).
- Using titanium plates instead of stainless steel increases total cost by ~30%.
- If parts are imported (AliExpress DZ or Alibaba bulk), the total may reach 70,000–80,000 DZD with shipping.
- Local 3D printing can be done in Jijel or Algiers workshops at 500–700 DZD per isolant.

Chapter III: Fabrication and Assembly of the Hydrogen Cell Prototype

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1. Preparation of Components

After defining the final dimensions of all components, the individual parts were purchased and prepared for assembly. The prototype consists of a nine-plate duplex booster cell arranged as follows:

- 2 negative plates (cathodes)
- 1 positive plate (anode) without holes, positioned in the center
- 6 neutral plates distributed symmetrically between the positive and negative plates

Ten 3 mm-thick isolants (13.5 × 13.5 cm outer, 11.5 × 11.5 cm inner) were 3D-printed to ensure uniform spacing and electrical insulation between adjacent electrodes. Two end-covers (stainless steel or acrylic) close the stack, and four M6 stainless tie-rods pass through the corners to hold the assembly under compression.

2. Surface Preparation of Plates

To increase the effective catalytic area, each stainless-steel plate was mechanically roughened:

a) Vertical sanding with fine-grit metal sandpaper to create micro-grooves.
b) Horizontal sanding to cross-hatch the surface, producing microscopic peaks that improve gas nucleation and bubble release.
c) Cleaning with distilled water to remove metallic dust.
d) Final degreasing with alcohol or acetone and wiping with lint-free cloths to remove fingerprints, which could cause localized corrosion.

Reason: A slightly rough surface enhances bubble detachment and promotes faster water decomposition without increasing current demand.

3. Stack Assembly Procedure

a) Bottom Cover Placement – The lower cover was positioned on a clean surface, and the four M6 tie-rods were inserted through the mounting holes.
b) First Isolant Installation – A 3 mm isolant was placed on the cover to prevent direct electrical contact between the cover and the first electrode.
c) Electrode and Isolant Alternation –
    - Negative plate
    - Isolant
    - Neutral plate
    - Isolant
    - Neutral plate
    - Isolant
    - Neutral plate
    - Isolant
    - Central positive plate (no holes)
    - Then mirrored symmetrically with additional neutral → isolant → negative sequence.

d) Top Cover – After the final isolant, the top cover was installed, and the tie-rods were gradually tightened in a diagonal (star) pattern to ensure uniform compression of all gaskets.

This arrangement isolates each negative section so that each generates hydrogen independently on both sides, while the neutral plates help equalize current distribution and stabilize gas flow, typical of a duplex-booster configuration.

4. Integration of Reservoir and Tubing

A 1 L distilled-water reservoir was mounted above the cell to feed electrolyte by gravity.
Four silicone/PTFE tubes (Ø 6–10 mm) were connected:

- Two inlet tubes – from the bottle to each half of the cell (supply of water/electrolyte).
- Two outlet tubes – carrying produced gas from each half of the cell to the bubbler system.

This symmetric connection ensures equal flow through both chambers and prevents uneven pressure.

5. Electrical Connection

- The positive terminal of the 12 V car battery was connected to the flange screw that clamps the central positive plate.
- The negative terminal was connected to the outer tie-rod attached to the negative plates.
- A 15 A inline fuse and ON/OFF switch were installed for circuit protection and operational control.

The system operates at 5–15 A, producing approximately 0.05–0.15 L/min of HHO gas under standard conditions.

6. Safety and First-Run Procedure

1. Visual inspection of all seals and bolts before energizing.
2. Leak-test using soapy-water spray around joints.
3. Temperature sensor set to cut off at 60 °C.
4. Hydrogen outlet connected to a bubbler + flame arrestor before entering the engine intake.
5. Ventilation fan switched on during operation.
6. Initial power-up limited to 5 A for 5 minutes to confirm gas formation and stable operation, followed by gradual increase to full load.

After successful testing, the prototype delivered stable gas output with no visible leaks or overheating.

The assembly confirmed that the designed dimensions and component selection provide a compact, safe, and effective duplex hydrogen booster cell. The 3D-printed isolants maintained perfect spacing, the 15 × 15 cm electrodes provided uniform gas generation, and the overall structure remained leak-free under continuous operation.

7. How the hydrogen cell works (duplex booster)

7.1 Power and activation

The device is connected to a 12 V DC source (car battery or bench supply) through a cable connected between the battery and both the negative and positive plates. When we do the connection, current begins to flow from battery (+) → central positive plate (anode) → electrolyte → neutral plates (carry current) → outer negative plates (cathodes) →battery(–).



Figure 3.1 Using the battery of the car as a source of power



Figure 3.2 Connecting our cell to the car's battery

In a duplex layout, the stack is split into two half-cells mirrored around the central positive plate. That single positive plate serves both sides, so each side produces gas simultaneously.

7.2 Electrolyte and the role of the isolant

The reservoir supplies distilled water (often with a small amount of alkaline electrolyte like KOH/NaOH to increase conductivity). Our 3D-printed isolant frames (13.5 × 13.5 cm outer, 11.5 × 11.5 cm inner, 3 mm thick) sit between the 15 × 15 cm plates and create sealed electrolyte chambers with a 3 mm gap. That 3 mm gap is the "reaction channel" where bubbles form and rise; the square inner window defines the active zone.

7.3 The electrochemical reactions (water → hydrogen + oxygen)

As current passes, water molecules split. The fundamental reaction is:

$$2\,H_2O \xrightarrow{\text{electric current}} 2\,H_2 + O_2$$

At the cathodes (outer negative plates):

$$2\,H_2O + 2e^- \rightarrow H_2 + 2\,OH^-$$

Hydrogen gas forms as bubbles on the cathode surfaces and detaches upward.

At the anode (central positive plate):

$$2\,H_2O \rightarrow O_2 + 4\,H^+ + 4e^-$$

Oxygen bubbles form on the positive plate and rise.

If we use a single common headspace, the outlet gas is the familiar HHO mixture (2 parts H_2 : 1 part O_2). If the two sides are separated with separate outlets to a common bubbler, the effect is similar for cleaning.

7.4 What the neutral plates do

The neutral plates don't connect directly to the battery; they conduct current through the electrolyte from the anode to the cathodes across multiple gaps. This "multi-gap" path multiplies the effective cell voltage into several small drops, giving more reaction area at a given supply voltage (12 V) and improving gas output per amp, while keeping each gap at a safe voltage and temperature.

The duplex-booster hydrogen cell operates by splitting water supplied from the upper reservoir (indicated by the cyan arrows) into hydrogen and oxygen gases through the process of electrolysis, powered by a safe 12-volt DC supply (orange arrows).

The internal stack consists of a central positive plate, two outer negative plates, and multiple neutral plates separated by 3 mm 3D-printed isolant frames, forming several reaction chambers.

When electrical current passes through the electrolyte, hydrogen forms on the negative plates and oxygen on the positive. The generated hydrogen bubbles detach and flow upward through the outlet ports (white arrows), pass through the bubbler and flame arrestor, and are then directed toward the engine intake (blue arrows).

The controlled injection of hydrogen into the engine air stream enhances combustion efficiency and promotes the oxidation of carbon deposits, aiding in catalytic converter regeneration.

System parameters such as temperature, current, and time are continuously monitored for safety. Once the switch is turned off, gas generation stops instantly, ensuring no high-pressure hydrogen storage within the system.



Figure 3.3 Showing how our cell works

7.5 Notes and Observations

During prototype testing, a small amount of water leakage was observed around some plate joints. This phenomenon is primarily attributed to manufacturing tolerances rather than a design flaw. Because the plates were not perfectly identical in hole alignment,

the compression provided by the tie-rods was slightly non-uniform, allowing minor seepage at certain points along the isolant edges.

Given the limited resources and fabrication tools available in the university workshop, these minor leaks were considered acceptable for the prototype stage. They did not affect hydrogen generation performance or electrical stability, but they highlight the need for tighter machining tolerances and improved sealing methods in a future industrial version.

General Conclusion & Perspectives

General Conclusion & Perspectives

This project aimed to design and prototype a compact hydrogen cell capable of generating hydrogen through water electrolysis for use in cleaning and regenerating automotive catalytic converters. By relying on the principles of electrochemistry, the device produces a mixture of hydrogen and oxygen gases (HHO) that, when introduced into the engine intake, promotes more complete combustion and the removal of carbon deposits from the catalytic converter. The conception and realization of this system required balancing performance, safety, and portability.

The successful fabrication and testing of the prototype demonstrated the feasibility and reliability of hydrogen-based cleaning as an eco-friendly alternative to chemical or mechanical methods. Minor water leakage was observed during operation due to limited manufacturing precision and non-identical plate alignment, a consequence of the restricted resources available in the university workshop. Nevertheless, this limitation did not compromise functionality or safety and highlights areas for future improvement through more precise fabrication and optimized sealing. In conclusion, the project validated the technical concept of a practical, sustainable hydrogen cleaning device that contributes to

reducing automotive pollution and offers promising opportunities for innovation and commercialization in the field of green automotive maintenance.

Since the system is simple, safe, and low-cost, it can be produced locally and offered to automotive workshops as an eco-friendly cleaning tool. Many Algerian drivers face catalyst clogging and expensive replacements, which makes this device very attractive. The perspectives of the project focus on improving sealing quality using CNC or laser-cut plates, integrating electronic monitoring sensors, and developing a user-friendly digital interface. We also plan to test the device on different vehicles to validate emission improvements.

Finally, with incubator support, the system can move from prototype to industrial production, creating a viable startup specialized in green automotive maintenance technology.

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