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HYDROGEN PEROXIDE BASED GREEN PROPELLANTS FOR FUTURE SPACE PROPULSION APPLICATIONS

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ABSTRACT

Recent space developments are implementing several simpler and less expensive rocket technologies. Environmental concerns and following governmental restrictions necessitate to replace current (hydrazine-based) toxic propellants with green ones, with a minimum loss of performance. Hydrogen peroxide is a promising candidate for the future of green propellants due to its flexibility and its benign nature allows the advancement of simple, cost-effective, and environmentally friendly propulsion with sufficient performance to replace hydrazine or other high-performing toxic propellants. Consequently, this thesis is devoted for the study of hydrogen peroxide-based propellants for future space propulsion applications. The main objective of this work is to study the combustion properties of green propellants. Foremost we discussed the hydrogen peroxide use, properties, and management of in-space propulsion, and later, various combinations and compositions with hydrogen peroxide have been studied using NASA CEA code. The activity performed concerns the study of hydrogen peroxide as the mono propellant, bi propellant and hybrid propellant. The main purpose is to find combustion temperature and specific impulse values at different O/F ratios of 2,4,6,8,10 and various pressure chamber values of 20, 25, and 30 bar. For this purpose, two cases have been considered to study the bi propellant of ethanol, RP-1 and liquid methane and mass fraction variation is obtained at different O/F ratio and at chamber, throat and exit. Four cases have been studied in the hybrid propellant condition with various paraffin waxes (SASOL 0907, SASOL 6003, SASOL 6805) as fuel and addition of aluminum effects have been studied efficiently. Analysis has done considering all the compositions and comparison of combustion products in the case of bi propellant in order to achieve the best efficiency at proper O/F ratio and fixed chamber pressure. It is observed that concentration of hydrogen peroxide has the significant effect on combustion performances and the chemical composition effects due to weight concentration. It is concluded that hydrogen peroxide is useful for the future development of the research activity.

SOMMARIO

I recenti sviluppi nell'ingegneria spaziale, con specifico riferimento alla propulsione spaziale, stanno portando allo sviluppo di nuovi endoreattori, più semplici e meno costosi, e a tecnologie anch'esse più semplici e meno costose. Le crescenti preoccupazioni per l'impatto ambientale e le conseguenti restrizioni governative impongono di sostituire gli attuali propellenti tossici (a base di idrazina) con propellenti "verdi", contenendo al minimo le perdite di prestazioni. Il perossido di idrogeno è un candidato promettente per il futuro dei propellenti verdi in virtù della sua flessibilità e della sua natura benigna permettendo l'avanzamento verso sistemi propulsivi più semplici, economici e rispettosi dell'ambiente, con prestazioni sufficienti a sostituire l'idrazina o altri propellenti tossici caratterizzati da più alte prestazioni. A seguito di queste considerazioni, questa tesi è dedicata allo studio di propellenti a base di perossido di idrogeno per le future applicazioni di propulsione spaziale. Il principale obiettivo di questo lavoro è studiare le proprietà di combustione dei propellenti verdi. Viene prioritariamente discusso l'uso del perossido di idrogeno, quindi le sue proprietà e la sua gestione nel contesto della propulsione spaziale, e successivamente vengono studiate varie combinazioni e composizioni con perossido di idrogeno utilizzando il codice NASA CEA. L'attività svolta riguarda lo studio del perossido di idrogeno come mono-propellente, bi-propellente e propellente nel contesto della propulsione di tipo ibrido. Lo scopo principale è quello di trovare la temperatura di combustione e i valori di impulso specifico al variare del rapporto di miscela O/F e della pressione in camera di combustione. Sono state considerate diverse coppie propellente, per studiare miscele bi-propellente di etanolo, RP-1 e metano liquido indagando la composizione dei prodotti di combustione all'equilibrio, ottenuta per diversi rapporti O/F, all'uscita della camera di combustione, nella sezione di gola dell'ugello e allo scarico. La configurazione di endoreattore ibrido è stata studiata con diverse cere paraffiniche (SASOL 0907, SASOL 6003, SASOL 6805) impiegate come combustibile, considerando pure l'aggiunta di alluminio. L'analisi è stata condotta considerando le diverse composizioni, e confrontando i prodotti di combustione per ottenere la migliore efficienza con un adeguato rapporto O/F, a pressione fissa della camera di combustione. I risultati ottenuti evidenziano che la concentrazione di perossido di idrogeno ha un effetto significativo sulle prestazioni della combustione e sugli effetti della composizione chimica dovuti alla concentrazione. Complessivamente il lavoro condotto mette in luce come il perossido di idrogeno possa costituire un utile propellente per lo sviluppo futuro di sistemi propulsivi meno inquinanti, più efficienti e meno costosi.

ACKNOWLEDGEMENTS

"Great things are not done by one person. They're done by a team of people."

Steve Jobs

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Foremost, we want to offer this endeavor to our **GOD Almighty** for the wisdom he bestowed upon us, the strength, peace of mind and good health in order to finish this research.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Abbreviations

MMH	Monomethylhydrazine
UDMH	Unsymmetric Dimethylhydrazine
REACH	Registration, Evaluation, Authorisation, and Restriction of Chemicals
ISP	Specific Impulse
HTP	High Test Peroxide
H_2O_2	Hydrogen Peroxide
H_2O	Water
O_2	Oxygen
ALM	Additive Layer Manufacturing
HYPROGEO	Hybrid Propulsion Module for transfer to GEO
CEA	Chemical Equilibrium with Applications
NASA	National Aeronautics and Space Administration
TRL	Technology Readiness Level
wt.%	Weight Concentration
FMC	Food Machinery and Chemical Corporation
AOL	Active Oxygen Loss
NIOSH	National Institute for Occupational Safety and Health
ICBMs	Intercontinental Ballistic Missiles
IRBM	Intermediate-range Ballistic Missile
AFRL	Air Force Research Laboratory
MnO_2	Manganese (IV) oxide
Mn_2O_3	Manganese (III) oxide
MnO	Manganese (II) oxide

ICB	Instrumented Catalyst Beds
HRE	Hybrid Rocket Engines
HTPB	Hydroxyl Terminated Polybutadiene
EVA	Ethylene Vinyl Acetate Copolymer
PE	Polyethylene
$C_{50}H_{120}$	SASOL Wax 0907
$C_{32}H_{66}$	SASOL Wax 6003
$C_{40}H_{48}$	SASOL Wax 6805
CO_2	Carbon dioxide
O/F Ratio	Oxidizer to Fuel Ratio
AMU	Atomic Mass Unit
CO	Carbon monoxide
ORPHEE	Operational Research Project on Hybrid Engine in Europe
RATO	Rocket-assisted take-off
NFPA	National Fire Protection Association
CH_4	Methane
C_2H_5OH	Ethanol
$C_{12}H_{24}$	RP-1
H_2	Hydrogen

Latin Letters

A	Area
a	Speed of Sound
C	Concentration
c	Effective exhaust velocity
c^*	Characteristic velocity
C_d	Discharge coefficient
D	Diameter
F	Thrust
g	Specific Gibbs free energy
g_0	Gravitational acceleration at sea level
h	Specific enthalpy

L	Length
M	Mach number
m	Mass
p	Pressure
R	Specific gas constant
T	Temperature
t	Time
r	Radius
u	Specific internal energy
V	Velocity
W	Weight
S	Entropy
Q	Heat energy
n	Number of moles
ν	Specific volume

Greek Letters

γ	Specific heat constant
λ	Nozzle efficiency
μ	Viscosity
φ	Void space fraction
ρ	Density

Other Characters

$\dot{m}$	Mass flow rate
$\mathcal{M}$	Molar mass
$\mathcal{V}$	Volume

CHAPTER 1

INTRODUCTION

The use of green propellants promises benefits in terms of overall life cycle cost reduction, lowering the cost of access to space, and reducing environmental impact. The term "Green Propellant" refers to a family of propellants, whether liquid, solid, hybrid, mono- or bi-propellant, that meet criteria such as low toxicity, low pollution impact, good storability, broad material compatibility, and good performance [1]. Green propellants are low-toxicity, high-energy liquid rocket propellants that will provide future spacecraft with a high-performance, high-efficiency alternative to conventional chemical propellants. Hydrazine is a dangerously unstable and highly toxic substance. Importantly, its use as a propellant has been restricted by strict legislation designed to protect workers who work with extremely toxic and carcinogenic substances [1]. Hydrogen peroxide (H_2O_2) is one of the most desirable alternatives, not only because it is non-toxic and non-carcinogenic, but also because of its many benefits, including its high density and low cost. H_2O_2 also offers substantial cost savings due to the dramatic simplifications in health and safety security procedures during the propellant's processing, storage, and handling. In this thesis, hydrogen peroxide was investigated as a mono propellant, hybrid propellant, and bi-propellant with various fuels using the CEA code, and its use in future space propulsion applications was discussed.

1.1. Motivations

1.1.1. Why Green Propellants?

Hydrazine-based propulsion systems are cutting-edge for a wide range of applications, including launchers and large and small satellites. They have a long and illustrious history, as well as a wide range of space-qualified, off-the-shelf components. Hydrazine is a toxic, carcinogenic, and mutagenic monopropellant, and MMH (Monomethylhydrazine) or UDMH (Unsymmetric Dimethylhydrazine) is a toxic, carcinogenic, and mutagenic bipropellant. When Hydrazine or its compounds are used, special care must be taken during both field and operational phases. After the REACh legislation designated hydrazine as a drug of high concern in 2011, there is a possibility that these systems will be banned in the future [2].

The following are the most promising characteristics of green propellants that seek to minimize costs, complexity, and pollution [1]:
Low toxicity: — Operational risks are reduced (simple and safe handling of non-toxic fluids, other work in parallel possible).
During handling and storage, there were fewer safety precautions taken.
Low Pollution Impact: — Pollution of the ground environment (production plants, test benches, launch sites, stage impact areas (soil and oceans)) is reduced.
Pollution of the atmosphere is minimized (ozone depletion, green-house effect).
Pollution in space is minimized (optical sensors, spacesuits).
Low cost: — Because of the lower toxicity, manufacturing and operating (transport) costs are minimized.
Reduced costs as a result of less complexity (e.g. No cryo-cooling to 20 K).
Performance: — Both mass- and volume-specific performance must be taken into account.
With an increased ISP and density more impulse (Δv) can be loaded into the spacecraft. This allows longer mission duration or missions that previously require more complex technologies (e.g. bipropellants). For the same Δv, the satellite can be smaller and lighter which allows transporting more satellites during one launch.
A large number of green propellant pairs can be classified using these parameters. Based on previous research, the most interesting propellants were chosen for the analysis.

1.1.2. A Green, Cheap and Effective Propellant: Hydrogen Peroxide

The chemical compound hydrogen peroxide has the formula (H_2O_2). It is a colorless liquid that is slightly more viscous than water in its pure form. Hydrogen peroxide is a powerful oxidizer that is used as a bleaching and disinfectant. Since 1934, concentrated hydrogen peroxide, also known as 'high-test peroxide' (HTP), has been used as a rocket propellant.

HTP is currently used on the Soyuz Launcher for the first stage gas generator and the Soyuz capsule for the reaction control thrusters used during re-entry. The manufacturing and transport of 98 percent were qualified within the framework of the H_2O_2 project HYPROGEO, and this propellant blend is now commercially available on the market [3]. Hydrogen Peroxide was studied at ASL in the context of a fully ALM printed thruster [4], and it is now regarded as a low-cost option for orbital propulsion. When compared to traditional Hydrazine, it has the following advantages:

Advantages of H_2O_2:

- Non-Toxic, non-carcinogenic
- Cheap, commercially available
- Cold-start capable (monopropellant with catalyst)

- Low decomposition temperature (<1000°C) - conventional materials can be used
- High Density (1450 kg/m3).
- Can be used as an oxidizer in bipropellant and pure as a mono prop (dual-mode system)

Recent space developments are implementing several simpler and less expensive rocket technologies. Aside from the facts stated above, H_2O_2 is a promising candidate for the future of green propellants due to its flexibility. To summarize, the benign nature of H_2O_2 allows for the advancement of simple, cost-effective, and environmentally friendly propulsion with sufficient performance to replace hydrazine or other high-performing toxic propellants.

1.2. Objectives

The main objective of this work is to study the combustion properties of green propellants. Foremost we discussed the hydrogen peroxide use, properties, and management of in-space propulsion, and later, various combinations and compositions with hydrogen peroxide have been studied using NASA CEA code. The main purpose of this study is to find the efficient combination of bi propellant and hybrid propellant at a proper O/F ratio. Following are the combinations of fuels studied for combustion temperature and specific impulse values at different O/F ratios of 2,4,6,8,10 and various pressure chamber values of 20, 25, and 30 bar.

- Hydrogen peroxide as a mono propellant
- Hydrogen peroxide as a hybrid propellant
    - Pure hydrogen peroxide to paraffin waxes (SASOL 0907, SASOL 6003, SASOL 6805)
    - 95% Hydrogen peroxide and 5% H_2O to paraffin waxes
    - 90% Hydrogen peroxide and 10% H_2O to paraffin waxes
    - Effect of Aluminum addition of fuel in the waxes at 10%, 15%, and 20%
- Hydrogen peroxide as a bipropellant
    - Pure hydrogen peroxide to ethanol, RP-1 (Kerosene), and liquid methane
    - 90% Hydrogen peroxide to ethanol, RP-1 (Kerosene), and liquid methane
    - Comparison studies have been made for these three fuels in form of combustion products

1.3. Plan of Presentation

The workflow of the thesis is organized as listed below:

- In Chapter 2, the propulsive properties, physicochemical properties, toxicological properties, decomposition properties and explosive characteristics of highly concentrated hydrogen peroxide for use in space propulsion have been studied in detail by extensive literature research.
- In Chapter 3, the hydrogen peroxide usage as the mono propellant thruster and chronological development of the hydrogen peroxide as a green propellant has been studied using six research papers.
- In Chapter 4, the case study of hydrogen peroxide as an oxidizer in hybrid rockets has been conducted. Furthermore, a detailed study of propellant system hydrogen peroxide/paraffin waxes has been done using NASA CEA code. Combustion temperature and specific impulse values have been evaluated at different O/F ratios and various pressure chamber values
- In Chapter 5, a detailed case study of propellant system hydrogen peroxide to ethanol, RP-1, and liquid methane has been done using CEA code, and a comparison study of combustion products have been performed between H_2O_2 - ethanol, H_2O_2 - liquid methane, and H_2O_2 - kerosene.
- In Chapter 6, the entire research work is concluded and suggestions for future applications are expressed.

CHAPTER 2

HYDROGEN PEROXIDE PROPERTIES, MANAGEMENT & USE IN SPACE PROPULSION

This chapter is assigned to explain the propulsive properties, physicochemical properties, toxicological properties, decomposition properties, and explosive characteristics of highly concentrated hydrogen peroxide for use in space propulsion. It also includes product handling and safety instructions, storage of H_2O_2.

2.1. Propulsive Properties

Green propellants used for satellite-level propulsion systems have become attractive in recent years because of the non-toxicity and lower requirements of safety protection [5]. According to Ventura and Mark [6], hydrogen peroxide becomes more stable with higher peroxide content. For example, 98% hydrogen peroxide is more stable than 70% hydrogen peroxide. Water acts as a contaminant, and the higher the water concentration the less stable the peroxide is. The storability of peroxide is dependent on the surface-to-volume ratio of the materials the fluid is in contact with. To increase storability, the ratio should be minimized. As specified by Werminont et al. [7], hydrogen peroxide for propulsion applications has been produced by an electrolytic process, anthraquinone process or oxidation of propane or its derivatives and purified by rectified distillation which provides concentrations of 85-90%, or by fractional distillation for higher purity levels, throughout the history of its usage.

Hydrogen peroxide with a high concentration (80 wt.%) was first used as a working fluid for propulsion by Hellmuth Walter in 1935. Walter's works took the lead in the development of aircraft and rocket engines, submarines, and torpedos working with HTP (High-test peroxide) in Germany before and during World War II and influenced many advancements in the UK after the war. Aircraft rocket engines in the early 50s and bipropellant liquid launchers Black Knight (1957), Black Arrow (1971), and Black Prince (never used, only conceptual design) were the main British designs with the rocket grade peroxide.

Hydrogen peroxide was widely used at the beginning of the Space Race but was replaced later by hydrazine and dinitrogen tetroxide for performance considerations. During the Cold War, various technologies based on hydrazine and dinitrogen tetroxide were developed and today they have a high technology readiness level (TRL). However, these high-performing liquid propellants and their combustion products are highly hazardous for human health and the environment; hence, hydrogen peroxide recently became popular again for environmental reasons. Because of the reduced usage of hydrogen peroxide in the second half of the 20th century, the TRL for H_2O_2 based technologies are much lower than the ones based on toxic propellants [8]; also, there are fewer available resources about H_2O_2 in the literature. Eventually, TRL of H_2O_2 based technologies will increase since it is the most promising green liquid propellant in terms of performance, safety, availability, and price.

2.2. Physico-Chemical Properties

Green Propellants have shown high favorability not only in terms of operability, cost efficiency, and environmental safety but also in performance and physicochemical properties. As widely interpreted, green propellants are defined as low-hazard, low-toxicity, environmentally friendly propellants during various phases of spacecraft development, launch, and operations.

The physical properties of hydrogen peroxide are close to those of water, with two notable differences: H_2O_2 has a significantly higher density and a much lower vapor pressure. It remains in the liquid state at ambient pressure in a wide range of temperatures and is relatively easy to handle for other common liquid rocket propellant oxidizers like dinitrogen tetroxide, nitric acid, and liquid oxygen [9]. The propulsive performance of hydrogen peroxide monopropellant rockets is about 20% lower than hydrazine, but the volume-specific impulse achievable with 90% H_2O_2 is higher than most other propellants due to its high density. This is particularly useful for systems with significant aerodynamic drag losses and/or stringent volume constraints. Concerning bi-propellant and hybrid rocket engines, hydrogen peroxide yields a specific impulse comparable to other liquid oxidizers like dinitrogen tetroxide, nitric acid, and even liquid oxygen.

Rocket-grade hydrogen peroxide is used as decomposed in propulsion applications. What makes it advantageous as a rocket propellant in terms of chemistry is its high energy, low corrosivity, the possibility of hypergolic ignition with catalysts or energetics, very low decomposition rate, non-reactivity with the atmosphere, and compatibility with various pressurant gases. Weak corrosivity, with being non-volatile and non-cryogenic, also refers to high stability and, thus, high storability. To indicate non-cryogenity, data for boiling and freezing points of hydrogen peroxide is presented in Fig. 2.1.

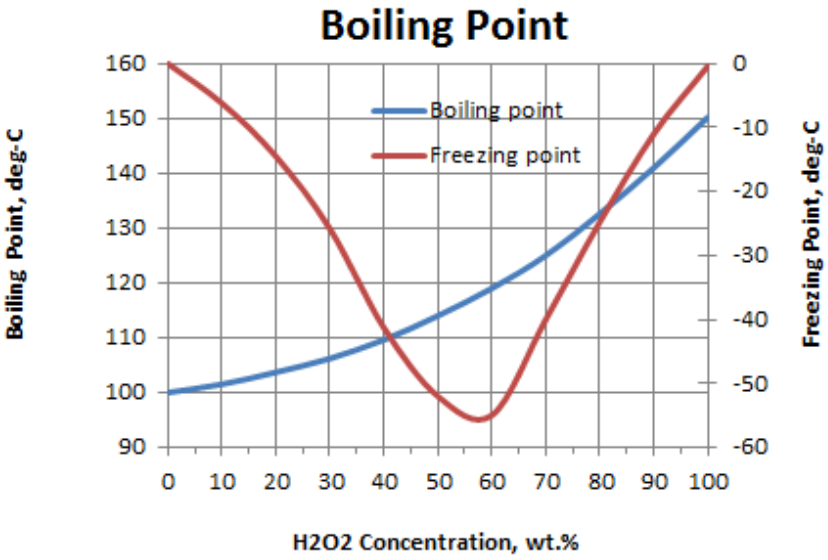


Figure 2-1 Freezing and boiling points of Hydrogen Peroxide.

Properties of H_2O_2

- H_2O_2 is non-toxic, making the mission more cost-effective in the long run. Toxic propellants necessitate the use of additional safety precautions and procedures at an additional expense.
- It is not a cryogenic propellant, so no need for support devices like thermal control units to maintain cryogenic temperatures that add extra mass to the spacecraft.
- Simple thruster design that in small spacecraft is very helpful and highly desirable.
- In the stage of decomposition (in which thrust generates), hot gasses are produced mostly containing environmentally friendly water molecules.
- In nature, low volatility.
- Greater propulsion efficiency.
- High expansion to its initial value during decomposition (volume expansion exceeds 4500 times under normal conditions) which is favorable in nozzles.
- Highly stable and storable liquid.
- Can be used as a monopropellant and as well as bipropellant oxidizer.
- It has low vapor pressure (at room temperature about 2 mm Hg), it can be handled relatively easily.

2.3. Decomposition Properties

Hydrogen peroxide is a high-density liquid having the characteristic of being able to decompose exothermically into water (steam or liquid) and oxygen according to the reaction:

$$H_2O_2\ (l) \rightarrow H_2O\ (g) + \frac{1}{2} O_2\ (g) \qquad H = -54.4\ \text{kJ/mole}$$

$$H_2O_2\ (l) \rightarrow H_2O\ (l) + \frac{1}{2} O_2\ (g) \qquad H = -98.4\ \text{kJ/mole}$$

The decomposition process will take place in either a liquid or a gaseous state. Homogeneous decomposition happens when HTP comes into contact with a substance that is in the same phase as it. Otherwise, the reaction is defined as heterogeneous, as it occurs on all material surfaces and is highly dependent on the materials in contact as well as the peroxide and contacting material's surface conditions [10]. Temperature, degree of contamination, surface movement, pH, and solution concentration (to a lesser extent) all influence the rate of decomposition.

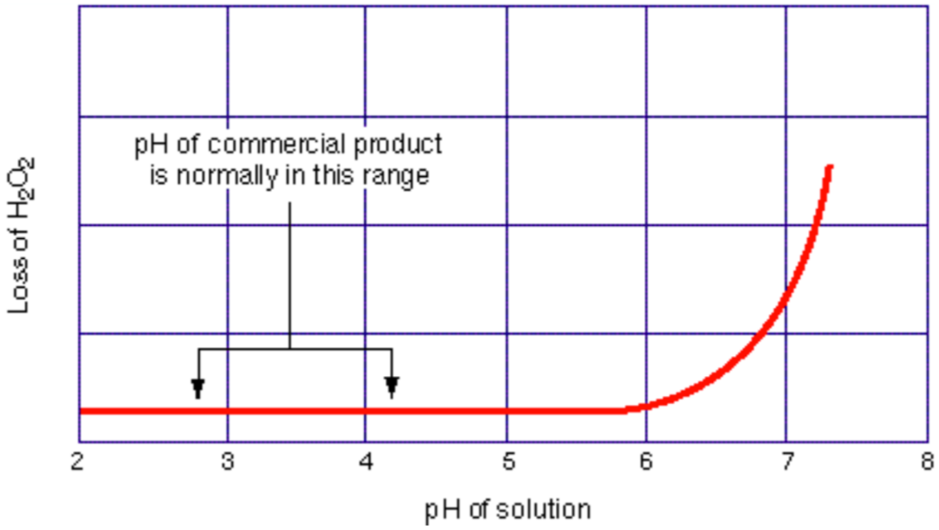


Figure 2-2 Effect of pH on the rate of decomposition of H_2O_2.

From Figure 2.2, We understand that in an alkaline solution, the rate of decomposition increases rapidly as the pH is increased. When we think of environmentally safe, green, and toxic-free propellants for rocket propulsion, HTP (98 % +) comes to mind first and foremost. RGHP stands for high test peroxide (Rocket Grade Hydrogen Peroxide). HTP is a high-purity aqueous solution containing more than 98 % hydrogen peroxide. HTP is essentially non-toxic, low irritation, and corrosive-free. As HTP is decomposed, it produces environmentally friendly hot gaseous decomposition products, which are mainly water and contain around 46% oxygen by weight. HTP propellant can act as a monopropellant as well as a strong-liquid oxidizing agent with hypergolic properties. Hydrogen Peroxide has a significantly higher density with much lower vapor pressure and is closely related to the physical properties of H_2O. Hydrogen

Peroxide is a nonplanar molecule, with C_2 symmetry. The molecular structures of gaseous and crystalline H_2O_2 are significantly different. This difference is attributed to the effects of hydrogen bonding, which is absent in the gaseous state. Crystals of H_2O_2 are tetragonal.

Based on how the reaction is accelerated, the decomposition of hydrogen peroxide can be divided into two categories: catalytic decomposition and thermal decomposition. Catalysts or energetic materials are used in the first form. Fuels can be promoted by energetic materials to initiate decomposition of HTP in the combustion chamber after the injection, if it is used as an oxidizer. Catalytic decomposition systems are easy because they only require catalysts or fuels that are catalytically or energetically promoted; however, obtaining or manufacturing these chemicals is a major challenge because manufacturing necessitates the use of specialized laboratory equipment, which makes the materials costly. Furthermore, the promoted fuels make the machine hypergolic, lowering overall safety and rethrottleability of the engines [11].

Thermal decomposition, on the other hand, occurs at high temperatures. If the temperature of the propellant increases, the reaction accelerates. Thermal decomposition accelerates exponentially since it is an exothermic reaction, which means that more heat is emitted over time, resulting in an increase in temperature and, thus, a faster rate of decomposition [11].

As a result of the temperature increase as the propellant is decomposed more and more, it is safe to assume that thermal decomposition occurs during catalytic decomposition as well. However, if thermal decomposition is the only method of decomposition, a device to preheat the HTP is needed, which adds to the design complexity. Furthermore, it takes time to heat H_2O_2 to a temperature high enough to start the decomposition, which may be a drawback for space missions that need precise maneuvers. To conclude, if procurement or manufacturing are straightforward, a decomposition device with a suitable catalyst becomes the most straightforward alternative.

2.4. H_2O_2 Stability and Storability

Characteristics such as heat resistance, storage duration, and other parameters that describe how well the chemical can be stored and treated are used to assess the stability of a liquid propellant. Chemicals that are unstable are especially susceptible to conditions that are difficult or impossible to control. Liquid ozone is one example of a chemical that is commonly considered unstable. Ethanol and kerosene are examples of hydrocarbon fuels that are considered stable. Monopropellants and solid propellants have a unique place in the discussion of stability since they can behave independently and thus pose a more precise danger. When it comes to chemicals that can react entirely on their own, the concept of stability becomes more precise and important. In practice, there are some common, but not always reliable, methods for defining and testing chemical stability. For identifying and classifying solid chemistries, which determines stability for solid propellants, there are unique parameters and test specifications for solid propellants. Hydrazine and hydrogen peroxide have evolved stability requirements that are similar but not identical. Schmidt goes into great depth regarding the stability of hydrazine. Several sources address the general characteristics of hydrogen peroxide stability [12,13,14,15].

Hydrogen peroxide has been shown to be safe enough for use as a propellant and power fluid in previous studies and applications. Hydrogen peroxide can withstand a wide range of temperatures and has been shown to be safe to store for long periods of time. It's likely that hydrogen peroxide's stability has improved recently as a result of changes in industrial hydrogen peroxide manufacturing purity requirements to support the electronics industry's higher cleanliness standards [6]. FMC is an example of long-term hydrogen peroxide production that is healthy. FMC has a long history of processing and storing high-concentration hydrogen peroxide in a healthy and productive manner. FMC has been manufacturing hydrogen peroxide at levels of 90% and greater than 98% for more than 30 years.

During this time, there has been no incident in the manufacturing or storage of the product at any FMC venue. FMC has carried out comprehensive material compatibility testing. To ensure that no hydrogen peroxide leakage occurs, equipment passivation and cleaning are done regularly. FMC follows its own rigorous general hydrogen peroxide protection rules to ensure safe service [12]. FMC expanded its monitoring and safety training for all new customers following recent accidents involving hydrogen peroxide created by others. Until supplying hydrogen peroxide to any potential customers, FMC offers consumer safety training and an on-site plant inspection. As a result of this activity, no accidents involving the storage and transportation of 90% and 98% hydrogen peroxide have been recorded by any of FMC's customers [12]. Since WWII, hydrogen peroxide has been stored and used in several propulsion and control systems. It's been used in submarine and torpedo propulsion systems, telecommunications satellites, and rocket and manned spacecraft primary and secondary propulsion systems.

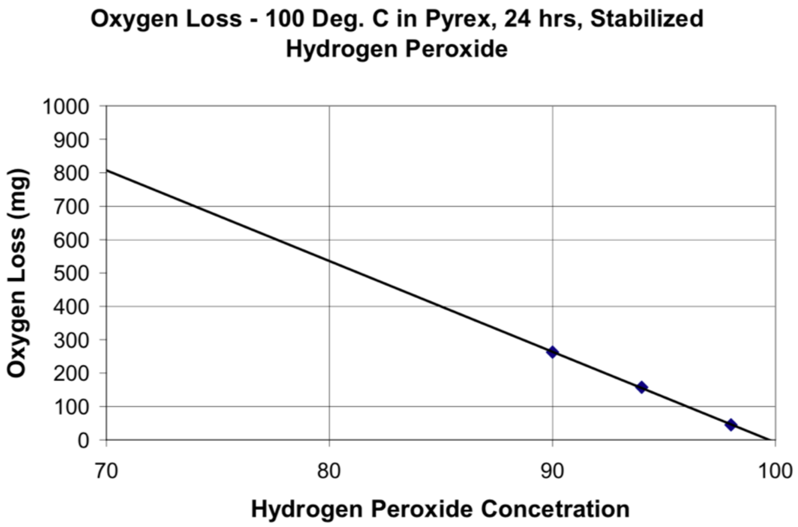


Figure 2-3 The effect of water on hydrogen peroxide stability.

Furthermore, it is a common misconception that H_2O_2 cannot be kept in a sealed container for long periods of time. H_2O_2 of propellant grade has been securely stored in vented containers for more than 17 years [6] and in sealed spacecraft for many years [15,16] (an example is the COMSAT spacecraft). Another curious aspect is that the storability of hydrogen peroxide improves as the concentration increases, which is very counterintuitive.

In order to meet the propulsive criteria in aerospace, hydrogen peroxide is stabilized very lightly. Because of the small number of stabilizer additives, the susceptibility to contamination is much higher. This necessitates extra care when shipping, treating, and storing the propellant on-site in order to protect the propellant from pollutants and rapid reactions caused by interaction with improper storage materials. Because of the heterogeneous decomposition that occurs on many materials surfaces, light stabilization strongly restricts tolerable materials. Regardless of the increase in decomposition rate, the concentration of HTP does not decrease [17]. As a consequence, pollution is an issue of protection rather than results, and Musker et al. [17] say that the only thing that can be done is to reduce the risk of contamination.

The stability of highly concentrated hydrogen peroxide is influenced by a number of factors, including contamination and the peroxide and contacting material's properties. Both the HTP and the substance in contact have an effect on each other, allowing the solution's stability to fluctuate. Experiments are by far the best way to understand the stability actions of hydrogen peroxide. Defining parameters is the method of describing the significance of the outcomes of these measures. According to Ventura [6], stability is usually characterized by active oxygen loss (AOL) and a concept known as "the Stability" for this reason. AOL is determined for a given concentration, purity, and stabilizer content of HTP, as well as a particular material in contact with HTP, with or without surface treatment or processing, at a specific temperature and time. Furthermore, it is a very good and widely used indicator of material compatibility with H_2O_2; compatibility classes have also been established using it.

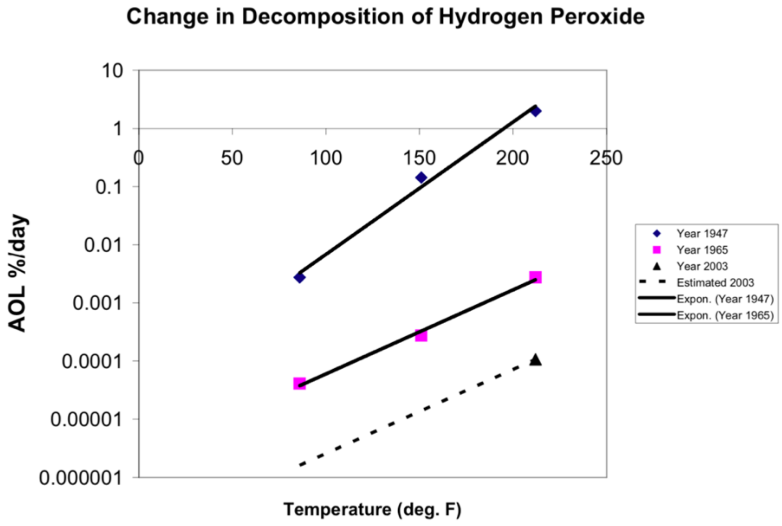


Figure 2-4 Improvements in Hydrogen Peroxide Stability with Time.

Figure 2.4 illustrates the proposed pattern [6] for hydrogen peroxide's current future stability. It's possible that modern hydrogen peroxide, which is pure, refined, and distilled, such as anhydrous ultra-high pure hydrogen peroxide created by fractional crystallization, has fundamentally superior storability. To this end, materials for vessels are split into four classes with respect to their compatibility with hydrogen peroxide-based on AOL and stability values. Existing data show that numerous means exist to demonstrate and or show improvements to the long-term storage of hydrogen peroxide [6]. If one were to try and make a system to have the maximum long-term storability, the general design criteria would be:

Surface to Volume Ratio	Less than 0.5 cm^{-1}
Hydrogen Peroxide Concentration	Higher is better, anhydrous may be the best.
Temperature	Lower is better, preferably less than 100 deg. Fahrenheit.
Hydrogen Peroxide Purity	The cleaner is better. Ppb or ppt purity may offer improvements.
Materials	Compatibility is similar to or better than Syncom (i.e.1060 Aluminum). AOL < 1.5% at 66 deg. Celsius for 1 week Stability > 98.8%

Table 2-1: General design criteria to have maximum long-term storability

According to Mark C. Ventura [6], using technologies dating back to about 1965, hydrogen peroxide has previously demonstrated long-term storage of several years in deployed spacecraft applications. Following that date, major improvements in propellant purity and materials technology have been made, which could increase the actual long-term storage capacity. The storability of hydrogen peroxide is 2 to 10 times higher than it was in 1965, according to increased propellant purity. Based on advances in propellants and materials since 1965, the previous demonstrated long-term use of 3 years in a spacecraft could easily be extended to 15 years or more.

Since the bulk of the literature data are collected, strides have been made in the direction of enhancing hydrogen peroxide's long-term storability. Materials research, passivation process research and development, propellant purification, and the characterization of anhydrous hydrogen peroxide are only a few examples of research and development opportunities that can help sustain and demonstrate improved long-term storage. Recent successes in some of the areas mean that further change is on the way. With current technology, it is possible to store hydrogen peroxide for many weeks to several years, making it ideal for immediate use in applications such as short-life satellites, reusable launch vehicles, expendable launch vehicles, and upper stages.

2.5. Risk Management

2.5.1. H_2O_2 Toxicity

Hydrogen peroxide is a widely used commercial chemical that is increasingly being used as a substitute for other, more toxic chemicals. Hydrogen peroxide is a common and naturally occurring chemical that is very non-toxic, according to a detailed discussion of its toxicity and interactions with humans and the environment [18].

When hydrogen peroxide comes into contact with human skin, it does not cause burns. Hydrogen peroxide is a chemical that is found in nature and is produced in the human body as part of normal body metabolism and chemical reactions. Hydrogen peroxide has water-like properties and can be absorbed through the skin like water. The hydrogen peroxide that penetrates the skin reacts quickly with a variety of body chemicals such as blood, glutathione, and other compounds, decomposing into water and oxygen. Decomposed hydrogen peroxide forms gas bubbles in skin surface capillaries, causing micro-embolisms, which block blood flow in the skin locally, resulting in a lack of blood flow and a change in skin color from its natural flesh tone to white. Blood flow returns to the skin and the color returns to normal once the oxygen bubbles are absorbed into the body. Excessive exposure can cause distended gas bubbles in the skin, giving the appearance of a chemical burn. It's important to note that, unlike nitric acid, hydrogen peroxide does not cause traditional chemical burns that destroy skin or flesh.

According to a recent comparison of hydrogen peroxide and hydrazine [19], hydrogen peroxide's toxicity and handling characteristics are comparable to or better than hydrazine's. Inhalation is typically the most dangerous mode of transport for toxic propellants, as hydrogen peroxide has a low vapor pressure and is less likely to cause tissue damage. The NIOSH limit of 1 ppm is a common source of hydrogen peroxide misunderstanding. This low level is compared to other chemicals with 1 ppm levels, and hydrogen peroxide is assumed to have similar toxicity. The 1 ppm limit is based on a conservative estimate of a 10ppm irritation limit. Humans are regularly exposed to more than 1 ppm in some common foods, and the natural hydrogen peroxide produced inside humans can exceed 1 ppm in human breath [20]. For over a century, hydrogen peroxide has been routinely handled in large quantities in the commercial industrial community, with little evidence of toxicity to industrial workers or the surrounding community.

2.5.2. H_2O_2 Detonability

There are three types of hydrogen peroxide detonations and other mono-propellant combustion phenomena: gas phase, liquid phase, and gas-liquid two-phase. The gas-phase of hydrogen peroxide has well-documented ignition and detonation conditions, and like other monopropellants, it is prone to ignition, deflagration, and possibly detonation. In general, methods and procedures must be used to avoid the formation of certain vapor phase conditions for safe operations, and this is a known and accepted condition for all monopropellants. The possibility of a liquid explosive or an aberrant combustion event, such as a hard start, that could initiate a detonation in the liquid mass and propagate through a system, causing extensive damage, is of greater concern.

Testing is carried out to decide if a detonation can be started in the liquid phase, what kind of atmosphere is needed to start a detonation, and whether the detonation will spread within a device. Finally, two-phase mixtures can detonate differently than single-phase liquids, and the presence of small bubbles in liquid explosives is a cause for concern because the propagation of a detonation wave can refract around existing bubbles in the liquid, creating reinforced pressures that aid in detonation wave propagation.

Under certain conditions, liquids with small amounts of gas bubbles can help propagate detonations. The normal slow decomposition of a monopropellant creates small quantities of dissolved gases or small bubbles in the propellant, so this is of concern. Like other monopropellants, gas-phase hydrogen peroxide will ignite, fire, combust, and detonate. Since there is almost always a small amount of dissolved oxygen in hydrogen peroxide and since the remaining case of liquids can provide some information about each of these conditions, little research has been found that discusses two-phase mixtures of hydrogen peroxide. There is some controversy about whether liquid phase hydrogen peroxide detonates and, if so, under what conditions, and if all hydrogen peroxide reactions are detonations or some other explosive reaction.

If the pressure inside a container or plumbing device exceeds the design margins, it may cause a mechanical failure or explosion. In an energetic material, a detonation is a reaction front that moves faster than the material's sound speed.

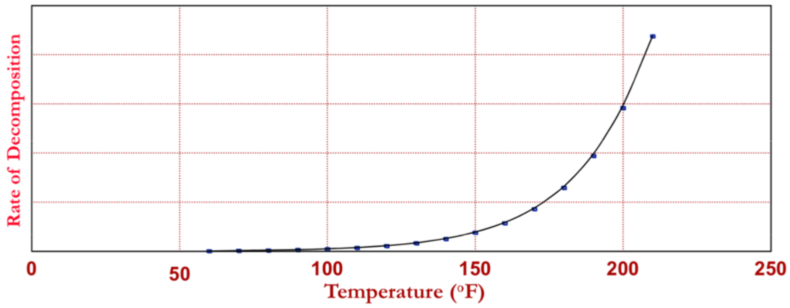
Detonations can cause much more harm than simple pressure failure explosions because the shock pressures are much greater. Analytical modeling or component failure analysis may show whether the failure was caused by a simple over-pressure due to rapid decomposition or a true detonation event. Because of the time, it takes to transform hydrogen peroxide into gaseous materials, the bulk of explosive events will be classified as deflagrating reactions and not a true detonation.

Recent demonstrations and studies of exceptionally high material compatibility [19], as well as recent advances in catalyst bed durability, indicate that current hydrogen peroxide chemistry is purer than previous propellants and that detonation sensitivity may have improved. Re-testing hydrogen peroxide, ideally with new techniques equivalent to other shock-sensitive materials, would be useful.

In conclusion, hydrogen peroxide tends to be immune to mechanical impacts and can spread a liquid phase detonation with substantial confinement and a heavy initiating charge at concentrations above 90-92 %. It appears that at concentrations of less than 90-92% a detonation is much harder to initiate.

2.6. Safety and Handling

According to FMC, there are four rules of H_2O_2 use and handling. They never contaminate, never confine, never contact, and always have water available. Types of contamination can be Heat & Energy, Materials of Construction, and Externally Introduced Materials. The chemical reaction caused by contamination is H_2O_2 + Contamination = Oxygen + Water + Heat (If fuel is present, it leads to FIRE). The figure below shows the effect of heat on Hydrogen Peroxide with respect to the rate of decomposition.



Temperature (°F)	Rate of Decomposition
72	1% per Year
151	1% per Week
218	2% per Day

Figure 2-5 Effect of Heat on Hydrogen Peroxide.

Below is the partial list of common materials to avoid:

- Graphite
- Copper
- Magnesium Alloys
- Brass
- Chromium
- Lubricating Oil
- Bronze
- Iron/Steel
- Lead
- Nickel
- Monel
- Pipe Dope

There are four indications of hydrogen peroxide decomposition like pressure build-up, H_2O_2 visually active (rapid bubbling), temperature increase, and gas or steam evolution.

The reason for not confining H_2O_2 is because it always decomposes, only the rate varies; a volume ratio of 200:1 of oxygen liberated to decomposed is possible; pressure build-up will occur in a closed system, and excess pressure build-up can result in tank or line rupture or failure. There are two types of contact like personal exposure and contact with flammable or combustible materials.

Proper Personal Protection Equipment

- Typical/Daily work around H_2O_2 equipment – Chemical safety goggles, rubber gloves.
- Increased exposure due to spillage, maintenance, or sampling – Neoprene or vinyl acid suit, Neoprene boots, Full face shield.

Possible Health Hazards Caused by Exposure to H_2O_2

- Eyes – May cause irreversible tissue damage, including blindness.
- Skin – Causes whitening of the skin or, after prolonged exposure leads to redness and blistering.
- Inhalation – May cause irritation and inflammation in the nose and throat.
- Taken Internally – Swallowing may produce corrosion of the gastrointestinal tract that may be life-threatening.

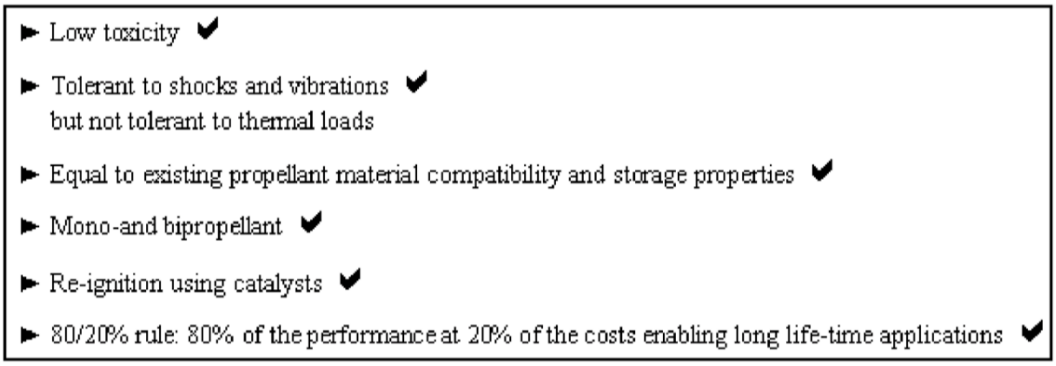
Water dilutes H_2O_2, dilute solution is less hazardous, and emergency equipment while handling H_2O_2 is safety showers, eyewash, water-hose.

There are four ways to maintain safety and quality:

- Passivation – Making sure that all components of H_2O_2 are properly passivated.
- Inspection – Tanks and delivery system should be inspected once every two years.
- Sampling – Hydrogen peroxide testing, Water quality testing.
- Maintenance – Repair defects immediately and Re-passivate equipment if needed.

2.7. Application of H_2O_2 In Space Propulsion

Since it meets the key criteria set out for this description below, hydrogen peroxide is confirmed to be a "green" propellant [21].



► Low toxicity ✓

► Tolerant to shocks and vibrations ✓
but not tolerant to thermal loads

► Equal to existing propellant material compatibility and storage properties ✓

► Mono-and bipropellant ✓

► Re-ignition using catalysts ✓

► 80/20% rule: 80% of the performance at 20% of the costs enabling long life-time applications ✓

Figure 2-6 H_2O_2 – A "green" propellant

For most space-based applications, hydrogen peroxide has been replaced by other chemicals such as hydrazine and its derivatives, as well as blends of nitrogen tetroxide and nitric oxide. The monopropellant hydrazine has a significantly higher specific impulse than hydrogen peroxide, which is critical for long-duration spacecraft to sustain long satellite life. While hydrazine has a lower density than hydrogen peroxide, the density impulse is often less significant than the specific impulse in applications such as spacecraft.

However, all monopropellant propulsion devices used in the early space program were hydrogen peroxide. Syncom, COMSAT, and early Bird spacecraft, the Centaur upperstage, the Mercury Spacecraft, the X-15 rocket plane, the X-1 rocket plane, the D558 X-plane, the NF-104A Aerospace Trainer Plane, the Lunar Landing Simulator, and other US aerospace vehicles all used hydrogen peroxide. Syncom II was in active service for six years, from 1963 to 1969, and the last recorded longitude of Syncom II was measured in 1995.

Hydrogen peroxide competed most specifically with nitrogen tetroxide and to a lesser degree with liquid oxygen as a liquid oxidizer. The use of nitrogen tetroxide and hydrazines as a standard for storable propellants has resulted in a major investment in industrial expertise and supply base for these chemicals. With the development of the Atlas and Titan Intercontinental Ballistic Missiles (ICBMs) and the Thor Intermediate Range Ballistic Missile in the early 1950s, nitrogen tetroxide and liquid oxygen were chosen as the main oxidizers over hydrogen peroxide (IRBM). Due to the large size of nuclear warheads at the time, these systems were very concerned with results.

Almost all parameters were sacrificed in the propellant selection process, with the exception of launch system flight results. Toxic and even cryogenic chemicals were used in these devices, which were not suitable for a launch-on-demand device. Today's launch systems, such as Atlas, Titan, and Delta, are advanced variants of these early ICBMs (derived from Thor IRBM).

The choice of propellants would have been different if the cold war's severe performance criteria had not been a driving design necessity and a focus on cost and operations had been more important, as it is today with the need for low-cost non-weaponized launch systems.

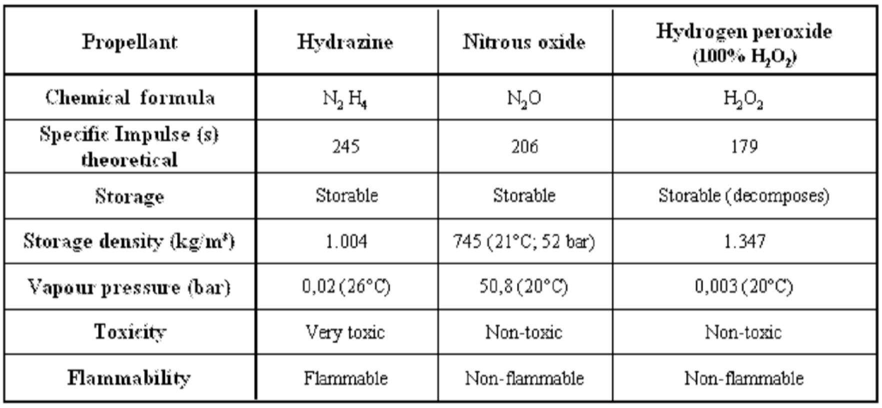
Launch System	**Main Propellants**
Beal Aerospace BA-1	Hydrogen peroxide – Kerosene
Virgin Galactic, Spaceship Two	Nitrous Oxide – Rubber
SpaceX, Falcon	Liquid Oxygen – Kerosene
Blue Origin, New Shepard	Hydrogen peroxide – Kerosene
Armadillo Aerospace	Liquid oxygen –

	hydrocarbon fuels
Pioneer Rocketplane	Liquid oxygen – hydrocarbon fuels

Table 2-2: Examples of privately funded launch systems

Hydrogen peroxide had previously been used extensively in launch systems as a power system fluid, especially for driving turbo-pumps, and as the propellant for reaction control fluids for a period of time. The argument that hydrogen peroxide has never been used in launch systems is inaccurate. With the Black Arrow launch system, England advanced the use of hydrogen peroxide as a primary propellant to a high degree of maturity. This technology would have progressed even further if England had not wanted to abandon its launch vehicle activities for other reasons. The Black Arrow launch system was shut down for reasons other than the hydrogen peroxide is used. If England had wanted to continue working on launch vehicles, hydrogen peroxide will most likely be one of the industry's standard propellants today.

The figure below explains the monopropellant comparison of hydrogen peroxide to hydrazine and nitrous oxide. The replacement of hydrogen peroxide by hydrazine was surely determined by the higher energy content of the latter.



Propellant	Hydrazine	Nitrous oxide	Hydrogen peroxide (100% H_2O_2)
Chemical formula	N_2H_4	N_2O	H_2O_2
Specific Impulse (s) theoretical	245	206	179
Storage	Storable	Storable	Storable (decomposes)
Storage density (kg/m^3)	1.004	745 (21°C; 52 bar)	1.347
Vapour pressure (bar)	0,02 (26°C)	50,8 (20°C)	0,003 (20°C)
Toxicity	Very toxic	Non-toxic	Non-toxic
Flammability	Flammable	Non-flammable	Non-flammable

Figure 2-7 Monopropellant Comparison

Hydrogen peroxide proves to be a promising propellant for selected space applications. The current applications of hydrogen peroxide are listed below.

NASA X37 – Figure below will be the first X-vehicle demonstrator to use advanced technologies during both orbital and re-entry phases of flight [22]. A single AR-2/3 H_2O_2 and JP 10 engine will power it. It is less toxic, less damaging to the atmosphere, and more lightweight than today's rockets or vehicles.

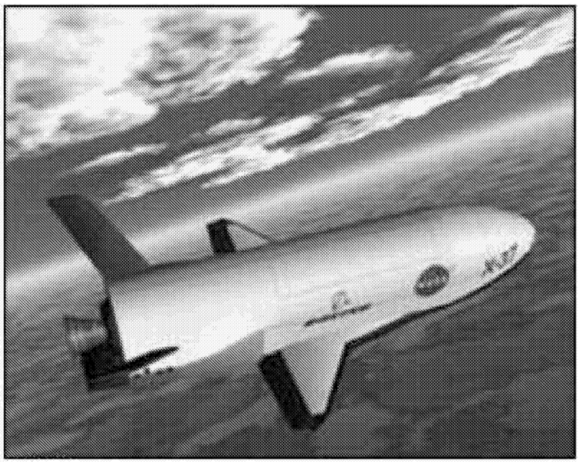


Figure 2-8 NASA X-37

Boeing Rocketdyne- Over the last few years, Boeing Rocketdyne has performed tests on non-toxic propulsion component technologies, including hot-fire testing of a reusable pump-fed AR-2/3 engine with 90 % HP/JP8 at Stennis Space Center, demonstrating a liquid/liquid 98 % HP/JP8 injector at AFRL, and demonstrating hypergolic fuel for use with 98 % HP [23].

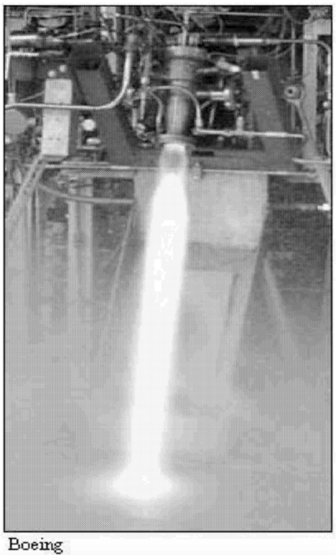


Figure 2-9 Boeing Rocketdyne HP-kerosene test run

CHAPTER 3

HYDROGEN PEROXIDE AS MONO PROPELLANT

In this section, it is explained briefly about the hydrogen peroxide usage as the monopropellant thruster and chronological development of the hydrogen peroxide as a green propellant. Furthermore, a detailed case study of six research papers is added for better understanding.

3.1. Hydrogen Peroxides Outweigh Other Green Monopropellants

Low toxicity storable liquid propellants have become considerably more attractive as possible substitutes for oxides of nitrogen and hydrazines. The most advantage of these alternative propellants is the significant cost saving associated with the drastic simplification of the health and safety protection procedures. The most eminent high thrust generating green propellants, as AND, HAN, and HNF have given by Wucherer E. J [39], are based on complex organic molecules and compensate the large molecular weight of their decomposition products which generates high operating temperatures of the exhaust gases. These results use the high use of extremely expensive materials and manufacturing processes for the thrust chamber, and, at the same time, the operational life of the catalytic beds is drastically reduced. On the contrary, hydrogen peroxide does not suffer from these disadvantages and has therefore been reconsidered as a promising green propellant for low and medium thrust applications.

As discussed in the previous section Hydrogen peroxide is a high-density liquid having the characteristic of being able to decompose exothermically into water (steam) and oxygen according to the reaction according to the Schoyer H.F.R [33]. Furthermore, hydrogen peroxide has significantly lower vapor pressure which makes it remains in the liquid state at room pressure in a wide range of temperatures and is relatively easy to handle with respect to other common liquid rocket propellant oxidizers like dinitrogen tetroxide, nitric acid, and liquid oxygen.

3.2. Chronological Evolution of Hydrogen Peroxide as Monopropellants

Firstly, the propulsive performance of hydrogen peroxide monopropellant rockets is about 20% lower than hydrazine, but the volume-specific impulse achievable with 90% H_2O_2 is higher than most other propellants due to its high density. Consequently, which has more density than the RP-1 [28].

Secondly, the most significant technology challenge for the realization of hydrogen peroxide monopropellant thrusters is the development of effective, reliable, long-lived catalytic beds, giving fast and repeatable performance, insensitivity to poisoning by the stabilizers and impurities contained in the propellant, capable of sustaining the large number of thermal cycles imposed by typical mission profiles and not requiring pre-heating for efficient operation.

In general, the most frequently used catalyst materials for H2O2 are metallic silver, permanganates of alkali metals illustrated by Musker [30], manganese oxides like manganese dioxide (MnO2), and di-manganese trioxide (Mn2O3). Some experience is also available with alumina deposited platinum, ruthenium dioxide, divanadium pentoxide, and lead oxide, as given by Rusek [32]. Although having many models on the compositions, none of these solutions is free from drawbacks, the most important being temperature limitations and poisoning for metallic silver which is suggested by Wernimont [39] and Ventura [36].

In addition, powdering and thermomechanical resistance for ceramic-deposed catalysts, excessive flow resistance for pellet beds, and flow stratification for channel matrix support catalysts (Beutien, [26]).

Along with the application of hydrogen as a monopropellant, there was also an evolution of the methods used for catalyst decomposition and development. The workhorse catalyst for 90% hydrogen peroxide has long been the silver screen pack Ventura [36]. Furthermore, this catalyst proved to be a robust choice, but it has relatively low melting temperature limits, these are also used to lower than 92% hydrogen peroxide. Earlier 98% HP catalytic beds, realized in the 1950s and 1960s, were based on the use of screens made of different materials, such as high melting point silver alloys (silver palladium), platinum, palladium, iridium, ruthenium, manganese dioxide, and cobalt. However, no one of these candidate materials provided adequate performance. Alternative techniques for decomposing hydrogen peroxide greater than 90% are necessary to fully exploit the higher performance offered by 98% H2O2.

Kappenstein [29] has recently investigated the thermal decomposition and the hydrothermal reduction of different permanganate precursors of manganese oxide-based catalysts, finding that a higher reaction surface area and activity are exhibited when using potassium permanganate rather than sodium permanganate.

Furthermore, an extensive experimental study carried out by Rusek [32] indicated that catalysts based on MnO2 or Mn2O3 on different ceramic pellets led to an activity about 1 order of magnitude higher than obtained with silver. Other catalysts, such as ruthenium dioxide, displayed activities about 3 times higher than manganese oxides. Moreover, a series of thermal tests in the same study showed that the activity of platinum on alumina is 1 order of magnitude higher than exhibited by manganese oxides-based catalysts. These findings, however, are not fully consistent with those obtained by Pirault-Roy [31] who investigated the activity of platinum supported on silica, silver, and iridium and platinum-tin or manganese oxides supported on alumina, observing that silver on alumina yielded the highest activity, followed by manganese oxides on alumina and by platinum on silica.

Moreover, another experimental activity was carried out by (Eloirdi 2000)using a constant-volume batch reactor. Two catalysts, manganese oxide, and silver supported on alumina were tested. The manganese oxide catalyst showed a better activity with good repeatability after several firings, whereas the supported silver sample was less active and showed a slight loss of activity after the first firings.

In addition, Tian [35] has investigated the performance of the Ir=γ-Al2O3 catalyst for the decomposition of high-concentration hydrogen peroxide in a monopropellant thruster, finding that catalyst oxidation and surface Sun poisoning are the main reasons for catalyst deactivation. Beutien,[26] has illustrated the evaluation of cordierite-based catalytic beds for 98% hydrogen peroxide. The most interesting characteristic of cordierite as a catalyst supporting material, together with its relatively good mechanical strength, is that it does not melt or break when exposed to 98% hydrogen peroxide decomposition. Then, Rusek [32] illustrated that the high-channel density catalytic beds tend to result in higher temperatures and a more complete decomposition with respect to low pore density ones.

3.3. Hydrogen Peroxide as A MonoPropellant Thruster

In the beginning, the earliest research on hydrogen peroxide-based rockets was conducted by Walter. H [36] in Germany during the 1930s. He invented the idea of using a catalytic bed to generate a hot stream of oxygen and steam, which could either be directed towards an exhaust nozzle or used to auto-ignite a fuel. Later these catalytic beds were used in the fighter flights (ME163) to drive the turbomachinery. Consequently, it has been used by US X-1 and X-15 space planes, together with the early Mercury and Gemini manned spacecraft, used hydrogen peroxide in their reaction control systems.

Then, significant research was carried out in the 1960s at NASA laboratories on hydrogen peroxide decomposition and its application to monopropellant rockets, but this effort was subsequently abandoned with the advent of effective hydrazine catalysts. On contrary, the Russian Russian Soyuz launch vehicle, which has been inactive service for over forty years, continues to rely on hydrogen peroxide in its gas generator to drive the main turbine pump and in the RCS, thrusters used for the descent phase. Furthermore, the highly reliable Gamma 301 engine, developed by Bristol Siddeley in the 1950s, was used for both the first and second stages of the Black Arrow satellite launcher, which flew from Woomera, Australia in 1971. Later in 1997, Whitehead illustrated the development work of small monopropellant satellite thrusters using hydrogen peroxide.

A lightweight thruster was successfully flown in a 25 kg satellite and worked flawlessly with a total propellant throughput of 3.5 kg. Finally, the rocket propulsion community, Alta S.p.A. (Italy)and DELTACAT Ltd. (United Kingdom) are carrying out a joint activity for the development of hydrogen peroxide monopropellant thrusters based on the use of advanced catalytic beds.

3.4. Monopropellant Thruster

Monopropellants play a pivotal role in spacecraft attitude control, orbit insertion, maintenance, and maneuvering as their pressure feed and control systems are simpler and relatively cheaper than bipropellant ones [28]. As discussed in the previous section hydrogen peroxide decomposes when it is combined with the catalyst bodies and researchers were interested in the composition of the propellant which gives high temperatures. Sub-consequently, this heat energy is used in the bi-propellant design. In this following section, two models were reviewed based on the performance of the mono propellants by the thrusters from the paper Cervone [9].

To begin with, Cervone et. al has developed a hydrogen peroxide thruster using advanced catalyst beds with the nominal range of thrust with 5N AND 25N. Designs of these thrusters are dimensionally different and given in the following sections. Different catalytic bed configurations, including pure silver gauzes and pellets coated with manganese oxide or platinum, are going to be tested in the prototype thrusters, to find the optimum one for further industrial development.

Firstly, the design of the prototype thrusters was the definition of the design requirements and specifications. The following guidelines were considered for this purpose:

1. Results of literature overview of thrust chambers and catalytic beds for hydrogen peroxide monopropellant rockets (including a preliminary trade-off of catalytic bed technologies and thruster technologies).
2. Information obtained by past hydrogen peroxide rocket designs.
3. Other considerations are driven by cost reduction and safety for the operators.

Secondly, the propellant for which the thrusters are designed is PROPULSE 875 HTP Hydrogen Peroxide, produce by the Degussa. PROPULSE 875 HTP is a high concentration (87.5%) hydrogen peroxide solution having significant stability and easy handling with a relatively low portion of impurities. In this case, with respect to the operating pressure, nominal operating pressure of 10 bar has been chosen for the combustion chamber, taking into consideration of previous similar experimental conditions. Furthermore, the nozzle has been given by taking into account the exit pressure of 13800Pa. The resident values have been chosen by the author based on the complete and effective decomposition of the catalytic bed. Finally, catalyst loading and the nozzle section were designed in the lower limit of the range of values typically used in the past.

The catalytic bed is installed as a unique “cartridge” and joined to the other components of the prototype thruster by means of flanges. Different catalytic bed cartridges, for example with different lengths or catalyst geometry, can be installed in the prototype using the same nozzle and connecting flange.

This conceptual solution has the interesting advantage of being adaptable to different catalyst geometries like gauzes or pellets are chosen. Pure silver grids were obtained by 80 mesh gauze woven from a 0.115 mm diameter wire. In this case, some gauzes with greater wire diameter (made of silver or nickel) are alternated with the more active ones, in order to provide sufficient mechanical strength to the bed. Alternation of different metallic gauzes can be done, commercially available manganese oxide-covered pellets. Self-impregnated manganese oxide pellets (on the ceramic substrate). A technique made for the impregnation and calcination of high contact surface (up to 300 m2 /g) spheres made of Alumina-γ, using particular organic compounds as promoters. The diameter of the spheres is between 0.5 and 1 mm and, as a consequence, retaining grids are needed at the beginning and the end of the catalytic bed to avoid loss of the spheres in the flow through the distribution plate. The same calcination technique can also be applied to platinum-covered spheres, which are being used as another possible catalyst material for the tests.

Furthermore, 5 N thruster was tested in Alta S.p.A. by Pasini [25]. Before the tests, the design is optimized further, and the catalyst bed dimensions are fixed to diameter 8 mm and 8 of length over diameter. Nozzle expansion has an expansion ratio of 3.48 with a 2 mm throat diameter and a 15o divergent half angle. This is in turn to prevent the overexpansion condition. For the tests in (A. Pasini 2008), two types of platinum catalysts supported by γ-alumina spheres with 0.6 mm diameter were used and their performances were compared with silver screens. The interpretation of results was done based on the relative efficiency of characteristic based on the ratio of c* from measured chamber pressure and c* computed from isentropic expansion using the measured chamber temperature, decomposition efficiency based on normalized temperatures with respect to the ambient conditions, and pressure drop across the catalyst bed. Results for the platinum conditions at 5.5 and 6 bar chamber pressure are 2.05 N and 2.3 N thrust respectively, with an adiabatic flame temperature of 703.15K. The resultant efficiencies for c* are 0.52 and 0.58 and 0.62 for decomposition, while the measured catalyst bed pressure drops were 3.2 bar and 6 bar. This phenomenon is due to the incomplete decomposition which probably was caused by rupture of pellets and thus, blockage of the catalyst bed and thermal cracks on the pellets. On the other hand, when the pellets were compared with the results of silver screen catalyst, it was seen that the performance of the silver screen is undoubtedly above the ones of platinum catalysts, despite relatively more adverse values of the silver screen (0.8 c* efficiency, 0.72 decomposition efficiency, and 2 bar catalyst bed pressure drop) comparing to the other applications in the literature. Moreover, this is due to the channeling effect and the catalyst bed length are the two main reasons for the decrease in the efficiencies.

Based on the above sizing effect to efficiencies, a further study was done by Sejin [34] on monopropellant catalyst bed sizing. Ninety percent of hydrogen peroxide has used a propellant. A scaled-down thruster with platinum on aluminum oxide in the reaction chamber was tested to determine propellant decomposition onto a catalyst. Then, the size of the catalyst bed was determined as 3 cm in diameter and 4 cm in length from the scale-up method with 50 N thrust. The propellant density was 1392 kg/m3 at 20 °C. Theoretical adiabatic temperature and characteristic velocities were 750 o C and 936 m/s 2, respectively, obtained by the author from the CEA code. Platinum was selected as a catalyst for the decomposition of hydrogen peroxide. The catalyst bed was prepared from γ-type bimodal alumina from Alfa Aesar, which displays 255 m2 /g of surface area, 1.14 cc/g of total pore volume, and 70 and 5000 Å of median pore size. For the catalyst bed, they introduced a parameter called decomposition capacity. They considered catalyst bed volume, instead of the cross-sectional area of the catalyst bed. This is because the length of the catalyst bed also affects the decomposition rate. Further defined the catalyst bed decomposition capacity as the ratio of the mass flow rate of the propellant to the velocity of the flame.

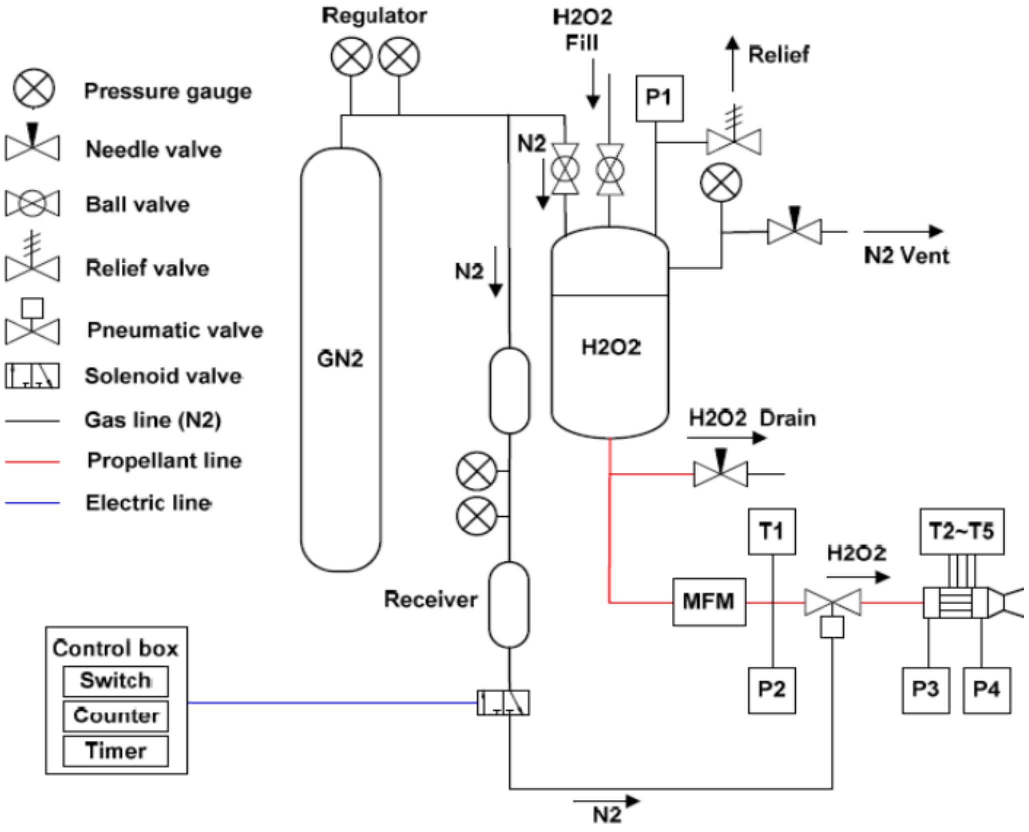


Figure 3-1 Schematic diagram of Sejin's monopropellant test rig

The cylindrical vessel reactor is scaled down to 1 cm in diameter and 4 cm in length. Through a full cone spray injector, the liquid propellant is injected with an estimated pressure drop of 3 bar. A simple convergent-divergent nozzle was assembled at the exit of the catalyst bed. A pressure transducer is used to measure the inlet and outlet pressures of the bed and supply line before the injector and temperature are measured by the 4 K-type thermocouples placed along the catalyst bed. Analysis of the results was made by the temperature of product gases, decomposition efficiency, and effective exhaust velocity c*. It is depicted that the maximum temperature occurs downstream of the reactor. This is due to the 90% efficiency of the characteristic velocity with respective propellant mass flow rates. Which in turn results in the maximum decomposition of the catalyst bed 1.27 g/s/cm3. Later, the catalyst bed was scaled up in terms of an increase in the diameter with the same decomposition capacity as the smaller reactor. The length of the catalyst bed was kept unchanged, to know the dependency of diameter on the decomposition rate. The same injector was used for the scaled-up thruster, yet after the tests, its pressure drop was measured above 3 bar. The operation was started and stopped by a pneumatic valve actuated by nitrogen, which is also the pressuring gas for the propellant tank. For the safety of the entire system, needle, relief valves were adapted along with the feeding and pressurization systems. In addition, 3 pressure transducers and 4 thermocouples are used to measure the pressures and temperatures.

Coriolis type mass flow meter issued to find the HTP flow rate. The combination of these instruments on the test bench can be seen in the schematics in (Fig 1). Initially, as the main valve opened, there is a significant increase in the temperature rise and the transition time is qualitatively short. When the decomposition efficiency reached 100 percent, then there is a maximum temperature reached to adiabatic condition. Eventually, there is a stable chamber pressure measured at 16.2 bar by the pressure inducer. Finally, it is concluded that the catalyst bed size is important to the thruster size e since the bed size is optimized for HTP to be decomposed completely.

Krishnan et al. [40] conducted another fascinating study on the development of a lab-scale monopropellant thruster. The engine was designed to run tests under extreme conditions with H_2O_2 concentrations above 90% wt. The emphasis of the design chamber pressure is 20 bar, and the force is 100 N. Silver screens are used to decompose HTP as a catalyst, they were introduced. The engine was built with the ideal governing equations of the rocket and design values. In addition to thrust and chamber pressure, other important design choices are catalyst bed loading and average residence time for the decomposition, which are regarding the catalyst bed. Through computation of the component sizes, it is estimated 95% of the thrust efficiency and 90% of c*.

As a result, for loading of 200 kg/s/m2, the catalyst bed length was set at 55 mm and the diameter was set at 25 mm, based on an average residence time of 1.5 ms and the inclusion of anti-channeling plates at the beginning, center, and end. Although the injector plate was constructed as a single orifice with a discharge coefficient of 0.8 and a diameter of 1.8 mm, orifices of various diameters were used to examine the difference in propellant-injection characteristics. The nozzle was created with a 2.6713 expansion ratio and a divergent half-angle of 13°. The pressure drops across the catalyst bed are measured to be 8.5 bar, 7 bar across the injector, and 2 bar across the solenoid valve.

As a result, the propellant tank pressure was estimated to be 37.5 bar. The propellant tank was a commercial 1 L tank with a burn time of approximately 12 seconds. The propellant volume used is 0.9 L after 5% ullage volume and 5% volume for non-decomposed propellant remained in the feeding line. During the process, the propellant tank was pressurized with nitrogen to maintain steady tank pressure.

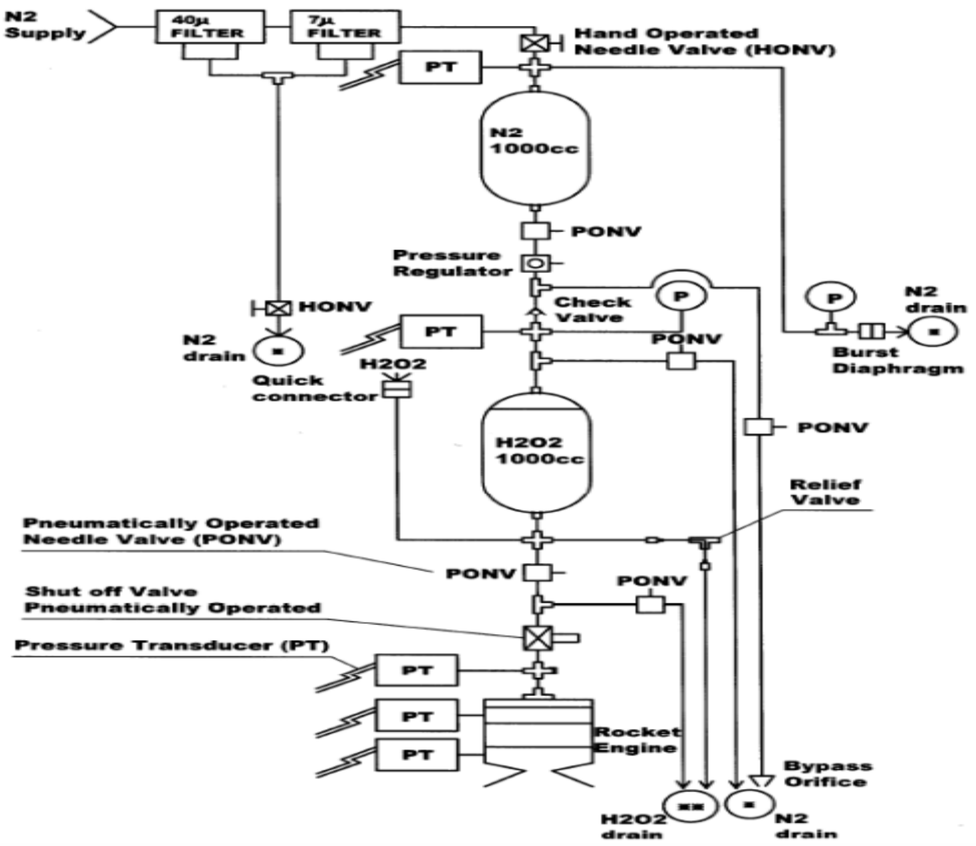


Figure 3-2 Schematics of Krishnan et al.'s monopropellant test

Both control valves in the feeding and pressurization systems are pneumatically controlled, with a burst diaphragm and a relief valve included for system protection. A pressure regulator was mounted between the propellant and nitrogen tanks to regulate the feeding pressure which is shown in Figure3-2. For a thorough pressure observation, pressure transducers were mounted at the pressurization tank, propellant tank, upstream of the injector, inlet, and exit of the catalyst bed.

During the initial trials, HTP did not decompose, likely due to the low ambient temperature (5°C), inadequate surface contact between HTP and the catalyst, or contaminants in the propellant. Heating jackets were used to heat the propellant tank and the thruster itself, and the catalyst pack was compacted at 35 MPa. The latter tests were successful, but there were substantial oscillations in the chamber pressure (nearly 25%).

Palmer [35] conducted a catalyst evaluation research, and the motivation and findings related to catalyst actions were published. Instrumented catalyst beds (ICB) and a monopropellant thruster were developed as part of the catalyst evaluation. Because of problems with the preliminary catalyst bed's configuration and test schedule, only a few experiments were conducted with it. The preliminary instrumented catalyst bed (PICB) is a basic design made of AISI 316 stainless steel and consists of an injector (single hole, 0.5 mm diameter), a catalyst bed, a catalyst retainer plate at the catalyst bed's exit, and a nozzle. For loading of 17.6 kg/s/m2, the bed diameter is 16 mm, and the length-over-diameter ratio is 6.5, leading to a length of 104 mm. It is worth noting that this L/D ratio is higher than what's expected for full propellant decomposition. One K-type thermocouple was placed in the nozzle and 7 K-type thermocouples were placed along the bed (5 on the flow axis, 2 near the wall).

Furthermore, the pressure was measured across the bed. A solenoid valve was mounted upstream of the injector to control the flow. Silver gauze and 0.5 percent Pt on alumina pellets were tested in this setup. In terms of normalized decomposition efficiency, platinum clearly outperformed silver (95 percent for Pt and 74% for Ag). For the second bed, or highly instrumented catalyst bed (HICB), the catalyst bed loading was significantly increased to 70 kg/s/m2 with the same bed diameter. The goal is to hasten the degradation of the catalyst. Furthermore, the bed was shortened to 96 mm in length and more instrumentation pipes were integrated; as a result, pressure and temperature were measured on the central flow axis, near the wall, and at the seven locations of the catalyst bed.

Palmer et al. [35,] have developed a monopropellant H_2O_2 thruster for catalyst characterization and attitude control missions. It was planned to provide 20 N thrust at sea level with 87.5 wt% H_2O_2 and a 12 bar chamber design pressure. According to the authors, bridging the gap between thruster lifetime and size is important, since thrusters with more catalysts than needed do not provide a better performance, but rather a lower thrust-to-weight ratio and response time with some catalyst degradation. The injector pressure drop was determined to be 4 bar, the injector discharge coefficient to be 0.7, the catalyst bed pressure drop to be 1 bar, and the decomposition efficiency to be 0.95. The design bed loading was set at 50 kg/s/m2 (in accordance with the literature), which corresponds to a bed diameter of 21 mm. Since there is no connection between catalyst bed loading and L/D, three catalyst beds with two different L/D ratios, 2.25 and 3.25, were built. Each catalyst bed had a baffle to prevent the channeling effect, but at different locations. Three injector configurations were planned and tested: a 4-holed plate with a diameter of 0.5 mm (type A), a 16-holed plate with a diameter of 0.22 mm and a diffuser (type B), and a 16-holed plate with a diameter of 0.22 mm and a diffuser (type C) The explanation for the increased number of holes is that the first form caused the catalyst material to quench. A bulkhead kept the injectors together while also allowing for pressure and temperature measurement instruments. Viton O-rings were used to seal the gaps between the described components.

A retainer plate was mounted between the catalyst bed and the nozzle to hold the catalysts within the bed without ejection and with the least amount of pressure drop and open area possible. To maximize the open space, square holes were favored. A basic convergent-divergent nozzle with a 2.3822 expansion ratio and a 15° divergent half-angle was planned for sea level. Thrust, mass flow rate, heat, and temperature were all calculated during the experiments. A load cell mounted behind the thruster was used to calculate thrust. At the inlet, center, and outlet, pressure transducers and K-type thermocouples test pressure and temperature.

CHAPTER 4

HYDROGEN PEROXIDE IN HYBRID ROCKETS

In this section, it is explained briefly about hydrogen peroxide as an oxidizer in hybrid rockets. Furthermore, a detailed case study of propellant system hydrogen peroxide/paraffin has been done using CEA code.

4.1. Hybrid Propellant Rocket

Solid, liquid, and hybrid propellants are the three different types of chemical rocket propellants. In solid and liquid rockets, the oxidizer and fuel phases are the same, but in a hybrid rocket, the phases are different. The oxidizer is liquid in most hybrid rockets, while the fuel is solid. Solid rockets have a simple device, but they are explosive due to a premixed oxidizer and fuel. On the other hand, the separation of two propellants in hybrid rockets makes them safer and thrust generation can be managed by changing the propellant flow rate. They can also be re-ignited and have a potential advantage over solid rockets in terms of specific impulse efficiency. Hybrid rockets have a lower specific impulse than liquid rockets, but they have advantages in that they only need a tank, supply line, and fluid control equipment for half the propellants that liquid rockets require [40]. On contrary, they also have a high specific impulse Isp, which can be changed with the inclusion of sufficient additives. They are also throttleable, with the capacity to shut down and restart on demand [52]. Because of the low fuel regression rate, hybrid thrusters' practical implementation is still limited [48].

Firstly, depending on the ignition systems, a hybrid rocket becomes much simpler. There are two types of hybrid rockets, each with a different form of ignition: a spark ignition system or torch, and a catalyst bed for the exothermic reaction of one of the propellants. The temperature of the catalyst bed is high enough that the fuel will self-ignite without the use of an external ignition source.

Furthermore, a high-concentration solution of hydrogen peroxide, also known as high-test peroxide, is one of the most widely used oxidizers in catalyst ignited hybrid rockets. Since its first significant use as a propellant in the 1950s, the stability of this green propellant has improved dramatically [41]. As a result, a broad body of evidence supports the use of H_2O_2 as a propulsion propellant [42, 43]. However, the long-term storability of H_2O_2 remains a problem, and the impact of stabilizing agents on H_2O_2 propulsion efficiency is also a concern, as stated in [44].

4.2. Past Applications of H_2O_2 in Hybrid Rockets

Several groups and organizations have recently studied H_2O_2 as an oxidizer in hybrid rocket systems, including the Bloodhound SSC (OK) [45] supersonic car squad, ONERA (France) [46], and Nammo Raufoss (Norway) [47]. These ventures have all had varying degrees of success, but they all have significant technical shortcomings that leave a lot of room for progress. Ignition problems and long ignition transients appear to be endemic to the application, particularly at larger scales. For its supersonic car design, the UK Bloodhound team is designing a hybrid rocket motor using HTP (98%) and the legacy solid rocket binder material, Hydroxyl Terminated Polybutadiene (HTPB). This team has had a lot of trouble getting their motor to light consistently, so they've had to "dope" the fuel grain with ammonium perchlorate (AP) to get it to light and stay lit. The addition of an oxidizer to the fuel content has caused problems with motor stability as well as trouble extinguishing the motor after it has been ignited.

For ignition, the ONERA motor uses pyrotechnics as well as catalytic decomposition with swirl injection. The device was successfully ignited using lower grade (87.5%) peroxide using pyrotechnic ignition. The catalytic system, which was based on a silver-screen cat bed, required 98% HTP. Static test firings using a solid cone nozzle that created a central flow distribution with very coarse fluid droplets showed significant difficulty in initiating combustion for both ONERA configurations. Instead, the ONERA researchers discovered that using a hollow cone injector nozzle increased combustion efficiency significantly. With no central flow distribution, the hollow cone pattern provided the best degree of atomization. The Nammo Raufoss (Project), which is sponsored by the European Space Agency, has been running since 2003 and is actually the most advanced of the existing peroxide-hybrid projects. HTPB was used as a companion in the Nammo design.

After peroxide flow is initiated in a standard Nammo motor ignition series, the chamber pressure gradually rises from ambient to a plateau of around 1500 kPa (220 psi). A rapid increase in chamber pressure to approximately 2500 kPa bars follows this “smoldering” accumulation of chamber pressure, which takes slightly more than 2 seconds (360 psi). The initial pressure buildup is referred to as "mono-propellant combustion mode" by NAMMO, while the steep increase and subsequent plateau are referred to as "hybrid combustion mode" by NAMMO. The pressure ratio (1500 kPa/2500 kPa) at the threshold where the Nammo motor switches from monopropellant to hybrid combustion mode is precisely this.

A peroxide-based hybrid system, once fully developed, could revolutionize the commercial space industry by providing a high-performance but inherently safe space propulsion solution for rideshare payloads and other space propulsion applications. The technology has the ability to disrupt the industry.

4.3. Paraffin-Based Hybrid Rocket

To begin with, for synthetic polymeric fuels, many approaches have been pursued, including multi-port grains, specialized injection processes, metal additives, and solid particles, but this has resulted in an increase in system complexity and related costs without achieving substantial increases in engine overall efficiency [49]. As a result of the various processes involved in the fuel surface/gaseous flow interactions, there has recently been a growing interest in paraffin-based fuels as regression rate enhancers [50].

The lower burning rate of hybrid rocket engines (HRE) is one of those drawbacks, which was resolved with the use of paraffin waxes [52]. Firstly, paraffin creates the entrainment of fuel liquid droplets into the main gas stream which is caused by the development of a low-viscosity unstable melt layer on the burning surface, which greatly increases the solid regression rate [53]. The liquid layer instability induces this phenomenon, which is determined significantly by the fuel composition and thermo-mechanical properties [51]. As a consequence, depending on the particular fuel composition, manufacturing methods, and motor operating conditions, the behavior of paraffin-based fuels can vary significantly.

In general, paraffin waxes have 3 to 5 times higher regression rates than traditional fuels hydroxyl-terminated polybutadiene (HTPB). Paraffin waxes have many benefits over the traditional HTPB scheme, including being non-toxic, non-hazardous, shippable as freight cargo, low cost, and reusable (recycling possibilities). Furthermore, they have the same energy per unit mass as kerosene but have a 16 percent higher density, no scrap potential, and a long shelf life [54,56]. Finally, because this fuel is non-explosive, grains can be manufactured on-site, reducing both manufacturing and launch costs [55]. Despite the benefits mentioned above, which encourage the use of paraffin waxes to replace HTPB, they have two drawbacks: poor mechanical properties and a complex manufacturing process.

Several authors have developed paraffin wax blends with polymers, such as polyethylene (PE) [57] or ethylene-vinyl acetate copolymer (EVA) [58,59], to strengthen the weak mechanical properties. On the other hand, aluminum or other energetic additives were added, with the aim of improving the reduced regression rate [57]. The manufacturing of fuel grains is still an open question, particularly when large-diameter grains must be manufactured. In fact, during the solidification of paraffin wax, the high shrinkage of about 15%–25% [54] causes grain deformations, internal stresses, rips, holes, micro-cracks, and other microstructural discontinuities. Furthermore, the material's inherent brittleness limits its workability, and its thermal inertia prevents uniform cooling of the whole fuel grain. Obviously, as the diameter of the fuel cylindrical grain increases, the effect of these phenomena grows. Finally, cracks or voids can potentially cause a detachment of large pieces of fuel, which could obstruct the rocket nozzle.

4.4. Fuel selection

Firstly, the chemical formulae of the waxes were examined, namely Sasol Wax 0907, Sasol Wax 6003, and Sasol Wax 6805 for the CEA analysis. Secondly, CEA (Chemical Equilibrium and Applications) is a NASA program that calculates the equilibrium concentration of products from a series of reactants and calculates transport and thermodynamic properties, as well as theoretical rocket efficiency parameters.

Four different waxes were considered as potential fuels for hybrid rockets, i.e., H1, C80, 6003, and 0907, all manufactured by the SASOL®. They are made up of varying fractions of linear (n) and branched (iso) hydrocarbons, as seen in Figure 4-1.

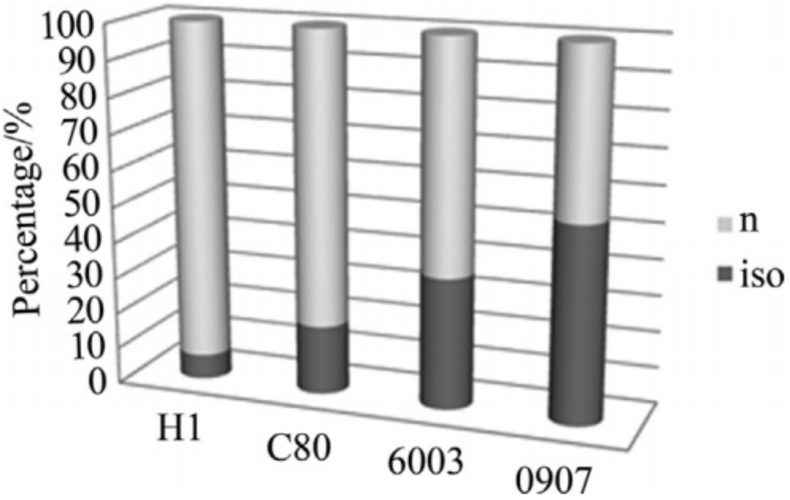


Figure 4-1 Content of linear (n) and branched (iso) alkanes.

Furthermore, the molecular weight distribution of linear and branched alkanes in SASOL's 0907 paraffin wax (data supplied by SASOL) is also seen in Figure 4-2.

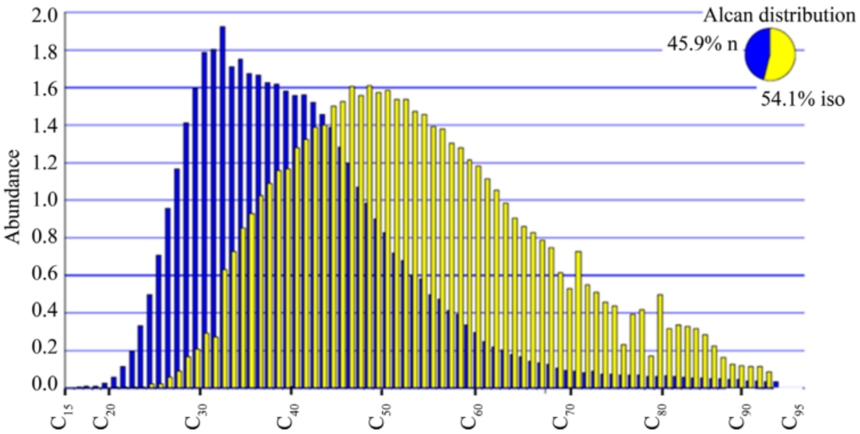


Figure 4-2 wt (%) distribution of linear and branched alkanes in SASOLs 0907 paraffin wax.

Besides that, as seen in Figure 4-3, the distribution of their molecular weights is based on different values, with percentages greater than 10% by weight of maximum abundance recorded as a function of carbon number for both linear and branching fractions.

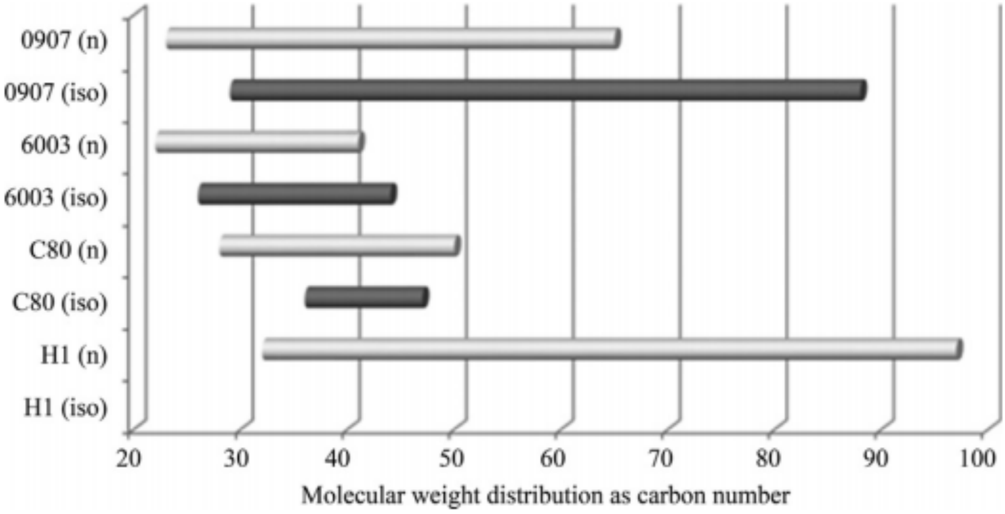


Figure 4 -3 Molecular weight distribution (higher than the 10 wt% vs the maximum abundance) as Carbon number in linear (n) and branched (iso)

On all linear and branched fractions, the carbon number is the same. In terms of melting and congealing points, penetration, and viscosity, Table 1 indicates the wax properties quoted by the manufacturer SASOL®.

The H1 composition tends to be primarily made up of linear alkanes with a broad molecular weight range, spanning from C32 to C97 and based at C65. In comparison to branched alkanes, SASOLs 6003 has more linear alkane chains, but all linear and branched molecular weight distributions are based on the same value. Unlike the other kinds of paraffin, SASOL® 0907 is mostly made up of branched alkanes, which also have the highest material**.**

Furthermore, the SASOL® 0907 branched alkanes' molecular weight distribution is based on the highest value. In contrast to linear paraffin waxes, SASOL® 0907's high fraction of branched iso-alkanes could be more favorable for forming microcrystals, which makes for higher fracture resilience and hence greater workability during the processing of the fuel grain. In addition, paraffin solid wax is an inherently porous substance, at least under the working conditions studied.

As a result, higher values of fracture hardness, according to Griffith's theory, improve the resistance to the surface or internal microcracks and other microstructural faults of increased radius [59]. Finally, it is necessary to have information about the chemical formulas of the following waxes for further CEA analysis. In the next subsequent section, the chemical formula is explained in detail.

4.4.1 Sasol Wax 0907 (W1)

As discussed in the previous section the SASOL® 0907 chemical configuration consists of both linear and branched structures. From Figures 4-1 and 4-2, the composition Table 4-1 is obtained.

Linear alkanes %	Linear alkanes range of carbon atoms	Linear alkanes average number of carbon atoms	Branched alkanes %	Branched alkanes range carbon atoms	alkanes average number of carbon atoms
50	22-64	43	50	28-88	58

Table 4-1Sasol Wax 0907 molecular properties

The number of carbon atoms on an average in a Sasol Wax 0907 molecule:

$$No. of\ carbon\ atoms = \left(\left(\frac{Linear\ alkanes\ \%}{100}\right) * (Linear\ alkanes\ avg\ No. of\ C\ atoms)\right) + \left(\left(\frac{Branched\ alkanes\%}{100}\right) * (Branched\ alkanes\ avg\ No. of\ C\ atoms)\right)$$

$No. of\ carbon\ atoms\ = (0.5\ * 43\ ) + (0.5\ *\ 58)\ =\ 50.5\ \approx\ 50$ (Because the number of carbon atoms must be a whole number).

Since Sasol Wax 0907 is a type of paraffin, and a paraffin's general molecular structure is CnH2n+2, the chemical formula for Sasol Wax 0907 is $C_{50}H_{102}$. It should be remembered that the same molecular formula for Sasol Wax 0907 was used in the following paper [55], suggesting that the technique used to find the chemical formula is accurate.

4.4.2 Sasol Wax 6003 (W2)

Furthermore, the same approach is used to measure the molecular structure of Sasol Wax 6003 as it was for the previous wax.

Linear alkanes %	Linear alkanes range of carbon atoms	Linear alkanes average number of carbon atoms	Branched alkanes %	Branched alkanes range carbon atoms	alkanes average number of carbon atoms
70	21-24	31	30	25-43	34

Table 4-2 Sasol Wax 6003 molecular properties

$$No.of\ carbon\ atoms = \left(\left(\frac{Linear\ alkanes\ \%}{100} \right) * (Linear\ alkanes\ avg\ No.of\ C\ atoms) \right) + \left(\left(\frac{Branched\ alkanes\%}{100} \right) * (Branched\ alkanes\ avg\ No.of\ C\ atoms) \right)$$

$$No.of\ carbon\ atoms\ = (0.7\ *31\,) + (0.3\ *\ 34)\ =\ 31.9\ \approx\ 32$$

Sasol Wax 6003 is a kind of paraffin, and a paraffin's general molecular structure is C_nH_{2n+2}, so the chemical formula for Sasol Wax 6003 is $C_{32}H_{66}$.

4.4.3 Sasol Wax 6805 (W3)

Owing to the lack of such details for Sasol Wax 6805, a separate procedure was used to calculate its average chemical composition. Since Sasol Wax 6805 is a pure paraffin wax with a high proportion of unbranched alkanes, Figure 4-4 was used to compare its complex viscosity to the number of carbon atoms in its molecular formula (using an approximated curve for 100 degrees Celsius).

The kinematic viscosity of Sasol Wax 6805 at 100°C is about 6-8 mm^2/s (average 7 mm^2/s or 7x10-6 m^2/s) and its density is 911 kg/m^3, as is known that the dynamic viscosity of a compound is directly proportional to the number of carbon atoms in its chemical composition. which is 6.37x10-3 Ns/m$_2$ or 6.37cP.

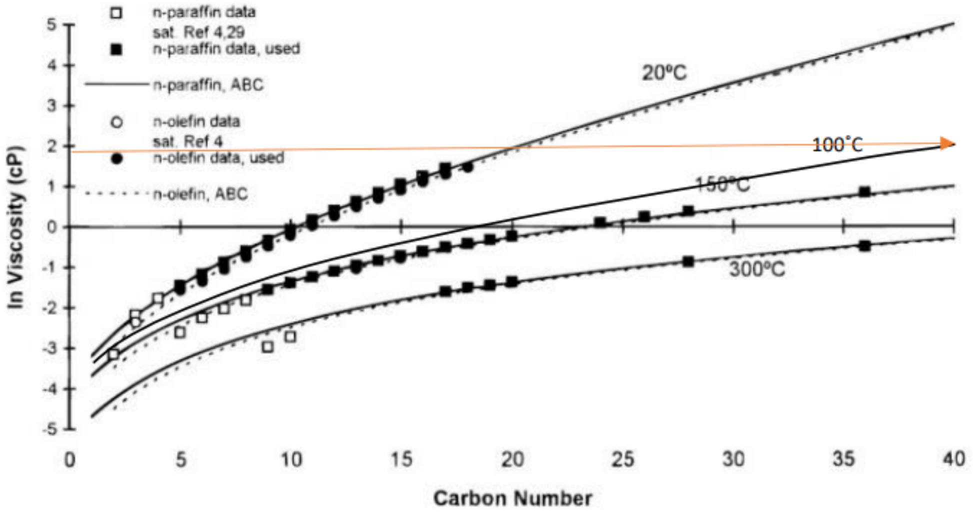


Figure: 4 -4 Viscosity of the n-paraffin as a function of carbon atoms

The chemical formula for Sasol Wax 6805 is $C_{40}H_{82}$, dependent on the number of carbon atoms for the resulting viscosity, which is roughly equal to 40. This finding makes sense as well, since the viscosity of Sasol Wax 6805 is between that of Sasol Wax 0907 and that of Sasol Wax 6003, and as previously said, viscosity is directly proportional to molecular weight (i.e., the number of carbon atoms), and Sasol Wax 6805 has 40 carbon atoms, which is more than Sasol Wax 6003 (30) and less than Sasol Wax 0907.

4.5. Enthalpy of the fuels

Since the CEA software includes the enthalpy of the chemical compounds used, the enthalpy of the fuels has been measured in this section. Furthermore, the previous sections chemical formula was used to measure the average enthalpy of forming for various paraffin waxes:

$$n\ C_{(c,\ graphite)} + (n+1)\ H_{2\ (gas)} = C_nH_{2n+2(liq)}$$

$$\Delta Hf^{\circ}\ (at\ 298.16K) = -10.887 - 6.106 * n\ (Kcal/mol)$$

The latent heat of fusion is subtracted from the enthalpy in the liquid state to quantify enthalpy in the solid-state, and the effects are summarized in the table below.

Parameter	*Sasol Wax 0907*	*Sasol Wax 6003*	*Sasol Wax 6805*
Number of carbon atoms (n)	50	32	40
Enthalpy of liquid paraffin (cal/mol)	-316187	-206279	-255127
Enthalpy of liquid paraffin (J/mol)	-1322926.40	-863071.33	-1067451.36
Latent heat of fusion of paraffin (J/kg)	200000	200000	200000
Latent heat of fusion of paraffin (J/mol)	99600	90000	112400
Number of hydrogen atoms	102	66	82
Mass of 1 mole of carbon atoms (g)	12	12	12
Mass of 1 mole of hydrogen atoms (g)	1	1	1
Mass of 1 mol of paraffin (Kg)	0.498	0.45	0.562
Enthalpy of solid paraffin (in J/mol)	-1422526.40	-953071.33	-1179851.36
Enthalpy of solid paraffin (in kJ/mol)	**-1422.526**	**-953.071**	**-1179.851**

Table: 4-3 Parameters considered for evaluating the enthalpy of different waxes

Finally, in the following sections, CEA analysis and the parameter analysis have been executed for these waxes.

4.6. Stoichiometric Mixture Ratio Calculation

Oxidation with liquid hydrogen peroxide (H_2O_2)

Sasol Wax 0907 (W1)

$$C_{50}H_{120} + 151\ H_2O_2 \rightarrow 50\ CO_2 + 202\ H_2O$$

The molecular weight of 1 carbon atom = 12 amu

The molecular weight of 1 hydrogen atom = 1 amu

The molecular weight of 1 oxygen atom = 16 amu

Therefore, molecular weight of $C_{50}H_{120}$ = 50*12 + 102*1 = 702 amu

Molecular weight of H_2O_2 = 2*1 + 16*2 = 34 amu

Stoichiometric O/F ratio of Sasol Wax 0907 = $\frac{(151*34)}{702} = 7.313$

Sasol Wax 6003 (W3)

$$C_{32}H_{66} + 97\ H_2O_2 \rightarrow 32\ CO_2 + 130\ H_2O$$

Therefore, molecular weight of $C_{32}H_{66}$ = 32*12 + 66*1 = 450 amu

Molecular weight of H_2O_2 = 2*1 + 16*2 = 34 amu

Stoichiometric O/F ratio of Sasol Wax 6003 = $\frac{(97*34)}{450} = 7.328$

Sasol Wax 6805 (W2)

$$C_{40}H_{48} + 121\ H_2O_2 \rightarrow 40\ CO_2 + 162\ H_2O$$

Therefore, molecular weight of $C_{40}H_{82}$ = 40*12 + 82*1 = 562 amu

Molecular weight of H_2O_2 = 2*1 + 16*2 = 34 amu

Stoichiometric O/F ratio of Sasol Wax 6003 = $\frac{(131*34)}{562} = 7.320$

4.7. Case Study: Hydrogen Peroxide - Paraffin

4.7.1. CEA Analysis

CEA analysis has been performed using paraffin (w/wo 10%, 15%, 20% Aluminum) as the fuel and 1) Hydrogen peroxide liquid, 2) 5% H_2O and 95% H_2O_2 and 3) 10% H_2O and 90% H_2O_2 as the oxidizers for hybrid rocket analysis. Here below the conditions given for the analysis have been tabulated.

Condition	***Unit***	***Value***
Low pressure	bar	20
High pressure	bar	30
Pressure Interval	bar	5
O/F ratio	N/A	2, 4, 6, 8, 10
The temperature of the fuel	K	298.16
Chamber Pressure/Exit pressure (Pc/Pe)	N/A	30

Table: 4-4 Parameters considered for CEA Analysis

Propellant	***Chemical Formula***	***Enthalpy (kJ/mol)***
Fuel		
1. *Sasol Wax 0907 (W1) (solid)*	$C_{50}H_{102}$	1. -1422.526
2. *Sasol Wax 6805 (W2) (solid)*	$C_{40}H_{82}$	2. -1179.851
3. *Sasol Wax 6003 (W3) (solid)*	$C_{32}H_{66}$	3. -953.071
Oxidizer		
1. *Hydrogen Peroxide (liquid)* 2. *5% H_2O and 95% H_2O_2* 3. *10% H_2O and 90% H_2O_2*	H_2O_2	Default values by CEA
Additive		
1. *Aluminum*	*Al*	Pre-defined by CEA

Table: 4-5 Chemical formulae and enthalpies used for the propellants

4.7.2. Combustion Temperature

4.7.2.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the paraffin fuels (Sasol Wax 0907, Sasol Wax 6805, Sasol Wax 6003).

CASE A- Paraffin Waxes with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
2	2615.55	2602.61	2606.41
4	3470.31	3466.87	3468.0
6	3540.99	3539.55	3539.90
8	3526.44	3525.55	3525.69
10	3501.19	3500.54	3500.59

Table: 4-6 Combustion temperature values for different waxes at various O/F ratios at a fixed chamber pressure of 25 bar

From the above Table 4.6, it can be noted that all the three waxes have very similar values of the combustion temperature at a fixed O/F ratio as all the three waxes have similar chemical formulae and hence very similar C/H ratio (around 0.4), however since Sasol Wax 0907 has the highest molecular weight (most number of carbon atoms) as well as the highest negative enthalpy (-1422.526), hence its combustion temperature is the highest among the three, followed by Sasol Wax 6805 and then Sasol Wax 6003.

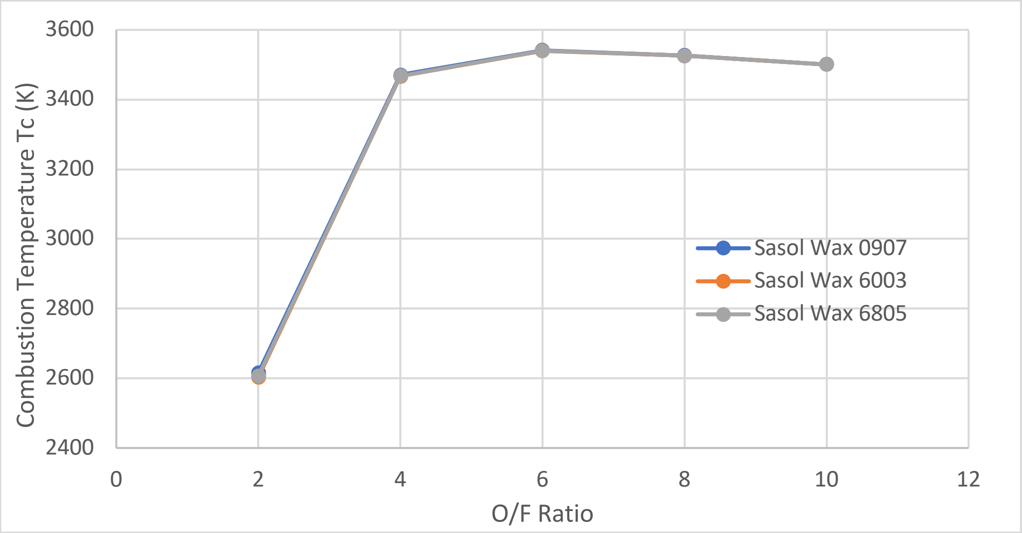


Figure: 4-5 Variation of Tc for different waxes at different O/F ratios at a fixed pressure of 25 bar

From the above Figure 4-5, it is noted that, on increasing the O/F ratio, the Tc increases sharply with the peak value of 3540.99 K for all three waxes at O/F ratio 6 and decreases slightly after that. Therefore, it can be said that the maximum combustion temperature occurs near stoichiometric conditions. Since the maximum amount of heat, release occurs at the stoichiometric condition and by adding more fuel than the stoichiometric ratio causes the formation of partly oxidized products like CO, which release l ess energy than the products of complete combustion, the maximum combustion temperature does not increase to the left of the peak, even though the fuel content is increased.

A.2) Variation with respect to Chamber Pressure Pc

Further, a parametric study was performed to determine the effect of chamber pressure on co mbustion temperature as a function of oxidizer to fuel ratio. In addition, the analysis is extended and compared with the three waxes, i.e., Sasol 0907, Sasol 6003, Sasol 6805. the results were depicted as shown in Tables 4-7-1 to 4-7-5.

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2612	2599.22	2602.98
25	2615.55	2602.61	2606.41
30	2618.23	2605.17	2609

Table: 4-7-1 ***O/F = 2***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3441.12	3427.82	3438.89
25	3470.37	3466.87	3468
30	3494.1	3490.54	3491.71

Table: 4-7-2 ***O/F = 4***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3507.66	3506.27	3506.61
25	3540.99	3539.55	3539.9
30	3568.38	3566.9	3567.27

Table: 4-7-3 ***O/F = 6***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3493.53	3492.67	3492.8
25	3526.44	3525.55	3525.69
30	3553.49	3552.58	3552.72

Table: 4-7-4 ***O/F = 8***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3469.29	3468.66	3468.71
25	3501.19	3500.54	3500.59
30	3527.37	3526.71	3526.76

Table: 4-7-5 ***O/F = 10***

Table: 4-7 Variation of Combustion Temperature values for different waxes at different chamber pressures and at a fixed O/F ratio

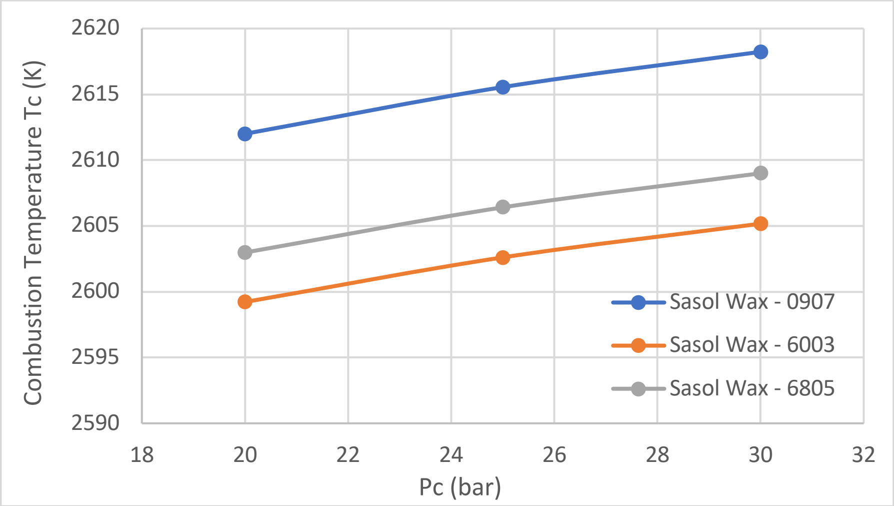


Figure: 4-6-1 ***O/F ratio 2***

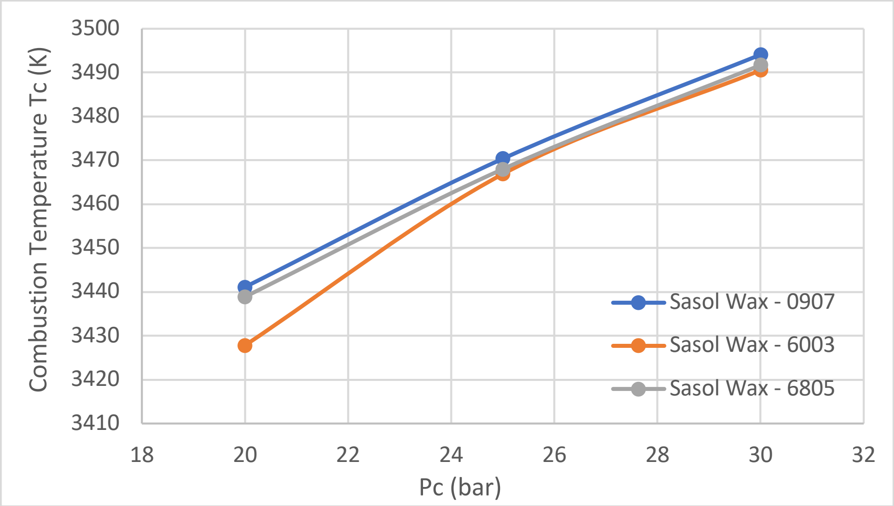


Figure: 4-6-2 ***O/F ratio 4***

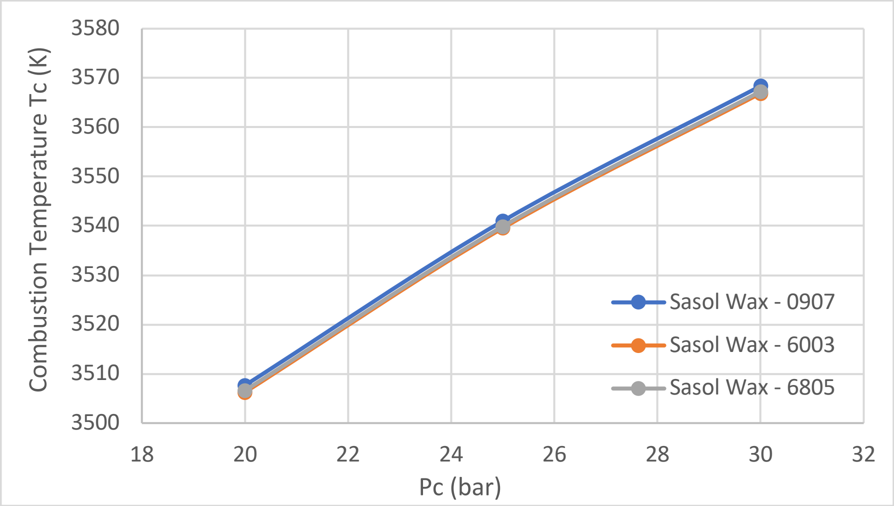


Figure: 4-6-3 ***O/F ratio 6***

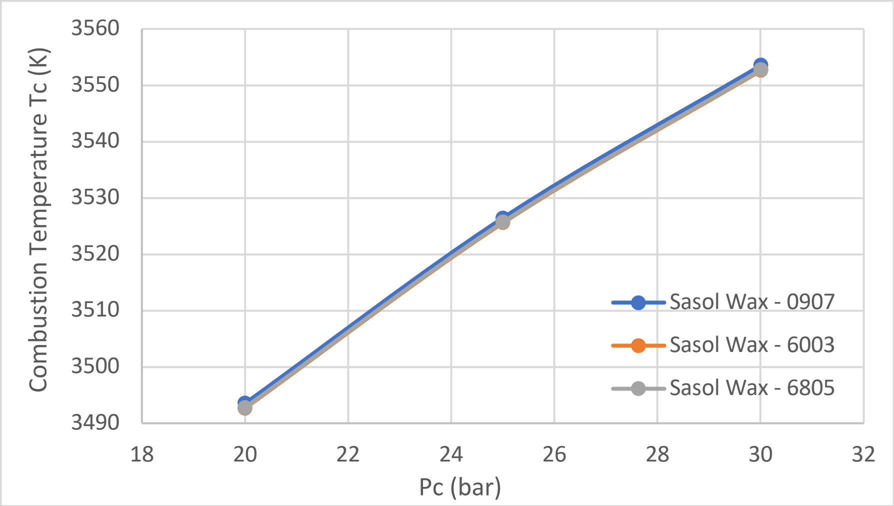


Figure: 4-6-4 ***O/F ratio 8***

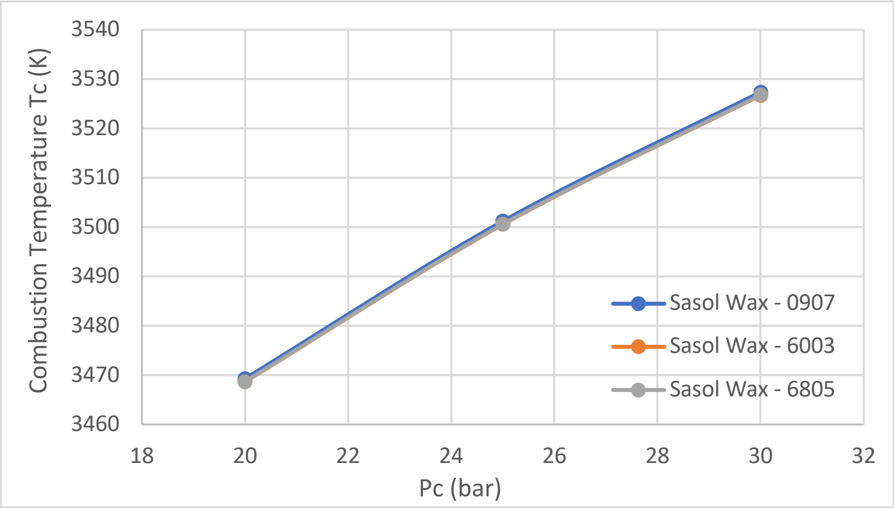


Figure: 4-6-5 ***O/F ratio 10***

Figure: 4-6 Variation of combustion temperature values for different waxes at different chamber pressures at a fixed O/F ratio

It can be seen in Table and Figure 4-6 that as the chamber pressure is increased, the combustion temperature rises as well. This occurs because the combustion products behave like an ideal fluid at such high temperatures, and it is a characteristic feature of an ideal gas to have an increase in temperature with an increase in pressure.

Consequently, when comparing the trends of different Sasol Waxes, it can be seen that although all three have very similar values at O/Fs of 6 and 10, there are some significant variations at O/F = 2. Since the fuel content is very high at an O/F ratio of 2, the variations in the properties of the three waxes are the most important in this case, and since Sasol Wax 0907 has the highest molecular weight, it has the highest combustion temperature.

Finally, it can also be interpreted from the above graphs that the peak temperature is achieved at the stoichiometric value and further increase in the oxidizer to fuel ratio, there is a significant decrease in the temperature of the chamber as is discussed in the above section.

4.7.2.2 Addition of the H_2O to Hydrogen Peroxide

Firstly, High-test peroxide (HTP) is a highly concentrated (85 to 98 percent) solution of hydrogen peroxide, with the remainder consisting predominantly of water. In contact with a catalyst, it decomposes into a high-temperature mixture of steam and oxygen, with no remaining liquid water.

Highly high concentrations of hydrogen peroxide perform best as a propellant (roughly over 70 percent). While any concentration of peroxide will produce some hot gas (oxygen plus steam), at concentrations above about 67 percent, the heat of decomposing hydrogen peroxide becomes high enough to fully vaporize all of the liquid at normal pressure. This represents a protection and utilization tipping point since any concentration above this level of decomposition will fully convert the liquid into heated gas (the higher the concentration, the hotter the resulting gas). This extremely hot steam/oxygen mixture will then be used to produce the most thrust possible.

It is important to note that with a higher peroxide content, hydrogen peroxide becomes more stable. For instance, hydrogen peroxide with a concentration of 98 percent is more stable than hydrogen peroxide with a concentration of 70 percent. Water is a contaminant, and the more water present, the less stable the peroxide becomes. Peroxide's storability is defined by the surface-to-volume ratio of the materials with which it comes into contact. The ratio should be kept as low as possible to improve storability [60].

Besides in the above section, the analysis is done for the pure hydrogen peroxide as the oxidizer. Now in the following section, the concentration of the hydrogen peroxide is changed by adding the H_2O. sub-consequently, the combustion chamber temperature, and the stability vary for three waxes has significantly affected.

CASE B- 95% Hydrogen Peroxide and 5% H_2O

This is section is to investigate the effect of adding the 5% of H_2O to the hydrogen peroxide for three different waxes at different oxidizer to fuel ratios. Furthermore, no addition of other additives added to the hydrogen peroxide. The enthalpy of the H_2O is considered as the default values of the CEA code at room temperature.

B.1) Variation with respect to O/F ratio

Then, as the procedure followed for Case A.1, the same is executed to this section. An analysis is performed for the different oxidizer to the fuel ratio for three different waxes. The results were illustrated in Table 4-8.

O/F	*Combustion Temperature Tc (K)*		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
2	2587.08	2574.19	2577.96
4	3456.09	3452.52	3453.7
6	3539.05	3537.56	3537.94
8	3530.49	3529.58	3529.73
10	3508.97	3508.3	3508.37

Table: 4-8 Combustion temperature values for different waxes at various O/F ratios on the addition of 95% H_2O_2 at a fixed chamber pressure of 25 bar

The below graph depicts the combustion chamber temperature variation with change in the oxidizer to fuel ratio, for three different paraffin waxes. Consequently, the values from Table 4-8 suggest that the combustion chamber temperature increases significantly when comparing with the pure hydrogen peroxide as the oxidizer. Moreover, the same trend followed as the pure hydrogen peroxide in Case A.1. Finally, the highest chamber temperature is achieved at the O/F ratio of 6 for all three waxes and Sasol 0907 has the largest value among other fuels.

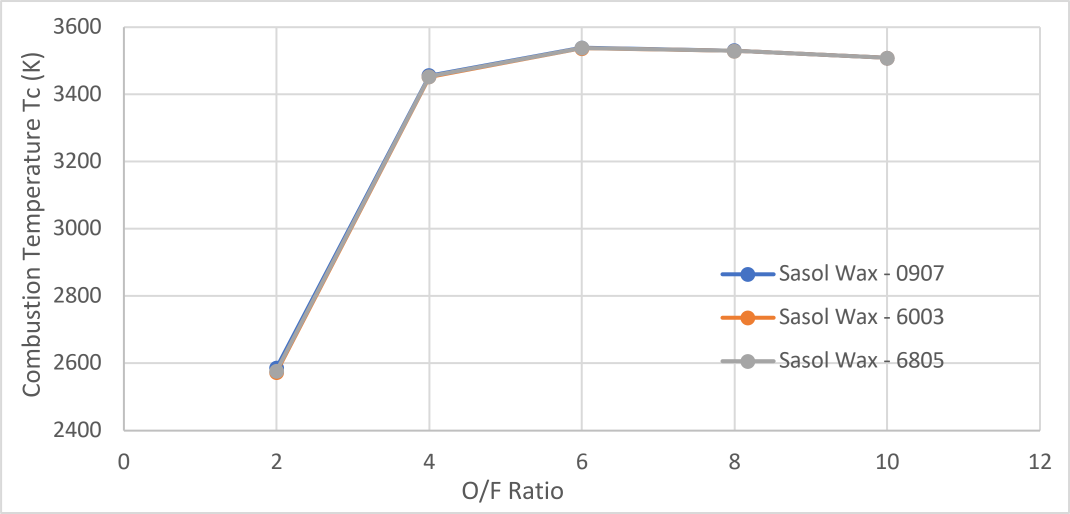


Figure: 4 -7 Variation of Tc for different waxes at different O/F ratios on the addition of 95% H_2O_2 at a fixed pressure of 25 bar

B.2) Variation with respect to Chamber Pressure Pc

After that, in this segment, it is investigated how pressure affects the temperature of the combustion chamber in this chapter. A study of different oxidizer to fuel ratios is conducted to understand the effect of fuel mixture ratio on pressure and temperature. Furthermore, the results are given in Tables 4-9-1 to 4-9-5 and illustrated by Figures 4-8-0 to 4-8-5.

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2583.87	2571.13	2574.85
25	2587.08	2574.19	2577.96
30	2589.51	2576.5	2580.3

Table: 4-9-1 ***O/F = 2***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3427.61	3424.18	3425.31
25	3456.09	3452.52	3453.7
30	3479.27	3475.58	3476.8

Table: 4-9-2 ***O/F = 4***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3505.85	3504.41	3504.77
25	3539.05	3537.56	3537.94
30	3566.33	3564.8	3565.19

Table: 4-9-3 ***O/F = 6***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3497.42	3496.54	3496.69
25	3530.49	3529.58	3529.73
30	3557.67	3556.74	3556.9

Table: 4-9-4 ***O/F = 8***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3476.76	3476.11	3476.18
25	3508.97	3508.3	3508.37
30	3535.42	3534.74	3534.81

Table: 4-9-5 ***O/F = 10***

Table: 4-9 Variation of Combustion Temperature values for different waxes at different chamber pressures on the addition of 95% H_2O_2 at a fixed O/F ratio

Figure: 4 -8-1 ***O/F ratio 2***

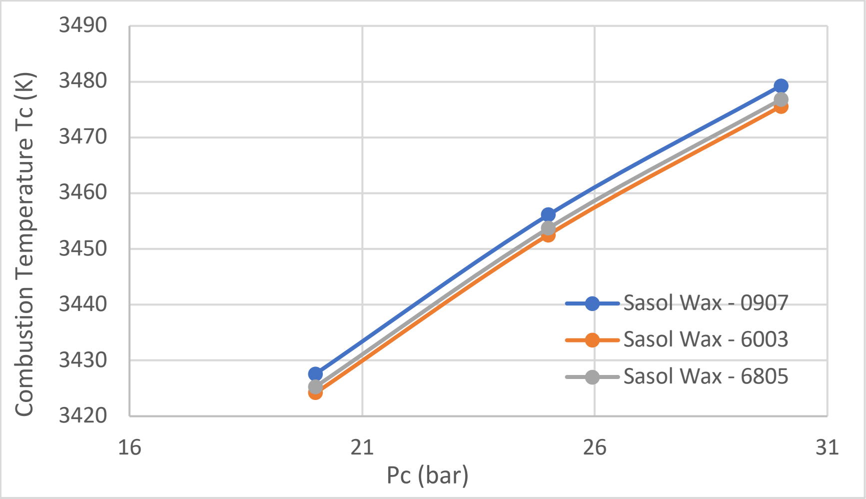


Figure: 4 -8-2 ***O/F ratio 4***

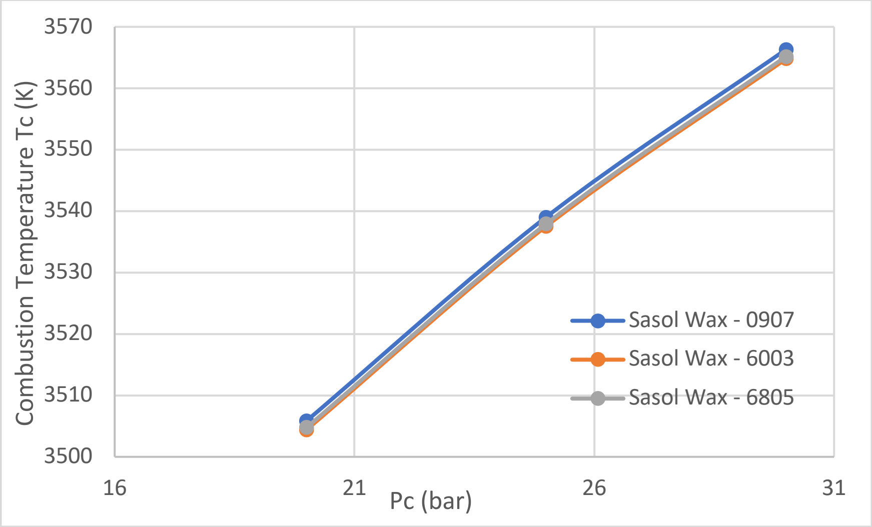


Figure: 4 -8-3 ***O/F ratio 6***

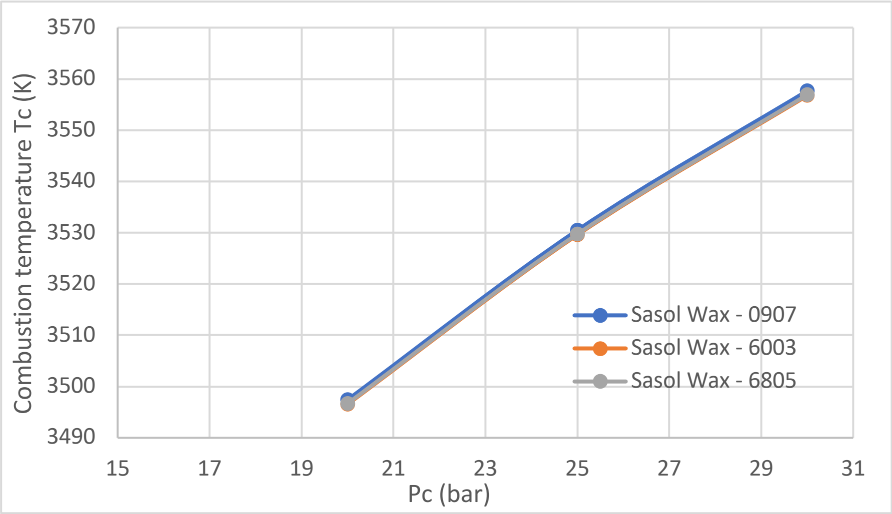


Figure: 4 -8-4 ***O/F ratio 8***

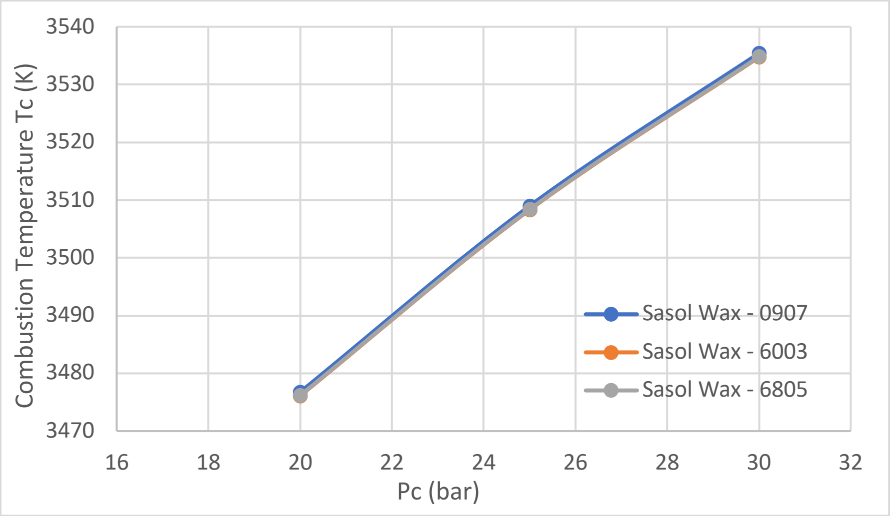


Figure: 4 -8-5 ***O/F ratio 10***

Figure: 4 -8 Variation of combustion temperature values for different waxes at different chamber pressures on the addition of 95% H_2O_2 at a fixed O/F ratio

The above graphs show that combustion components follow ideal gas properties. Such that as the pressure increases, there is a steady increase in the combustion chamber temperature. Furthermore, it is noticeable that at oxidation fuel ratio 6 the waxes showed the highest temperature.

CASE C- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for three different waxes with a different oxidizer to fuel ratios. In addition, as in the previous section, no other additives were added to the hydrogen peroxide. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

C.1) Variation with respect to O/F ratio

O/F	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
2	2558.88	2546.06	2549.78
4	3440.85	3437.15	3438.38
6	3536.02	3534.48	3534.89
8	3533.5	3532.56	3532.73
10	3515.69	3515.01	3515.09

Table: 4-10 Combustion temperature values for different waxes at various O/F ratios on the addition of 90% H_2O_2 at a fixed chamber pressure of 25 bar

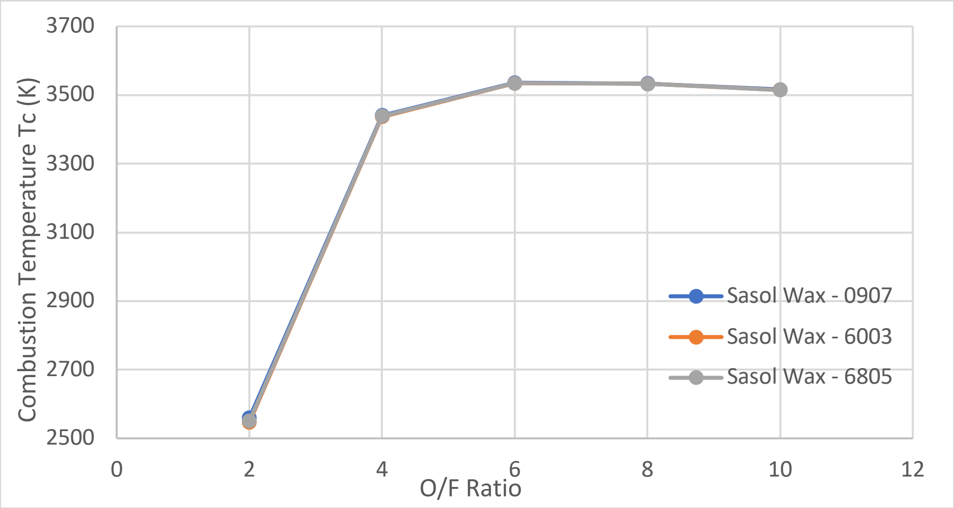


Figure: 4-9 Variation of Tc for different waxes at different O/F ratios on the addition of 90% H_2O_2 at a fixed pressure of 25 bar

The graph above demonstrates how the temperature of the combustion chamber varies as the oxidizer to fuel ratio changes for three different paraffin waxes. As a result, the values in Table 4-10 show that the combustion chamber temperature rises substantially when pure hydrogen peroxide is used as the oxidizer.

Furthermore, the pure hydrogen peroxide in Case A.1 followed the same pattern as the pure hydrogen peroxide. Finally, for all three waxes, the highest chamber temperature is reached at the O/F ratio 6, with Sasol 0907 having the highest value among other fuels.

C.2) Variation with respect to Chamber Pressure Pc

Further to that, in this part, it is examined how pressure affects the temperature of the combustion chamber. To better understand the effect of fuel mixture ratio on pressure and temperature, an analysis of various oxidizer to fuel ratios is performed. In addition, the results are presented in Tables 4-11-1 to 4-11-5 and shown in Figures 4-10-0 to 4-10-5.

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2555.98	2543.29	2546.98
25	2558.88	2546.06	2549.78
30	2561.07	2548.14	2551.89

Table: 4-11-1 ***O/F = 2***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3413.11	3409.56	3410.74
25	3440.85	3437.15	3438.38
30	3463.28	3459.56	3460.83

Table: 4-11-2 ***O/F = 4***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3503	3501.5	3501.9
25	3536.02	3534.48	3534.89
30	3563.15	3561.56	3561.98

Table: 4-11-3 ***O/F = 6***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3500.31	3499.4	3499.58
25	3533.5	3532.56	3532.73
30	3560.77	3559.81	3559.99

Table: 4-11-4 ***O/F = 8***

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3483.2	3482.55	3482.63
25	3515.69	3515.01	3515.09
30	3542.37	3541.68	3541.76

Table: 4-11-5 ***O/F = 10***

Table: 4-11 Variation of Combustion Temperature values for different waxes at different chamber pressures on the addition of 90% H_2O_2 *at a fixed O/F ratio*

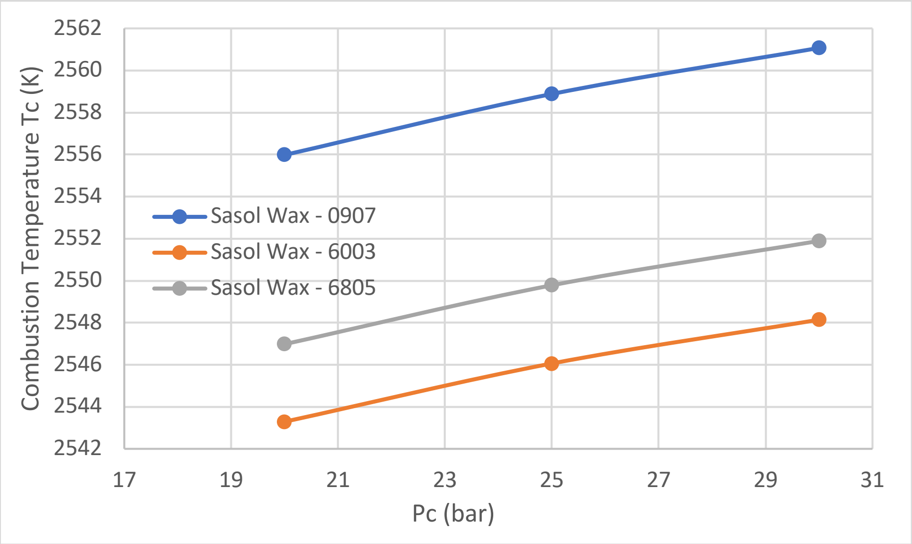


Figure: 4 -10-1 ***O/F ratio 2***

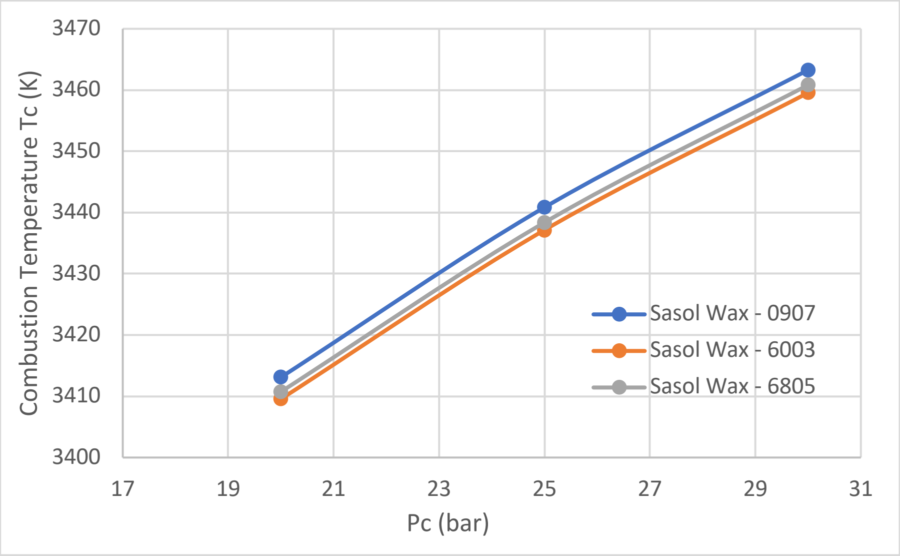


Figure: 4 -10-2 ***O/F ratio 4***

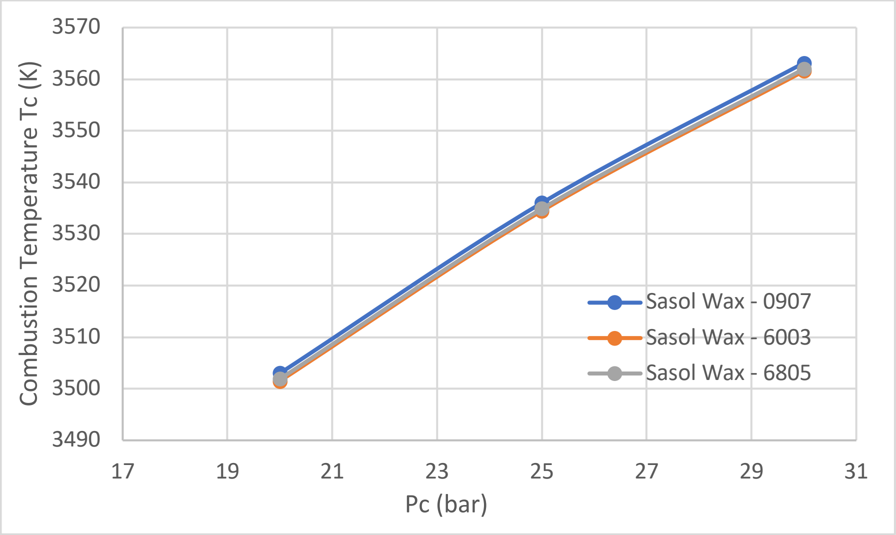


Figure: 4 -10-3 ***O/F ratio 6***

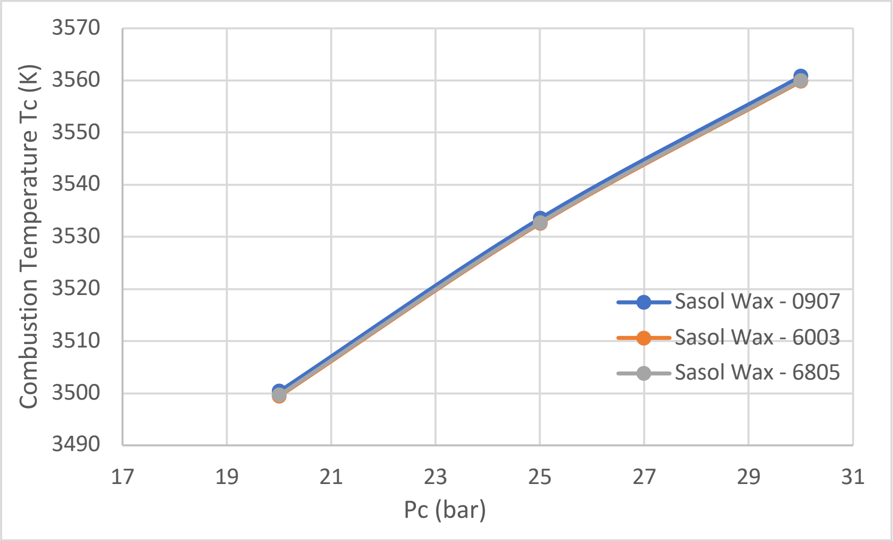


Figure: 4 -10-4 ***O/F ratio 8***

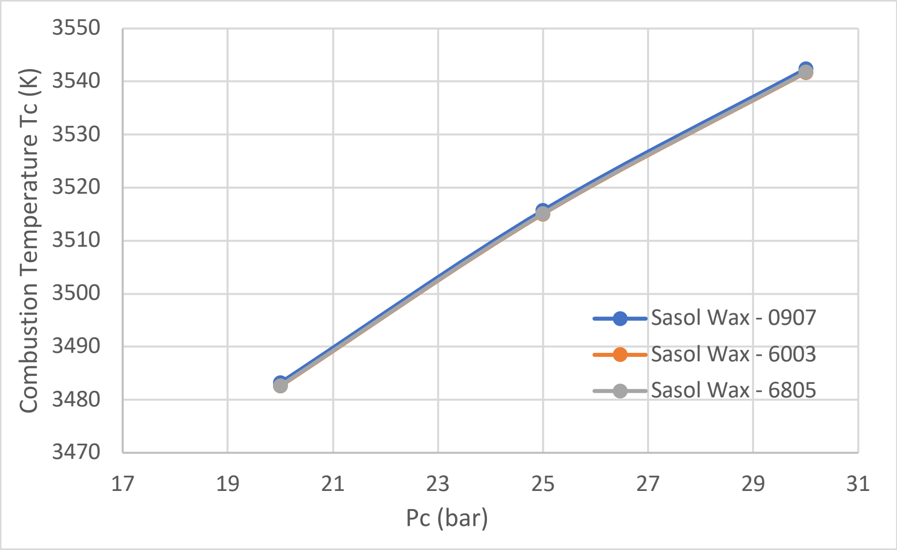


Figure: 4 -10-5 ***O/F ratio 10***

Figure: 4 -10 Variation of combustion temperature values for different waxes at different chamber pressures on the addition of 90% H_2O_2 at a fixed O/F ratio

The above graph shows that the increase in the pressure will not affect the combustion temperature for the 10% of the H_2O case. Further, it is almost become linear for the O/F ratios 2,4,10 and exhibited a slight increase for the O/F ratio 6, 8. Moreover, this linear trend is not evident in 95% of the H_2O_2. Finally, the Sasol 0907 has the highest temperatures among the waxes as the number of the carbon atoms are more.

4.7.2.3 Effect of Addition of Aluminum fuel in the Waxes

Metal combustion, due to its high heat of reaction and density, has inherent advantages in theory. Metal powders have been extensively studied as a way of increasing both the burning fuel mass flow rate and the specific impulse when opposed to pure fuel. Metal combustion, due to its high heat of reaction and density, has inherent advantages in theory.

Metal powders have been extensively studied as a way of increasing both the burning fuel mass flow rate and the specific impulse as opposed to pure fuel [60]. Researchers have found a small change in the rate of regression after applying aluminum or other metal powders to the fuel grain since the 1960s.

In general, the blocking effect is solely dependent on the gas blowing rate; the density of the fuel volatile portion is $\rho_v=(1-k)\ \rho_f$, where k is the metal particle weight fraction and ρ_f is the fuel density. As a result, the blocking effect should be decreased, and the regression rate should increase almost proportionally to factor $(1-k)^{-1}$. Moreover, since nonvolatile particles are only heated to surface temperature, the decrease in effective heat of gasification (referred to the total mass of fuel grain, i.e. binder plus metal additive) and the increased radiation heat flux are also expected to contribute to the regression rate enhancement. In addition, the flame temperature is elevated, which results in a regression rate rise, but to a lesser extent [61].

Finally, several additives, such as nano-sized aluminum, nano-sized Viton-coated aluminum, magnesium hydride, magnesium, nano-sized iron, or iron and magnesium, have been considered and tested in the context of the Operational Research Project on Hybrid Engine in Europe (ORPHEE). In addition, the inclusion of aluminum particles within fuels can lead to an increase in specific impulse, volumetric heat of oxidation, adiabatic flame temperature, the heat of combustion, and radiative heat transfer.

CASE D- Addition of Aluminum with 95% Hydrogen Peroxide (liquid) and 5% H_2O as the Oxidizer

D.1) Variation with respect to O/F ratio

<u>For Sasol Wax 0907</u>

O/F	*Combustion Temperature Tc (K)*		
	Aluminum 10 %	*Aluminum 15 %*	*Aluminum 20 %*
2	2915.15	3051.41	3174.86
4	3520.62	3552.01	3581.29
6	3559.7	3572.86	3585.52
8	3539.41	3546.89	3554.17
10	3513.11	3517.97	3522.73

*Table: 4-12 Combustion temperature values for **SASOL Wax 0907** with different addition of aluminum percentage as fuel at various O/F ratios for 95% H_2O_2 at a fixed chamber pressure of 25bar*

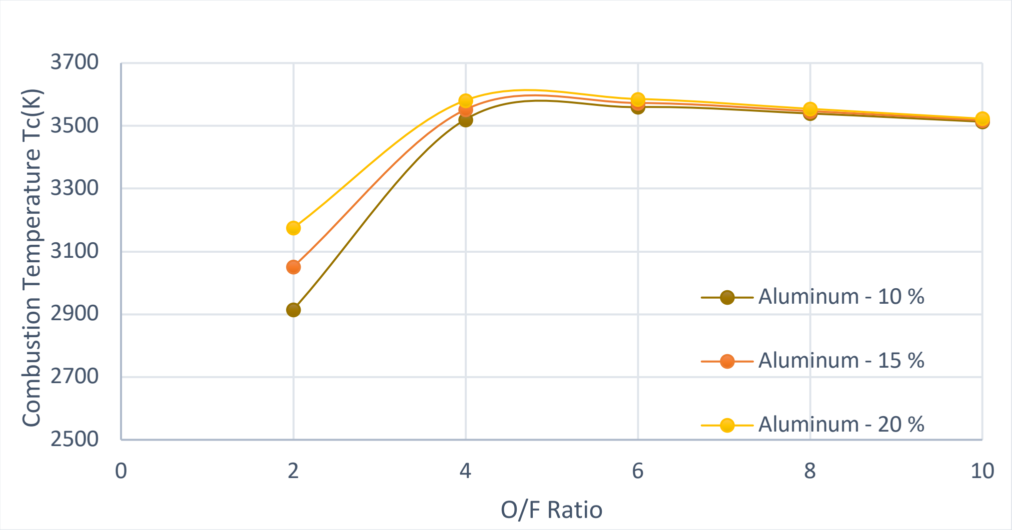


*Figure: 4 -11 Variation of combustion temperature for **SASOL Wax 0907** with different addition of aluminum percentage as fuel at various O/F ratios for 95% H_2O_2 at a fixed chamber pressure of 25bar*

For Sasol Wax 6003

O/F	*Combustion Temperature Tc (K)*		
	Aluminum 10 %	*Aluminum 15 %*	*Aluminum 20 %*
2	2888.10	3026.97	3153.01
4	3513.14	3545.43	3575.50
6	3557.14	3570.56	3583.46
8	3538.29	3545.88	3553.27
10	3512.58	3517.50	3522.31

Table: 4-13 Combustion temperature values for ***SASOL Wax 6003*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25bar*

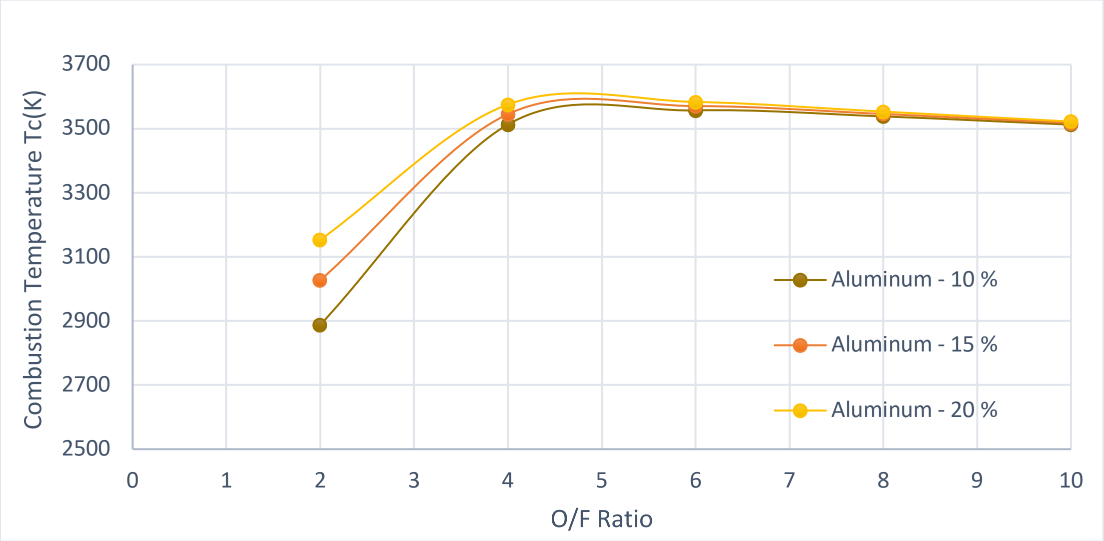


Figure: 4 -12 Variation of combustion temperature for ***SASOL Wax 6003*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25bar*

For Sasol Wax 6805

O/F	*Combustion Temperature Tc (K)*		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %
2	2891.35	3029.91	3155.65
4	3514.05	3546.23	3576.20
6	3557.45	3570.84	3583.71
8	3538.42	3546.0	3553.37
10	3512.64	3517.55	3522.35

Table: 4-14 Combustion temperature values for ***SASOL Wax 6805*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25 bar*

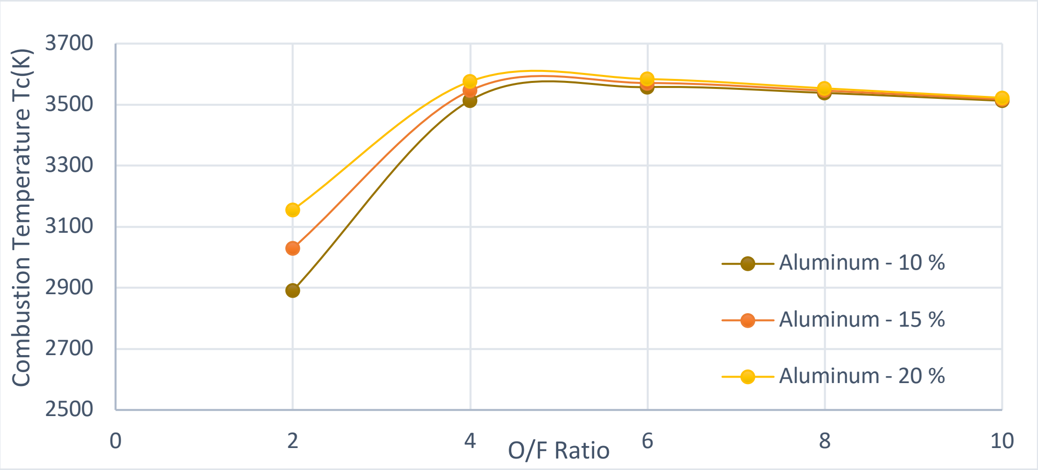


Figure: 4 -13 Variation of combustion temperature for ***SASOL Wax 6805*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25 bar*

D.2) Variation with respect to Chamber Pressure Pc

For Sasol Wax 0907

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20%
20	3525.92	3538.71	3551.04
25	3559.7	3572.86	3585.52
30	3587.48	3600.94	3613.88

Table: 4-15 Combustion temperature values for ***SASOL Wax 0907*** *with different addition of aluminum percentage as fuel at various chamber pressures for 95%* H_2O_2 *at a fixed* ***O/F ratio 6***

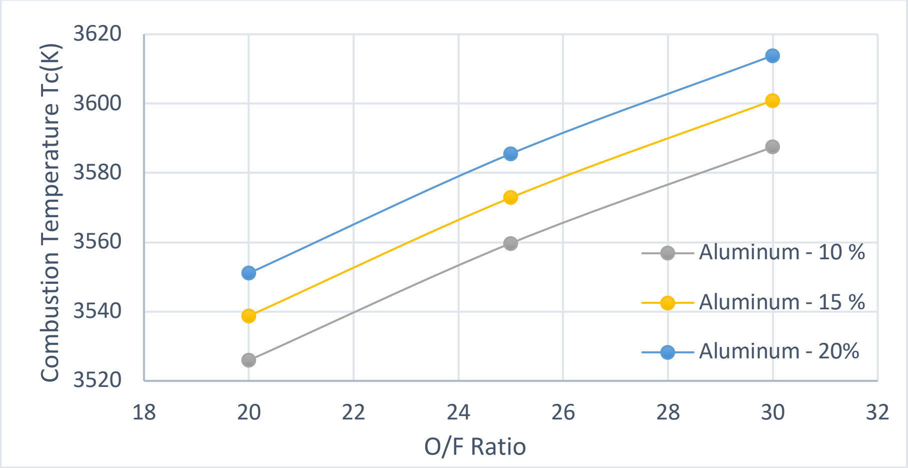


Figure: 4 -14 Variation of combustion temperature for ***SASOL Wax 0907*** *with different addition of aluminum percentage as fuel at various chamber pressures for 95%* H_2O_2 *at a fixed* ***O/F ratio 6***

For Sasol Wax 6003

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20%
20	3523.45	3536.49	3549.05
25	3557.14	3570.56	3583.46
30	3584.84	3598.58	3611.78

*Table: 4-16 Combustion temperature values for **SASOL Wax 6003** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

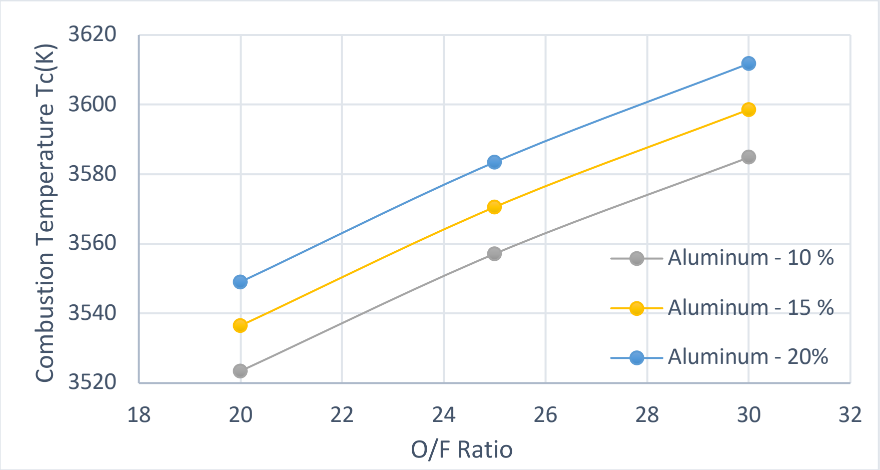


*Figure: 4 -15 Variation of combustion temperature for **SASOL Wax 6003** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

For Sasol Wax 6805

Pc (Bar)	***Combustion Temperature Tc (K)***		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20%
20	3523.74	3536.76	3549.28
25	3557.45	3570.84	3583.71
30	3585.16	3598.86	3612.03

*Table: 4-17 Combustion temperature values for **SASOL Wax 6805** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

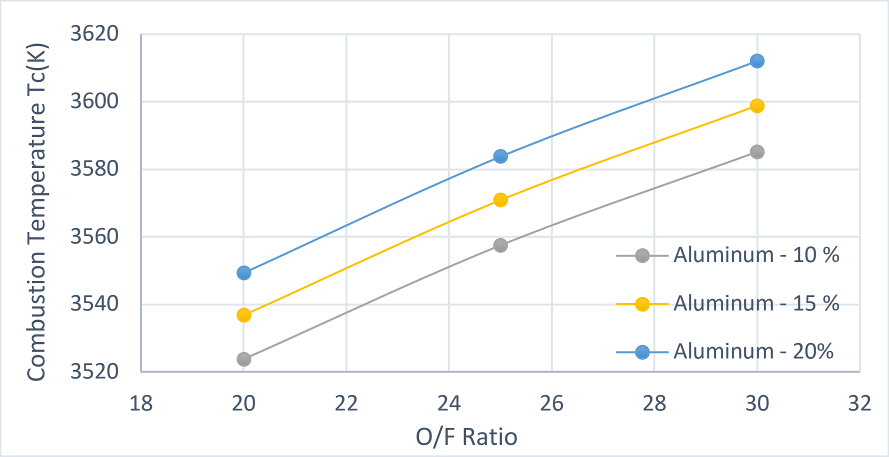


*Figure: 4 -16 Variation of combustion temperature for **SASOL Wax 6805** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

To sum up, all three cases, the addition of aluminum raises the combustion temperature in all three cases; however, the sensitivity to the addition of aluminum is greater at lower O/F ratios since the percentage of fuel is higher at lower O/F ratios, and because aluminum makes up 10% - 20% of the fuel, the net ratio of aluminum to the total fuel is higher. At O/F of 2, as with Sasol Wax 0907, the rise in combustion temperature is approximately 93.3 percent, falling to less than 1% (approximately 0.73 percent) at O/F of 10.

Moreover, this phenomenon happens because adding aluminum increases the amount of heat generated by combustion while also improving combustion stability, as the aluminum particles break free from the fuel grain surfaces and react vigorously in the gas flow, as described earlier.

It is noteworthy, that aluminum content to the paraffin increases the regression rate drastically and combustion performances. Furthermore, the volumetric specific impulse is also increased due to the fact that the aluminum increases the density of the propellant, which in turn increases the volumetric specific impulse of the fuel [63]. The reduced O/F ratio, which results in a smaller oxidizer tank, is another advantage of using aluminum powder [64].

Finally, when comparing the patterns of combustion temperature vs. change in chamber pressure, all mixtures of different aluminum compositions have essentially the same slope (as the net ratio of aluminum to the total mixture (O/F) is fixed) in the range, and these values increase as the aluminum content increases. At chamber pressures of 20 bar and 30 bar, there is a leap in combustion temperatures of around 2.45 percent and 2.54 percent, respectively, which is roughly equivalent to Sasol Wax 0907.

4.7.2.4 Comparison Studies

Variation with respect to O/F Ratio

O/F	*Combustion Temperature Tc (K)*			
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %	No Additive
2	2915.15	3051.41	3174.86	2587.08
4	3520.62	3552.01	3581.29	3456.09
6	3559.7	3572.86	3585.52	3539.05
8	3539.41	3546.89	3554.17	3530.49
10	3513.11	3517.97	3522.73	3508.97

*Table: 4-18 Combustion temperature values for **SASOL Wax 0907** with different addition of aluminum percentage at various O/F ratios for **different cases** at a fixed chamber pressure 25 bar*

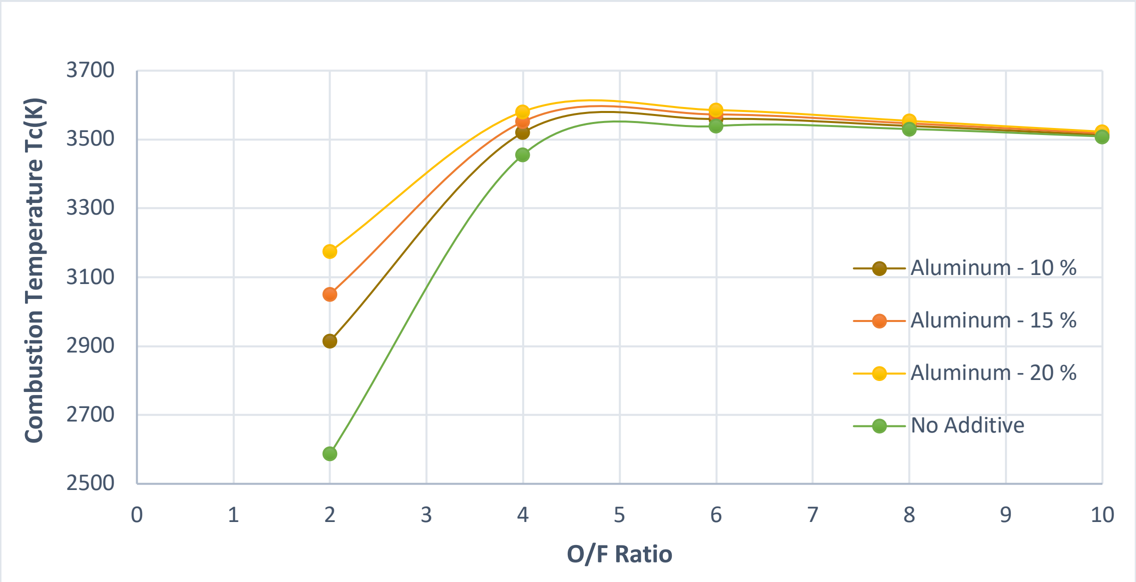


*Figure: 4 -17 Variation of combustion temperature for **SASOL Wax 0907** with different addition of aluminum percentage at various O/F ratios for **different cases** at a fixed chamber pressure 25 bar*

The above graph shows that the aluminum composition of the paraffin waxes increased the combustion temperature dramatically. Firstly, a peak is not observed at O/F ratio 6. moreover, at O/F ratio 2, it is registered the maximum difference of temperature with aluminum content to no additive composition. Furthermore, as the O/F ratio increases the effect is faded.

Variation with respect to Chamber Pressure Pc

Pc (Bar)	*Combustion Temperature Tc (K)*			
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %	No Additive
20	3525.92	3538.71	3551.04	3505.85
25	3559.7	3572.86	3585.52	3539.05
30	3587.48	3600.94	3613.88	3566.33

*Table: 4-19 Combustion temperature values for **SASOL Wax 0907** with different addition of aluminum percentage at various chamber pressure for **different cases** at a fixed O/F ratio 6*

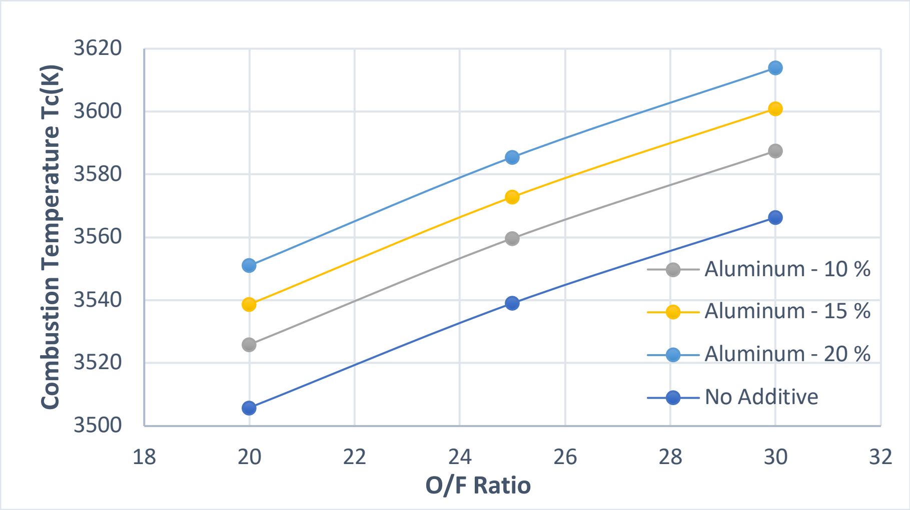


*Figure: 4 -18 Variation of combustion temperature for **SASOL Wax 0907** with different addition of aluminum percentage at various chamber pressure for **different cases** at a fixed O/F ratio 6*

The above graphs demonstrate the variation of the combustion temperature with pressure as the function of the composition of the additive. A clear comparison is established to show the effect of aluminum in the paraffin waxes. Firstly, as it can be seen that the temperature increased linearly with the pressure because the combustion flow acts as an ideal fluid so there is a significant increase in the temperature. Moreover, 20% aluminum has the highest temperature as it is increasing the reactiveness of the propellent.

4.7.3. Specific Impulse

A rocket's thrust is the force that propels it through the air. The reaction of accelerating a mass of gas produces thrust in the rocket engine. The rocket accelerates in the same direction as the gas accelerates to the rear. The propulsion system is required to propel the gas. Furthermore, it can be described as a force as the shift in the momentum of an object with a change in time, as defined by Newton's second law of motion.

The mass of an object multiplied by its velocity equals its momentum. The basic thrust equation when dealing with gas is as follows:

$$F = \dot{M}e * Ve - \dot{M}o * Vo + (Pe - Po) * Ae$$

Thrust F is equal to the exit mass flow rate $\dot{M}e$ times the exit velocity Ve minus the free stream mass flow rate $\dot{M}o$ times the free stream velocity Vo plus the pressure difference across the engine pe - p0 times the engine area Ae minus the free stream mass flow rate $\dot{M}o$ times the free stream velocity Vo plus the pressure difference across the engine Pe - Po times the engine area Ae.

Now, it is defined a new velocity called the equivalent velocity (Veq) and its results.

$$Veq = Ve + (pe - po) * Ae / \dot{M}$$

Further, impulse can be defined as the product of the mass of the propellant and the equivalent velocity.

$$I = m * Veq$$

Finally, a specific impulse is derived as the ratio of the impulse to the weight of the propellant.

$$Isp = Veq / go$$

$$Isp = F / (\dot{M} * go)$$

First, understanding the weight flow rate through the nozzle helps one to easily measure the thrust of a rocket.

Second, it's a measure of the engine's performance. The exact impulse of two different rocket engines is different. Since it generates more thrust for the same amount of propellant, the engine with the higher specific impulse is more powerful.

Third, it simplifies our rocket thermodynamics mathematical study. Fourth, it helps us to easily "scale" an engine during preliminary testing. The consequence of our thermodynamic analysis is a particular impulsive value.

4.7.3.1 With Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide H_2O_2 liquid as the oxidizer with the paraffin fuels (Sasol Wax 0907, Sasol Wax 6805, Sasol Wax 6003).

CASE A- Pure Paraffin Waxes

A.1) Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
2	2691.6	2687.6	2687.8
4	3004.1	3004.1	3003.4
6	2971.0	2971.8	2971
8	2760.7	2922.2	2921.5
10	2883.1	2883.7	2883.1

Table: 4-20 Specific Impulse values for different waxes at various O/F ratios at a fixed chamber pressure of 25 bar

Since all three waxes have similar chemical formulae and therefore very similar C/H ratios (around 0.4), it can be seen in Table 4-20 that their specific impulse is very similar at a fixed O/F ratio. But, since Sasol Wax 0907 has the highest molecular weight (the greatest number of carbon atoms) and the highest negative enthalpy (-1422.526),

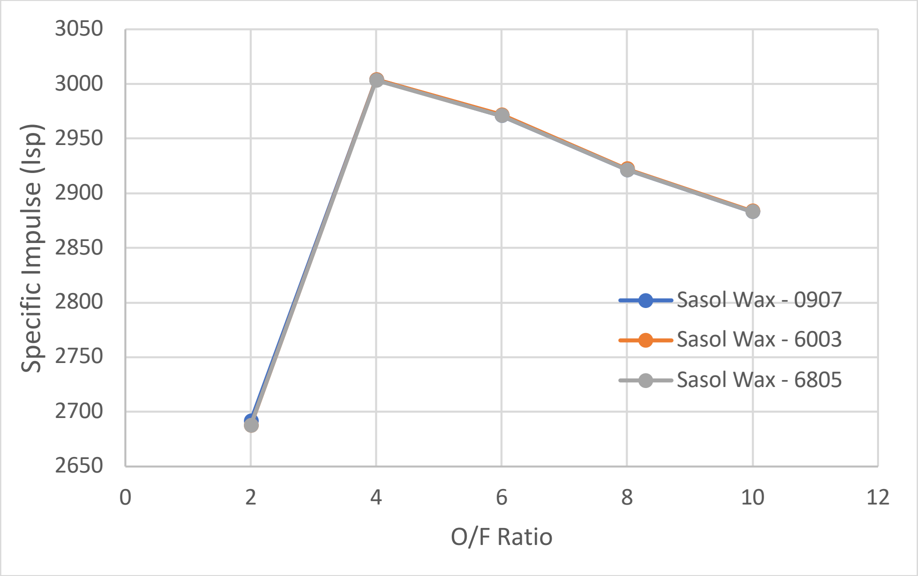


Figure: 4 -19 Variation of Specific Impulse for different waxes at different O/F ratios at a fixed pressure of 25 bar

The Isp rises steadily with increasing the O/F ratio up to O/F ratio 6, topping at 3004.1s for all three waxes at O/F ratio 6, and then decreasing marginally after that, as shown in Figure 4-19. As a consequence, the maximum combustion temperature is located near the stoichiometric condition.

Since the maximum amount of heat release occurs at the stoichiometric condition and adding more fuel than the stoichiometric ratio causes the creation of partly oxidized products like CO, which release less energy than full combustion products, the maximum combustion temperature does not increase to the left of the peak, even though the fuel content is increased.

A.2) Variation with respect to Chamber Pressure Pc

Having followed previous section A.1, in this section of the chapter, it is investigated how pressure affects the specific impulse of the combustion chamber. To better understand the effect of fuel mixture ratio on pressure and specific impulse, an analysis of various oxidizer to fuel ratios is performed. In addition, the results are presented in Tables 4-21-1 to 4-21-5 and shown in Figures 4-20-0 to 4-20-5.

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2691.4	2687.4	2687.6
25	2691.6	2687.6	2687.8
30	2691.7	2687.7	2687.9

Table: 4-21-1 ***O/F = 2***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2998.9	2998.9	2998.3
25	3004.1	3004.1	3003.4
30	3008.2	3008.1	3007.5

Table: 4-21-2 ***O/F = 4***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2963.7	2964.5	2963.7
25	2971	2971.8	2971
30	2976.9	2977.6	2976.9

Table: 4-21-3 ***O/F = 6***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2914.3	2915	2914.3
25	2921.5	2922.2	2921.5
30	2927.3	2928	2927.3

Table: 4-21-4 ***O/F = 8***

Pc (Bar)		***Specific Impulse (Isp)***	
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2876.3	2876.8	2876.3
25	2883.1	2883.7	2883.1
30	2888.6	2889.2	2888.6

Table: 4-21-5 ***O/F = 10***

Table: 4-21 Variation of Specific Impulse values for different waxes at different chamber pressures and at a fixed O/F ratio

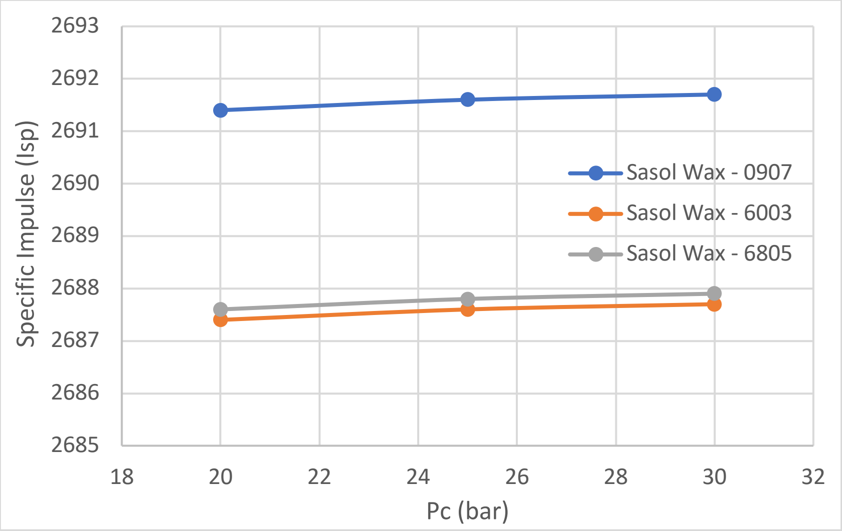


Figure: 4 -20-1 ***O/F ratio 2***

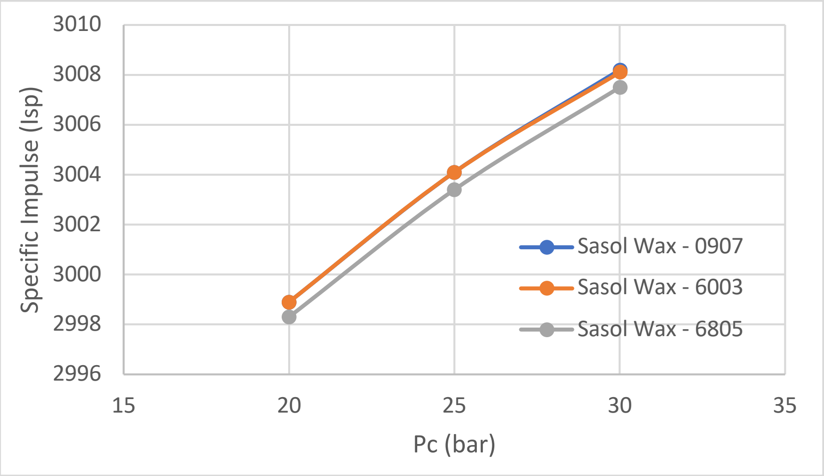


Figure: 4 -20-2 ***O/F ratio 4***

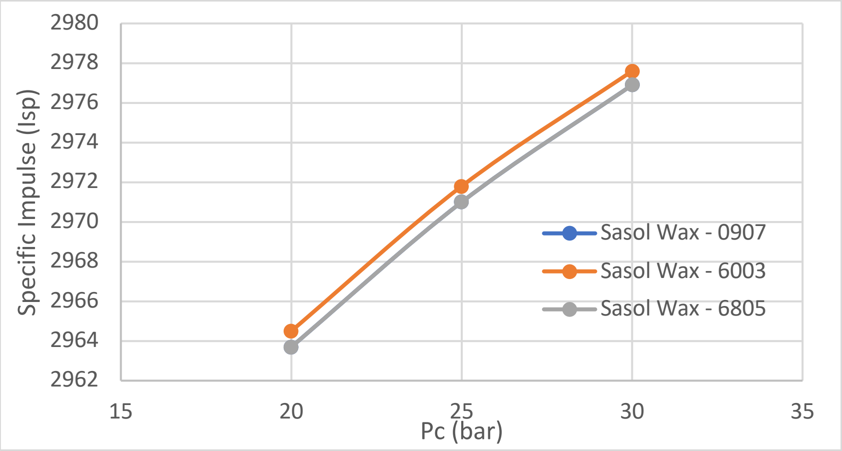


Figure: 4 -20-3 ***O/F ratio 6***

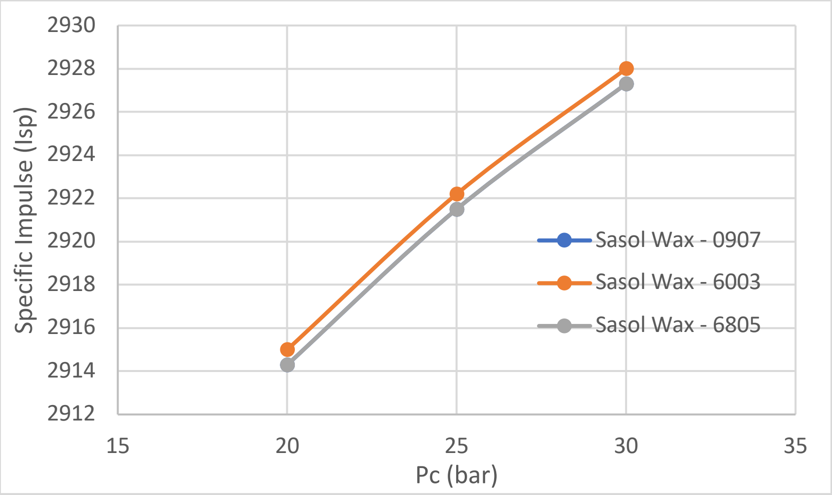


Figure: 4 -20-4 ***O/F ratio 8***

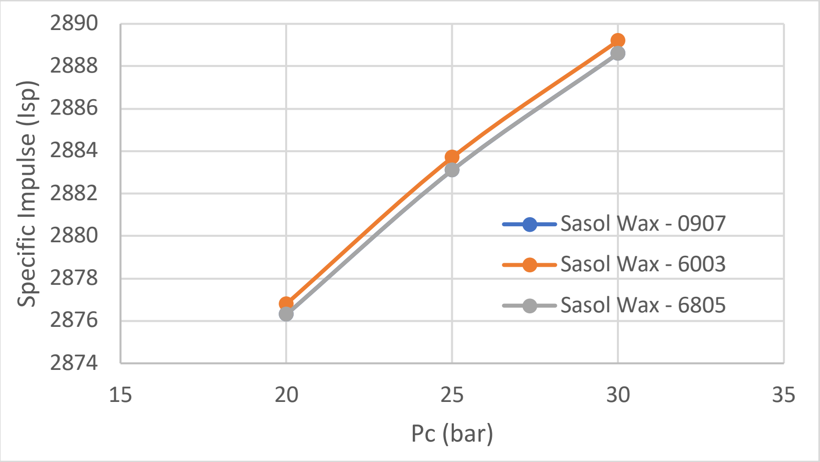


Figure: 4 -20-5 ***O/F ratio 10***

Figure: 4 -20 Variation of Specific Impulse values for different waxes at different chamber pressures and at a fixed O/F ratio

4.7.3.2 With Hydrogen Peroxide (liquid) and H_2O as the Oxidizer

CASE B- 95% Hydrogen Peroxide and 5% H_2O

This segment will consider the effects of adding 5% H_2O to hydrogen peroxide for three different waxes with a different oxidizer to fuel ratios. In addition, no other additives were added to the hydrogen peroxide. At room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

B.1) Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
2	2690.8	2686.8	2687
4	3015.9	3015.7	3015.1
6	2992.7	2993.3	2992.6
8	2946.8	2947.5	2946.8
10	2910.5	2911.1	2910.5

Table: 4-22 Specific Impulse values for different waxes at various O/F ratios on the addition of 95% H_2O_2 at a fixed chamber pressure of 25 bar

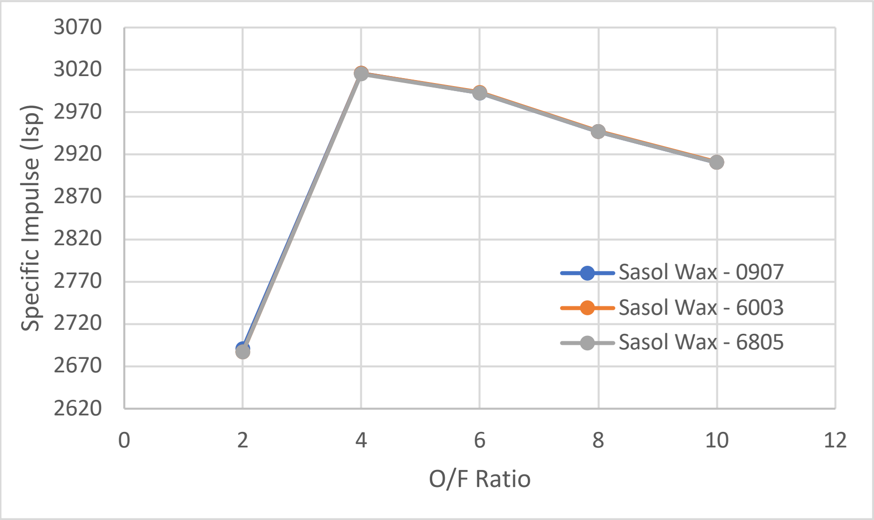


Figure: 4-21 Variation of Specific Impulse for different waxes at different O/F ratios on the addition of 95% H_2O_2 at a fixed pressure of 25 bar

The graph above illustrates how the specific impulse of the combustion chamber increases as the oxidizer to fuel ratio varies for three different paraffin waxes. As a result, the values in Table 4-22 show that the specific impulse (Isp) increases steadily till O/F ratio 6 and shows decreasing trends after that. In addition, the 95 percent hydrogen peroxide as oxidizer met a different pattern than the pure hydrogen peroxide, as in Case A.1.

Finally, at the O/F ratio 6, all three waxes attain the highest specific impulse (Isp), with Sasol 0907 having the highest value among the other fuels. Furthermore, the impulse reached a plateau after oxidizer to fuel ratio 6 was reached.

B.2) Variation with respect to Chamber Pressure Pc

Following on from section B.1, this section of the chapter investigates how pressure influences the specific impulse. The study of different oxidizer to fuel ratios is conducted to better understand the effect of fuel mixture ratio on pressure and specific impulse. The findings are also presented in Tables 4-23-1 to 4-23-5 and illustrated in Figures 4-22-0 to 4-22-5.

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2690.6	2686.6	2686.8
25	2690.8	2686.8	2687
30	2690.9	2686.9	2687.1

Table: 4-23-1 ***O/F = 2***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3011	3010.9	3010.3
25	3015.9	3015.7	3015.1
30	3019.8	3019.6	3019

Table: 4-23-2 ***O/F = 4***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2985.4	2986.1	2985.3
25	2992.7	2993.3	2992.6
30	2998.5	2999.2	2998.5

Table: 4-23-3 ***O/F = 6***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2939.6	2940.2	2939.6
25	2946.8	2947.5	2946.8
30	2952.7	2953.4	2952.7

Table: 4-23-4 ***O/F = 8***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2903.5	2904.11	2903.5
25	2910.5	2911.1	2910.5
30	2916.1	2916.7	2916.1

Table: 4-23-5 ***O/F = 10***

Table: 4-23 Variation of Specific Impulse values for different waxes at different chamber pressures on addition of 95% H_2O_2 *at a fixed O/F ratio*

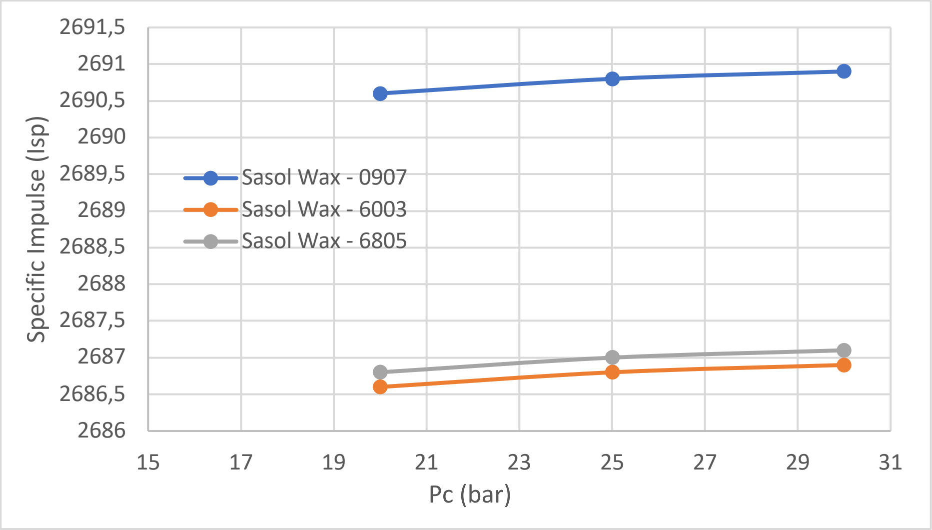


Figure: 4 -22-1 ***O/F ratio 2***

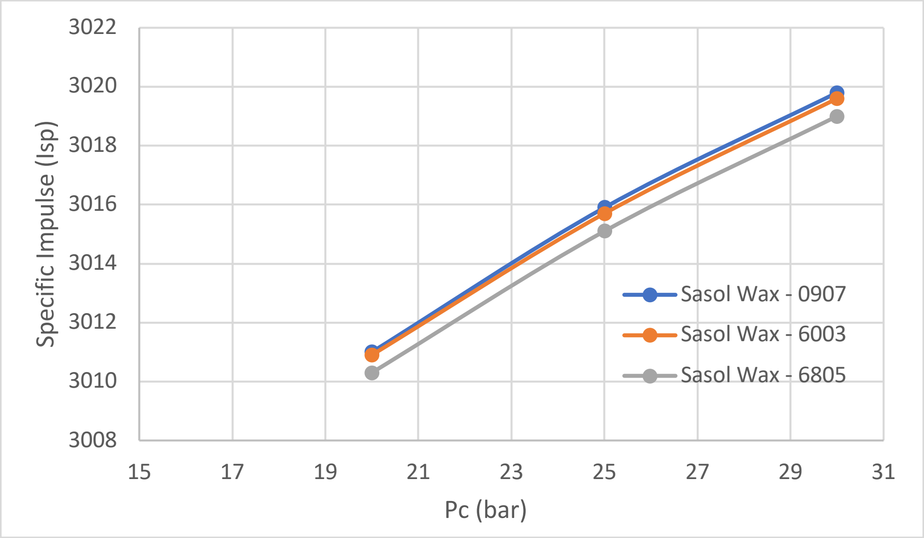


Figure: 4 -22-2 ***O/F ratio 4***

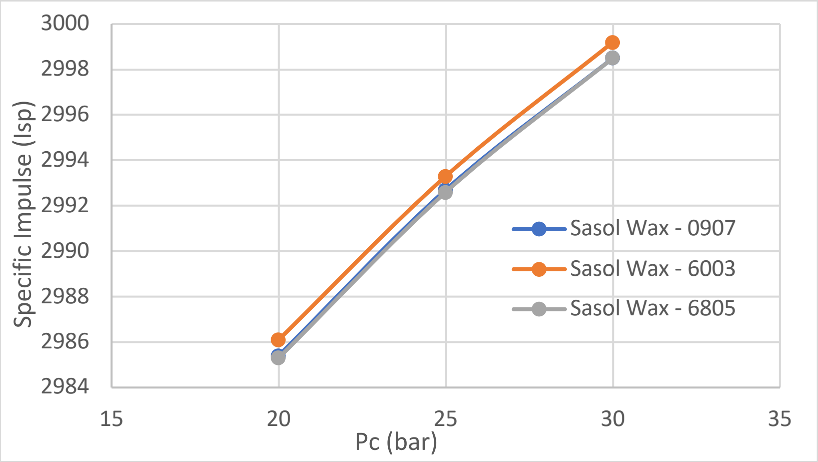


Figure: 4 -22-3 ***O/F ratio 6***

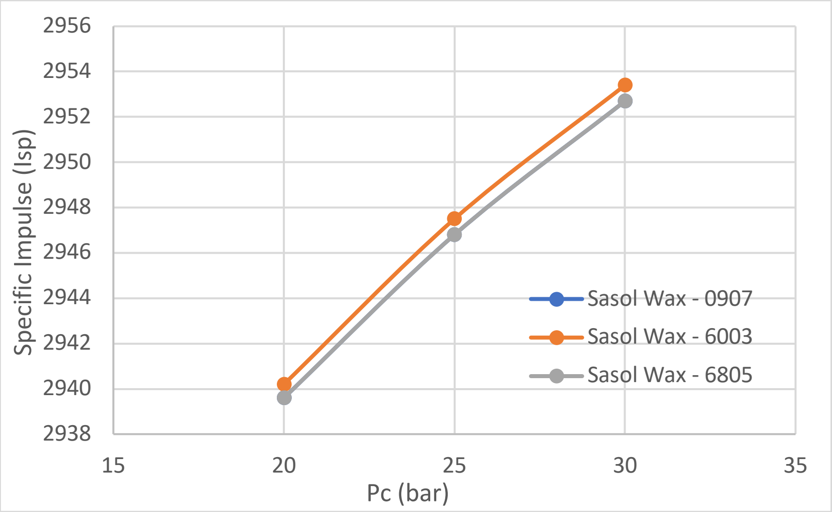


Figure: 4 -22-4 ***O/F ratio 8***

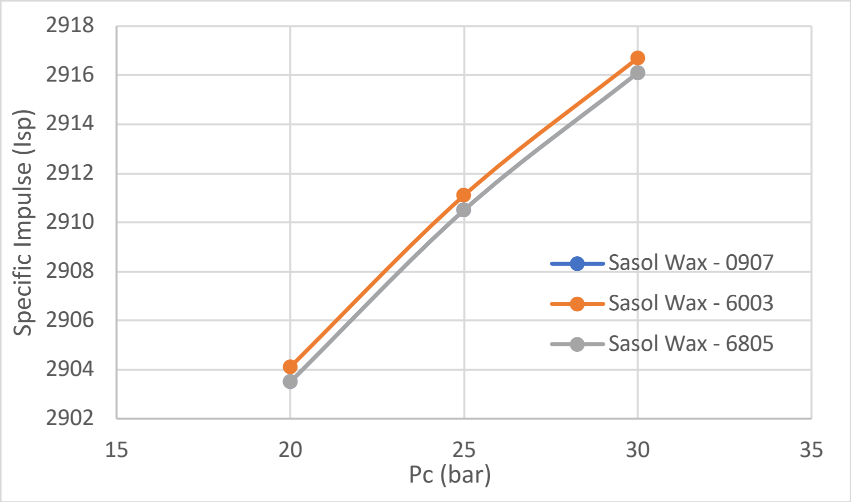


Figure: 4 -22-5 ***O/F ratio 10***

Figure: 4 -22 Variation of Specific Impulse values for different waxes at different chamber pressures on the addition of 95% H_2O_2 *at a fixed O/F ratio*

For the 5% H_2O case, the increase in pressure has no effect on the specific impulse, as seen in the graphs above. Furthermore, for the O/F ratio 2, it has a steady increase, with a marginal improvement for the pressure. Furthermore, this linear pattern is not visible in pure H_2O_2 oxidizers. Finally, since there are more carbon atoms in the Sasol 0907, it has the highest impulse among the waxes.

CASE C- 90% Hydrogen Peroxide and 10% H_2O

This segment would further look at the effects of adding 10% H2O to hydrogen peroxide for three different waxes at various oxidizer to fuel ratios. There were no other chemicals added to the hydrogen peroxide. At room temperature, the enthalpy of H2O is used as the CEA code's default values.

C.1) Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
2	2689.9	2685.8	2686
4	3026.8	3026.6	3026
6	3013.6	3014.2	3013.5
8	2971.6	2972.3	2971.6
10	2937.4	2937.9	2937.4

Table: 4-24 Specific Impulse values for different waxes at various O/F ratios on the addition of 90% H_2O_2 at a fixed chamber pressure of 25 bar

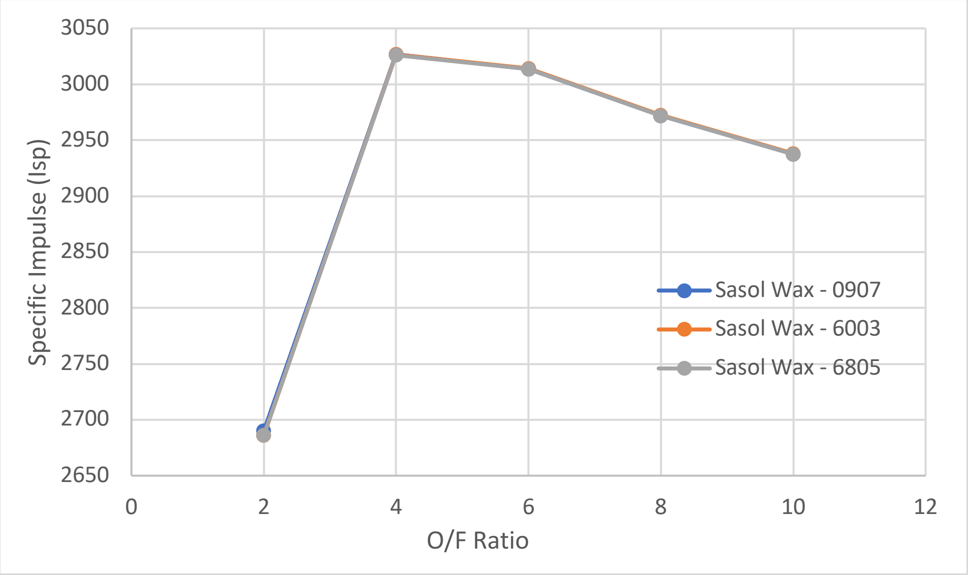


Figure: 4-23 Variation of Specific Impulse for different waxes at different O/F ratios on the addition of 90% H_2O_2 at a fixed pressure of 25 bar

For three different paraffin waxes, the graph above shows how the specific impulse of the combustion chamber increases as the oxidizer to fuel ratio changes. As a result, the values in Table 4-24 indicate that when 10% hydrogen peroxide is used as the oxidizer, the specific impulse (Isp) rises steadily. In addition, as in Case A.1, the 90% hydrogen peroxide followed a different trend as the pure hydrogen peroxide.

Finally, the highest chamber temperature is achieved for all three waxes at the O/F ratio 6, with Sasol 0907 having the highest value among the other fuels. Furthermore, after oxidizer to fuel ratio 6, the specific impulse hit the plateau.

C.2) Variation with respect to Chamber Pressure Pc

Thereafter, in this section, it is investigated how pressure affects the specific impulse of the combustion in this chapter. An analysis of different oxidizer to fuel ratios is conducted to understand the effect of fuel mixture ratio on pressure and specific impulse. In addition, the results are presented in Tables 4-25-1 to 4-25-5 and shown in Figures 4-24-0 to 4-24-5.

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2689.7	2685.7	2685.9
25	2689.9	2685.8	2686
30	2690	2685.9	2686.1

Table: 4-25-1 ***O/F = 2***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3022.2	3022	3021.5
25	3026.8	3026.6	3026
30	3030.5	3030.2	3029.7

Table: 4-25-2 ***O/F = 4***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	3006.4	3007	3006.3
25	3013.6	3014.2	3013.5
30	3019.4	3020	3019.3

Table: 4-25-3 ***O/F = 6***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2964.3	2965	2964.3
25	2971.6	2972.3	2971.6
30	2977.6	2978.2	2977.6

Table: 4-25-4 ***O/F = 8***

Pc (Bar)	***Specific Impulse (Isp)***		
	Sasol Wax 0907	Sasol Wax 6003	Sasol Wax 6805
20	2930.3	2930.9	2930.3
25	2937.4	2937.9	2937.4
30	2943.1	2943.7	2943.1

Table: 4-25-5 ***O/F = 10***

Table: 4-25 Variation of Specific Impulse values for different waxes at different chamber pressures on the addition of 90% H_2O_2 *at a fixed O/F ratio*

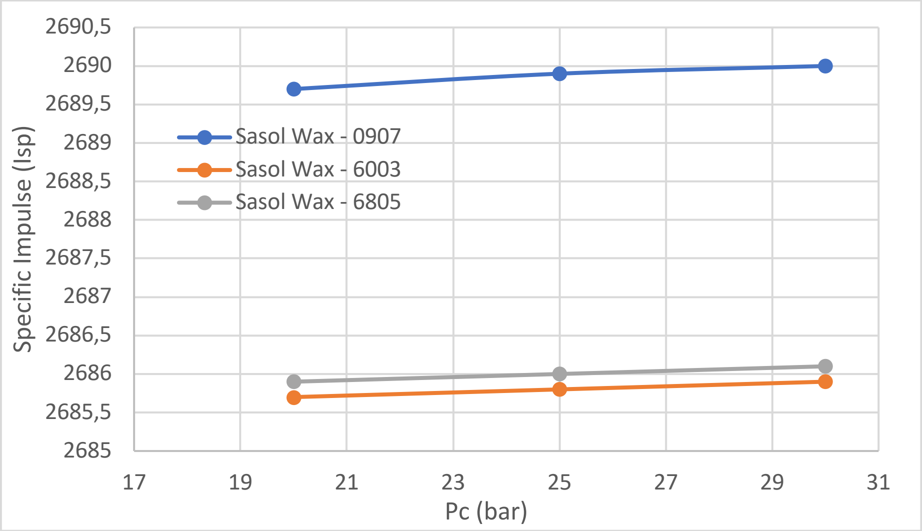


Figure: 4 -24-1 ***O/F ratio 2***

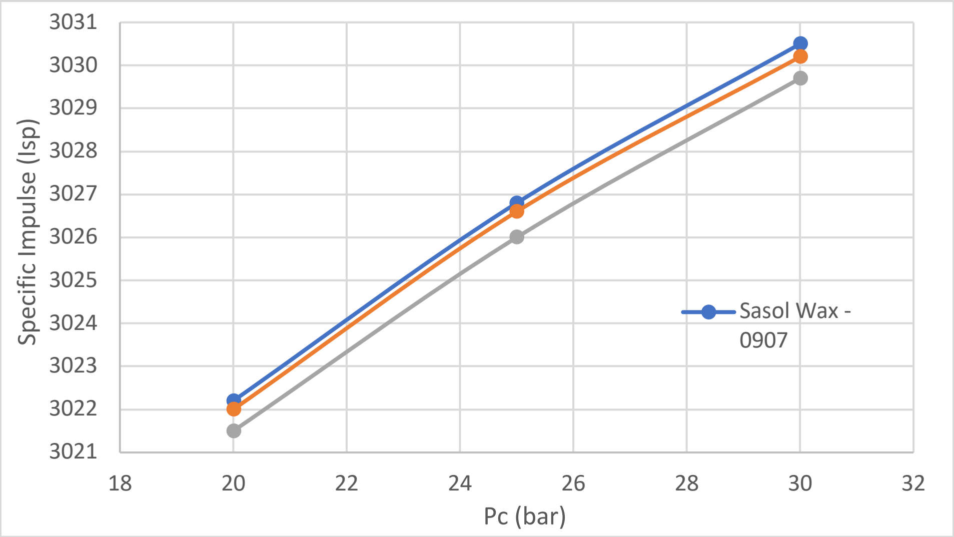


Figure: 4 -24-2 ***O/F ratio 4***

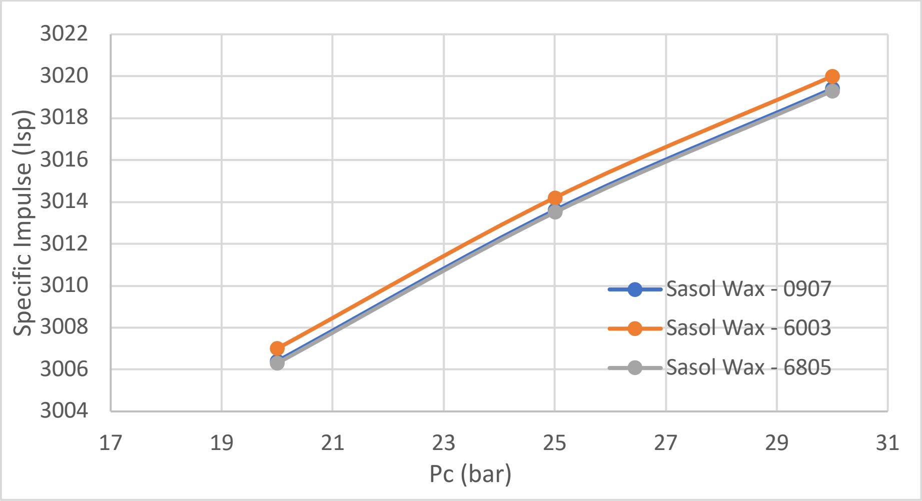


Figure: 4 -24-3 ***O/F ratio 6***

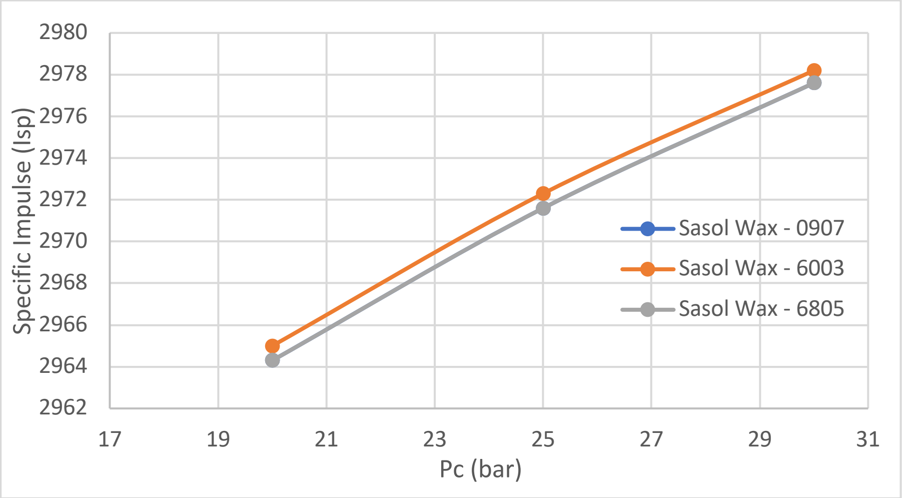


Figure: 4 -24-4 ***O/F ratio 8***

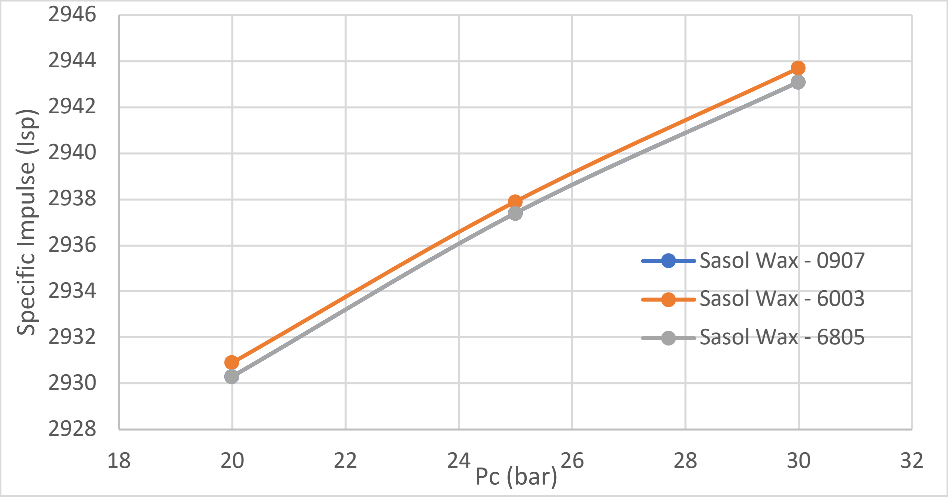


Figure: 4 -24-5 ***O/F ratio 10***

Figure: 4 -24 Variation of Specific Impulse values for different waxes at different chamber pressures on the addition of 90% H_2O_2 *at a fixed O/F ratio*

For the 10 % H_2O case, the increase in pressure has no effect on the specific impulse, as seen in the graph above. Furthermore, specific impulse has nearly become linear. This trend is not exhibited by the other cases with different compositions.

4.7.3.3 Effect of Addition of Aluminum fuel in the Waxes

CASE D- Addition of Aluminum with 95% Hydrogen Peroxide (liquid) and 5% H_2O as the Oxidizer

D.1) Variation with respect to O/F ratio

This current section investigates the effect of aluminum on the three different waxes at different oxidation to fuel ratios as a function of the specific impulse (Isp). Firstly, analysis is done with the same initial conditions as mentioned in the previous sections and with a 95% weight ratio of the hydrogen peroxide at 25 bars.

Furthermore, results are shown in Tables 4-(26 to 28) and graphs were extracted for illustration of trends.

<u>For Sasol Wax 0907</u>

O/F	*Specific Impulse (Isp)*		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %
2	2808.0	2854.4	2891.3
4	3004.4	2997.6	2988.4
6	2964.7	2953.3	2941.4
8	2921.3	2911.2	2900.8
10	2888.3	2879.5	2870.6

Table: 4-26 Specific Impulse values for ***SASOL Wax 0907*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25 bar*

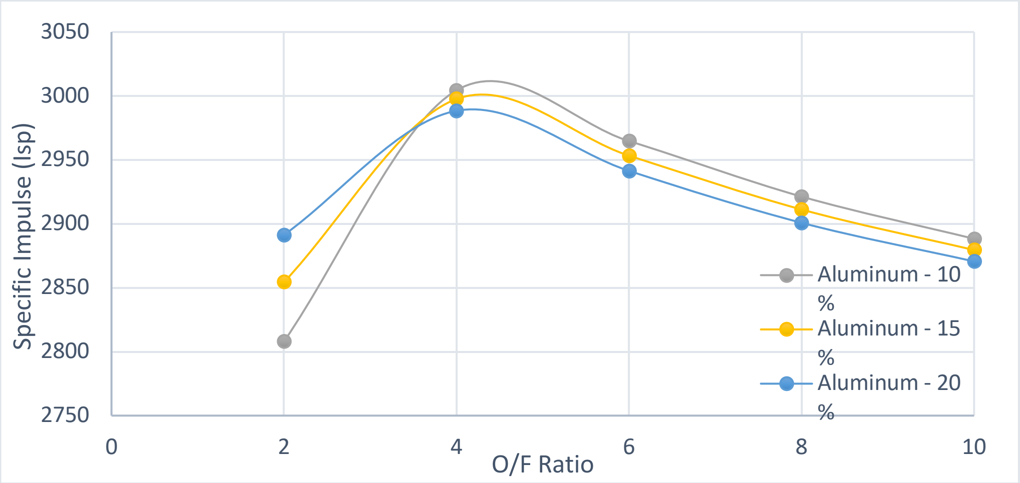


*Figure: 4 -25 Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage as fuel at various O/F ratios for 95% H_2O_2 at a fixed chamber pressure of 25 bar*

For Sasol Wax 6003

O/F	*Specific Impulse (Isp)*		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %
2	2807.7	2855.2	2893.2
4	3009.9	3003.3	2994.3
6	2970.4	2958.8	2946.7
8	2926.1	2915.8	2905.2
10	2892.4	2883.4	2874.3

*Table: 4-27 Specific Impulse values for **SASOL Wax 6003** with different addition of aluminum percentage as fuel at various O/F ratios for 95% H_2O_2 at a fixed chamber pressure of 25 bar*

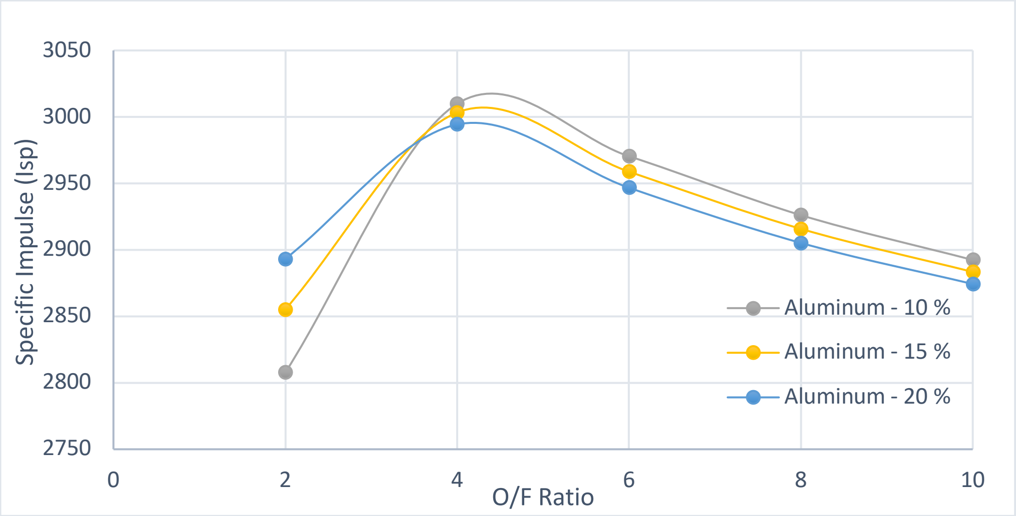


*Figure: 4 -26 Specific Impulse values for **SASOL Wax 6003** with different addition of aluminum percentage as a fuel at various O/F ratios for 95% H_2O_2 at a fixed chamber pressure of 25 bar*

For Sasol Wax 6805

O/F	*Specific Impulse (Isp)*		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %
2	2807.7	2855.1	2892.9
4	3009.2	3002.6	2993.5
6	2969.7	2958.1	2946.1
8	2925.5	2915.2	2904.6
10	2891.9	2882.9	2873.8

Table: 4-28 Specific Impulse values for ***SASOL Wax 6805*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25 bar*

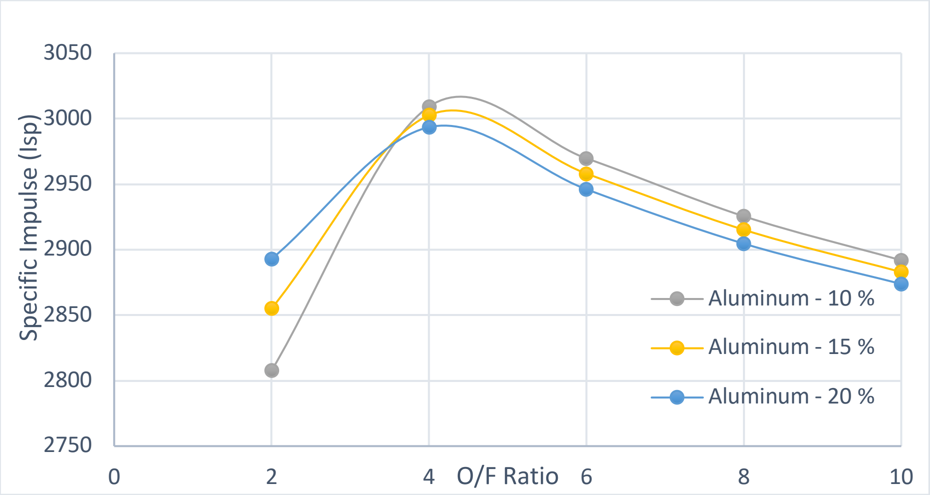


Figure: 4 -27 Specific Impulse values for ***SASOL Wax 6805*** *with different addition of aluminum percentage as fuel at various O/F ratios for 95%* H_2O_2 *at a fixed chamber pressure of 25 bar*

To sum up, in all three cases, the addition of aluminum increases the specific impulse all three cases; however, the sensitivity to the addition of aluminum is greater at lower O/F ratios since the percentage of fuel (the content of aluminum) is higher at lower O/F ratios.
At O/F of 2, 20% of aluminum content has a more specific impulse than the other composition. Further, it is observed that the stoichiometric ratio is not observed at the 6.

D.1) Variation with respect to Chamber Pressure Pc

For Sasol Wax 0907

Pc (Bar)		***Specific Impulse (Isp)***	
	Aluminum 10 %	Aluminum 15 %	Aluminum 20%
20	2957.3	2945.9	2934.1
25	2964.7	2953.3	2941.4
30	2970.6	2959.2	2947.4

*Table: 4-29 Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage as fuel at various chamber pressures for 95%* H_2O_2 *at a fixed **O/F ratio 6***

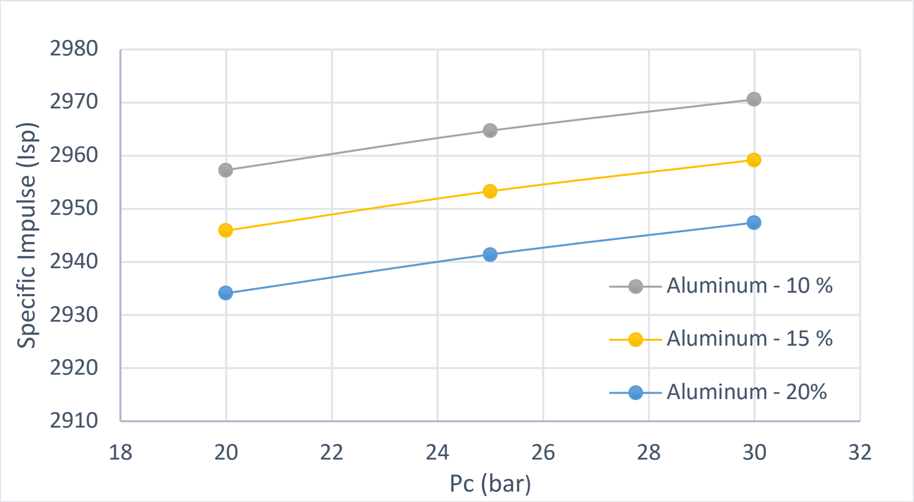


*Figure: 4 -28 Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage as fuel at various chamber pressures for 95%* H_2O_2 *at a fixed **O/F ratio 6***

For Sasol Wax 6003

Pc (Bar)		***Specific Impulse (Isp)***	
	Aluminum 10 %	Aluminum 15 %	Aluminum 20%
20	2963.0	2951.4	2939.4
25	2970.4	2958.8	2946.7
30	2976.3	2964.7	2952.7

*Table: 4-30 Specific Impulse values for **SASOL Wax 6003** with different addition of aluminum percentage as fuel at various chamber pressures for 95%* H_2O_2 *at a fixed **O/F ratio 6***

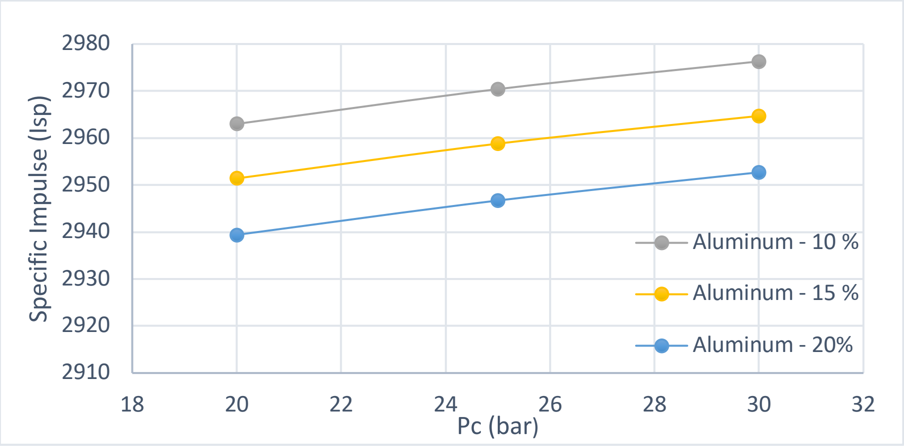


*Figure: 4 -29 Specific Impulse values for **SASOL Wax 6003** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

For Sasol Wax 6805

Pc (Bar)	Specific Impulse (Isp)		
	Aluminum 10 %	Aluminum 15 %	Aluminum 20%
20	2962.3	2950.7	2938.7
25	2969.7	2958.1	2946.1
30	2975.6	2964.0	2952.0

*Table: 4-31 Specific Impulse values for **SASOL Wax 6805** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

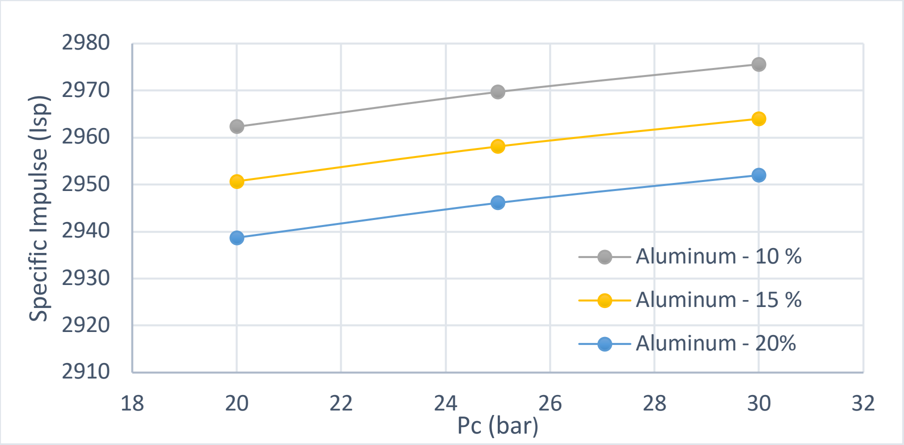


*Figure: 4 -30 Specific Impulse values for **SASOL Wax 6805** with different addition of aluminum percentage as fuel at various chamber pressures for 95% H_2O_2 at a fixed **O/F ratio 6***

Finally, when comparing the patterns of specific impulse vs. change in chamber pressure, all mixtures of different aluminum compositions have essentially the same slope (as the net ratio of aluminum to the total mixture (O/F) is fixed) in the range, and these values decrease as the aluminum content increases. Furthermore, there is a dramatic difference between the trends with the aluminum content 20 to the aluminum contents 15% and 10%. Finally, the linearly increasing trend is observed with respect to chamber pressure.

4.7.3.4 Comparison Studies

Variation with respect to O/F Ratio

O/F	*Specific Impulse (Isp)*			
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %	No Additive
2	2808.0	2854.4	2891.3	2690.8
4	3004.4	2997.6	2988.4	3015.9
6	2964.7	2953.3	2941.4	2992.7
8	2921.3	2911.2	2900.8	2946.8
10	2888.3	2879.5	2870.6	2910.5

*Table: 4-32 Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage at various O/F ratios for **different cases** at a fixed chamber pressure 25 bar*

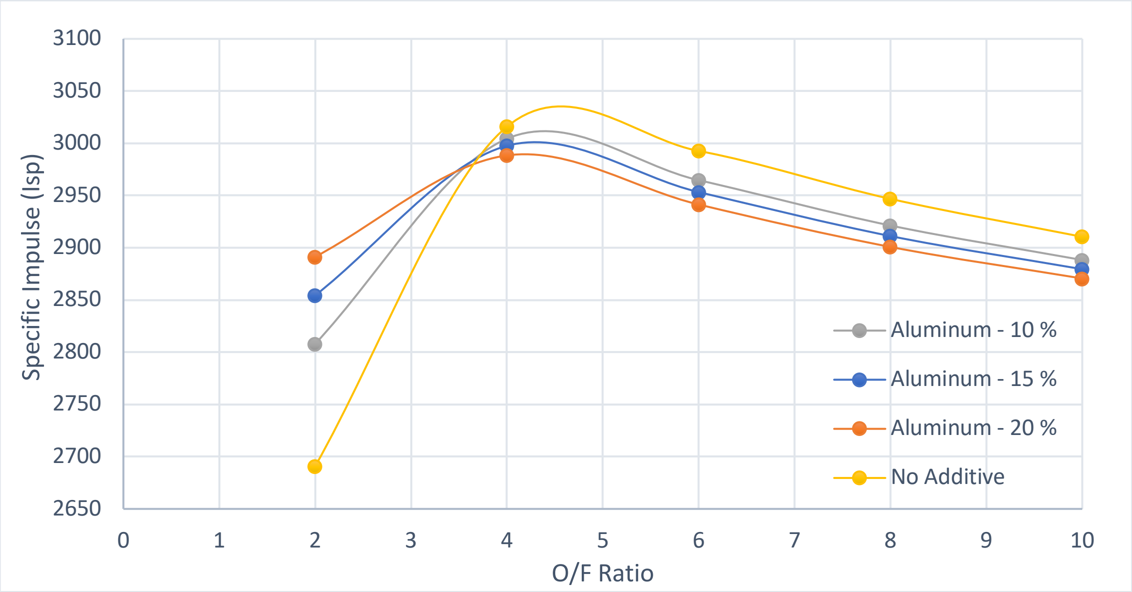


*Figure: 4 -31 Variation of Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage at various O/F ratios for **different cases** at a fixed chamber pressure 25 bar*

The above graph depicts the variation of the specific impulse to O/F ratio with respect to the change in the composition of the aluminum content in the fuel. Further, a detailed difference is illustrated between the waxes with the addition of aluminum and no additive waxes. At O/F ratio 2, there is a significant difference that can be seen as the total content of the aluminum more in the propellant.

Variation with respect to Chamber Pressure Pc

Pc (Bar)	*Specific Impulse (Isp)*			
	Aluminum 10 %	Aluminum 15 %	Aluminum 20 %	No Additive
20	2957.3	2945.9	2934.1	2985.4
25	2964.7	2953.3	2941.4	2992.7
30	2970.6	2959.2	2947.4	2998.5

*Table: 4-33 Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage at various chamber pressure for **different cases** at a fixed O/F ratio 6*

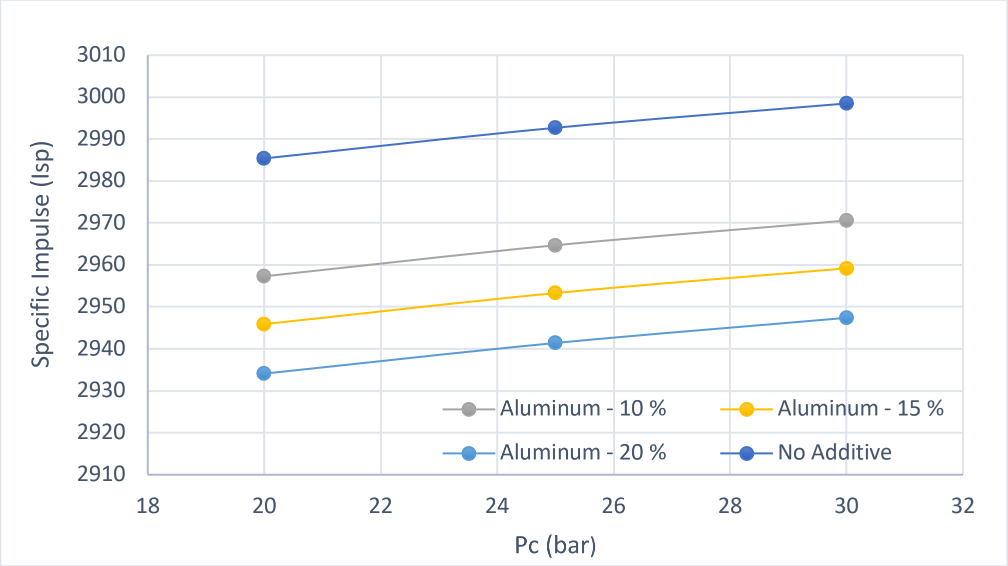


*Figure: 4 -32 Variation of Specific Impulse values for **SASOL Wax 0907** with different addition of aluminum percentage at various chamber pressure for **different cases** at a fixed O/F ratio 6*

The graphs above show how the specific impulse varies with pressure as a function of the additive's composition. To demonstrate the effect of aluminum in paraffin waxes, a clear comparison is established. Moreover, the specific impulse increased linearly with pressure because the combustion flow behaves like an ideal fluid, resulting in a specific impulse increase. Furthermore, 20% aluminum has the lowest specific impulse.

CHAPTER 5

HYDROGEN PEROXIDE IN LIQUID BI-PROPELLANT SYSTEMS

This section it is explained briefly the behavior of hydrogen peroxide in liquid bi-propellant systems. Furthermore, a detailed case study of propellant system hydrogen peroxide to ethanol, RP-1, and liquid methane has been done using CEA code and a comparison study has been performed between H_2O_2 -ethanol, H_2O_2 -liquid methane, and H_2O_2 -kerosene.

5.1. Bi-Propellant Systems

The demand for better performance properties such as higher thrust increased specific impulse, and/or increased velocity gain no longer drives the production of rocket propulsion systems. Instead, criteria, which were historically known as secondary, are becoming increasingly prominent [65,66]. These include, among other things, a free and flexible thrust variation capability, easy handling and storage characteristics, low toxicity and health hazard risks for both propellant and exhaust flow species, improved handling and use protection, environmental friendliness, reusability, and strategies for upgrading and decommissioning under the aforementioned aspects. Furthermore, mission scenarios are becoming increasingly complex, and current propulsion systems using traditional propellants are unable to meet all of the anticipated mission requirements.

The propellant is stored in tanks outside the combustion chamber in liquid-propellant systems. The majority of these engines use a liquid oxidizer and liquid fuel, both of which are pumped from their respective tanks. The pumps boost the pressure above the engine's operating pressure, and the propellants are then pumped into the engine in such a way that the propellants are atomized and combined rapidly. Liquid-propellant engines have a range of benefits over solid-fuel engines in a variety of applications.

These features include (1) higher attainable effective exhaust velocities (Ve), (2) higher mass fractions (propellant mass divided by the mass of inert components), and (3) control of operating level in flight (throttle ability), sometimes including stop-and-restart capability and emergency shutdown. The engine, fuel tanks, and vehicle structure that hold these parts in place and connect to the payload and launchpad are typical components of a liquid-rocket propulsion system (or vehicle). Since they run at low pressure, fuel and oxidizer tanks are typically made of very light materials.

Bipropellant systems, in which an oxidizer and a fuel are tanked separately and combined in the combustion chamber, are used in the majority of liquid-propellant rockets. Low molecular mass and high temperature of reaction products (for high exhaust velocity), high density (to reduce tank weight), low danger factor (e.g., corrosivity and toxicity), low environmental effect, and low cost are all attractive properties for propellant combinations. Trade-offs are used to make decisions based on the applications.

5.2. Properties of Ethanol, Liquid Methane, and Kerosene

The fact that liquid fuels are easy to transport and handle is one of their most common characteristics. Liquid fuels' physical properties differ with temperature, but not as much as gaseous fuels. The flashpoint is the lowest temperature at which a flammable concentration of vapor is produced; the fire point is the lowest temperature at which a continuous burning of vapor occurs; the cloud point for diesel fuels is the lowest temperature at which dissolved waxy compounds begin to coalesce, and the pour point is the lowest temperature at which the fuel is too thick to pour freely. These characteristics have an effect on the fuel's safety and handling.

The use of hydrogen peroxide as an oxidizer and kerosene as a fuel for a bi-propellant rocket engine dates back to the 1940s when considerable research was conducted on the subject, particularly in the United Kingdom. The following engines were notable among those created [7]:

- DeHavilland Super Sprite, rocket-assisted takeoff pack
- Saunders-Roe Spectre, rocket power system for the SR-53 interceptor aircraft
- Napiers Scorpion, rocket propulsion of the RAF Lightning interceptor aircraft
- Bristol Siddeley Gamma 2 / Gamma 201, launch vehicle engine for Black Knight and Black Arrow
- Rolls Royce Gamma 301 / Stentor, Blue Steel nuclear stand-off bomb propulsion unit
- KP series of engines, for tactical missiles
- Beta Mk I and Mk II development engines at R.O. Westcott

In addition to the United Kingdom, the United States was interested in hydrogen peroxide/kerosene engines in the late 1950s, and this culminated with the AR series of engines produced by Rocketdyne for the United States Air Force. The AR2-3 engine with 6,0001bf (26,700N) thrust was the culmination of the effort, and it was used to good effect in the NF-104, the rocket-powered Lockheed F-104 Starfighter. When Reaction Motors Inc developed the AR2-3 for the US Navy, it was renamed the LR-40 [7].

To feed the propellants into the chamber, the vast majority of the hydrogen peroxide/kerosene rocket engines used a turbopump. The KP series of rocket engines appear to be the sole exception to the rule. A pump-fed system was used even in the relatively simple Super Sprite, which was designed as a RATO unit. The HTP and kerosene were injected directly into the KP-1 engine, which used a hypergolic slug to ignite the propellants. The KP-3 3,000 lbf (13,345 N) engine was the first in the series to use thermal ignition and silver-coated screens, but due to long ignition delays, 83% HTP was chosen over the initial baseline of 80% HTTP. This engine was later used as the sustainer propulsion system on the Red Shoes ground-to-air missile [67].

Petroleum-based fuels include various types of alcohol, such as ethyl alcohol or ethanol, gasoline, and kerosene, as well as especially refined kerosene fuels like jet fuel and Rocket Propellant (RP)-1 and RP-2 [68]. Although non-hypergolic, the fuels and their vapors are highly flammable [69, 70, 71]. They are non-corrosive [70, 72, 73], normally chemically stable (not self-reacting), and can be stored at room temperature with no special precautions other than good ventilation [69, 70, 71]. However, if not properly ventilated, the combustion products of these fuels (for example, CO2) can reach dangerous levels, "causing unconsciousness, suffocation, and death" [69].

Strong acids, e.g., Nitric acids, and other oxidizing chemicals should be avoided [69, 70, 71]; contact with ethanol will cause violent reactions and possibly explosions and for the remaining fuels, incompatibility is suspected [74] [75, 76, 77]. Regarding health hazards and toxicity, the fuels are confirmed to be carcinogenic for animals but whether they are for humans is unknown. Skin contact causes mild to moderate irritation for all fuel types and eye exposure causes mild irritation with kerosene, moderate with gasoline, and serious with ethanol and jet fuel. With the kerosene-type fuels and gasoline, inhalation of fuel vapors causes moderate irritation of the respiratory system and with ethanol, it has intoxicating effects.

Mild to moderate dizziness might also occur. Prolonged exposure to ethanol and gasoline can cause more severe damage, such as skin inflammation and organ damage [69, 70, 71, 78]. Sourced from natural gas, Liquid Methane (CH4) is a relatively common hydrocarbon fuel. Compared to petroleum-derived fuels, liquid CH4 is the most hazardous in terms of flammability and health according to the National Fire Protection Association (NFPA) [79, 74, 75, 76].

It is extremely flammable and will explode if mixed with strong oxidizers, however chemically it is normally stable [79]. Other incompatible chemicals are fluorinated and halogenated compounds [80]. It is non-corrosive to most common plastics and metals, including stainless and carbon steel, brass, copper and aluminum alloys [81, 82].

The fuel is cryogenic [68], entailing more complicated storage than for other hydrocarbon fuels. Also, direct skin contact with the fuel can cause frostbite and eye exposure can result in blindness. Vapour inhalation is not considered to be toxic however inhaling large quantities is asphyxiating. Skin or eye contact with the vapours is harmless. CH4 does not cause cancer in humans [80, 81].

5.3. Stoichiometric Mixture Ratio Calculation

Oxidation with liquid hydrogen peroxide (H_2O_2)

Ethanol

$$C_2H_5OH + 6\ H_2O_2 \rightarrow 2\ CO_2 + 9\ H_2O$$

The molecular weight of 1 carbon atom = 12 amu

The molecular weight of 1 hydrogen atom = 1 amu

The molecular weight of 1 oxygen atom = 16 amu

Therefore, molecular weight of C_2H_5OH = 2*12 + 5*1 + 1*16 + 1*1 = 46 amu

Molecular weight of H_2O_2 = 2*1 + 16*2 = 34 amu

Stoichiometric O/F ratio of Ethanol = $\frac{6*34}{46} = 4.434$

RP-1

$$C_{12}H_{24} + 36\ H_2O_2 \rightarrow 12\ CO_2 + 48\ H_2O$$

Therefore, molecular weight of $C_{12}H_{24}$ = 12*12 + 24*1 = 168 amu

Molecular weight of H_2O_2 = 2*1 + 16*2 = 34 amu

Stoichiometric O/F ratio of RP-1 = $\frac{(36*34)}{168} = 7.285$

Liquid Methane

$$CH_4 + 4\ H_2O_2 \rightarrow CO_2 + 6\ H_2O$$

Therefore, molecular weight of CH_4 = 1*12 + 4*1 = 16 amu

Molecular weight of H_2O_2 = 2*1 + 16*2 = 34 amu

Stoichiometric O/F ratio of Liquid Methane = $\frac{(4*34)}{16} = 8.5$

5.4. CEA Analysis

CEA analysis has been performed using ethanol as the fuel and 1) Hydrogen peroxide liquid, and 2) 10% H_2O and 90% H_2O_2 as the oxidizers for hybrid rocket analysis. Here below the conditions given for the analysis have been tabulated.

Condition	***Unit***	***Value***
Low pressure	bar	20
High pressure	bar	30
Pressure Interval	bar	5
O/F ratio	N/A	2, 4, 6, 8, 10
The temperature of the fuel	K	298.16
Chamber Pressure/Exit pressure (Pc/Pe)	N/A	30

Table: 5-1 Parameters considered for CEA Analysis

Propellant	***Chemical Formula***
Fuel 1. *Ethanol* 2. *RP-1 (Kerosene)* 3. *Liquid Methane*	 C_2H_5OH $C_{12}H_{24}$ CH_4
Oxidizer 1. *Hydrogen Peroxide (liquid)* 2. *10% H_2O and 90% H_2O_2*	 H_2O_2

Table: 5-2 Chemical formulae used for the propellants

5.5. Case Study: Hydrogen Peroxide - Ethanol

5.5.1. Combustion Temperature

5.5.1.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with ethanol as a fuel. Firstly, the initial conditions are taken as per the previous section. The chamber pressure varying from 20 bar to 30 bar and the oxidizer varying from 2 to 10. Moreover, pure hydrogen is analyzed in this section and the plots were extracted.

CASE A- Ethanol with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	*Combustion Temperature Tc (K)*
2	2743.62
4	3031.81
6	2856.18
8	2650.23
10	2473.17

*Table: 5-3 Combustion Temperature values for **Ethanol** at various O/F ratios at a fixed chamber pressure 25 bar*

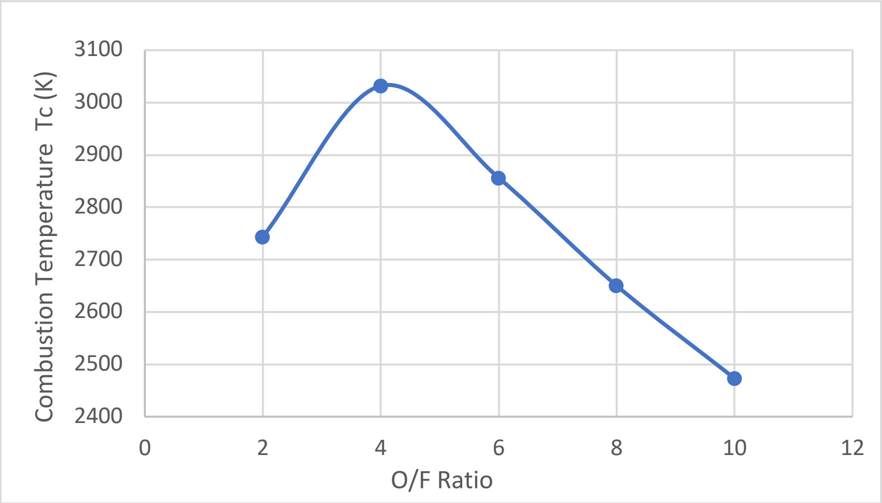


*Figure: 5-1 Variation of Combustion Temperature values for **Ethanol** at various O/F ratios at a fixed chamber pressure 25 bar*

The above graph illustrates the effect of the oxidizer fuel ratio on the combustion chamber temperature. It is noticeable that there is a significant increase in the combustion chamber initially up to 4 and started decreasing dramatically till O/F 10. Furthermore, it is observed that the highest temperature is attained at the stoichiometric ratio 4.

A.2) Variation with respect to Chamber Pressure Pc

Pc (Bar)	*Combustion Temperature Tc (K)*
20	2842.68
25	2856.18
30	2866.99

*Table: 5-4 Combustion Temperature values for **Ethanol** at various chamber pressures at a fixed O/F ratio 6*

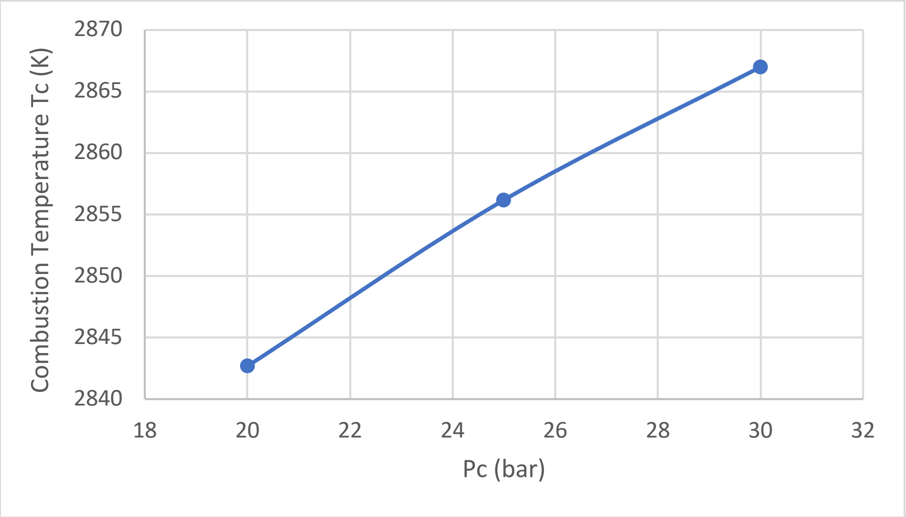


*Figure: 5-2 Variation of Combustion Temperature values for **Ethanol** at various chamber pressures at a fixed O/F ratio 6*

As the chamber pressure is raised, the combustion temperature increases as well, as seen in Table and Figure 5-2. This happens since, at such high temperatures, the combustion products behave like an ideal fluid, and it is a characteristic function of an ideal gas to see an increase in temperature with an increase in pressure. The slope observed initially till 25 bar is 2.7 and further decreased to 2.18 till 30 bars.

5.5.1.2 Addition of H_2O to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for ethanol with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	*Combustion Temperature Tc (K)*
2	2794.04
4	3100.7
6	3001.43
8	2866.61
10	2745.54

Table: 5-5 Combustion Temperature values for ***Ethanol*** *at various O/F ratios for 90% H_2O_2 at a fixed chamber pressure 25 bar*

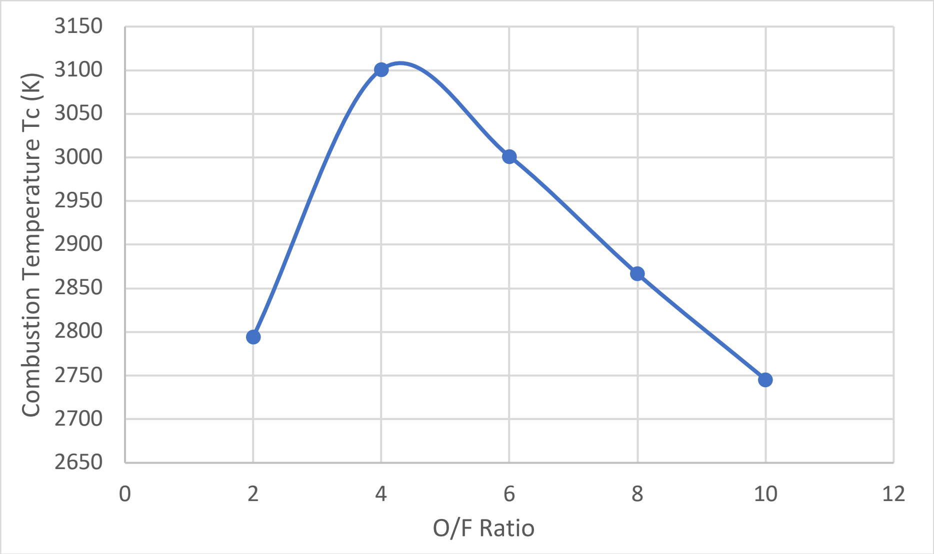


Figure: 5-3 Variation of Combustion Temperature values for ***Ethanol*** *at various O/F ratios for 90% H_2O_2 at a fixed chamber pressure 25 bar*

The effect of the oxidizer fuel ratio on the combustion chamber temperature with a 90% concentration of hydrogen peroxide is depicted in the graph above. It is clear that the combustion chamber increased significantly up to 4 and then began to decrease sharply till O/F 10. Furthermore, the peak temperature of 3100.7°C is achieved when the oxidizer fuel ratio is 4. On the other hand, it is achieved 3031°C of combustion temperature with hydrogen peroxide as the pure oxidizer fuel ratio.

5.5.2. Specific Impulse

5.5.2.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with ethanol. Further analysis has been done on the effect of the oxidizer to fuel ratio on the specific impulse.

CASE A- Ethanol with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***
2	2574.5
4	2602.7
6	2446.2
8	2306
10	2200.1

Table: 5-6 Specific Impulse values for ***Ethanol*** *at various O/F ratios at a fixed chamber pressure 25 bar*

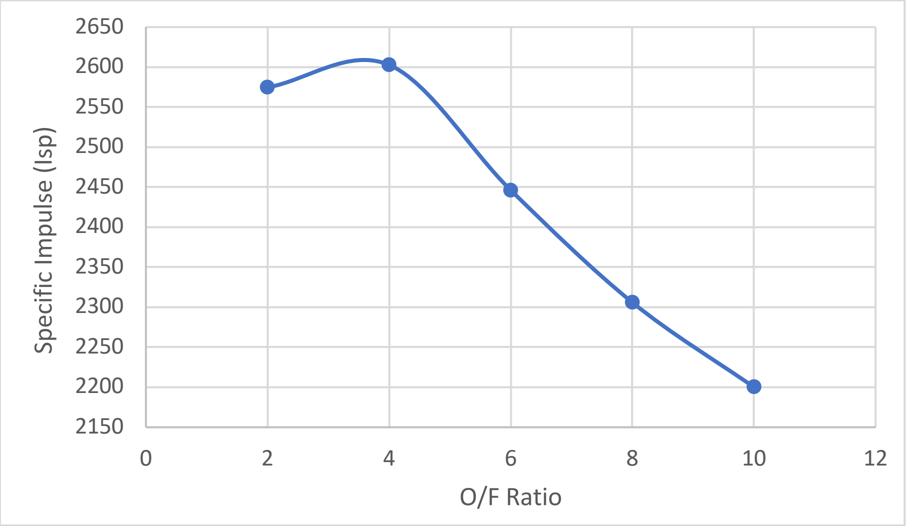


Figure: 5-4 Variation of Specific Impulse values for ***Ethanol*** *at various O/F ratios at a fixed chamber pressure 25 bar*

The above graphs depict the trend of the specific impulse with respect to the variation of the oxidation to fuel ratio. It is seen that at O/F 2 there is increasing in the trend till 4 and followed by a decreasing trend till 10. Further, having the highest specific impulse 2602.7 at the O/F ratio of 4.

A.2) Variation with respect to Chamber Pressure Pc

Pc (Bar)	*Specific Impulse (Isp)*
20	2444.4
25	2446.2
30	2447.6

Table: 5-7 Specific Impulse values for ***Ethanol*** *at various chamber pressures at a fixed O/F ratio 6*

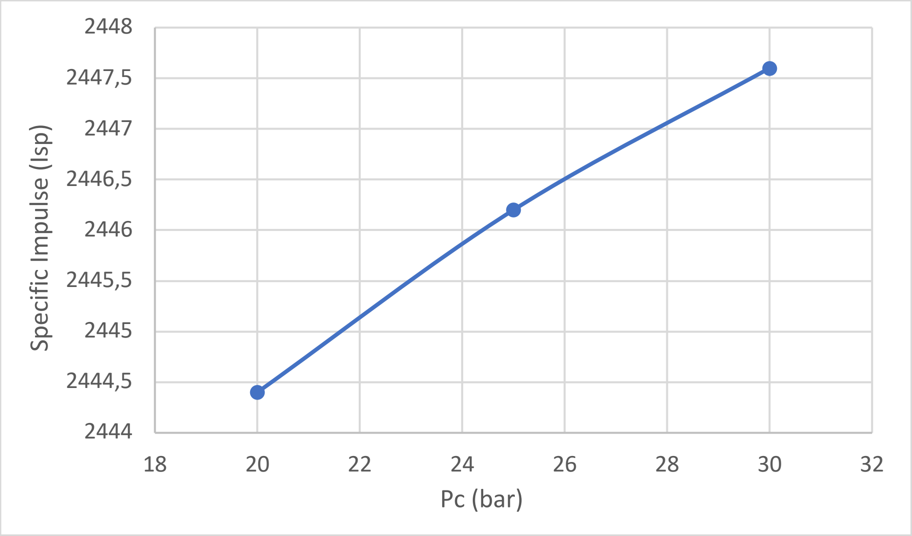


Figure: 5-5 Variation of Specific Impulse values for ***Ethanol*** *at various chamber pressures at a fixed O/F ratio 6*

The specific impulse rises as the chamber pressure rises, as seen in Table and Figure 5-5. This is because the combustion products behave like an ideal fluid at such high temperatures as discussed in the above section. Thus, the specific impulse increases with increasing the pressure.

5.5.2.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for ethanol with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	*Specific Impulse (Isp)*
2	2640.3
4	2683.6
6	2579.3
8	2472.8
10	2389.3

*Table: 5-8 Specific Impulse values for **Ethanol** at various O/F ratios for 90% H_2O_2 at a fixed chamber pressure 25 bar*

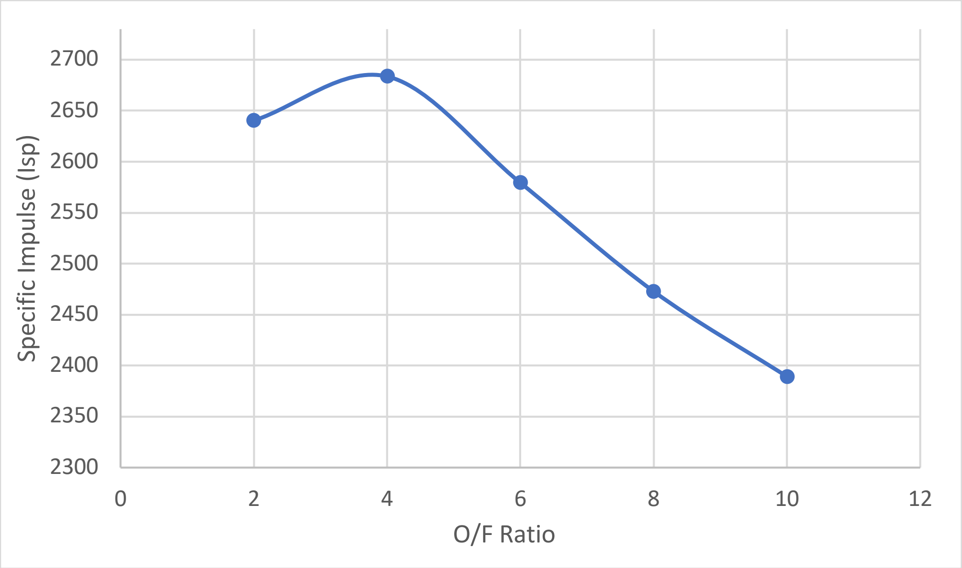


*Figure: 5-6 Variation of Specific Impulse values for **Ethanol** at various O/F ratios for 90% H_2O_2 at a fixed chamber pressure 25 bar*

The above graph illustrates the variation of oxidation and fuel ratio on the specific impulse for 90 percent concentration of hydrogen peroxide at 25 bar combustion chamber pressure. It can be observed that initially there is a significant increase in the specific impulse till 4 and later decreased dramatically. Further highest specific impulse 2683.6 is observed at the stoichiometric ratio.

5.6. Case Study: Hydrogen Peroxide – RP-1

In the 1950s, hydrogen peroxide was used as an oxidizer of kerosene in British rockets. It represented a comparatively high-density propellant mixture when combined with kerosene. It was non-toxic, unlike other storable propellant combinations. However, since hydrogen peroxide can react with trace elements, it must be stored and handled with caution. With the cancellation of the British space projects at the end of the 1960s, it was discontinued. It was resurrected in the 1990s as a proposed propellant for the black horse spaceplane and later other USAF proposed spaceplanes [5].

The propellant formulation is h_2o_2-98 percent /RP-1, and the optimal oxidizer to fuel ratio is 7.07. The combustion temperature is 2,975 degrees Celsius. Relevant heat ratio: 1.2; density: 1.31 g/cc and the signature velocity c is 1,665 meters per second (5,462 feet per second). Propeller formulation: h_2o_2-95 percent /RP-1. optimum oxidizer to fuel ratio: 7.35. combustion, which gives the temperature 2,915 degrees Celsius and density 1.30 g/cc. Further, the oxidizer boiling point 150 deg c and the Fuel freezing point is -73 degrees C [6].

5.6.1. Combustion Temperature

5.6.1.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the RP-1.

CASE A- RP-1 with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	*Combustion Temperature Tc (K)*
2	1336.31
4	2541.57
6	2915.51
8	2865.17
10	2725.53

*Table: 5-9 Combustion Temperature values for **RP-1** at various O/F ratios at a fixed chamber pressure 25 bar*

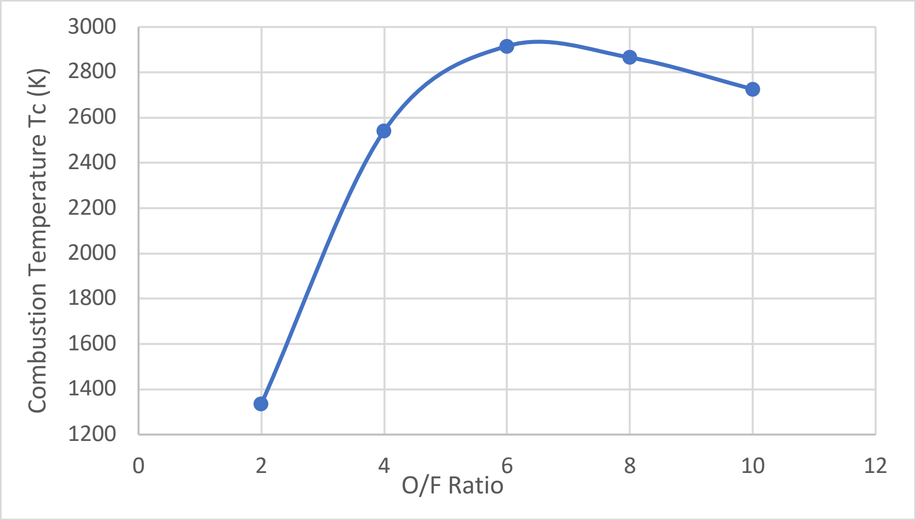


Figure: 5-7 Variation of Combustion Temperature values for ***RP-1*** *at various O/F ratios at a fixed chamber pressure 25 bar*

The combustion temperature Tc rises dramatically with rising the O/F ratio, peaking at 2915.03 K at O/F ratio 6 and then declining marginally after that, as seen in Figure 5-7. As a result, the ultimate combustion temperature can be said to occur near stoichiometric conditions.

Since adding more fuel than the stoichiometric ratio allows the creation of partially oxidized products like CO, which emit less energy than the products of full combustion, the overall combustion temperature does not rise to the left of the peak, even if the fuel content is raised.

A.2) Variation with respect to Chamber Pressure Pc

Further, this section investigates the effect of the combustion chamber pressure on the chamber temperature for the RP -1 /H_2O_2. Moreover, pure hydrogen peroxide is used as the oxidizer at the same initial conditions. Results were in Table 5-10 and graphs were extracted.

Pc (Bar)	***Combustion Temperature Tc (K)***
20	2900.98
25	2915.51
30	2927.11

Table: 5-10 Combustion Temperature values for ***RP-1*** *at various chamber pressures at a fixed O/F ratio 6*

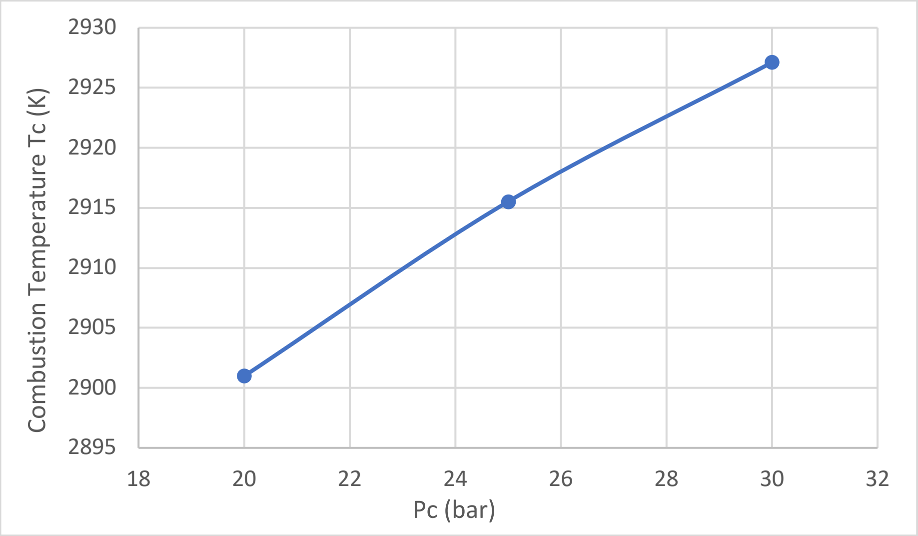


*Figure: 5-8 Variation of Combustion Temperature values for **RP-1** at various chamber pressures at a fixed O/F ratio 6*

The above graph demonstrates the variation of the combustion chamber pressure on the chamber temperature at oxidizer fuel ratio 6. As discussed for the above case ethanol, the combustion particle act as an ideal flow and followed the same linearly increasing trend. Further, the slope decreases significantly as the combustion chamber pressure increases.

5.6.1.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for RP-1 with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	***Combustion Temperature Tc (K)***
2	1417.32
4	2616.52
6	2980.69
8	2989.83
10	2911.71

*Table: 5-11 Combustion Temperature values for **RP-1** at various O/F ratios for 90% H_2O_2 at a fixed chamber pressure 25 bar*

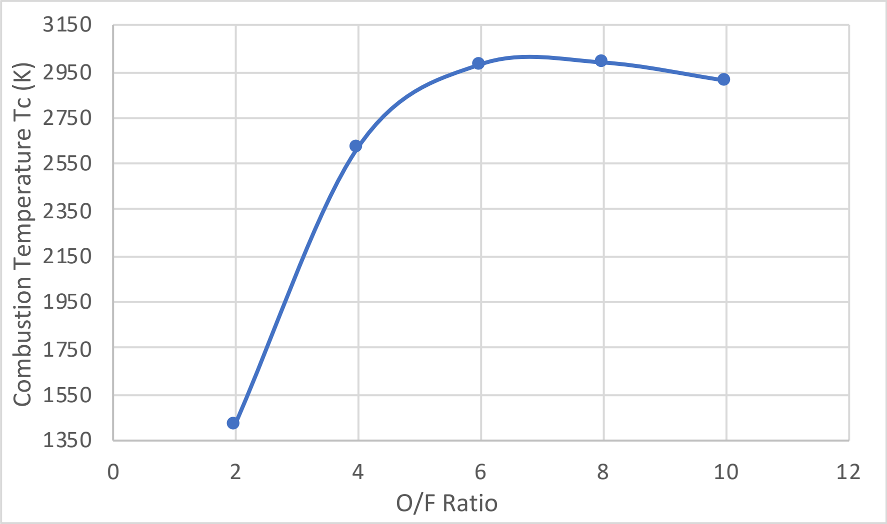


*Figure: 5-9 Variation of Combustion Temperature values for **RP-1** at various O/F ratios for 90% H_2O_2 at a fixed chamber pressure 25 bar*

The graph above shows the effect of the oxidizer fuel ratio on the combustion chamber temperature at 90% concentration with RP-1. The combustion chamber relatively increased until it reached 6 and then started to decrease dramatically until O/F 10. Furthermore, when the oxidizer fuel ratio is 6, the peak temperature of 2980.6°C is reached. On the other hand, using hydrogen peroxide as the pure oxidizer fuel ratio, a combustion temperature of 2915.51°C was reached.

5.6.2. Specific Impulse

5.6.2.1 Hydrogen peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the RP-1.

CASE A- RP-1 with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***
2	1963.1
4	2380.7
6	2492.5
8	2445.4
10	2340

*Table: 5-12 Specific Impulse values for **RP-1** at various O/F ratios at a fixed chamber pressure 25 bar*

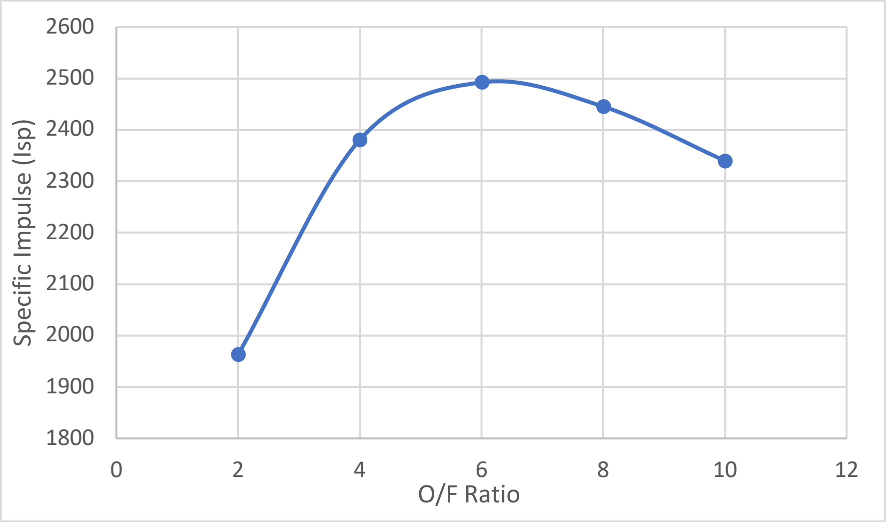


Figure: 5-10 Variation of Specific Impulse values for ***RP-1*** *at various O/F ratios at a fixed chamber pressure 25 bar*

The graphs above demonstrate the pattern of the specific impulse in response to changes in the oxidation to fuel ratio. It can be seen that the trend increases at O/F 2 until 6, then decreases until it reaches 10. Furthermore, with the maximum specific impulse of 2492.5 at an O/F ratio of 4, it has the highest specific impulse.

A.2) Variation with respect to Chamber Pressure Pc

Pc (Bar)	*Specific Impulse (Isp)*
20	2491.8
25	2492.5
30	2493.7

Table: 5-13 Specific Impulse values for ***RP-1*** *at various chamber pressures at a fixed O/F ratio 6*

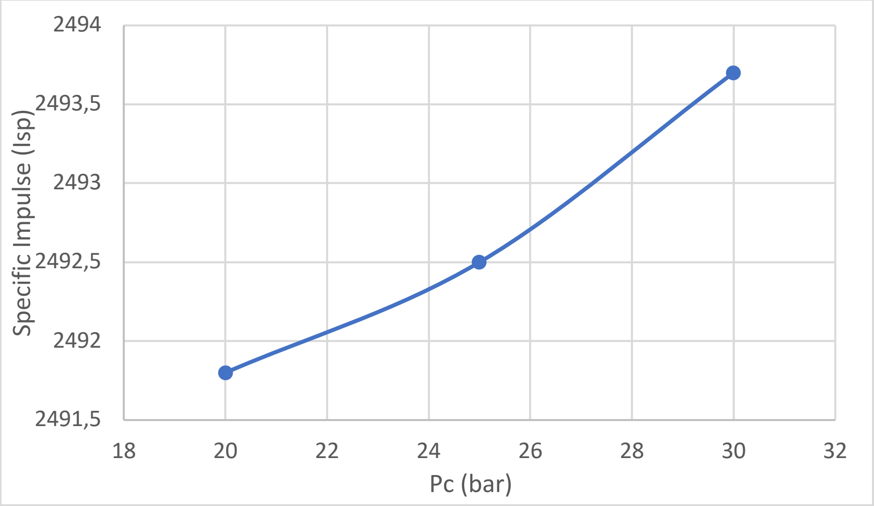


Figure: 5-11 Variation of Specific Impulse values for ***RP-1*** *at various chamber pressures at a fixed O/F ratio 6*

The above graph illustrates the variation of the specific impulse (Isp) to change in the combustion chamber pressure for RP-1 at oxidizer to fuel ratio 6. Firstly, the specific impulse rises as the chamber pressure rises, as seen in Table and Figure 5-10. This is because the combustion products behave like an ideal fluid at such high temperatures as discussed in the above section. Thus, the specific impulse increases with increasing the pressure.

5.6.2.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for RP-1 with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	*Specific Impulse (Isp)*
2	2032.2
4	2464.4
6	2576.4
8	2569.2
10	2497.9

*Table: 5-14 Specific Impulse values for **RP-1** for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar*

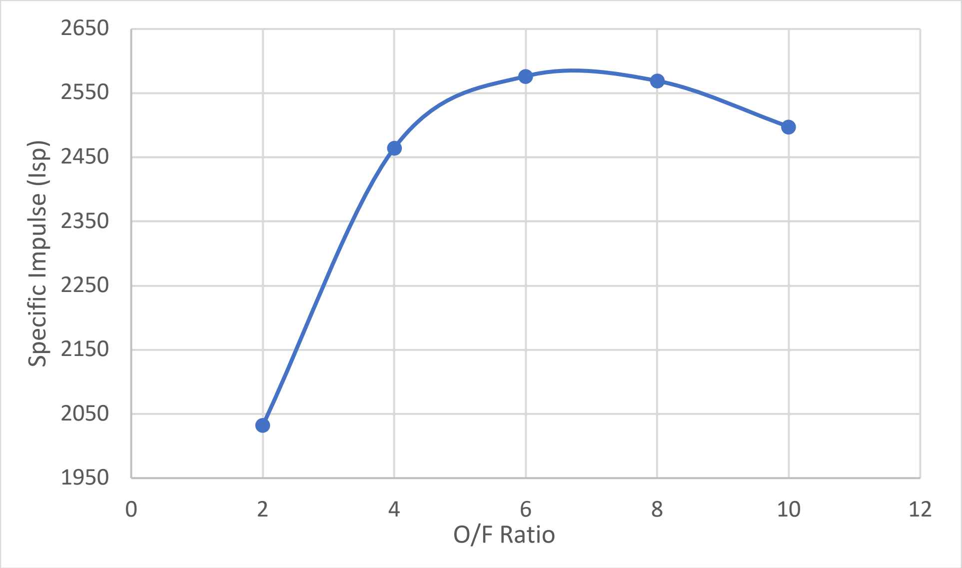


*Figure: 5-12 Variation of Specific Impulse values for **RP-1** for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar*

The graph above shows the effect of oxidation and fuel ratio on specific impulse for a 90 percent hydrogen peroxide concentration at 25 bar combustion chamber pressure. It can be shown that the specific impulse initially increased substantially before 6 and then gradually decreased. At the stoichiometric ratio, the maximum specific impulse of 2683.6 is observed.

5.7. Case Study: Hydrogen Peroxide – Liquid Methane

5.7.1. Combustion Temperature

5.7.1.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the liquid methane.

CASE A- Liquid Methane with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	***Combustion Temperature Tc (K)***
2	1153.62
4	2117.3
6	2694.87
8	2850.28
10	2764.48

*Table: 5-15 Combustion Temperature values for **Liquid Methane** at various O/F ratios at a fixed chamber pressure 25 bar*

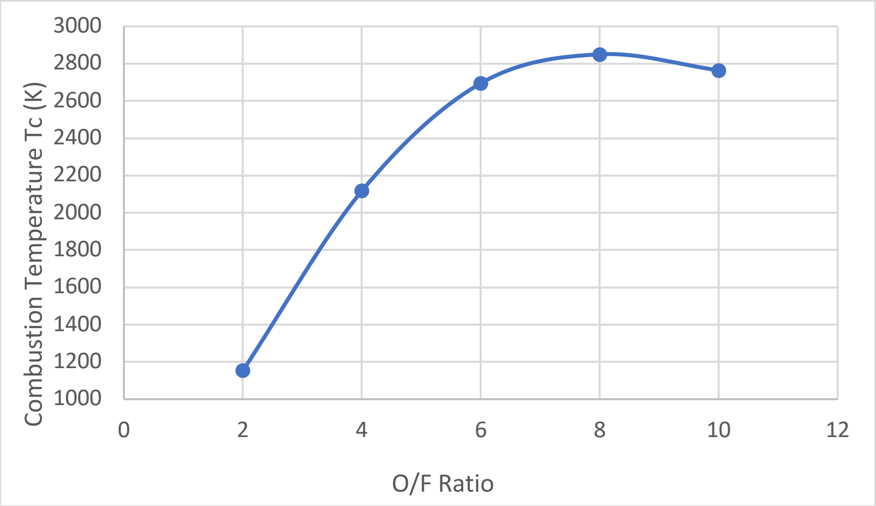


*Figure: 5-13 Variation of Combustion Temperature values for **Liquid Methane** at various O/F ratios at a fixed chamber pressure 25 bar*

As the O/F ratio increases, the combustion temperature Tc rises dramatically, peaking at 2850.25 K at O/F ratio 8 and then decreasing slightly after that, as seen in Figure 5-13. As a result, the final combustion temperature is said to be equivalent to stoichiometric.

And if the fuel volume increased, the average combustion temperature does not climb to the left of the peak so adding more fuel than the stoichiometric ratio enables the production of partly oxidized products like CO, which release less energy than the products of full combustion.

A.2) Variation with respect to Chamber Pressure Pc

In addition, for the Liquid Methane /H_2O_2, this segment evaluates the effect of combustion chamber pressure on chamber temperature at an oxidizer fuel ratio 6. Furthermore, at the same initial conditions, pure hydrogen peroxide is used as the oxidizer. Tables 5-16 contained the results, and graphs were extracted.

Pc (Bar)	***Combustion Temperature Tc (K)***
20	2689.34
25	2694.87
30	2699.08

*Table: 5-16 Combustion Temperature values for **Liquid Methane** at various chamber pressures at a fixed O/F ratio 6*

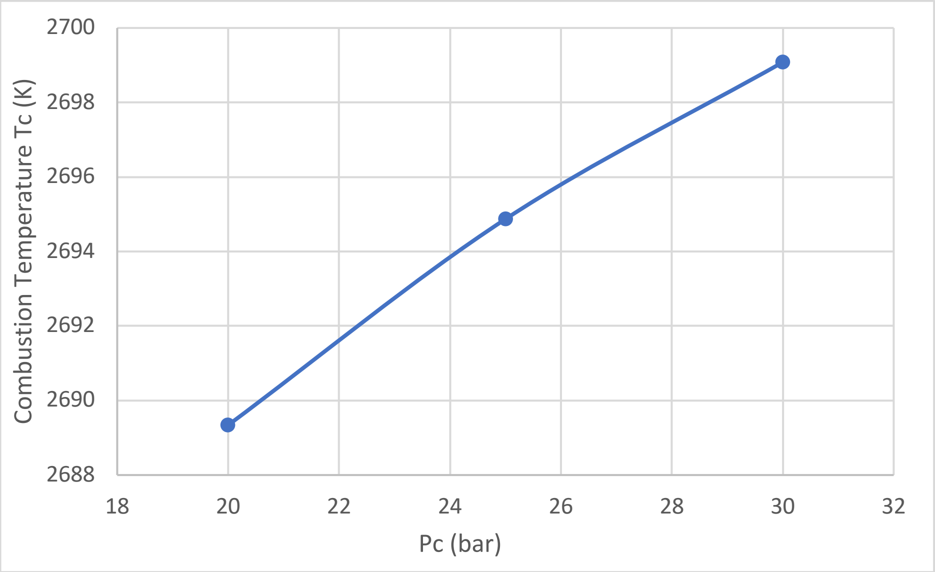


*Figure: 5-14 Variation of Combustion Temperature values for **Liquid Methane** at various chamber pressures at a fixed O/F ratio 6*

At oxidizer fuel ratio 6, the above graph shows the effect of combustion chamber pressure on chamber temperature. The combustion particle acted as an ideal flow as in the previous cases and followed the same linearly rising pattern. Furthermore, as the combustion chamber pressure rises, the slope gradually decreases.

5.7.1.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for liquid methane with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	***Combustion Temperature Tc (K)***
2	1181.89
4	2204.81
6	2759.98
8	2939.36
10	2919.88

*Table: 5-17 Combustion Temperature values for **Liquid Methane** for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar*

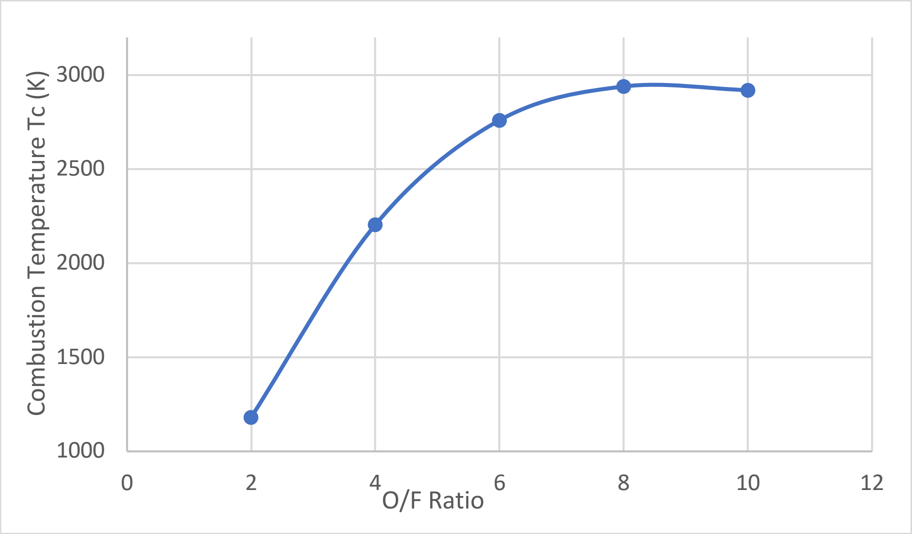


*Figure: 5-15 Variation of Combustion Temperature values for **Liquid Methane** for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar*

The graph above depicts the effect of the oxidizer fuel ratio on the temperature of the combustion chamber by using 90 percent hydrogen peroxide with methane. The combustion chamber increased until it reached 8 and hit a plateau after that. Furthermore, when the oxidizer fuel ratio is 8, the temperature reaches a limit of 2939.36°C. Using hydrogen peroxide as the pure oxidizer fuel ratio, on the other hand, a combustion temperature of 2850.25°C was achieved.

5.7.2. Specific Impulse

5.7.2.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the liquid methane.

CASE A- Liquid Methane with pure hydrogen peroxide as oxidizer

A.1) Variation with respect to O/F ratio

O/F	*Specific Impulse (Isp)*
2	1969.3
4	2327.4
6	2488.1
8	2528.5
10	2438.7

Table: 5-18 Specific Impulse values for ***Liquid Methane*** *at various O/F ratios at a fixed chamber pressure 25 bar*

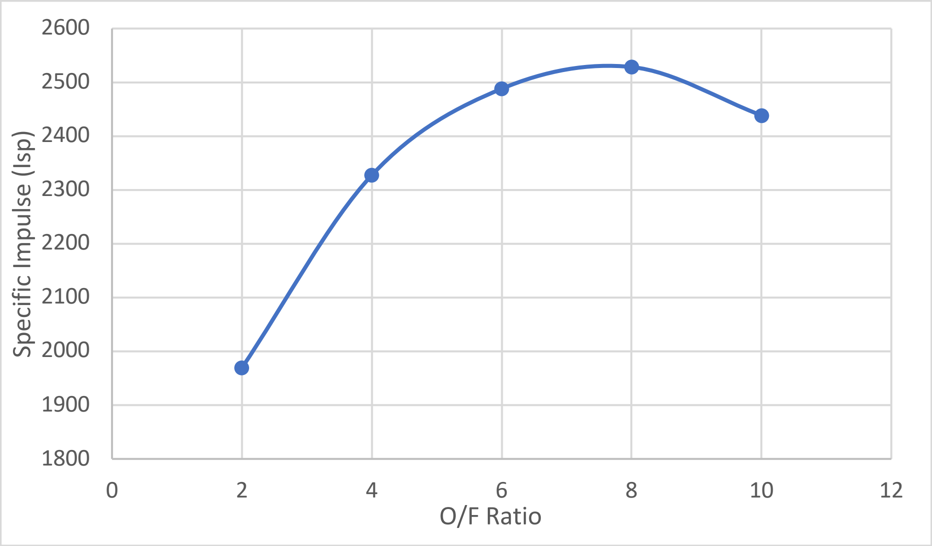


Figure: 5-16 Variation of Specific Impulse values for ***Liquid Methane*** *at various O/F ratios at a fixed chamber pressure 25 bar*

The above graphs depict the trend of the specific impulse with respect to the variation of the oxidation to fuel ratio. It is seen that at O/F 2 there is a steady increase in the trend till 8 and followed by a decreasing trend till 10. Further, having the highest specific impulse 2528.5 at the O/F ratio of 4.

A.2) Variation with respect to Chamber Pressure Pc

Pc (Bar)	*Specific Impulse (Isp)*
20	2487.7
25	2488.1
30	2488.3

*Table: 5-19 Specific Impulse values for **Liquid Methane** at various chamber pressures at a fixed O/F ratio 6*

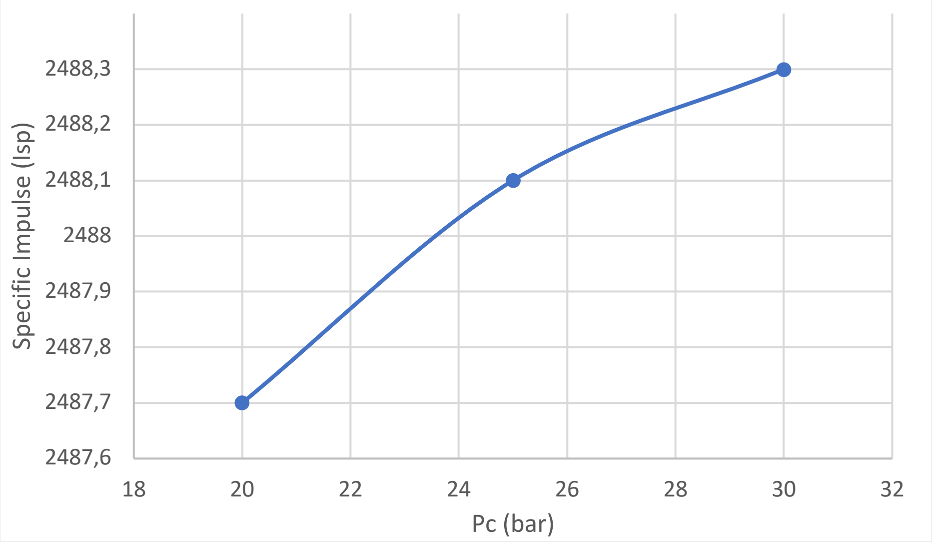


*Figure: 5-17 Variation of Specific Impulse values for **Liquid Methane** at various chamber pressures at a fixed O/F ratio 6*

The graph above shows the variation of specific impulse (Isp) changes in relation to rising in combustion chamber pressure for methane at oxidizer to fuel ratio 6. First, as seen in Table and Figure 5-17, the specific impulse increases as the chamber pressure increases. This is since, at such high temperatures, the combustion products behave like ideal fluid, as described in the previous section. As a result, as the chamber pressure rises, the specific impulse rises as well.

5.7.2.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for liquid methane with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***
2	2030.8
4	2414.2
6	2572.9
8	2618.7
10	2582.9

Table: 5-20 Specific Impulse values for ***Liquid Methane*** *for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar*

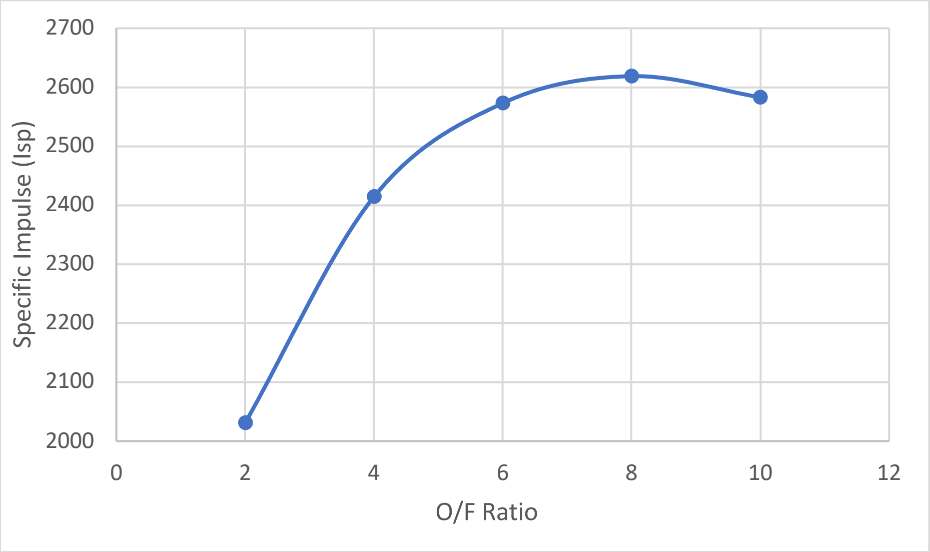


Figure: 5-18 Variation of Specific Impulse values for ***Liquid Methane*** *for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar*

The graph above evaluated the dependence of oxidation and fuel ratio on real impulse for a 90% hydrogen peroxide concentration at 25 bar combustion chamber pressure. The specific impulse initially increased significantly until 8 and then decreased slightly. At the stoichiometric ratio, the maximum real impulse is found to be 2618.7.

5.8. COMPARISON STUDIES

5.8.1. Combustion Temperature

5.8.1.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the Ethanol, RP-1, Liquid Methane.

CASE A- With pure hydrogen peroxide as oxidizer

Variation concerning O/F ratio

O/F	***Combustion Temperature Tc (K)***		
	Ethanol	RP-1	Methane(L)
2	2743.62	1336.31	1153.62
4	3031.81	2541.57	2117.3
6	2856.18	2915.51	2694.87
8	2650.23	2865.17	2850.28
10	2473.17	2725.53	2764.48

Table: 5-21 Combustion Temperature values for three fuels at various O/F ratios at a fixed chamber pressure of 25 bar

The below graph depicts the effect of oxidizer to fuel ratio on the combustion chamber temperature for three different fuels (Ethanol, RP-1, Methane(L)) with pure hydrogen peroxide as the oxidizer fuel ratio at a fixed chamber pressure of 25 bars. Firstly, it is observed that the combustion temperature increased significantly till the stoichiometric ratio and then decreased substantially for the Ethanol and steadily for the other two fuels. Secondly, three fuels exhibited high temperatures at different oxidizer fuel ratios. Such as 4,6,8 oxidizer fuel ratios for Ethanol, RP-1, Methane(L) respectively. Interestingly, RP-1 and Methane (L) have lower temperatures at the fuel-rich mixtures when comparing with Ethanol. Furthermore, the highest temperature 3031.81 is achieved for hydrogen peroxide as an oxidizer with Ethanol at oxidizer fuel ratio 4.

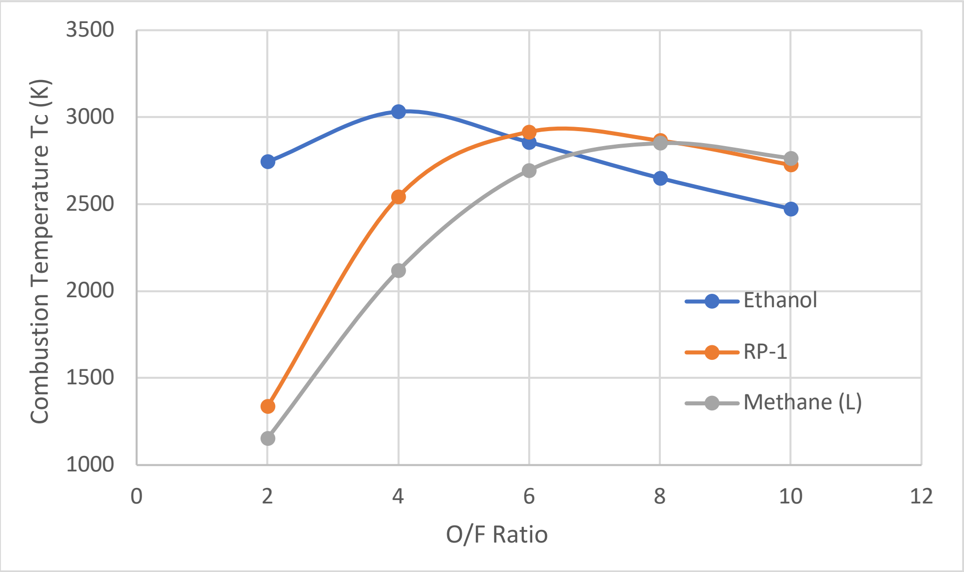


Figure: 5-19 Variation of Combustion Temperature values for three fuels at various O/F ratios at a fixed chamber pressure 25 bar

5.8.1.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for Ethanol, RP-1, Liquid Methane with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation concerning O/F ratio

O/F	***Combustion Temperature Tc (K)***		
	Ethanol	RP-1	Methane (L)
2	2794.04	1417.32	1181.89
4	3100.7	2616.52	2204.81
6	3001.43	2980.69	2759.98
8	2866.61	2989.83	2939.36
10	2745.54	2911.71	2919.88

Table: 5-22 Combustion Temperature values for three fuels for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar

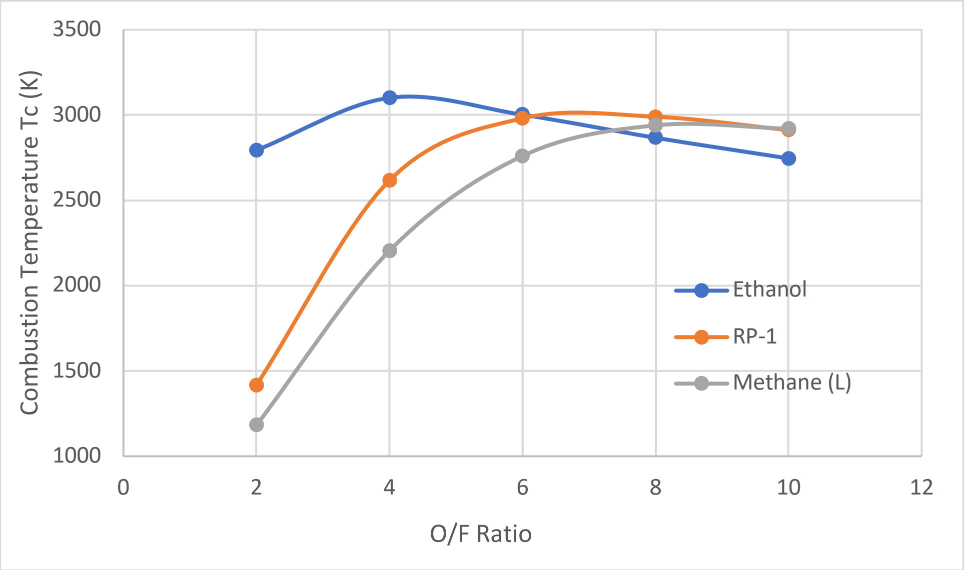


Figure: 5-20 Variation of Combustion Temperature values for three fuels for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar

At 90% concentration of hydrogen peroxide as the oxidizer, the effect of oxidizer to fuel ratio on combustion chamber temperature for three different fuels (Ethanol, RP-1, Methane(L)) at a fixed chamber pressure 25 bar is shown in the graph above. To begin, the combustion temperature increased significantly until the stoichiometric ratio was reached, after which it decreased significantly for ethanol and steadily for the other two fuels, which is similar to the pure hydrogen peroxide case. Second, at different oxidizer fuel ratios, three fuels showed high temperatures. As such for the oxidizer fuel ratios for Ethanol, RP-1, and Methane(L) are 4,6,8. In fuel-rich mixtures, RP-1 and methane (L) have lower temperatures than ethanol. Finally, in decreasing the concentration of hydrogen peroxide, there is a substantial increase in the combustion chamber temperature.

5.8.2. Specific Impulse

5.8.2.1 Hydrogen Peroxide (liquid) as the Oxidizer

This section is assigned to analyze the hydrogen peroxide (H_2O_2) liquid as the oxidizer with the Ethanol, RP-1, Liquid Methane.

CASE A- Liquid Methane with pure hydrogen peroxide as oxidizer

Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***		
	Ethanol	Rp-1	Methane (L)
2	2574.5	1963.1	1969.3
4	2602.7	2380.7	2327.4
6	2446.2	2492.5	2488.1
8	2306	2445.4	2528.5
10	2200.1	2340	2438.7

Table: 5-23 Specific Impulse values for three fuels at various O/F ratios at a fixed chamber pressure 25 bar

The below graph depicts the effect of oxidizer to fuel ratio on the specific impulse for three different fuels (Ethanol, RP-1, Methane(L)) with pure hydrogen peroxide as the oxidizer fuel ratio at a fixed chamber pressure of 25 bars. To begin with, the specific impulse rose dramatically before the stoichiometric ratio was reached, after which it decreased significantly for Ethanol and gradually for the other two fuels. Second, at various oxidizer fuel ratios, three fuels showed high specific impulses. In the illustration, the oxidizer fuel ratios for Ethanol, RP-1, and Methane(L) are 4,6,8 respectively have the highest specific impulses.

As compared to Ethanol, RP-1 and Methane (L) have lower temperatures at the fuel-rich mixtures. Furthermore, using hydrogen peroxide as an oxidizer with Ethanol at oxidizer fuel ratio 4 results in the maximum specific impulse of 2602.7.

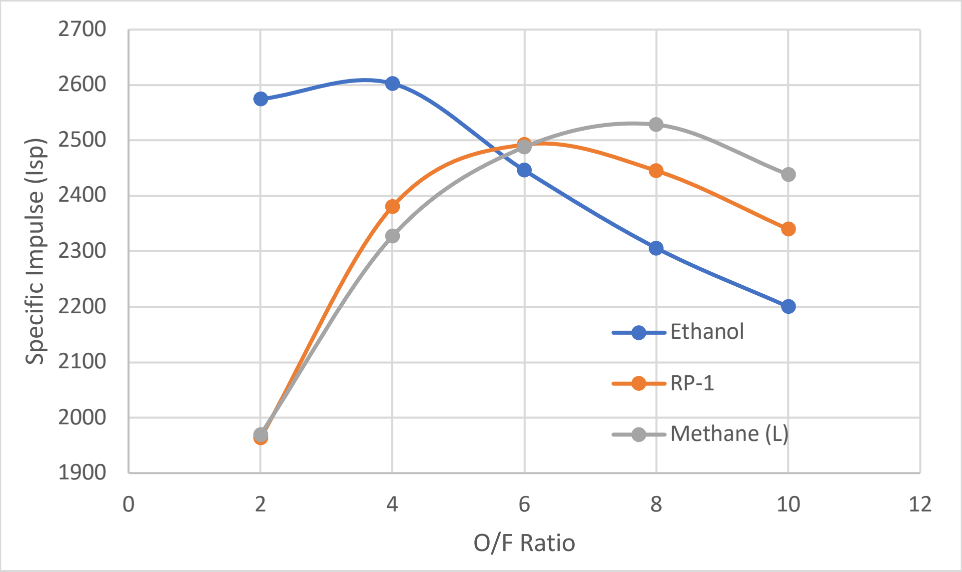


Figure: 5-21 Variation of Specific Impulse values for three fuels at various O/F ratios at a fixed chamber pressure 25 bar

5.8.2.2 Addition of H_2O_2 to Hydrogen Peroxide

CASE B- 90% Hydrogen Peroxide and 10% H_2O

This section would look at the results of adding 10% H_2O to hydrogen peroxide for Ethanol, RP-1, Liquid Methane with a different oxidizer to fuel ratios. Furthermore, it is considered at room temperature, the enthalpy of H_2O is used as the default value for the CEA code.

Variation with respect to O/F ratio

O/F	***Specific Impulse (Isp)***		
	Ethanol	RP-1	Methane (L)
2	2640.3	2032.2	2030.8
4	2683.6	2464.4	2414.2
6	2579.3	2576.4	2572.9
8	2472.8	2569.2	2618.7
10	2389.3	2497.9	2582.9

Table: 5-24 Specific Impulse values for three fuels for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar

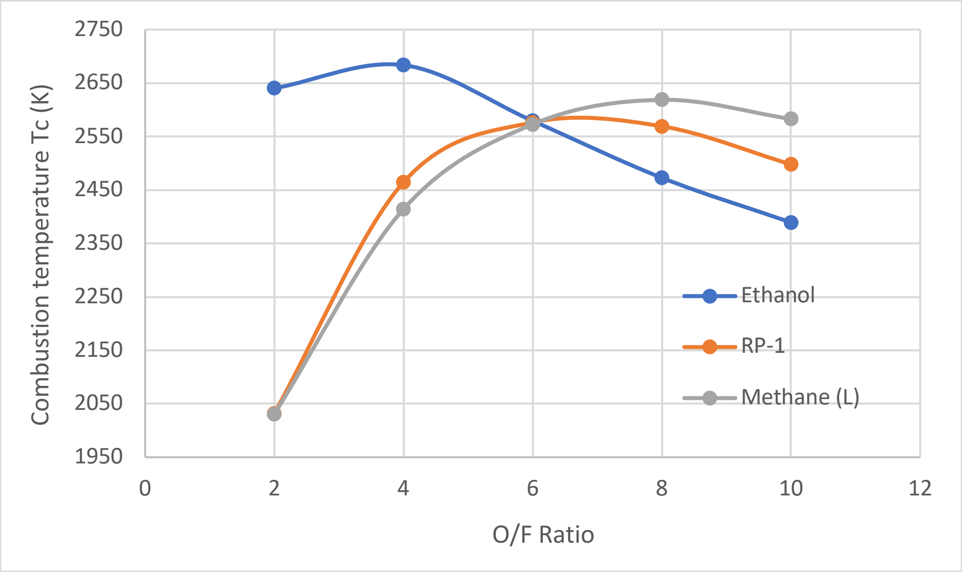


Figure: 5-22 Variation of Specific Impulse values for three fuels for 90% H_2O_2 at various O/F ratios at a fixed chamber pressure 25 bar

At 90% concentration of hydrogen peroxide as the oxidizer, the effect of oxidizer to fuel ratio on specific impulse for three different fuels (Ethanol, RP-1, Methane(L)) at a fixed chamber pressure 25 bar is shown in the graph above.

The specific impulse grew substantially before the stoichiometric ratio was achieved, then decreased significantly for ethanol and slowly for the other two fuels, equivalent to pure hydrogen peroxide. Second, three fuels showed the highest specific impulse at various oxidizer fuel ratios.

Consequently, for Ethanol, RP-1, and Methane(L), the oxidizer fuel ratios are 4,6,8 respectively. RP-1 and methane (L) have lower temperatures than ethanol in fuel-rich mixtures. Finally, as the concentration of hydrogen peroxide is decreased, the specific impulse increases dramatically to 2683.6 from 2602.7.

5.9. Comparison of Combustion Products

5.9.1 Variation of Mass Fraction with respect to O/F Ratio

ETHANOL

This present segment is evaluated the emission of carbon monoxide and carbon dioxide for Ethanol/Hydrogen peroxide at a constant combustion chamber pressure of 25 bars.

O/F Ratio	***Mass Fraction***	
	CO	CO_2
2	0.246	0.25
4	0.037	0.322
6	0.00034	0.272
8	0.00001	0.212
10	0	0.1736

*Table: 5-25 Mass Fraction values of CO and CO_2 for **Ethanol** at various O/F ratios at a fixed chamber pressure 25 bar*

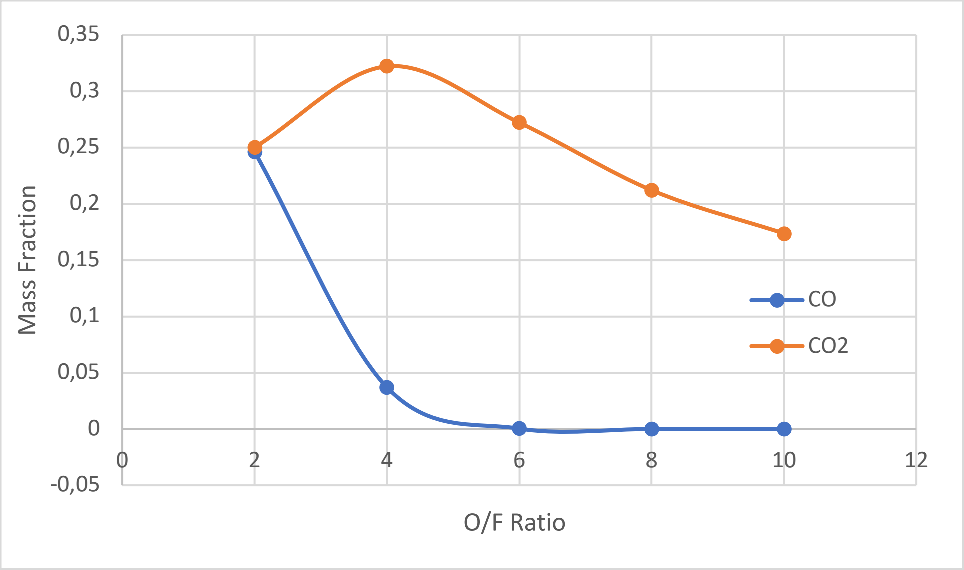


*Figure: 5-23 Variation of Mass Fraction values of CO and CO_2 for **Ethanol** at various O/F ratios at a fixed chamber pressure 25 bar*

The above graph illustrated the emission of mass fraction of carbon monoxide and carbon dioxide with respect to the oxidizer to fuel ratio. Firstly, it observed that at a high oxidizer to fuel ratio there is less emission of carbon monoxide and carbon dioxide.

Secondly, CO2 increased steadily initially till O/F 4 and decreased steadily later. Finally, carbon monoxide decreased dramatically as the oxidizer to fuel ratio increased.

RP-1

This segment evaluates the emission of carbon monoxide and carbon dioxide for RP-1 / hydrogen peroxide at a constant combustion chamber pressure of 25 bars.

O/F Ratio	***Mass Fraction***	
	CO	CO_2
2	0.3054	0.405
4	0.202	0.311
6	0.071	0.337
8	0.0013	0.3478
10	0.00006	0.286

Table: 5-26 Mass Fraction values of CO and CO_2 for ***RP-1*** *at various O/F ratios at a fixed chamber pressure 25 bar*

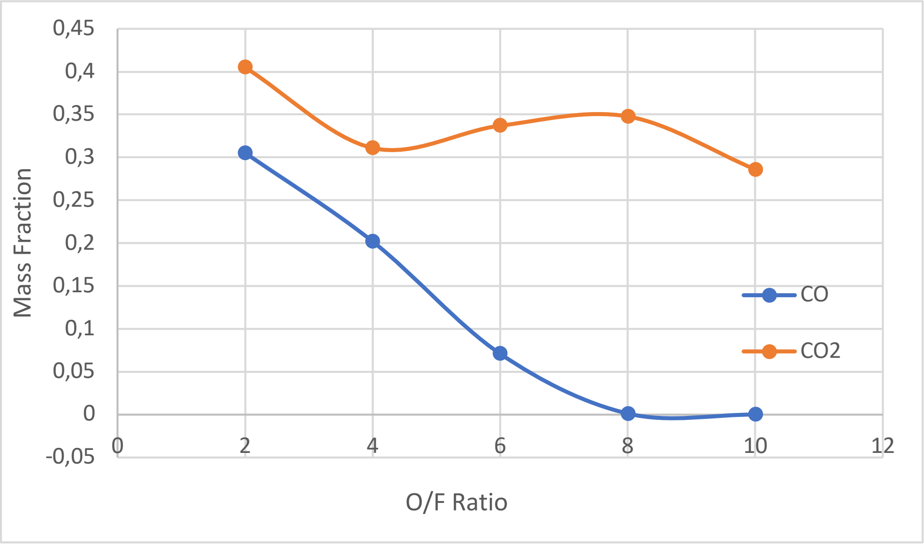


Figure: 5-24 Variation of Mass Fraction values of CO and CO_2 for ***RP-1*** *at various O/F ratios at a fixed chamber pressure 25 bar*

The graph above depicted the mass fractions of carbon monoxide and carbon dioxide emitted in relation to the oxidizer to fuel ratio. Initially, it was discovered that when the oxidizer to fuel ratio is high, carbon monoxide and carbon dioxide emissions are reduced. Second, CO_2 decreased steadily until O/F 4 and then gradually increased. Finally, as the oxidizer to fuel ratio rose, carbon monoxide levels dropped sharply.

LIQUID METHANE

This segment evaluates carbon monoxide and carbon dioxide emissions for Methane(L) / hydrogen peroxide at a constant combustion chamber pressure of 25 bars

O/F Ratio	***Mass Fraction***	
	CO	CO_2
2	0.1142	0.388
4	0.156	0.302
6	0.091	0.248
8	0.017	0.276
10	0.00015	0.249

*Table: 5-27 Mass Fraction values of CO and CO_2 for **Liquid Methane** at various O/F ratios at a fixed chamber pressure 25 bar*

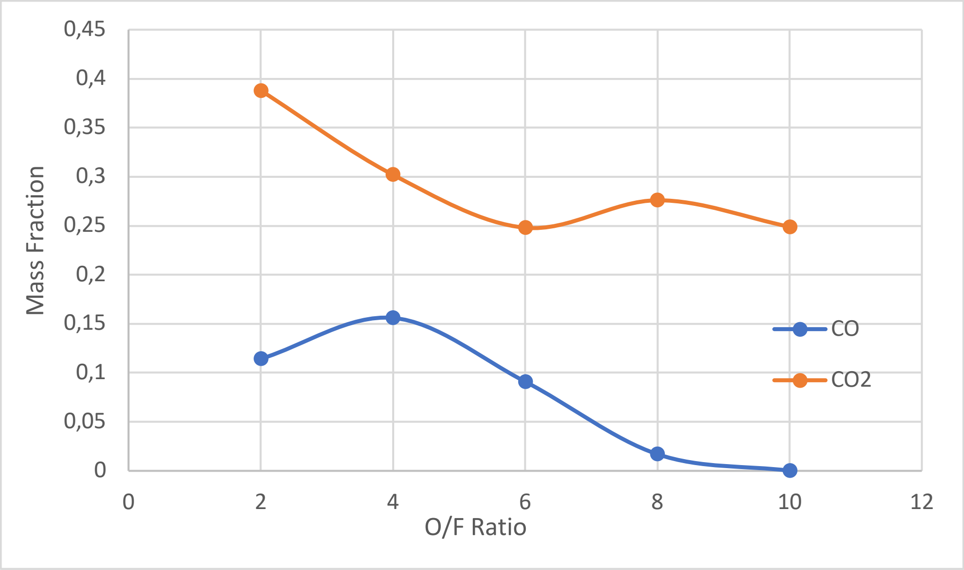


*Figure: 5-25 Variation of Mass Fraction values of CO and CO_2 for **Liquid Methane** at various O/F ratios at a fixed chamber pressure 25 bar*

The mass fractions of carbon monoxide and carbon dioxide extracted in comparison to the oxidizer to fuel ratio are represented in the graph above. Carbon dioxide is lowered when the oxidizer to fuel ratio is increased till O/F 6 and later has a slight fluctuation as the increase in oxidizer fuel ratio. Moreover, CO slowly increased until O/F 4, after which it eventually decreased. Finally, Carbon monoxide levels fell sharply as the oxidizer to fuel ratio improved.

5.9.2 Variation of Mass Fraction with respect to Chamber, Throat, and Exit

This section investigates the mass fractions of the decomposed species at chamber, throat, and exit. Further, the analysis is done for Ethanol, Methane(L), and RP-1 as fuels at a fixed oxidizer fuel ratio of 4 and combustion chamber pressure at 25 bar.

ETHANOL

	CO	***CO_2***	***H***	***H_2***	***H_2O***	***O***	***OH***	***O_2***
Chamber	0.084	0.249	0.00037	0.00472	0.595	0.0026	0.032	0.029
Throat	0.074	0.264	0.00029	0.00421	0.604	0.0018	0.025	0.024
Exit	0.037	0.322	0.00003	0.00258	0.633	0.00003	0.002	0.0007

*Table: 5-28 Mass Fraction values of combustion products for **Ethanol** at Chamber, throat, and exit at a fixed chamber pressure 25 bar and **O/F ratio 4***

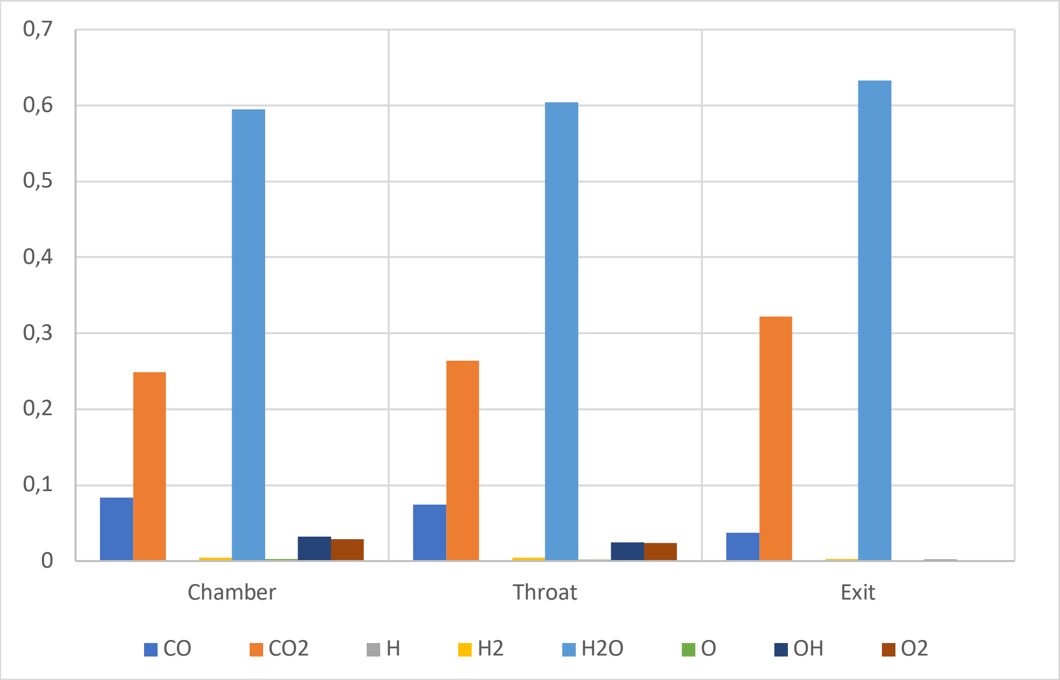


*Figure: 5-26 Variation of Mass Fraction values of combustion products for **Ethanol** at Chamber, throat, and exit at a fixed chamber pressure 25 bar and **O/F ratio 4***

The graph illustrates the mass fraction of the combustion products for Ethanol/Hydrogen peroxide at chamber, throat, and exit with constant combustion chamber pressure 25 bar. Further, analysis has been done considering the oxidizer/fuel ratio at 4 because ethanol exhibits maximum temperature and specific impulse at the 4 O/F.

Firstly, it can be seen that H_2O has the maximum amount of composition in the combustion products and then is followed by carbon dioxide and carbon monoxide respectively. Secondly, mass fraction along the combustion chamber increased significantly for the H_2O and CO_2 and decreased steadily for the CO. Combustion products like H, H_2, O, have the least significant values of the mass fraction.

RP-1

	CO	CO_2	H	H_2	H_2O	O	OH	O_2
Chamber	0.105	0.284	0.00026	0.0051	0.574	0.001	0.0187	0.0101
Throat	0.097	0.296	0.00019	0.0048	0.581	0.00056	0.0128	0.0059
Exit	0.071	0.337	0.00001	0.0053	0.585	0	0.00014	0

*Table: 5-29 Mass Fraction values of combustion products for **RP-1** at Chamber, throat, and exit at a fixed chamber pressure 25 bar and **O/F ratio 6***

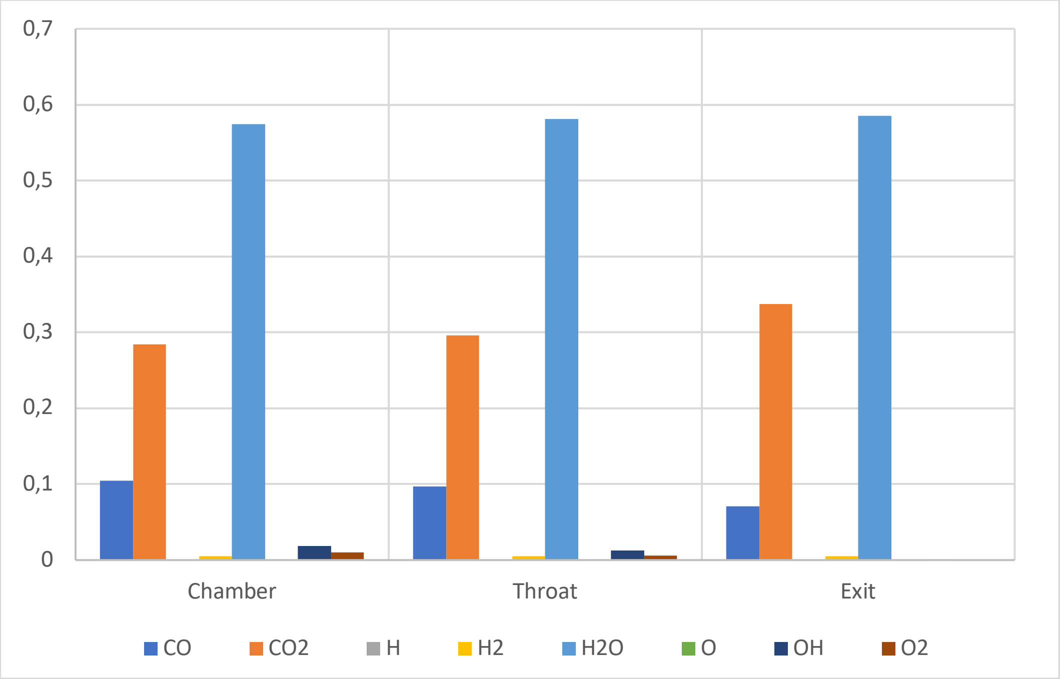


*Figure: 5-27 Variation of Mass Fraction values of combustion products for **RP-1** at Chamber, throat, and exit at a fixed chamber pressure 25 bar and **O/F ratio 6***

With a constant combustion chamber pressure of 25 bar, the above graph shows the mass fraction of combustion products for RP-1/ Hydrogen peroxide in chamber, throat, and exit. Furthermore, the oxidizer/fuel ratio of 6 was used in the study because RP-1 has the highest temperature and specific impulse at this ratio.

To start, it can be seen that H_2O has the highest composition in the combustion products, followed by carbon dioxide and carbon monoxide, in that order. Second, mass fractions along with the combustion chamber for CO_2 increased steadily, while CO decreased gradually. The mass fraction of combustion products such as H, H_2, and O is the least important as in the previous case. Furthermore, the mass fraction of the H_2O has no variation at three different locations.

LIQUID METHANE

	CO	***CO_2***	***H***	***H_2***	***H_2O***	***O***	***OH***	***O_2***
Chamber	0.047	0.2298	0.00018	0.0034	0.676	0.0011	0.021	0.02
Throat	0.04	0.2413	0.00013	0.0029	0.684	0.00071	0.015	0.014
Exit	0.017	0.2767	0.00001	0.0019	0.703	0	0.00036	0.00005

Table: 5-30 Mass Fraction values of combustion products for ***Liquid Methane*** *at Chamber, throat, and exit at a fixed chamber pressure 25 bar and* ***O/F ratio 8***

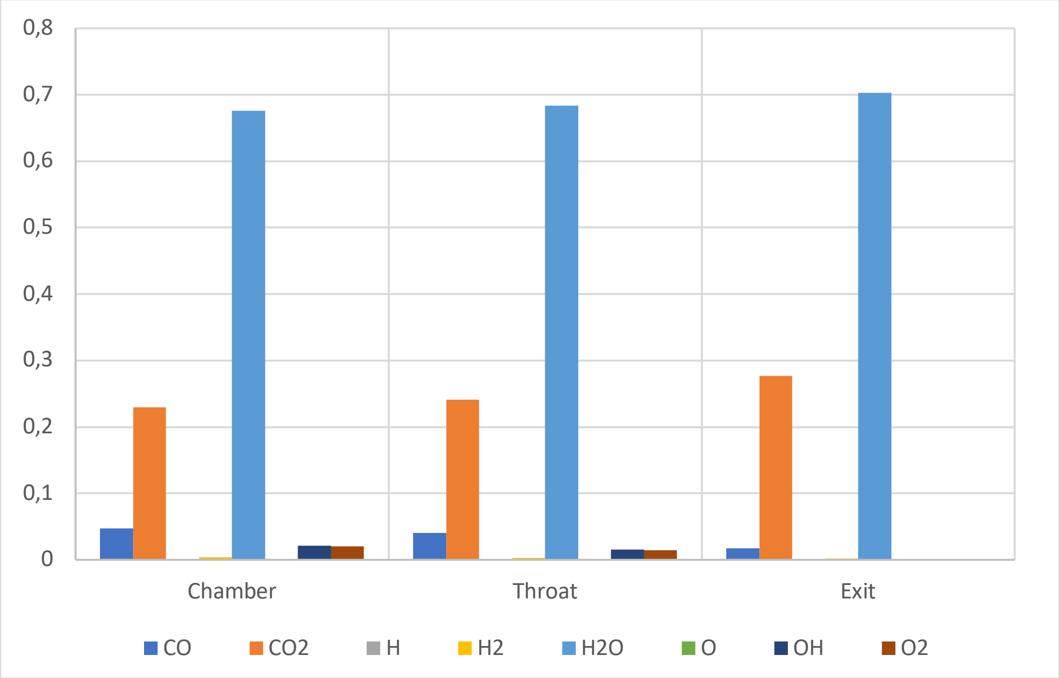


Figure: 5-28 Variation of Mass Fraction values of combustion products for ***Liquid Methane*** *at Chamber, throat, and exit at a fixed chamber pressure 25 bar and* ***O/F ratio 8***

The above graph indicates the mass fraction of combustion products for Methane(L)/ Hydrogen peroxide in chamber, throat, and exit at a constant combustion chamber pressure of 25 bar. Furthermore, since Methane(L) has the maximum temperature and specific impulse at this ratio, the oxidizer/fuel ratio of 6 was used in the analysis.
To begin, the combustion products show that H_2O has the highest composition, followed by carbon dioxide and carbon monoxide, in that order. Second, though CO decreased gradually, mass fractions and the combustion chamber for CO_2 rose steadily. As in the previous example, the mass fraction of combustion products such as H, H_2, and O is the least significant.

CHAPTER 6

CONCLUSION AND FUTURE WORK

In this section, it is explained briefly the results of hydrogen peroxide as an oxidizer in hybrid and bi-propellant rocket motors. Moreover, the future scope of improving hydrogen peroxide as the oxidizer is explained significantly.

6.1. Results and Discussions

The results of the current study suggest that hydrogen peroxide has a similar combustion performance when it is used as the oxidizer for all three types hybrid, bipropellant, monopropellant. A detailed literature survey has been done for hydrogen peroxide as the monopropellant. Later, a parametric analysis is done for different compositions of the propellant and oxidizer at different oxidizer/fuel ratios and combustion chamber pressures. Results and discussion of the various cases are summarized and explained in the following section in a case wise.

6.1.1 Hydrogen Peroxide as the oxidizer for Hybrid Rocket Motor

This segment is to summarize the results for the different concentrations of hydrogen peroxide as the hybrid rocket motors at different oxidizer/fuel ratios and combustion chamber pressure. Furthermore, the aluminum additive is used in combination with the Sasol waxes for enhancement of the combustion chamber performance.

6.1.1.1 Effect of The Concentration H_2O_2 On the Combustion Performances

Firstly, at different three different concentrations are examined to know the importance of the composition of hydrogen peroxide and water. Further, it is observed that at a lower oxidizer fuel ratio, the higher concentrations of hydrogen peroxide have high combustion chamber temperature. On contrary, at a higher oxidizer fuel ratio, the higher concentrations of hydrogen

peroxide resulted in lower temperatures. This is effect is more evident at the lower oxidizer to fuel ratio as the portion of oxidizer is more at the lower oxidizer.
Secondly, the specific impulse does not show any effect with concentrations of the hydrogen peroxide at a lower oxidizer to fuel ratio. Besides, at a higher oxidizer to fuel ratio, less concentration has the highest specific impulse.

6.1.1.2 Effect of the Oxidizer to Fuel Ratio on the Combustion Performances

Oxidizer to fuel ratio has a significant effect on the combustion chamber temperatures and specific impulse. To begin, combustion chamber temperature has drastically increased for all three combinations of the fuels to the stoichiometric ratio and decreased steadily after the stoichiometric ratio. Further, it is seen that at stoichiometric ratio the chamber temperature and the specific impulse have the highest values among other ratios.

6.1.1.3 Effect of the Chamber Pressure on the Combustion Performances

When the pressure in the combustion chamber increases, so does the temperature in the combustion chamber increases. This is because the combustion products behave like an ideal fluid at such high temperatures, and an ideal gas has a rise in temperature with an increase in pressure as a characteristic function. Moreover, the combustion chamber pressure does not have a significant effect on the specific impulse. Finally, this effect varnished at higher oxidizer fuel ratios.

6.1.1.4 Effect of the Chemical Composition of the Propellant

when analyzing the patterns of various Sasol Waxes, it is clear that, while all three have very close values at O/Fs of 6 and 10, there are some major differences at O/F = 2. The differences in the properties of the three waxes are the most significant in this situation since the fuel content is very high at an O/F ratio of 2, and because Sasol Wax 0907 has the highest molecular weight.

6.1.1.5 Effect of the Addition of Aluminum as of the Propellant

The aluminum element in paraffin waxes greatly improved the combustion temperature and specific impulse in all three Sasol waxes compositions. However, the sensitivity to the addition of aluminum is greater at lower O/F ratios since the percentage of fuel is higher at lower O/F ratios because the net ratio of aluminum to the total fuel is higher at the lower oxidizer to fuel ratio.

Moreover, it is illustrated that at a lower oxidizer to fuel ratio the increase in the aluminum amount in the fuel increases the specific impulse. On contrary, at a higher oxidizer to fuel ratio the specific impulses decrease as the increase in the aluminum content increased.

6.1.2 Hydrogen Peroxide as the Oxidizer for the Bi Propellant

The hydrogen peroxide in liquid bi-propellant systems is briefly explained in this section. A comprehensive description of the effects of hydrogen peroxide on ethanol, RP-1, and liquid methane propellant system is also included. The oxidizer varies from 2 to 10 and the chamber pressure varies from 20 to 30 bar.

6.1.2.1 Effect of the Concentration H_2O_2 on the Combustion Performances

To begin, the importance of hydrogen peroxide and water composition is investigated in three separate fuels (ethanol, methane, and RP-1). Furthermore, it is discovered that at a lower oxidizer fuel ratio, the concentration has little effect. Higher amounts of hydrogen peroxide resulted in higher temperatures as the oxidizer fuel ratio was increased.
Moreover, as the concentration of the hydrogen peroxide increases, there is a small amount of the increase in specific impulse is observed.

6.1.2.2 Effect of the Oxidizer to Fuel Ratio on the Combustion Performances

The ratio of oxidizer to fuel has a huge effect on combustion chamber temperatures and specific impulses. To continue, the temperature of the combustion chamber increased dramatically until it reached the stoichiometric ratio for all three fuel combinations, then gradually decreased after it reached the stoichiometric ratio. The chamber temperature and the specific impulse, among other ratios, have the maximum values at the stoichiometric ratio.

6.1.2.3 Effect of the Chamber Pressure on the Combustion Performances

As the pressure within the combustion chamber rises, the temperature inside the combustion chamber rises as well. This is since, at such high temperatures, the combustion products behave like an ideal fluid, and an ideal gas's signature feature is a rise in temperature with an increase in pressure. Furthermore, the friction in the combustion chamber has no bearing on the specific impulse. Finally, at higher oxidizer fuel ratios, this result varnished.

6.1.2.4 Effect of the Chemical Composition of the Propellant

The chemical composition of the propellant has a considerable effect on combustion performance. Firstly, ethanol has the highest chamber temperature and specific impulse when compared with methane(L) and RP-1. Further, methane and RP-1 have a similar trend in the increase in the combustion temperature and specific impulse with respect to oxidizer to fuel ratio. All in all, ethanol outweighs the performance characteristics when compared with other compositions of the propellants at different oxidizer to fuel ratios and chamber pressure.

6.1.2.5 Decomposition Combustion Products

The mass fractions of carbon monoxide and carbon dioxide extracted in comparison to the oxidizer to fuel ratio are illustrated and it is observed that carbon dioxide and carbon mono oxide reduced qualitatively as there is an increase in oxidizer to fuel ratio for all three fuels. Furthermore, H_2O has the highest composition of the combustion products, followed by carbon dioxide and carbon monoxide in that order. Second, though CO levels rapidly declined, mass fractions for CO_2 are steady. The mass fraction of combustion products such as H, H_2, and O is the least important, as in the previous case.

6.2. Conclusion

To sum up, It is first discussed the use, properties, and management of hydrogen peroxide in in-space propulsion, and then we looked at different configurations and compositions of hydrogen peroxide using NASA's CEA code. The investigation of hydrogen peroxide as a monopropellant, bipropellant, and composite propellant was carried out. The main purpose is to find combustion temperature and specific impulse values at different O/F ratios of 2,4,6,8,10 and various pressure chamber values of 20, 25, and 30 bar. The bi-propellant of ethanol, RP-1, and liquid methane has been studied in two cases, with mass fraction heterogeneity obtained at various O/F ratios and chamber, throat, and exit. The incorporation of aluminum impact has been tested efficiently in four cases in the hybrid propellant state with different paraffin waxes (SASOL 0907, SASOL 6003, SASOL 6805) as fuel. In the case of bi-propellant, analysis was performed taking into account all compositions and comparing combustion products to obtain the maximum performance at the correct O/F ratio and fixed chamber pressure. It is observed that hydrogen peroxide has remarkable advantages similar to other propellants and it has fewer metallic oxides at the exit, which makes hydrogen peroxide the rewarding green propellant for the next generation.

6.3. Future Work

1. To carry out a computation by adding an additive like magnesium dioxide to the Sasol waxes reacting with the hydrogen peroxide.

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