COMPARISON OF ENGINE PERFORMANCE FOR DIFFERENT TYPE OF ENGINES WITH ALTERNATIVE FUELS DURING COMPLETE FLIGHT TRAJECTORY

By

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ENDORSEMENT

I, Aiqa Arbila Binti Abdul Halim hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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(Signature of Supervisor)

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Date :

(Signature of Examiner)

Name :

Date :

DECLARATION

This thesis is the result of my own 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.

(Signature of Student)

Date :

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COMPARISON OF ENGINE PERFORMANCE FOR DIFFERENT TYPE OF ENGINES WITH ALTERNATIVE FUELS DURING COMPLETE FLIGHT TRAJECTORY

ABSTRACT

Airline industry has experienced a huge amount of improvements in fuel efficiency and this is due to the increasing harmful effects caused by them. One of the contributing approaches is using alternative fuels which are plant-based, and it wasn't in vain as there have been three successful biofuel flights which are Air New Zealand's Boeing 747-400, Continental Airlines Boeing 737-800 and Japan Airline Boeing 747-300. Thus, this study is conducted to compare and analyze the engine performance (thrust, specific fuel capacity, and mass fuel flow) of different type of engines (single-spool and double-spool engine) operating with alternative fuels (Jet- A, JSPK, CSPK, mixture of 50% JSPK + 50% Jet-A, mixture of 50% CSPK + 50% Jet-A, Palm Methyl Ester, Canola and Halophyte) during complete flight trajectory (take-off, top of climb, cruise, low power and ground idle). The engines are modelled, and the simulation is performed using the Gas Simulation Program software. This research analyzes the effect of alternating fuels on the engine performance during a complete flight trajectory. The results show that the best alternative fuel that could replace the conventional Jet-A is JSPK. It has the capability to produce similar and better engine performance in terms of thrust, lower specific fuel consumption and a reduction of mass fuel flow. JSPK blend, CSPK and CSPK blend fuels can also produce similar engine performance and used as alternative fuels. However, POME, POME blend, Canola and Halophyte are not able to produce similar or better engine performance compared to Jet-A fuel hence is not a

suitable choice to replace the conventional Jet-A. This thesis draws the conclusion on the possibility of incorporating alternating fuels for GHC effects prevention.

PERBANDINGAN PRESTASI ENJIN UNTUK JENIS ENJIN YANG BERBEZA MENGGUNAKAN BAHAN ALTERNATIF YANG BERBEZA SEMASA PENERBANGAN TRAJEKTORI YANG MENYELURUH

ABSTRAK

Industri penerbangan mengalami peningkatan yang besar dalam kebolehan bahan bakar disebabkan peningkatan kesan yang berbahaya. Salah satu penedekatan yang menyumbang kepada peningkatan ini adalah penggunaan bahan api alternatif yang berasaskan tumbuhan. Pendekatan ini tidak sia-sia kerana terdapat tiga penerbangan biofuel yang berjaya iaitu Boeing 747-400 Air New Zealand, Continental Airlines Boeing 737-800 dan Boeing 747-800 Airline -300 Oleh itu, tesis FYP ini ditujukan untuk memahami analisis perbandingan prestasi enjin (teras, keupayaan bahan bakar tertentu dan aliran bahan bakar) dari pelbagai jenis enjin (jet tunggal, dan poros dua enjin) dengan bahan api alternatif (Jet-A, JSPK, CSPK, campuran 50% JSPK + 50% Jet-A,campuran 50% CSPK + 50% Jet-A, Metil Ester Sawit, Canola dan Halophyte) semasa trajektori penerbangan lengkap (pelepasan, penaikan, pelayaran, keturunan, dan pendaratan). Enjin dimodelkan, dan disimulasikan menggunakan perisian Program Simulasi Gas. Kajian ini menganalisis kesan bahan api alternatif pada prestasi enjin semasa trajektori penerbangan lengkap. Kajian telah merumuskan bahawa bahawa bahan bakar alternatif terbaik yang boleh menggantikan Jet-A konvensional ialah JSPK. JSPK mempunyai keupayaan untuk menghasilkan prestasi enjin yang serupa dan lebih baik dari segi tujah, penggunaan bahan api tertentu yang lebih rendah dan pengurangan aliran bahan api massa. Campuran JSPK, CSPK dan bahan api campuran CSPK juga boleh menghasilkan prestasi enjin yang sama dan digunakan sebagai bahan api alternatif. Walau

bagaimanapun, campuran POME, POME, Canola dan Halophyte tidak dapat menghasilkan prestasi enjin yang serupa atau lebih baik berbanding dengan bahan bakar Jet-A dan bukan merupakan pilihan yang sesuai untuk menggantikan Jet-A konvensional. Tesis ini menarik kesimpulan mengenai kemungkinan menggabungkan bahan api berselang untuk pencegahan kesan GHC.

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LIST OF ABBREVIATIONS

BPR	Bypass Ratio
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
CSPK	Camelina Bio-Synthetic Paraffinic Kerosene
JSPK	Jatropha Bio-Synthetic Paraffinic Kerosene
LHV	Low Heating Value
HPC	High Pressure Compressor
HPT	High Pressure Turbine
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
NOx	Nitrogen Oxide
GHC	Greenhouse Carbon Emissions
SPK	Synthetic Paraffinic Kerosene
TET	Turbine Entry Temperature
TSFC	Thrust Specific Fuel Consumption

LIST OF SYMBOLS

$\dot{m}_o$	Mass Flow Rate [kg/s]
$\dot{m}_a$	Air Mass Flow Rate [kg/s]
$\dot{m}_c$	Core Mass Flow Rate [kg/s]
$\dot{m}_f$	Fan Mass Flow Rate [kg/s]
Cp	Heat Capacity [kJ/kgK]
f	Fuel to Air Ratio
F	Thrust [kN]
P_0	Ambient Pressure [bar]
P_2	Fan Inlet Pressure [bar]
P_3	Compressor Inlet Pressure [bar]
Q_{im}	Heat Added [J/kg]
Q_{Rej}	Heat Rejected [J/kg]
T_o	Ambient Temperature [K]
T_2	Fan Inlet Temperature [K]
T_3	Compressor Inlet Temperature [K]
T_4	Turbine Entry Temperature [K]

T_5	Turbine Exit Temperature [K]
T_9	Exhaust Exit Temperature [K]
W_C	Compressor Work [J/kg]
W_N	Net Work Output [J/kg]
W_T	Turbine Work [J/kg]
FN	Engine Thrust [kN]
N_H	High-Pressure Spool Speed [RPM]
N_L	Low-Pressure Spool Speed [RPM]
ρ	Density
γ	Specific Heat Ratio
Δp	Change in Pressure Loss
Δh	Change in Specific Enthalpy
R	Gas Constant
η	Efficiency

CHAPTER 1

INTRODUCTION

This chapter presents an introduction to the topics of area covered in this research. The background, objectives, problem statement, scope and outline which supports this research conducted is explained. The understanding of the gap analysis that exists between previous researchers and how this current research will benefit the area of study.

1.1 Background

The aviation industry is globally recognized as an industry which has revolutionized over the years to meet the demands and needs of the era progression. Uniting Aviation (2018, para.2) reported that air transport has doubled in size every 15 years and growing faster than the other industries. In the report, it states that in 2016 itself, airlines worldwide transported 3.8 billion passengers with around 100,000 flights and 10 million passengers a day (Uniting Aviation,2018). No doubt, the airline governance has made travelling easier, as it is the only wide-range and far-reached transportation network that allows a wide area coverage. Travelling by air is now safer, affordable and profitable with the rapid advancement of technology.

The Aviation Benefits Beyond Borders (2019) presented the aviation industry's support of 3.6% of the world's gross domestic product (GDP) (Aviation Benefits Beyond Borders,2019). Thus, it is no surprise that the aviation industry will continue to expand for economic progression and serve passengers better experience. However, despite the airline contribution, there is no denial that there are environmental challenges especially with the global greenhouse emissions. It is reported that the emissions have increased by 3.3% per annum since 1990 due to rapid growth in traffic volumes of 5.2% per annum (IATA,2017) and the improvement to condone these emissions are currently about 1.9% per annum (Larsson et al., 2018). With a negative impact on climate change and global warming, these emissions have increased by 4.6% in 2010 compared to 2009 (Yilmaz and Atmanli, 2017). Following the statistics, 36% of the total carbon dioxide emissions are petroleum-based and 22% of it is from the transportation industry and predicted to increase by 80% by 2030 (Nduagu and Gates, 2014). Carbon dioxide emissions stand at 2% in 2012 and is expected to project 3% by 2050.

The aviation sector derivation of petroleum fuels with the commercial and cargo service has contributed to negative impact on the quality with the greenhouse emissions. This usage must be reduced as the fuels used in the aviation industry is not sustainable (Yilmaz and Atmanli, 2017). Thus, the International Civil Aviation Organization (ICAO), a focused agency of the United Nations (UN) is working hard to achieve the vision of the sustainable growth of the global aviation system (Chiaramonti, 2019) also incorporating the necessary infrastructure design in pace with air transport growth. Coupled with these greenhouse emissions, is the continuous depletion of the production of petroleum-based fuels. Hence more initiatives are being made to produce alternative fuels where biofuels have gained attention globally with it being a clean alternative.

Biofuels have been effectively used in the transportation industry and has a high potential in the aviation sector as it reduces greenhouse effects, enhance air quality, and reduce oil dependency. With the current precedence set on the importance of securing alternative fuels for the aviation industry, there are a number of researches conducted on the impact of alternative fuels for different type of engines during different flight conditions. However, it is found that the research carried out was only on certain conditions and did not fully comply with all. The recent study by Senebahven was only on a two-spool engine model running on alternative fuels (JSPK, 50%JSPK + 50%Jet-A, CSPK, 50%CSPK + 50% Jet-A) during a complete flight trajectory (Senebahven, 2018). On the other hand, Azami and Savill only studied a three-shaft high-bypass-ratio engine similar to RB211-524 during complete flight trajectory (Savill et al., 2017). Gaspar's research was on a two-spool turbo fan where the performance and pollutant emissions are studied during a complete flight trajectory (Gaspar and Sousa, 2016). Thus, this current research will incorporate the study of the engine performance for several type of engines with more number of alternative fuels during a complete flight trajectory.

1.2 Objective

This research is conducted to study the impact of using alternative fuels, on the engine performance of single-spool turbojet and double-spool turbofan engines. The analysis of these engine comparison performance will give a thorough view on the moving-forward strategy to fully incorporate the usage of these biofuels in the aviation industry. On another note, the research will not only benefit the aviation industry, but the transportation sector as a whole. Since the current transportation sector depends heavily on petroleum-based energy, the findings of this study and potential validation might contribute to a revolutionary switch of energy consumption and environmental protection. The study used a readily available software to model and simulate the proposed conditions of the engine parameters and flight conditions. The breakdown of the objectives is as follow:

1. To study the effect of alternative biofuels (include mixing of fuels percentage) on entire engine performance during a complete flight trajectory.
2. To provide a solid and thorough research on the possibility of incorporating alternative fuels for greenhouse emissions reduction.

1.3 Scope

The single-spool turbojet and double-spool turbofan engines analyzed in this research is modelled using a readily available software which is the Gas Turbine Simulation Programme. Publicized data based on previous researches is used to model the engine component model and the alternative biofuel properties. The result comprises of the engine performance comparison which are the thrust, mass fuel flow and specific fuel consumption. The fuels used in this research are Jet-A, JSPK, CSPK, 50%JSPK + 50%Jet-A, 50%CSPK + 50%Jet-A, POME, 50%POME + 50%Jet-A, Canola and Halophyte.

1.4 Outline

Chapter 1 explains the thorough introduction on the basis of this research. This chapter will introduce research objectives, scope, background as well as the outline for each chapter.

Chapter 2 focuses on the detailed literature review of the air pollution in the aviation industry comprises of the greenhouse emissions. A review on biofuels as alternative fuels in the aviation industry is studied as well. In addition to that, the turbofan and turbojet engine and the engine performance using alternative fuels is explained.

Chapter 3 discusses methods taken to complete this study. A flowchart of how the study is conducted is presented. All type of engines and fuels used in this study are explained.

Chapter 4 presents the result and discussion of this study. The validation and verification of the design point is explained for all three types of engines. The off-design simulation results are discussed and the engine performance between fuels and biofuels is compared in terms of thrust, mass fuel flow and specific fuel consumption.

Chapter 5 summarizes the thesis in a nutshell with the conclusion and recommendation for future work. This chapter discusses the prime achievements of this research, the problems encountered, research limitation and elaboration on future work.

CHAPTER 2

LITERATURE REVIEW

This chapter explains the air pollution in the aviation industry, greenhouse emissions and the impact towards the people and environment. Previous studies on using biofuels as alternative fuels for aircrafts, along with performance of the turbofan and turbojet engine is explained.

2.1 Air Pollution in The Aviation Industry

It is apparent that the level of air pollution today has reached dangerous levels with over 90% of the world's population living in areas where the ambient air pollution exceeds the World Health Organization guidelines. Harmful air pollutants such as Nitrogen Dioxide, Ozone, Sulfur Dioxide and fine atmospheric particulate matter are increasing with high concentrations (McNeill, 2019). The increased in air pollution has led to the millions of deaths worldwide where in 2015, 2.8 million came from household air pollution and 4.2 million from ambient air pollutions (Landrigan, 2017). According to Scharaufnagel, air pollution is considered one of the greatest environmental risk to health and is the fifth leading risk factor of death in the world, causing 4.2 million deaths and more than 103 million disability-adjusted life years lost in 2015 (Schraufnagel et al., 2019). A study by Wang found out that nine out of ten people are now breathing polluted air causing in 7 million people killed by polluted air every year. One-third of the polluted air deaths caused stroke, lung cancer and heart disease while 90% of the children under the age of 15 faces serious consequences for their health, well-being and development (Wang et al., 2019). An alarming finding by Min states long-term exposure to air pollution even contributes to an increased risk of suicide death especially people living in metropolitan areas (Min et al., 2018).

There are indeed different contributing factors resulting in carbon and greenhouse gas emissions and one of them is the aviation industry. Aviation activities contribute to the pollution source as the growth in the aviation industry has resulted in local air pollution due to the increased number of arriving and departing travelers, air traffic and supporting ground services (Psanis et al., 2017). The emissions of pollutants from the aircraft and supporting airport infrastructure affects the environment by impacting human health and well-being as well as the climate (Stettler et al., 2011). These emissions emitted from the aviation industry include greenhouse gases particularly Carbon Monoxide, Carbon Dioxide, Sulphur Dioxide and Nitrogen Dioxide (Stettler et al., 2011). Although the emissions from the aircraft engines exhaust accounts for most of the pollution, there are other sources which includes brake, tyre and re-suspension of particles due to turbulence by the aircraft movements (Masiol and Harrison, 2014). The impact of air pollution proves to affect humans and the environment at a very dangerous scale and must abide to the standard set by international bodies on the allowable level of pollution.

The International Civil Aviation Organization (ICAO) through the Committee on Aircraft Engine Emissions (CAEE) has implemented emission standards for new types of aircrafts since the late 1970s (Stettler et al., 2013). This supports the study by Baledon where she said alternative jet fuels are indeed one of the four mechanisms by the United Nations International Civil Aviation Organization to limit and further reduce carbon and greenhouse gas emissions (Soria Baledón and Kosoy, 2018). Despite the efforts to rigorously monitor the measurement of the level of air pollution and a reduction in direct aircraft emissions, the improvements are still small considering the increase in air traffic as well as the growth of the aviation industry (Masiol and Harrison, 2014). Masiol and Harrison revealed in their study that there are other factors than engine aircraft emissions which are emissions from units providing power to aircraft on ground, traffic due to airport ground service, and maintenance (Masiol and Harrison, 2014). In addition to that, concerns regarding the high production cost of alternative biofuels. Thus, more strategies are now employed by airports, fuels producers and airlines in effort to reduce the fuel consumption and emissions of air pollutants including from takeoffs, taxiing and even at the taxiways near the end of runaways (Yim et al., 2013). Yilmaz and Atmanli mentioned that manufacturers of air and ground vehicles overall are trying to focus on designing engines and vehicles which would be compatible with alternative biofuels and subsequently support energy policies of countries (Yilmaz and Atmanli, 2017).

Deonandan and Balakrishnan evaluated the single engine taxiing which involves using one engine on a twin-engine aircraft or two engines on a four engine aircraft for the taxi phases without the taxi time changed (Deonandan and Balakrishnan, 2010). Barrett discussed the desulphurization of jet fuel that can potentially reduce the fuel Sulphur content of aviation fuel to minimize health impacts of the aviation industry (R. H. Barrett et al., 2012). Interestingly enough, Carter discussed the possibility of using biomass-derived alternative jet fuels which has zero Sulphur content and can equally apply to the emissions reduction of desulphurization of jet fuel (Aaron Carter, 2013). It is evident that the efforts to reduce harmful emissions from the aviation industry particularly aircrafts have been an on-going process and will continue to be as the airspace management is constantly revolutionizing with the rapid progression of this digital age.

The most common contributing threat to air pollution is the increased level of greenhouse emissions. The air travelling demand has increased tremendously and it comes with damaging effects of carbon risks. In 2017, the estimated Carbon Dioxide emissions was 844 million tonnes including both passenger and freight transport hence representing 1.7% and 2.3% of the global Carbon Dioxide emissions from fossil fuels the industry (Becken and Shuker, 2019). The numbers will only rise in the future especially with the growing aviation sector where 7.2 billion air passengers are expected to travel in 2035, double the 3.8 billion in 2016 (O'Connell et al., 2019). The International Civil Aviation Organization has initiated the goal to stabilize the GHC emissions by 2020 but according to the trend assessment by their own Committee on Aviation Environmental Protection, the emissions will still increase to the rapid growth of the aviation sector (O'Connell et al., 2019).

Baumeister studied the aircraft emissions in Finland for long-haul trips and short-haul routes and in effort to reduce the greenhouse gas emissions. He discussed the possibility to replace short-haul flights with land-based transportation mode as short-haul flight produce the highest emissions per passenger (Baumeister, 2019). Becken and Shuker suggested other alternatives to reduce the carbon emissions for a given flight by managing the load factors, flight paths in response to weather forecasts and efficient sharing of civil aviation and military airspace (Becken and Shuker, 2019). A different study by Baumeister suggested flying with the most modern aircraft or flying non-stop is the least polluting option in proving the carbon emissions of individual flights can differ on a large scale (Baumeister, 2017). Numerous previous studies prove that countless efforts are being made to reduce the carbon emissions effect in the aviation industry as it evidently contributes to a large percentage of the air pollution worldwide.

2.2 Alternative Fuels in the Aviation Industry

Today, most of the global energy demand is supplied by coal, natural gas and petrochemicals. Many countries have developed different fuel markets that causes less environmental impact associated with fossil fuels burning. Besides the environmental concern, the price fluctuation on international crude oil and the decreasing oil reserves have propelled countries to take cautious measures to turn to alternative fuels (Lobo et al., 2009). The growth in the aviation industry has led the development of renewable and safer fuels to ensure a sustainable growth of aviation transport. The development of alternative fuels is based on Ranucci's study where she said 3.8 billion passengers will be transported in the coming years and the aviation traffic will double within 15 years from 2012 with Carbon Dioxide emissions in 25 years (Ranucci et al., 2018). The greenhouse gas emissions which contain Nitrous Oxide, Carbon Dioxide and Methane will only increase with the requirement of oil transport by 1.3% per year up to 2030 (Cican et al., 2019).

The growing concern of the environmental impact has pressured the aviation industry to continuously work on the impact reduction and promote the concept of green aviation to reach the target of carbon neutral growth status by 2020 (Bwapwa et al., 2017). However, Staples said that if the aviation's greenhouse gas emissions were to be reduced by 50% by 2050, prices and policies must prioritize the production of biofuels over other potential uses of the resources and focus on the global biofuel production capacity (Staples et al., 2018). According to a study by Kandaramath, the only alternatives to reduce the environmental impact are modifications of vehicle designs and the replacement of conventional fuels with alternative advances fuels and technologies (Kandaramath Hari et al., 2015). The awareness of the importance of finding alternative fuels especially biomass has sparked interest for a wide range of companies and industry to stay committed and work towards the production of alternative biofuels. The efforts are certain despite having gaps where the International Civil Aviation Organization regulation only addresses 4 main pollutants (Masiol and Harrison, 2014). The end objective is to have better renewable resources which has a low greenhouse gas life cycle, reduction in greenhouse gas emissions and sustainable competitive price.

Although biofuels has been identified as the most promising alternative by the International Air Transport Association to reduce Carbon Dioxide emissions and will allow at least partial fuel independence, there are indeed challenges to begin with (Gutiérrez-Antonio et al., 2017). According to Gegg and Budd, despite a number of successful test flights, the aviation biofuels are still not widely commercialized as it is being constrained by high production costs, limited availability of suitable feedstocks, the sustainability criteria and a perceived lack of national and international policy support for biofuels (Gegg et al., 2014). Not only that, a study by Nygren mentioned that even if the aviation fuel production is predicted to decrease once the crude oil production peak is reached, there will be a shortage of jet fuel by 2026 (Nygren et al., 2009). The timeline of available jet fuel and the possibility of having alternative biofuels to completely replace them is increasingly worrying as the whole air transport industry might globally affected. The dependence of air travel will only contribute to a dysfunctional transportation system. Thus, it is crucial for companies, organizations and all responsible bodies to realign their strategy to meet the increasing demand of the air transport industry while reducing the environmental impact on a noticeable scale.

Biofuels are simply fuel which are derived from biomass and are plant-based or of animal wastes. They are the major readily available resources for the bulk energy production especially camelina, jatropha, algae, halophytes, municipal, sewage wastes and forest residues. The expected contribution of Bio jet fuel is 30% by 2030 and with the annual 100 trillion kilograms universal production of biomass, the bulk of feedstock would not be a problem for the aviation industry (Kandaramath Hari et al., 2015). The amount of resources available proves that with time, the industry will be able to reduce the harmful emission of greenhouse gases and promote the concept of green aviation.

According to a study by Gutierrez Antonio, one of the reasons why biofuels are able to reduce these emissions is due to the similar composition to fossil jet fuel that contains aromatic compounds (depending on the production process used) and if there is an absence of this compound, it will only contribute to a lower emitted fuel particles (Gutiérrez-Antonio et al., 2017). On the contrary, a research by Jie Fu mentioned that although biofuels have demonstrated their compatibility with land vehicles, the high energy density and heating value needed for aviation fuels derived from crude oil is still difficult to achieve (Fu et al., 2015). Blakey explained that aviation fuel must possess very specific characteristics like high calorific value, high energy density, good atomization, low explosive risk on the ground, suitably low viscosity, zero water content, thermal and chemical stability, low corrosivity and lastly extremely low freezing point (Blakey et al., 2011). Not only that, there are concerns regarding the high production cost and investment to have biofuels manufacturing plants, a very expensive approach.

2.2.1 Alternative Fuels on Engine Performance

There are a number of researches conducted to study the suitability and impact of using alternative biofuels for aircraft engines. R.M.P Gaspar conducted a study on the impact of alternative fuels on the operational and environmental performance of a small turbofan engine. The alternative fuels used were from varying feedstocks such as camelina oil, corn, biomass, and vegetable oil. He concluded that these alternative fuels improve engine performance, prominently the specific fuel consumption as the decrease in fuel consumption resulted in a reduction of greenhouse emissions like Carbon Dioxide and soot pollutant. The study mentioned depending on the operating condition, the overall performance enhancement with better life cycle emissions of Carbon Dioxide will ensure the sustainable approach of the green aviation industry (Gaspar and Sousa, 2016).

Mazlan and Savill also conducted a research on the effect of biofuel properties, Jatropha Bio-synthetic Paraffinic Kerosene (JSPK) and Camelina Bio-synthetic Paraffinic Kerosene (CSPK) on the aircraft engine performance. The study simulated the influence of heat capacity and the density of both fuels using a two-spool high-bypass turbofan engine at a cruise condition. The study concluded the increase in the percentage of the kerosene and biofuel mixture contributes to an increase in engine thrust and reduction in fuel consumption which could eventually reduce the dependency on crude oil (Mazlan et al., 2015). Mazlan's work propose that contributing factors such as heat capacity and density must be taken into consideration when selecting a new alternative fuel for aircraft engines.

Azami and Savill conducted a similar study using different blended mixing ratio percentages of Camelina and Jatropha but with a three-shaft high-bypass ratio engine. His focus was on the aircraft engine performance and analysis specifically thrust, fuel flow and specific fuel consumption and concluded that Jatropha biofuel gives better performance result. The gross thrust is higher, reduction in fuel flow and specific fuel consumption were observed. He mentioned all blended fuels have an increase in performance at a higher mixing ratio percentage and the results indicated that the low heating value of a fuel influences thrust, fuel flow as well specific fuel consumption (Savill et al., 2017). The result can be supported by the work of Wolters when he mentioned the direct consequences of the combustion of alternative fuels must consider the fuel heating and the chemical composition (Wolters et al., 2012).

Carbon emissions from gas turbines are known to be related to aromatic content and be significantly reduced if alternative fuels are which are low in aromatic content. Raymond Speth conducted a study on the black carbon emissions from combustion of alternative fuels and used different models of turbofan and turbojet engines. He confirmed that results show carbon emissions is proportional to the fuel aromatics content and concluded that it is possible for future alternative jet fuels be produced with different chemical compositions but similar specifications of Jet A fuel (Speth et al., 2015). Thus, consideration of the use of biofuels in air transportation are expected to progress between the year 2010 and 2050 (Winchester et al., 2013). Staples expressed that the sustainable growth of the aviation industry and the reduction of the emissions would require 60 new bio-refineries annually which is similar to the global growth of biofuel production capacity (Staples et al., 2018).

2.3 Turbojet Engine Performance

Turbojet engine is a jet engine that produces propulsive thrust by ejecting hot gases from the engine exhaust nozzle. According to a study by Haider on the parametric analysis of a single-spool turbojet engine, the propulsive thrust is produced by the compression of air in the inlet and compressor, mixture of air with fuel, burn in the combustor and expansion of gas steam through the turbine and nozzle. The power to turn the compressor is supplied by the expansion of gas and the net thrust is then delivered by the engine through energy conversion (Haider et al., 2011)

Engine thrust and specific fuel consumption are the important parameters in characterizing overall performance of a turbojet engine. These performance at different flight conditions and throttle setting can be analyzed using the application of mass, energy, momentum and entropy to the steady flow of a perfect gas (Domitrovidr et al., 2019). According to Virdi's study, the turbojet engine typically works on the principle of Brayton Cycle with multiple thermodynamic processes namely isentropic and isobaric (Virdi et al., 2017) Figure 2.3.1 and Figure 2.3.2 below shows a typical schematic diagram of a single-spool turbojet engine with and without an afterburner respectively.

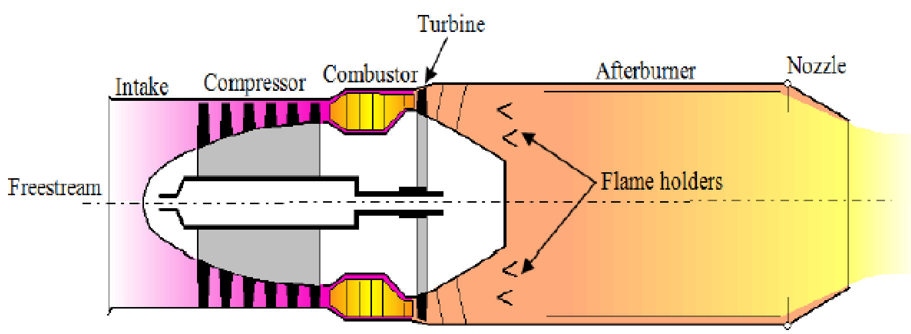

Figure 2.3.1 : Single-spool Turbojet Engine with Afterburner (Haider et al., 2011)

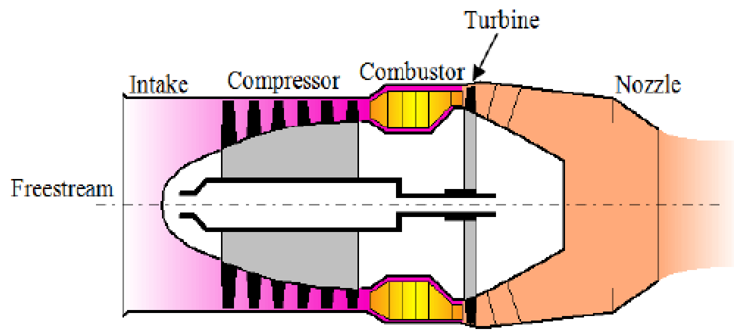

Figure 2.3.2 : Single-spool Turbojet Engine Without Afterburner (Haider et al., 2011)

Both figures show the simplest form of a turbojet engine and the function of engine component is further explained in Abbas and Riggins's study on the entropy-based performance analysis of a single-spool turbojet. The inlet component or also known as diffuser in a turbojet engine configuration is used to capture the induced air to pass it through the compressor. The compressor increases the pressure and temperature by mechanical compression just before the fuel-air combustion. The burner or also known as a combustion chamber uses the airstream entering the chamber and burns the injected fuel. The turbine extracts the energy from the combustion chamber to provide power to the compressor and other needs to the engine where the nozzle will finally expand the flow producing thrust (Abbas and Riggins, 2016).

Domitrovic's study emphasized on assumptions which are crucial for thermodynamic calculations. The turbine cooling and leakage effects are neglected and the turbine entrance and exit nozzle are considered choked as well. Not only that, the gases are considered perfect both upstream and downstream from the burner. Apart from that, the total pressure ratios of the burner, exit nozzle and component efficiencies remain the same as reference values (Domitrovidr et al., 2019)

2.4 Turbofan Engine Performance

The turbofan is a type of engine which is typically used for aircraft propulsion and has been a mainstay of aircraft propulsion systems. It is a gas turbine engine that uses the shrouded fan to deliver a high performance in the transition between high subsonic to low supersonic flight application range and this includes the ability to provide efficiency up to Mach number 0.85, a slightly better advantage than turboprop engines (R. Greatrix, 2012). The revolution of turbofan engine is coupled with engine manufacturers continuously improving the overall engine efficiency specifically lower fuel consumption and reduction in noise and emissions (Van Zante, 2016). Commercial and fighter planes invariably uses turbofan engines, a modified version of turbojet for reduction in het noise and propulsive efficiency.

Unlike the turbojet engine, thrust is a result of two components which are the cold steam or fan trust and hot steam thrust. According to Pashilkar, this is possible due to a portion of the total flow bypasses compressor, combustor chamber, turbine and hot nozzle before finally being ejected through a separate cold nozzle (Yadav et al., 2005). This possibility is supported by the study of Mustafa and Kadri where they mentioned the complication of the turbofan design is due to the two nozzles, one for flow and the other for hot flow. The figure below shows a turbofan engine (Koçer and Çakır, 2018).

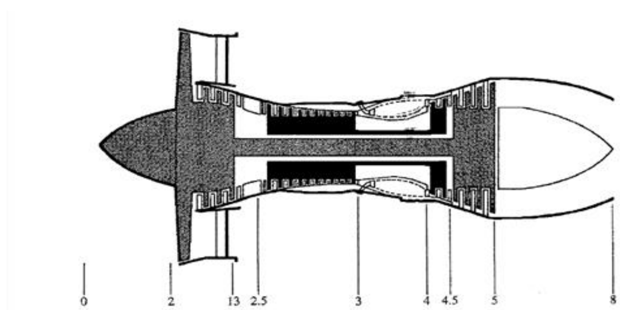

Figure 2.4.1 : Turbofan Engine (Koçer and Çakır, 2018)

The turbofan engine in Figure 2.4.1 shows two parts of low pressure and high pressure divided from the turbine and compressor component. There are two spools which separate the exhaust nozzles where the high-pressure turbine drives the high-pressure compressor through the high-pressure spool and the low-pressure turbine drives the fan and low-pressure compressor through the low-pressure spool. An important note, the analysis the turbofan exit state is similar to the low-pressure compressor exit state. (Koçer and Çakır, 2018). Each engine component is modelled using physical laws, dimensionless performance characteristic maps and empirical data (Chuankai et al., 2011).

Gaspar conducted a similar study using a double-spool turbofan engine and explained a typical model of a turbofan engine with engine components of low-pressure compressor (LPC), high-pressure compressor (HPC), low-pressure turbine (LPT), high-pressure turbine (HPT), combustor chamber, fan, convergent fan nozzle and convergent core nozzle. Figure 2.4.2 shows a typical engine component model of a turbofan engine in Gaspar's study (Gaspar and Sousa, 2016).

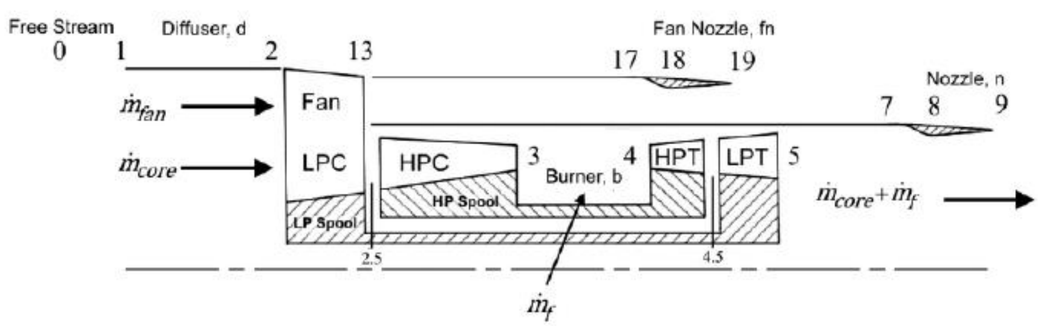

Figure 2.4.2 : Typical Turbofan Engine Configuration (Gaspar and Sousa, 2016)

Mustafa and Kadri pointed out the few correlations between the specification of engine components and how they affect the overall engine performance. The thrust is greatly influenced by altitude (difference in density), Mach number, bleed speed, mass fuel rate, specific fuel consumption and bypass ratio. This current study focuses on engine performance specifically thrust, mass fuel rate and specific fuel consumption hence giving a better understanding on Mustafa and Kadri's conclusion. Burning more fuel will increase the temperature and causes air to accelerate thus an increase in thrust is obtained. A high compression ratio engine on the other hand will have a lower specific fuel capacity. The compressor ratio affects the fan compressor ratio and overall thrust. This is because the increase in compression pressure ratio results in the decrease in specific thrust and specific fuel consumption with a constant level of thermal efficiency. The fan compressor ratio affects the bypass flow and subsequently thrust. This is due to the increase in bypass ratio which would lower the fan pressure ratio. Last but not least, the fan bypass which plays a significant contributing factor the thrust, specific fuel consumption and thermal efficiency (Koçer and Çakır, 2018). Below are some example calculations used for the engine components.

Compression Ratio,

$$CR = \frac{P_a}{P_2} \tag{1}$$

Bypass Ratio,

$$BPR = \frac{\dot{m}_f}{\dot{m}_c} \tag{2}$$

Thrust,

$$F = \left(\dot{m}_f V_f - \dot{m}_f V_o\right) + (\dot{m}_e V_e - \dot{m}_c V_o) \tag{3}$$

Specific Thrust,

$$F_s = \frac{F}{\dot{m}_a} \tag{4}$$

Thrust Specific Fuel Consumption,

$$TSFC = \frac{f}{F_s} \tag{5}$$

$$TSFC = \frac{\dot{m}_{ff}}{F} \tag{6}$$

For Energy Balance Cycle,

$$W_c + Q_{in} = W_N + Q_{Rej} \tag{7}$$

Energy Ideal Cycle,

$$W_C = W_T \tag{8}$$

$$W_N = Q_{in} - Q_{Rej} \tag{9}$$

CHAPTER 3

METHODOLOGY

This chapter explains the detailed flowchart, analysis and discussion on the method that is used in conducting this research. The Gas Simulation Programme that is used to model the engine and the validation of the raw data is explained. The modelling of the off-design engine performance is presented as well.

3.1 Flowchart of Research

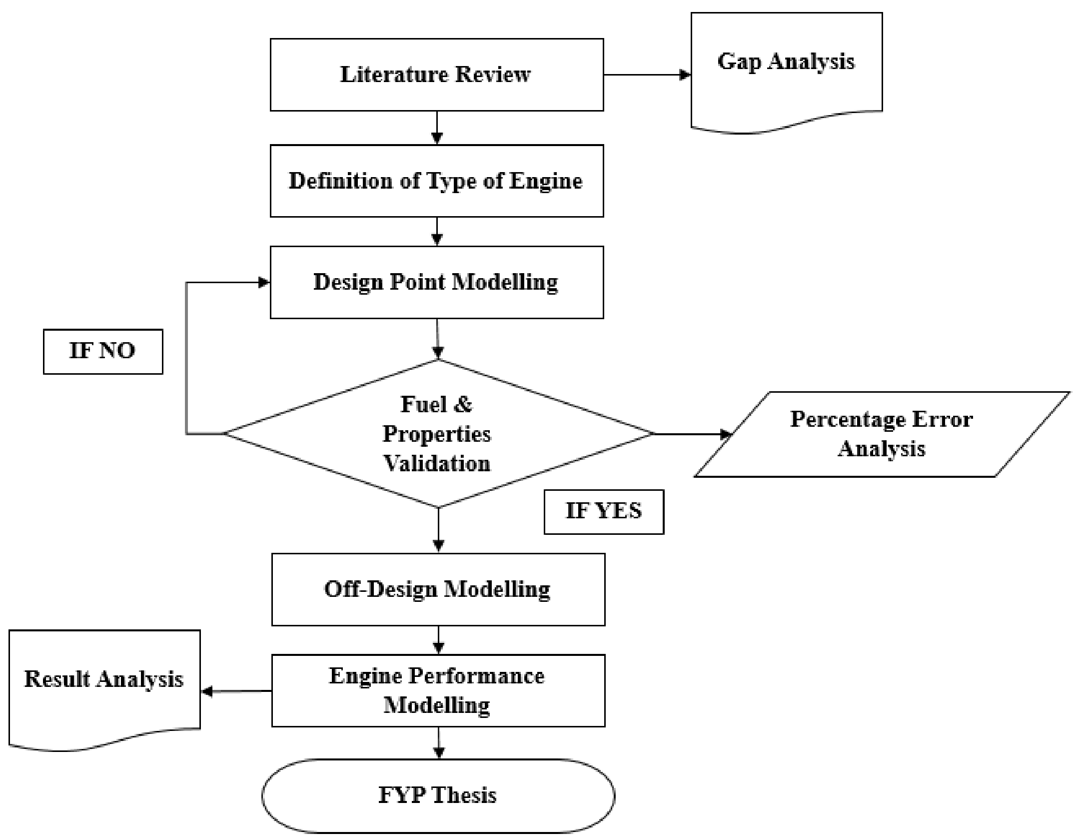

Figure 3.1.0 : Flowchart of Research

Figure 3.1.0 above shows the detailed flowchart with the input and output at every stage of the research. The study was split into three phases. The initial phase consists of reviewing previous literatures on the topic and identifying type of engine that will be used for evaluation. The second phase consists of the design phase in which the design point engine parameters are defined, and the raw data is validated. The final stage is the off-design stage where the off-design engine performance is analyzed.

In the initial phase, the literature review study is conducted, and a gap analysis is carried out to understand the comparison between previous research and the potential significance of current research. Type of engine used in this study is finalized. Two type of engines were considered which are the single spool turbojet engine and double spool turbofan engine which was evaluated during a complete flight trajectory.

The second phase starts with the design point modelling of both single spool and double spool engine. The generic single spool turbojet engine is modelled based on Abbas and Riggins's research (Abbas and Riggins, 2016) while the double spool turbofan engine is modelled based on the CFM56-3 turbofan engine research conducted by Gaspar (Gaspar and Sousa, 2016). The design point parameters are set and the fuel properties considered in the study are included to validate the design point performance. If the simulation results show a difference of more than 10%, another engine model with new design parameters will be chosen. If the percentage difference is within the allowable range, the design point is validated and will proceed to the off-design point.

The final phase is the off-design engine performance phase. In this phase both single and double spool engines are modelled with the different fuel properties at a complete flight trajectory. The low speed spool is altered to represent the different flight condition environment. The comparison of engine performance for the two type of engines will be analyzed and the contribution of the different type of alternative fuels affecting the engine performance is studied. The comparison of engine performance will focus on the thrust, specific fuel consumption and mass fuel rate.

3.2 Single Spool Turbojet Engine

The single-spool turbojet engine was modelled with fixed-geometry consisting of conventional components such as nozzle, compressor, combustion chamber, turbine, and exhaust. This modelled was taken from Abbas and Riggin's research who studied the performance analysis, methodology and application of a generic single-spool turbojet engine (Abbas and Riggins, 2016). According to Haider's study, the variability of a turbojet engine depends on the present available technology and the principal application of an engine and hence contributing to the design of the gas turbine engine (Haider et al., 2011). The figure below shows an example of Abbas's scale engine that corresponds a medium scaled operational engine with the layout and station-numbering.

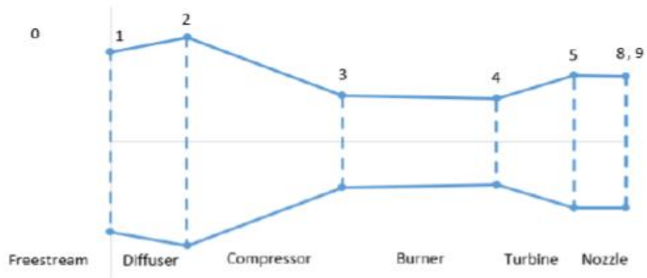

Figure 3.2.0 : Single-Spool Engine Layout and Station-Numbering (Haider et al., 2011)

3.2.1 Design Point Modelling

The single-spool turbojet engine was modelled using the Gas Turbine Simulation Program version 11 and the engine parameters were extracted from Abbas's work as a foundation to validate the engine. His modelled engine was obtained from Mattingly's work which covers subsonic and supersonic flight ranges and is modelled with an ideal burner and nozzle (D. Mattingly et al., 2018). In this study, design point simulation was performed according to the case considered in Abba and the comparison between the two cases was compared. If the comparison between Abbas's engine and the modelled engine is less than 10%, the design-point is validated and can proceed to the off-design performance stage. The figure below shows the modelled generic single-spool turbojet engine using the Gas Simulation Program.

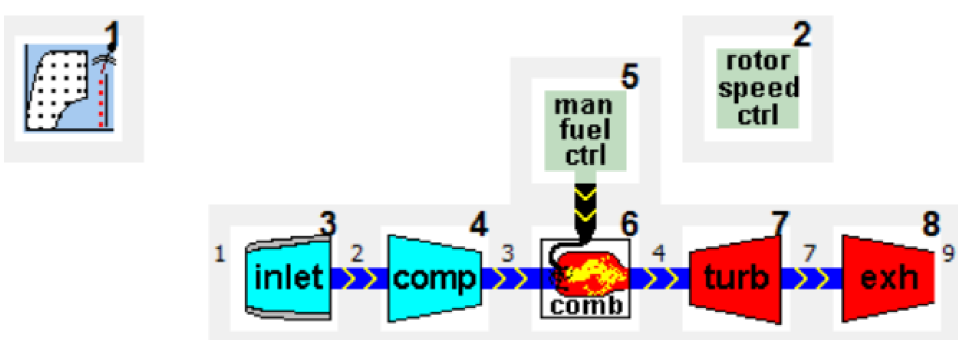

Figure 3.2.1 : Single-Spool Turbojet Engine Modelled in Gas Simulation Program