EVALUATION OF MULTI-FUEL HYBRID ENGINE PERFORMANCE USING GAS TURBINE SIMULATION PROGRAM

by

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ENDORSEMENT

I, Hafriz Najmi Bin Nekmat hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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DECLARATION

This thesis is the result of my investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

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EVALUATION OF MULTI-FUEL HYBRID ENGINE PERFORMANCE USING GAS TURBINE SIMULATION PROGRAM

ABSTRACT

This project paper presents the evaluation of multi-fuel hybrid engine performance with different types of fuels using the Gas Turbine Simulation Program (GSP). The multi-fuel hybrid engine is a modern engine design with many new technologies such as contra-rotating fan, a dual-combustion sequential system and a Cryogenic Bleed Air Cooling System (CBACS). A latest study shows the performance assessment of the multi-fuel hybrid engine by using two types of fuels which are Liquified Natural Gas (LNG) and kerosene. Biofuels such as Camelina Bio-Derived Synthetic Paraffinic Kerosene (BSPK), Jatropha BSPK and Hydro-processed Ester and Fatty Acid (HEFA) are the fuel that are used in evaluating the multi-fuel hybrid engine performance in this study. In addition to evaluating the effect of fuel properties on the engine, the engine performance and emissions are compared with the multi-fuel hybrid engine with hydrogen. The first part of this study is biofuels are combusted in the second combustor which is the inter-stage turbine burner (ITB) replacing kerosene. Hydrogen is combusted in the main combustor replacing LNG for the second part of this study. From the result obtained, the MFHE with hydrogen gives the best performance in the most aspects and is proven in reducing the emission of Nitrogen Oxide (NOx).

PENILAIAN PRESTASI ENJIN HIBRID YANG BERSIFAT PELBAGAI BAHAN BAKAR MENGGUNAKAN PROGRAM SIMULASI TURBIN GAS

ABSTRAK

Kertas projek ini membentangkan penilaian prestasi enjin hybrid bersifat pelbagai bahan bakar (EHPBB) dengan pelbagai jenis bahan bakar menggunakan Program Simulasi Turbin Gas (PST). EHPBB adalah reka bentuk enjin moden dengan pelbagai teknologi baru seperti kipas berputar kontra, sistem urutan pembakaran ganda dan sistem penyejukan udara aliran kriogenik (SPUAK). Kajian terbaru menunjukkan penilaian prestasi EHPBB dengan menggunakan dua jenis bahan bakar iaitu gas asli cecair (GAC) dan kerosin. Bahan bakar bio seperti bahan bakar kamelina bio-berasal kerosin paraffin sintetik (BKPS), jatropha BKPS dan ester hidrosis dan asid lemak (EHAL) adalah bahan bakar yang digunakan dalam menilai prestasi EHPBB dalam kajian ini. Selain menilai pengaruh sifat bahan bakar pada enjin, prestasi dan pelepasan enjin dibandingkan dengan EHPBB yang menggunakan hidrogen. Bahagian pertama kajian ini adalah biofuel dibakar dalam pembakar kedua yang merupakan pembakar turbin peringkat (PTP) menggantikan kerosin. Hidrogen dibakar dalam pembakar utama menggantikan LNG untuk bahagian kedua kajian ini. Dari hasil yang diperoleh, EHPBB dengan menggunakan hidrogen memberikan prestasi terbaik dalam pelbagai aspek dan terbukti dapat mengurangkan pelepasan Nitrogen Oksida (NOx).

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LIST OF ABBREVIATIONS

GSP	Gas turbine Simulation Program
MFHE	Multi-fuel hybrid engine
ACARE	European Advisory Council for Aeronautics Research and Innovation in Europe
LNG	Liquified Natural Gas
ITB	Interstage Turbine Burner
TSFC	Thrust Specific Fuel Consumption
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
HPC	High Pressure Compressor
HPT	High Pressure Turbine
BPR	Bypass Ratio
VHBR	Very High Bypass Ratio
MFBWB	Multi-fuel Blended Wing Body
BLI	Boundary Layer Ingestion
CBACS	Cryogenic Bleed Air Cooling System
CHEX	Cryogenic Heat Exchanger
CRF	Counter-Rotating Fan
AMOT	Allowable Metal Operating Temperature

HEFA	Hydro-processed Esters and Fatty Acids
BSPK	Bio-Derived Synthetic Paraffinic Kerosene
ATJ-SPK	Alcohol-to-jet Synthesized Paraffinic Kerosene
FT-SPK	Fischer-Tropsch Synthesized Paraffinic Kerosene
PtL	Power-to-Jet
SIP	Synthesized Iso-Paraffin
FPR	Fan Pressure Ratio
EI	Emission Index
OPR	Overall Pressure Ratio
GSP	Gas turbine Simulation Programme
LHV	Heat of combustion
MFHE-LNG	Multi-fuel hybrid engine LNG
MFHE-Hydrogen	Multi-fuel hybrid engine Hydrogen

LIST OF SYMBOLS

NO_x	: Nitrogen oxide
CO	: Carbon monoxide
H_2	: Hydrogen
CO_2	: Carbon dioxide
T_{T4}	: Entry temperature of HPT
T_{T46}	: Entry temperature of LPT
ρ	: Density

CHAPTER 1

INTRODUCTION

This chapter briefly explains the research background of the study, the problem statement and objectives of the research, and the layout of the thesis.

1.1 Research Background

The aviation industry has equipped with technological advancements that would improve the economic, operational, and environmental aspects of flying (Maria, 2014). Some of the large aviation companies have taken an advanced step in order to achieve sustainability. With respect to the eco-friendly environment, aviation technology has encountered a lot of developments in recent years. Such incentives in the aviation industry are to be accomplished in the form of the use of renewable fuel, which has been shown to decrease the environmental impact.

With the implementation of the sustainable environment, alternative fuel has now become a phenomenon. One of the example of the alternative fuels is biofuel, which can be defined as a fuel made from a biological source such as plant material (Nigam & Singh, 2011). Alternative fuels provide a new supply of energy as a replacement to the depleting conventional fossil fuels. Furthermore, it is environmentally friendly and can be used in a variety of modes of transportation, including air, land, and sea transportation (Yilmaz & Atmanli, 2017).

To reduce the fuel cost and emissions, biofuels which are recently been used in land transportation also can be applied in the aviation sector. In recent years, there has been an increase in research into biomass-based alternative aviation fuels as there has been a slew of industrial initiatives aimed at finding new ways to obtain bio-aviation fuels (Yilmaz & Atmanli, 2017).

Hydrogen is another option in replacing current fuel used in aircraft to obtain sustainability and prevent climate change and pollution. The use of hydrogen in aircraft will result in lesser production of greenhouse gases. But currently, there are very little hydrogen that is produced using low-carbon energy sources (Brewer, 2017).

Back in 2008, Boeing has already made a hydrogen aircraft on a manned mission powered by hydrogen fuel cell which achieved straight and level flight, where a constant heading and altitude are maintained (FCB, 2008). Currently, Boeing and Airbus are developing for commercial aircraft powered by hydrogen. In September 2020, Airbus announced plans for three different hydrogen-fueled concepts that could enter commercial service by 2035 with the aim of developing zero-emission aircraft (Airbus, 2020).

In line with the sustainability and green environment requirements, the hybrid engine concept was introduced to aid in the reduction of greenhouse gas emissions produced by the aviation industry. Hoping for a reduction in emissions without penalizing the thrust, this novel concept is known as multi-fuel hybrid engine (MFHE) as the hybrid concept consist of two type of fuels that will be combusted in two different combustor chambers which are the main combustor and the inter-stage turbine burner (ITB) (Arvind Gangoli Rao et al., 2014).

The current research paper for multi-fuel hybrid engine used liquified natural gas (LNG) and kerosene as the fuel for the research. By introducing hydrogen as the alternative fuel for this project, hopefully the emission from the aircraft can be reduce as it eliminates carbon dioxide (CO_2) emissions in flight (Krein, 2021). This paper suggests hydrogen and biofuels such as Camelina BSPK and Jatropha BSPK, as the fuel used for this research and the comparison between obtained results with the existed results will be made in this research.

1.2 Problem Statement

Nowadays air transports like aircraft are used widely all over the world to ease people movement to travel from one country to another. As widely as the aircraft is used for travel, the emissions from the aircraft need to be highlighted as well as 5% contribution of the total anthropogenic climate change including the CO_2 effects is from aviation (Yin, Gangoli Rao, et al., 2018). Given the current state where pollution and climate are something that often occur, the emissions of unwanted substances from aircrafts need to be reduced. Therefore, the European Advisory Council for Aeronautical Research and Innovation (ACARE) has set an ambitious target for the year 2050 which are a 75% reduction in CO_2 emissions, a 90% reduction in NOx emissions, and a 65% reduction in noise emissions relative to the levels back in the year 2000 (Yin et al., 2013).

Multi-fuel hybrid engine is an engine that can reduce engine emissions. The engine consists of hybrid combustion system, contra-rotating fan (CRF) and cryogenic bleed air cooling system (CBACS). The hybrid dual combustion is applied to reduce the emission of carbon monoxide (CO) and nitrogen oxide (NOx). LNG is combusted in the main combustor in order to provide flameless combustion for kerosene which will be combusted in ITB (Arvind G Rao & Bhat, 2015). Using LNG is not enough in order to achieve the stringent requirement of the aviation emission as LNG still emits CO_2 although LNG has a reduction of more than 15% of CO_2 compared to other conventional aircraft fuel (Rompokos et al., 2020). CRF is used instead of normal fan in hybrid engine to provide better sustain the non-uniform inlet flow caused by the Boundary Layer Ingestion (BLI). The CBACS is another non-conventional feature used to reduce the high pressure turbine (HPT) cooling requirement (Rao et al., 2018).

1.3 Objective

The purpose of this study is to analyse performance of MFHE using a combination of alternative fuels and kerosene. In other words, the specific objectives of this study are to:

1. Investigate the performance of MFHE, including its energy consumption and emissions with different fuel combination of biofuels and kerosene compare to LNG and kerosene.
2. Analyse the difference in engine performances and emission between the usage of hydrogen and LNG as the fuels.
3. Study the influence of fuel properties towards the performance and emission of the MFHE at cruise condition.

1.4 Thesis Layout

The thesis is divided into five chapters which consist of introduction, literature review, methodology, results and discussion and conclusion and recommendations. The first chapter of this thesis explains the overall scope and objectives of the research. The theory of propulsion in aircraft is demonstrated in Chapter 2 of the study. Chapter 3 explains the methodology carried out in order to achieve the study's goal, while Chapter 4 presents and discusses the findings. The research is summarised in Chapter 5 along with feedback for future work.

CHAPTER 2

LITERATURE REVIEW

The studies that are related to this research are summarised in this chapter which are the propulsion system, type of propulsion, type of fuel, type of emission and the uniqueness of this study.

2.1 Propulsion System

Propulsion can be referred as to push or to drive a thing forward whereas system can be defined as a group of entities that act together as part of a mechanism or a network of interconnections. In general, an aircraft's propulsion system is responsible for providing thrust force that allows the aircraft to be launched. In the design and operation of an aircraft or spacecraft mission, the propulsive force is the most critical aspect. (Arvind G. Rao & van Buijtenen, 2010). Compressor, combustion chamber, turbine and nozzle are the part of the propulsion system that are responsible for providing the aircraft with propulsive force (Sforza, 2016). The most typical aircraft engine operation is by using the power generated by the combustion of fuel in the combustor to drive the turbine, which then drives the compressor (Arvind G. Rao & van Buijtenen, 2010).

There are some parameters that can be evaluated to differentiate the engine performance which are thrust, thrust-specific fuel consumption (TSFC), emissions and energy consumption. The best design of the propulsion system is the one that can supply the thrust required by the aircraft to achieve its desired flying state while emitting less greenhouse gases.

2.2 Type of Propulsion

An aircraft's propulsion system can be divided into jet propulsion, electric propulsion and hybrid propulsion. By applying Newton's Third Law of action and reaction, the operating concept of jet propulsion is the engine accelerates a gas, or working fluid, and the reaction to this acceleration exerts a force on the engine. On the contrary, with the assistance of generators and motors, electric propulsion allows electricity to generate propulsive force (Ma et al., 2017). As for hybrid propulsion, the system integrates two or more propulsion systems in one design that may be operated simultaneously or alternately. However, due to the study's relevance, this section will primarily cover jet propulsion and hybrid propulsion.

2.2.1 Jet Propulsion

Jet propulsion can be described as a propulsion system that consumes air into its engine and then compresses, heats, and expands the air via a nozzle to produce a jet of hot air (Patrício & Tavares, 2010). Jet propulsion concept is usually used in an air-breathing engine and not suitable in a non-breathing engine as the combustion cannot occur due to the prevention of the air from entering the engine. Turbojet, turbofan, and ramjet engines are the examples of engines that used this principle as their propulsion system.

2.2.1.1 Gas Turbine Engine

Air-breathing engines such as turbojet and turbofan engine are usually used in the commercial aircraft. The main components of both engines are the inlet, compressor, combustor, turbine and nozzle each of which serves a specific purpose in the operation of the engine (Patrício & Tavares, 2010). The turbofan engine, however, has a fan and a two-spool mechanism that allows for an additional compressor and turbine to ensure a high thrust level. The installation of a fan, low-pressure compressor (LPC), and low-pressure turbine (LPT) are on one shaft, while the high-pressure compressor (HPC) and high-pressure turbine (HPT) are on another shaft (Saleh & Abdel Gawad, 2017). Table 2.1 summarises the functions of all of these components.

Table 2.1: Engine components function

Component	**Function**
Inlet	Brings free-flowing air to enter the engine.
Fan	Allows air to flow into the core and the duct
Compressor	Increase the pressure and temperature of the gas.
Combustion chamber	The place where hot air and fuel are mixed for combustion.
Turbine	Drive the compressor via a shaft
Nozzle	Produce high-velocity jet

The configuration of the turbofan engine which are divided into duct and core section permits bypass feature with a standard bypass ratio (BPR) of 5:1 (Ruíz, 2015). The air that enters the duct remains cold at the nozzle's end, whereas the air that enters the core becomes heated. In comparison to the turbojet engines, both cold and hot air contribute to a larger magnitude of thrust in turbofan engines (El-Sayed, 2016). Depending on the turbofan engine's design, these airs can be combined or unmixed. Figure 2.1 and Figure 2.2 shows the configuration of the turbojet and turbofan engine respectively.

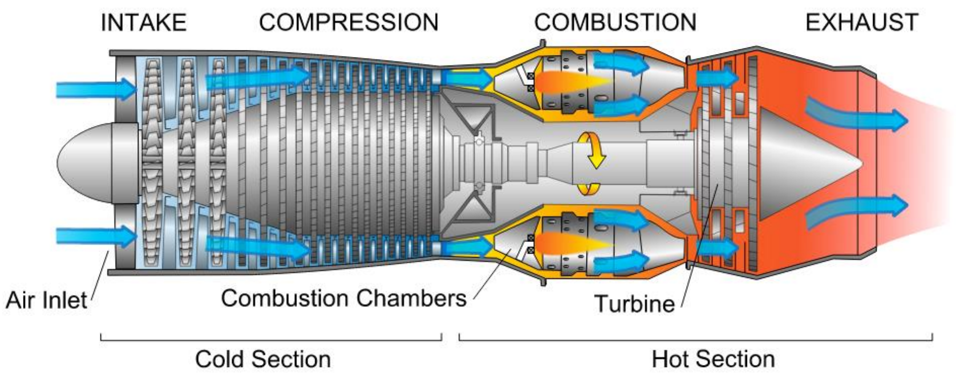

Figure 2.1: Turbojet engine (Singh Virdi et al., 2017)

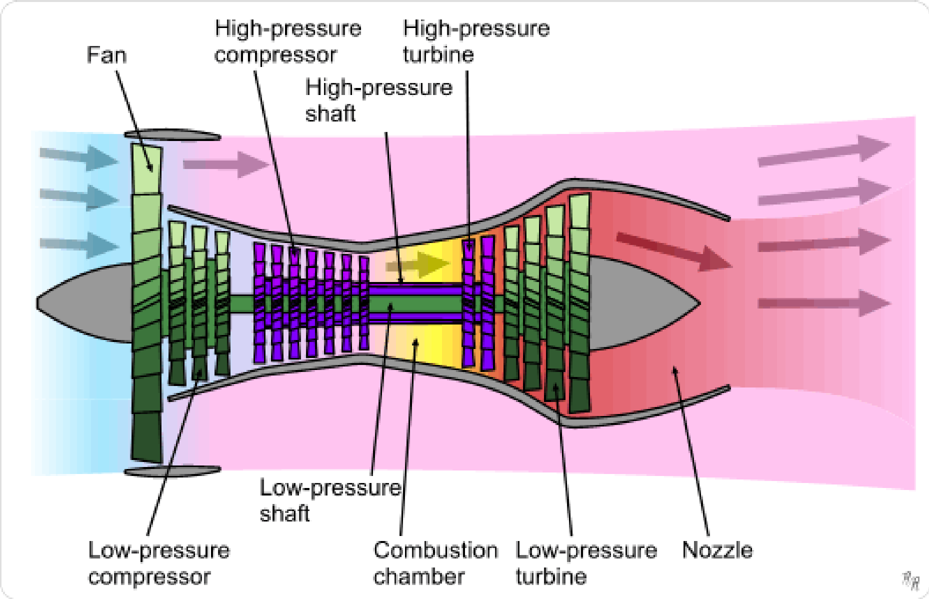

Figure 2.2: Turbofan engine (El-Sayed, 2016)

In terms of performance and fuel efficiency, the turbofan engine is better than turbojet engine (Bensel & Scholz, 2018). Furthermore, a higher BPR leads to improved efficiency. The technology of a turbofan engine with a very high bypass ratio (VHBR) is ideal since a high BPR offers the engine better efficiency.

2.2.2 Hybrid Propulsion

There are several types of hybrid propulsion introduced such as multi-fuel hybrid propulsion and electric hybrid propulsion in order to achieve a greener aviation. Multi-fuel hybrid propulsion uses a jet engine with kerosene and alternative fuel as its fuel (Arvind Gangoli Rao et al., 2014). This type of propulsion allows two types of fuel to be combusted as an extra combustor is added to the engine design. As for electric hybrid propulsion, a gas turbine engine and electrical components such as batteries, generators and electric motor are combined to produce this type of propulsion (Brelje & Martins, 2019). In conjunction with the purpose of the research, the electric hybrid propulsion will not be discussed in this study.

2.2.2.1 Multi-fuel Hybrid Engine

A latest research focused on a new technology engine that emits less pollutants for greener aviation without downgrading its performance. The research leads to the development of a hybrid engine with distinct functions. This concept is designed to meet the requirement of the propulsion system of future aircraft which features the multi-fuel blended wing body (MFBWB) design. The engine requirements for the MFBWB are as follows (Arvind Gangoli Rao et al., 2014):

- **Multi-fuel capability:** The ability to use multiple fuels is one of the main requirements of the MFBWB aircraft propulsion system. The engine should be able to utilise both fuels to their full potential.
- **Low emission:** To achieve ACARE's CO_2, NOx and noise reduction objective for flight path 2050. As soot emissions have an impact on local air quality and the development of contrail cirrus, its reductions are also taken into consideration.
- **Lower installation penalty:** The current trend is to enhance the BPR of the engine, resulting in larger and bigger engines. While still such engines have a lower Specific Fuel Consumption (SFC), the associated aerodynamic drag and weight are larger, increasing the installation penalty.
- **Boundary layer ingestion (BLI):** The implementation of BLI is encouraged by the potential of increasing the propulsive efficiency. Some of the advantages of BLI are:
    i. Increases the engine's propulsive efficiency.
    ii. Allows the installation of embedded engine which can greatly reduce noise.
    iii. Helps the reduction of nacelle wetted surface.
    iv. The thrust component would be desirable from the standpoint of aircraft stability.

Contra-rotating fan (CRF), dual combustion, and Cryogenic Bleed Air Cooling System (CBACS) with cryogenic heat exchanger (CHEX) are some of the engine's unique features (Yin, Gangoli Rao, et al., 2018). Figure 2.3 shows the schematic of the hybrid engine concept with LNG and kerosene as its fuel.

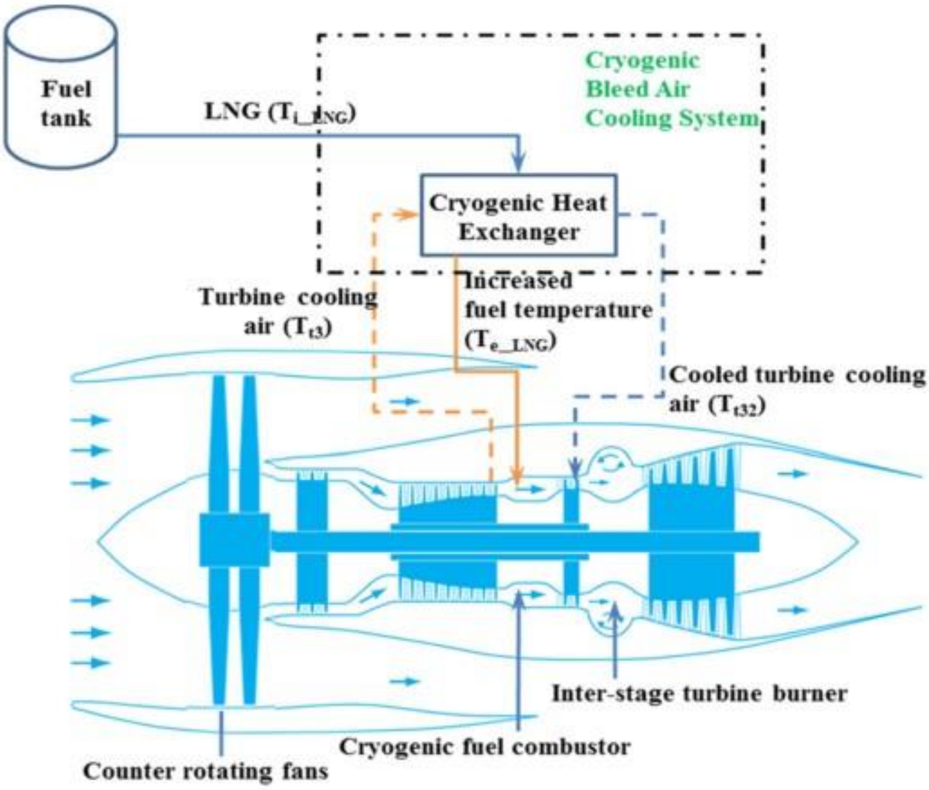

Figure 2.3: Schematic of a hybrid engine concept using LNG and kerosene (Yin, Gangoli Rao, et al., 2018)

2.2.2.1.1 Contra-rotating Fan

The design of a CRF consists of two axial fans connected in series, revolving in opposite direction against each other (Huo et al., 2014). The CRF's configuration is expected to allow the engine to have a BPR greater than 10 without having to change the low-pressure turbine's design as well as its shaft diameter (Yang & Shan, 2011). Due to sustain the non-uniform inlet flow caused by BLI, the CRF is used in the MFBWB aircraft propulsion system. Furthermore, when compared to a turbofan with a conventional ducted fan and open rotors, this feature generates higher thrust (Druzhinin et al., 2017). The schematic of contra-rotating fan is shown figure 2.4.

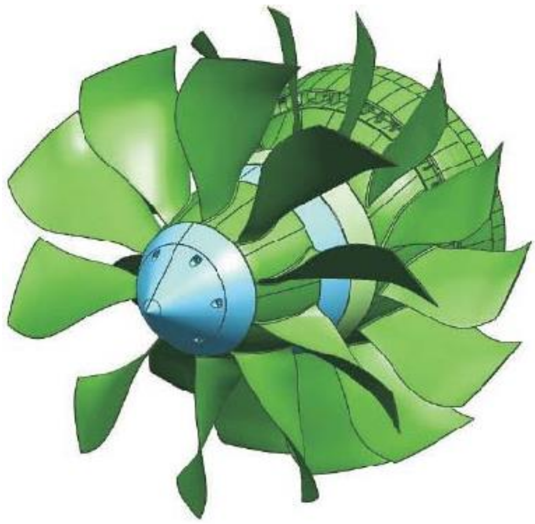

Figure 2.4: Contra-rotating fan (Arvind G. Rao et al., 2011)

2.2.2.1.2 Dual Combustor

The MFHE is consist of two combustion chambers which is the main combustor and the ITB (Arvind G. Rao et al., 2011). In comparison to a normal afterburner, the ITB is a reheat cycle that burns the fuel at a greater pressure with better thermal efficiency (Liew et al., 2006). The dual combustor concept enables two types of fuels, such as LNG and kerosene, to be burned in separate combustors. This unique feature allows them to compensate for each other's performance and emission deficiencies.

In recent past study, LNG is placed in the main combustor in order to produce flameless combustion for kerosene in ITB (Arvind Gangoli Rao et al., 2014). As a result, the penalty for utilising alternative fuel on output thrust may be minimised, and kerosene emissions can be reduced. This is due to the presence of ITB in the engine, which results in a lower maximum operating temperature for the same power output. The following are some of the benefits of utilising an ITB (Yin & Rao, 2017):

- **High Specific Thrust:** The power output for a particular engine size can be boosted thanks to the two combustion chambers. As a result, the ITB engine's specific thrust is higher.
- **Low Nitrogen Oxide (NO_x) emission:** ITB provides an ideal environment for a new combustion technology that significantly reduces NOx emissions. As a result, NOx emissions in the ITB engine are reduced and has been proven in several industrial gas turbine applications.
- **The fuel flexibility:** The dual combustor system allows for the use of alternative fuels. A multi-fuel hybrid engine has been designed using this feature, in which multiple fuels are burned simultaneously in two combustion chambers.
- **The operating flexibility:** Due to the implementation of the ITB, the dual combustor system adds additional degree-of-freedom to the engine's operation.

2.2.2.1.3 Cryogenic Bleed Air Cooling System

The cooling system for the turbine has been improved over the past year, allowing the turbine to function at temperatures higher than its maximum allowable metal operating temperature (AMOT) (Yin, Tiemstra, et al., 2018). The use of a large volume of cooling air to cool the turbine blade, on the other hand, reduces the turbine's efficiency. Therefore, there is a strong need to reduce turbine cooling air. CBACS is a non-conventional cooling system that is among the unique features of the proposed multi-fuel hybrid engine, and it appears to be a solution for decreasing turbine cooling air consumption.

The core element for CBACS is the cryogenic heat exchanger (CHEX). Due to the expected high turbine inlet temperature (TIT), a heat exchanger with a cold cryogenic fuel reservoir helps the turbine cool down more efficiently, improving the specific thrust of fuel consumption (Fohmann, 2015). The hybrid engine cooling path is shown in Figure 2.5.

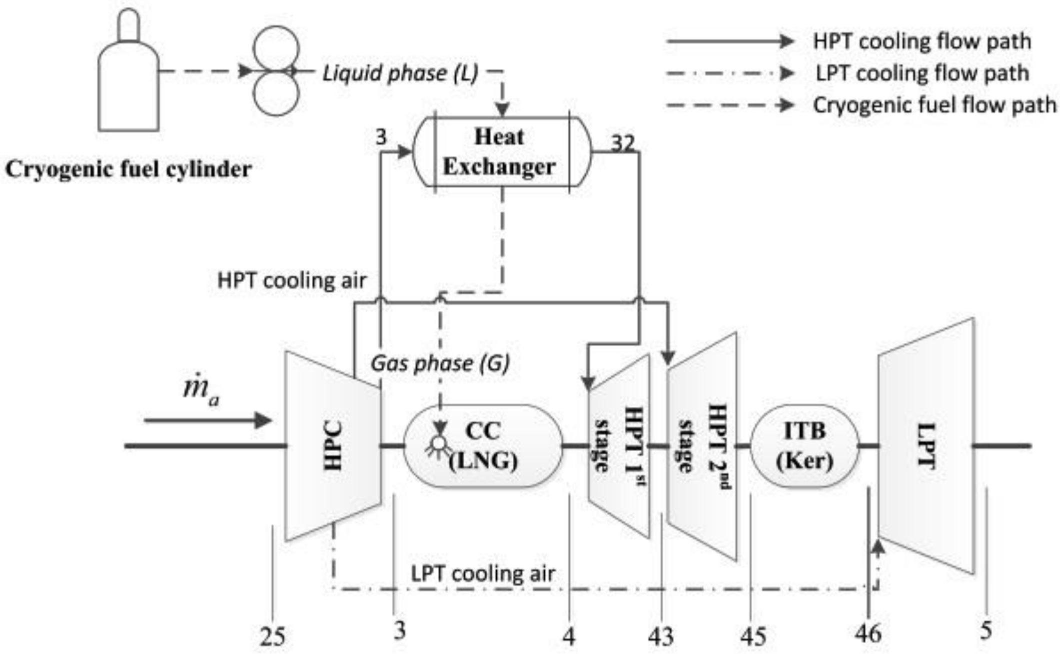

Figure 2.5: A cooling path of the hybrid engine (Yin, Gangoli Rao, et al., 2018)

In order to reduce the cooling requirement for high pressure turbine (HPT), the cryogenic fuel in the heat exchanger serves as a coolant to precool the cooling air in the HPT. Furthermore, when the temperature of cryogenic fuel reaches its boiling point in the heat exchanger before entering the main combustor, the phase shift occurs, reducing fuel consumption (Yin, Gangoli Rao, et al., 2018).

2.3 Type of Fuel

Over the last decade, the production of fossil fuels including coal, oil, and gas has increased rapidly due to strong demand, contributing significantly to global greenhouse gas emissions. Oil reserves are decreasing as a result of recent high production, leading in a spike in fuel costs owing to a supply and demand imbalance (Yin, Gangoli Rao, et al., 2018). Thus, there are initiatives on developing sustainable jet fuel that will be playing part in the reduction of fossil fuel depletion and emissions. Alternative fuels have been introduced and it has since been used by 22 airlines on nearly 2000 commercial flights (Iata, 2016).

2.3.1 Alternative Fuel

Alternative fuels will play a crucial role in helping to reduce carbon emissions. Its certification is necessary to guarantee that it fits the jet fuel standard specification, which leads to a variety of conversion pathways (Pavlenko et al., 2019). These pathways are hydro-processed esters and fatty acids (HEFA), synthesis gas Fischer-Tropsch synthesized paraffinic kerosene (FT-SPK), power-to-liquids Fischer-Tropsch synthesized paraffinic kerosene (PtL), alcohol-to-jet synthesized paraffinic kerosene (ATJ-SPK) and synthesized iso-paraffins (SIP). A brief explanation about the pathways are as follows (Pavlenko et al., 2019):

- **HEFA:** The pathway starts with fatty feedstocks such as vegetable oils or waste fats, which are deoxygenated before being combined with hydrogen to break down the fatty molecules into hydrocarbons, which then can be processed into a variety of different liquid fuels.
- **FT-SPK:** The gasification of feedstocks into synthesis gas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2), is part of this fuel conversion pathway. The synthesis gas is mixed with a catalyst to produce a mixture of hydrocarbons, which may subsequently be processed into various liquid fuels.
- **PtL or FT-SPK:** Similar to FT-SPK from bio-feedstocks, synthesis gas can be generated from the electrolysis of water and mixed with captured carbon to provide a viable feedstock for FT synthesis.
- **ATJ-SPK:** Fermentation is used in this fuel conversion pathway to convert sugars, starches, hydrolysed cellulose into an intermediate alcohol, such as isobutanol or ethanol, which is subsequently processed and upgraded into a mix of hydrocarbons.

- **SIP:** This fuel conversion pathway, also known as direct sugar-to-hydrocarbons (DSHC), converts sugary feedstocks into farnesene ($C_{15}H_{24}$) followed by upgrading into farnesane ($C_{15}H_{32}$), which can be used as a drop-in fuel.

Camelina, jatropha, and algae are examples of bio-feedstock for alternative fuels. Azami and Savill (2017) conducted a comparative study on various alternative fuel sources to assess their performance. All biofuels show a slight increase in overall thrust, however not all biofuels exhibit a decrease in TSFC, which is algae biofuel (Azami & Savill, 2017). Nevertheless, the research does not include used cooking oil as an alternative fuel source. The biofuel sources mentioned above will be addressed in further detail later.

2.3.1.1 Biofuel Sources

Bio-jet fuel is a type of biofuel designed specifically for use in jet aircraft. It is a renewable alternative jet fuel that requires the extraction of bio-feedstocks from sustainable sources such as vegetable oils and animal fats (Te Raa, 2010). This section will explain the sources of the biofuel such as camelina, jatropha and used cooking oil.

2.3.1.1.1 Camelina

Camelina sativa, often known as gold-of-pleasure or false flax, is a flowering plant of the *Brassicaceae* family. Thanks to its ease of growth, including its capability to thrive in very poor soil (Chaturvedi et al., 2019) with minimal pesticide and fertilizer requirements (Moser, 2010), its biofuel production is expected to reach 1 billion gallons by 2025 (Ross et al., 2013). Camelina has a variety of applications including wax esters for cosmetics, biological feedstock, lubricants, culinary oil, and transportation.

Furthermore, a single camelina seeds have a maximum lipid content of 45 percent, and the crop production per hectare ranges from 336 to 2240 kg of seeds (Moser, 2010).

Since its jet fuel has been used in commercial and military aircraft, it has been confirmed to be safe for use in aviation. Camelina-based jet fuel is favourable since it reduces carbon emissions as compared to standard jet fuel (Parthasarathy & Narayanan, 2014).

2.3.1.1.2 Jatropha

Jatropha is a flowering plant species belongs to the *Euphorbiaceae* family. It has 175 species and originated in tropical America before spreading to Asia and Africa. Jatropha production has increased substantially in recent years due to its reputation as a versatile plant. A hectare may contain around 2500 jatropha plants, with a maximum yield of 20kg of jatropha fruit per plant, harvesting four times a year, and the fruit seeds containing more than 33% oil (Wang, 2016). Therefore, it is evident that jatropha has grown in popularity as an alternative energy crop.

Jatropha as a bio-feedstock makes it possible to achieve the objective of the second-generation biofuel, which is to augment biofuel supply with crops. Due to its endurance on poor soils, idle lands (Baroutian et al., 2013), drought tolerance, insect resistance (Moniruzzaman et al., 2017), and ability to grow well under stress situations, Jatropha appears to be an effective biofuel feedstock. The fruit dehulling process initiates the process for jatropha fruit whereas its oil begins from the oil upgrading process (Wang, 2016).

2.3.1.1.3 Used Cooking Oil

Used cooking oil are oils and fats that have been used for cooking or frying in the food processing industries, restaurants and in households. Due to its low cost, which is two to three times lower than vegetable oil, this type of oil has emerged as one of the most promising feedstocks for biofuel production. This is because bio-jet fuel is in high demand in the aviation sector to reduce carbon emissions. To determine the best outcome for jet fuel production, a research of several catalytic hydro-conversions of spent cooking oil into jet fuel was conducted by Zhang et al. (2017).

Used cooking oil is said to have similar properties as sunflower oil, but with a little higher viscosity (Chiaramonti et al., 2015). It is made up of long-chain carbon fatty acids and triglycerides (Zhang et al., 2018), as well as several impurities that might interfere with the hydrotreatment process. Hydrodeoxygenation, decarboxylation, and decarbonylation are all required in the process of transforming used cooking oil into bio-jet fuel. The optimal conditions for conversion are 380°C and a H_2/oil ratio of 250 (Zhang et al., 2018), using NiMo/SBUY-MCM-41 as the catalyst (Zhang et al., 2019).

2.3.1.2 Biofuel Pathways

There are numerous renewable jet fuel conversion pathways that have been discovered. The summarization of the fuel conversion pathways is shown in Figure 2.6. The processes of biofuel production pathways such as HEFA and FT-SPK are thoroughly discussed in this section.

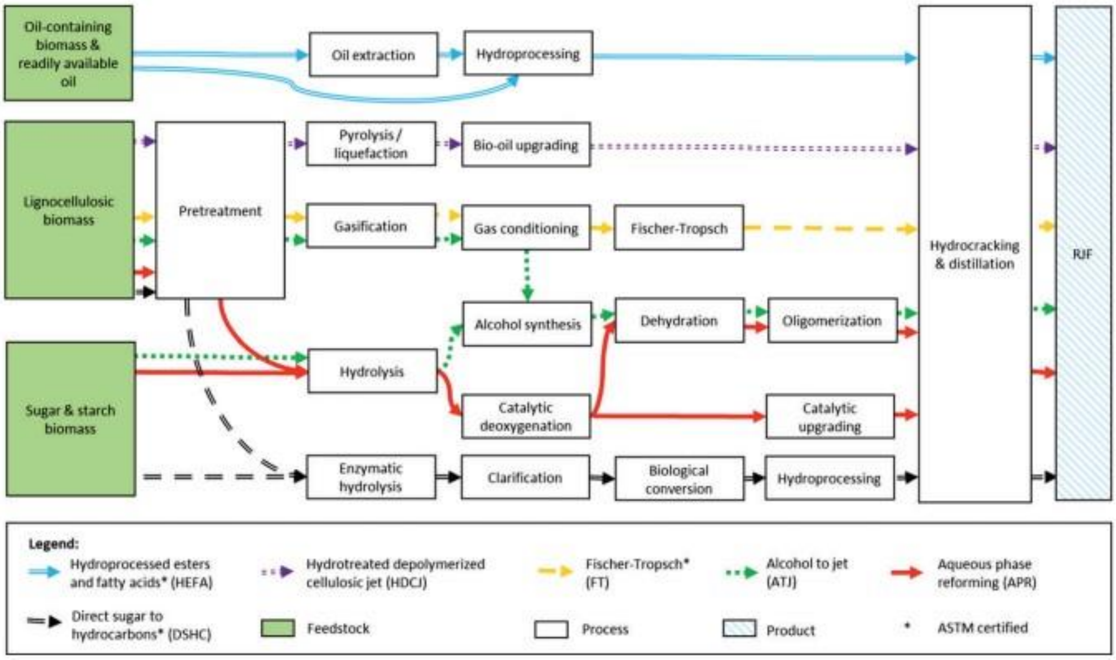

Figure 2.6: Renewable jet fuel conversion pathways (Mawhood et al., 2016)

2.3.1.2.1 HEFA Process

With higher cetane, less aromatic and sulphur content, and the possibility for lower greenhouse gas emissions, HEFA fuel has similar properties to conventional fuel. Hydrotreatment and hydro-isomerization are two main processes that are carried out consecutively in the HEFA process of creating bio-jet fuel (Starck et al., 2016). The aim of the hydrotreatment is to eliminate oxygen from the fuel in order to produce pure paraffinic diesel. The oxygen can be removed in two ways which are by hydrogenating the fatty acid chain that creates water and paraffinic product, or by hydrogenating the fatty acid chain, which creates carbon oxides and paraffinic product.

This pure paraffinic product is in linear form and it must be transformed into iso-paraffin via the isomerization process (Starck et al., 2016). This process is necessary to guarantee that it satisfies the jet fuel standard by increasing its cold flow properties and converting its boiling point to the boiling range of jet fuel (Tao et al., 2017). Because jet fuel is an intermediate product between diesel and gasoline, the best degree of conversion in terms of jet fuel yield is achieved by using the right catalyst under the right operating conditions.

2.3.1.2.2 FT-SPK Process

The fuel generated via the FT-SPK process has a greater specific energy, allowing for a bigger payload capacity. There are four main processes of the production of biofuel using FT-SPK method which are (Bi et al., 2015):

i. Bio-syngas production by biomass gasification
ii. Syngas cleaning and conditioning
iii. High-pressure FT synthesis

iv. Upgrading fuels for various applications such as diesel and jet fuel

Prior to the gasification process, the biomass feedstocks are dried to reduce its particle size and prepare them for gasification. The biomass is converted into bio-syngas at a high temperature of roughly 1300ºC in the presence of steam and high purity oxygen during the gasification process (Wang & Tao, 2016). The residual tar, methane, and light hydrocarbons are subsequently reformed to syngas in the fluid catalytic cracker after further conditioning.

The FT process produces paraffin by reacting carbon monoxide and hydrogen with the addition of a catalyst at either high or low temperature and using a different type of catalyst depending on the product to be generated. On the one hand, FT synthesis will yield gasoline and low molecular mass olefins, whereas low-temperature FT synthesis will yield linear wax (Liu et al., 2013). Overheating and deactivating the catalyst must be avoided in order to prevent the formation of unwanted methane by rapidly removing the heat of reaction. To achieve the desired properties, the FT synthesis product is improved into liquid fuel via isomerization and hydrocracking processes.

2.3.2 Hydrogen

Hydrogen (H_2) is the most abundant chemical element in the universe, accounting for approximately 75% of all baryonic mass. With its availability, better specific energy properties and impact on environment, hydrogen has become a focus of study for researchers and combustion specialists in recent years (Arat & Sürer, 2017). There are two types of use of hydrogen as fuel in aircrafts which are to use the hydrogen instead of kerosene in large aircrafts and the other one is to utilize hydrogen fuel cells instead of jet engines in small propeller aircrafts (Dincer & Acar, 2016).

Hydrogen is an excellent energy store since it is generated sustainably and has the highest energy per unit mass of any chemical fuel. However, for usage in aviation, the volumetric density of hydrogen with a relatively low energy density per unit volume should be increased (Sharpe et al., 2015). When hydrogen is used in aircraft instead of petroleum-based fuels, the percentage of water vapour that raises the specific heat of combustion gases increases. This leads to a lower pressure drop in the turbine, which results in higher thrust (Verstraete, 2013). The advantages of using hydrogen as fuel in aircraft are summarized below (Arat & Sürer, 2017):

- **High energy content per unit mass:** Hydrogen has the highest energy content per unit mass of all known fuels; 2.8 times higher than compared to kerosene. This is an essential property since it allows a larger payload.
- **Green environment sustainability:** Hydrogen offers long-term growth in aviation by preserving the environment. It produces only water vapour and a small amount of NOx and does not produce emission that affect the environment, such as carbon dioxide (CO_2) and sulphur dioxide (SO_2), as the combustion product.
- **High auto-ignition temperature:** Hydrogen has a relatively high auto-ignition temperature which is 585°C. This will prevent the hydrogen or other air mixture from auto-ignition without any additional ignition sources.

2.3.2.1 Hydrogen Production

Despite being one of the most abundant elements in the universe, hydrogen does not exist independently since it interacts easily with other elements. As a result, the principle of hydrogen production is dependent on the separation of other molecules (Lanz et al., 2014). Hydrogen can be made from a variety of feed stocks such as fossil fuels like natural gas and coal, and renewable resources like water and biomass (Riis et al., 2006). The percentage of hydrogen production sources is shown in Figure 2.7.

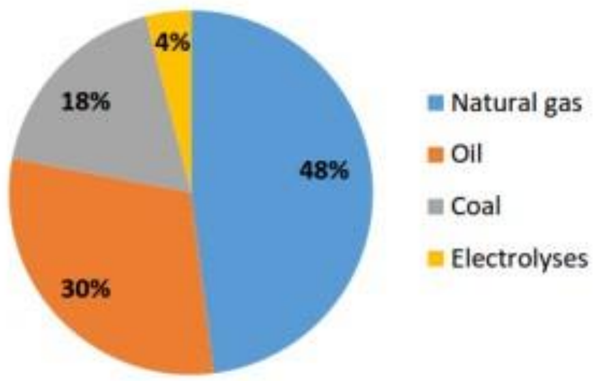

Figure 2.7: Percentage of hydrogen production sources (Arat & Sürer, 2017)

2.4 Type of Emission

Environmentalists are concerned about aviation emissions since they are increasing year after year and do not appear to be decreasing anytime soon. Aviation emissions are expected to rise over the next two decades (Kounsoulidou et al., 2016). Aircraft emissions are highest at around 3000 feet above ground, accounting for roughly 90% of all emissions, while the remaining 10% are emitted near to the earth's surface during take-off, initial ascent, and landing (Overton, 2019). Carbon dioxide (CO_2), nitrogen oxide (NOx), water vapour (H_2O), hydrocarbon, carbon monoxide (CO), sulphur oxide (SOx) and particulate matter (PM) are all examples of aircraft emissions. Only the emission of NOx, CO_2 and hydrocarbon are discussed in this section. Figure 2.8 illustrates the emissions of the aircraft.

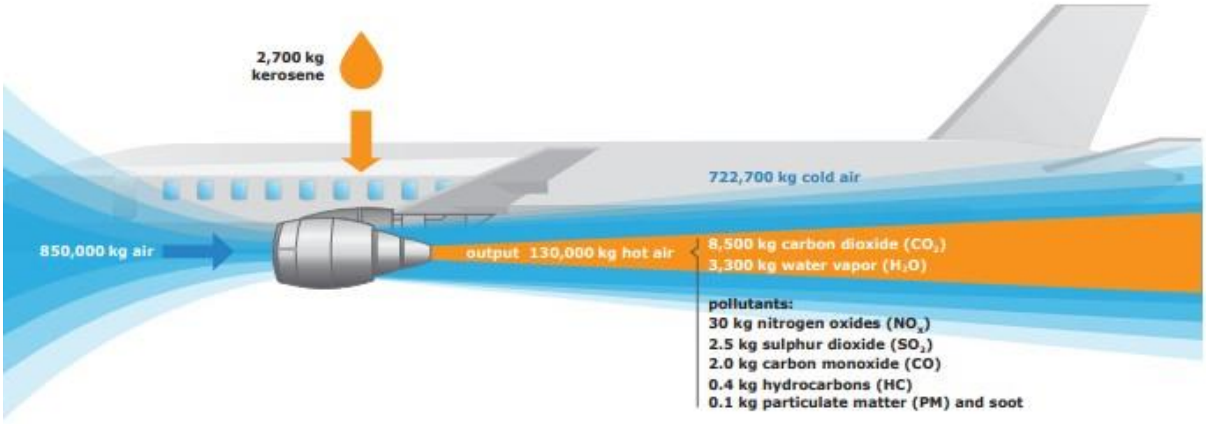

Figure 2.8: Aircraft emission (Kounsoulidou et al., 2016)

2.4.1 Nitrogen Oxide

One of the current trends in aviation industries is increasing the engine bypass ratios in order to achieve higher propulsive efficiency. Higher propulsive efficiency has the disadvantage of promoting NOx emissions, as high temperatures tend to raise NOx levels (Schaefer, 2013). Fortunately, each engine's emission indices vary from one another due to the difference in combustion efficiency. This NOx aids in the formation of ozone layer and the destruction of methane, both of which contribute to climate change (Grewe et al., 2019), though the extent where this occurs is very dependent on the location of the emission (Wasiuk et al., 2016).

There are three methods of the NOx to form which are thermal NOx, prompt NOx and fuel NOx. Thermal NOx is produced when the temperature is high enough to cause rapid production, whereas prompt NOx is produced when the reaction between nitrogen, oxygen, and a hydrocarbon radical occurs quickly. Fuel NOx is formed when direct oxidation of nitrogen happens during the fuel combustion (Khanal, 2014). Some engine designs utilize technologies like water injection, Rich-burn Quick Quench Lean Burn (RQL), Lean Premix Pre-vaporized (LPP), and Lean Direct Injection (LDI) to reduce NOx emissions. Each methods’ concept are as follows (Ommi & Azimi, 2012):

- **Water Injection:** To reduce the temperature of the combustor, atomized water is pumped directly into it.
- **RQL:** To limit NOx emissions, the residence time of the fuel-air mixture is minimised by utilising quick fuel-air mixing in the stoichiometric area of the combustor.
- **LPP:** To avoid the formation of a NOx hotspot, fuel and air are premixed in fuel-lean proportions.

- **LDI:** The combustor runs fuel-lean without a rich front end by mixing directly injected liquid fuel with air over the shortest distance possible.

2.4.2 Carbon Dioxide

CO_2 is the highest emission produced in all emission type in aviation emissions, accounting for almost 70% of all emissions. In the next ten years, this emission is expected to grow by 4% (Cokorilo, 2019). Unlike NOx emissions, CO_2 is thought to have the same impact regardless of altitude (Golui, 2020). Between 2021 and 2035, a programme named CORSIA is expected to reduce emissions by 2.5 billion tonnes. In addition, a new CO_2 emissions certification standard that emphasises improving fuel economy by not only fulfilling the regulatory limit, but also having a favourable relative product positioning in terms of margin to the limit, helps to minimise CO_2 emissions (ICAO, 2007). To gain a better grasp of how aircraft release CO_2, the factors that contribute to the emissions are as follows (CAA, 2017):

- **Aircraft type:** The efficiency of an engine is affected by the variety of operations it can perform owing to its design to fly. Newer aircraft are more fuel efficient, resulting in lower emissions.
- **Flight profile and distance:** Because each flight profile burns fuel at a different rate, cruising is the most fuel-efficient stage, while medium-haul flights generate the least emissions per kilometer travelled.
- **Weight of aircraft:** As lighter planes consume less fuels, they generate less emissions.
- **Operational procedure:** Changing the operation process in the air and on the ground to a smoother one, such as take-off and landing at a lower angle, reduces the quantity of fuel burned and, as a result, decreases emissions.

- **Utilization of biofuel:** Compared to traditional fuel, alternative fuel emits fewer emissions.
- **Weather:** A headwind causes more fuel to be consumed, whereas a tailwind helps to reduce emissions.

2.4.3 Hydrocarbon

Compared to the other emissions, the emission of hydrocarbon is relatively low (Li et al., 2020). An increase in cruise altitude will result in a reduction in emissions. Furthermore, this emission is highly dependent on an engine's power setting with an increase in it reducing hydrocarbon emissions caused by improper fuel-air mixing (Pawlak et al., 2018). This factor has an impact on the hydrocarbon that are emitted. The emission of hydrocarbon is also affected by elements such as the ambient atmospheric condition, current flying speed, and engine type. During the taxiing phase of the aircraft, hydrocarbons are released. Reducing the taxi-out time by a minute results in a greater reduction in hydrocarbon emissions when compared to the taxi-in time. Ethene, ethyne, and propene are the most common hydrocarbons released at low engine power, whereas n-heptane and toluene are more prevalent at higher engine power (Anderson et al., 2006).

2.5 Research Gap

In the recent multi-fuel hybrid engine research, LNG is combusted in the main combustor whereas kerosene is combusted in ITB. In comparison to both mentioned fuels, hydrogen and alternative fuels such as BSPK and HEFA fuel are believed to have better fuel properties than LNG and kerosene in achieving the objectives of this research. Both LNG and kerosene have higher carbon content than the alternative fuels mentioned, which results in greater NOx emission. This paper will analyze the utilization of hydrogen and alternative