



PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research



N° d'ordre :

N° de série :

University of Echahid Hamma Lakhdar – El Oued

Institute of Exact Sciences

Department of Physics

This dissertation is submitted for the degree of

Master in Physics

Specialty: Radiation physics

By: **GUERRICHA Safa**

NESRATE Soumaia

Subject of the thesis:

**Theoretical study of H₂Fuelled Internal Combustion
Engine**

Publicly defended on 24/06/2024 to the jury composed by:

Dr. RAHAL Achour

University of El Oued - Algeria

President

Pr. BOURAS Fethi

University of El Oued - Algeria

Thesis Director

Dr. GHERAISSAN Nadjat

University of El Oued - Algeria

Thesis Co-director

Dr. LABBI Abdelkader

University of El Oued - Algeria

Examiner

University years : 2023/2024



Dedication

First of all, I would like to thank my God, the almighty for providing me this chance and granting me the capability to complete this thesis successfully. Over the past years, there have been many people who have made my achievements possible.

I would like to take this opportunity to thank them for their help and support. Foremost, I wish to convey my appreciation and sincere gratitude to my supervisor Pr. BOURAS Fethi for his valuable guidance and countless support during my research. I would also like to thank Professor GheraissaNadjet for their help in preparing of this work. I would especially like to thank my dissertation committee members: Dr. RAHAL Achour, Dr. LABI AbdelKader for reviewing the manuscript and providing helpful comments

I want to express my deep thanks to my dear parents for encouragement and support throughout my life and especially during my research career. Last but never least, I convey my sincere thanks to my husband for his endless patience and constant support, also to my sisters, brothers, and my friends. Generally, I would to thank all who helps me to complete this thesis project.

Safa Guerricha
Soumaïa Nesrate



TO MY BELOVED PARENTS

TO MY SMALL & BIG FAMILY

TO ALL MY TEACHERS & FRIENDS ...

Table of Contents

table of Contents	IV
List of Figures.....	VI
List of Tables	VII
Nomenclature	VIII
General Introduction	10
a. Motivation and Objective	10
b. Literature Survey	10
c. Objective of This Study	12
d. Accomplishments	12
CHAPTER I: Overview Of Internal Combustion Engine	15
I.1. Historical Overview.....	15
I.2. Types Of Automotive Engines.....	16
I.3. Types of Automotive Fuels	17
I.4. Internal Combustion Engines (ICEs)	18
I.4.1. Components of IC Engines	20
e. Fixed Components:.....	20
f. Moving Components:	21
I.4.2. Combustion System in IC Engines.....	23
a. Cooling System:	23
b. Lubrication System:.....	24
c. Ignition System:.....	25
d. Fuel System:	26
e. Starting System:.....	26
f. Generation and Charging System:	26
I.4.3. Operating Principle of IC Engines	27
I.4.4. Types of Hydrogen Tanks.....	28
I.5. Conclusion	29
CHAPTER II: Energy And Exergy Analyses.....	31
II.1. The First Law of Thermodynamics	31
II.1.1. Energy Change	31
II.1.2. Energy Transfer.....	32
a. Mass Transfer	32
b. Heat Transfer	32

c. Work	32
II.1.3. The First Law of Thermodynamics	33
II.1.4. Energy Efficiencies	34
II.1.5. Heating Values	35
II.1.6. Combustion Efficiency	35
II.2. Limitations of the First Law:	36
II.3. The Second Law of Thermodynamics (SLT)	36
II.3.1. Entropy	37
a. The entropy transport equation	39
II.3.2. Exergy	41
a. Exergy Definition	41
b. Reversibility and Irreversibility	42
II.4. The Analyses of Combustion Process	42
II.4.1. Energy Analysis	42
II.4.2. Exergy Analysis	44
II.5. The Conclusion	47
CHAPTER III: Application Of Energy And Exergy Analysis In Internal Combustion	
Engine.....	49
III.1 Control Volume and Operating Conditions	49
a. Case 1:.....	50
b. Case 2:	50
c. Case 3:	51
III.2. Results and discussion	52
III.2.1. Total Energy flow and Exergy flow, Entropy.....	52
III.2.2.Total Energy flow	53
III.2.3.Total Exergy flow	55
III.2.4.Entropy.....	57
III.3.Conclusion.....	58
General Conclusion.....	61
The References	64

List of Figures

Figure 1 An internal combustion engine.....	18
Figure 2 The spark-ignition engines (Gasoline Vehicle).....	19
Figure 3 The compression-ignition engines (Diesel Vehicle)	19
Figure 4 The Fixed Components of IC engine.....	21
Figure 5 Engine Pistons and Connecting Rods.....	21
Figure 6 Engine Crankshaft	22
Figure 7 Engine Valves.....	22
Figure 8 Engine Bearings.....	23
Figure 9 The cooling system in IC engine	24
Figure 10 The Lubrication System in IC engine.....	25
Figure 11 The ignition system in IC engine.....	25
Figure 12 The starting system in IC engine	26
Figure 13 The generation and charging system in IC engine	27
Figure 14 The operation of internal combustion engines	28
Figure 15 Energy transfer by work, heat and mass.....	33
Figure 16 Schema of Engine Combustion Chamber.....	49
Figure 17 The total energy flow, exergy flow, and entropy generation for considered fuels.....	52
Figure 18 The total energy flow versus temperature for considered fuels	53
Figure 19 The total energy flow versus mass flow for considered fuels	54
Figure 20 The total exergy flow versus temperature for considered fuels	55
Figure 21 The total exergy flow versus mass flow for considered fuels	56
Figure 22 The entropy flow versus temperature for considered fuels	57
Figure 23 The entropy flow versus mass flow for considered fuels	58

List of Tables

Table 1 The features of the most popular types of automobile fuels and their uses.....	17
Table 2 The Boundary conditions and proprieties of inlet	50
Table 3 The combustion characteristics of preheating fuels.....	51
Table 4 The combustion characteristics of impact mass flow	51

Nomenclature

Latin letters

C_p	Specific heat of capacity
E	Energy
e	Internal energy
$\dot{E}n_{\text{air}}$	Energy rate of air
$\dot{E}n_{\text{exh}}$	Exhaust energy rate
$\dot{E}n_{\text{fuel}}$	Energy rate of fuel
$\dot{E}n_{\text{in}}$	Input energy rate
$\dot{E}n_{\text{loss}}$	Energy loss rate
$\dot{E}n_{\text{out}}$	Output energy rate
$\dot{E}n_w$	Work rate
$\dot{E}x_{\text{air}}$	Exergy rate of air
$\dot{E}x_{\text{dest}}$	Exergy destruction rate
$\dot{E}x_{\text{exh}}$	Exhaust exergy rate
$\dot{E}x_{\text{fuel}}$	Exergy rate of fuel
$\dot{E}x_{\text{in}}$	Input exergy rate
$\dot{E}x_{\text{loss}}$	Exergy loss rate
$\dot{E}x_{\text{out}}$	Output exergy rate
$\dot{E}x_w$	Exergy rate of work
h	Enthalpy
H	Fuel lower heating value
h_i	Enthalpy of species i
N	Total number of elements in the mesh
n	Boundary-normal coordinate
n_i	number of moles of the species i
\dot{m}	Mass flow rate
p	Pressure
Q	Heat energy loss of the wall
R	Universal gas constant
S	Entropy generation rate
S_i	Source term
t	Time
T	Temperature
u	Velocity

Greek symbols

λ	Air factor
κ	Thermal diffusivity
ϕ	Equivalence ratio

Subscripts

ch	Chemical
des	Destroyed
En	Energy
Ex	Exergy
gen	Generation
i	Specie
loss	Energy and exergy loss
ph	Physical

Abbreviations

LHV	Lower heating value
-----	---------------------

General Introduction

General Introduction

a. Motivation and Objective

The internal combustion engine is the primary power source in most vehicles, driving their movement through the combustion of fuel. It functions by igniting fuel within its chambers to generate the energy required for motion. This innovation has significantly advanced transportation, offering a more efficient means of travel. The advancement of energy systems, especially in industrial contexts, demands the enhancement of mechanisms to improve efficiency based on fundamental thermodynamic principles. The major goal is to minimize inherent inefficiencies in how processes and changes occur. Exergy analysis emerges as a critical tool for facilitating thorough thermodynamic assessments, thereby fostering a more profound comprehension of energy utilization and optimization strategies. Additionally, the design and structure of internal combustion engines are influenced by thermodynamic inefficiencies. By understanding and addressing these inefficiencies, it is possible to improve engine performance and efficiency, which has significant implications not only for automotive engineering but also for the environment and fulfilling consumer needs.

b. Literature Survey

Throughout the years, numerous studies have investigated various aspects of internal combustion engines (ICEs), focusing on enhancing efficiency and reducing emissions through advanced computational and experimental methods. Gheraissa (2021) conducted a numerical study on the global combustion parameters of multiple fuels, including Algerian biogas, CH₄, C₃H₈, H₂, natural gas, and diesel. The study used computational fluid dynamics (CFD) to analyze non-premixed combustion in a cylindrical burner. It was found that Algerian biogas and hydrogen exhibited superior characteristics in terms of mixture quality, combustion energy efficiency, and low pollutant emissions (CO and NO) compared to other fuels[1]. Attia (2017) simulated the non-premixed combustion of methane and propane using CFD to find aero-thermo-chemical characteristics like temperature, axial velocity, and CO mass fraction. The study aimed at reducing CO emissions and found that methane combustion produced lower CO levels compared to propane[2]. Ozyalcin et al. (2024) explored the use of selective catalytic reduction (SCR) to minimize NOX emissions from hydrogen-fueled ICEs. The study compared copper-zeolite and vanadium-based SCR catalysts, finding that a combination of both could achieve high efficiency and low secondary emissions, making hydrogen engines a viable zero-impact emission alternative[3]. Wang et al. (2023) optimized the design of a direct injection turbocharged hydrogen ICE. Using a combination of one-dimensional modeling and bench testing, the study achieved a peak power of 133 kW and maximum torque of 339 N·m. The optimized engine demonstrated high thermal efficiency and could guide future H₂ICE development[4]. Gammaldoni et al. (2024) investigated the effect of injection timing on a single-cylinder SI hydrogen engine using CFD

simulations. The study found that port-fuel injection (PFI) provided higher combustion efficiency at lean air-fuel ratios compared to direct injection (DI). Advancing the start of injection timing improved combustion stability and efficiency[5]. Sfriso et al. (2024) proposed a numerical methodology for 3D-CFD simulations of hydrogen-fueled ICEs. The study validated the predictive capabilities of the model against experimental data, paving the way for future research on emission modeling and engine optimization[6]. Xin et al (2024) examined the impact of direct ethanol injection on port-injected hydrogen engines. Their results indicated that ethanol addition reduced NO_x emissions and improved the engine's performance, although it increased hydrocarbon emissions slightly[7]. Algayyim et al. (2024) provided a comprehensive review of natural gas and hydrogen properties and their impact on ICE performance and emissions. The study highlighted the benefits of hydrogen in reducing fuel consumption and toxic emissions, despite challenges in its direct use in diesel engines[8]. Luet al. (2024) studied hydrogen injection strategies to improve combustion and reduce NO emissions in pure hydrogen engines. The study found that hydrogen direct injection, combined with lean burn technology, enhanced engine performance and met stringent emission standards[9]. Jayaprabakar et al. (2024) reviewed current developments in hydrogen-enriched fueling for ICEs. The review covered hydrogen production technologies, injection systems, and the performance and emission characteristics of hydrogen-enriched engines, emphasizing the need for further research to optimize these systems[10]. Abubakar (2024) conducted a bibliometric analysis of research trends in hydrogen-fueled ICEs. The analysis identified key research areas and challenges, such as NO_x emissions and engine efficiency, and suggested future research directions to address these issues[11]. These studies collectively highlight the significant progress in understanding and optimizing internal combustion engines, particularly with the use of hydrogen and other alternative fuels. The findings underscore the importance of computational modeling, experimental validation, and innovative fuel strategies in advancing engine technology for better performance and lower emissions.

In addition, many works have explored the foundational methodologies for deriving entropy generation equations, aiming to simplify them into forms comprising essential variables such as velocity, temperature, and mass fraction. An example can be found in the utilization of theoretical models and technical processes to reduce energy losses and optimize power output in energy systems. Bouras&Khaldi (2016) focused on entropy generation in gaseous combustion processes. Their study analyzed the effects of various factors such as viscosity friction, thermal diffusion, species diffusion, and chemical reactions on the entropy generation rate at different inlet temperatures of air and CH₄. This comprehensive analysis helps in understanding the impact of each factor on the overall system's efficiency[12]. Bouraset al (2018) performed an energy and exergy analysis of carbon-based fuels compared to hydrogen fuel in a cylindrical combustion chamber. The analysis indicated that hydrogen was the optimal fuel for the given configuration, providing superior performance and efficiency[13]. Gheraissaet al (2024) investigated an energy and exergy analysis of various fuels under the same conditions. The study used numerical methods, including a turbulent dynamic k- ϵ model and a probability density function (PDF) approach. The First and Second Laws of thermodynamics were applied to determine energy loss, exergy

destruction, and their efficiencies for each fuel. Additionally, the study examined the effects of varying the air factor, air inlet temperature, and fuel inlet temperature affects combustion performance and energy losses. The results showed that using a fuel-air mixture with a λ value greater than 1 improves combustion performance. Preheating the air going into the system had a positive impact on energy parameters, but preheating the fuel did not significantly improve efficiency or reduce losses. Biogas was found to have the highest energy efficiency at 89.64%, while hydrogen had the highest exergy efficiency at 78.70%, followed by biogas at 74.96% [14].

c. Objective of This Study

The objective of this study is to conduct a comprehensive energy and exergy analysis on internal combustion engines supplied with different fuels. By evaluating the performance, combustion characteristics, and emissions of various fuels, this study aims to identify optimal fuel choices that maximize efficiency while minimizing environmental impact. Through detailed energy and exergy analysis, we seek to advance the understanding of fuel dynamics in combustion processes, contributing to the development of more sustainable and efficient internal combustion engines.

d. Accomplishments

o Chapter I

In this chapter, we dive into the general aspects of internal combustion engines. First, we provide a historical overview, tracing the evolution of engine technology from its early beginnings to the latest innovations. Next, we describe the main components of an internal combustion engine, such as the cylinder, piston, and crankshaft, and explain how each part contributes to the engine's operation. Additionally, we explore the combustion process in detail, covering the stages of fuel injection, ignition, and how these steps result in power generation.

o Chapter II

In the second chapter, we focus on the thermodynamics of combustion. We discuss the theoretical frameworks for energy and exergy analysis in combustion processes, providing detailed explanations of these methods. This includes the derivation of key equations and the assumptions behind the models used. The chapter also presents the final set of governing equations for energy and exergy analyses, defining each term that influences the combustion system. This theoretical groundwork prepares us to apply these concepts to our specific study in the later chapters.

o Chapter III

In the final chapter, we present the results of our energy and exergy analysis of the internal combustion engine. We focus on how the inlet parameters (such as air and fuel preheating) affect the energy and exergy results. The influence of the air-fuel ratio on the combustion process is also

examined. This chapter concludes by summarizing the key insights from our analysis and offering recommendations for optimizing internal combustion engines to enhance performance and reduce environmental impact.

This structure ensures a coherent flow from the introduction and general background to specific analyses and results, culminating in a discussion of findings and their practical implications.

CHAPTER I

Overview of Internal Combustion Engine

CHAPTER I

Overview of Internal Combustion Engine

This chapter offers a historical overview of automotive engines, exploring the evolution of car engines and the diverse range of fuels that power them. It also outlines the various types of automotive engines and fuels. The focus is on internal combustion engines, delving into their components and systems to unravel their intricate workings and functionalities. Additionally, the operational principles of internal combustion engines are illustrated to simplify understanding and enhance accessibility.

I.1. Historical Overview

The internal combustion engine (ICE) is the main power source for modern cars and has changed a lot since it was first invented. This historical overview highlights how this important technology has developed, using information from main references[15–19].

The beginning of the internal combustion engine (ICE) era was in 1807 when Swiss engineer François Isaac de Rivaz built an engine powered by hydrogen and oxygen, marking a significant milestone in engine development. In 1826, English inventor Samuel Brown made progress by using a hydrogen-fueled ICE to power a vehicle, demonstrating early advancements in automotive technology. By 1860, Belgian engineer Jean-Joseph Lenoir had created a gasoline-powered spark-ignition engine, which set the stage for the emergence of modern engines and paved the way for future innovations. In 1876, Nicolaus Otto and Eugen Langen developed the four-stroke engine, a groundbreaking invention that became the basis for modern ICEs, contributing to the evolution of automotive engineering. The first modern car was made in 1886 by Karl Benz, who built a gasoline-powered automobile, revolutionizing personal transportation. A year later, Gottlieb Daimler made a similar vehicle independently, further advancing automotive technology[15,16,19].

The 20th century marked a period of significant advancements in automotive technology. In 1897, Rudolf Diesel introduced the diesel engine, offering improved efficiency and torque compared to gasoline engines, thereby reshaping the landscape of automotive powertrains. Charles Kettering's development of the electric starter in 1909 represented a significant leap forward, eliminating the need for manual hand cranking and enhancing the convenience and accessibility of automobiles. Subsequent decades witnessed the emergence of electronic fuel injection (EFI) during the 1950s and 1960s, a transformative technology that enhanced engine control, leading to improved fuel efficiency and reduced emissions. Additionally, the 1970s witnessed the widespread adoption of catalytic converters, playing a crucial role in mitigating harmful exhaust emissions and contributing to cleaner air quality[16–18].

In the 1980s and 1990s, the pursuit of sustainability and the search for alternative power sources gained momentum with the development of hybrid electric vehicles (HEVs) and electric vehicles (EVs), offering cleaner and more efficient options compared to traditional internal combustion engines (ICEs). These advancements represented a significant shift towards greener transportation solutions, driven by growing environmental concerns and the need for energy independence. As we entered the 21st century, further progress in battery technology and the implementation of government incentives have accelerated the adoption of HEVs and EVs, making them increasingly viable alternatives for environmentally conscious consumers[16–19].

In the coming years, internal combustion engines (ICEs) are expected to continue evolving as they incorporate advancements in electrification, hybridization, and alternative fuels[15–19]. These changes will shape the future of mobility alongside emerging alternative powertrains, influencing the automotive industry's direction. As we move towards more sustainable transportation, ICEs will adapt and coexist with various propulsion technologies, driving innovation in the field.

I.2. Types Of Automotive Engines

The car engine stands as the heart of any vehicle, serving as the primary source of energy to propel the vehicle's wheels. For many drivers, understanding the intricacies of various car engine types remains a challenge, yet it remains a pivotal aspect of automotive technology. Traditionally, car engines were predominantly associated with internal combustion, igniting fuel like diesel or gasoline to generate power. However, with the advent of hybrid and electric vehicles, comprehending modern engine operations requires a broader scope of knowledge[20,21].

Functionally, a car engine operates as the core mechanism responsible for propelling the vehicle forward. It orchestrates a sophisticated interaction of components to convert energy into motion. For example, consider the gasoline engine, which functions by internally combusting fuel ignited through an electric spark generated by a spark plug. Structurally, a gasoline engine is composed of two primary groups of components: fixed and moving parts. The fixed elements include the cylinder cover, cylinder block, oil sump, intake, and exhaust manifold, while the moving parts comprise pistons, connecting rods, valves, camshafts, timing gears, and crankshaft [20,21].

In essence, modern automobile engines can be comprehended more readily when categorized into three fundamental types[21,22]:

1. **Internal Combustion Engines:** These engines facilitate combustion within the cylinder, converting fuel into kinetic energy.
2. **Electric Motors:** Employed predominantly in electric cars, electric motors rely on electrical energy to generate motion.

- Hybrid Engines: Combining elements of internal combustion engines with electric motors, hybrid engines represent a fusion of traditional and contemporary propulsion technologies.

I.3. Types of Automotive Fuels

The use of automobile fuel traces back to the late nineteenth century when steam was predominantly used as the primary fuel for the earliest cars. As the twentieth century began, internal combustion engines emerged, and gasoline and diesel became the predominant fuels. With technological advancements and growing environmental concerns, hybrid technology and electric vehicles have emerged, gradually capturing a portion of the automobile market[23].

There are various types of automobile fuels used worldwide. Gasoline stands out due to its popularity and widespread use across different vehicle types. Diesel, on the other hand, is commonly used in larger vehicles such as trucks and buses. Additionally, clean alternative fuels like biodiesel, ethanol, and compressed natural gas are utilized to mitigate environmental impacts. Hydrogen, which only produces water when burned, holds promise as a future fuel. Developments in the automobile fuel industry aim to maximize efficiency, reduce harmful emissions, and promote sustainability. The following table summarizes the most popular types of automobile fuels[23,24]:

Table 1 *The features of the most popular types of automobile fuels and their uses.*

FUEL TYPE	FEATURES	USES
Gasoline	Available in different octane ratings; suitable for various internal combustion engines.	Used in cars, motorcycles, boats, lawnmowers, and machinery.
Diesel	Produces fewer carbon emissions than gasoline; preferred for trucks, buses, and heavy equipment.	Operates larger vehicles and heavy machinery.
Biodiesel	Consists of organic compounds; emits minimal carbon emissions; used as an environmentally friendly biofuel.	Powers vehicles using biodiesel without engine modifications.
Ethanol	Derived from natural products; may work in newer car models designed for 100% ethanol.	Enhances gasoline to reduce emissions and increase efficiency.
Compressed natural gas	Clean fuel with minimal odor; environmentally friendly option for vehicles powered by compressed natural gas.	Operates vehicles designed for compressed natural gas.
Liquefied Petroleum Gas	Clean fuel option with low carbon emissions; alternative to petrol and diesel for LPG-powered vehicles.	Operates vehicles specifically designed for liquefied petroleum gas.
Hydrogen	Renewable fuel producing only water when burned; used in fuel cell vehicles powered by hydrogen.	Operates vehicles with fuel cell technology, utilizing hydrogen to generate electricity.

I.4. Internal Combustion Engines (ICEs)

An internal combustion engine (ICE) is a type of heat engine where fuel burns with an oxidizer (usually air) inside a combustion chamber(*Figure 1*). This process involves four main steps: intake, compression, combustion (power), and exhaust. During combustion, the fuel-air mixture ignites—either by a spark plug in spark-ignition engines or by the heat of compressed air in compression-ignition engines—creating high-pressure gases that push the pistons. These pistons are connected to a crankshaft, converting their linear motion into rotational motion to do mechanical work. This mechanism powers a wide variety of machines and vehicles. Over the years, significant advancements such as turbocharging, direct fuel injection, and the use of advanced materials have been made to enhance the efficiency, power output, and environmental impact of internal combustion engines[21,25,26].

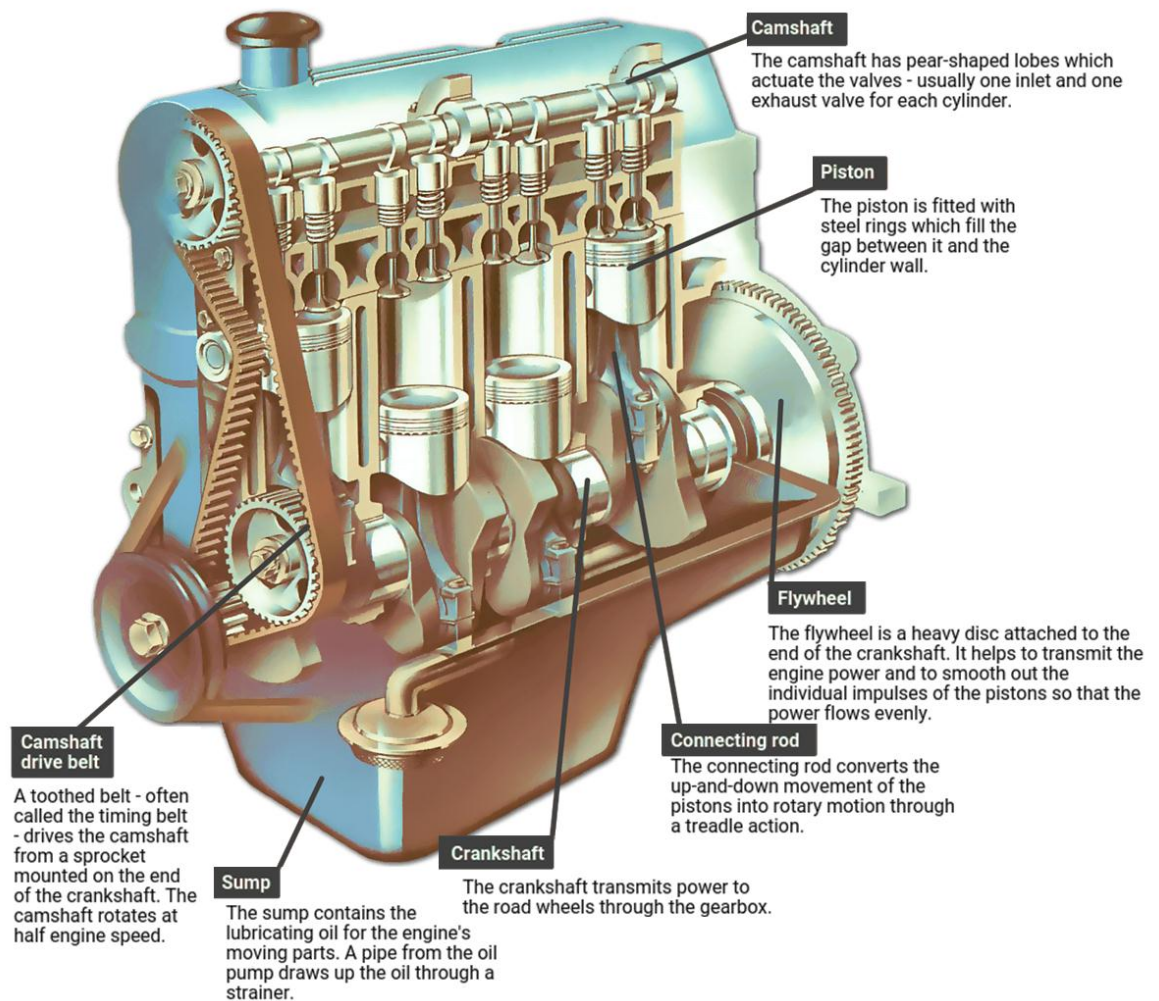


Figure 1 An internal combustion engine [57]

In automotive, internal combustion engines (ICEs) play a pivotal role in propelling vehicles. The combustion process inside these engines produces high-pressure gases that move pistons, which then rotate the crankshaft to drive the vehicle's wheels. ICEs in cars engines come in two

main types: spark-ignition engines and compression-ignition engines. Spark-ignition engines, typically used in gasoline-powered vehicles, employ an electric spark to ignite the fuel-air mixture inside the combustion chamber (Figure 2). On the other hand, compression-ignition engines, also known as diesel engines, rely on the heat generated by compressing air within the combustion chamber to ignite the fuel(Figure 3). Each type has its own features and applications in the automotive world[21].

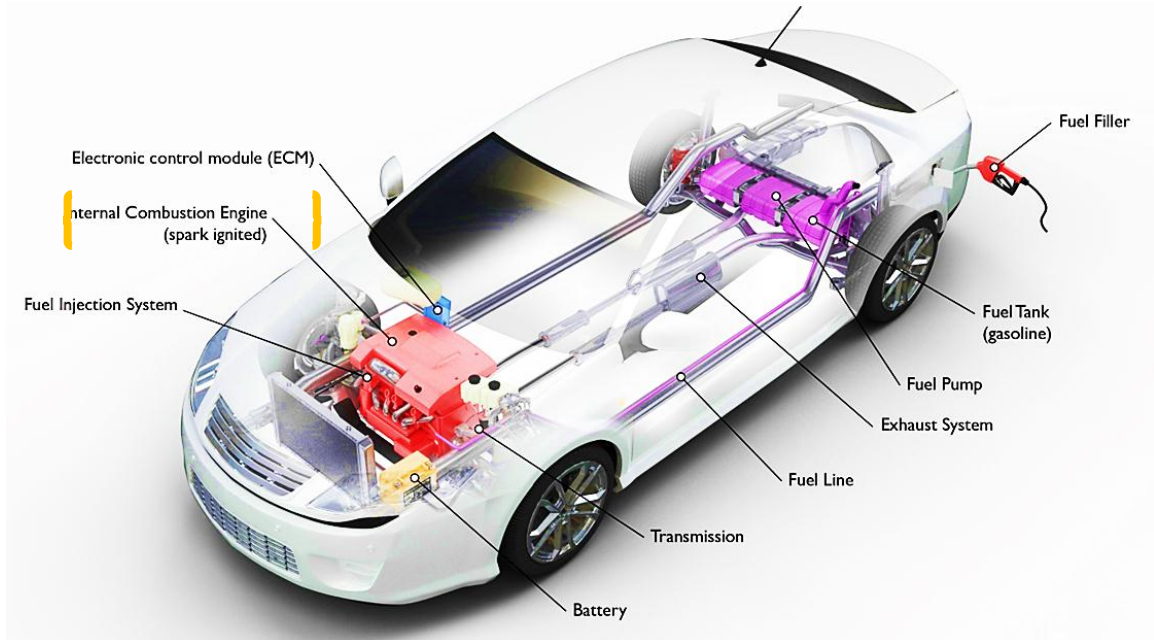


Figure 2 The spark-ignition engines (Gasoline Vehicle) [58]

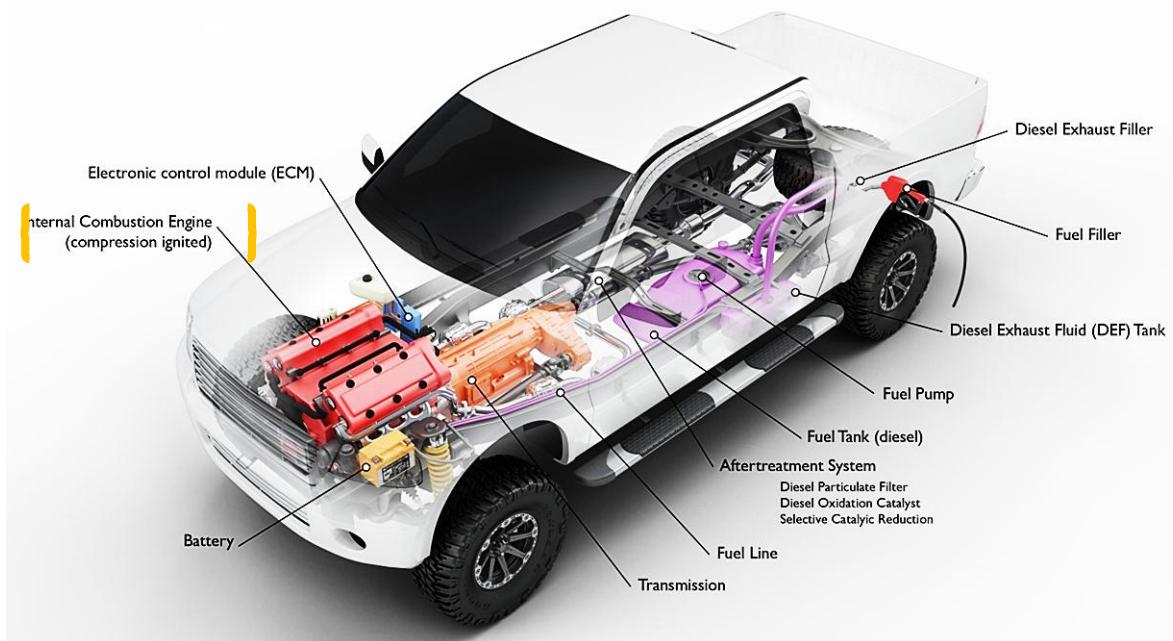


Figure 3 The compression-ignition engines (Diesel Vehicle) [58]

The widespread use of ICEs in cars is due to their high energy density and established fueling infrastructure, making them efficient and powerful for automotive applications. Although electric

vehicles are becoming more popular, ICEs continue to dominate because of their proven technology and ongoing advancements aimed at enhancing efficiency and reducing emissions[26].

I.4.1. Components of ICEs

The internal combustion engine in cars operates by burning fuel within a specialized chamber known as the combustion chamber to generate kinetic energy. This engine consists of various components that can be categorized into two main types: fixed components and moving components [25–28]

e. Fixed Components:

- *Cylinder Block*: The cylinder block serves as the fundamental component of the engine, providing the chamber for fuel combustion and guiding piston movement to regulate pressure on the exhaust resulting from fuel combustion. Typically, it is crafted from high-quality cast iron through casting methods to ensure durability under high pressure and temperature conditions.
- *Cylinder Head Cover*: Positioned atop the engine cylinder, the cylinder head cover is a detachable lid that seals the cylinder block, preventing gas ingress and egress.
- *Spark Plug*: A spark plug is employed to initiate the combustion process within the combustion chamber by creating a spark, which ignites the fuel-air mixture.
- *Crankcase*: Serving as the primary framework of the engine, the crankcase accommodates the cylinder, crankshaft, and piston assembly, with engine oil utilized for cooling purposes.
- *Fuel Injector*: Responsible for injecting fuel into the combustion chamber under extreme pressure, the fuel injector aids in the efficient mixing of fuel with air.

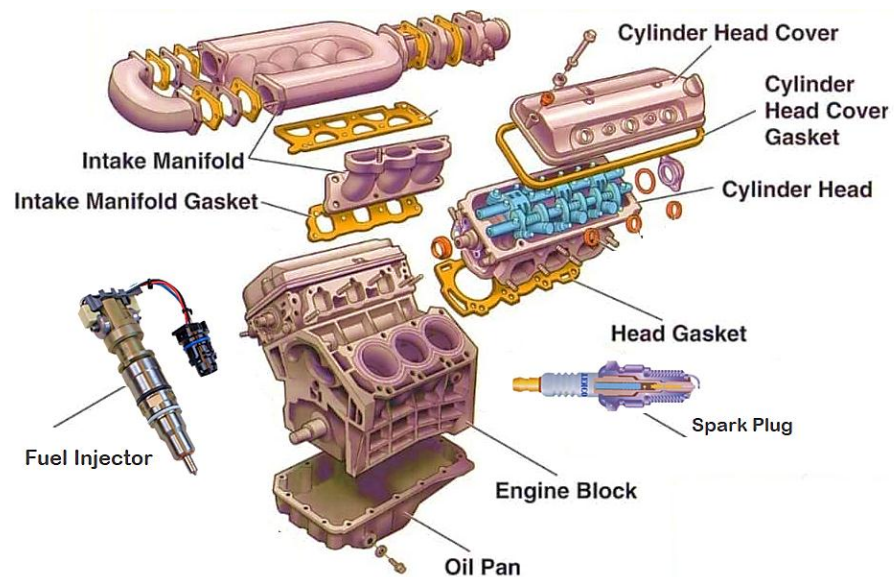


Figure 4 The Fixed Components of IC engine[59]

f. Moving Components:

- Piston: Located within the cylinder, the piston moves reciprocally to transmit power via the connecting rod.
- ConnectingRod: Connecting the piston to the crankshaft, the connecting rod converts the reciprocating motion of the piston into rotational motion.



Figure 5 Engine Pistons and Connecting Rods[59]

- Crankshaft: The crankshaft receives motion from the connecting rod and converts it into rotational energy.

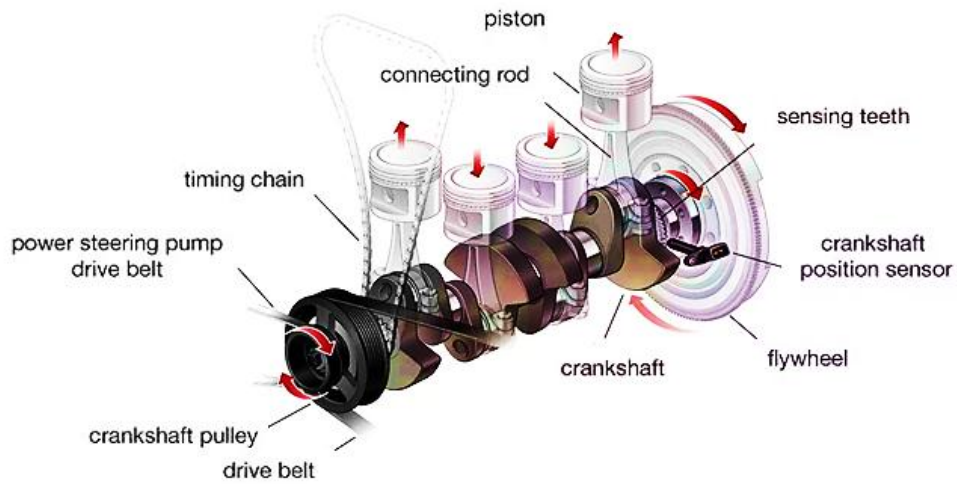


Figure 6 Engine Crankshaft [60]

- Valves: Typically, each cylinder within the engine contains two valves: one for regulating fuel and air intake and the other for managing the exhaust gases resulting from the combustion process.

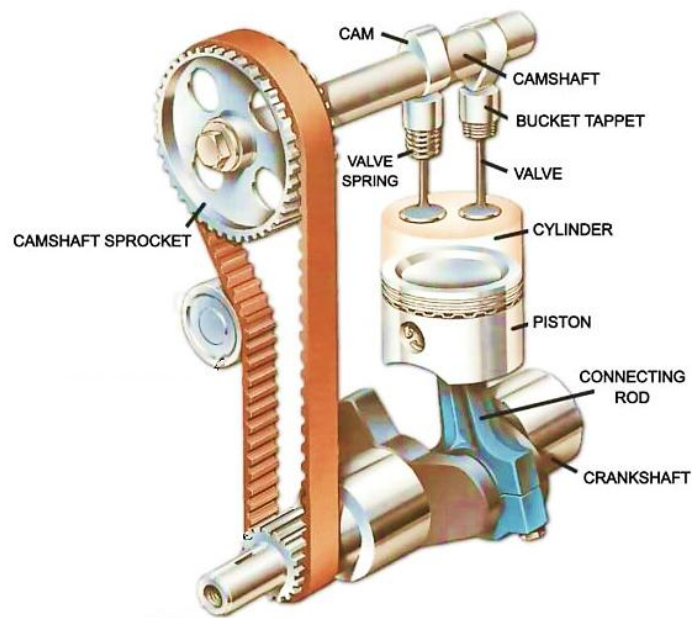


Figure 7 Engine Valves[61]

- EngineBearings: Engine bearings are situated between moving components such as the connecting rod, piston, and crankshaft to reduce friction during operation.

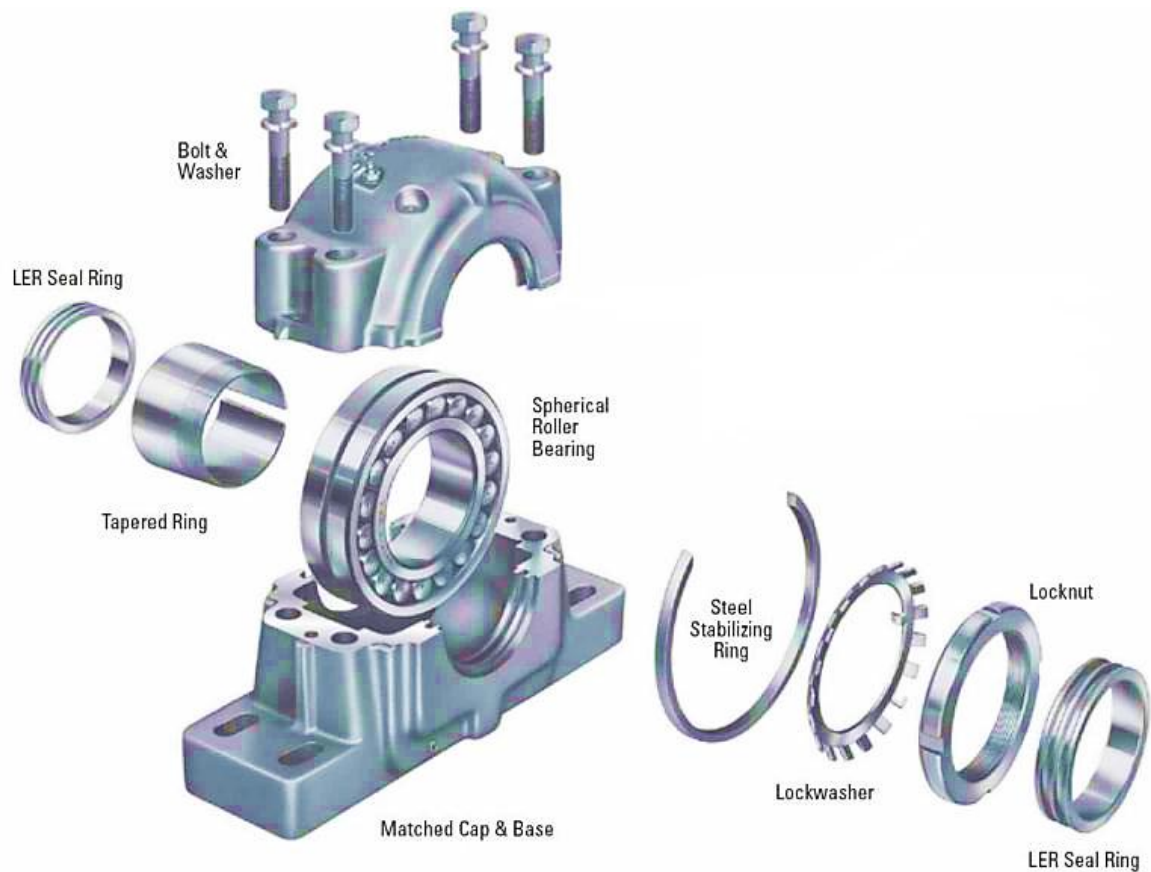


Figure 8 Engine Bearings [61]

I.4.2. Combustion System in IC Engines

The combustion system in internal combustion engines encompasses several crucial subsystems that facilitate engine operation and efficiency. These subsystems, often referred to as systems, consist of various components working in tandem to execute specific functions essential for engine performance.

a. Cooling System:

The cooling system is crucial for regulating the engine's temperature, ensuring it remains within optimal operating conditions. By dissipating excess heat generated during the combustion process, this system facilitates efficient engine performance. While older vehicles commonly feature traditional air-cooled systems, utilizing finned surfaces to enhance heat dissipation, modern vehicles predominantly employ liquid cooling systems (*Figure 9*). In these systems, components such as the thermostat, water pump, radiator cap, upper radiator hose, radiator, and lower radiator hose work synergistically to circulate coolant through channels, effectively absorbing and dissipating heat[27].

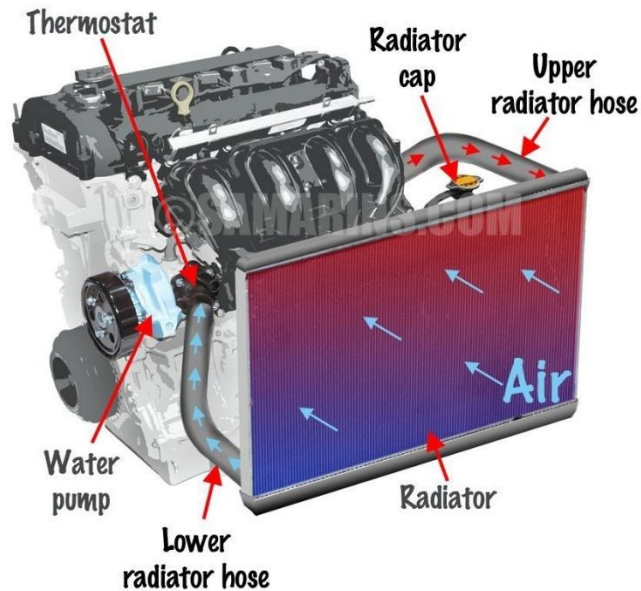


Figure 9 The cooling system in IC engine[62]

b. Lubrication System:

Friction between engine components can lead to wear and damage, necessitating effective lubrication systems, minimizing friction between engine parts. Engine oil plays a dual role[25,27]:

- ***Friction Reduction***: A thin film of oil separates moving components, reducing friction and wear.
- ***Cooling***: Oil circulation helps absorb heat generated by friction, contributing to overall engine temperature control.

The lubrication system comprises several key components (*Figure 10*), including the oil pump, oil filter, and oil pan (sump). These components work together to ensure efficient oil distribution and filtration throughout the engine. There are two main lubrication methods[27]:

- ***Splash Lubrication***: This simpler method, used in older or smaller engines, relies on the crankshaft to splash oil onto engine parts, such as the camshaft, valve rocker, push rod, tappet, crankshaft, connecting rod bearing, big-end bearing, and oil pan (sump), as it rotates.
- ***Pressure Lubrication***: Modern engines employ an oil pump that pressurizes and distributes oil throughout the engine. The oil is pumped through the oil filter to remove impurities, and then it circulates under pressure to lubricate critical components, such as the cam, cylinder, feed to the main bearings, crankshaft bearings, and drifts. This ensures proper lubrication and cooling of all critical engine components.

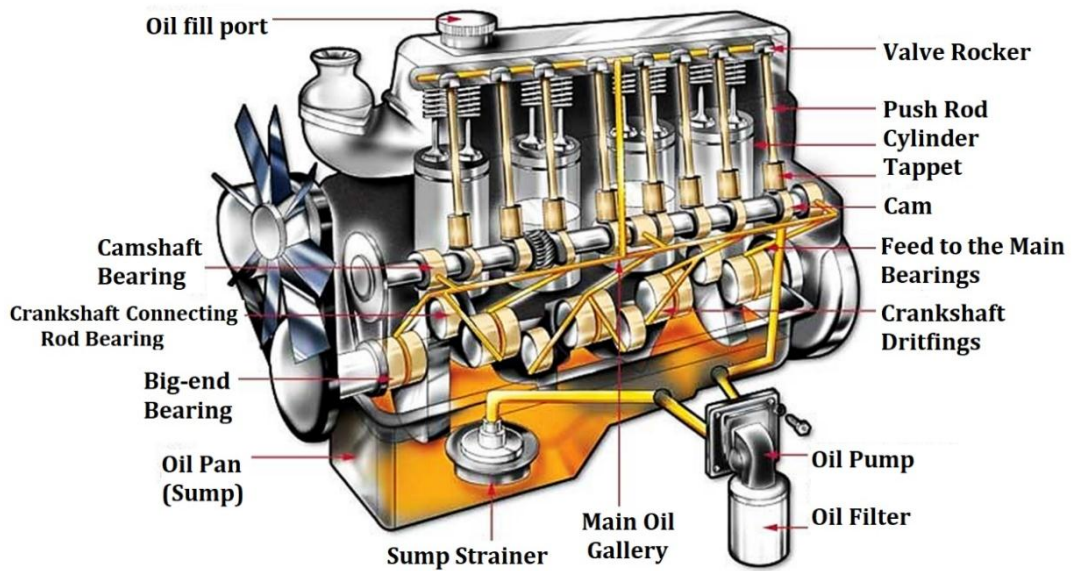


Figure 10 *The Lubrication System in IC engine*[63]

c. Ignition System:

The ignition system, comprising components like spark plugs, plays a pivotal role in initiating combustion within engine cylinders. This system generates high-voltage electric sparks, igniting the air-fuel mixture to ensure efficient engine operation across various speeds and loads (*Figure 11*). Modern ignition systems have evolved significantly, incorporating elements such as the battery earth strap to bodywork, ignition warning light, negative terminal battery, positive terminal, starter solenoid, ignition switch, alternator, and multi-connector plug. These advancements achieve high efficiency and precise timing, thereby enhancing combustion performance and overall engine reliability [21,25,26].

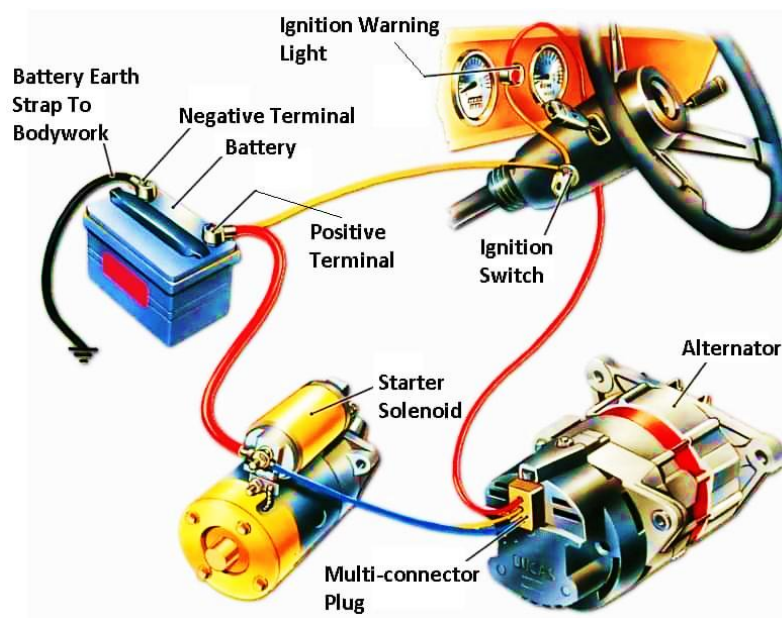


Figure 11 *The ignition system in IC engine* [64]

d. Fuel System:

Fuel systems deliver the required air-fuel mixture to engine cylinders, maintaining the appropriate fuel-to-air ratio for combustion. Different fuel systems, such as carburetors in traditional vehicles and fuel injection systems in modern cars, cater to varying engine requirements and fuel types, including gasoline and diesel[28].

e. Starting System:

The starting system, centered around the starter motor, initiates engine operation by engaging the starter gear with the flywheel gear. Key components of this system include the starter circuit, battery, ignition switch, starter safety switch, control circuit, solenoid, and starter motor (*Figure 12*). When the ignition switch is turned on, it activates the control circuit, which in turn engages the solenoid. This engagement allows current to flow from the battery to the starter motor, causing it to crank the engine and initiate combustion. This coordinated action ensures a smooth and efficient engine startup[21,26].

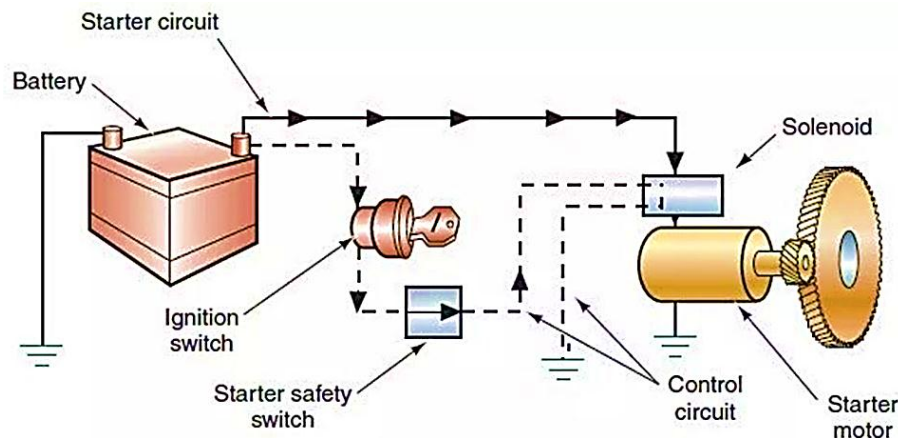


Figure 12 The starting system in IC engine[65]

f. Generation and Charging System:

The generation and charging system ensures a continuous supply of electrical power to various vehicle components by converting mechanical energy from the engine into electrical energy. This system includes the alternator, voltage regulator, battery, and starter motor, along with components such as the main fuse block, accessory fuse block, battery terminal, battery cable, charge indicator, and alternator drive belt (*Figure 13*). The alternator generates electricity, which charges the battery and powers the vehicle's electrical systems and accessories. The voltage regulator maintains consistent voltage levels, while the battery stores energy and powers the starter motor to initiate engine operation. This integrated system ensures the vehicle's electrical needs are met efficiently [26,27].

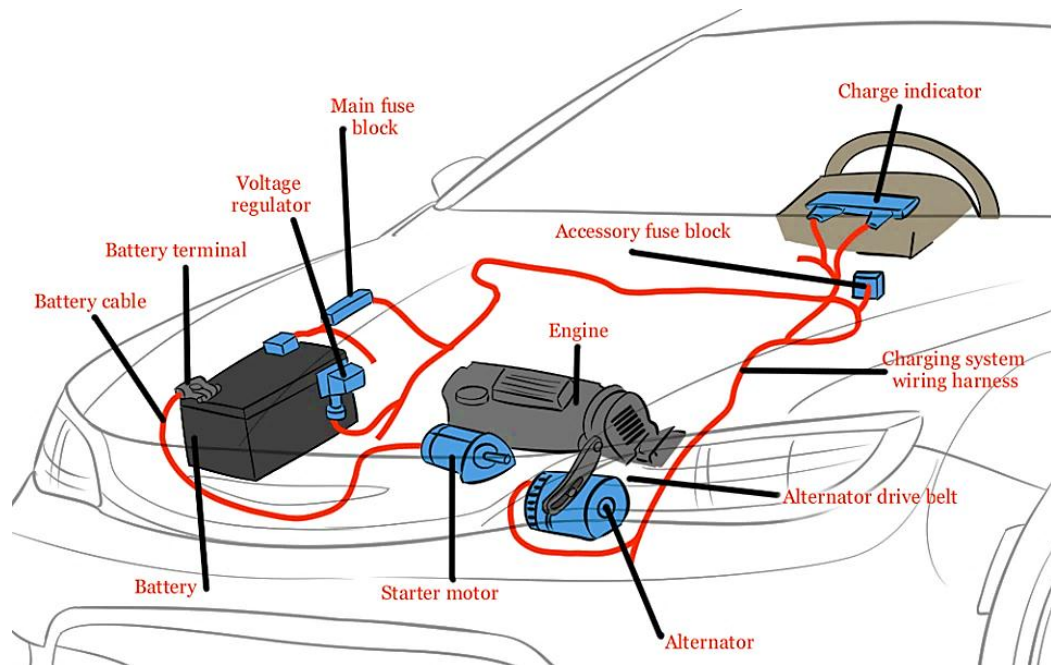


Figure 13 The generation and charging system in IC engine [66]

These subsystems collectively contribute to the efficient operation and performance of internal combustion engines, underscoring their significance in automotive engineering.

I.4.3. Operating Principle of IC Engines

The operation of internal combustion (IC) engines is based on the combustion of a fuel-air mixture within a combustion chamber, generating energy that is converted into kinetic energy to power the engine and subsequently move the vehicle. The operation of an IC engine can be divided into four main steps (*Figure 14*)[25–28]:

- *Intake Stroke*: The cycle begins with the piston moving from its highest point (top dead center) to its lowest point (bottom dead center). During this movement, the intake valve opens, allowing a mixture of air and fuel to enter the combustion chamber. Even a small volume of fuel can be sufficient to cause combustion due to its energy content.
- *Compression Stroke*: The piston then moves upward, compressing the air-fuel mixture. This compression increases the mixture's temperature and pressure, enhancing the efficiency of the combustion process.
- *Power Stroke*: At the top of the compression stroke, the spark plug ignites the compressed air-fuel mixture (in spark-ignition engines), causing it to combust. This combustion generates a rapid increase in temperature and pressure, producing a high-energy force that pushes the piston downward, generating mechanical work.

- *Exhaust Stroke*: Finally, the piston moves back up to its highest point, and the exhaust valve opens. This allows the combustion products (exhaust gases) to be expelled from the combustion chamber. The cycle then repeats with the intake of a new air-fuel mixture.

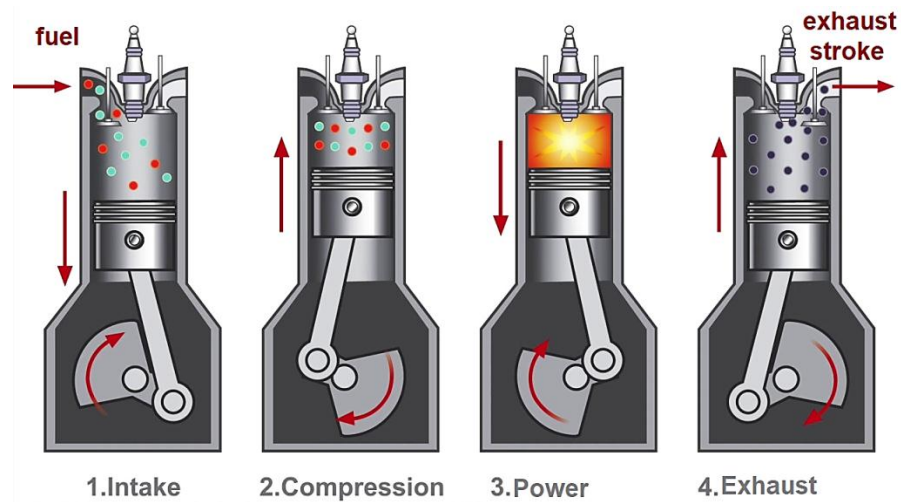


Figure 14 The operation of internal combustion engines [67]

These steps collectively enable the engine to convert chemical energy from the fuel into mechanical energy, propelling the vehicle.

I.4.4 Types of Hydrogen Tanks

There are five types of gas tanks that can be used for both stationary and mobile applications to store hydrogen.

Type 1

This is the most common gas tank, which is a simple cylinder made of steel. The operating pressure is from 200 to 300 bar, and it is typically used for industrial applications. The density of such a type 1 storage is around 15 grams per liter.

Type 2

This type of tank is an improvement over type 1, as it has additional fiberglass reinforcement on the outside, which increases its stability and allows gas storage at a higher pressure. The operating pressure for this tank is typically 100 to 500 bars, and it is mainly used in industrial applications. The density of hydrogen in a type 2 tank is around 20 grams per liter.

Type 3

This is where the interesting tanks for hydrogen begin. The inner liner of this tank is made of aluminum, and it is often found in vehicles. Type 3 tanks can store hydrogen at pressures up to 350 bar, and the typical density is 25 grams per liter.

Type 4

This type of tank is a further development of the type 3 tank, with a plastic bladder inside to seal off the hydrogen. This allows for greater expansion than the aluminum liner and enables the tank to contain a higher pressure of hydrogen, leading to a higher density, typically around 40 grams per liter at an operating pressure of up to 875 bar. Type 4 tanks are commonly used in the passenger car and heavy-duty commercial vehicle sectors.

Type 5

This is the most exotic type of hydrogen storage tank and has no inside bladder, polyamide, or aluminum. The matrix that makes the gas seal is the only component, which presents a significant challenge with hydrogen as it can migrate through even the dense matrices. The density of hydrogen in a type 5 tank is around 20 grams per liter.

I.5. Conclusion

The chapter on internal combustion engines offers a detailed exploration of this pivotal technology. It starts by defining internal combustion engines as devices that convert the chemical energy stored in fuel into kinetic energy through controlled combustion inside cylinders. The discussion then covers various types of internal combustion engines, such as gasoline and diesel engines, as well as four-stroke and two-stroke configurations, explaining their basic principles and applications. The chapter proceeds to explain the fundamental combustion process, describing how fuel mixes with air, ignites, and generates pressure to move pistons and, consequently, the crankshaft, creating mechanical energy. It also examines critical components like cylinders, pistons, valves, crankshafts, fuel systems, and ignition systems, highlighting their roles in ensuring engine efficiency and performance. Technological advancements in combustion techniques, materials, and electronic controls are emphasized for their contributions to improving efficiency, reducing emissions, and enhancing overall engine performance. Moreover, the chapter addresses challenges faced by internal combustion engines, such as emissions regulations and the need for better fuel efficiency. It also explores future trends, including electric engines, hybrid technologies, and alternative fuels, illustrating the ongoing evolution and significance of internal combustion engines in modern technology, transportation, and energy sectors.

CHAPTER II

Energy and Exergy Analyses

CHAPTER II

Energy and Exergy Analyses

Thermodynamics serves as a fundamental framework for understanding system performance and energy efficiency. Moreover, energetic analysis based on the first law of thermodynamics, involves balancing input and output energy within a system. This analysis categorizes outputs into useful products and waste. Furthermore, efficiencies serve as crucial metrics for comparison. Additionally, exergy analysis draws upon the second law of thermodynamics and goes beyond energy quantity to consider energy quality. It provides insights into how closely actual performance aligns with theoretical ideals, highlighting reasons and locations of thermodynamic losses more clearly than energy analysis alone. Furthermore, exergy analysis considers the impact of the built environment on the natural environment, offering valuable insights for sustainable energy utilization and environmental management.

II.1. The First Law of Thermodynamics

II.1.1. Energy Change

Energy is the ability of a system to perform work. It includes kinetic energy (KE), potential energy (PE), and internal energy (U), which encompasses thermal, chemical, and nuclear energies. When there are no influences from magnetic fields, electric fields, or surface tension, the total energy change of a system is determined by comparing the system's energy at the beginning and end of the process. This can be expressed mathematically [29-33]:

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state} \quad (\text{II-1})$$

$$\Delta E = E_2 - E_1 = \Delta U + \Delta KE + \Delta PE \quad (\text{II-2})$$

The internal energy change

$$\Delta U = m(u_2 - u_1) \quad (\text{II-3})$$

The kinetic energy change

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2) \quad (\text{II-4})$$

The potential energy change

$$\Delta PE = \frac{1}{2}mg(z_2 - z_1) \quad (\text{II-5})$$

For most cases, the effects of potential and kinetic energy changes are neglected and the energy change is due to the internal energy change:

$$\Delta E = \Delta U = m(u_2 - u_1) \quad (\text{II-6})$$

Energy per unit of time is the rate of energy and is expressed as:

$$\dot{E} = \frac{E}{\Delta t} \quad (\text{II-7})$$

Energy per unit mass is called specific energy:

$$e = \frac{E}{m} \quad (\text{II-8})$$

II.1.2. Energy Transfer

Energy can be transferred to or from a system in three ways: through mass, heat, and work. Here's a brief overview of each form of energy transfer [30-32,34]:

a. Mass Transfer

The amount of mass entering a system loads energy with it, and the energy of the system increases. Likewise, the mass leaving a system decreases the energy content of the system. The mass and energy can be converted into one another according to the equation proposed by Einstein; $E = mc^2$. When a fluid flows into a system at a mass flow rate of \dot{m} (kg/s), the rate of flow energy entering is equal to mass times enthalpy $\dot{m}h$ (kW).

b. Heat Transfer

Heat (Q) transfer to a system during a process increases the energy of the internal energy of the system, while heat transfer from a system reduces it since the energy transferred outside as heat comes from the energy of the molecules of the system. Heat is generally the thermal form of energy, and it always requires a temperature difference for its transfer. Higher temperature differences obviously provide higher heat transfer rates. Heat or heat transfer has the same unit as energy.

c. Work

Work (W) is the energy that is transferred by a difference in pressure or force of any kind and is subdivided into shaft work and flow work. Shaft work is mechanical energy applied to power a mechanism such as a turbine, compressor, or pump. Work transfer to a system increases the energy of the system, and work transfer from a system decreases it since the energy transferred out as work comes from the energy contained in the system.

These processes are illustrated in *Figure 15*, which depicts energy transfer by work, heat, and mass.

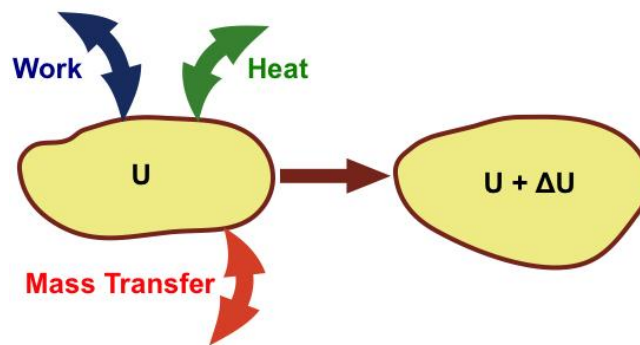


Figure 15 Energy transfer by work, heat and mass

II.1.3. The First Law of Thermodynamics

The first law of thermodynamics, also known as the law of energy conservation, states that the net change in the total energy of a system during a process is equal to the difference between the total energy entering and the total energy leaving the system. This principle can be expressed for any general system, emphasizing that energy cannot be created or destroyed, only transferred or transformed. The energy balance equation for this law can be detailed as follows [30-32]:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad (\text{II-9})$$

In rate form;

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (\text{II-10})$$

For a closed system, undergoing a process between initial and final states with heat and work interactions with the surroundings:

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta U + \Delta KE + \Delta PE \quad (\text{II-11})$$

If there is no change in kinetic and potential energies:

$$(Q_{in} + W_{in}) - (Q_{out} + W_{out}) = \Delta U = m(u_2 - u_1) \quad (\text{II-12})$$

In a steady-flow process, the total mass and energy content within the control volume remain constant, and the initial and final states of the system are identical. Under these conditions, the first law of thermodynamics can be formulated using the balance equation as follows [30, 32]:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = 0 \quad (\text{II-13})$$

$$\dot{E}_{in} = \dot{E}_{out} \quad (\text{II-14})$$

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m} \left(h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right) = \dot{Q}_{out} + \dot{W}_{out} + \dot{m} \left(h_{out} + \frac{V_{out}^2}{2} + gz_{out} \right) \quad (\text{II-15})$$

If the changes in kinetic and potential energies are considered negligible, it results in

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}h_{out} \quad (\text{II-16})$$

Consider an unsteady-flow process, assuming uniform flow conditions, the mass and energy balance relations may be written as [30]:

$$m_{in} - m_{out} = m_2 - m_1 \quad (\text{II-17})$$

$$E_{in} - E_{out} = \Delta E_{system} \quad (\text{II-18})$$

$$\begin{aligned} Q_{in} + W_{in} + m_{in} \left(h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right) - Q_{out} - W_{out} - m_{out} \left(h_{out} + \frac{V_{out}^2}{2} + gz_{out} \right) \\ = m_2 u_2 - m_1 u_1 \end{aligned} \quad (\text{II-19})$$

II.1.4. Energy Efficiencies

One of the most commonly used concepts in thermodynamics is efficiency (η), which measures how effectively an energy conversion or transfer process is performed. Generally, the definition of energy efficiency is grounded in the first law of thermodynamics. Efficiency can take different forms and names depending on the type of the system. It can be expressed as follows [32, 35]:

$$\eta = \frac{\text{Energy output}}{\text{Energy input}} = \frac{E_{out}}{E_{in}} = 1 - \frac{E_{loss}}{E_{in}} \quad (\text{II-20})$$

Or in rate form:

$$\eta = \frac{\dot{E}_{out}}{\dot{E}_{in}} = 1 - \frac{\dot{E}_{loss}}{\dot{E}_{in}} \quad (\text{II-21})$$

II.1.5. Heating Values

The heating value of fuel represents the amount of heat produced per unit mass of fuel at room temperature when it is completely burned, and the combustion products are cooled to room temperature (298 K). Since most fuels contain hydrogen, which forms water when reacting with oxygen, the heating value varies based on whether the water in the combustion products is in liquid or vapor form. The heating value is referred to as the lower heating value (LHV) when the water leaves as vapor and the higher heating value (HHV) when the water in the combustion gases is fully condensed, recovering the heat of vaporization. The difference between the higher and lower heating values of the fuel is equal to the product of the amount of water produced and the enthalpy of vaporization of water at room temperature. In vehicles and jet engines, efficiency is usually based on LHV because water commonly exits as vapor in the exhaust gases, making it impractical to recover the heat of vaporization [30, 32].

II.1.6. Combustion Efficiency

Generally, the efficiency of equipment involving fuel combustion is determined by the heating value of the fuel. This value represents the amount of heat released when a unit of fuel at room temperature (298 K) is completely burned, with the combustion products then cooled to room temperature. The performance of combustion equipment can be described by combustion efficiency, which is expressed as [30, 32]:

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}} \quad (\text{II-22})$$

$$\eta_{combustion} = \frac{\dot{Q}_{released}}{\dot{m}_{fuel} HV} \quad (\text{II-23})$$

Where $\dot{Q}_{released}$ is the rate of heat released during a combustion process.

In this context, the losses in the burner are primarily due to heat escaping through the walls and incomplete combustion. These losses can be evaluated using the concept of LHV (Lower

Heating Value) efficiency, which is the ratio of useful energy produced in the combustion chamber to the heating value of the fuel [36].

$$\eta_c = \frac{\text{useful energy}}{LHV} \quad (\text{II-24})$$

$$\eta_c = \frac{LHV - \text{losses by walls} - \text{losses by incomplete combustion}}{LHV} \quad (\text{II-25})$$

A combustion efficiency of 100% refers that the heat quantity released through a combustion process is equal to the heating value of the fuel[32].

II.2. Limitations of the First Law:

The first law of thermodynamics, known as the law of energy conservation, states that energy cannot be created or destroyed during a process. However, it doesn't tell us which direction a process will naturally occur in, such as whether it's reversible. Additionally, it doesn't explain why heat can't be completely converted into work in a thermodynamic process, or why mixtures don't separate on their own. To address these questions and characterize energy availability, we need another principle. This is where the second law of thermodynamics comes in [37].

II.3. The Second Law of Thermodynamics (SLT)

The first law of thermodynamics is valuable for analyzing efficiencies but doesn't explicitly address thermodynamic irreversibility. On the other hand, the second law of thermodynamics introduces the concept that energy possesses both quantity and quality. It explains that processes tend to occur naturally in the direction of decreasing energy quality. This law allows us to quantify thermodynamic irreversibility, focusing on entropy production and the irreversibilities in processes that result in energy loss. Overall, there are various statements of the second law, with two classical ones being particularly notable [31,37-40]:

- The Kelvin–Planck postulate: “It is impossible to construct a device that works in a cycle (e.g., heat engine) and produces no other effect than the production of work and the transfer of heat from a single body”. This simply shows the impossibility of having a heat engine with a thermal efficiency of 100%.
- The Clausius postulate: “Heat can never pass from a cooler to a heater body without some other change, connected therewith, occurring at the same time”. This simply shows the impossibility of running a refrigerator or heat pump without any work input.

In last contracts, much endeavor has been devoted to minimizing the entropy generation (irreversibility) in thermodynamic systems and applications. The second law of thermodynamics is known as a helpful tool in determining the following:

- Direction of process,
- Behavior of system,
- Irreversibility level,
- Actual performance,
- Effect of surroundings,
- Effect of varying operating conditions and state properties,
- Operational possibilities.

Therefore, the second law of thermodynamics appears to establish a direct connection between entropy and the usefulness of energy, providing a means to assess energy quality within combustion systems. As a result, the second law offers a comprehensive understanding of the thermodynamic processes involved in combustion. Furthermore, the analysis based on the second law has found widespread applications across various fields, extending beyond traditional engineering thermodynamic applications to include economics, sociology, ecology, and environmental studies [32, 40].

II.3.1. Entropy

Entropy is a property that quantifies the degree of disorder or randomness within a system. It can be defined as a thermodynamic property that measures the level of randomness or disorder of the molecules within a system. Similar to internal energy and enthalpy, entropy is also a state function, meaning that changes in entropy only depend on the initial and final states of the thermodynamic system. According to the second law of thermodynamics, the entropy of the universe always increases, meaning that every process that occurs in the universe leads to an overall increase in entropy. The Clausius inequality, derived from the second law, encapsulates this concept [32, 41-43].

$$\oint \frac{\delta Q}{T} \leq 0 \quad (\text{II-26})$$

The ratio Q/T is the entropy transfer related by Q . The entropy (S) introduced by Rudolf Clausius (1822- 1888), is defined as:

$$dS = \left(\frac{\delta Q}{T} \right)_{int rev} \quad (\text{II-27})$$

The inequality mentioned in the preceding relations is a constant reminder that the entropy change of a closed system during an irreversible process will always be greater than the entropy transfer. This means that during an irreversible process, some entropy is generated or created. This generation of entropy occurs solely due to the presence of irreversibilities and is not an inherent property of the system itself. The term used to describe this phenomenon is entropy generation (S_{gen}), which represents the entropy created in a process. In a closed system, the difference between the entropy change and the entropy transfer is equal to the entropy generation, and this relationship can be expressed as follows:

$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right) + S_{gen} \quad (II-28)$$

Where;

The entropy change is greater than the entropy transfer by an amount equal to the entropy produced during a process in a system, and the entropy balance is given as:

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} \quad (II-29)$$

Entropy can be transferred by heat and mass. Entropy transfer by heat is defined as:

$$S_{heat} = \frac{Q}{T} \quad (II-30)$$

Entropy transfer by mass is expressed as:

$$S_{mass} = ms \quad (II-31)$$

The entropy balance in Equation (II-29) can be expressed in the rate form as:

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \frac{dS_{system}}{dt} \quad (II-32)$$

The entropy generation increases as the range of irreversibilities increases. Hence, entropy generation can be employed as a quantitative measure of irreversibilities attached with a process. Additionally, it is used to define standards for the performance of engineering devices.

a. The entropy transport equation

The flow field and the distribution of scalar properties, such as temperature and mass fraction of species, are determined through numerical analyses of the governing equations. Based on these flow and scalar field distributions, the rate of entropy generation can be calculated using the entropy transport equation. This equation can be expressed in the following form [44]:

$$T\rho \frac{Ds}{Dt} = \rho \frac{De}{Dt} + p\rho \frac{Dv}{Dt} - \sum_{\alpha=1}^{N_s} \mu_{\alpha}\rho \frac{DY_{\alpha}}{Dt} \quad (\text{II-33})$$

The D/Dt indicates the material derivative;

$$D/Dt = \partial/\partial t + u_i \partial/\partial x_i \quad (\text{II-34})$$

μ_{α} indicates the chemical potential;

$$\mu_{\alpha} = h_{\alpha} - Ts_{\alpha}^o \quad (\text{II-35})$$

In which;

$$s_{\alpha}^o = \frac{1}{M_{\alpha}} \left(\frac{\partial S}{\partial n_{\alpha}} \right)_{T,p,n_{\beta}(\beta \neq \alpha)} \quad (\text{II-36})$$

s_{α}^o is the partial entropy, n_{α} and M_{α} are the number of moles and molecular mass of species α , respectively. S denotes the entropy.

$$S = ms = m \sum_{\alpha=1}^{N_s} Y_{\alpha} s_{\alpha}^o \quad (\text{II-37})$$

Where m is the total mass. For an ideal gas, the partial entropy can be defined in terms of entropy of pure substance as:

$$s_{\alpha}^o = s_{\alpha} - R_{\alpha} \ln X_{\alpha} \quad (\text{II-38})$$

In this equation, s_{α}^o denotes the entropy of pure species α , X_{α} denotes the mole fraction of species α and R_{α} is the gas constant for species α ($R_{\alpha} = R_u/M_{\alpha}$) and R_u is the universal gas constant. In Equation (II-35), h_{α} is the enthalpy of species α ,

$$h_\alpha = h_\alpha^0 + \int_{T_r}^T c_{p\alpha}(T')dT' \quad (\text{II-39})$$

In which h_α^0 denotes the enthalpy of species α at reference temperature T_r and $c_{p\alpha}$ represents specific heat at constant pressure for species α . By substituting for De/Dt and DY_α/Dt from conservation equations of energy and chemical species mass fraction, we obtain a transport equation for entropy:

$$\frac{\partial \rho s}{\partial t} + \frac{\partial \rho u_i s}{\partial x_i} = \frac{1}{T} \left[\tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\partial \dot{q}_i}{\partial x_i} + \sum_{\alpha=1}^{N_s} \mu_\alpha \frac{\partial J_i^\alpha}{\partial x_i} - \sum_{\alpha=1}^{N_s} \rho \mu_\alpha S_{\omega_\alpha} \right] \quad (\text{II-40})$$

In this equation, τ_{ij} and J_i^α denote the viscous stress tensor and the scalar fluxes, respectively. Assuming a Newtonian fluid and Fick's law of diffusion, these are represented as:

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) \quad (\text{II-41})$$

$$J_i^\alpha = -\gamma_\alpha \frac{\partial Y_\alpha}{\partial x_i} \quad (\text{II-42})$$

Where, μ is the molecular viscosity and γ_α denotes the mass molecular diffusivity of species α . In Equation (II-40), S_{ω_α} is a source term due to chemical reaction, defined as:

$$S_{\omega_\alpha} = \frac{1}{\rho} M_\alpha \dot{\omega}_\alpha \quad (\text{II-43})$$

$\dot{\omega}_\alpha$ is the molar rate of production/destruction of species α due to chemical reactions. Also in Equation (II-40), \dot{q}_i is the energy flux term, expressed as:

$$\dot{q}_i = -\lambda \frac{\partial T}{\partial x_i} + \sum_{\alpha=1}^{N_s} h_\alpha J_i^\alpha = -\lambda \frac{\partial T}{\partial x_i} - \sum_{\alpha=1}^{N_s} \gamma_\alpha h_\alpha \frac{\partial Y_\alpha}{\partial x_i} \quad (\text{II-44})$$

Another useful form of entropy transport equation can be obtained:

$$\begin{aligned} \frac{\partial \rho s}{\partial t} + \frac{\partial \rho u_i s}{\partial x_i} &= \frac{\partial}{\partial x_i} \left(\gamma \frac{\partial s}{\partial x_i} \right) + \frac{1}{T} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\rho}{T} \sum_{\alpha=1}^{N_s} \mu_\alpha S_{\omega_\alpha} + \frac{\lambda}{T^2} \frac{\partial T}{\partial x_i} \frac{\partial T}{\partial x_i} \\ &+ \sum_{\alpha=1}^{N_s} \gamma R_\alpha \frac{1}{Y_\alpha} \frac{\partial Y_\alpha}{\partial x_i} \frac{\partial Y_\alpha}{\partial x_i} - \sum_{\alpha=1}^{N_s} \gamma R_\alpha \frac{1}{n} \frac{\partial Y_\alpha}{\partial x_i} \frac{\partial n}{\partial x_i} \end{aligned} \quad (\text{II-45})$$

In this equation, the last five terms on the RHS constitute the volumetric rate of generation of entropy \dot{S}_g''' [45-47].

$$\dot{S}_g''' = \frac{1}{T} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\rho}{T} \sum_{\alpha=1}^{N_s} \mu_{\alpha} S_{\omega_{\alpha}} + \frac{\lambda}{T^2} \frac{\partial T}{\partial x_i} \frac{\partial T}{\partial x_i} + \sum_{\alpha=1}^{N_s} \gamma R_{\alpha} \frac{1}{Y_{\alpha}} \frac{\partial Y_{\alpha}}{\partial x_i} \frac{\partial Y_{\alpha}}{\partial x_i} - \sum_{\alpha=1}^{N_s} \gamma R_{\alpha} \frac{1}{n} \frac{\partial Y_{\alpha}}{\partial x_i} \frac{\partial n}{\partial x_i} \quad (\text{II-46})$$

As depicted by this equation, the irreversible phenomena contributing to entropy generation include: viscous dissipation, heat conduction, chemical reactions, mass transfer resulting from changes in the mass fraction of individual species, and mass transfer resulting from changes in the total number of moles [48].

II.3.2. Exergy

a. Exergy Definition

In thermodynamics, the exergy of a system refers to the maximum theoretical work that can be obtained when the system reaches equilibrium (thermal, mechanical, and chemical equilibrium) with its surroundings. Unlike energy, exergy is not a conserved property; it is destroyed due to irreversibilities in any process. Exergy analysis involves assessing exergy transfers related to heat, work, and mass transfers, as well as exergy destruction. The magnitude of exergy destruction serves as a quantitative measure of the irreversibilities present in the system. Exergy analysis provides efficiencies that offer a true measure of how closely actual performance approaches the ideal, and it identifies the locations and sources of thermodynamic losses more clearly than energy analysis. Therefore, exergy analysis can aid in the development and optimization of designs [29, 37, 49-50].

For a process stream, its exergy can be decomposed into two terms: physical exergy and chemical exergy. Physical exergy (Ex_{ph}) represents the maximum reversible work achievable when a substance stream is brought from its actual state to the environmental state. Physical processes involve only mechanical and thermal interactions with the environment (T_0, P_0). Assuming that potential and kinetic energy can be disregarded, physical exergy can be defined by the following equation [39, 51,14]:

$$Ex_{ph} = m[(h - h_0) - T_0(s - s_0)] + Q(1 - \frac{T_0}{T}) \quad (\text{II-47})$$

Where, h and s are specific molar enthalpy (kJ/kmol) and specific molar entropy (kJ/kmol K), respectively. h_0 and s_0 are the values of h and s at standard conditions (T_0, P_0).

Chemical exergy (Ex_{ch}) of a substance is the maximum quantity of work attainable by taking it from the environmental state (T_0, P_0) to a full equilibrium with the chosen environment. The molar chemical exergy of an ideal mixture can be written by this Equation as:

$$Ex_{ch_{total}} = \sum_i x_i Ex_{ch_i} + RT_0 \sum_i x_i \ln x_i \quad (\text{II-48})$$

Where, x_i and Ex_{ch_i} are molar fraction and molar chemical exergy (kJ/ kmol), respectively, of each component in the mixture, and R is the universal gas constant. Exergy loss can be evaluated by finding the difference between the exergy of inlet and outlet streams:

$$Ex_{loss} = Ex_{total_{in}} - Ex_{total_{out}} \quad (\text{II-49})$$

Total exergy of stream is taken as the sum of its physical and chemical exergy:

$$Ex_{total_{in}} = Ex_{ph} + Ex_{ch} \quad (\text{II-50})$$

b. Reversibility and Irreversibility

These two concepts are highly significant in the analysis of thermodynamic processes and systems. Reversibility implies that both the system and its surroundings can be restored to their initial states. Irreversibility, on the other hand, involves the destruction of exergy. During an irreversible process, neither the system nor its surroundings can be returned to their initial states due to irreversibilities such as friction, heat rejection, electrical and mechanical effects, and so forth [30-31].

II.4. The Analyses of Combustion Process

Thermodynamics based analyses and performance assessments are applied to the combustion chamber with isothermal wall. In this regard, energy and exergy analyses are applied to the system. The cylinder burner was selected as the control volume. Accordingly, the total inlet and outlet exergy of the control volume are determined in the thermodynamic equilibrium state of this engine.

II.4.1. Energy Analysis

Energy analysis is connected to the first law of thermodynamics through energy balances and efficiencies. It serves as a valuable tool for assessing operating conditions, particularly in optimizing physical and chemical mechanisms within combustion chambers. Moreover, this method is often integrated with other applications, including energy conversion and enhancement. The energy balance equations for a steady system are presented as follows [29, 52]:

$$\sum \dot{E}n_{in} = \sum \dot{E}n_{out} \quad (\text{II-51})$$

$$\dot{E}n_{air} + \dot{E}n_{fuel} = \dot{E}n_W + \dot{E}n_{exh} + \dot{E}n_{loss} \quad (\text{II-52})$$

Where,

$\sum \dot{E}n_{in}$; the total input energy [kW],

$\sum \dot{E}n_{out}$; the total output energy [kW],

$\dot{E}n_{air}$; the energy rate of air [kW],

$\dot{E}n_{fuel}$; the energy rate of fuel [kW],

$\dot{E}n_W$; is the work rate [kW],

$\dot{E}n_{exh}$; the exhaust energy rate [kW],

$\dot{E}n_{loss}$; the energy loss rate [kW].

The air energy rate is written as:

$$\dot{E}n_{air} = \dot{m}_{air} h_{air} = \rho_{air} \dot{V}_{air} h_{air} \quad (\text{II-53})$$

\dot{m}_{air} ; the air mass flow rate [kg/s],

h_{air} ; the air enthalpy [kJ/kg],

\dot{V}_{air} ; the volumetric flow rate of air [m³/s],

ρ_{air} ; the density of air [g/L].

The energy rate of fuel is determined from:

$$\dot{E}n_{fuel} = \dot{m}_{fuel} H_u \quad (\text{II-54})$$

Where;

\dot{m}_{fuel} ; the fuel flow mass rate [kg/s],

H_u ; the Fuel Lower Heating Value (LHV) [kJ/kg].

The work rate of the system is calculated from:

$$\dot{E}n_w = \omega T \quad (\text{II-55})$$

ω ; the angular velocity [rad/s],

T; the torque of the engine [Nm³].

The angular velocity of the engine is given by:

$$\omega = \frac{2\pi n}{60}$$

n; the speed of the engine in revolutions per minute (1800 rpm).

The exhaust energy of the system is determined as follows [52-53]:

$$\dot{E}n_{exh} = \sum_{i=1}^n \dot{m}_i h_i = \dot{m}_{CO} h_{CO} + \dot{m}_{NO_x} h_{NO_x} + \dot{m}_{CO_2} h_{CO_2} + \dots \quad (\text{II-56})$$

\dot{m}_i ; the mass flow rate of chemical species i [kg/s],

h_i ; the enthalpy of the products chemical species i [kJ/kg].

The energy loss rate of the system is found from the energy balance equation as follows:

$$\dot{E}n_{loss} = \dot{E}n_{air} + \dot{E}n_{fuel} - \dot{E}n_w - \dot{E}n_{exh} \quad (\text{II-57})$$

The energy efficiency of the combustion system:

$$\eta_{en} = \left(\frac{\dot{E}n_w}{\dot{E}n_{air} + \dot{E}n_{fuel}} \right) 100 \quad (\text{II-58})$$

II.4.2. Exergy Analysis

Dependence solely on energy analysis isn't sufficient for comprehensively assessing all energy consumption within a reactive system. It also lacks the capability to estimate and compute the energy sources influencing efficiency. Consequently, solely relying on the first law of thermodynamics is inadequate for fully gauging the quality of various energy forms, including volume control. However, exergy analysis, grounded in both the first and second laws of thermodynamics, provides a more holistic understanding. It aids in grasping and enhancing efficiency based on operational parameters, evaluating potential energy and its role in the entire system. Through exergy analysis, sustainable energy quality of any system can be investigated. Its primary aims include determining true system efficiency under diverse operating conditions.

Additionally, the destruction of exergy in a process is directly linked to entropy generation, a principle governed by the second law of thermodynamics. This destruction arises due to irreversibility. The exergy balance equations are outlined as follows [54-55]:

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \dot{E}x_{dest} \quad (\text{II-59})$$

$$\dot{E}x_{air} + \dot{E}x_{fuel} = \dot{E}x_W + \dot{E}x_{exh} + \dot{E}x_{loss} + \dot{E}x_{dest} \quad (\text{II-60})$$

Where;

$\dot{E}x_{in}$; the exergy input rate [kW],

$\dot{E}x_{out}$; the exergy output rate [kW],

$\dot{E}x_{dest}$; the exergy destruction rate [kW],

$\dot{E}x_{air}$; the exergy rate of air [kW],

$\dot{E}x_{fuel}$; the exergy rate of fuel [kW],

$\dot{E}x_W$ is the exergetic work rate [kW],

$\dot{E}x_{exh}$; the exhaust exergy rate [kW],

$\dot{E}x_{loss}$; the exergy loss rate [kW].

The inlet air exergy given by:

$$\dot{E}x_{air} = \dot{E}_{air} c_{p, air, in} \left[(T_{air, in} - T_0) - T_0 \ln \left(\frac{T_{air, in}}{T_0} \right) \right] \quad (\text{II-61})$$

$c_{p, air}$; the specific heat capacity of air [J/(kg.K)],

T_{air} ; the inlet temperature [K],

T_0 ; the reference temperature (298K).

The exergy rate of fuel is as follow:

$$\dot{E}x_{fuel} = \dot{m}_{fuel} H_u \varepsilon_{fuel} \quad (\text{II-62})$$

ε_{fuel} ; the chemical exergy factor of fuel,

The exergetic work rate of the system is equal to energetic work rate as follows:

$$\dot{E}x_w = \dot{E}n_w \quad (\text{II-63})$$

The exhaust exergy of the system is written as:

$$\dot{E}x_{exh} = \sum_{i=1}^n \dot{m}_i (ex_{tm,i} + ex_{ch,i}) \quad (\text{II-64})$$

ex_{tm} ; the specific physical exergy rates of the combustion products [kW],

ex_{ch} ; the specific chemical exergy rates of the combustion products [kW].

The specific thermomechanical (physical) exergy rate of the exhaust gas component is determined from:

$$ex_{tm,i} = [(h_i - h_0) - T_0(s_i - s_0)] = c_{p,i} \left[(T_{exh} - T_0) - T_0 \ln \left(\frac{T_{exh}}{T_0} \right) \right] \quad (\text{II-65})$$

T_{exh} ; the exhaust temperature of the combustion products [K].

The specific chemical exergy rate is found as:

$$ex_{ch,i} = \bar{R}T_0 \ln \left(\frac{y_i}{\sum y_i} \right) \quad (\text{II-66})$$

Where,

R ; the universal gas constant 8.314 [kJ/kmol.K],

y_i ; the mass fraction of chemical specie i .

The exergy loss rate of the system is determined as follows:

$$\dot{E}x_{loss} = Q_w \left(1 - \frac{T_0}{T_w} \right) = \dot{E}n_{loss} \left(1 - \frac{T_0}{T_w} \right) \quad (\text{II-67})$$

Where,

T_w ; the wall temperature [K],

Q_w ; the heat energy loss through the wall during the cooling water [kW].

In this study, we considered all exergy sources to assess the combustion system's destroyed exergy, such as the input exergy of both fuel and air, output exergy of combustion products, and the exergy loss through the burner wall. The destroyed exergy rate equation of the considered combustion system is calculated as follows [54-55]:

$$\dot{E}x_{dest} = \dot{E}x_{air} + \dot{E}x_{fuel} - \dot{E}x_W - \dot{E}x_{exh} - \dot{E}x_{loss} \quad (\text{II-68})$$

The exergy efficiency of the system is given as:

$$\eta_{Ex} = \left(\frac{\dot{E}x_W}{\dot{E}x_{air} + \dot{E}x_{fuel}} \right) 100 \quad (\text{II-69})$$

The entropy generation rate can be given by:

$$S_{gen} = \frac{\dot{E}x_{dest}}{T_0} \quad (\text{II-70})$$

II.5. The Conclusion

The third chapter focuses on the theoretical thermodynamics analysis of combustion process, which based on the first and second thermodynamics law for the turbine combustion chamber. Generally, the first law of thermodynamics is mainly expressed the conservation of energy in the burner. However, the second law of thermodynamics describes the type energy as physical or chemical sources. Indeed, the processes of transport and/or convert of energy by new properties called entropy and exergy. Entropy is a quantitative measure of macroscopic physical processes, and exergy is a measure of the quality and quantity of energy sources in a system. The purpose from these analyses is the calculation of the lost exergy during the combustion chamber, where exergy efficiency assesses the efficiency of combustion by considering the second law of thermodynamics. In addition, we can give solution with some modification in the inlet parameters like the equivalence ratio and preheating the inlet reactive mixture.

In the next chapter, we begin with simulation of the combustion based on the aerothermo chemical combustion parameters. The results obtained in the next chapter exploit to evaluate the thermodynamics parameters that used in after for the improvement of the combustion system.

CHAPTER III

**Application of Energy & Exergy
Analysis in Internal Combustion Engine**

CHAPTER III

Application of Energy & Exergy Analysis in Internal Combustion Engine

Thermodynamics permits describing a system performance, behavior and efficiency for the energy transfer from one form to another. Energetic analysis is based on the first law of thermodynamics, which represents the conservation of energy principle. An energy analysis is primarily a balancing of the input and output amount of energy in an energy conversion system. Energy output can be divided into products and wastes. Efficiencies are usually measured as ratios of energy amounts and are often used to evaluate and compare various systems. Exergy analysis is a powerful thermodynamic analysis relies on the second law of thermodynamics. The second law of thermodynamics confirms that energy has both quality and quantity, and actual processes occur in the direction of decreasing quality of energy.

III.1. Control Volume and Operating Conditions

The present chapter focused on the combustion system, the burner confined the fuel and air injected by two coaxial jets. Actually, we are chosen the cylindrical combustion chamber because it is similar to a gas turbine combustor. Moreover, the combustor configuration is given in this figure:

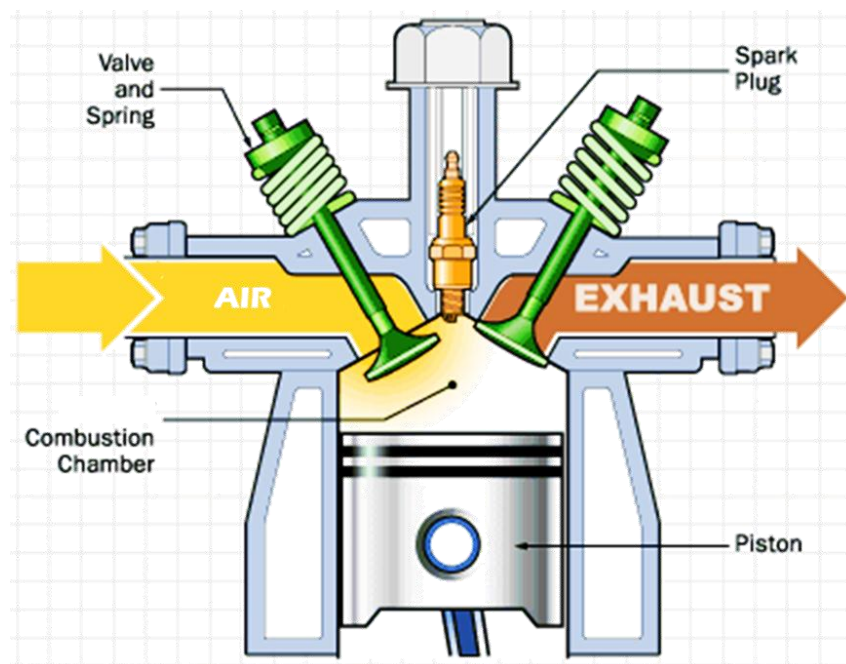


Figure 16 Schema of Engine Combustion Chamber [68]

In this study, we will investigate the numerical simulation for different fuels cases conceding both effects of inlet mass flow and preheating of the fuel. The combustion chamber illustrates in figure 1 is used for all this work with boundary conditions recapitulate in three cases (table 1, 2 ,and table 3).

a. Case1:

In this case, we compute the different energetic parameters using the operating conditions given in table 2. This computation used different fuels for the same inlet parameters to compare the control variables mentioned previously. The table presents the initial properties of various fuels and air used for combustion processes with an equivalent ratio equal 0.9. The high LHV values of methane, hydrogen, and LPG highlight their potential for energy generation, while the specific fuel and air flow rates, along with the temperatures, are critical for optimizing combustion efficiency and minimizing emissions. The equivalence ratio (λ) of 1.11 suggests a lean combustion mixture, contributing to cleaner and more efficient combustion processes.

Table 2 *The Boundary conditions and proprieties of inlet*

Fuel	Chemical formula	LHV [kW]	Q_{fuel} [kg/s]	T_{fuel} [K]	Q_{air} [kg/s]	T_{air} [K]	λ
Methane	CH ₄	350085.12	0,0072	300	0.142	750	1.11
Hydrogen	H ₂	839856.5			0.283		
Biogas	59.50% CH ₄ , 38.5% CO ₂ , 2% N ₂	123463.27			0.050		
Liquid Petroleum Gas (LPG)	C ₃ H ₈ 50% C ₄ H ₁₀ 50 %	321935.25			0.128		

b. Case 2:

This table illustrates the initial properties of various fuels (methane, hydrogen, biogas, and LPG) used in combustion processes under an equivalent ratio (λ) of 0.9, which indicates a lean fuel mixture. Key properties such as the Lower Heating Value (LHV), fuel and air flow rates, and initial temperatures are detailed:

Table 3 The combustion characteristics of preheating fuels

Fuel	T _{fuel} [K]	Q _{fuel} [kg/s]	Q _{air} [kg/s]	T _{air} [K]	λ
Methane	100	0,0072	0.142	750k	1.11
	300				
	500				
	700				
	900				
Hydrogen	100		0.283		
	300				
	500				
	700				
	900				
Biogas	100		0.050		
	300				
	500				
	700				
	900				
LGP	100		0.128		
	300				
	500				
	700				
	900				

c. Case 3:

The current case based on the variation of the inlet mass flow rate of the fuels with same inlet temperature to evaluate the identical parameters of the case 3. The table 4 shows the main variables used for this step:

Table 4 The combustion characteristics of impact mass flow

Fuel	T _{fuel} [K]	Q _{fuel} [kg/s]	Q _{air} [kg/s]	T _{air} [K]	Λ
Methane	300	0.0018	0.036	750	1.11
		0.0036	0.071		
		0.0072	0.142		
		0.009	0.178		
		0.0108	0.213		
Hydrogen		0.0018	0.071		
		0.0036	0.141		

		0.0072	0.283		
		0.009	0.353		
		0.0108	0.424		
Biogas		0.0018	0.013		
		0.0036	0.025		
		0.0072	0.050		
		0.009	0.063		
		0.0108	0.075		
LGP		0.0018	0.032		
		0.0036	0.064		
		0.0072	0.128		
		0.009	0.160		
		0.0108	0.192		

III.2. Results and discussion

In this section, we present and analyze the results of a combustion chamber system, where four different fuels methane, hydrogen, biogas, and liquid petroleum gas (LPG), were tested under identical operating conditions. This investigation aims to evaluate the performance, energetic characteristics of each fuel. The operating conditions, including the equivalent ratio (λ) and air temperature, were kept constant to ensure a fair comparison.

III.2.1. Total Energy flow and Exergy flow, Entropy

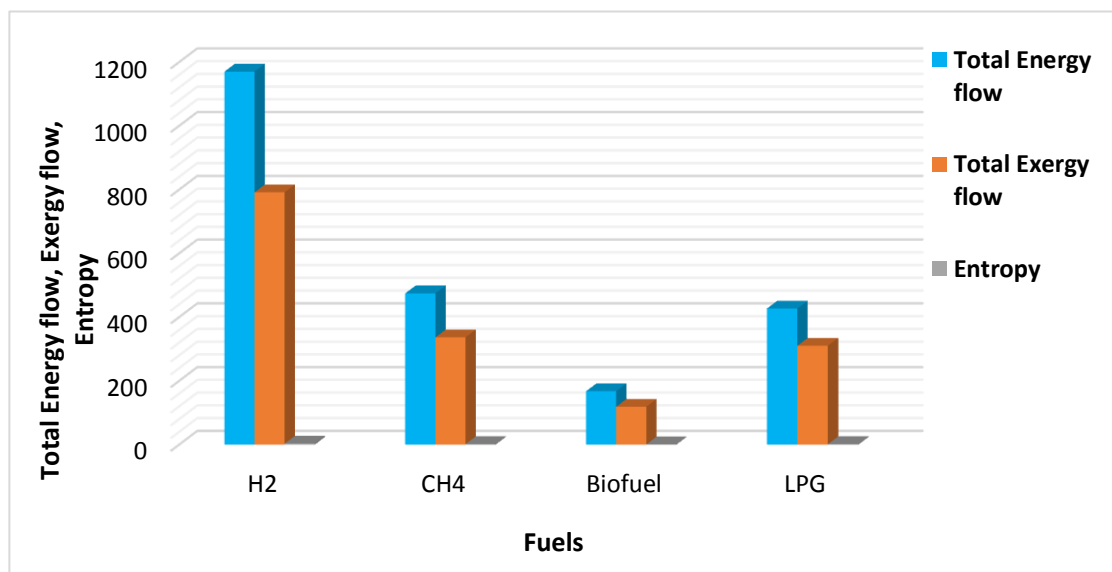


Figure 17 The total energy flow, exergy flow, and entropy generation for considered fuels

The bar charts illustrate the total energy flow, exergy flow, and entropy generation for H₂, CH₄, Biofuel, and LPG, revealing distinct patterns in their energy characteristics and combustion behavior. Hydrogen shows the highest total energy flow, followed by Methane, Biofuel, and LPG. Hydrogen’s high reactivity and low molecular weight result in significant energy release per unit mass. Methane delivers substantial energy output despite its lower density, while Biofuel and LPG release less energy due to their molecular structures and lower efficiency. In addition, exergy flow follows a similar trend, with Hydrogen having the highest exergy output, indicating great potential for useful work extraction. Methane offers considerable exergy, Biofuel provides moderate useful work, and LPG has the lowest potential for useful work. In other hand, Entropy generation differs, with Hydrogen generating the highest entropy, followed by Methane, Biofuel, and LPG. Hydrogen’s reactive combustion leads to significant molecular disorder, while Methane and Biofuel generate less entropy due to their combustion properties. LPG’s controlled combustion produces the least entropy. Generally, hydrogen is the most energy-dense and exergy-rich fuel with the highest entropy generation. Methane balances energy output, exergy, and entropy. Biofuel is moderate in all aspects, while LPG is the least energy-dense and exergy-rich with the lowest entropy generation.

III.2.2. Total Energy flow

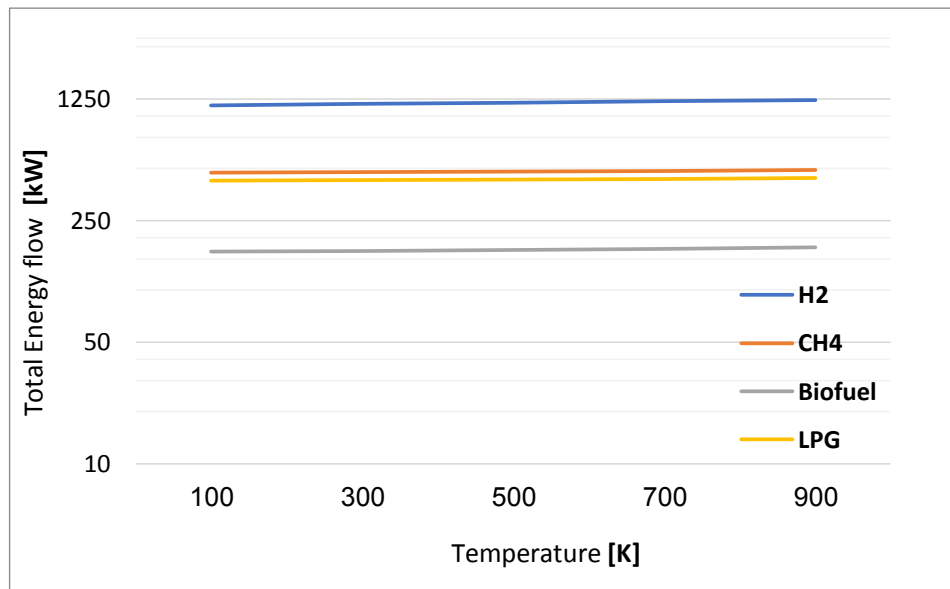


Figure 18 *The total energy flow versus temperature for considered fuels*

The graph in this Figure shows the total energy flow versus temperature for four fuels: H₂, CH₄, LPG, and biofuel. Despite increasing temperatures, the energy flow for each fuel remains relatively stable. Hydrogen has the highest energy flow, around 1100 kW, due to its high energy content. Methane and LPG have slightly lower but similar energy flows, reflecting their efficient combustion. Biofuel shows the lowest energy flow, attributed to its lower energy density. This stability indicates efficient energy release and combustion for each fuel across the temperature range.

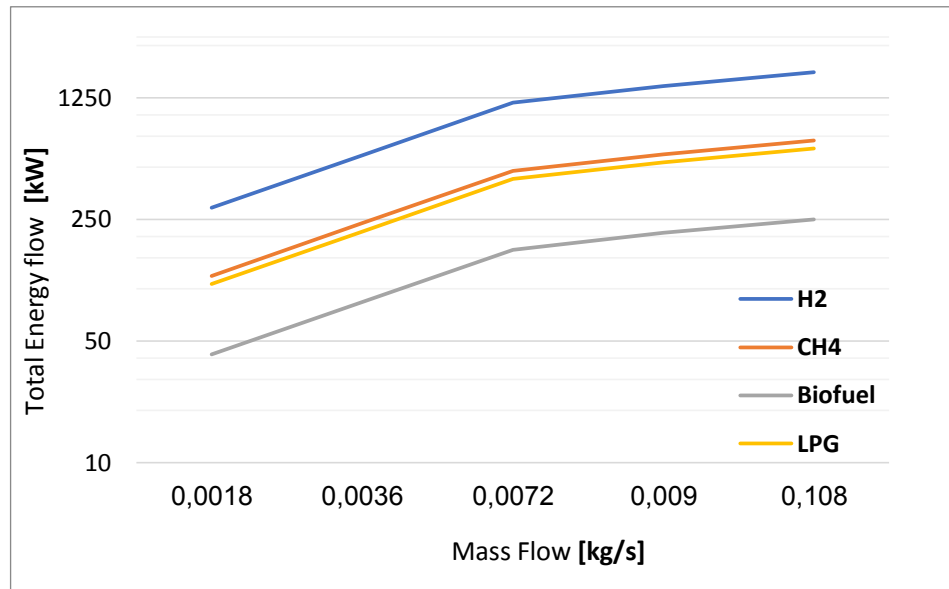


Figure 19 The total energy flow versus mass flow for considered fuels

The graph illustrates the relationship between energy output and mass flow rate for H₂, CH₄, Biofuel, and LPG. It demonstrates that higher mass flow rates lead to increased energy output across all fuels, which aligns with the principle of energy conservation. Hydrogen exhibits the steepest slope, it reaches its maximum energy flow rate at approximately 1754.82 kW, indicating the most significant energy output increase due to its high reactivity. Moreover, Methane follows with a slightly less steep slope, indicating a moderate increase in energy output. Biofuel shows a more gradual increase, suggesting slower energy release owing to its complex molecular structure. Furthermore, LPG displays the gentlest slope. It exhibits the lowest energy flow rate at a mass flow rate of 0.0108 kg/s approximately 639.74 kW, indicating the smallest increase in energy output, likely due to its less efficient combustion process. Overall, the trend of increasing energy output with rising mass flow rate underscores the direct relationship between fuel flow and energy release. These trends are influenced by factors such as fuel composition, combustion efficiency, and system conditions. Understanding these dynamics is crucial for optimizing combustion processes to enhance energy output and efficiency. Each fuel exhibits an optimal mass flow rate for achieving maximum energy output, underscoring the significance of mass flow rate in evaluating the energy potential of different fuels.

III.2.3. Total Exergy flow

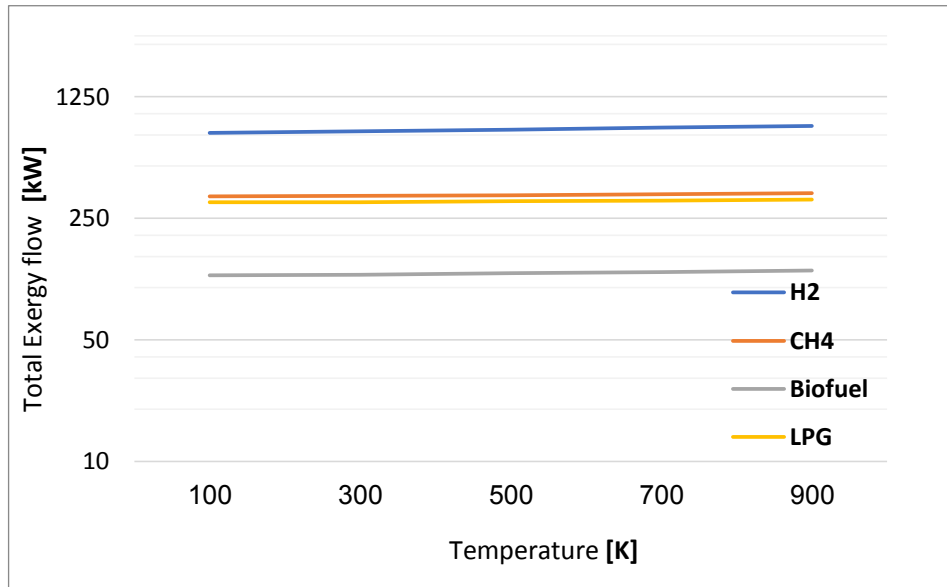


Figure 20 The total exergy flow versus temperature for considered fuels

Figure 20 illustrates the relationship between temperature and exergy flow for various fuels: H₂, CH₄, LPG, and Biofuel. Hydrogen has the highest exergy flow, peaking around 1200 kW at 100 K, and remains stable as the temperature increases. This indicates efficient energy recovery and minimal exergy losses. CH₄ and LPG show similar exergy flows, approximately 300 kW, suggesting comparable combustion characteristics and energy efficiencies. Their exergy flows also remain stable across the temperature range. Biofuel has a significantly lower exergy flow, reflecting its different chemical composition and higher exergy losses during combustion. Overall, Hydrogen stands out for its superior exergy flow, while Methane and LPG exhibit similar moderate performance. Biofuel, though less efficient, provides insights into the characteristics of alternative fuels.

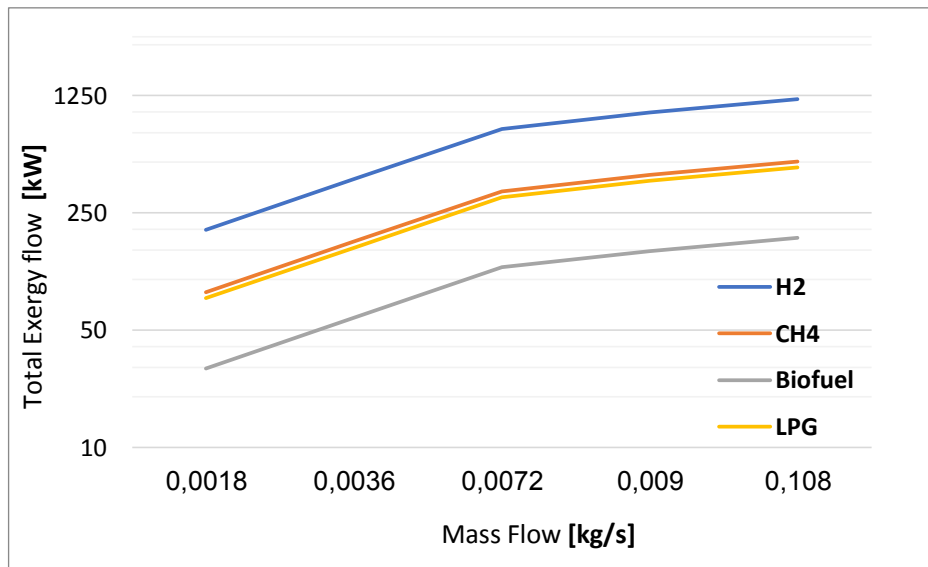


Figure 21 The total exergy flow versus mass flow for considered fuels

Figure 21 offers the relationship between exergy and mass flow rate for H₂, CH₄, Biofuel, and LPG fuels. Exergy, representing the maximum useful work extractable from a system, shows an increasing trend with higher mass flow rates across all fuels. Hydrogen exhibits the most pronounced increase in exergy per unit mass flow rate, reflecting its high reactivity and efficient energy release during combustion. Methane follows with a slightly less steep slope, indicating substantial exergy potential but at a slower rate of increase compared to hydrogen. Biofuel demonstrates a moderate increase in exergy, influenced by its complex molecular structure and combustion characteristics. LPG fuel shows the least steep slope, suggesting lower exergy output per unit mass flow rate, possibly due to less efficient combustion processes and lower energy density. These observations highlight the varying efficiencies and potentials for useful work extraction among different fuels in combustion systems. Factors such as fuel composition, combustion dynamics, and system conditions play critical roles in determining the exergy output. Understanding these relationships is essential for optimizing combustion processes to maximize energy conversion efficiency and overall system performance.

III.2.4. Entropy

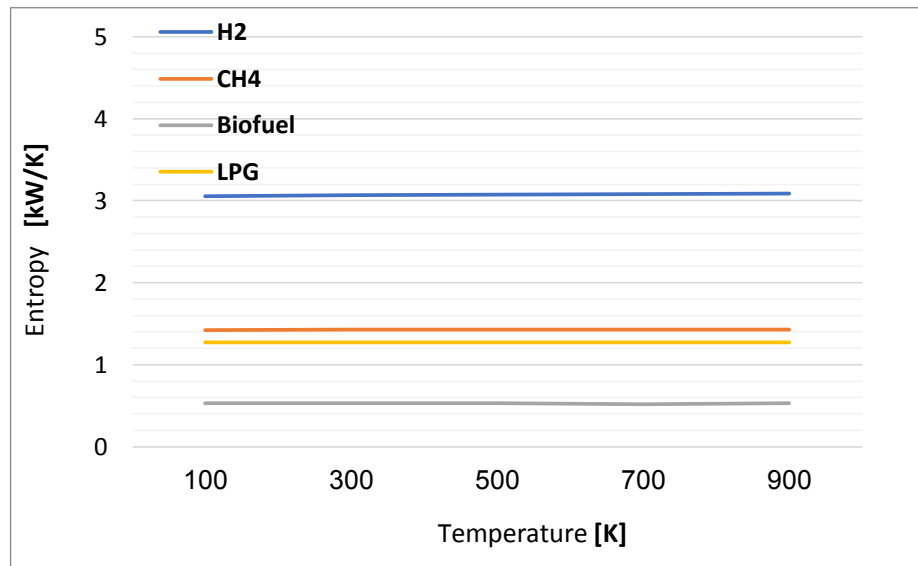


Figure 22 The entropy flow versus temperature for considered fuels

The figure 22 illustrates the relationship between temperature and entropy for various fuels, including H₂, CH₄, LPG, and Biofuel. The data indicates that as the temperature increases, the entropy values for all the fuels remain relatively constant. Notably, hydrogen exhibits the highest entropy value, stabilizing around 3 kW/K, which is indicative of its high level of molecular disorder and reactivity during combustion. Methane and LPG have similar entropy values, suggesting that their combustion processes generate comparable levels of disorder and energy distribution. Biofuel, on the other hand, shows the lowest entropy, indicating less molecular disorder compared to the other fuels. This consistent entropy across varying temperatures implies that higher thermal energy at elevated temperatures leads to increased molecular activity, resulting in a balanced state where entropy levels off. This behavior underscores the efficiency and stability of the combustion processes for these fuels, maintaining entropy at a steady level despite temperature changes.

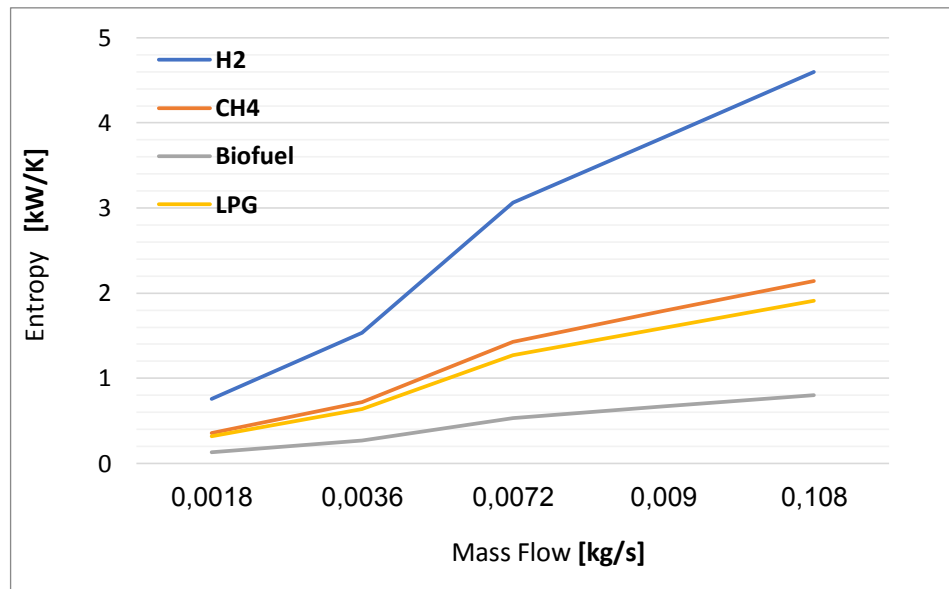


Figure 23 The entropy flow versus mass flow for considered fuels

This graph presents how entropy increases with flow rate for H₂, Biofuel, CH₄, and LPG fuels, reflecting greater disorder in combustion systems as energy distribution becomes more dispersed with higher flow rates. Hydrogen exhibits the most rapid increase in entropy due to its high reactivity, followed by biofuel, CH₄, and LPG, which show progressively slower entropy generation. These trends highlight the fundamental thermodynamic principle linking energy flow to increased molecular interactions and disorder in combustion processes across different fuel types.

III.3. Conclusion

In this chapter, the analysis focuses on the energy characteristics and combustion behavior of H₂, CH₄, Biofuel, and LPG, revealing clear differences among these fuels. Hydrogen demonstrates the highest energy flow and exergy potential due to its high reactivity and substantial energy release per unit mass. However, it also generates the most entropy because of significant molecular disorder. Methane follows, offering substantial energy output and exergy with moderate entropy generation. Furthermore, Biofuel, with its complex molecular structure, has moderate energy and exergy outputs along with entropy generation. In addition, LPG, being the least efficient, shows the lowest energy and exergy outputs and minimal entropy generation. These observations highlight the varying efficiencies and potential for useful work among different fuels. Specifically, the trends indicate that energy output and exergy increase with mass flow rate, while entropy generation rises with increased molecular interactions and disorder. Therefore, these findings emphasize the need to optimize fuel composition, combustion efficiency, and mass flow rates to maximize energy output and efficiency while maintaining stable combustion processes. Understanding these dynamics is crucial for selecting appropriate fuels for specific applications and optimizing combustion systems. The results offer insights into the relative advantages and limitations of each fuel type, providing a comprehensive understanding of their behavior in a controlled combustion setting. Overall, the

results underline the importance of considering both the first and second laws of thermodynamics to accurately evaluate and optimize the performance of combustion systems using different fuels.

General Conclusion

General Conclusion

In this study, we conducted a comprehensive comparison of four different fuels: CH₄, H₂, Biogas, and LPG. We focus on the computing the energetic parameters such as with respect to their energy, entropy, and exergy. The analysis aimed to provide insights into the energy efficiency of these fuels to inform future energy industrial applications.

Our energy analysis revealed that CH₄ exhibits a high energy content and is widely used due to its well-established infrastructure, providing a reliable and efficient energy source but contributing significantly to greenhouse gas emissions. H₂, on the other hand, possesses the highest energy per unit mass among the fuels studied, with its combustion producing only water, making it an exceptionally clean fuel. However, challenges related to storage, transportation, and production from non-renewable sources currently limit its widespread adoption. Biogas, generated from organic waste, offers a renewable energy source with moderate energy content, aiding in waste management and reducing landfill emissions. However, the energy yield can be variable depending on the feedstock and production methods. Liquefied Petroleum Gas (LPG) offers a good balance between energy content and ease of storage and transportation. It is commonly used in residential and commercial applications and produces fewer emissions compared to conventional fossil fuels.

The entropy analysis showed that CH₄ and LPG demonstrated lower entropy generation during combustion processes, indicating relatively higher thermal efficiency. H₂ exhibited higher entropy changes, which can be mitigated by using advanced combustion techniques to improve overall efficiency. Biogas showed variability in entropy generation depending on its composition and production methods, but it generally had higher entropy changes compared to CH₄ and LPG, highlighting the need for optimization in its usage. The exergy analysis provided insights into the potential for work and the efficiency of energy conversion processes. CH₄ and LPG both showed high exergy efficiency, making them suitable for applications requiring consistent and reliable energy. H₂, despite its high energy content, can have lower exergy efficiency if not managed properly due to losses in storage and conversion processes. Optimizing hydrogen production, storage, and utilization technologies is crucial for maximizing its exergy potential. Biogas exhibited lower exergy efficiency, reflecting the variability in its composition. Enhancing biogas purification and upgrading processes can improve its exergy performance.

Perspectives and Recommendations

The CH₄ could mitigate greenhouse gas emissions through power plants and investing in renewable methane from biomass can create a sustainable energy economy. For H₂, accelerating green hydrogen production, improving storage methods, and advancing combustion and engine technology will enhance its viability and reduce fossil fuel reliance. Biogas production efficiency can be improved through optimized feedstock and advanced anaerobic digestion, with upgraded technologies making it a competitive alternative to natural gas. Last fuel, LPG can benefit from

hybrid applications with renewable energy, advanced combustion technologies, and expanded use in rural areas like biogas, offering cleaner energy solutions and improving public health.

Based on our analysis, we recommend continuing the use of CH₄ and LPG in applications where infrastructure is established while exploring ways to reduce their environmental impact. For H₂, investment in research and development is crucial to address the challenges of storage, transportation, and production from renewable sources, unlocking its full potential as a clean energy carrier. Biogas should be promoted for waste management and as a renewable energy source, with a focus on improving production and upgrading technologies to enhance its efficiency and exergy performance. Overall, each fuel has unique advantages and challenges. A balanced approach, leveraging the strengths of each fuel while mitigating their weaknesses, will be essential for a sustainable energy future.

The References

The References

- [1] Gheraissa N, Bouras F, Khaldi F, Hidouri A, Rehouma F, Dogga A. A comparative study of the combustion supplied by multi-fuels: Computational analysis. *Energy Reports* 2021;7:3819–32. <https://doi.org/10.1016/j.egy.2021.06.073>.
- [2] El M, Attia H, Bouras F, Khechekhouche A, Driss Z. Investigations CFD numerical of the combustion of methane or propane: Aero-thermo-chemical study. *International Journal of Mechanics and Energy (IJME)*, 2017.
- [3] Özyalcin C, Sterlepper S, Roiser S, Eichlseder H, Pischinger S. Exhaust gas aftertreatment to minimize NOX emissions from hydrogen-fueled internal combustion engines. *Appl Energy* 2024;353. <https://doi.org/10.1016/j.apenergy.2023.122045>.
- [4] Wang K da, Sun B gang, Luo Q he, Li Q, Wu X, Hu T, et al. Performance optimization design of direct injection turbocharged hydrogen internal combustion engine. *Applications in Energy and Combustion Science* 2023;16. <https://doi.org/10.1016/j.jaecs.2023.100204>.
- [5] Gammaidoni T, Miliozzi A, Zemi J, Battistoni M. Hydrogen mixing and combustion in an SI internal combustion engine: CFD evaluation of premixed and DI strategies. *CASE STUDIES IN THERMAL ENGINEERING* 2024;55.
- [6] Sfriso S, Berni F, Fontanesi S, d'Adamo A, Frigo S, Antonelli M, et al. Proposal and validation of a numerical framework for 3D-CFD in-cylinder simulations of hydrogen spark-ignition internal combustion engines. *Int J Hydrogen Energy* 2024;53:114–30.
- [7] Xin G, Ji C, Wang S, Meng H, Hong C, Yang J. Effect of direct injection of small amounts of ethanol on port-injected hydrogen internal combustion engines. *Int J Hydrogen Energy* 2024;49:980–96. <https://doi.org/10.1016/j.ijhydene.2023.09.300>.
- [8] Algayyim SJM, Saleh K, Wandel AP, Fattah IMR, Yusaf T, Alrazen HA. Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review. *Fuel* 2024;362. <https://doi.org/10.1016/j.fuel.2023.130844>.
- [9] Lu C, Chen W, Zuo Q, Kou C, Wang H, Xiao G, et al. Numerical investigation on gaseous fuel injection strategies on combustion characteristics and NO emission performance in a pure hydrogen engine. *Fuel* 2024;363:130911.
- [10] Jayaprabakar J, Arunkumar T, Rangasamy G, Parthipan J, Anish M, Varshini G, et al. Prospectus of hydrogen enrichment in internal combustion engines: Methodological insights on its production, injection, properties, performance and emissions. *Fuel* 2024;363. <https://doi.org/10.1016/j.fuel.2024.131034>.
- [11] Abubakar S, Muhamad Said MF, Abas MA, Ismail NA, Khalid AH, Roslan MF, et al. Hydrogen-fuelled internal combustion engines - Bibliometric analysis on research trends,

- hotspots, and challenges. *Int J Hydrogen Energy* 2024;61:623–38. <https://doi.org/10.1016/j.ijhydene.2024.02.280>.
- [12] Bouras F, Khaldi F. Computational modeling of thermodynamic irreversibilities in turbulent non-premixed combustion. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung* 2016;52:671–81. <https://doi.org/10.1007/s00231-015-1587-2>.
- [13] Bouras F, Khaldi F, Gheraissa N, Dogga A. Comparative Study of the Carbon Based Fuels to Hydrogen Fuel. 2018 International Conference on Communications and Electrical Engineering (ICCEE), IEEE; 2018, p. 1–4.
- [14] Gheraissa N, Bouras F, Khaldi F, Hidouri A, Agrebi S, Chrigui M, et al. Comparative study of combustion processes generated by the use of different fuels: energy and exergy analysis. *Combustion Theory and Modelling* 2024:1–27. <https://doi.org/10.1080/13647830.2024.2357613>.
- [15] Law CK. *Combustion physics*. Cambridge university press; 2010.
- [16] Chan CC, Chau KT. *Modern electric vehicle technology*. Oxford University Press, USA; 2001.
- [17] Larminie J, Lowry J. *Electric vehicle technology explained*. John Wiley & Sons; 2012.
- [18] Miller JM. *Propulsion systems for hybrid vehicles*. vol. 45. Iet; 2004.
- [19] Rațiu S. The history of the internal combustion engine. *Ann Fac Eng Hunedoara* 2003;1:145–8.
- [20] Tudorache A, Velev GT. Types of engines. *Annals of Constantin Brancusi University of Targu-Jiu Engineering Series/Analele Universității Constantin Brâncuși Din Târgu-Jiu Serial Inginerie* 2019.
- [21] Heywood JB. *Internal combustion engine fundamentals*. (No Title) 1988.
- [22] Miller JM. Hybrid electric vehicle propulsion system architectures of the e-CVT type. *IEEE Trans Power Electron* 2006;21:756–67.
- [23] Hansdah MD. *LECTURE NOTES ON SUB: INTERNAL COMBUSTION ENGINE & GAS TURBINES* n.d.
- [24] Rajput RK. *Internal combustion engines*. Laxmi Publications; 2005.
- [25] Stone R. *Introduction to internal combustion engines*. vol. 3. Springer; 1999.
- [26] Ferguson CR, Kirkpatrick AT. *Internal combustion engines: applied thermosciences*. John Wiley & Sons; 2015.
- [27] Pulkrabek WW. *Engineering fundamentals of the internal combustion engine* 2004.

- [28] Ganesan V. Internal combustion engines. (No Title) 1996.
- [29] I. Dincer and M. A. Rosen, Exergy: energy, environment and sustainable development: Newnes, 2012.
- [30] M. Kanoğlu, Y. A. Çengel, and İ. Dinçer, Efficiency evaluation of energy systems: Springer Science & Business Media, 2012.
- [31] I. Dincer, Refrigeration systems and applications: John Wiley & Sons, 2017.
- [32] Y. A. Cengel, M. A. Boles, and M. Kanoğlu, Thermodynamics: an engineering approach vol. 5: McGraw-hill New York, 2011.
- [33] M. Tabatabaei and M. Aghbashlo, Biodiesel: From Production to Combustion vol. 8: Springer, 2018.
- [34] J. Bennett, P. Cheah, M. A. Orlic, and E. Grosz, New materialisms: Ontology, agency, and politics: Duke University Press, 2010.
- [35] V. Mrzljak, I. Poljak, and V. Medica-Viola, "Dual fuel consumption and efficiency of marine steam generators for the propulsion of LNG carrier," Applied Thermal Engineering, vol. 119, pp. 331-346, 2017.
- [36] R. Gicquel, Energy Systems: CRC Press, 2011.
- [37] I. Dincer, M. A. Rosen, and P. Ahmadi, Optimization of energy systems: John Wiley & Sons, 2017.
- [38] T.-W. Xue and Z.-Y. Guo, "What is the real Clausius statement of the second law of thermodynamics?," Entropy, vol. 21, p. 926, 2019.
- [39] M. Razmara, M. Bidarvatan, M. Shahbakhti, and R. Robinett III, "Optimal exergy-based control of internal combustion engines," Applied energy, vol. 183, pp. 1389-1403, 2016.
- [40] S. Shirvani and S. Shirvani, "Thermodynamic energy and exergy analysis of low-temperature combustion strategies," SAE International Journal of Engines, vol. 14, p. 345, 2021.
- [41] S. Agarwal, Engineering chemistry: Fundamentals and applications: Cambridge University Press, 2019.
- [42] A. V. Da Rosa and J. C. Ordóñez, Fundamentals of renewable energy processes: Academic Press, 2021.
- [43] R. W. Fox, A. T. McDonald, and J. W. Mitchell, Fox and McDonald's introduction to fluid mechanics: John Wiley & Sons, 2020.
- [44] A. M. Briones, A. Mukhopadhyay, and S. K. Aggarwal, "Analysis of entropy generation in hydrogen-enriched methane-air propagating triple flames," international journal of hydrogen energy, vol. 34, pp. 1074-1083, 2009.

- [45] F. Bouras, M. Attia, and F. Khaldi, "Entropy generation optimization in internal combustion engine," *Environmental Processes*, vol. 2, pp. 233-242, 2015.
- [46] N. Gheraissa. *Computational Modeling of the Biofuel Combustion: Energy and Exergy Study*. PhD Dissertation, University of EchahidHammaLakhdar – El Oued, 2022.
- [47] F. Bouras and F. Khaldi, "Numerical analysis of entropy generation in a turbulent diffusion flame," *Journal of Applied Mechanics and Technical Physics*, vol. 57, pp. 20-26, 2016.
- [48] M. Safari, M. R. H. Sheikhi, M. Janbozorgi, and H. Metghalchi, "Entropy transport equation in large eddy simulation for exergy analysis of turbulent combustion systems," *Entropy*, vol. 12, pp. 434-444, 2010.
- [49] A. K. Agarwal, S. De, A. Pandey, and A. P. Singh, *Combustion for Power Generation and Transportation: Technology, Challenges and Prospects*: Springer, 2017. Energy and Exergy Analyses 68
- [50] S. Jafarmadar, "Three-dimensional modeling and exergy analysis in Combustion Chambers of an indirect injection diesel engine," *Fuel*, vol. 107, pp. 439-447, 2013.
- [51] S. Mukherjee, P. Kumar, A. Hosseini, A. Yang, and P. Fennell, "Comparative assessment of gasification based coal power plants with various CO₂ capture technologies producing electricity and hydrogen," *Energy & fuels*, vol. 28, pp. 1028-1040, 2014.
- [52] H. Caliskan and K. Mori, "Thermodynamic, environmental and economic effects of diesel and biodiesel fuels on exhaust emissions and nano-particles of a diesel engine," *Transportation Research Part D: Transport and Environment*, vol. 56, pp. 203-221, 2017.
- [53] Ü. Ağbulut, "Understanding the role of nanoparticle size on energy, exergy, thermoeconomic, exergoeconomic, and sustainability analyses of an IC engine: A thermodynamic approach," *Fuel Processing Technology*, vol. 225, p. 107060, 2022.
- [54] B. Ma, A. Yao, C. Yao, T. Wu, B. Wang, J. Gao, and C. Chen, "Exergy loss analysis on diesel methanol dual fuel engine under different operating parameters," *Applied Energy*, vol. 261, p. 114483, 2020.
- [55] F. Ries, Y. Li, K. Nishad, J. Janicka, and A. Sadiki, "Entropy generation analysis and thermodynamic optimization of jet impingement cooling using large eddy simulation," *Entropy*, vol. 21, p. 129, 2019.
- [56] <https://www.addcomposites.com/post/types-of-hydrogen-tanks-technological-differences-and-advantages-explained>.
- [57] <https://afdc.energy.gov/vehicles/how-do-gasoline-cars-work>.
- [58] <https://www.vectorstock.com/royalty-free-vector/an-internal-combustion-engine>.
- [59] <https://www.facebook.com/MechanicalEngineeringBlog/posts/ic-engine-components-and-their-functions-types-and-terminologyit-is-an-engine>.

- [60] <https://www.howacarworks.com/basics/the-engine-how-the-valves-open-and-close>.
- [61] https://en.wikipedia.org/wiki/Connecting_rod.
- [62] <https://mrmekanix.com.au/engine-rebuild/>.
- [63] <https://www.lubrita.com/news/78/671/How-The-Lubrication-System-Works-In-An-Engine/>.
- [64] <https://www.onallcylinders.com/2017/08/22/automotive-ignition-system-designs/>.
- [65] <https://www.blog-teknisi.com/2020/05/how-starting-system-works.html>.
- [66] <https://www.facebook.com/engine.consultation/posts/charging-systemcomponents-functions-working-principle-and-diagnosis-tipsthe>.
- [67] <https://www.almasryalyoum.com/news/details/2861108>
- [68] https://www.thecartech.com/KnowYourCar/Engine/Hemiengine_files/Hemiengine.aspx

ملخص

تعتبر المحركات الحرارية الوسيلة الأساسية لإنتاج أو لتحويل الطاقة الكيميائية المخزنة في الوقود الطاقة ميكانيكية أو كهربائية. في هذه العمل قمنا بدراسة نظرية ومحاكات لمحرك الاحتراق الداخلي بإدراج أربع أنواع من الوقود: CH_4 , H_2 , GPL و الوقود العضوي. اعتمدنا في الحسابات على المقادير الطاقوية مثل الطاقة المنتجة، الانتروبيا، فعالية الاحتراق و حراره المحرك. اثبتت النتائج ان لكل نوع من الوقود خصائصه المميزة, كما ان هذه الأنواع هي الأكثر استعمالا في مجال السيارات الى جانب الوقود البترولي. كنتيجة فان الهيدروجين يعتبر وقود نظيف وذلك لإمكانية تقليل الانبعاثات مثل ثاني أكسيد الكربون والملوثات الضارة الأخرى. بالإضافة الى تأثير الهيدروجين على معايير أداء المحرك مثل الكفاءة الحرارية وثبات الاحتراق والطاقة المولدة والكفاءة العامة مقارنة بالوقود العضوي.

الكلمات المفتاحية : المحرك الداخلي ، الطاقة الكيميائية ، الوقود، الطاقة الميكانيكية.

Abstract

Thermal engines are the primary means of producing or converting the chemical energy stored in fuel into mechanical or electrical energy. In this work, we conducted a theoretical study and simulation of an internal combustion engine by incorporating four types of fuel: CH_4 , H_2 , LPG, and biogas. Our investigation focuses on calculations of energy quantities such as the energy produced, entropy, combustion efficiency (exergy), and combustion temperature. The results showed that each type of fuel has its distinctive characteristics, and these types are the most commonly used in the automotive field alongside petroleum fuel. Consequently, hydrogen is considered a clean fuel due to its low emissions of carbon dioxide and other harmful pollutants. Moreover, hydrogen impacts engine performance parameters such as thermal efficiency, combustion stability, generated power, and overall efficiency compared to biogas.

Keywords: internal engine, chemical energy, fuel, mechanical energy.

Resumé

Les moteurs thermiques sont les principaux moyens de produire ou de convertir l'énergie chimique stockée dans le carburant en énergie mécanique ou électrique. Dans ce travail, nous avons réalisé une étude théorique et une simulation d'un moteur à combustion interne en incorporant quatre types de carburant différents : CH_4 , H_2 , GPL et biogaz. Notre étude se concentre sur les calculs des paramètres énergétiques tels que l'énergie produite, l'entropie, l'efficacité de combustion (exergie) et la température de combustion. Les résultats montrent que chaque type de carburant a ses caractéristiques distinctives, et ces types sont les plus couramment utilisés dans le domaine automobile aux côtés des carburants pétroliers. Par conséquent, l'hydrogène est considéré comme un carburant propre en raison de ses faibles

émissions de dioxyde de carbone et d'autres polluants nocifs. De plus, l'hydrogène impacte les paramètres de performance du moteur tels que l'efficacité thermique, la stabilité de la combustion, l'énergie produite et l'efficacité globale par rapport au biogaz.

Mots clés : moteur interne, énergie chimique, carburant, énergie mécanique.