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-THEME-

**Extraction and Utilisation of H₂ from Produced
Water Specially from Abandoned Wells**

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DEDICATION

To my beloved parents MAATALLAH EL-AKHDHAR Feroui and HANANE Lessoued,
Your unwavering love and boundless support have been the foundation of my journey. From the earliest days of my life to this momentous achievement, you have been my guiding light. Thank you for believing in me and nurturing my dreams. Your encouragement and belief in my abilities have given me the strength to overcome any obstacle that came my way.

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Thank you for being a part of my story and for reminding me that I am never alone.

This achievement is dedicated to all of you.



Dedication

**To the spirit of my father, may Allah bless him,
To my mother the source of love and tenderness,
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Azza, Meftah, Rahma and Lakhder,
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LATIFA

Abstract

The energy transition to sustainable sources is imperative for global environmental challenges. Hydrogen (H₂) seems to be a promise since is a key energy carrier in this transition. However, electrolysis of underground water presents challenges due to mechanical and chemical parameters. This study investigates these complexities using MATLAB simulations and emphasizes the importance of predicting H₂ production and optimizing electrolysis efficiency. To accomplish this aim, more than 20 experiments examined the impact of chemical reactions on electrolysis using complex underground water. Sufficient direct current (DC) power supply and studying treatment effects using the FM experiment were crucial. In addition, this work explores the challenges of utilizing H₂ in perforation and fracturing operations, emphasizing the need for research, tool development, and process refinement to ensure safety and minimize environmental impact. Therefore, this study underscores the need for a comprehensive understanding of the electrolysis process in the energy transition to hydrogen. It highlights the challenges of underground water electrolysis, the role of mechanical and chemical parameters, and the importance of precise treatments and predictions. By addressing these factors, optimal H₂ production can contribute to a successful and sustainable energy transition.

Keyword: Electrolysis, Gibbs free energy, HSPEU, FM experiment of electrolysis, H₂, perforation, fracturing.

المخلص

إن انتقال الطاقة إلى مصادر مستدامة أمر حتمي لمواجهة التحديات البيئية العالمية. في هذه الحالة يبدو الهيدروجين واعداً كناقل رئيسي للطاقة في هذا الانتقال. ومع ذلك، فإن التحليل الكهربائي للمياه الجوفية يمثل تحديات بسبب العوامل الميكانيكية والكيميائية. لهذا تسلط هذه الدراسة الضوء على هذه التعقيدات باستخدام محاكاة ماتلاب الرياضي وتؤكد على أهمية التنبؤ بإنتاج الهيدروجين وتحسين كفاءة التحليل الكهربائي. لإتمام هذا الهدف فحصت أكثر من 20 تجربة تأثير التفاعلات الكيميائية على التحليل الكهربائي باستخدام المياه الجوفية المعقدة. كان توفير الطاقة الكافية للتيار المباشر ودراسة تأثيرات المعالجة باستخدام تجربة فروي -مدني للتحليل الكهربائي للمياه الجوفية ذات تركيب كيميائي معقد وتغييرات شديدة للتركيبية الكيميائية لهاته المياه أمراً بالغ الأهمية. بالإضافة إلى ذلك، تستكشف هذه الدراسة تحديات استخدام الهيدروجين في عمليات الثقب والتكسير، مع التأكيد على الحاجة إلى البحث وتطوير الأدوات وصقل العمليات لضمان السلامة وتقليل التأثيرات على البيئة. بناءً على ذلك تؤكد هذه الدراسة على الحاجة إلى فهم شامل لعملية التحليل الكهربائي في انتقال الطاقة إلى الهيدروجين. يسلم الضوء على تحديات التحليل الكهربائي للمياه الجوفية، ودور المعالجة الميكانيكية والكيميائية، وأهمية المعالجات والتنبؤات الدقيقة. من خلال معالجة هذه العوامل، يمكن أن يساهم إنتاج الأمثل في انتقال الطاقة الناجح والمستدام.

الكلمات المفتاحية: التحليل الكهربائي؛ الطاقة الحرة لجيبس؛ تجربة فروي-مدني للتحليل الكهربائي؛ الهيدروجين؛ التثقيب؛ التكسير.

Résumé

La transition énergétique vers des sources durables est cruciale pour faire face aux défis environnementaux mondiaux. L'hydrogène (H₂) représente un vecteur énergétique prometteur dans cette transition. Cependant, l'électrolyse de l'eau souterraine présente des défis liés aux paramètres mécaniques et chimiques. Cette étude explore ces complexités à l'aide de simulations MATLAB et souligne l'importance de prédire la production de H₂ et d'optimiser l'efficacité de l'électrolyse. Pour accomplir cet objectif, Plus de 20 expériences ont été menées pour étudier l'impact des réactions chimiques sur l'électrolyse de l'eau souterraine complexe. Une alimentation suffisante en courant continu (DC) et l'étude des effets des traitements à l'aide de l'expérience FM se sont révélés cruciaux. De plus, cette étude aborde les défis liés à l'utilisation de H₂ dans les opérations de perforation et de fracturation, mettant en évidence la nécessité de recherches, du développement d'outils et de l'amélioration des processus pour garantir la sécurité et réduire l'impact sur l'environnement. Par conséquent, cette étude souligne l'importance d'une compréhension approfondie du processus d'électrolyse dans la transition énergétique vers l'hydrogène. Elle met en évidence les défis de l'électrolyse de l'eau souterraine, le rôle des paramètres mécaniques et chimiques, ainsi que l'importance de traitements précis et de prédictions. En abordant ces aspects, une production optimale de H₂ peut contribuer à une transition énergétique réussie et durable.

Mots-clés : Electrolyse, énergie libre Gibbs, HSPEU, l'expérience FM de l'électrolyse, H₂, perforation, fracturation.



List of Figures

Figure I.1: The evolution of Gibbs, Enthalpy, and Entropy versus Temperature	2
Figure I.2: HSPEU different units.	4
Figure I.3: Typical AHF generation process at specified Temperature and Pressure	6
Figure I.4: The micromolecular instruction of a typical AHF fluid	7
Figure I.5: Schematics of an agitated vessel with a Rushton turbine and baffles	14
Figure I.6: Industrial-size Electrolyser	16
Figure I.7: Typical electrolyser used experiments with Temperature measurement.....	16
Figure I.8: Figure shows an SCR command unit (ENTP-DMP).....	17
Figure I.9: A 9-12V SCR unit used for experiments.....	18
Figure I.10: Electrolysis process at micromolecular level.....	25
Figure I.11: Different factors.....	28
Figure I.12: Depositions of NRF deposits of a water model after electrolyzed	28
Figure I.13: Different gain clouds at different HSF values.....	31
Figure I.14: FMP point	32
Figure I.15: FMTC triangle.....	33
Figure II.1: Non-Treated Water with NaCl.....	35
Figure II.2: Non-Treated Water with NaHCo3	35
Figure II.3: Non-Treated Water with NaHCo3 and NaCl	36
Figure II.4: Fresh water with NaCl.....	36



Figure II.5: Fresh water with NaHCO_3	37
Figure II.6: Fresh water with NaHCO_3 and NaCl	37
Figure II.7: HTF-14 technical sheet	39
Figure II.8: Compositional variation of HTF-14 well after different operations	41
Figure II.9: Water depositions after electrolysis	42
Figure II.10: HTF-14 water composition in different samples after electrolysis.....	43
Figure II.11: pH of HTF-14 well's water of different samples after electrolysis	43
Figure II.12: FM-01 fluid model.	45
Figure II.13: Estimated production versus time at 60°C	46
Figure II.13: Estimated production versus time at 80°C	47
Figure III.1: PUH/FUH tool.....	50
Figure III.2: Castrol oil (NMF fluid).....	51
Figure III.3: Upper and lower movable packing disks (Isolation parts).....	52
Figure III.4: Principal PUH/FUH parts	53
Figure III.5: An AHF prototype	54
Figure III.6: PUH process using HPERF tool.....	62
Figure III.7: FUH process using HFRC tool.....	68



List of Tables

Table I.1: Main comparison between Alkaline/SPE/SOEC electrolysis	3
Table I.2: Different HSPEU units.....	18
Table II.1: Electrolysis of NTW and fresh water in presence of NaCl and NaHCO ₃	38
Table II.2: Location and statue of HTF-14 well.....	39
Table II.3: HTF-14 well's change of composition (mg/l) after different operations.....	40



List of Abbreviations

HER	Hydrogen Evolution Reaction
OER	Oxygen Evolution Reaction
PEM	Proton Exchange Membrane
AEM	Anion Exchange Membrane
SOEL	Solid Oxide electrolysis
HSPEU	Hydrogen Surface Production and Exportation Unit
AHF	Adsorbed Hydrogen Fluid
MSU	Main Separation Unit
HSF	Hydrogen Separation Factor
FMP	Feroui-Madani Peak
FMTC	Feroui-Madani Triangle of Choice
PUH/FUH	Perforation/Fracturing Using Hydrogen
NMF	Non-Miscible Fluid
HC-HV	Highly Complicated-Highly Variable

Nomenclatures

G	The Gibbs free energy.	J/mole
H	The enthalpy.	J/mole
T	The absolute temperature.	K
S	The entropy.	(J/(mole*K))
Z	The moles electrons / moles substance	/
θ	The fractional coverage or the amount of gas adsorbed on the surface.	/
K	The Langmuir constant related to the affinity of the gas to the surface.	mol^{-1}
P	The pressure of the gas.	Pa
μ	Dynamic viscosity.	Pa*s



Table of Contents

ACKNOWLEDGMENT.....	I
DEDICATION.....	II
ABSTRACT	IV
LIST OF FIGURES	V
LIST OF TABLES	VII
LIST OF ABBREVIATIONS	VIII
NOMENCLATURES	IX
TABLE OF CONTENTS	X
GENERAL INTRODUCTION	XI

Chapter I

The Theory of Under-Ground's Water Electrolysis

Introduction	1
I.1 Presentation of Hydrogen Surface Production and Exportation Unit (HSPEU).....	3
I.2 From the separator to exportation pipelines	4
I.2.1 Separation	5
I.2.2 Treatment	5
I.2.3 Electrolysis.....	5
I.2.4 Decantation/Storage.....	5
I.2.5 Exportation.....	6
I.3.1. Separator	12
I.3.2 Main Treatment Unit (MTU)	13
I.3.3 Mechanical Treatment (SCU)	13
I.3.4 Chemical Treatment (MHCU)	14
I.3.5 Main Separation Unit (MSU).....	15
I.3.6 Decantation/Storage unit.....	18
I.4 different parameters that influence the production.....	19
I.5 Optimization of H ₂ production through mechanical/chemical optimizations	19
I.6 Influence of water composition on production (Feroui-Madani experiment).....	20
I.6.1 Ion's influence.....	21
I.6.2 Density	21
I.6.3 Viscosity	21



I.6.4 Other rheological factors (Fick's first law).....	22
I.6.5 Hydrogen Separation Factor (HSF).....	22
I.6.6 Influence of Temperature and Pressure on H ₂ production	23
I.7 Generation of general simulation through the ideal and the real production	30
I.7.1 Presentation of the FM gain low and FM gain experiment.....	30
I.7.2 Data generation using MATLAB program.....	31
I.7.3 Analyse, interpretation, solutions and conclusions	32
Conclusion.....	33

Chapter II

Technical Solutions to Optimize Hydrogen Production

Introduction	34
II.1 Influence of different ions in two different water models	34
II.1.1 Non-Treated Water NTW (presence of sand, lemon and other sediments).....	34
II.1.2 Fresh water (no sediments no ions).....	36
II.1.3 General results	38
II.2.2 General informations about HTF-14 well	38
II.2.3 Production of H ₂ gas from an HTF-14 water sample	41
II.2.4 Optimization via use of FM-01 fluid.....	44
Conclusion.....	48

Chapter III

Use of Hydrogen Gas in Petroleum Industrial Applications

Introduction	49
III.1 Presentation of the PUH/FUH unit.....	49
III.1.1 Isolation parts	50
III.1.2 Fluid Transmit Conductors.....	51
III.1.3 Chock Orientation Chamber.....	52
III.2 In perforation	57
III.2.1 Background about Perforation.....	57
III.2.2 Present technics of perforation	58
III.2.3 Different parameters influence the perforation efficiency	60
III.2.4 Perforation Using Hydrogen (PUH) technics.....	61
III.2.5 Presentation of the PUH system	61



III.3 In fracturing	63
III.3.1 Process of hydraulic fracturing	64
III.3.2 Benefits of hydraulic fracturing	64
III.3.3 Environmental concerns and challenges	64
III.3.4 Technics of fracturing	65
III.3.5 Different parameters influence the fracturing efficiency	65
III.3.6 Fracturing Using Hydrogen (FUH) technic.....	65
III.3.7 Presentation of the FUH system	66
Conclusion.....	69
GENERAL CONCLUSION.....	XVI
REFERENCES	XVIII

**GENERAL
INTRODUCT
ION**

The global demand for clean and sustainable energy sources has thrust hydrogen into the spotlight as a promising alternative fuel. Electrolysis, the process of using electrical energy to split water into hydrogen and oxygen, presents a viable pathway for large-scale hydrogen production. However, to fully unlock the potential of electrolysis, it is crucial to study and optimize its objectives.

The present work is consisted of three chapters. In the first chapter, the researcher is going to define why, in electrochemistry, the sufficient Gibbs free energy required to split a water molecule (H_2O) is essential. The pioneering work of physicist Michael Faraday demonstrated the use of electricity for water splitting through specific equations. This chapter aims to introduce the experiment of Feroui-Madani for underground water electrolysis and the principal factors that influence the production.

Chapter II is devoted to study the technics to achieve optimal efficiency, it is essential to explore and identify effective treatment strategies. These strategies may involve modifying electrode materials, fine-tuning operating conditions, or implementing catalysts to facilitate faster reaction rates. In addition, this chapter aims to identify the importance of achieving the optimal mechanical/chemical treatments and the results of not ensuring those treatments on both the used materials and the electrolysis efficiency.

The last chapter highlights the application of Hydrogen-Based Fluids for reservoir stimulation, particularly in perforation and hydraulic fracturing. It discusses the potential benefits, challenges, and associated engineering considerations. By utilizing new technologies like **Perforation/Fracturing Using Hydrogen (PUH/FUH)**, engineers are able to enhance stimulation and well operations by employing H_2 -based fluids and other techniques to increase efficiency.

Chapter I

The Theory of Under-Ground's Water Electrolysis

Introduction

Today, the term 'Energy Transition' has become the main subject for almost all energy and industrial companies all over the world as "global warming" and the great destructive influence of CO₂, the importance of finding more over clean resources and the way to use them to the maximum is now the big trend in the technological and industrial community, in which oil and gas industry is not a consumption.

Recently, H₂ production and utilization, as a green fuel and big resource of energy, became more and more a trusted to be the next carburant of the near future [1].

In the electrochemistry, to split one molecule of H₂O, it is important to offer sufficient Gibbs free energy that is equal to the covalent compounds, which relate hydrogen to oxygen. The first who discussed the physics of electrochemical split of water was **FARADAY**, a physician that discovered the use of electricity as a way to split water via the follow equations [2]:

$$\Delta G = \Delta H - T * \Delta S \dots \dots \dots (I. 1) [1]$$

$$\Delta G = - Z * F * E \dots \dots \dots (I. 2) [1]$$

G is the Gibbs free energy (J/mole).

H is the enthalpy (J/mole).

T is the absolute temperature (K).

S is the entropy (J/(mole*K)).

Z is the moles electrons / moles substance.

F is the faradays constant 96500 As/mole.

E is the equilibrium cell voltage (V).

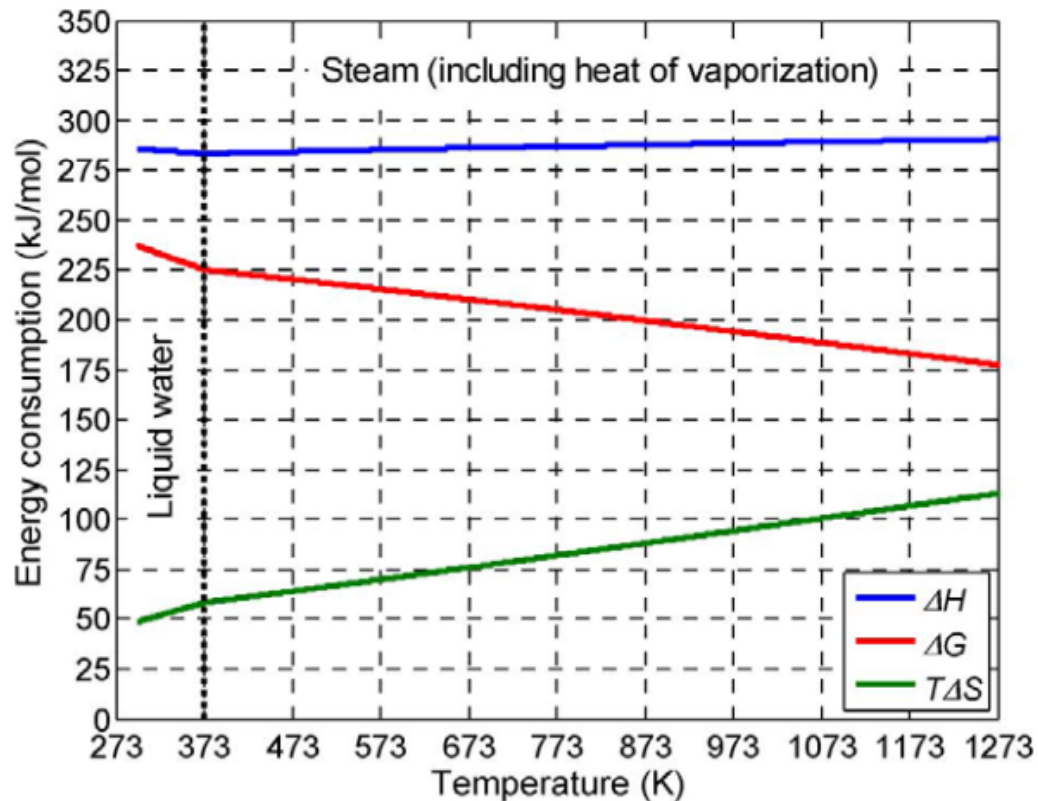


Figure I.1: The evolution of Gibbs, Enthalpy, and Entropy versus Temperature [1].

The main components required to achieve an electrolysis operation are:

- **An electrolyte**

It is a substance that contains free ions, which are the carriers of electric current in the electrolyte. If the ions are not mobile, as in a solid salt then electrolysis cannot occur.

- **A direct current (DC) supply**

It provides the energy necessary to create or discharge the ions in the electrolyte. Electric current is carried by electrons in the external circuit.

- **Two electrodes**

The cathode is the conductor in which the **Hydrogen Evolution Reaction (HER)** is affected and the anode that has the positive charge in which **Oxygen Evolution Reaction (OER)** is affected [2].

There are four main types of electrolysis: **Alkaline electrolysis**, **Proton Exchange Membrane (PEM) electrolysis**, **Anion Exchange Membrane (AEM) electrolysis**, and **Solid Oxide electrolysis (SOEL)**. In the Table I.1, the main differences between each process are mentioned.

Table I.1: Main comparison between Alkaline/SPE/SOEC electrolysis [1].

Technology	Alkaline water electrolysis	SPE (Solid polymer electrolyte) electrolysis	SOEC (Solid oxide electrolysis cell)
Process	Aqueous electrolysis	"Reversed PEFC"	"Reversed SOFC"
Feed	80% KOH, 80°C	Pure H ₂ O, 100°C	Steam, 800-900°C
Charge carriers	OH ⁻ , K ⁺	H ⁺	O ²⁻
Industrial use	Well developed Large scale	High current densities Differential pressure Expensive catalysts	Not yet commercial Pilot scale

The use of catalysts is also a valuable technic to enhance H₂ production. The best catalysts for the HER are noble metals, particularly platinum. Whereas, for the OER, iridium and ruthenium oxides are the best candidate materials [5].

Thus, the H₂ produced in gas form is not a pure substance; many impurities of different compositions are carried out while H₂ gas travel across the exportation pipes. The requirements for the purity of hydrogen that is produced from electrolysis will vary based on the end use of the hydrogen. Hydrogenation processes can utilize a hydrogen gas feed with a purity of 98% whereas fuel cells require hydrogen purity to be more than 98.98% [1].

In this chapter, we are going to discover the electrolysis of **Highly Complicated Highly Variable (HC-HV)** water's systems and how to define a water system's gain in specified environmental and rheological conditions and the ways of optimization using the Feroui-Madani equations of electrolysis.

I.1 Presentation of Hydrogen Surface Production and Exportation Unit (HSPEU)

It's very clear that production of hydrogen gas, besides of the exportation procedures, is not easy as that occurs at the level of laboratories. Starting from the well into the industry's ready use of gas, several special steps and process of treatment, production and exportation are

mandatory. This section presents the way HSPEU station works and the main steps to obtain H₂ gas from underground water.

The HSPEU station is defined as the group of equipments, pipes and valves...etc., that enrolled in a fully safe, effective and well-treated H₂ production starting from the separator in which the water is separated from mixed oil, ending with the exportation pipes. At the end of the process, a fluid called Adsorbed Hydrogen Fluid is being pumped onto the industrial use.

The main objectives of the HSPEU station are summarized below:

- A) Transform produced water from the well into H₂ gas via electrolysis after water being produced from separation.
- B) Ensure the safety of the process and the protection against any kind of risk especially any **risk of burst** due to brutal change of pressure/volume of Hydrogen gas.
- C) Ensure the effectiveness of the electrolysis via the optimization of water characteristics, which allows the maximum production of H₂ from a volume of water.
- D) Since electrolysis can be harmful to environment by direct or indirect influence on the nearby area, via the use of several products that ensure well-ready-to-electrolyze water or from the rejection of non-desired chemicals or elements in the nearby, the well-use of standards and norms of production and treatment is a first key in the design and operatory of an HSPEU station.

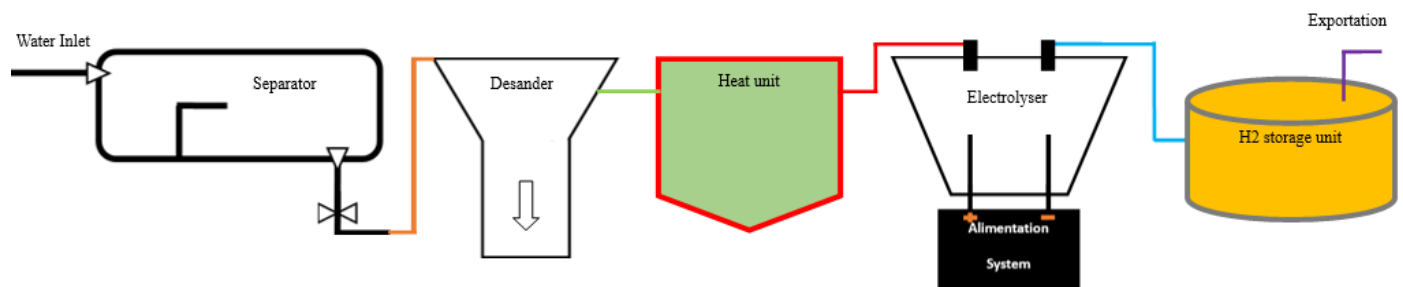


Figure I.2: HSPEU Different Units.

I.2 From the separator to exportation pipelines

After water being well extracted from mixed oil, it is directly pumped into the resting HSPEU units, in which a process of chemical and mechanical treatments followed by the electrolysis process are affected, ending with the final step of pumping H₂ gas in secured form.

The different HSPEU processes are:

I.2.1 Separation

Water separation is the first step of HSPEU station rules, because water can be produced with huge amounts -either from free water well and in emulsion form with the Oil Gas phases for oil onshore wells, or from offshore wells beside of the sea water characterized by its high salinity and rich compositions-.

For this study, where the focus is on water extracted basically from different wells and especially from abandoned ones, the start point is from the water being separated in separator into the electrolyser unit and then the exportation pipelines.

I.2.2 Treatment

It is the main important phase of the electrolysis operation that includes both mechanical treatments using desander/desilter machineries, followed by chemical treatment using Mixer/Heater units where the electrolyte becomes ready-to-electrolyzed fluid.

I.2.3 Electrolysis

After water becomes ready-to-electrolyzed fluid, the electrolyte then is pumped into the electrolyser unit in which enters the reservoir container and becomes in direct contact with the electrodes alimented with the necessary Gibbs free energy in form of already-defined DC electrical current from DC alimentation unit (SCR, batteries....).

Following the configuration of the electrolysis process in the HSPEU station, the electrolysis procedure (Alkaline, PEM, AEM...) also with the electrolyser design are chosen basically for obtaining several needs like the wanted production, H₂ purity, general and additional costs, technical, operational and environmental parameters.

I.2.4 Decantation/Storage

After H₂ is produced, the gas is being pumped into a decantation unit where H₂ gas gets separated from impurities that transferred with the hydrogen gas. The main objective of cleaning H₂ gas is to eliminate maximum of impurities that have an impact on both transportation conditions, deposition risks, and also hydrogen's full energetic efficiency and economic value.

The norms of cleaning, beside of H₂ final purity and composition are determined by the official contract between both producers and consumers.

I.2.5 Exportation

After getting hydrogen cleaned, H₂ now is ready to get exported into consumers by the intermediate of pipelines, boats or others.

However, H₂ should not be transported in a gas form, meanwhile liquefying H₂ in atmosphere pressure demands a temperature below or equal to -160 degree which, in technical and operational overview, is impossible. The solution to get safe and secure H₂ production is to use a special fluid model called **Adsorbed Hydrogen Fluid (AHF)**.

AHF fluid is a great candidate to get a secure and sufficient H₂ transportation by the intermediate of special materials that have the ability to form strong physical relations, which allow adsorbing H₂ molecules into the surface of those materials.

AHF fluid is defined as the result of adsorption process between adsorbed molecules in different forms (liquid form is preferred) and H₂ molecules in gas form which requires a specific Temperature and Pressure conditions to get the physical liaisons between surface of the adsorbed (chosen material) and adsorbent (hydrogen molecules).

Following the definition, the AHF process can be summarized in the following equation:

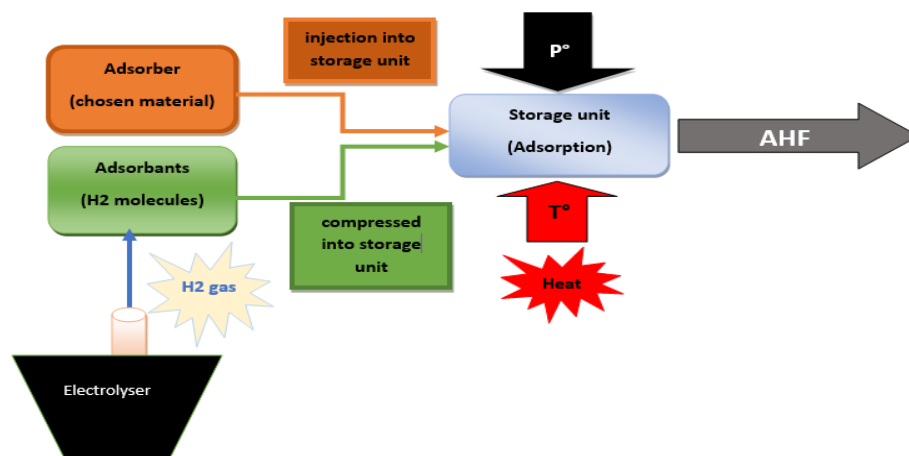


Figure I.3: Typical AHF generation process at specified Temperature and Pressure.

To get the best-chosen candidate, there are several technical and operational conditions and norms that should be verified which are:

- The chosen material should exist in huge amounts naturally or able to be produced by industrial process on large quantities.
- The adsorption process (which demand specific Temperature and Pressure) should not require non-valuable technical and operational configurations, which are the state where high Temperature and/or Pressure conditions.
- The chosen material to form the AHF fluid with hydrogen molecules should be able to form strongest physical relations to ensure maximum security during hydrogen transportation through pipelines.
- The chosen material should have maximum adsorption surface, in order to have maximum hydrogen molecules to the minimum amount possible of chosen adsorbed.

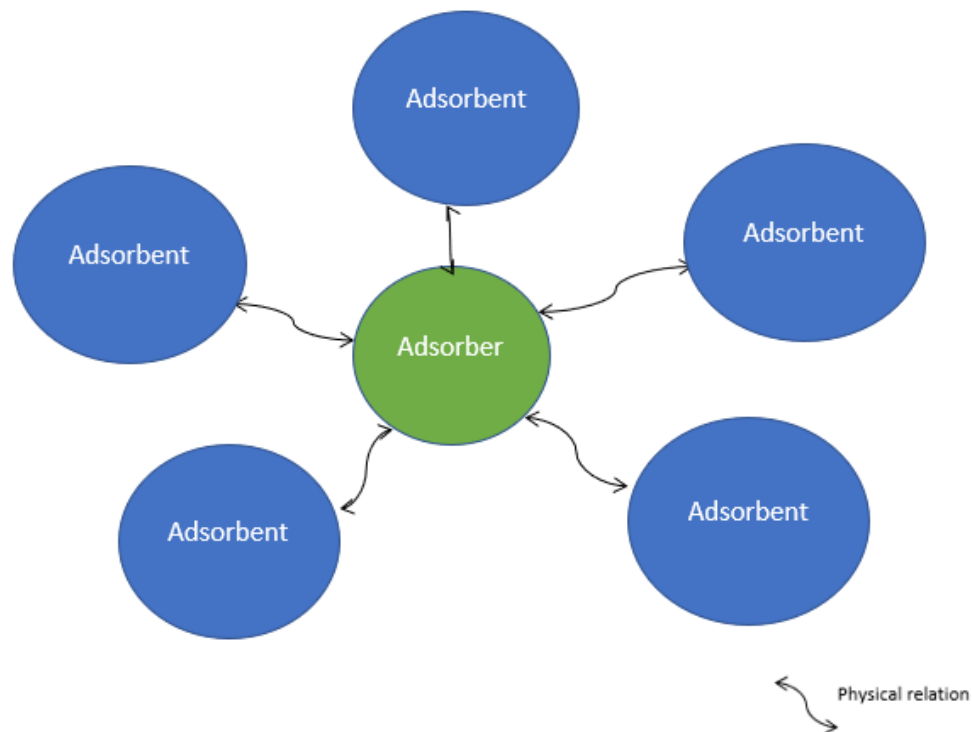


Figure I.4: The micromolecular instruction of a typical AHF fluid.

✚ The general process to obtain AHF fluid

The process of obtaining adsorbed hydrogen (from an electrolysis process) typically involves the generation of hydrogen gas through an electrochemical reaction and subsequent adsorption of the hydrogen onto a suitable adsorbent material. Here is a general outline of the process:

1. Gas production via electrolysis:

- Using a typical HSPEU prototype, the water is pumped into the electrolyser unit in which a DC current is transmitted into the water then the H₂ is produced.

2. Gas separation:

- Once the hydrogen gas is generated, it needs to be separated from the impurities and associated mixture.
- Various methods such as condensation, membrane separation, or selective adsorption can be employed for gas separation.

3. Adsorption:

- Select a suitable adsorbent material that has a high affinity for hydrogen gas (like Metal hybrids).
- The adsorbent material should have a large surface area and be capable of adsorbing and storing hydrogen atoms or molecules.
- Common adsorbents for hydrogen include activated carbon, metal hydrides, and certain zeolites.

4. Adsorption process:

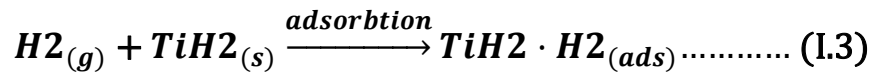
- Expose the generated hydrogen gas to the adsorbent material.
- The adsorbent will attract and trap the hydrogen gas through physical or chemical interactions.
- This results in the adsorption of hydrogen onto the surface or within the pores of the adsorbent material.

It is important to note that the specific conditions and techniques used for obtaining adsorbed hydrogen from sulfuric acid may vary depending on the intended application and desired purity of the hydrogen. The process outlined above provides a general overview, and the details may differ based on the specific requirements of your project or application.

In the adsorption process, metal hybrids can be used widely as adsorbents of H₂ where high Temperature (like that of the **Bottom Hole Temperature BHT**) can start the opposite process and release H₂ and start the FUH operation.

In this case, the next example defines the adsorption process using metal hydride (exp: TiH₂) in detailed form as following:

When hydrogen is adsorbed onto TiH₂, the process can be described by the following equation:



This next section presents a succinct overview of the crucial elements concerning the adsorption of hydrogen onto TiH₂.

- **Energy change**

The energy change associated with the adsorption process can be expressed as the enthalpy change (ΔH). Generally, the adsorption of hydrogen onto TiH₂ is exothermic, i.e., it releases heat energy. The specific value of ΔH will depend on the experimental conditions and the characteristics of the TiH₂ material.

- **Equilibrium**

The adsorption process reaches an equilibrium state, where the rate of adsorption equals the rate of desorption. The equilibrium constant (K) relates to the concentrations (or pressures) of the adsorbed and gaseous species. However, determining the exact equation for the equilibrium constant would require detailed experimental data and specific adsorption isotherms.

- **Thermodynamic parameters**

Thermodynamic parameters, such as the standard Gibbs free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°), provide insights into the spontaneity and energy changes of the adsorption process. The specific values of these parameters will depend on the experimental conditions and the TiH₂ material.

- **Adsorption isotherms**

Adsorption isotherms describe the relationship between the pressure (or concentration) of the adsorbed gas and the equilibrium adsorption capacity of TiH₂. Isotherms, such as the Langmuir or BET isotherms, can be used to model and analyze the adsorption behavior of hydrogen onto TiH₂.

It is important to note that the specific values of energy changes, equilibrium constants, and adsorption parameters for TiH₂ will vary depending on the experimental conditions, TiH₂ material properties, and the specific study.

Adsorption isotherms describe the relationship between the amount of gas adsorbed onto a solid surface (TiH₂ in this case) and the pressure or concentration of the gas. Here are two commonly used adsorption isotherms with their corresponding equations:

- **Langmuir isotherm**

The Langmuir isotherm assumes a monolayer adsorption on a homogeneous surface with no interaction between the adsorbed molecules. The equation for the Langmuir isotherm is:

$$\theta = \frac{K \cdot P}{(1 + K \cdot P)} \dots \dots \dots \text{(I. 4) [20]}$$

Where:

θ: represents the fractional coverage or the amount of gas adsorbed on the surface.

K: is the Langmuir constant related to the affinity of the gas to the surface in (mol^{-1}).

P: is the pressure of the gas in (Pa).

Langmuir equation can be used to model the adsorption behavior of hydrogen onto titanium hydride (TiH₂). This equation allows the estimation of the adsorption capacity, surface area, and other adsorption-related parameters based on experimental data.

It is important to note that the Langmuir and other isothermal equations are simplified models, and the adsorption behavior can deviate from these idealized equations in real-world

scenarios. Researchers often fit experimental data to these isotherms to determine the relevant parameters for a specific system.

The Langmuir isotherm assumes a monolayer adsorption on a homogeneous surface with no interaction between the adsorbed molecules. The modified Langmuir isotherm with the incorporation of Gibbs free energy (ΔG) and entropy change (ΔS) can be derived as follows:

It starts with the basic Langmuir isotherm equation, and introduces the thermodynamic parameters ΔG and ΔS into the equation. According to the relationship between Gibbs free energy, enthalpy, and entropy, we have:

$$\Delta G = \Delta H - T * \Delta S = -R * T * \ln(K) \dots \dots \dots (I.5)[1]$$

We obtain then,

$$T = \frac{-\Delta G}{R * \ln(K)} \dots \dots \dots (I.6)$$

Where:

T: is temperature in Kelvin.

R: is the gas constant (8.314 J/(mol*K)).

K: is the equilibrium constant.

It is assumed that the adsorption process is purely enthalpy-driven, that is to say that the entropy change is negligible compared to the enthalpy change. In this case, we can approximate:

$$\Delta S \approx 0 \dots \dots \dots (I.7)$$

To rearrange the Langmuir isotherm equation in terms of temperature (T) using a different state equation, let us consider the Redlich-Kwong equation of state:

$$P = \frac{R*T}{V-b} - \frac{a}{\sqrt{T}*V*(V+b)} \dots \dots \dots (I.8) [16]$$

By replacing T in P we find:

$$P = \frac{R * \left(\frac{-\Delta G}{R * \ln(K)} \right)}{V - b} - \frac{a}{\sqrt{\left(\frac{-\Delta G}{R * \ln(K)} \right) * V * (V + b)}} \dots \dots \dots (I.9)$$

Rewrite the Langmuir equation by substituting the value of P:

$$\theta = \frac{K * \left(\frac{R * \left(\frac{-\Delta G}{R * \ln(K)} \right)}{V - b} - \frac{a}{\sqrt{\left(\frac{-\Delta G}{R * \ln(K)} \right) * V * (V + b)}} \right)}{\left(1 + K * \left(\frac{R * \left(\frac{-\Delta G}{R * \ln(K)} \right)}{V - b} - \frac{a}{\sqrt{\left(\frac{-\Delta G}{R * \ln(K)} \right) * V * (V + b)}} \right) \right)} \dots \dots \dots (I.10)$$

I.3 Different HSPEU units

Typical HSPEU stations are composed of the following units based on the different process offered by the station:

- **Separator (active/abandoned wells).**
- **Desander/desilter.**
- **Mixer/Heat unit.**
- **Electrolysis unit.**
- **Decantation unit.**
- **Storage unit.**
- **Delivery units.**
- **Exportation pipelines.**

I.3.1. Separator

Separator is defined as a cylindrical or spherical vessel used to separate oil, gas and water from the total fluid stream produced by a well. Separators can be either horizontal or vertical. Separators can be classified into two-phase and three-phase separators (commonly called free-water knockout). The two-phase type deals only with oil and gas, while the three-phase type handles oil, water and gas.

Separators are used in a variety of industrial processes to separate different components of a mixture. In the case of water separation, a separator is typically used to remove water from oil

or gas streams, allowing each component to be used or processed separately. The separation of water from oil or gas is important in many industries, including the oil and gas industry, where the presence of water can negatively impact the performance of equipment and the quality of the final product.

The use of separators in the separation of water from oil or gas is governed by various laws and regulations, including environmental regulations, health and safety regulations, and industry standards. These laws and regulations are designed to ensure that the separation process is safe, efficient, and environmentally responsible.

Separators can be classified based on several criteria:

✚ **Based on Function**

✚ **Based on Shape**

✚ **Based on Size**

I.3.2 Main Treatment Unit (MTU)

The objective of the **MTU** is to ensure ready-to-electrolyzed fluid by both Mechanical and Chemical treatment using respectively two combined systems composed of **Solid Control Unit (SCU)** and **Mixer/Heat Control Unit (MHCU)** in which the resulting fluid is ready-to-electrolyzed.

I.3.3 Mechanical Treatment (SCU)

Desanders are solid control equipment with a set of hydro-cyclones that separate sand and silt from the drilling fluids in drilling rigs, they have no moving parts. The larger the internal diameter of the desander is, the greater the amount of drilling fluids it is able to process, and the larger the size of the solids removed [8].

For the same objectives, desander and desalter in HSPEU station are also a big necessity for eliminating all kinds of solid particles in which a risk of precipitations can be provoked on the appropriate surfaces, making a serious danger, which must be considered.

The fact that those solid particles don't have any major or minor influence of electrolysis process -following the non-influence on the chemical composition of the electrolysis fluid- doesn't mean that it's not necessary to treat them the best possible.

The existence of different valves and cross-overs beside of the huge danger resulting exportation of H₂ gas, which is characterized by the explosivity and the fact that precipitation is followed by section's changes and also risk of clogging encounter those situations, makes the desandering/desalting process a very important step on the way to obtain a ready-to-electrolyzed fluid.

I.3.4 Chemical Treatment (MHCU)

In industrial process engineering, mixing is a unit operation that involves manipulation of a heterogeneous physical system with the intent to make it more homogeneous. Familiar examples include pumping of the water in a swimming pool to homogenize the water temperature, and the stirring of pancake batter to eliminate lumps (deagglomeration).

Mixing is performed to allow heat and/or mass transfer to occur between one or more streams, components or phases. Modern industrial processing almost always involves some form of mixing. Some classes of chemical reactors are also mixers. With the right equipment, it is possible to mix a solid, liquid or gas into another solid, liquid or gas.

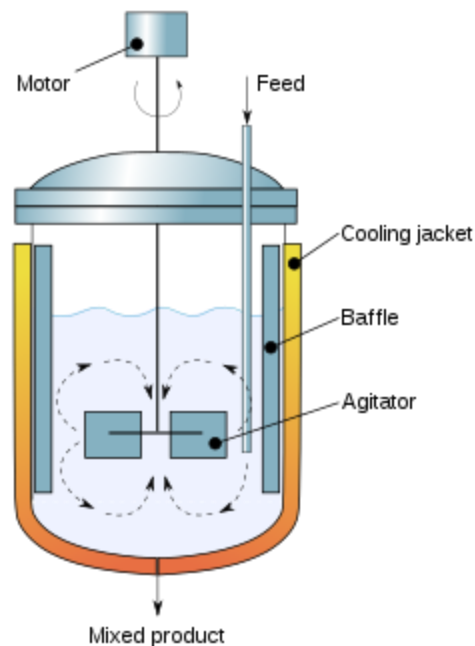


Figure I.5: Schematics of an agitated vessel with a Rushton turbine and baffles [10].

The mathematics of mixing is highly abstract, and is a part of ergodic theory, itself a part of chaos theory.

Mixing classification

The type of operation and equipment used during mixing depends on the state of materials being mixed (liquid, semi-solid, or solid) and the miscibility of the materials being processed. In this context, the act of mixing may be synonymous with stirring-, or kneading-processes. We can define several types of mixing units:

- Turbines.
- Ribbon Blender.
- V Blender.^[10]

I.3.5 Main Separation Unit (MSU)

The main Separation Unit (MSU) is the system in which the ready-to-electrolyzed fluid or the electrolyte arrives into the electrolysis process and returns into H₂ gas.

The MSU is composed of:

- Electrolyser unit
- DC alimentation unit

A. Electrolyser

Electrolyser is an electric unit which uses a DC alimentation current to feed the electrolyte with the necessary Gibbs free energy to separate Hydrogen ions from Oxygen ions and produce H₂ gas.

A typical electrolyser unit is composed of:

- a) Reservoir container in which the ready-to-electrolyzed fluid is stored.
- b) Two conductors in which one of them handles the positive charge (called the anode) and the other handles the negative charge (called the cathode). The main objectives of those conductors are:
 - Ensure the efficient contact with the electrolyte molecules.
 - Transmit the DC current into the emerged electrolyte.
 - Create the necessary voltage inside the electrolyte between two sides of the electrolyser.
- c) Gas transportation pipes where produced gas is being evacuated into the storage containers.

The shape of the electrolyser doesn't have any kind of influence on the electrolysis efficiency, however, the construction model, size and the building materials are very important factors to be considered in building an electrolyser unit in HSPEU station. Following the influence of Pressure and Temperature on the volume of both electrolyte (liquid) and H₂ (gas) beside of the electrolysis type (Alkaline/PEM/SOEL/AEM), the shape, inner construction and the other factors should be compatible with the general modeling of the electrolysis.

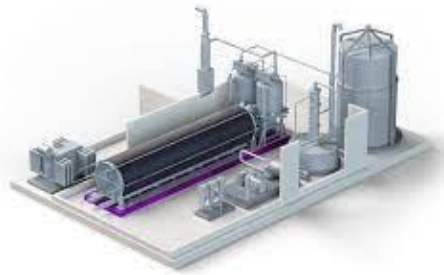


Figure I.6: Industrial-size Electrolyser.

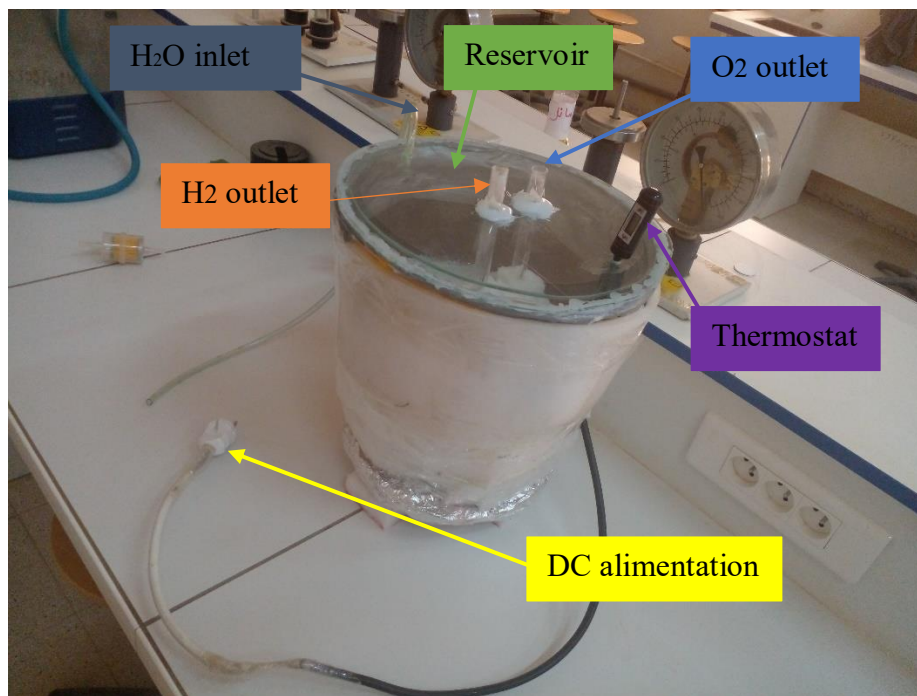


Figure I.7: Typical electrolyser used for experiments with temperature measurement.

B. DC current alimentation unit

The alimentation unit ensures feeding the electrolyser unit with the necessary DC current which being transmitted into the electrolyte by direct contacting between both the conductors and the electrolyte fluid. As the negative charge being transmitted by the cathode meanwhile the positive one is by the anode, a specified voltage is mandatory to ensure complete Gibbs free energy adsorption by the electrolyte [2].

In the field size, there is many choices to feed our electrolyser with the necessary DC current:

- First: the use of high size batteries (industrial size).
- Second: the use of combination Generators-SCR: where alimentation could be using renewable resources or diesel (similar to drilling generators).

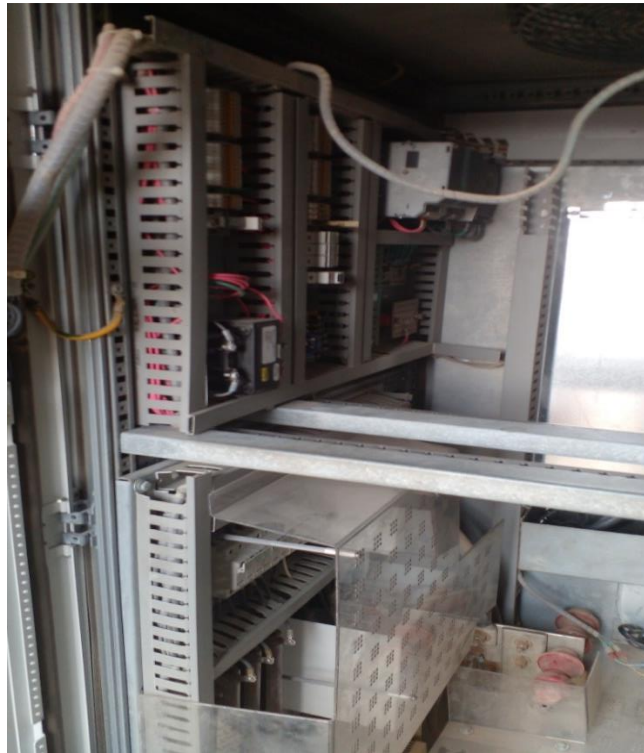


Figure I.8: Figure shows an SCR command unit (ENTP-DMP).



Figure I.9: A 9-12V SCR unit used for experiments.




I.3.6 Decantation/Storage unit

The main role of this unit is to allow H₂ decantation and storage after arriving from the MSU unit.

In the following table, different criteria of the HSPEU main units are defined:

Table I.2: Different HSPEU Units.

Process	Unit	Operational characteristics	Figure
Separation	Separator	<ul style="list-style-type: none"> • Low-Pressure: 10 to 180 psi. • Medium-Pressure: 230 to 700 psi. • High-Pressure: 975 to 1500 psi. 	
Treatment	SCU	<ul style="list-style-type: none"> • 10" cone: 50% efficiency with 40-50 μm solids and flow of 500 USG/min. • 4" cone: 50% efficiency with 15-20 μm solids and flow of 60 USG/min. • Micro-fines cone: 50% efficiency with 10-15 μm solids and flow of 15 USG/min. 	

	MHCU	Based on the used units	
Electrolysis	Electrolyser Group	Based on the used units	 [23]
Storage	Storage Container	Based on the used unit	

I.4 different parameters that influence the production

Besides of Temperature and Pressure, electrolyte's chemical composition with technical and configurational parameters (including design, different sections, length and building's materials...) of different HSPEU station's units like those of the electrolyser, desander, mixer.... are also core components in the road to a specific gain. The general design of an HSPEU station and the electrolysis process of a treated electrolyte define the H₂ produced volume and what HSPEU station's model is necessary to get a safe, sufficient and effective H₂ production.

Those parameters can be divided into two big categories:

- Mechanical parameters.
- Chemical parameters.

I.5 Optimization of H₂ production through mechanical/chemical optimizations

H₂ production's value in specified conditions can be influenced by two categories of parameters:

- ✓ Chemical parameters: which related directly to the electrolyte, including
 - Chemical composition of electrolyte.
 - Undesired reactions inside the electrolyte.
 - Electrodes-Electrolyte interactions.

- The different phenomena between Electrode, Electrode-Electrolyte, Electrolyte:
- ✓ Mechanical parameters: related to design, building materials, construction model and different units enrolled in the production and transportation process including its functionalities, desired conditions for best performance.... Those parameters at the level of the electrolyser unit can be summarized in:
 - Type of electrodes.
 - Form and design of electrodes.
 - Electrode's interface.
- ✓ For the HSPEU unit we can define:
 - Units' configuration and HSPEU design.
 - Electrolysis's Working Temperature and Pressure (EWTP).

- **Limitations**

To quantify an electrolysis process and determine or predict H₂ gain which obtained by electro-splitting process, it is enough to study the entire process via the observation and consideration of different molecular and intermolecular phenomena and how mechanical and chemical parameters can influence directly or indirectly on those levels.

I.6 Influence of water composition on production (Feroui-Madani Experiment)

Water composition represents a principal chemical property that has a direct influence on H₂ production through the influence on different phenomena that we encounter when we do electrolysis. Beside of the exchangeable impact with the mechanical properties such temperature and pressure, there is also external factors that influenced by this parameter such rheological and intermolecular factors which also are very important in electrolysis process.

Feroui-Madani Experiment defines and shows those influences on production, helps engineers to predict, design and to produce in total security and efficiency H₂ gas from a reservoir water.

Based on gain equation with considering series of electrolysis laws (Merouane-Latifa zero, first, second and third laws of electrolysis), engineers can study the production process through electrolysis in a micro and macromolecular interval.

I.6.1 Ion's influence

As different chemical elements exist in ionic form which, in existing of other chemical elements, several reactions can be occurred where general and specific properties can influence.

Reservoir water, like that extracted of HTF-14 that is our sample used for this study, has a very interesting chemical composition, which can influence deeply the H₂ gain by both negative and positive impact.

During the life cycle of those active wells where different operations can be affected using different techniques like CTU and Snubbing, the chemical composition encounter several changes in result of using operational and technical fluids which in some cases can be pumped into the reservoir rock, effecting directly on the reservoir properties.

I.6.2 Density

Density is defined as the regular distribution of principal and secondary building materials of a specific fluid in liquid or gas state for a specific volume of this fluid.

Following the density impact on rest of the rheological factors, which impact also on the principal fluid properties, it is necessary to quantify density in specific condition and determine the best value for obtaining the maximum gain.

Density has direct impact on water's molecular mobility, moreover, molecular velocity which determines the flow value and how much is the wave flow of water molecules in a specified time.

I.6.3 Viscosity

Other rheological factor which is the water viscosity. Viscosity is a primer factor which used in gain equation to indicate the influence of chemical composition on electrolysis gain.

It's important to note that viscosity is much important to consider more than density factor, which can be concluded by comparing H₂ gain of different systems with different composition and with the same density but in different mechanical and conditional conditions in which viscosity is not the same in all those fluid systems. This comparison shows clearly that viscosity is a main parameter in gain equation.

I.6.4 Other rheological factors (Fick's first law)

Fick's first law indicates that in fluid system (most likely liquid ones), the molecules are travelling through a specific surface in a wave-flow form from a highly concentrated zone into lower concentrated zone in a spontaneous process.

Fick's first law:

$$J = -D_{iff} * \left(\frac{dc}{dx}\right) \dots \dots \dots (I. 11) [24]$$

Where:

J: the flow-wave in (mol/ (m² * s)).

D_{iff} : the diffusion constant in (m²/s).

($\frac{dc}{dx}$) : the concentration gradient in (mol/m⁴).

The importance of Fick's first law occurs as it helps us in studying the mechanism of water molecules in specific conditions and how we can orient maximum of water molecules into the conductors.

As Diffusion can be defined using the principals of thermodynamics (Entropy) which known as Stokes-Einstein equation:

$$D_{iff} = \frac{K*T}{6*\pi*\mu*r} \dots \dots \dots (I. 12) [24]$$

Where:

K: Boltzmann coefficient in **1.380649×10⁻²³ J*K⁻¹**.

T: **Temperature** in (K).

μ : Dynamic viscosity in (Pa*s).

R: molecule's radius in (m).

I.6.5 Hydrogen Separation Factor (HSF)

At different scales, there are a huge number of water models in which everyone is unique by several properties including chemical compositions, place of existing or extraction, rheological properties like density, viscosity and others (Yield Point, Bubble Point....). for this reason, the general comportment of water molecules in the electrolyte used to H₂ production is unique and several phenomena occur during this electrochemical operation. It's noted that during electrolysis

of different electrolytes models, which even have the same rheological properties like density or viscosity, H₂ production is not similar, which in this case, a principal factor must be defined as a representative property of the electrolyte, which we call Hydrogen Separation Factor HSF, defined by the Feroui-Madani zero law of electrolysis (FM-00 law of electrolysis):

$$\text{HSF} = \frac{V_{H2}}{V_{total H2O}} \dots\dots\dots (I.13)$$

We can define three types of HSF factors:

- HSF at real conditions (operating conditions), noted HSF_{real} or HSF:

It represents the produced amount in specific operation conditions in specified chemical properties. The determination of the specific value is occurred by using simulation to predict or by experiments.

- HSF at theoretical conditions (reference conditions), noted HSF_{th} :

Represents the produced amount in reference's operation conditions in specified chemical properties, in which $T = 298.15 \text{ }^\circ\text{K}$ and $P = 1 \text{ atm}$.

- HSF at ideal conditions (distillated water), noted HSF_{ideal} :

Represents the produced amount in reference's operation conditions using ideal chemical properties and distillated water model (only water molecules), in which $T = 298.15 \text{ }^\circ\text{K}$ and $P = 1 \text{ atm}$.

The importance of using different HSF factor is to generate appropriate equations which allow us to determine specifically the possible amount of H₂ in an HSPEU station, and to determine in the other hand the necessary chemical and mechanical conditions to obtain a specific production of H₂ from an electrolyte model.

I.6.6 Influence of Temperature and Pressure on H₂ production

Temperature and pressure are mechanical parameters that relate directly into design, operating and technical process of electrolysis and the environmental parameters.

- **Influence of Temperature**

Temperature is considered a main mechanical parameter in which has a direct impact on gain through the influence on molecule's movement via a volume of electrolyte. Previous researches show that temperature is a keyword in electrolysis; however, those studies did not

quantify or show the direct impact of this parameter and what type of the relation between temperature and gain.

✓ **Distribution Factor (DF)**

Distribution Factor (DF) is defined as the number of water molecules get into the conductor from a total number of those molecules.

$$DF = \frac{N_{water\ to\ be\ electrolysed}}{N_{total\ H2O}} \dots\dots\dots (I.14)$$

Using the previous equations of both Fick and diffusion, this parameter can be defined by Merouane - Latifa first equation as following:

$$J' = DF * J \dots\dots\dots (I.15)$$

$$J' = - DF * D_{iff} * \left(\frac{dc}{dx}\right) \dots\dots\dots (I.16)$$

In which DF can be defined as follow:

$$DF = - \frac{J'}{D_{iff} * \left(\frac{dc}{dx}\right)} \dots\dots\dots (I.17)$$

Where:

- J' = wave-flow in specified position in $(mol / (m^2 * s))$.

By using Stokes-Einstein equation, we finally obtain Feroui-Madani first law of electrolysis:

$$\begin{aligned} DF &= - \frac{J' * 6 * \pi * \mu * r}{K * T * \left(\frac{dc}{dx}\right)} = - \frac{J' * L * \mu}{T} \\ &= - \frac{J' * L * \vartheta * \rho}{T} \\ &= - \frac{J' * L * \vartheta * d * \rho_w}{T} = f(\vartheta, d, T) \dots\dots\dots (I.18) \end{aligned}$$

Where:

ϑ = cinematic viscosity in $m^2 * s^{-1}$.

d = electrolyte density.

ρ_w = volumic weight of electrolyte in $Kg * m^{-3}$.

L = Electrolyte Technical Factor (ETF) = $\frac{6 * \pi * r}{K * \left(\frac{dc}{dx}\right)}$, in $[K * m^3 * s^2 * kg^{-1} * mol^{-1}]$.

✓ **Electrolysis Speed Factor (ESF)**

Electrolysis Speed Factor (ESF) is defined as the relation between theoretical time necessary to electrolyze one molecule on water and the real time, considering the time loss due the loss of the electricity and energy exchanges between both the conduction and the electrolyte fluid.

At the level of the conductor, several parameters like electrical conductivity, current density, electrical charge... are main parameters involves in electrolysis gain value:

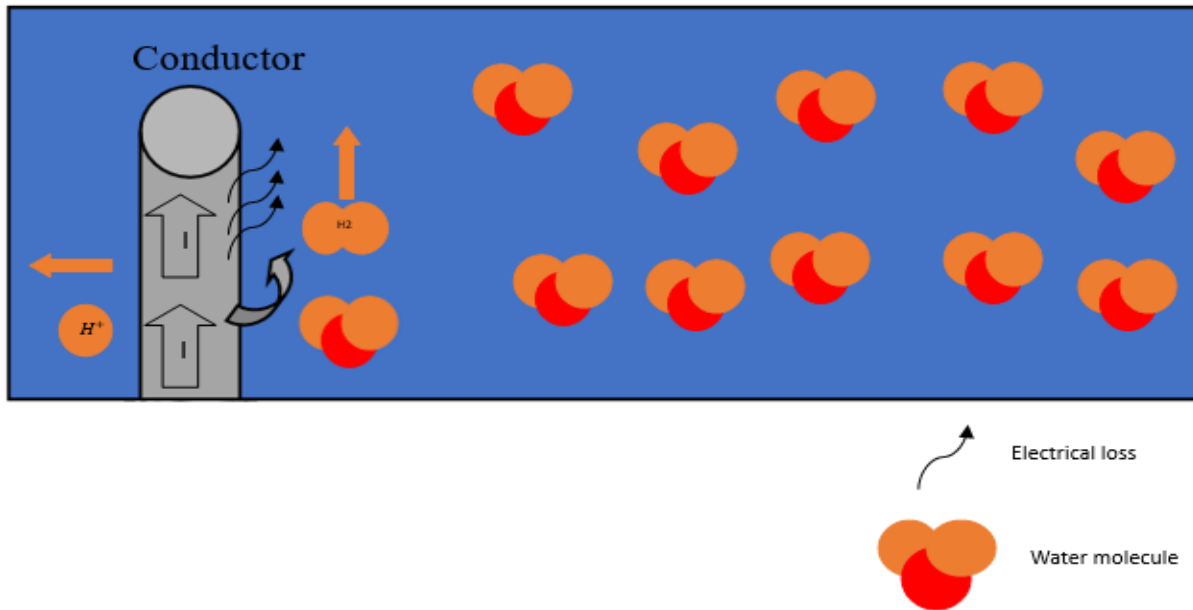


Figure I.10: Electrolysis process at micromolecular level.

At the level of the conductor, the following formulas can be defined:

The total electrical charge:

$$C = I * t = N * Q_{ele}^* \dots \dots \dots (I. 19) [24]$$

Where:

C = electrical charge of N electrons in coulomb.

I = current in Amp.

t = time (necessary to electrolysis) in second.

N = number of electrons.

Q_{ele}^* = electrical charge of one electron = $1.6 * 10^{-19}$ C.

And we have, the following definition of electrical capacity:

$$C_{ele} = \frac{N}{S} = \frac{I*t}{S*Q_{ele}^*} \dots\dots\dots (I.20)$$

Where:

C_{ele} = electrical capacity of the conductor in electron / m^2 .

S = conductor surface in m^2 .

And, the electrical density:

$$C_{ele} = \frac{I}{S} = \frac{C_{ele} * Q_{ele}^*}{t} \dots\dots\dots (I.21)$$

Where:

C_{ele} = electrical density in Amp / m^2 .

And as one H₂O molecule requires (2) electrons to get split and to give one H₂ molecule, we can conclude that:

$$V_{H2} = N_{H2} * V_{H2}^* \dots\dots\dots(I.22)$$

Where:

V_{H2} = produced hydrogen volume in m^3 .

N_{H2} = number of produced H₂ molecules.

V_{H2}^* = specified H₂ molecule volume in the specified Temperature / Pressure conditions in m^3 .

And as:

$$N_{H2} = \frac{N}{2} = \frac{I*t}{2*Q_{ele}^*} \dots\dots\dots(I.23)$$

We conclude that:

$$V_{H2} = \frac{I*t*V_{H2}^*}{2*Q_{ele}^*} \dots\dots\dots(I.24)$$

This means:

$$t = \frac{2*V_{H2}*Q_{ele}^*}{I*V_{H2}^*} \dots\dots\dots(I.25)$$

Following the previous definition of ESF factor, we can define t_r and t_{th} where:

$$t_r = \frac{2*V_{H2}*Q_{ele}^*}{I_r*V_{H2}^*} \dots\dots\dots(I.26)$$

and,

$$t_{th} = \frac{2 \cdot V_{H2} \cdot Q_{ele}^*}{I_{th} \cdot V_{H2}^*} \dots\dots\dots (I.27)$$

where:

$$I_r = I_{th} - \sum I_{loss}$$

t_r = real time to electrolysis in seconds where $I = I_r$ (with loss).

t_{th} = theoretical time to electrolysis in seconds where $I = I_{th}$ (without loss).

As a result:

$$ESF = \frac{t_{th}}{t_r} = \frac{I_r}{I_{th}} = \frac{I_r - \sum I_{loss}}{I_{th}} \dots\dots\dots (I.28)$$

Which is the Feroui-Madani second law of electrolysis?

✓ **Non-desired Reactions Factor (NRF)**

In reality, there are two principal types of energy loss in electrolysis process:

- Mechanical loss: at the level of the conductor, in which current enter the cathode is not the same as absorbed by the electrolyte by the direct contact in the interface. Electrical loss is occurred in form of radiation, heat, or other forms.... ESF is used to indicate this kind of loss.
- Chemical loss: at the electrolyte as loss of water molecules in form of Non-desired Reactions.

NRF factor is defined as the entire loss of water molecules at the level of the electrolyte I which is the total number of the water molecules becomes much less which can minimize the gain value.

First, we define the **Water's Total Volume to Electrolysis (WTVE)**:

$$WTVE = \sum \text{all volumes} =$$

$$V_{electrolysed\ already} + V_{ready\ to\ electrolisis} + V_{NRF} + V_{free\ volume} \dots\dots\dots (I.29)$$

Using the definition of DF and HSF (Hydrogen Separation Factor), NRF can be defined as following:

$$NRF = \frac{V_{NRF}}{V_{total\ H2O}} = (1-DF) * (1-a*HSF) - FVF \dots\dots\dots (I.30)$$

Where:

$$\text{HSF} = \text{Hydrogen Separation Factor} = \frac{V_{H_2}}{V_{\text{total } H_2O}}$$

$$a = \text{the volume conversion factor} = \frac{V_{H_2O \text{ at } T^\circ, P^\circ}}{V_{H_2 \text{ at } T^\circ, P^\circ}}$$

FVF = Free Volume Factor, which represents the rest of water molecules which didn't involves at any kind of reactions = $\frac{V_{\text{free volume}}}{V_{\text{total } H_2O}}$.

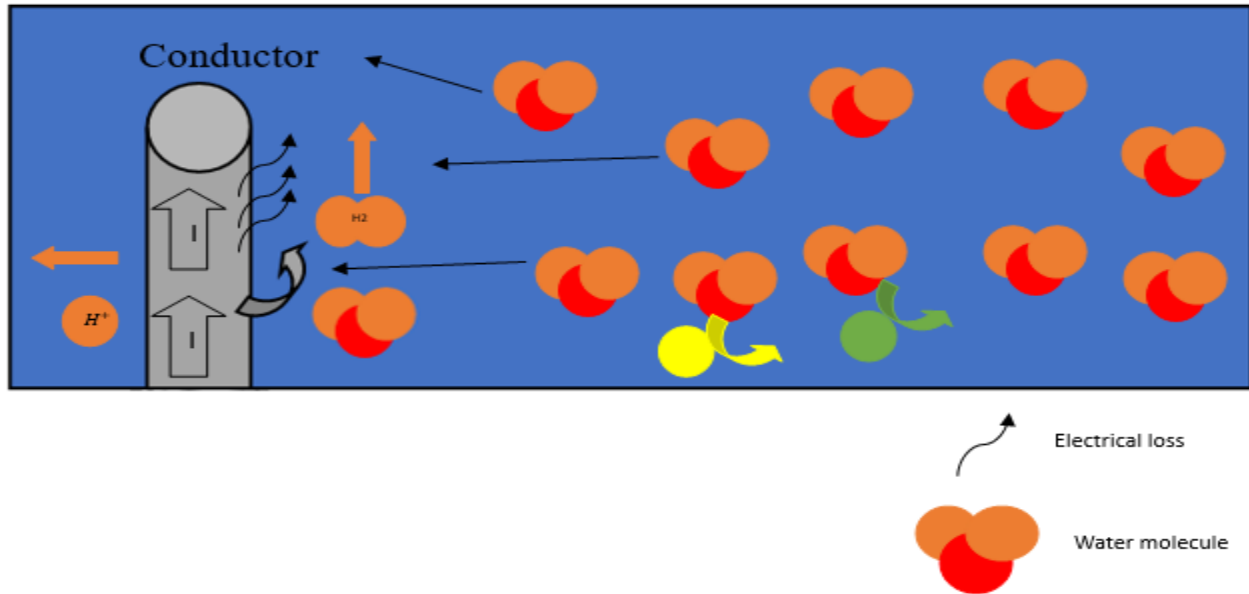


Figure I.11: Different factors.

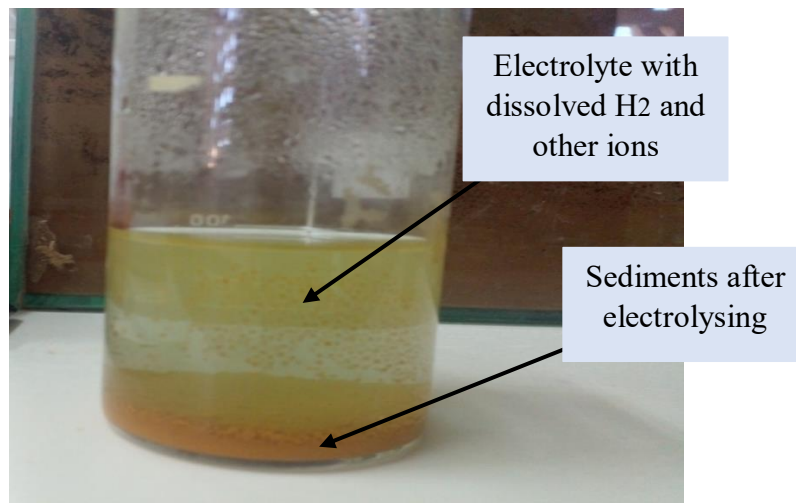


Figure I.12: Depositions of NRF deposits of a water model after electrolyzed.

At the figure up, we can see that:

$$DF = 3 / 11 = 0.2727 = 27.27 \%,$$

$$FVF = 6 / 11 = 0.5454 = 54.54 \%,$$

$$NRF = 2 / 11 = 0.1818 = 18.18 \%.$$

We conclude that:

$$DF + NRF + FVF = 1 \dots\dots\dots(I.31)$$

Which means that:

$$\begin{aligned} NRF &= 1 - DF - FVF = 1 - FVF + \frac{J' * L * \vartheta * d * \rho_w}{T} \\ &= f(\vartheta, d, T) \dots\dots\dots(I.32) \end{aligned}$$

Which is the Feroui-Madani third law of electrolysis?

According to the definition, NRF represents the general loss of hydrogen production at the level of the electrolyte -where loss at the level of the conductor is defined at ESF factor-. We conclude that **Availability Factor (AVF)** is defined by the formula:

$$\begin{aligned} AVF &= 1 - NRF = \frac{V_{ready\ to\ electrolyzed} + V_{free\ volume}}{V_{total\ H2O}} \\ &= \frac{V_{ready\ to\ electrolyzed}}{V_{total\ H2O}} + FVF \dots\dots\dots(I.33) \end{aligned}$$

- **Influence of Pressure**

Pressure, as mechanical parameter, doesn't involve in electrolysis process in direct way, however, the main influence of pressure is obviously in volumes specially when it comes to gas like hydrogen in which there's highly risks according to the check-ability of this gas in presence of other gas or the brutal change in pressure which results a fast and important temperature increase.

The pressure regulation is a corner stone in the design of the HSPEU station, since the compressibility and norms security of H2 transportation via different pipes and sections are very important considerations in design and realization of different HSPEU station units, which requires a full study in all sides, consideration of all scenarios and huge regarding of the entire production systems.

I.7 Generation of general simulation through the ideal and the real production

Using MATLAB and Gain general law, a simulation which including all the possible values is mandatory.

The importance of using global simulation is the ability to predict, study and conclude the targeting values of different parameters involving the electrolysis process in order to obtain a specified H₂ gain.

I.7.1 Presentation of the FM gain low and FM gain Experiment

Hydrogen gain is defined mathematically as the relation between produced hydrogen in real conditions versus the same produced in theoretical or reference conditions ($T^\circ = 298,15 \text{ K}$, $P^\circ = 1 \text{ atm}$), which also can be defined -by definition of HSF- as the relation of both real and theoretical Hydrogen Separation Factor (HSF).

$$G_{H2} = \frac{V_{H2 \text{ real}}}{V_{H2 \text{ th}}} \dots\dots\dots (I.34)$$

In physics, Hydrogen gain is the factor that represents what limit of production that we can produce over a specified electrolyte model characterized by its special HSF value.

FM gain law (Feroui-Madani forth law of electrolysis) is defined by the following formula:

$$G_{H2} = DF * ESF * AVF \dots\dots\dots (I.35)$$

$$= a_0 * DF^2 + b_0 * DF \dots\dots\dots (I.36)$$

$$= a_0 * \left(\frac{J' * L * \mu}{T}\right)^2 - b_0 * \left(\frac{J' * L * \mu}{T}\right) \dots\dots\dots (I.37)$$

Where:

$$a_0 = \text{descending production factor} = ESF * (1 - a * HSF) = \left(\frac{I_r - \sum I \text{ loss}}{I_{th}}\right) * (1 - a * HSF)$$

$$b_0 = \text{ascending production factor} = ESF * (a * HSF - FVF) = \left(\frac{I_r - \sum I \text{ loss}}{I_{th}}\right) * (a * HSF - FVF)$$

We can define another form of Gain general law (2D) as following:

$$G_{H2} = a_0 * (DF^2 - DF) + ESF * DF * (1 - FVF) \dots\dots\dots (I.38)$$

$$= b_0 * (DF - DF^2) + ESF * DF^2 * (1 - FVF) \dots\dots\dots (I.39)$$

I.7.2 Data generation using MATLAB program

Using MATLAB simulation of FM forth law of electrolysis with consideration of all possible values of different electrolysis parameters and for an HSF range of 100 to 500, we obtain the following results:

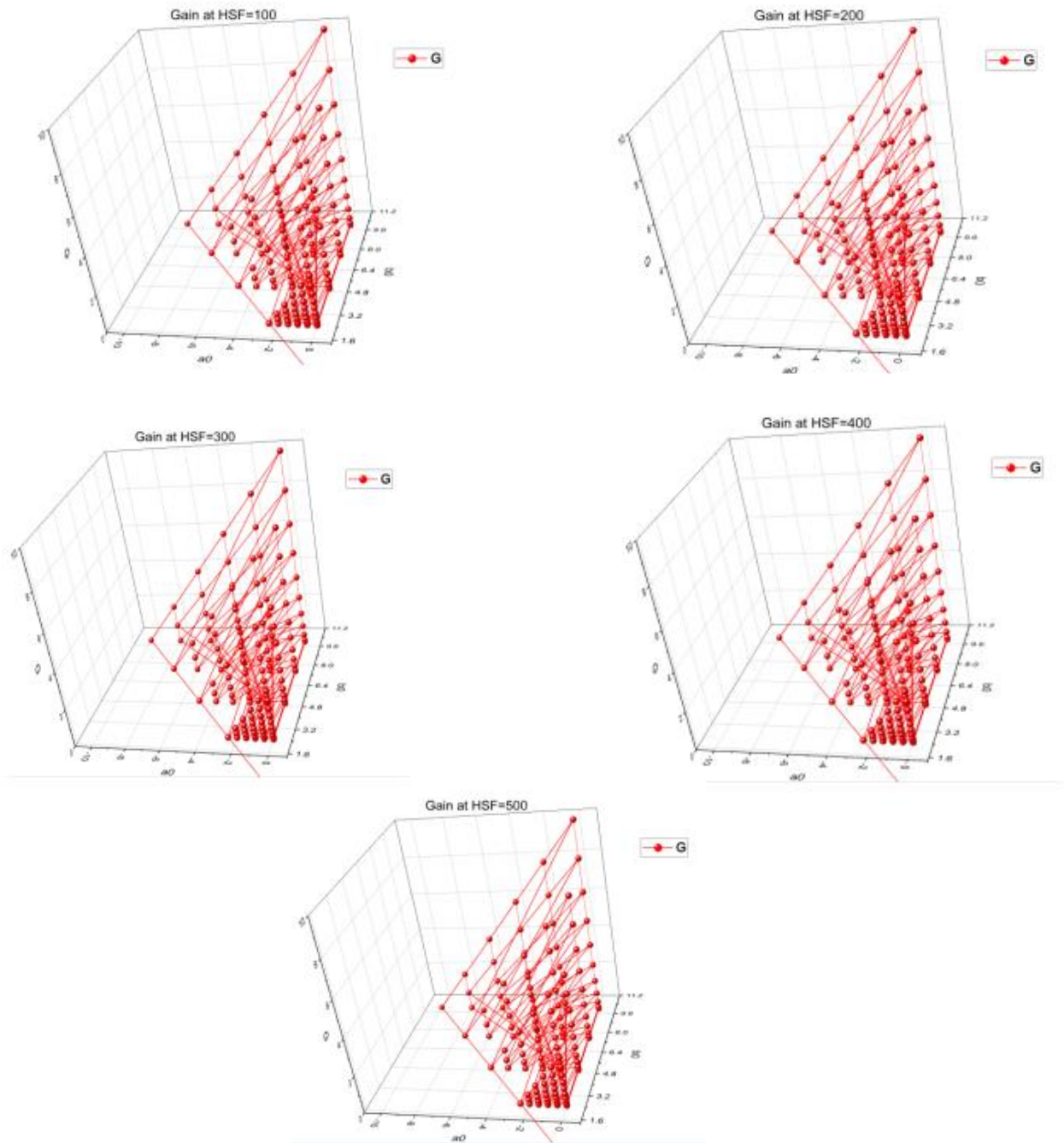


Figure I.13: Different gain clouds at different HSF values.

I.7.3 Analyze, interpretation, solutions and conclusions

A. Analyze of results

As shown in the figures up, which represent the H₂ Gain Cloud, we observe the following:

- The gain clouds are similar in different HSF values.
- The cloud has a 3D **Peak-Shaped** form with a range of 0.0 to 8.1 of gain.

B. Interpretation of results

We can Elucidate the reason why all those curves were identic even HSF value is not the same (which represents different electrolyte model) as following:

- First, -even if HSF is not the same but the other factors were the same for all the cases- the similarity means that for different electrolyte models, the general behavior is identic, which means that the type of the electrolyte is not a decisive factor for obtaining the targeting gain.
- Second, we conclude that Gain or HSF are not also decisive parameters, in other terms, we can obtain the same results for reservoir or sea water, lac or even water evaporated in air in condition of having the same DF, ESF and FVF factors.
- Third, in specific conditions, Gain has an upper-peak that called **Feroui-Madani Peak (FMP)**, which represents the maximum reachable gain, can be obtained by electrolysis in determined conditions.

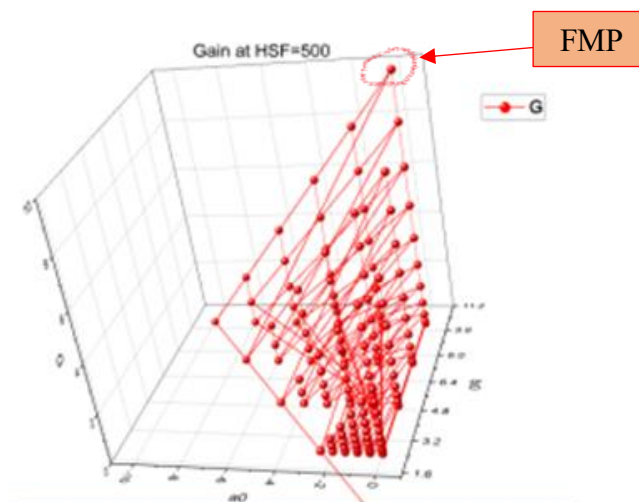


Figure I.14: FMP point.

We define based on this interpretation the **Feroui-Madani Triangle of Choice (FMTC)**:

The **FMTC** triangle is a tool used to determine the best efficient and economic candidate of different electrolyte models available in hand.

The importance of this triangle occurs as HSF, Gain or other are not alone a decisive factor.

The FMTC is composed of three parts: **Gain**, **HSF** and **Availability**.

C. How FMTC works?

Supposing we have two kinds of electrolyte models:

The first one has a high HSF value but low Gain with low availability, meanwhile, the second is the opposite of the first (low HSF with Gain and Availability are high). The choice would be the second one even the first has high HSF which means good H₂ produced volumes. The justification of this choice can be summarized as high Gain means that almost amount of possible H₂ produced volume is able to extract even the low HSF which means low H₂ amount from specified H₂O volume, and the availability means that the electrolyte is already exists with huge amounts, which in other terms that the availability can cover the low HSF value which is not the same in the first electrolyte model where low availability even the HSF is very high.

It's clear that HSF or Gain are not sufficient to get the greater production but also the existence of sufficient original volumes of the electrolyte which is the reason of why abandoned wells water shall be used for electrolysis even a chemical treatment is mandatory for getting into a ready-to-electrolysis state.

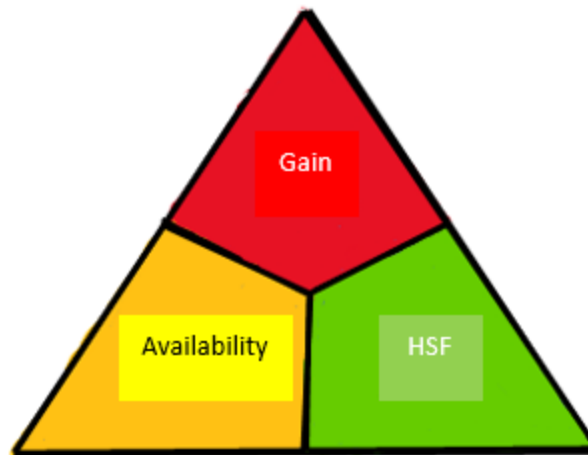


Figure I.15: FMTC triangle.

Conclusion

In sum, the utilization of Feroui-Madani (FM) equations in electrolysis studies plays a pivotal role in determining the estimated gain and optimizing the overall efficiency of the process. By incorporating FM equations into research and analysis, researchers can gain valuable insights into the complex electrochemical reactions occurring during electrolysis of HC-HV water systems. The FM equations provide a comprehensive framework for quantitatively understanding the relationship between the electrical charge passed through the system and the quantity of substances produced or consumed.

Furthermore, several chemical and mechanical factors can influence the rheological parameters of an electrolyte. These factors include the concentration of electrolyte components, temperature, density and viscosity, all with mechanical stress on the electrodes. Chemical and mechanical treatments are instrumental in obtaining the best electrolysis conditions. Chemical treatments involve modifying the composition of the electrolyte or incorporating additives to enhance the reaction kinetics and minimize side reactions. Mechanical treatments, on the other hand, focus on optimizing the physical properties of the system, such as electrode design and configuration, solids presence and others... to promote efficient mass and charge transport.

Chapter II

Technical Solutions to Optimize Hydrogen Production

Introduction

The increasing global demand for clean and sustainable energy sources has propelled hydrogen to the forefront as a promising fuel alternative. Electrolysis, the process of splitting water into hydrogen and oxygen using electrical energy, offers a viable pathway for large-scale hydrogen production. However, to fully harness the potential of electrolysis, it is imperative to study and optimize its efficiency.

The efficiency of electrolysis plays a crucial role in determining the economic viability and environmental sustainability of hydrogen production. To achieve optimal efficiency, it is essential to explore and identify the most effective treatment strategies. These strategies may involve electrode material modifications, fine-tuning operating conditions, or implementing catalysts to facilitate faster reaction rates.

II.1 Influence of different ions in two different water models

In this chapter, we are going to test two different water models that represent different electrolyte models. The importance of this simulation is to test, observe different phenomena and to get a sufficient idea about the water behavior in presence of different chemical ions (close to present ions in the field).

II.1.1 Non-Treated Water NTW (presence of sand, lemon and other sediments)

This water model is a simulation sample that is close to water extracted directly from the well. In this simulation, we are going to use different products (NaCl, NaHCO₃).

A. With the presence of NaCl

In this simulation, we used heated dusty water with an amount of NaCl salt. The observation after electrolysis of this water model is a good productivity with color turns into orange close to red and some electrode's corrosion.



Figure II.1: Non-Treated Water with NaCl.

B. With the presence of NaHCO₃

In this simulation, we used also a dusty water, but with the presence of Sodium Bicarbonate in which the results were non observed corrosion of the electrodes and the color becomes blue-green, with good productivity.

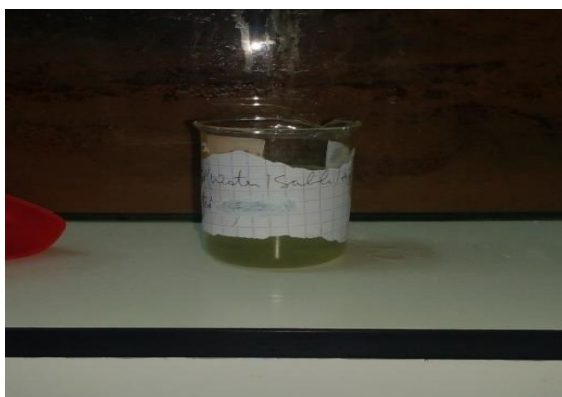


Figure II.2: Non-Treated Water with NaHCO₃.

C. With the presence of both

The corrosion doesn't seem observed with water's color turn into blue-green which means the high influence of bicarbonates more than chloride ions and the productivity is also very good.



Figure II.3: Non-Treated Water with NaHCO_3 and NaCl .

II.1.2 Fresh water (no sediments no ions)

This water model is a simulation sample that's close to water treated ideally after extracted from the well. In this simulation, we are going to use different products (NaCl , NaHCO_3).

A. With the presence of NaCl

It is similar to the dusty water model but with low productivity.

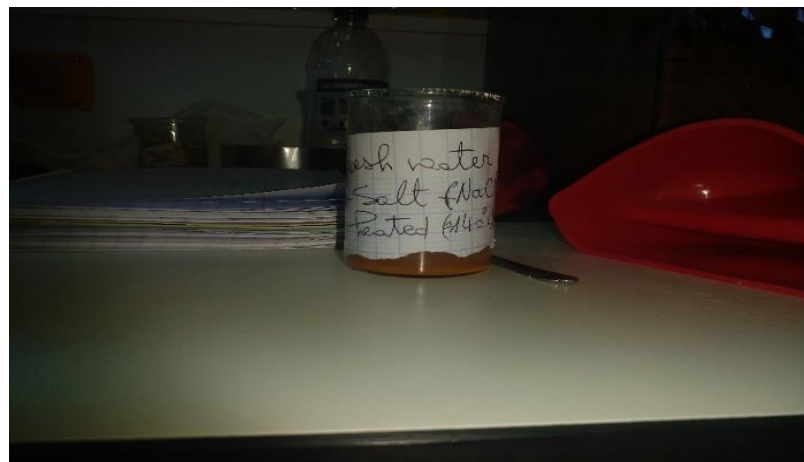


Figure II.4: Fresh water with NaCl .

B. With the presence of NaHCO_3

It is similar to dusty water model with good productivity.

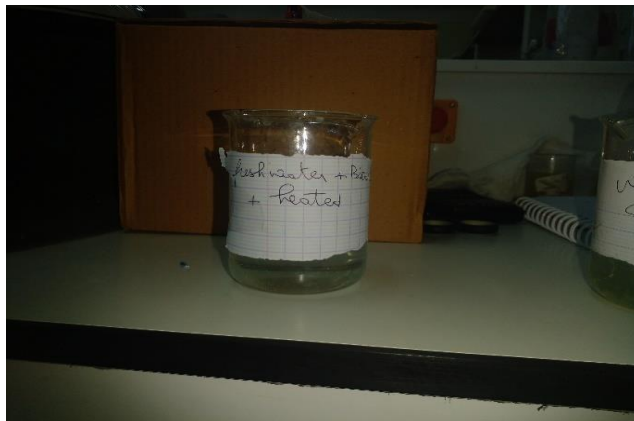


Figure II.5: Fresh water with NaHCO_3 .

C. With the presence of both

It is similar to dusty water with good productivity.



Figure II.6: Fresh water with NaHCO_3 and NaCl .

II.1.3 General Results

Table II.1: Electrolysis of NTW and fresh water in presence of NaCl and NaHCO₃.

	NaCl		NaHCO ₃	
	With heat	Without heat	With heat	Without heat
Non-Treated water	<ul style="list-style-type: none"> • High electrolysis • Corrosion • High deposition 	<ul style="list-style-type: none"> • Low electrolysis • No Corrosion • Natural deposition 	<ul style="list-style-type: none"> • High electrolysis • Corrosion • High deposition 	<ul style="list-style-type: none"> • Low electrolysis • No Corrosion • Natural deposition
Fresh Water	<ul style="list-style-type: none"> • High electrolysis • Corrosion • No deposition 	<ul style="list-style-type: none"> • Low electrolysis • No Corrosion • No deposition 	<ul style="list-style-type: none"> • High electrolysis • Corrosion • No deposition 	<ul style="list-style-type: none"> • Low electrolysis • No Corrosion • No deposition

II.2 Optimization of H₂ production through FM fluid model's applicationII.2.1 Production of H₂ through treated water from separator (case study of HTF-14 well)

HTF-14 is an active artificial-lifting well that is currently open to production. The reason behind choosing this type of wells is that water production generally high which results if more hydrostatic pressure of the produced oil in the well path.

II.2.2 General informations about HTF-14 well

A. Location and statue

Table II.2: Location and statue of HTF-14 well.

Well		HTF-14	
Zone	HZP		
Date of Drilling	01/12/2012		
Location	X : 819010.0907 Y : 85614.0441 Z _{SOL} : 157 (m) Z _{TABLE} : 165 (m)		
Depth	3461 (m)		
Statue	Artificial Lifting (Open)		
Manifold / Sous-Manifold	GOSP-HGA / HTFM2		

B. Technical sheet of HTF-14 well

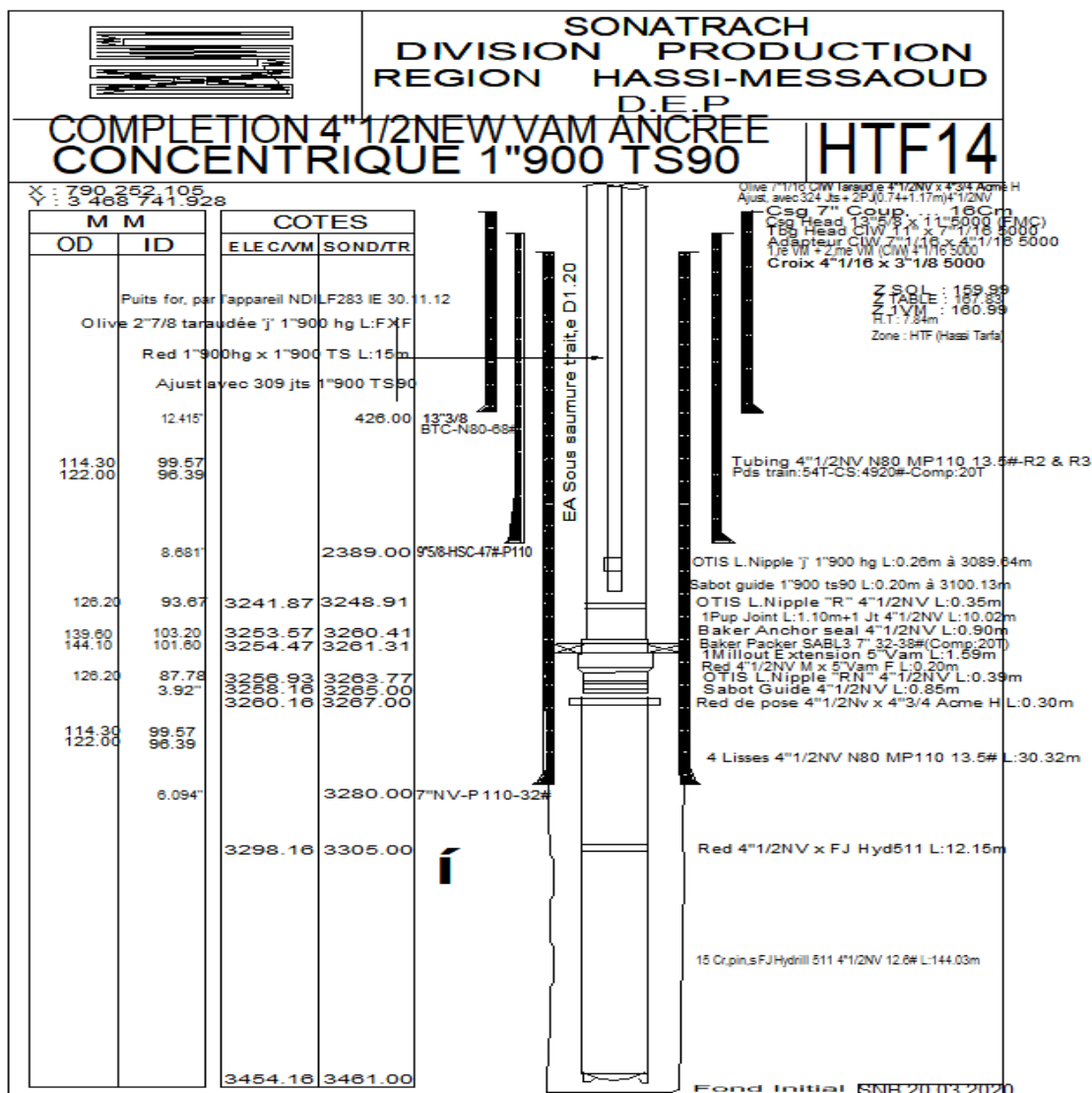


Figure II.7: HTF-14 technical sheet.

C. Water chemical compositions

During several operations that were handled on this well, water chemical composition and for using multiple chemical products was changing but not so deeply.

In general, HTF-14's produced water is considered Highly Magnesium Concentration, which is the thing we can use for both AHF and FM-01 preparation.

Table II.3: HTF-14 well's change of composition (mg/l) after different operations.

Well	Operation	Cl ⁻	Ca ⁺⁺	Mg ⁺⁺	Fer	SO4 ⁻⁻	K ⁺	pH	Density	Salinity (g/l)	Comment
<i>HTF14</i> (Before 2021)	After Fracturing	149,173	12,825	6,463	/	/	/	5.7	1.13	202	Mixture: Reservoir water+ sweet water
<i>HTF14</i> (09-29-2021)	Sample 01: Separator (Oil outlet)	/	/	/	/	/	/	/	0.78	/	Oil
	Sample 02: Separator (Water outlet)	151,548	16,432	8,262	703	/	/	5.7	1.15	244	Majority: reservoir water with highly Mg concentration
<i>HTF14</i> (20-04-2022)	Separator (Water outlet)	152,718	21,024	9,002	1,200	130	3,420	4.62	1.17	270	Mixture sweet water + reservoir water (majority reservoir water)
<i>HTF-14</i> (03-15-2023)	Separator (Water outlet)	107828	14829	5686	1135	53	/	4.4	1.12	188	Majority: reservoir water with highly Mg concentration

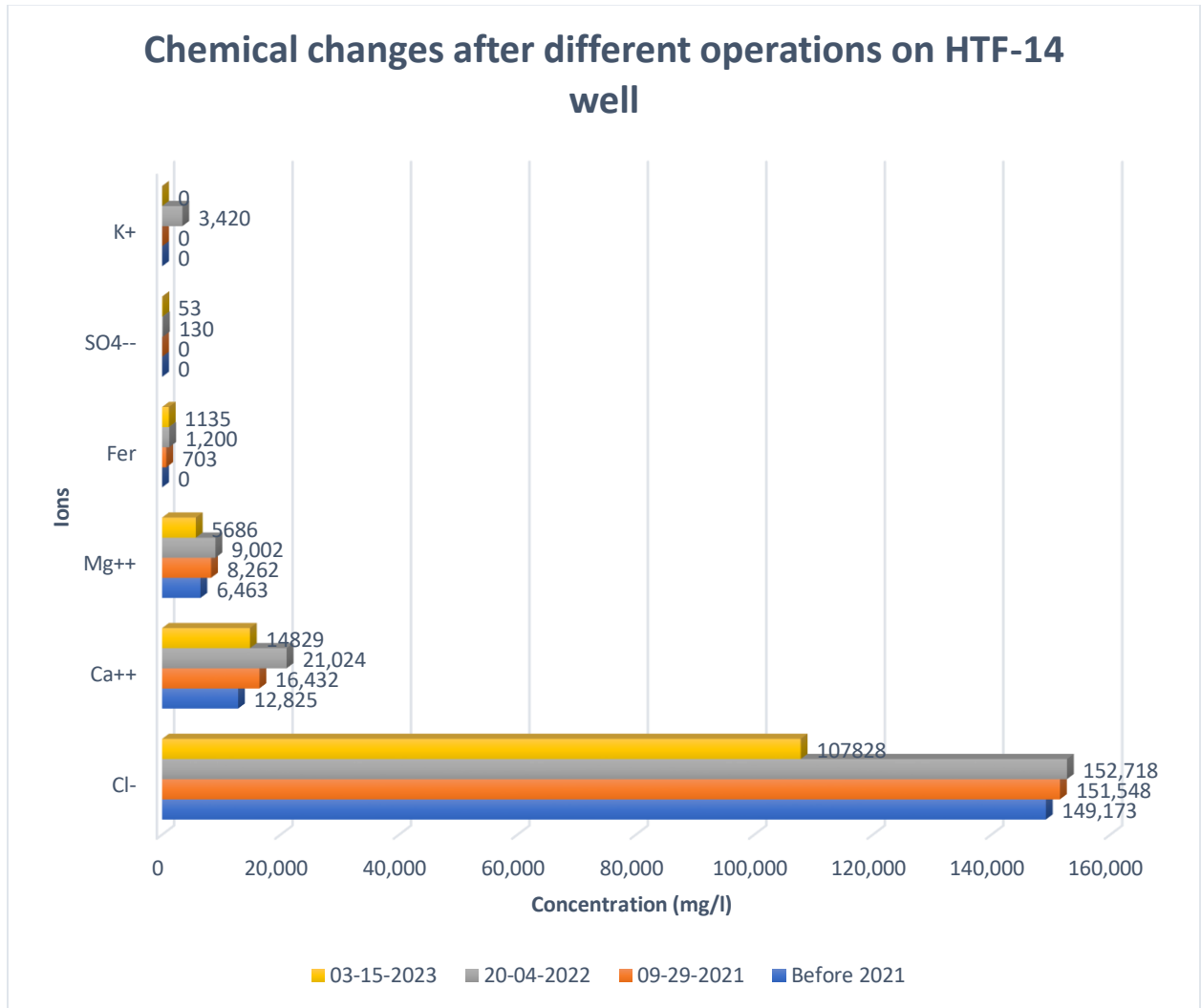


Figure II.8: Compositional variation of HTF-14 well after different operations.

The noticed remark of this chart is that the water composition after each operation does not look stable. Several changes occur as injection and the use of multiple products in the reservoir or well-nearby which means that any operations during the electrolysis of the water extracted can deeply influence the production by gain or loss.

II.2.3 Production of H₂ gas from an HTF-14 water sample

In those experiments, we are going to use different chemicals compositions with the basic water used from HTF-14 well and observing the chemical and mechanical variations and the influence on the productivity of H₂.

In those experiments, we are going to use several sels and acidic products: NaOH, KCl, KOH, NH₄Cl, NaCl, NaHCO₃ and HCl with the use of HTF-14 water sample as the principal solution without regarding the volumes to be used in those experiments. The objectives of those experiments are to observe the changes in chemical compositions when use of those products in contact with underground water and to figure after that the influence of those changes on the electrolysis's efficiency. Depositions, chemical compositions and pH analysis are affected on CRD-HMD by 05 May 2023.

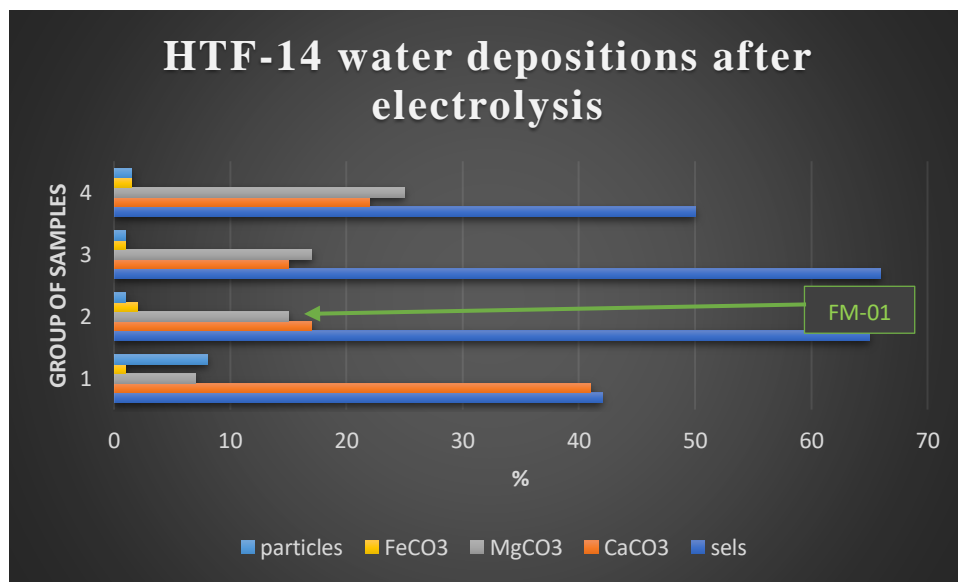


Figure II.9: Water depositions after electrolysis.

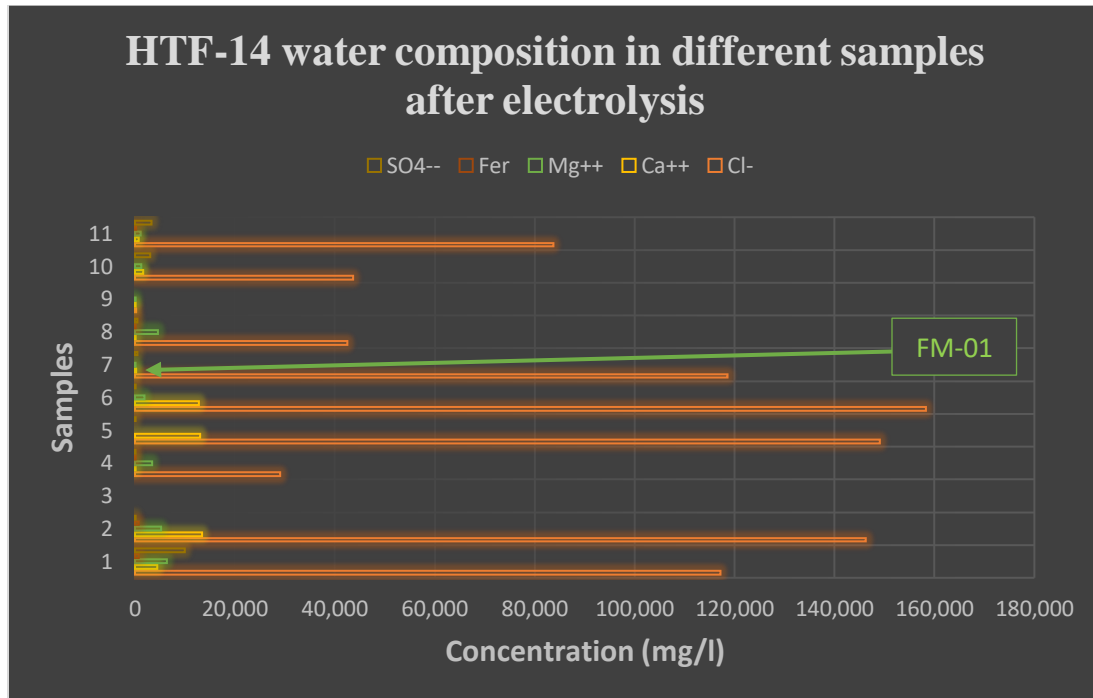


Figure II.10: HTF-14 water composition in different samples after electrolysis.

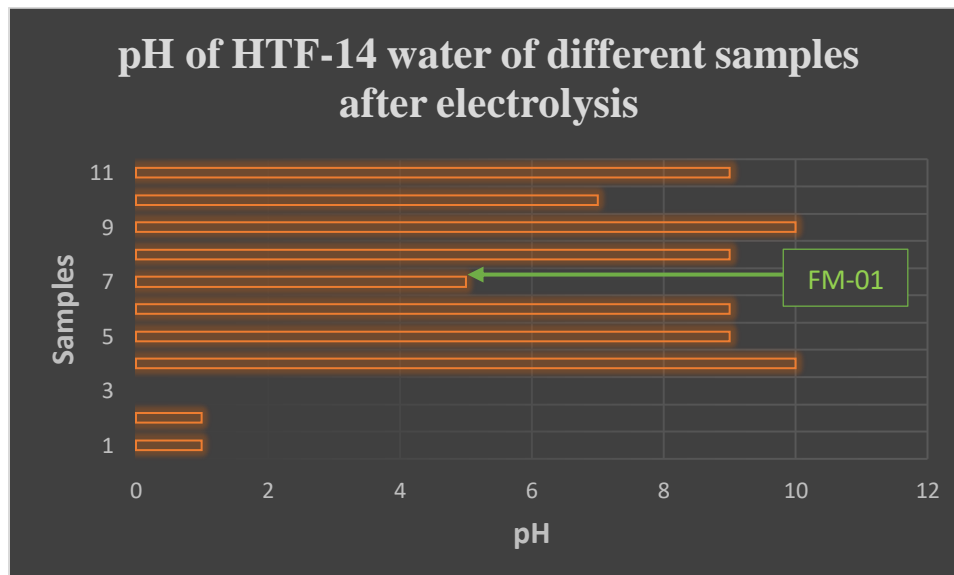


Figure II.11: pH of HTF-14 well's water of different samples after electrolysis.

From a first observation, we can see clearly the huge reactions between those products and the chemical composition of the underground water. Figure II.9 shows different depositions formed by those reactions; meanwhile Figures II.10 and II.11 show respectively the chemical compositions and the pH changes in those experimental samples. It's obvious that the use of those products makes a huge change in the chemical compositions, by comparison with the original

composition of the HTF-14, we observe high NRF value even when we use FM-01 fluid which designed to optimize the H₂ production in first hand. We can see that the importance of choosing the right products, specifying the volumes to be used and to carry out the chemical nature of the underground's water used for the electrolysis beside of the well-preparation of the job are all mandatory steps to be considered before doing the electrolysis operations.

II.2.4 Optimization via use of FM-01 fluid

The optimization of water's gain value can be done by both the mechanical and chemical optimization of properties.

By ensuring the low deposition, low NRF value and minimization of corrosion probabilities via the assuring of specific reactions in the electrolyte (with consideration of electrolysis reactions), the electrolysis productivity can be assisted or, in miner cases, avoiding the problems that can be encountered and minimize the gain.

A. Experiment

In this experiment, we used a mixture of NH₄Cl, KOH, HCl, and Mg based electrolyte (water model) and additional chemicals. The main objectives of choosing those ions are:

- Optimize the electrical conductivity of electrolyte-electrode interface.
- Elimination of undesired ions (especially those resulting corrosion) by formation of different deposition in the electrolyte fluid.
- Assuring lower possible deposition by assuring high particles solubility.

The use of FM-01 fluid on the HTF-14 water sample allows obtaining the following result:

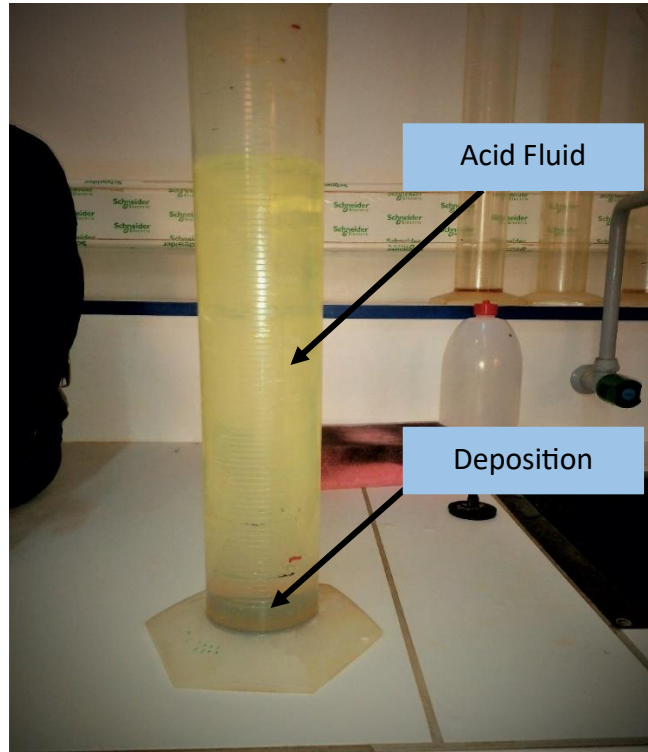


Figure II.12: FM-01 fluid model.

Using the FM-01 fluid with an SCR unit (13.77 volts and current of 1.74 A) at atmospheric pressure in two experiments, with considering $Q_{ele}^* = 1.6 * 10^{-19}$ c:

- The first experiment:

✚ $V_{H_2}^* = 4.52 * 10^{-26} \text{ m}^3$.

✚ $T_1 = 60^\circ\text{C}$.

✚ Necessary time to obtain one m^3 is: $t_1 = 4,068,762.079 \text{ s}$.

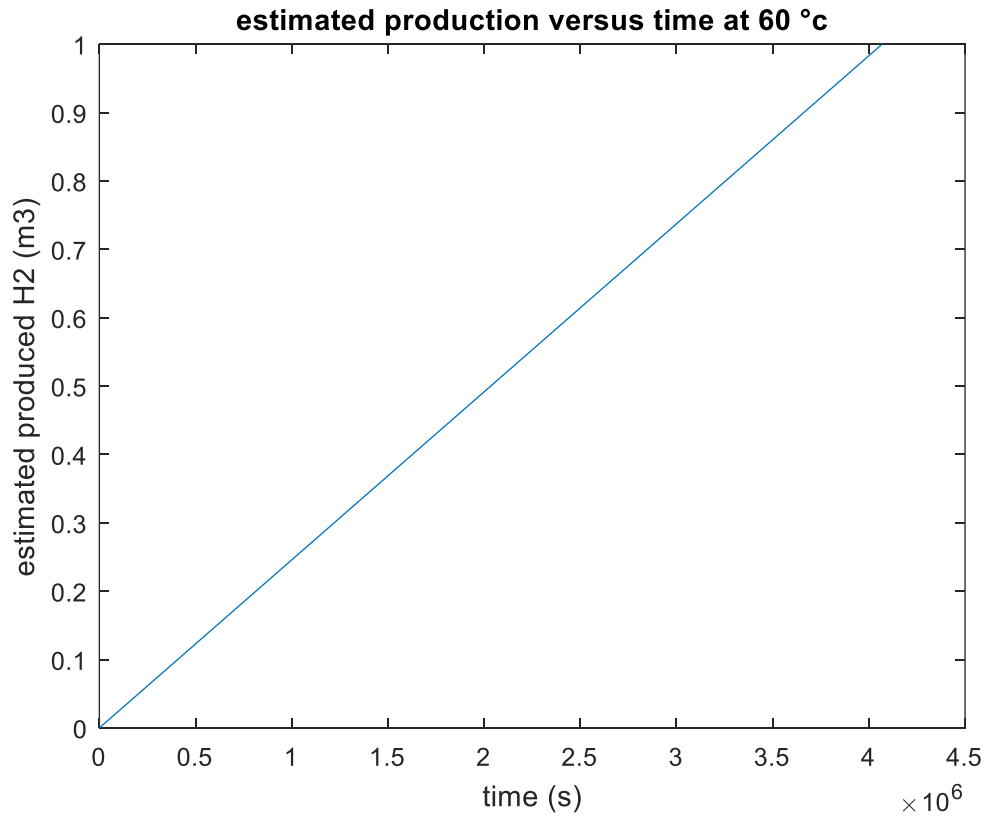


Figure II.13: estimated production versus time at 60 °c.

- The second experiment:
 - ✚ $V_{H_2}^* = 4.82 \cdot 10^{-26} \text{ m}^3$.
 - ✚ $T_2 = 80 \text{ °c}$.
 - ✚ Necessary time to obtain one m^3 is: $t_2 = 3,815,519.626 \text{ s}$.

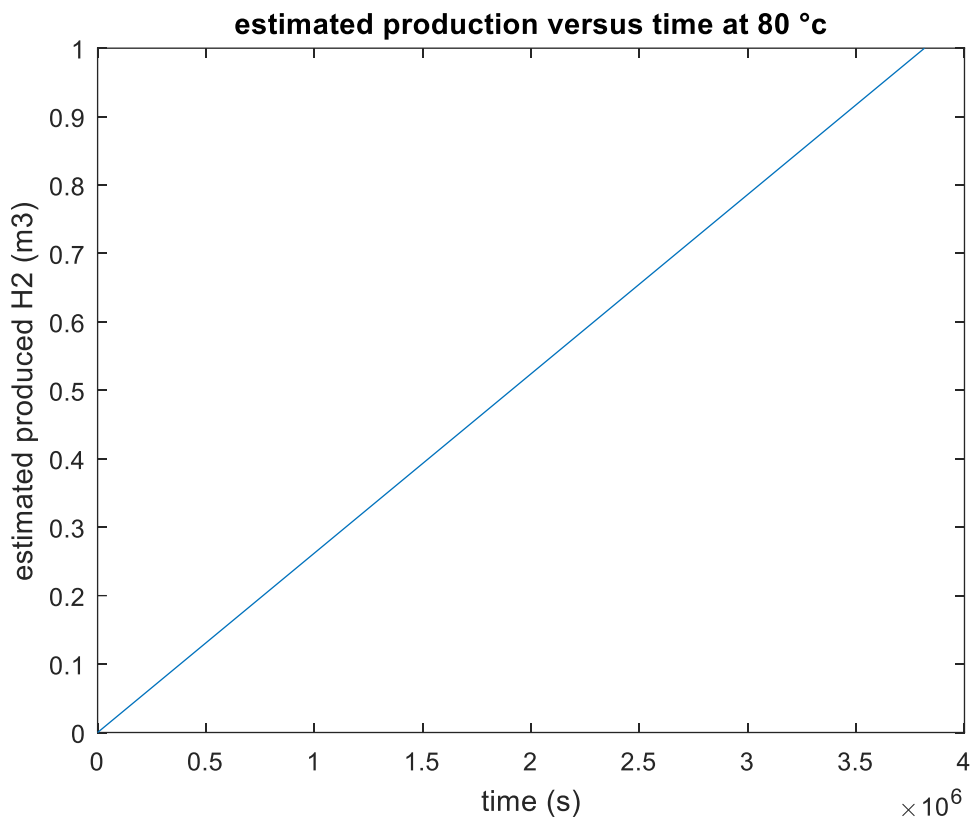


Figure II.14: estimated production versus time at 80 °c.

B. Results and discussion

With the comparison of both the simulation and experiments at 60 °c and 80 °c, we observe that the produced volumes are not considered as current is very low.

In the simulation, we can observe clearly that the estimated produced H₂ volumes at 80 °c is better than the estimated production at 60 °c. However, the chemical optimization via the use of FM-01 fluid model with more temperature (80 °c) didn't make more production than the non-use at 60 °c (which we can observe clearly in the Table II.1 and Figures II.9-II.10-II.11) were the high presence of different ions in solution especially negative ones (Cl^-) results in both corrosion and depositions which make the NRF factor very high and gain lower.

As observed in experimental water samples (Figures II.9 - II.10 - II.11), the use of FM-01 fluid model in mixture with HTF-14 water sample results in huge deposition ($FeCO_3$, $MgCO_3$, $CaCO_3$) along-side with presence of different sels ($NaCl$ and KCl , $MgCl_2$..) where their influence on H₂ production was mentioned in Table II.1.

The major impact of those chemical substances can be summarized as following:

- a) Bad influence:
 - Risk of corrosion.
 - Depositions.
 - Irregular NRF factor.
- b) Good influence:
 - Optimize the ESF factor.
 - Minimize the necessary temperature by exothermic reactions.
 - Ionic activities (more conductivity).

We conclude from these experiments that:

- Both mechanical and chemical treatments are mandatory.
- The importance of full study of the HSPEU design with consider of the continue changes in chemical compositions of water samples.
- The importance to use big SCR units to ensure sufficient DC current alimentation.
- The importance of use anti-deposition particles in order to avoid risk of burst, low gain explosion and loss.

Conclusion

The importance of chemical and mechanical treatment of water cannot be overstated when considering the electrolysis process and maximizing its efficiency. Chemical treatment involves removing impurities, such as dissolved minerals, organic compounds, and potentially harmful substances, through processes like coagulation, flocculation, and filtration. These treatments help prevent fouling of electrodes, reduce scaling, and minimize the formation of undesirable by-products during electrolysis. Mechanical treatment, on the other hand, involves physical processes such as sedimentation, clarification, and disinfection, which help remove suspended solids, bacteria, and other particulate matter.

A thorough understanding of the water composition is essential in order to tailor the treatment process effectively. Conducting a comprehensive study of water composition enables identification of specific impurities and their concentrations, allowing for the selection of appropriate treatment methods and the optimization of electrolysis conditions which, in the last, the electrolysis process can achieve higher efficiency, improved product quality, and reduced maintenance requirements, leading to enhanced overall electrolysis gains.

Chapter III
**Use of Hydrogen Gas in Petroleum Industrial
Applications**

Introduction

Perforation and hydraulic fracturing are essential techniques in the oil and gas industry for enhancing hydrocarbon production from reservoirs. These methods involve the injection of fluids, which can include H₂ (hydrogen), into wells to improve the permeability and productivity of the reservoirs.

Perforation involves creating small holes or channels in the well casing and surrounding rock formation to establish communication between the reservoir and the wellbore. This enables the flow of oil and gas into the wellbore, facilitating production. On the other hand, hydraulic fracturing is a process of injecting high-pressure fluids, such as H₂, into the reservoir to create fractures in the rock formation. These fractures act as pathways for oil and gas to flow more easily towards the wellbore.

The use of H₂ fluid in perforation and hydraulic fracturing processes offers several advantages. Hydrogen is a lightweight gas that can provide effective fracturing and perforation due to its high compressibility and ability to generate high pressure. It also offers environmental benefits, as hydrogen is a clean and renewable energy source, reducing carbon emissions compared to traditional hydrocarbon-based fluids.

This chapter aims to explore the application of Hydrogen Base Fluids for reservoir stimulation especially in perforation and hydraulic fracturing, discussing its potential benefits, challenges, and the associated engineering considerations. By the use of new technologies called **Perforation/Fracturing Using Hydrogen PUH/FUH**, we can use H₂ based fluids and others to make stimulation and well operations more sufficient.

III.1 Presentation of the PUH/FUH unit

The heart of the PUH/FUH system lies in the PUH/FUH unit, which is responsible for generating the necessary pressure and shock wave. AHF charges and AHF fluid, formulated with specially designed materials, are utilized in the PUH/FUH unit. These materials can be in liquid or solid form, depending on the specific application. The AHF charges are carefully calibrated to produce the desired pressure and energy release upon detonation. The controlled inner explosion

of the AHF charges creates a rapid expansion of gases, leading to the formation of a powerful chock wave. Meanwhile, the AHF fluid also is calibrated to create the necessary wave but with more complicated way as the wave shall transmit into another fluid called Fracturing Mixture. Main parts of the PUH/FUH unit are mentioned below.



Figure III.1: PUH/FUH tool.

III.1.1 Isolation parts

To ensure safety and optimal performance, the PUH/FUH unit incorporates isolation parts, including upper and lower sections. These parts serve as barriers that isolate the AHF charges and FUH mixture inside the **Chock Release Vessel (CRV)** from the surrounding environment and prevent any unintended propagation of pressure or energy via the external environment. The upper isolation part is designed to seal the wellbore above the PUH/FUH unit, while the lower isolation part is positioned below the PUH/FUH unit to prevent downward pressure transmission.

The isolation parts work as upper and lower packers that can be activated hydraulically or pneumatically to ensure an ideal isolation and packing from up and down of the tool. A **Non-Miscible Fluid (NMF)** can be used to make a secondary isolation from up and down respectively

to make sure the impossibility of having any leaking or energy transition from the CRV chamber into the out of the tool.

- **Non-Miscible Fluid (NMF)**

NMF Fluid is a security fluid that used for the aims of isolation of HFRC on both sides (top/bottom) of the rest of the well; maintain the chock produced in the specified zone in order to avoid its dispersion to the top and bottom of the HFRC which can be danger to the entire process. Moreover, NMF can protect the HFRC environment from the produced heat and to avoid and contact between different chemicals from and into the inside of the HFRC tool, which allow to a safe and efficient FUH operation. The other use of the NMF fluid is a barrier that separate between Fracturing Mixture and AHF fluid in order to allow the reaction between AHF and HBF and transmit the chock into the Fracturing Mixture then into the reservoir. An example of a NMF fluid is shown in Figure III.2.



Figure III.2: Castrol oil (NMF fluid).

III.1.2 Fluid Transmit Conductors

The fluid transmit conductors are crucial component that facilitate the transfer of used fluids from the surface into the PUH/FUH unit. It acts as a conduit, connecting the PUH/FUH unit to the surface and allows different fluids (**Hydrogen Break Fluid (HBF)**, **NMF**). The fluid transmit conductor is engineered to withstand the extreme conditions during the perforation or

fracturing process, ensuring efficient energy transmission without compromising the integrity of the system.

There are two combined conductors: the outer conductor allows the transmission of the Perforation/Fracturing fluids (AHF, HBF and NMF fluids) into the CRV vessel; meanwhile, the inner conductor permits the transmission of NMF in both upper and lower sides of the Isolation parts.

III.1.3 Chock Orientation Chamber

Also known as The **Chock Release Vessel (CRV)**, the chock orientation chamber plays a vital role in generating, directing the shock wave and pressure towards the desired direction for effective wellbore perforation or fracturing. It acts as a guiding mechanism chamber, controlling the orientation and trajectory of the shock wave as it propagates through the target point of perforation/fracturing. The design and configuration of the CRV are carefully optimized to achieve precise and accurate process, minimizing any potential damage to the surrounding formation and ensure appropriate shape of the perforation/fracturing.

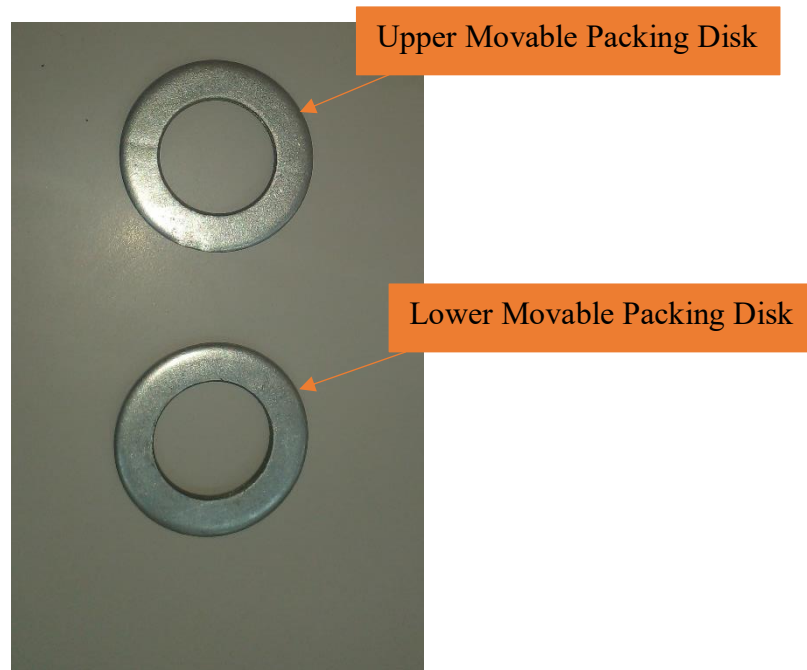


Figure III.3: Upper and lower movable packing disks (Isolation parts).

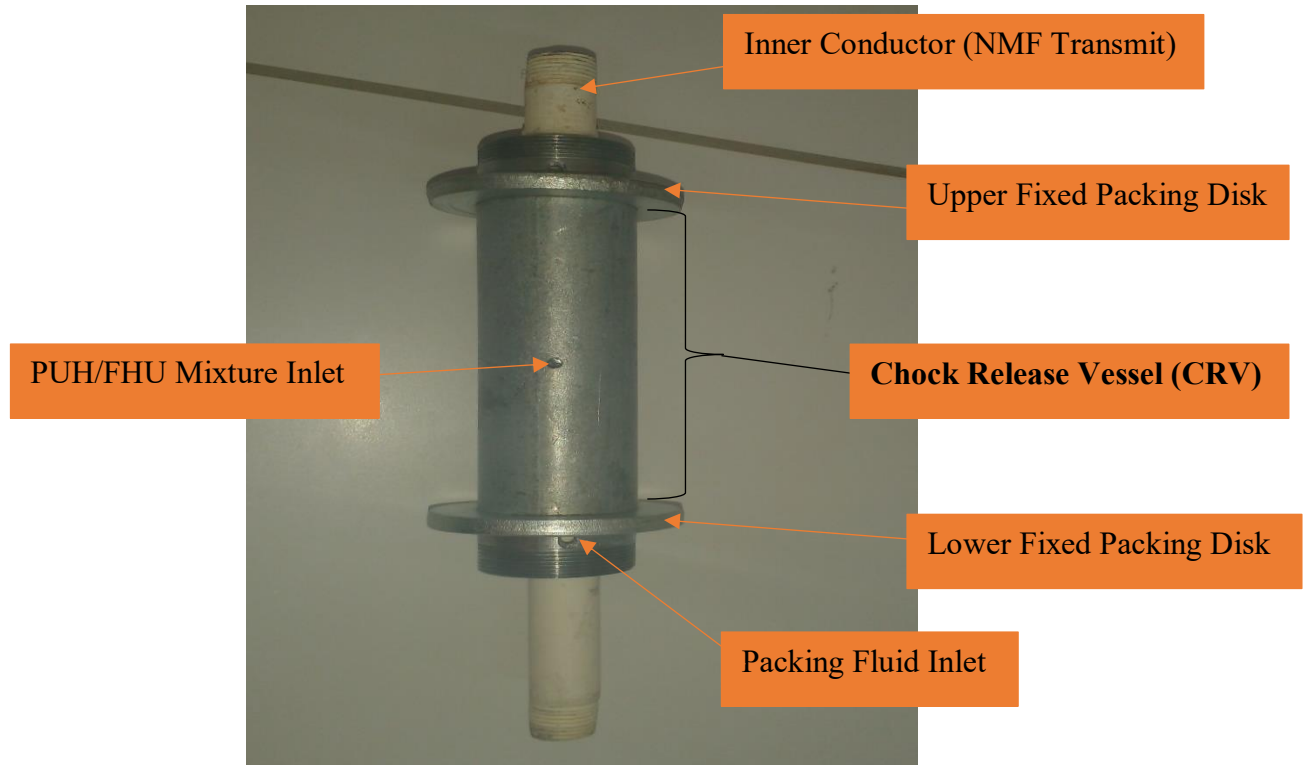


Figure III.4: Principal PUH/FUH parts.

The fluids used for PUH/FUH operations are:

- **Adsorbed Hydrogen Fluid (AHF)**

AHF fluid is a special mixture in which its main chemical composition is Hydrogen which (for security reasons) must be adsorbed in order to make the opposite reaction (desorption/release) easy and secure in the CRV chamber. The general process of adsorption process is identified in Chapter I (section I.2.5). An example of AHF fluid is shown in Figure III.5.

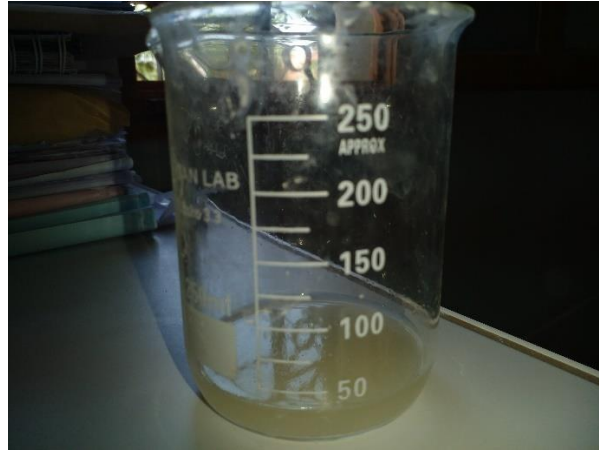


Figure III.5: An AHF prototype.

- **Hydrogen-Break Fluid (HBF)**

HBF Fluid is the second part of the FUH reaction in which the direct contact with the AHF fluid allows to release the necessary heat and pressure that allows by the consequence to create the sufficient chock wave, push the Fracturing Mixture into the reservoir, and create the fractures (Equations III.2 to III.4).

- **Perforation/Fracturing process**

When the PUH/FUH system is activated, the AHF fluid in the PUH/FUH unit are reacted with the HBF fluid which is generally either pure N₂ gas or hot air (O₂ and N₂), resulting in a rapid release of energy. The explosion generates a high-pressure shock wave that travels directly into the formation. As the shock wave reaches the wellbore, it interacts with the formation, creating intense pressure and shock forces. These forces are capable of creating perforations or fractures and channels that establish communication between the reservoir and the wellbore.

The reaction between AHF (CuH₂) and HBF (N₂ / O₂+N₂) can be summarized as follow:

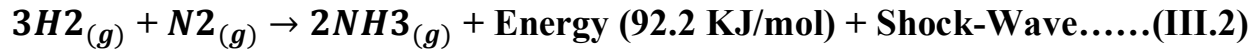
In presence of hot temperature by contact with hot fluids (N₂ / Hot Air), a desorption process that result in H₂ liberation is established (example of CuH₂):



H₂ gas get in form of dispersed bubbles meanwhile CuH₂ rest in solid form but dispersed in the Castrol oil.

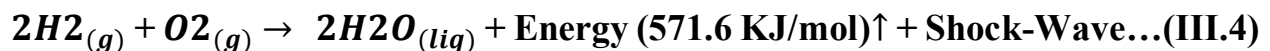
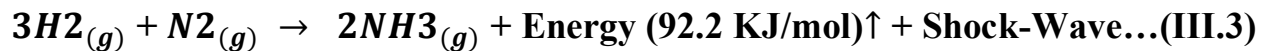
Then, the reaction with the HBF fluid gets in:

- **HBF (N₂):**



The resulting heat equals to 92.2 KJ/mol.

- **HBF (O₂ + N₂):**



The resulting heat equals to $571.6 \cdot 0.21 + 92.9 \cdot 0.78 = 192.498$ KJ/mol.

We conclude that the use of hot air is much efficient and valuable to the perforation/fracturing process.

The liberated energy during the reaction of AHF and HBF allows getting a brutal augmentation of pressure in short time, which take the form of a chock-wave. To determine the Concentration and chemical composition of both AHF and HBF in function of reservoir pressure (P_r) and Temperature (T_r) we use the following equations:

We consider a total change of liberated energy in the resulting mixture into the reservoir formation:

$$\Delta H = \Delta T * C_{eq} * m \dots \dots \dots \text{(III. 5) [17]}$$

Where:

ΔH : The liberated energy from a volume of AHF and HBF reaction in KJ.

ΔT : The difference of Temperature before and after the reaction in Kelvin = $T_f - T_r$.

C_{eq} : The mixture equivalent heat transfer capacity in KJ/(mol*K*kg) = $\sum_{i=1}^n C_i * x_i$.

C_i : is the component's heat transfer capacity in $\text{KJ}/(\text{mol} \cdot \text{K} \cdot \text{kg})$.

X_i : is the molar fraction of a specified component.

m : The total mass of the mixture in kg.

Considering the loss of heat during the transfer and the molar number of adsorbed H_2 in one CuH_2 molecule, we obtain:

$$\Delta H = N_{ads \text{H}_2} * n_{adsorbent} * E_{liberated} - \sum \text{energy loss} \dots \dots \dots \text{(III.6)}$$

Where:

$N_{ads \text{H}_2}$ is the number of adsorbed H_2 molecules for single CuH_2 molecule.

$n_{adsorbent}$ is the molar number of the adsorbent molecules in the AHF fluid.

$E_{liberated}$ is the liberated energy of a single reaction with single HBF molecule in KJ/mol .

$\sum \text{energy loss}$ total loss of energy in KJ .

And as

$$C_{adsorbent} = \frac{n_{adsorbent}}{V_{AHF}} \dots \dots \dots \text{(III.7)}$$

we obtain:

$$\begin{aligned} \Delta H &= N_{ads \text{H}_2} * V_{AHF} * C_{adsorbent} * E_{liberated} - \sum \text{energy loss} \\ &= \Delta T * C_{eq} * m \dots \dots \dots \text{(III.8)} \end{aligned}$$

We conclude:

$$\Delta T = T_f - T_r = \frac{\Delta H}{C_{eq} * m} = \frac{N_{ads \text{H}_2} * V_{AHF} * C_{adsorbent} * E_{liberated} - \sum \text{energy loss}}{C_{eq} * m} \dots \dots \dots \text{(III.9)}$$

Following the definition of RKB equation of state:

$$P_f = \frac{R * T_f * V}{V^3 + C * V^2 - a * C} - b \dots \dots \dots \text{(III.10)}$$

Or,

$$T_f = \left(\frac{V^3 + C * V^2 - a * C}{R * V} \right) * (P_f + b) \dots \dots \dots \text{(III.11) [16]}$$

Where:

P_f is the final pressure (fracturing pressure) after the reaction in Pa.

a, b, c are state parameters.

V is the mixture volume in m^3 .

T_f is the final temperature in Kelvin.

Using the previous equation, we can determine the necessary AHF concentration to obtain the fracturing pressure:

$$C_{adsorbent} = \frac{(T_f - T_r) * C_{eq} * m + \sum \text{energy loss}}{N_{ads H2} * V_{AHF} * E_{liberated}} =$$

$$\frac{\left(\frac{V^3 + C * V^2 - a * C}{R * V}\right) * (P_f + b) - T_r * C_{eq} * m + \sum \text{energy loss}}{N_{ads H2} * V_{AHF} * E_{liberated}} \dots \dots \dots (III.12)$$

From the final equation of PUH/FUH, we conclude that adsorbent concentration in the AHF is related directly to $E_{liberated}$, T_r , and $N_{ads H2}$ in non-consensual form and the opposite with P_f .

III.2 In perforation

III.2.1 Background about Perforation

The development of perforation techniques has evolved alongside the growth of the oil and gas industry. This section explores the historical context of perforation, including early methods, technological advancements, and the significance of perforation in hydrocarbon extraction.

The history of perforation in oil wells can be traced back to the early days of oil exploration and production. In the early years, the primary focus was on accessing oil-bearing formations and establishing a flow path to the surface. However, specific techniques for enhancing production through perforation had not yet been developed.

It was in the late 19th century that the use of explosives began to gain prominence in oil well operations. Pioneers like Edward Roberts and Sir James Brunlees experimented with dynamite for well stimulation, initially using it to create fractures in the formation.

However, it was the introduction of shaped charges in the mid-20th century that revolutionized the perforation process. Shaped charges, based on the concept of the Munroe Effect, were designed to generate focused jets of energy capable of penetrating well casings and rock formations.

Since then, perforation technology has continued to advance, with innovations such as **Wireline-Conveyed Perforating (WCP)** and **Tubing-Conveyed Perforating (TCP)** techniques enabling more accurate positioning of perforating guns.

Perforation, in oil well operations, refers to the process of creating channels or tunnels in the reservoir formation to establish communication between the reservoir and the wellbore. This section provides a clear definition of perforation, emphasizing its role in facilitating the flow of hydrocarbons and maximizing well productivity.

III.2.2 Present technics of perforation

A. Perforating guns

Perforating guns are devices used to create perforations in the well casing and surrounding formation. These guns are typically assembled with shaped charges that contain explosive materials.

The guns are lowered into the wellbore and fired, generating high-pressure jets that penetrate the formation [4].

B. Shaped charges

Shaped charges are explosive devices designed to create focused and directional jets of energy. They consist of a metal liner shaped in a specific geometry, such as a cone or a linear shape. When detonated, the shaped charges produce high-velocity jets that penetrate the casing and formation, creating perforation tunnels [4].

- **Munroe Effect equation:**

Measuring the penetration depth of the perforation:

$$Z_p = K * (\rho * V^3 / \sigma_{\text{yield}})^n \dots \dots \dots \text{(III. 13) [18]}$$

Where:

Z_p represents the depth of penetration into the target material.

K is a constant specific to the shaped charge design.

ρ is the density of the shaped charge liner material.

V is the velocity of the shaped charge jet.

σ_{yield} is the yield strength of the target material.

n is an empirical exponent typically ranging from 1.6 to 2.0.

C. Jet perforation

Jet perforation involves the use of high-pressure fluids, such as water or acid, to create perforations in the formation.

The fluid is pumped through specially designed nozzles or jets, which create high-velocity fluid jets that penetrate the formation.

Jet perforation is often used in soft or unconsolidated formations to minimize formation damage and improve well productivity [4].

$$J_P = K * (\rho * V^3 / \sigma_{yield})^n \dots \dots \dots \text{(III. 14) [19]}$$

Where:

JP represents the depth of penetration for jet perforation.

K is a constant specific to the jet perforation system.

ρ is the density of the fluid used for jet perforation.

V is the velocity of the fluid jet.

σ_{yield} is the yield strength of the target formation.

n is an empirical exponent typically ranging from 1.5 to 2.0.

D. Wire line Conveyed Perforating (WCP)

WCP is commonly used for perforating operations in both production and intervention scenarios [4].

E. Tubing Conveyed Perforating (TCP) [4].

F. Through Tubing Rotary Perforating (TTRP) [4].

G. Explosive perforation [4].

H. Ballistic perforation [4].

III.2.3 Different parameters influence the perforation efficiency

Perforation efficiency in oil wells can be influenced by various parameters. Here are some key factors that can impact the perforation efficiency:

A. Rock properties

Rock strength: The strength of the target formation plays a crucial role in determining the perforation efficiency. Softer formations may require lower energy for effective perforation, while harder formations may necessitate higher energy levels.

Rock density: The density of the rock formation affects the energy transfer during perforation. Higher density formations may require more energy to achieve the desired penetration depth.

B. Perforating gun configuration

Charge density: The density of the explosive charges within the perforating gun affects the energy released during detonation. Optimal charge density selection is critical to achieving the desired penetration and perforation characteristics.

Charge geometry: The shape and design of the explosive charges, such as linear or shaped charges, affect the formation of the high-velocity jets that create perforation tunnels.

C. Standoff distance

The standoff distance refers to the distance between the perforating gun and the well casing or target formation. The choice of an appropriate standoff distance is crucial to ensure optimal energy transfer, penetration depth, and tunnel geometry.

D. Flow-back and debris clearance

Efficient removal of perforation debris and flow-back of reservoir fluids play a significant role in perforation efficiency. Proper cleaning of the perforation tunnels allows for better communication between the reservoir and the wellbore, maximizing production rates.

E. Perforation orientation and density

The orientation and density of perforations affect the connectivity between the wellbore and the reservoir. Optimally placed perforations, strategically oriented to intersect natural fractures or productive zones, can enhance the productivity of the well.

F. Fluid and fracturing parameters

Fluid properties: Such as density and viscosity, affect the energy transfer and jet formation during perforation. The use of specialized fluids, such as high-density fluids or acid, can enhance perforation efficiency.

Fracturing parameters: Including injection rates, proppant selection, and fracturing fluid properties, can influence the effectiveness of subsequent fracturing operations after perforation.

G. Wellbore and casing integrity

The condition of the wellbore and casing integrity affects the success of the perforation process. Wellbore stability and casing integrity must be maintained to avoid formation damage and ensure proper perforation tunnel formation.

H. Formation damage and skin

Formation damage caused by drilling fluids, mud invasion, or fines migration can reduce the efficiency of perforations. The presence of a "skin" near the perforation tunnels can restrict fluid flow and reduce productivity [4].

III.2.4 Perforation Using Hydrogen (PUH) technics

The PUH system is a sophisticated technology used in the oil and gas industry for wellbore perforation. This system employs the use of AHF charges, either in liquid or solid form, to create a shock wave and generate extreme pressure within the wellbore. This section aims to provide a comprehensive overview of the PUH system, its operation, and the role of each component in achieving effective wellbore perforation.

III.2.5 Presentation of the PUH system

A. AHF charges

The AHF charge is a geometrical formed (spherical, cylindrical...) substance that composed of a metal hybrid (which is capable of adsorbing an amount of H₂ gas molecules) like TiH₂, CuH₂, ZnH₂.... etc., and it's positioned inside the AHF charge chamber called **AHF charges Chambers (AHFC)**. The Adsorbed H₂ in the metal hybrid is called the AHF fluid in which exists in emulsion with a solvent which characterized by its resistance of shock and explosibility (like Castor Oil). In presence of appropriate conditions (high Temperature, low

Pressure...) the H₂ get separated from the metal hybrid (equation III.1). The form of the AHF charge is directly proportional to the AHFC shape, which is determined already by the engineers.

B. PUH unit

The tool that used for the PUH operation is called the **Hydrogen PERF (HPERF)** tool. The HPERF is the type of PUH/FUH tool that used for perforation operations with the use of AHF charges that are carried in special geometrical formed vessels **AHF charges Chambers (AHFC)** in connect with the CRV chamber. After the HBF is pumped into the CRV, a direct reaction gets in process in which the desorption, by high temperature of the HBF (Equation III.1), then the shock-wave generation from the brutal het formed by the reaction between H₂ molecules and the HBF molecules inside the AHFC (Equations III.2 to III.4). The shape of the AHFC is the responsible on the perforation's geometrical form which can affect several production parameters including flow regime and productivity, skin....

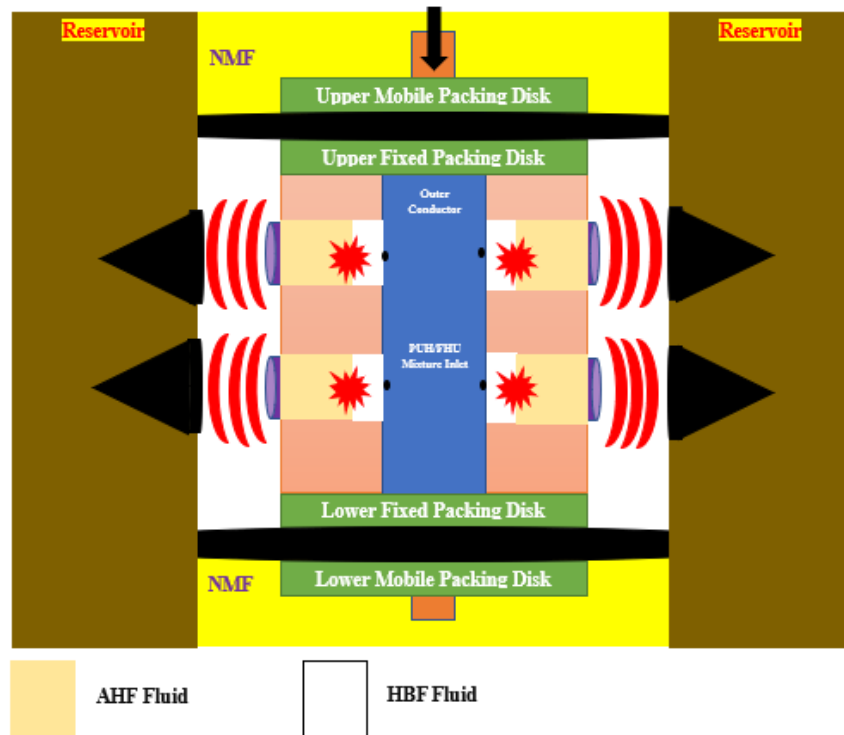


Figure III.6: PUH process using HPERF tool.

C. Risks and challenges

Using hydrogen (H₂) for the perforation of oil wells presents certain risks and challenges. Here are some key points to consider:

Safety concerns: Hydrogen is highly flammable and can form explosive mixtures with air. The use of H₂ for perforating oil wells requires careful handling and storage to minimize the risk of leaks or accidental ignition.

Infrastructure requirements: Hydrogen-based perforation would necessitate the development of specialized equipment and infrastructure to store, transport, and deliver the hydrogen to the well site.

Compatibility issues: Existing oil well perforation techniques often involve the use of energetic materials or pyrotechnics, which may not be directly compatible with hydrogen-based systems.

Environmental considerations: While hydrogen is considered a clean energy source when produced using renewable methods, its widespread use and large-scale production can have environmental impacts.

Cost implications: Implementing hydrogen-based perforation systems may involve higher upfront costs due to the need for specialized infrastructure and equipment.

Regulatory framework: The use of hydrogen for perforation may require the development of specific regulations and standards to ensure safety and environmental protection.

Technical feasibility: Hydrogen-based perforation systems would need to demonstrate their technical feasibility, reliability, and efficiency compared to existing methods.

III.3 In fracturing

Hydraulic fracturing, commonly known as "fracking," is a technique used in the extraction of natural gas and oil from deep underground reservoirs. It involves the injection of a high-pressure fluid mixture deep into the earth to create fractures in rock formations, releasing trapped hydrocarbons.

Hydraulic fracturing can be traced back to the 1940s when it was first employed as a method to increase oil and gas production. In the 1950s, the use of hydraulic fluid instead of explosives gained prominence. This technique involved injecting high-pressure fluids, primarily water, into wells to create fractures and stimulate production [15].

III.3.1 Process of hydraulic fracturing

Hydraulic fracturing involves several key steps. First, a wellbore is drilled vertically into the ground, reaching thousands of feet below the surface. Once the desired depth is reached, the drilling then turns horizontally, following the targeted rock formation.

Next, a high-pressure fluid mixture is pumped down the wellbore and into the horizontal section, composed of water, sand, and chemical additives. The pressure of the fluid creates fractures in the rock, and the sand particles act as proppants, holding the fractures open to allow the release of hydrocarbons. Finally, the fluid is recovered and the extracted natural gas or oil is brought to the surface [11].

III.3.2 Benefits of hydraulic fracturing

In hydraulic fracturing, advantages can be summarized in:

- Energy Independence.
- Economic Growth.
- Lower Carbon Emissions [11].

III.3.3 Environmental concerns and challenges

A. Water usage

The hydraulic fracturing process requires large volumes of water, raising concerns about water scarcity in regions already experiencing stress. However, efforts are being made to recycle and reuse water to minimize its impact.

B. Water contamination

There are concerns about the potential contamination of groundwater due to the migration of fracking fluids and methane leakage. Proper well construction, monitoring, and the appropriate handling and treatment of wastewater are essential to mitigate these risks.

C. Induced seismicity

Injection of fluids can induce seismic activity, although most of the resulting earthquakes are typically low-magnitude and pose minimal risk. Monitoring and regulation can help mitigate this issue.

D. Chemical additives

The composition of fracking fluids includes chemical additives, some of which may be toxic or harmful. Stricter regulations and disclosure requirements are necessary to address public concerns and ensure the safety of workers and communities [13].

III.3.4 Technics of fracturing

Hydraulic fracturing involves a series of stages and substages to extract natural gas or oil from deep underground reservoirs. Understanding the various steps involved in this process is essential for grasping the complexities and potential impacts of hydraulic fracturing. This article provides a comprehensive overview of the stages and sub-stages of hydraulic fracturing, shedding light on the intricacies of this technique.

- Preparatory Stage (Site Selection and Well Drilling).
- Well Construction (Casing and Cementing).
- Fracturing Fluid Preparation.
- Fracturing Stage.

Including Injection, Fracture Propagation, Proppant Placement.

- Flowback and Production.
- Post-Fracturing Stage (Well Monitoring and Wastewater Management) [12].

III.3.5 Different parameters influence the fracturing efficiency

- Geological Parameters (Rock Permeability and Rock Stiffness).
- Well Design and Construction (Well Orientation and Placement, Wellbore Diameter and Length).
- Fluid Parameters (Fluid Viscosity and Fracturing Fluid Composition).
- Operational Parameters (Injection Rate and Pressure and Fracture Stage Spacing).
- Environmental Factors (Stress Regime and Reservoir Fluid Properties) [12].

III.3.6 Fracturing Using Hydrogen (FUH) technic

Using the ability to create a quick and considerable chock by chemical reactions, the gas of H₂ is a great candidate to be used as a source of massive energy in form of pressure (with the condition of safe transportation and use).

Using special tool that we call **Hydrogen FRAC (HFRC)** tool which is an PUH/FUH tool used for fracturing operations, a special AHF fluid can be pumped in face of the target zone to be fractured using series of chemical reactions, leading into an effective fracturing of the target zone. CTU or Snubbing unit can be used in order to run down the HFRC tool into the well's bottom-hole.

III.3.7 Presentation of the FUH system

The FUH system is composed of:

A. CTU/ Snubbing unit

The major rule of this unit is to run down the HFRC tool into the target depth, pump into the HFRC the AHF fluid and the other fluids (Non-Miscible Fluid "NMF" and the Hydrogen-Break Fluid "HBF") which allow the launch of special series of chemical reactions in the HFRC tool and allow at the end the fracturing of the target zone.

B. FUH unit

The type of PUH/FUH tool that used for affecting the FUH operation is called the HFRC tool which used for reservoir fracturing by the use of Fracturing Mixture and the Chemical Fluids used for fracking operation (AHF, HBF, NMF).

In opposite to the HPERF, the process of desorption and Shock-wave release is done directly inside the CRV chambers. The process of fracturing using HFRC tool is mentioned below (section III.3.7 -D-).

C. The Chemical fluids

The chemical fluids used for a FUH operation are different and each one rule is mandatory for the entire process. Those fluids are mentioned before (AHF/NMF/HBF) in section III.1.

D. Fracturing Mixture

Fracturing Mixture is the combination of all the hydraulic fracturing fluid's chemicals in one single fluid. The main objective of using the combination is that the chock used to push horizontally the Fracturing Mixture direct into the target point in a very fast and brutal wave which allows breaking the formation with the mixture itself alongside with a continuous fill of the resulting fractures. Next to the fracturing is done, the evacuation process of the used fluids is launched using the flushing materials.

In the realm of hydraulic fracturing, a groundbreaking advancement has emerged: the development of a single fluid known as the "Fracturing Mixture." This innovative solution combines various fracturing fluids into one cohesive composition, transforming the way reservoirs are fractured and enhancing the efficiency of the process.

Traditionally, hydraulic fracturing operations involve the use of multiple fracturing fluids, each serving a specific purpose. These fluids may include slickwater, gels, foams, and proppants, among others. However, the introduction of the fracturing mixture streamlines the process by combining these fluids into a single, synergistic composition.

One crucial component of the fracturing mixture is the unique combination of hydrogen gas (H_2) and an AHF fluid. This pairing sets the stage for an extraordinary reaction that enables the fracturing mixture to push forcefully into the reservoir, creating and filling the fractures simultaneously.

The process starts when the Fracturing Mixture is pumped into the CRV chamber then the AHF then the HBF fluids respectively. The contact between both AHF and HBF causes the release of H_2 molecules in gas form (which called the desorption) and leads after that to the shock-wave release by the reaction between HBF and H_2 gas molecules.

The shock of the reaction occurs when the hydrogen gas interacts with the HBF fluid within the fracturing mixture. This reaction generates a rapid and controlled expansion, creating a surge of pressure that propels the mixture deep into the reservoir. This shockwave effect ensures that the fractures are created by ensuring the brutal augmentation of pressure up of the **Pressure of Fracturing (P_F)** with precision and that, the fracturing mixture is distributed thoroughly throughout the reservoir. The Equation III.12 explain the direct relation between the P_F value and the **Adsorbent Concentration ($C_{adsorbent}$)** inside the AHF fluid which is also the way to determine the HBF concentrations to use for the fracturing operation.

As the fracturing mixture infiltrates the fractures, it fills the void spaces with its well-balanced composition. The mixture contains suspended proppants, which act as a support structure to keep the fractures open, allowing for the effective extraction of hydrocarbons. Additionally, the

fracturing mixture possesses lubricating and viscosity-controlling properties, facilitating its flow within the fractures and enhancing overall performance.

Once the fracturing process is complete, the reservoir requires a thorough flushing to remove any remaining fracturing fluids and debris. Advanced flushing techniques are employed to ensure the efficient and complete removal of the fracturing mixture from the fractures and the reservoir matrix.

These flushing techniques may involve the use of compatible flush fluids or solvents that are specifically designed to dissolve and remove the fracturing mixture residues. The flushing process is carefully engineered to minimize environmental impact and ensure the safe extraction of the fracturing fluids from the reservoir.

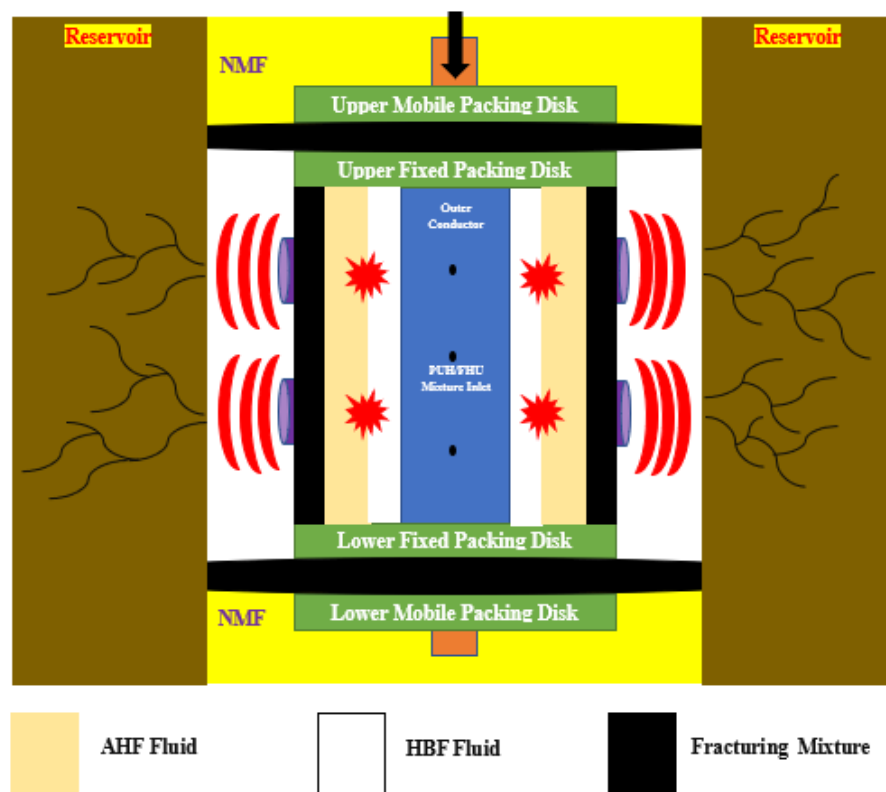


Figure III.7: FUH process using HFRC tool.

E. Risks and challenges

The most considerable risks in affecting an FUH operation are:

Safety concerns: including flammability and explosive hazards, risk of leakage and venting, compatibility and material selection.

Technical challenges: including fracture propagation and controllability, fluid rheology and proppant suspension, reservoir compatibility and performance.

Conclusion

In nutshell, the evolutionary path towards using hydrogen (H₂) in perforation and fracturing operations presents a transformative opportunity for the oil field industry. The potential environmental benefits, such as reduced carbon emissions and improved water management, are compelling drivers for exploring hydrogen-based fracturing fluids. However, it is essential to acknowledge and address the major challenges and risks associated with this approach. Environmental considerations, including carbon emissions and water usage, must be carefully managed to ensure the overall sustainability of hydrogen-based operations. Safety concerns related to hydrogen's flammability and potential leakage require stringent protocols and monitoring systems to safeguard workers and the environment. Technical complexities, such as optimizing fracture propagation and fluid properties, necessitate ongoing research and collaboration. By proactively addressing these challenges, the industry can unlock the true potential of hydrogen, achieving safer and more sustainable oil field operations.

To sum up, the adoption of hydrogen in perforation and fracturing operations represents a significant step forward, but it is crucial to approach it with a comprehensive understanding of the associated risks. While the benefits are compelling, including environmental advantages and improved efficiency, the major challenges identified earlier must be carefully considered and mitigated. By embracing a holistic approach that combines advanced technologies, robust regulations, and ongoing research, the industry can navigate these challenges and ensure the responsible and effective use of hydrogen in the future. By doing so, the oil field sector can contribute to a more sustainable energy transition while maximizing the potential of this innovative solution.

**GENERAL
CONCLUSIO
N**

The utilization of Feroui-Madani (FM) equations in electrolysis studies plays a pivotal role in estimating gains and optimizing overall process efficiency. These equations provide valuable insights into the complex electrochemical reactions occurring during the electrolysis of HC-HV water systems, allowing for a quantitative understanding of the relationship between electrical charge and substance production or consumption. Chemical and mechanical factors significantly impact the rheological parameters of an electrolyte, necessitating appropriate treatments for optimal electrolysis conditions. Chemical treatments involve modifying electrolyte composition or incorporating additives to enhance reaction kinetics and minimize side reactions, while mechanical treatments optimize system physical properties to promote efficient mass and charge transport.

The importance of chemical and mechanical treatment in water cannot be overstated when considering electrolysis, as they improve efficiency, product quality, and reduce maintenance requirements. Chemical treatments remove impurities and prevent fouling and undesirable by-products, while mechanical treatments remove suspended solids and bacteria. A comprehensive understanding of water composition enables tailored treatment processes, resulting in higher electrolysis efficiency. Furthermore, the adoption of hydrogen in perforation and fracturing operations offers transformative opportunities for the oil field industry. The potential environmental benefits and improved water management make hydrogen-based fracturing fluids compelling. However, challenges related to environmental considerations, safety concerns, and technical complexities must be addressed. By proactively managing these challenges through advanced technologies, robust regulations, and ongoing research, the industry can embrace the responsible and effective use of hydrogen, contributing to a more sustainable energy transition and maximizing its potential.

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