University of Southern Queensland

School of Engineering

Mini Jet Engine Performance testing using Alternative Fuels

A dissertation submitted by

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Abstract

Fossil-based fuels remain the dominant fuel source for turbine engines across all sizes. While substantial research has been conducted on the feasibility of alternative fuels for large-scale turbines, relatively little has been done to assess the applicability of such fuels in small to medium-sized jet engines. This project investigates the impact of alternative biofuel blends on the emissions and performance of a K60TPG4 micro gas turbine engine. The study involved designing and assembling a functional test bench, followed by experiments with the following fuel blends:

1. 100% Diesel
2. 25% Biodiesel/Diesel blend
3. 100% Biodiesel

Emissions data was collected using a gas analyser, and engine performance data was extracted from the Engine Control Unit (ECU). The results demonstrated that biodiesel blends led to lower emissions, particularly in unburnt hydrocarbons, with minimal impact on engine performance parameters. This research suggests that biofuel blends are a viable alternative for reducing the environmental impact of micro gas turbines while maintaining operational efficiency.

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ENP4111 Dissertation Project

(This is a 2-unit research project in Bachelor of Engineering Honours Program)

Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

David Coco

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04/11/2024

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Finaly, I would like to express my deepest gratitude to my wife, Rebecca, for her unwavering support and patience throughout the past 9 years of my study journey. She has been a constant source of strength, especially while maintaining the family household when I needed time for my studies. I could not have overcome this period of my life without her.

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Nomenclature

B100	100% Biodiesel Fuel Blend
B25	25% Biodiesel Fuel Blend
CHP	Combine Heating and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DO	Diesel Oil
DRM	Data Relay Module
ECU	Engine Control Unit
EGT	Exhaust Gas Temperature
FOD	Foreign Object Damage
FSR	Field Service Representative
GSU	Ground Support Unit
Hz	Hertz
HC	Hydrocarbons
ICE	Internal Combustion Engine
K60TPG4	KingTech Micro Turbine Turboprop Engine - Generation 4
LHV	Lower Heating Value
MGT	Micro Gas Turbine

MTG	Micro Turbine Generator
NiMH	Nickel Metal Hydride
NOx	Nitrogen Oxides
O_2	Oxygen
OEM	Original Equipment Manufacturer
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute
SAF	Sustainable Aviation Fuel
SOV	Shut Off Valve
Thr	Throttle
TpRPM	Propellor RPM
UniSQ	University of Southern Queensland

Chapter 1

Introduction

1.1 Introduction

For many decades, commercial aviation has been crucial for global connectivity, enabling the rapid movement of people and goods long distances, supporting international and domestic trade, tourism and economic growth. The engines powering this industry are predominantly large turbine-based powerplants that operate on kerosene-based fuel. In recent decades, the link between Carbon Dioxide (CO_2) emissions and climate change has driven the industry to pursue more environmentally friendly fuel sources, while still upholding the lofty standards of reliability and safety expected in aviation. While the 'industry's CO_2 contribution is relatively small in percentage terms, approximately 2.5% of global emissions annually, it is expected that emissions will triple by 2050 on current trends' (Kwan & Rutherford 2015).

The pursuit of solutions to this problem has led to the emergence of a specialised industry, known as Sustainable Aviation Fuel (SAF). The International Civil Aviation Organisation (ICAO) defines SAF as a renewable or waste-derived fuel that meets several sustainability criteria, including but not limited to: (i) the reduction in net life cycle greenhouse gas emissions by at least 10% relative to conventional fuels; (ii) not being produced from biomass in lands with high carbon stocks; and (iii) conserving the local water, soil, air quality, and food security (Teoh et al. 2022).

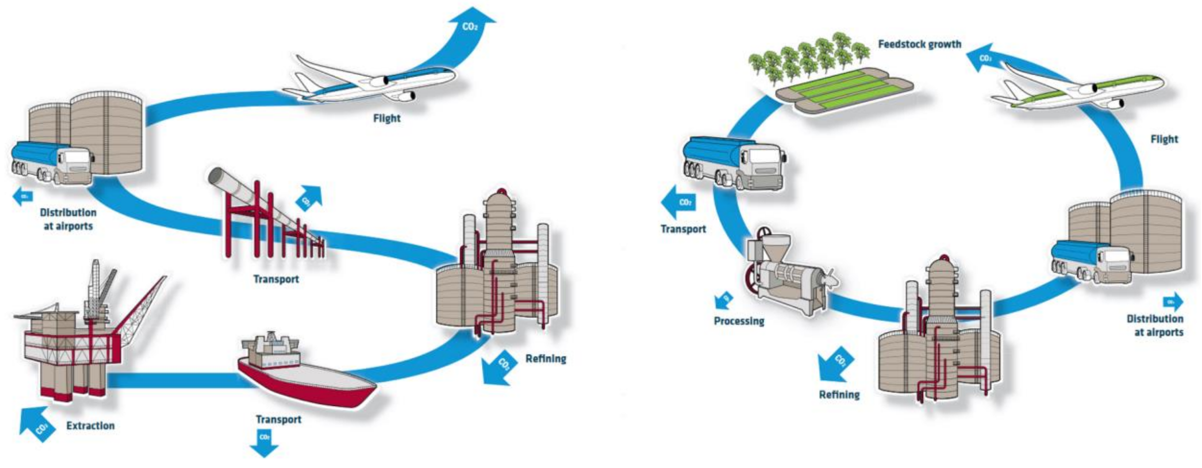

Figure 1 - Carbon Life cycle for Fossil Aviation Fuel vs Aviation Biofuel (Cabrera & de Sousa 2022)

While there is little doubt SAF offers environmental benefits, the question arises: do these benefits extend to engine performance and reliability? If engines are unable to deliver the same power output or result in a reduced lifespan due to SAF use, does this diminish the overall positive environmental impact?

This project will explore the relationship between alternative fuel blends and turbine engine performance, focusing specifically on a micro-turbine perspective.

1.2 Motivation

As a former Aircraft Maintenance Engineer in the defence sector, I regularly handled aviation fuel. Strict protocols were followed for testing the fuel at various stages, from storage facilities and transport trucks to pre-refuelling checks for each aircraft. Once inside the aircraft, a series of systems and components ensured that the fuel quality was maintained or enhanced before reaching the engine.

These experiences led me to consider the potential impact on engine performance if an alternative type of fuel were to be used. Would the aircraft's components and engines, accustomed to high-quality fuel, be able to adapt to a different type after years of exposure to the best standards?

Another interesting point is that, while the Australian Defence Force has not publicly adopted SAF for their assets, other nations are already well underway in their transition. For instance, all United States Navy (USN) ships and aircraft are certified to operate on a 50% blend of SAF (Lane 2017) and the United Kingdom's Air Force also permits up to 50% SAF blends in their aircraft fleet.

Conducting large-scale experiments to test SAF-type fuels on commercial or defence-specification engines is neither technically nor economically feasible for myself or the University of Southern Queensland (UniSQ). However, Dr. Khalid Saleh, my supervisor on this project, has led a similar study on a smaller scale using a KingTech K60TPG4 microturbine turbo propeller engine.

1.3 Project Aims and Objectives

The aim of this project is to design, construct, and commission a functional test bench for the K60TPG4 micro turbine engine. This test bench will be used to assess the suitability of different fuels by analysing their emissions and performance characteristics on the engine. Through this process, the aim is to gather valuable data and insights into the efficiency and environmental impact of various fuel options.

The primary objective of this project is to:

- Determine the effect of biofuel blends on microturbine performance and exhaust emissions.

This will involve evaluating how two different biofuel mixes impact both the power output of the microturbine, as well as analysing changes in emissions, such has hydrocarbons (HC), carbon dioxide (CO_2) and other pollutants, in comparison to baseline fuel of petroleum-based diesel.

To achieve this objective, several tasks were outlined to assess the project's feasibility.

Chronologically, they were as follows:

1. **Construct a Test Bench:** Assemble and mount the engine and its components in an ergonomic configuration on a mobile bench.

2. **Commission Test Bench:** Ensure the engine can be operated and controlled from a safe distance while providing data required for analysis.

3. **Run Different Fuels**: Implement a suitable fuel storage and delivery system to supply the engine from various fuel sources.

4. **Analyse Fuel Emissions:** Set up emissions testing equipment and ensure it captures relevant and accurate data.

5. **Analyse Engine Performance:** Capture and analyse engine operating parameters on different fuel sources and compare data.

If time allows, the following tasks should be completed to enable a continuing, in-depth analysis on the impact of different fuels on engine performance.

1. Create an instruction manual to ensure the test stand can be utilised for future studies, enabling safe operation by any relevant personnel.

2. Design, construct and commission a controllable load application to the propellor shaft end of the test bench.

1.4 Project Overview

This dissertation is organised in a structured format that chronologically follows the journey from the initial concept to the final data analysis of the engine running on 100% biodiesel. The major headings for each chapter are listed below.

Chapter 1 introduces the project by outlining its background, motivation, and aims. These aims are carefully aligned to support the project's main objective, ensuring a coherent and focused approach to addressing the key issues and achieving the desired results.

Chapter 2 provides a comprehensive review of the relevant literature, focusing on the operational principles of both commercial-sized gas turbine engines and the microturbines utilised in this project. It also examines the use and advantages of alternative fuels, with a particular emphasis on biodiesel. This chapter includes an analysis of previous experiments conducted by experts in the field, offering insights into similar studies and the outcomes achieved, which provide valuable context for the current project.

Chapter 3 outlines the process of setting up the experiment, from initial conception to the development of a fully operational remote-controlled test bench. It details the challenges encountered along the way and the solutions implemented to overcome these obstacles.

Chapter 4 discusses the methodology of the project, detailing the processes and techniques used to measure emissions and engine performance parameters during the tests.

Chapter 5 presents the test results, primarily through graphical representations. Some of these graphs are generated from manually recorded data, while others are directly sourced from the engine software. The results for each fuel type and throttle power setting are then comparatively analysed and discussed to highlight trends, performance variations, and key findings.

Chapter 6 offers a discussion of the analysed results from Chapter 5, emphasizing both the expected and unexpected findings. As well as detailing some B100 fuel blend specific effects on the engine during testing.

Chapter 7 concludes the dissertation by summarising the key findings of the research. It also offers recommendations for improving the tests conducted, addressing limitations encountered during the process, and suggesting potential avenues for further research and experimentation using the test bench. These recommendations aim to refine the methodology and enhance the understanding of the subject for future studies.

Chapter 2

Literature Review

2.1 Chapter Overview

A literature review was carried out to deepen the understanding of the technical functioning of gas turbine engines, along with the conventional and alternative fuels that can power them and their associated emissions.

There is a substantial amount of research into the manufacture and storage of alternative sustainable aviation fuels. However, when it comes to the effect of these fuels (of which each has a different chemical make-up) on the short and long-term load performance on the engines, published research is limited. This trend is also mentioned in an article written by Przysowa et al. (2021) which states 'Alternative fuel containing biocomponents produced in various technologies are introduced in aviation to reduce its carbon footprint but there is little data describing their impact on the performance and emissions of engines'. This lack of research was also mentioned in an article by Boomadevi et al. (2021) stating 'Aviation is a sector where a lot of safety procedures are followed cautiously and aviation engines are the one on which biofuel research is only limited'.

By analysing both conventional and alternative fuels, primarily in gas turbine applications. The literature review aims to understand how these fuel sources impact emissions and engine efficiency, addressing knowledge gaps and contributing to a broader understanding of fuel-related emissions and performance in engine systems.

2.2 Gas Turbine Engine Overview

Due to the primarily recreational nature and relatively low cost of sub-20kW microturbine engines, the amount of published literature available is limited. Where technically feasible, literature referencing large commercial aviation-sized gas turbine engines or microturbines exceeding 20kW has been utilised. The research areas of interest include the operation of gas turbines and turboprops, and subsequently micro gas turbines and turboprops.

2.2.1 Turbine Operation

To understand the operation of a microturbine, it is important to first grasp the functioning of a standard-sized gas turbine engine. Like a four-stroke piston engine, a turbine engine follows a four-stage combustion process: intake, compression, power, and exhaust—often referred to as 'suck, squeeze, bang, blow' (Figure 2).

- **Intake/Suck** - Air is ‘sucked’ in via a multistage fan, which itself is driven by the turbine once the engine has reached idle operation parameters at a minimum.
- **Compression/Squeeze** - This air is then compressed throughout the multi-stage compressor module, becoming extremely hot due to the forced compression.
- **Power/Bang** - This hot compressed air then enters the combustion section, where it is mixed with fuel delivered in a fine mist and ignited by an electric component.
- **Exhaust/Blow** - This ignited fuel/air mixture then passes through a series of turbines, subsequently turning both the compressor and fan and exits through the exhaust nozzle to produce forward thrust.

This continuous simultaneous operation provides a smooth and efficient system in comparison to 4-stroke piston powered engines.

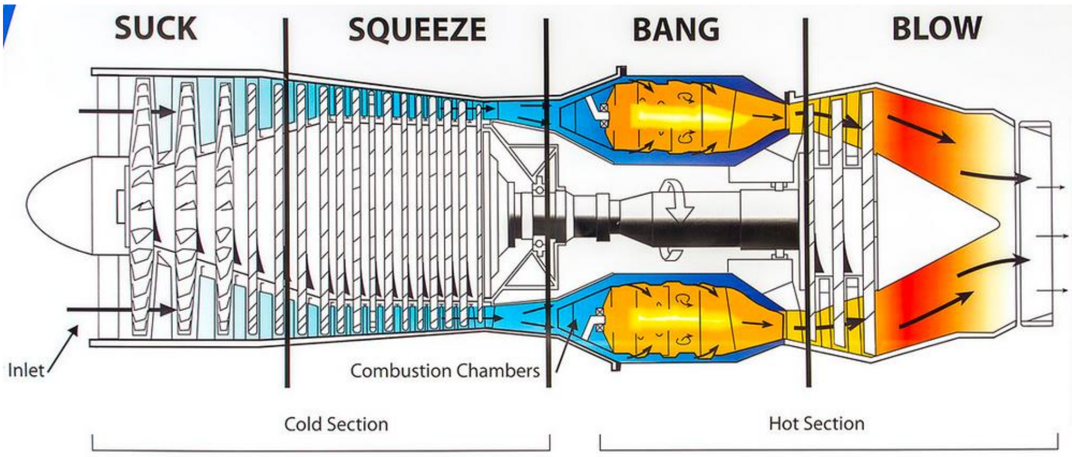

Figure 2 - Jet Engine Operation 'Suck, Squeeze, Bang, Blow'. (Gregory 2017)

2.2.2 Micro Turbines Operation

As the name suggest, micro turbines are scaled down versions of their larger, more commercially available counterparts. According to Frechette (2013), microturbines can be defined as ‘miniature rotating machines that convert fluid energy into mechanical energy, implemented using microelectromechanical systems technologies or other small-scale manufacturing approaches’.

Some operation advantages of micro turbines include a high power to weight ratio, trivial vibration, enhanced performance at high altitudes and capability to use heavy fuels (Frechette 2013).

Micro turbines, like gas turbine engines, operate as continuous-flow engines. ‘Unlike four-stroke engines, they maintain a steady flame during combustion, which enables them to efficiently use a variety of fuels while ensuring cleaner combustion within the turbine’ (Gupta et al. 2010).

Micro turbines also employ the ‘suck, squeeze, bang, blow’ process, albeit it in a much more compact arrangement. This arrangement greatly reduces the number of compressor and turbines to one of each.

As a result of these reduced stages of compression, the revolutions per minute (RPM) is greatly increased. A typical ‘commercial aircraft engines core compressor speeds can be anywhere between 10,000 and 15,000 RPM’ (Memon 2023), while the core engine of the KingTech K60TPG4+ can reach up to 160,000 RPM (KingTech 2023).

At the front of the mini jet engine is a radial compressor, which provides both the intake and compression in one stage. As previously stated, this occurs at an extremely high RPM, so after this ‘one stage’ of compression the air is passed through the diffuser and stator vanes into the combustion chamber.

The combustion process from this point is the same as in a normal sized jet engine, the compressed air is mixed with fuel, ignited, and then forced out through a turbine to produce both thrust and mechanical movement for the radial compressor. The internal components of a micro turbine are shown in Figure 3.

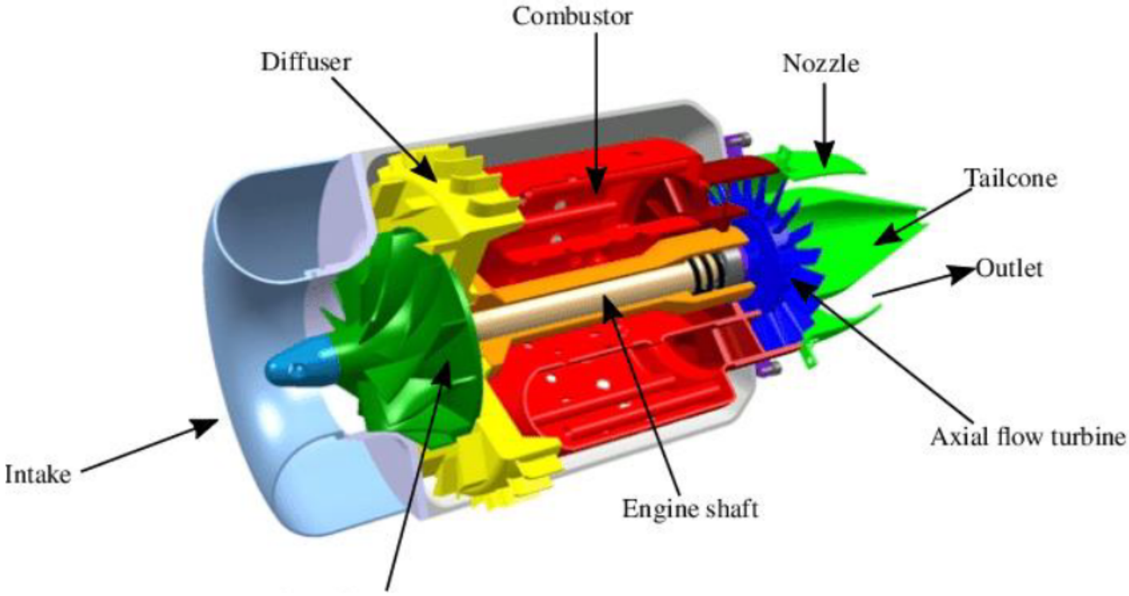

Figure 3 - Internal Components of a micro turbine (Oppong et al. 2017)

2.2.3 Turbo Propeller

A turbo propellor, also known as a turboprop, is described as 'a hybrid engine that provides jet thrust and also drives a propeller. It is similar to a turbojet except an 'added turbine, rearward of the combustion chamber, works through a shaft and speed reducing gearbox to turn a propeller at the front of the engine' (Britannica 2024).

Most of the energy from the exhaust in a turboprop is utilised to turn the additional turbine, which itself turns the turbine drive shaft. This drive shaft is connected to a speed reduction gearbox, which is connected to the propellor, providing the majority of the thrust (Figure 4).

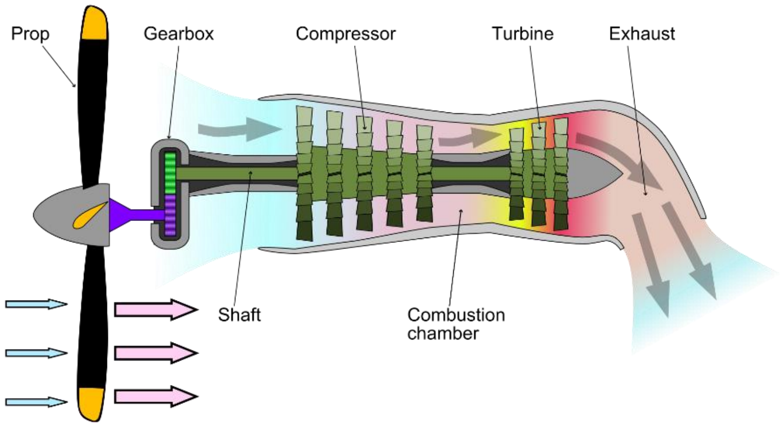

Figure 4 - Inner Workings of Turbo Propellor (Naji 2017)

2.2.4 Micro Turbo Propellor

The engine utilised for the experiments is a KingTech Generation 4 Gas Turbine, Model K60TPG4+. Of which the TP in the model number designates it as a turboprop variant.

As with the commercial sized turboprops, micro turboprops utilise a core engine to provide (a small amount of) jet thrust as well as driving the propellor. It is of note that 'KingTech uses the same turbine core for their turbojet and turboprop engines' (Runnels 2022).

One of the primary differences is that many commercial sized turbo props transfer the rotational energy from the core to the turboprop via a concentric drive shaft. Due to the complexities of scaling this system down, a micro turboprop design incorporates a form of 'add on' module with a separate shaft. A computer-generated image cutaway of a micro turbine 'add on' module is shown at Figure 5.

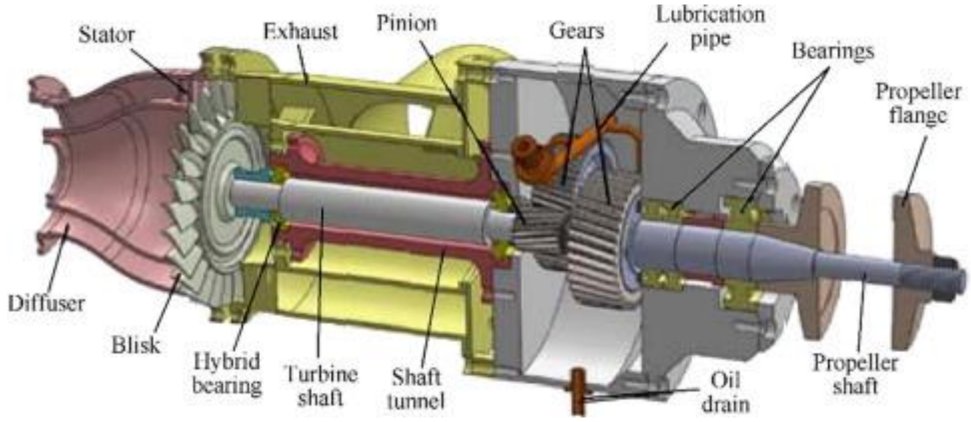

Figure 5 - Computer Generated Cutaway of the Turboprop section of a Microturbine. (Golchin et al. 2020)

Note: In Figure 5 the propeller turbine is labelled as a 'Blisk'. A blisk is a component that combines both the rotor disk and blades into a single piece of steel, unlike the older configuration where each blade was individually attached to the rotor disk as a separate component.

The thrust expelled from the exhaust of the core engine is of a high velocity. Therefore, the first subcomponent of the turboprop assembly is a diffuser. The diffuser reduces the velocity of the exhaust thrust, subsequently raising its pressure. This pressure then turns the propeller turbine ('blisk' in Figure 5) and the connected turbine shaft. After the exhaust gas has been utilised to power the propeller turbine, it exits the engine through the exhaust pipes. When installed to an aircraft, the exhaust pipes are directed rearward to supplementarily aid in propelling the aircraft forward. The power sent through the propellor turbine shaft is sent through a reduction gearbox, which in the case of the K60TPG4 'steps down the RPM by a factor of 10' (Runnels 2022). As with any gearbox, the turboprop module requires lubrication for friction reduction, cooling, and cleaning. The lubrication system for the gearbox of the K60TPG4, utilises the same fuel mix that is being utilised for combustion. The fuel/lubricant is transferred directly to the gearbox by a lubrication pipe (as seen in Figure 6). The reduction gearbox then drives the propellor shaft, which can have a propellor installed to provide the primary propulsion for the aircraft.

Figure 6 displays the K60TPG4+ to be utilised for the experiment, highlighting the separation between the core engine and turboprop modules. The main components of the turboprop have been labelled for ease of comparison to Figure 5. It is of note that a propellor will not be utilised in the experiment configuration. This is because micro turboprops do not have the ability for a variable pitch propeller, which subsequently limits any load control capability to be applied to the engine, particularly on a static test bench.

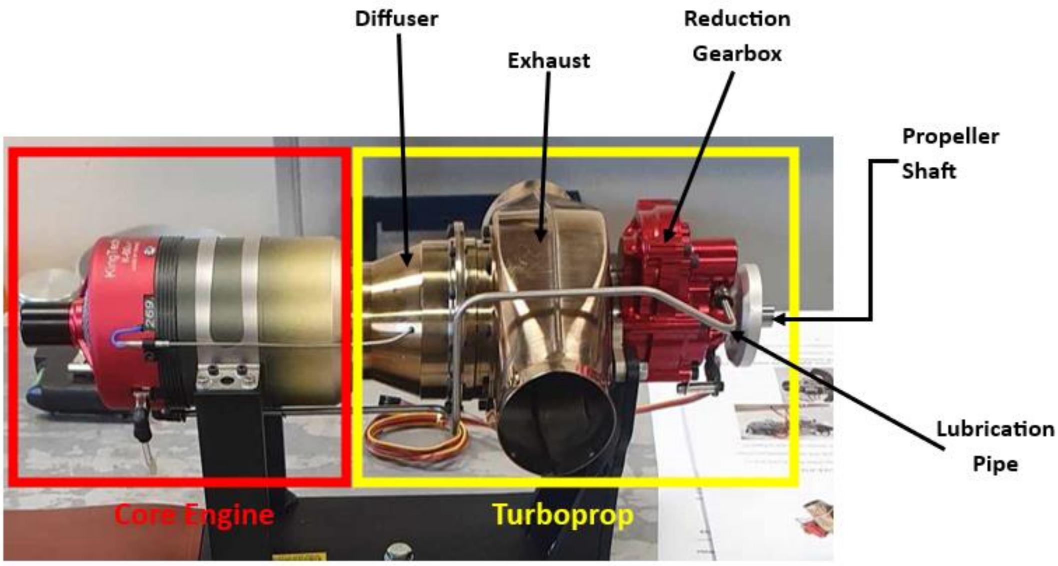

Figure 6 - The K-60TPG4+ with the relevant operating modules and Turboprop components highlighted.

2.3 Microturbine Uses

Microturbines or Micro Gas Turbines (MGT) are terms used to describe a wide range of non-commercial sized gas turbine combustion engines. They are primarily used in the aerospace sector to power high-end radio control aircraft and 'unmanned aerial vehicles (UAV) in applications used in missions such as national security, telecommunications, real-time reconnaissance, remote sensing, crime fighting, disaster management, agriculture and election monitoring' (Oppong, 2017).

There is a growing market for MGTs in the power generation industry, an article written by Jurado et al. (2004) looking into power distribution network stability stated that 'Micro-turbine systems are a new and increasingly exciting subset of combustion gas turbines being used and improved to stationary power generation'. The article also goes onto state that Microturbines are an important part of the ever evolving power generation landscape and 'In many geographical places, the micro-turbine may produce power at a competitive cost' (Jurado et al. 2004).

It is of note that the micro turbines used for power generation are of a larger physical dimension and subsequent power output then the K60TPG4+, which is rated to 7.3kW. Micro turbines utilised for power generation, known as Micro Turbine Gensets (MTGs), tend to fall into the 5 – 500kW size range (Jurado et al. 2004).

One such Mirco Turbine Genset is from UK company Bladon micro turbines, with their flagship 12kW MTG sold to the telecommunication industry to provide power to mobile phone towers in remote areas and developing markets (Bladon 2024). These MTGs also have the added flexibility to use many different types of fuels.

Larger steam-powered turbines have traditionally been used in combined heating and power (CHP) applications. However, recent technical advancements and environmental concerns have led to the development and use of small and micro gas turbines. 'Interest in biomass-based micro-CHP systems (<100 kW) has increased' (Obernberger 2010), particularly for:

- **Residential heating**: Provides both heat and electricity.
- **Small district heating**: Serves small communities.
- **Small businesses**: Meets process heat or cooling demands.

These systems are valued for their efficiency, mobility, reduced emissions, and sustainable use of local biomass.

In a pure mobile power generation play, Fusion Flight has developed what is deemed to be the smallest 8kW micro turbine generator with 'vast applications in hybrid-electric and emergency services' (FusionFlight 2024). The mobile generator delivers a steady DC power output and can run on various heavy fuels. There is no literature confirming if 'heavy fuel' encompasses alternative fuels such as biodiesel.

Figure 7 – ARC MTG utilising a KingTech Turbine as the power source (FusionFlight 2024).

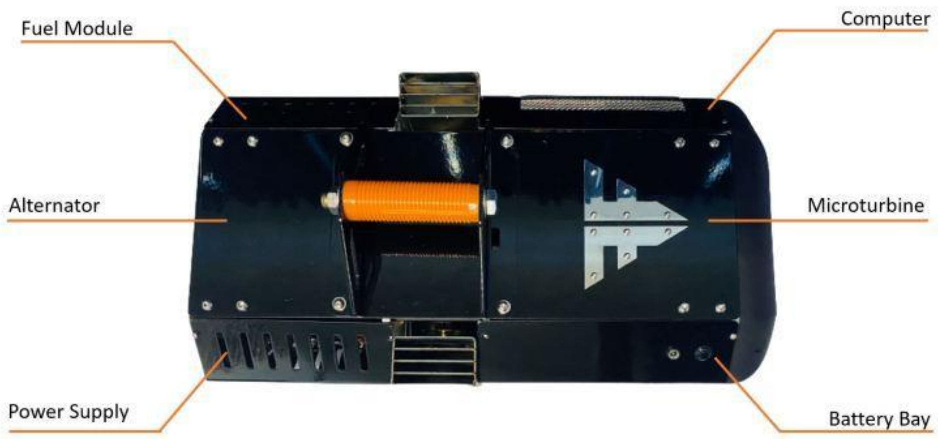

Figure 8 - The Component Layout of an ARC Micro Turbine Generator (Blain 2022)

The components and operating principles of microturbine generators (MTGs) available on the market vary, but they share significant similarities with each other and the K60TPG4+. As such, any findings within this dissertation are expected to be scalable and applicable to larger microturbines. With continuous innovations in microturbine engines, it is essential that sustainable fuel sources are regularly tested and evaluated to ensure the industry's long-term viability.

2.4 Fuels Overview

The objective of this project is to assess the impact of alternative fuels on mini jet engine performance. To support this, a comprehensive literature review of relevant fuel sources was conducted, examining fuel properties, applications, emissions, and engine performance.

The review places particular emphasis on the use of diesel and biodiesel in micro gas turbine engines. Like the gas turbine section of the literature review, the availability of published literature on sub-20kW microturbine engines is limited due to their primarily recreational use and relatively low cost. Where technically applicable, references to fuel based literature on larger commercial aviation gas turbine engines or microturbines exceeding 20kW have been utilised to supplement the research.

2.4.1 Emissions

A variety of emissions are released during the combustion of fuel, however this project focused on testing five key pollutants: hydrocarbons (HC), carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), and oxygen (O_2). Below is a brief description of each.

Hydrocarbons

Hydrocarbons (HC), in the context of fuel emissions, are organic compounds consisting of hydrogen and carbon atoms that are released during the incomplete combustion of fuels. When fuels like diesel, gasoline, or natural gas are burned, not all hydrocarbons are fully combusted, leading to the release of unburned or partially burned hydrocarbons into the atmosphere. Reducing hydrocarbon emissions is a key goal in developing cleaner fuel alternatives and more efficient combustion technologies.

Carbon Dioxide

Carbon dioxide (CO_2) is a colourless gas composed of one atom of carbon (C) and two atoms of oxygen. Naturally occurring the atmosphere, 'fossil fuels release carbon is the form of CO_2 when they are burned' (Mulligan 2010). These emissions are well researched in relation to climate change and 'it is well known that CO_2 plays an important role in the natural greenhouse warming of the Earth atmosphere' (Zhong & Haigh 2013). Lowering CO_2 emissions through cleaner fuel technologies, energy efficiency, and alternative fuels is essential for reducing global warming and its related environmental impacts.

Nitrogen Oxides

The Queensland Department of Environment, Land and Water (Goverment 2023) states nitrogen oxides (NOx) are a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2), which are gases produced from natural sources, motor vehicles and other fuel burning processes. Reducing NO_x emissions from fuel combustion, especially in the transportation and industrial sectors, is not only crucial for improving air quality but also for mitigating their contribution to the broader climate change effects.

Carbon Monoxide

Carbon Monoxide (CO) is a colourless, odorless, tasteless gas produced by incomplete combustion of carbon-based fuels. CO is a significant pollutant as it interferes a person's body from using oxygen effectively. In fact, 'in the United States alone there that over 40,000 Emergency Department visits that are related to carbon monoxide poisoning' (Goldstein

2008). While CO does not directly contribute to climate change, it reacts with other pollutants in the atmosphere, influencing concentration of other greenhouse gases.

Oxygen

One of the most vital elements for sustainment of life on Earth, oxygen (O_2) makes up approximately 21% of the earth atmosphere. It is also a highly reactive, and combines easily with other elements, subsequently playing a critical role in the combustion process. Monitoring oxygen levels helps optimise combustion and control emissions like CO and hydrocarbons.

2.4.2 Diesel

Diesel fuel is derived from crude oil and contains small quantities of sulphur, nitrogen, and oxygen, known as heteroatoms. It is a complex blend produced through the distillation of crude oil, mainly composed of hydrocarbons with carbon chains ranging from C_9 to C_{20}. The boiling point of diesel typically falls between approximately 163°C and 357°C (Lois et al. 2003; Gad 2005).

It is the standard liquid fuel for stationary gas turbines because of its 'excellent storage stability and favourable combustion properties' (Huth & Heilos 2013). It is readily available, has a high energy density, cetane number, and its combustion process is relatively clean compared to other heavy fuels, making it ideal for reliable, long-term operation in gas turbines. These characteristics allow for efficient energy production and extended storage without significant degradation.

While diesel fuel is an effective option for turbine operation, its combustion byproducts have raised concerns in recent times. Diesel exhaust emissions, which vary depending on operating conditions, are known to negatively impact human health, the environment, and the global climate. These emissions include harmful pollutants like particulate matter, nitrogen oxides, and unburned hydrocarbons, which contribute to respiratory problems, environmental pollution, and global warming.

Efforts to mitigate particulate emissions and nitrogen oxides from diesel engines have been through the combined use of a 'diesel oxidation catalyst , a catalysed diesel particulate filter, and selective catalytic reduction' (Zhang et al. 2022).

These environmental impacts associated with petroleum based diesel, coupled with its status as a finite resource, have increased the viability of alternative fuels such a biodiesel

2.4.2 Biodiesel

Biodiesel, classed as a sustainable alternative to petroleum based diesel, can be produced from renewable sources such a vegetable oils and animal fats. With the Australian Fuel Quality Standards Act 2000 defining biodiesel as 'a diesel fuel obtained by esterification of oil derived from plants or animals' (*Fuel Quality Standards (Biodiesel) Determination* 2019). Biodiesel fuel typically comprises of lower alkyl fatty acid (chain length C_{14}–C_{22}), and esters of short-chain alcohols, primarily, methanol or ethanol (Demirbas 2009). Figure 9 displays the biodiesel production process used by Brisbane-based biodiesel producer, Eco Tech. This diagram outlines the key steps involved in converting feedstocks into biodiesel.

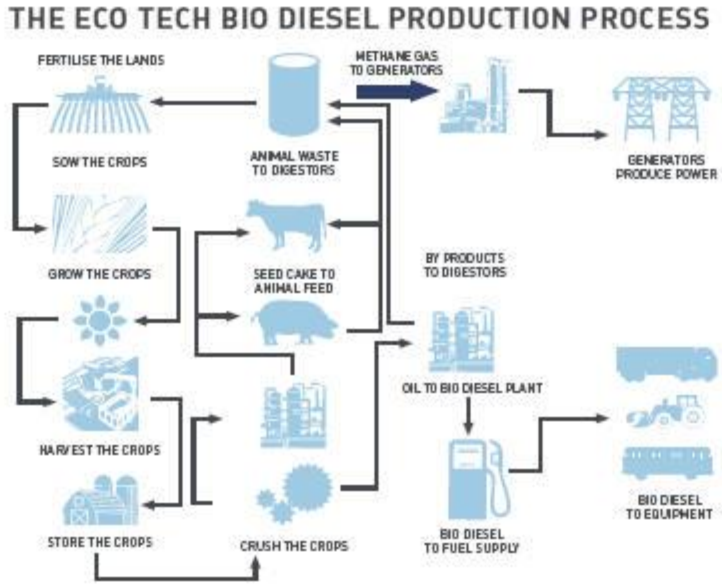

Figure 9 - Bio Diesel production process (EcoTech 2024)

One of the primary advantages of biodiesel is that it can be produced using current techniques, allowing for continuous production as needed. This contrasts with petroleum fuels, which are formed through geological processes that take millions of years, making biodiesel a more readily available and renewable option (Boomadevi et al. 2021).

Biodiesel can be used as a pure fuel or blended at any ratio with petroleum-based diesel for use in diesel engines. In industry, common blends range from B2 (2% biodiesel and 98% petroleum diesel) to B20 (20% biodiesel and 80% petroleum diesel). However, higher blends are not widely used yet due to biodiesel's susceptibility to freezing in cold weather, its lower energy density, and the degradation of its properties during long-term storage (Balat & Balat 2010).

On top of its sustainability advantages, of which one is being carbon neutral, biodiesel also possesses good performance and emission qualities (Boomadevi et al. 2021). These positive all-round qualities have resulted in a good amount of research conducted on biodiesel, however most of it is aimed at the automotive industry and specifically emission reduction. As mentioned by Nascimento et al. (2008) ‘Many Performance and emission tests have been carried out in reciprocating engines that use biodiesel fuel over the years and very few in gas turbine engines'.

2.4.3 Comparison

There is a growing push for biodiesel usage in the aviation industry, leading to an increase in research on the topic. This section reviews the existing literature on the application of biodiesel in both reciprocating and gas turbine engines, exploring its potential benefits, challenges, and comparative performance against Jet A1 and diesel in aviation and other industries.

Properties

A high-level comparative analysis of biodiesel properties provides an initial indication of how the fuel may perform during engine combustion. These properties were graphed alongside petroleum diesel, which serves as the project's baseline fuel, as well as Jet A1, the standard fuel used in the aviation industry. The following six figures (10 through 15) were developed using data from Chiong et al. (2018), offering a visual comparison across these three fuel types.

Lower Heating Value

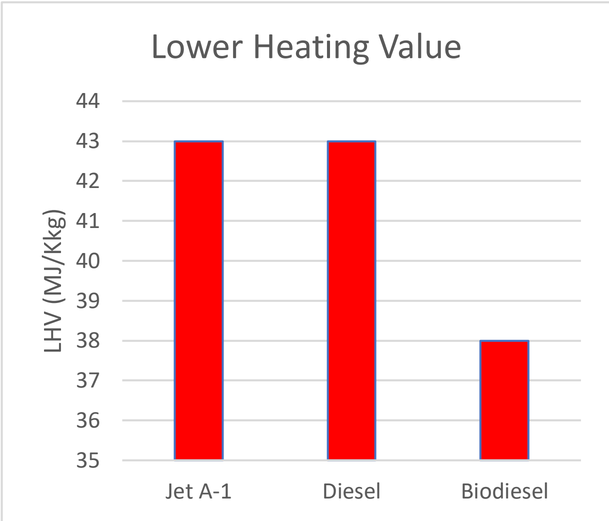

Figure 10 - Lower Heating Value Comparison

The Lower Heating Value (LHV) of biodiesel is approximately 10% lower than that of diesel and Jet A-1. Figure 10 indicates that biodiesel produces less energy per unit of fuel, which may lead to lower RPM or increased fuel consumption when biodiesel is used as the fuel source.

Viscosity

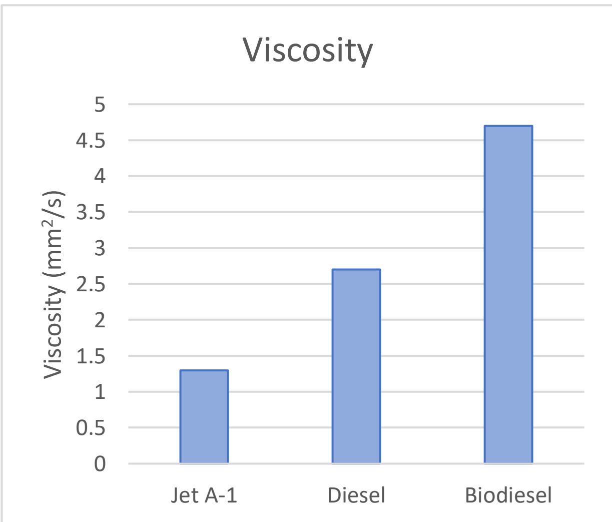

Figure 11 - Viscosity Comparison

Biodiesel's viscosity is nearly double that of diesel and about four times that of Jet A-1 (Figure 11). This higher viscosity is likely to place greater demands on the fuel pump, potentially straining fuel delivery systems. Additionally, combustion within the engine could be impacted, as fuel nozzles are typically calibrated for fuels with lower viscosity than biodiesel. This could potentially lead to less efficient atomization and mixing of fuel with air during combustion.

Pour Point

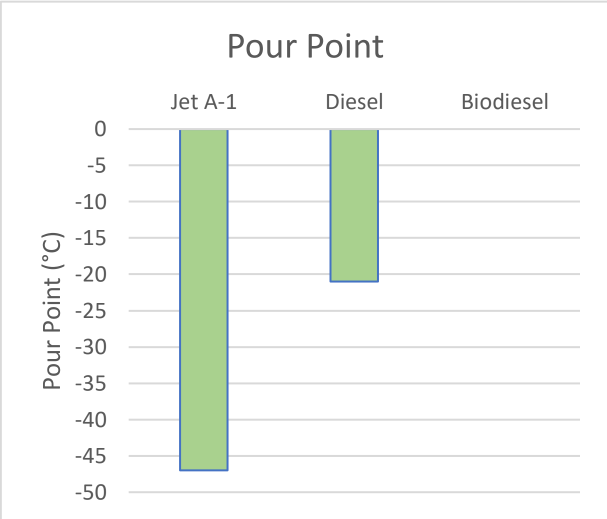

Figure 12 - Pour Point Comparison

Figure 12 shows a 0°C pour point for biodiesel, in stark contrast to the -21°C pour point of diesel and the -47°C of Jet A-1. While this difference is not expected to pose an issue in this project, it highlights a challenge for the universal acceptance of biodiesel. To prevent freezing in colder climates, additives will likely be required. However, the use of such additives could compromise some of the environmental benefits that biodiesel offers in its raw, unmodified form.

Flash Point

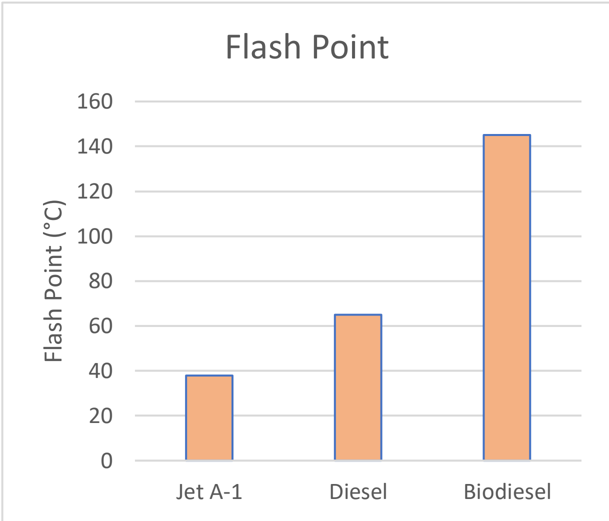

Figure 13 - Flash Point Comparison

The flash point of biodiesel, as shown Figure 13, is more than double that of diesel and over four times higher than Jet A-1. Due to its high flash point, biodiesel may cause a delayed engine start depending on the ignition sequence parameters. From a transport and safety perspective, the high flash point of biodiesel is beneficial because it reduces the risk of accidental ignition during handling, storage, and transportation, making it a safer fuel option compared to lower flash point fuels like diesel or Jet A-1.

Density

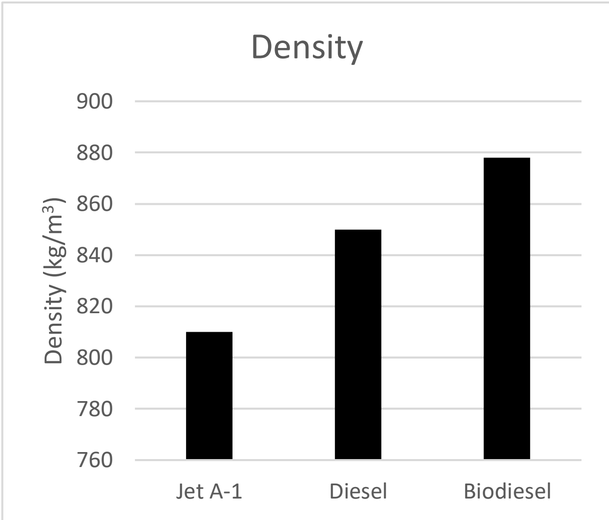

Figure 14 - Density Comparison

Biodiesel has the highest density in the comparison shown in Figure 14, indicating that it contains more energy per unit volume compared to diesel and Jet A-1. This higher density may help offset the previously mentioned lower LHV of biodiesel.

Cetane Number

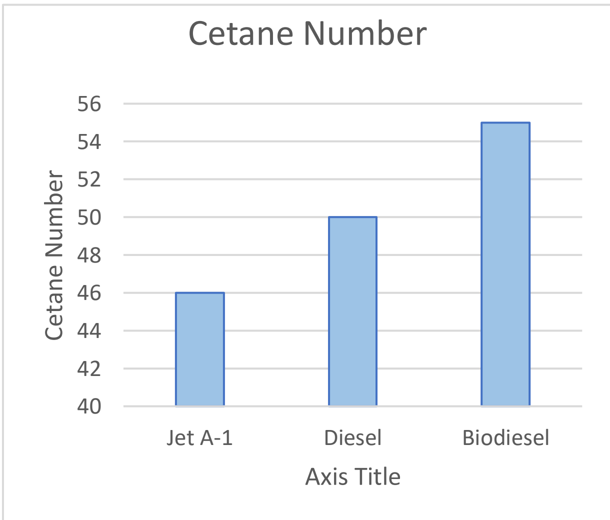

Figure 15 - Cetane Number Comparison

Figure 15 shows a linear increase in the cetane number, progressing from Jet A-1 to diesel and then to biodiesel. A higher cetane number indicates improved ignition properties, suggesting that biodiesel should ignite more readily in the combustion chamber compared to diesel and Jet A-1. While this could potentially mitigate the effect of biodiesel's higher flash point, it is important to note that the flash point of biodiesel is over 200% higher than diesel, while the cetane number shows only an 8% difference between diesel and biodiesel.

Emissions

The literature review on emissions focused on identifying experimental results where biodiesel was used in gas turbines. Due to the limited amount of research in this specialised area, biodiesel testing in reciprocating engines was referenced where applicable.

CO_2 emissions were an example where more literature was available in reciprocating engine applications, with a general consensus that biodiesel blends reduce CO_2 emissions compared to diesel. This trend was seemingly reversed when the biodiesel was produced with a high percentage of waste cooking oil, where CO_2 emissions were higher compared to diesel and other biofuels (Abed et al. 2019). In a micro turbine comparison test, biofuel blends show less CO_2 emissions, though tests were in comparison to Jet A1 as opposed to diesel. (Manigandan et al. 2020). The understanding is that the increased oxygen content in biodiesels leads to more complete combustion and therefore less pollutants.

In a significant portion of microturbine emissions tests, carbon monoxide (CO) levels increased when biodiesel was used, with consistently higher CO emissions compared to diesel under the same fuel injection temperature conditions. Experiments demonstrated that preheating biodiesel substantially reduced CO emissions (Chiaramonti et al. 2013), though the levels remained higher than those of diesel. However, an article by Rehman et al. (2011) reported an exception to this trend, where jatropha oil biodiesel blends used in a 60 Rovers gas turbine engine resulted in lower CO emissions than diesel. It was noted that all measurements were relatively small, as CO makes up only a minor percentage of the total emissions volume, especially when compared to CO_2, which is typically the dominant emission by volume.

The majority of literature on diesel and biodiesel emissions focuses on NOx emissions. This is due to the concern that, despite the many environmental benefits of biodiesel, one of its key disadvantages is its tendency to emit higher levels of harmful NOx compared to diesel. Micro turbine emission testing by Nascimento et al. (2008) observed this trend, with NOx emissions increasing from idle to full power. Similarly, research by Bolszo and McDonell (2009) showed an overall increase in average NOx emission when using biodiesel. To somewhat counter these findings, testing by Chiaramonti et al. (2013) found NOx emission for all fuels did not differ in any significant way, suggesting that under certain conditions, biodiesel may not always lead to higher NOx emissions compared to diesel. This is supported by Hoekman and Robbins (2012) who states, 'In most cases – though certainly not all – use of biodiesel or biodiesel blends increases NOx emissions in comparison with baseline petroleum diesel fuel. One reason for inconsistency in the literature is that no single factor is responsible for these NOx effects. Rather, numerous factors contribute, and their relative importance varies with engine technology and operating conditions'.

Engine Performance

While there is extensive literature on the performance impacts of biodiesel on reciprocating engines, this part of the review concentrated on studies where biodiesel was tested for its performance across a range of gas turbines. Although research in this area is more limited, it directly aligns with the project objective.

An experimental study by Manigandan et al. (2020) tested biofuel blends against Jet A-1 in a 170N microturbine. The results indicated that biofuel blends led to slightly lower static thrust and exhaust gas temperature (EGT) values, though thermal efficiency was found to increase. The study concluded that 'biofuel blends can be utilized legitimately in the micro gas turbine engine without any serious modifications to the engine.'

General Electric (GE), a leading manufacturer of both ground and aeroderivative gas turbines, has been involved in testing the viability of alternative fuels, including biodiesel in practical applications. One such study was performed in 2006 on a 6B gas turbine located in Switzerland, demonstrating the performance of biodiesel over a range of operational conditions. It was found that 'Power and efficiency levels were very close to the ones achieved with diesel oil (DO), and emissions were at least as low as with DO' (Jones 2011).

Nascimento et al. (2008) conducted testing of a 30kW micro turbine on biodiesel and found that 'there were no changes in the operation of the 30 kW micro-turbine diesel engine during the thermal performance tests, and no vibrations, noises, working failures and difficulties in starting the engine were noticed'. The study, focusing on thermal performance, observed no significant heat losses regarding engine performance when operating up to a B100 biodiesel fuel source. However, it was noted that the B100 had the highest fuel consumption compared to lower percentage blends and raw diesel.

Another study involving a 30kW microturbine was conducted by Habib et al. (2010), where biofuel blends were tested against a Jet A1 base fuel. The results showed that B100 fuels had a slightly lower Thrust Specific Fuel Consumption (TSFC) at low engine speeds, with this difference becoming insignificant at higher speeds. This trend was consistent with the EGT results, where biofuels exhibited lower EGT values at low speeds, converging with Jet A EGT values at higher engine speeds. The study concluded that biofuel–Jet A1 blends show promise, offering reduced pollutant emissions without a significant reduction in static thrust.

2.4 Literature Review Summary

As mentioned in the section overview, there is not a substantial amount of literature specifically addressing biodiesel use in microturbines the size of the K60TPG4. However, the review provided valuable insights into the use of biodiesel in gas turbines more broadly.

Most studies generally concluded that pollutant emissions are lower when using biodiesel compared to Jet A1 or diesel, though the results varied depending on the specific test engine and the biofuel blend used. Notably, CO_2 emissions were often higher with biodiesel, which subsequently led to lower CO emissions. This is explained by ‘the fact that the carbon atoms in the fuel molecule can only appear in the combustion products as either CO_2 or CO. As the CO_2 content increases, the CO content correspondingly decreases’ (Habib et al. 2010).

NOx emission levels also varied when biodiesel was tested against base fuels, though most studies reported an increase in NOx emissions with higher percentages of biodiesel in the fuel blends. These results were also significantly influenced by the diverse range of test engines and fuel blends used in the studies.

In the comparative performance metrics, the consensus was that biodiesel, and its blends reduce the static thrust of turbine engines, though by no more than 10%. Fuel consumption, when measured, was found to increase when biodiesel was used compared to base fuels. Both findings can be correlated to biodiesel's lower LHV (Lower Heating Value), as noted in the comparison section of the review.

Exhaust gas temperature showed a general trend of being slightly lower at lower speeds when using biodiesel, before converging towards the same values as the base fuels as turbine power increased.

Some studies employed a fuel-switching system during testing, where the engine was initially started using the base fuel before transitioning to the alternative bio-based blends once the engine was running. This approach addressed concerns about the potential difficulty or delay in starting the engine with biodiesel blends due to their higher flash point. Additionally, there was a prevailing view that engines should be ‘purged’ of biodiesel by running them on the base fuel at the end of testing. This practice aimed to prevent any residue or soot buildup from the organic matter and higher viscosity of the biofuel blends.

Overall, there was widespread agreement that biodiesel has little to no impact on the performance of gas turbine engines, suggesting that its potential for future widespread implementation warrants further investigation.

Chapter 3

Test Bench Setup

3.1 Chapter Overview

This section outlines the process of setting up the experiment test bench, starting from the initial concept to the creation of a fully operational remote-controlled test bench. It also details the challenges faced during the process and the solutions that were applied to overcome them.

3.2 Aims

For the experiment arrangement and design the primary aims are:

- Design the test bench to allow the K60TPG4 engine to safely operate using alternative fuel sources.
- Enable the test bench to facilitate the evaluation of turbine exhaust emissions.
- Allow for performance assessments of the engine when running on alternative fuels, ensuring the system is robust and adaptable for different testing scenarios.
- Ensure the experimental setup provides accurate and reliable test results under controlled conditions.
- Create an instruction manual to ensure the test stand can be utilised for future studies, enabling safe operation by relevant personnel.

These design considerations are essential for ensuring the successful and safe evaluation of alternative fuels in microturbine applications, allowing for a thorough analysis of both performance and emissions.

3.3 Assembly

3.2.1 K60TPG4 Assembly

The K60TPG4 turbine engine required minimal assembly straight out of the box. The only task involved was connecting the lubrication tube and support brackets from the 'Lube out' connection to the 'Lube in' connection on the turboprop assembly. Figure 16 displays the K60TPG4 turbine generator in its initial condition, immediately after being unpacked. The image showcases the unmodified state of the unit prior to any modifications, testing, or fuel integrations required for the experiment.

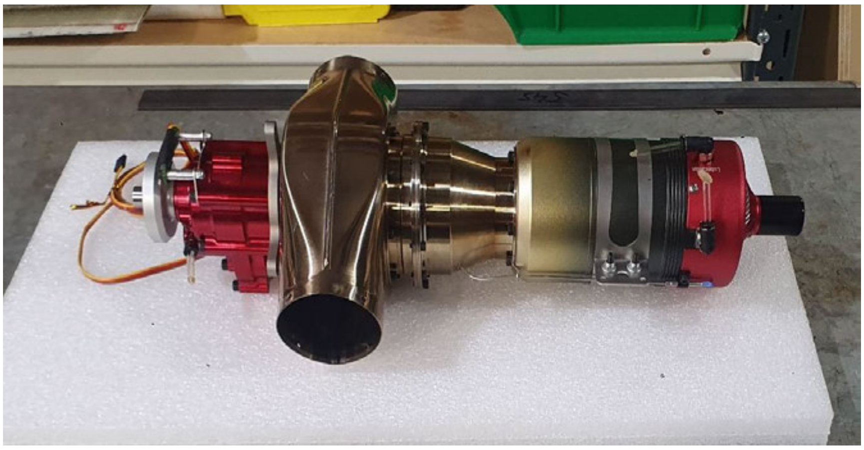

Figure 16 - K60TPG4 when first removed from packaging

3.2.2 Turbine Support Stand

A robust support structure was necessary to securely position the engine for testing. This stand needed to accommodate the rotational torque generated by the turbine and be strategically placed on the bench to ensure safe operations. Additionally, it had to provide sufficient space for the future installation of a load application system.

Given the specialised expertise needed to construct the support stand, the fitter and turners employed by UniSQ were consulted and ultimately manufactured the stand according to the agreed specifications.

3.2.2.1 Specifications

As per Figure 17, the K60TPG4 has mounting provisions via a fixed bracket on the engine core and support bracket in between the exhaust and turboprop assembly.

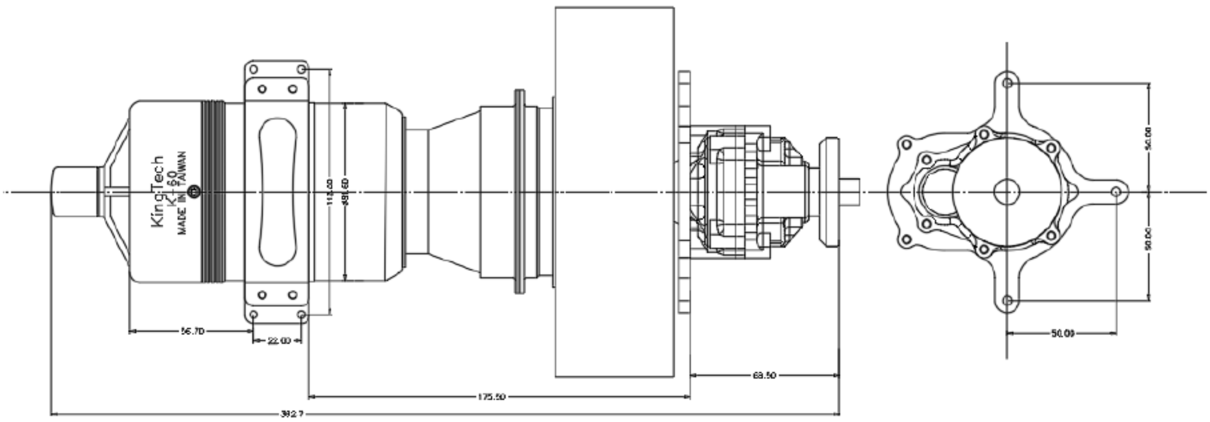

Figure 17 - K60TPG4 physical dimensions (KingTech 2023)

The K60TPG4 engines physical dimensions were provided, and additional measurements were taken as needed to facilitate the manufacture of a suitable support stand. It was determined that the centre of the propellor shaft should be at a height of 150mm, allowing for a wide range of load applications options to be considered.

With the engine mounted on the support stand, a decision had to be made regarding its placement on the bench. It was decided to offset the forward (intake) end close to the edge of the bench, to provide additional space for various load application setups. This positioning left 540mm by 550mm of usable bench space beyond the propeller shaft, accommodating future load application needs.

Figure 18 - K60TPG4 attached to support stand on test bench

3.3.3 Auxiliary Components Install

With the engine secured on the bench, the next step was to install the auxiliary components that accompanied it. These components, as shown in Figure 19, are listed as follows:

- Ground Support Unit (GSU)
- Data Relay Module (DRM)
- Fuel Filter
- Fuel Pump
- Fuel Lines
- Fuel Shut Off Valve (SOV)
- Electrical Leads
- ECU Battery
- Bluetooth Module

Figure 19 - K60TPG4 auxiliary components (KingTech 2023)

The *KingTech K60TPG4 Test Bench Operational Manual,* located in Appendix A, provides a detailed list of the components used in the setup. It includes relevant images and brief descriptions for each item, offering a clear understanding of the parts and their functions within the test bench system.

The auxiliary components were strategically installed on the bench, with particular attention to keeping the engine's inlet area as clear as possible. This precaution was taken to prevent any potential Foreign Object Debris (FOD) from entering and subsequently damaging the engine.

3.3.3.1 Fuel System Components

The fuel system components (pump, filter, SOV) were positioned in a separate area from the electrical components to provide redundancy in case of any potential fuel leaks. The pump and SOV were secured to the bench using the supplied hardware. The supplied fuel line was measured, cut to the appropriate length, and installed, creating a fuel path from the pump to the engine through the filter and SOV. Initially a small plastic fuel container was taped to the side of the bench for initial testing, see 3.7 Fuel Storage for final fuel storage solution.

3.3.3.2 Electrical Components

The electrical components were positioned in two separate locations based on their function. Since most of the electrical leads connect to the DRM, it was positioned away from the main test bench. This placement helps prevent potential fuel contamination and shielded the components from heat or vibrations generated by the engine test bench. The batteries were also placed in this location for the same reasons.

Initially, the Bluetooth and GSU modules were also placed on the separate bench. However, during initial testing, issues with Bluetooth connectivity were encountered (Section 3.5.2 Bluetooth Connectivity. To address this, the Bluetooth module was relocated to the test bench, positioned away from the engine inlet and fuel systems, to enhance connectivity. The GSU had to be moved along with the Bluetooth module as they share a common line from the DRM through a splitter cable.

3.4 Exhaust Extraction

As the K60TPG4 is operated in an inside environment, proper provision had to made to ensure the exhaust gases were effectively extracted to the outside environment. Building P7 is equipped with direct and room air extraction systems to allow for this.

To ensure the turbine exhaust could be safely extracted from the room, a functional test of the air extraction ducts was conducted using an anemometer. First, a velocity reading of 8.21 m/s was recorded from the direct exhaust duct with the inlet attachment. Next, a reading of 15.9 m/s was obtained from the direct exhaust duct without the attachment. These results confirmed the effectiveness of the extraction system. The expected increase in velocity from the larger inlet attachment to the smaller ducting further validated both the system's functionality and the accuracy of the anemometer.

Figure 20 - Testing the airflow rate of the exhaust extraction system

Manually testing the exhaust flow of a turbine engine is not safe, so data was not collected to verify the expected results. According to the literature review, a significant portion of exhaust gases from the K60TPG4 engine is used to power the turbine, which in turn drives the propeller shaft. Based on this, it was anticipated that the air extraction ducting could manage the heat and velocity of the residual exhaust gases. While it was confident that the building's air extraction system could handle the turbine engine's output, it could not be adjusted to adequately cover the horizontal plane of the engine exhaust. Upon consulting with the KingTech Field Services Representative (FSR), it was learned that specialised exhaust tips for the K60TPG4 were available for purchase and might provide a solution to this issue. These exhaust tips were purchased and installed on the engine. Typically mounted toward the rear in an aircraft configuration, the exhaust tips were installed vertically in this setup to provide the most direct path to the air extraction system. Figure 21 demonstrates the installation of the engine exhaust tips along with the positioning of the exhaust extraction system. The setup efficiently manages and directs exhaust gases away from the testing environment, ensuring safe operation while allowing for the collection and analysis of emissions data.

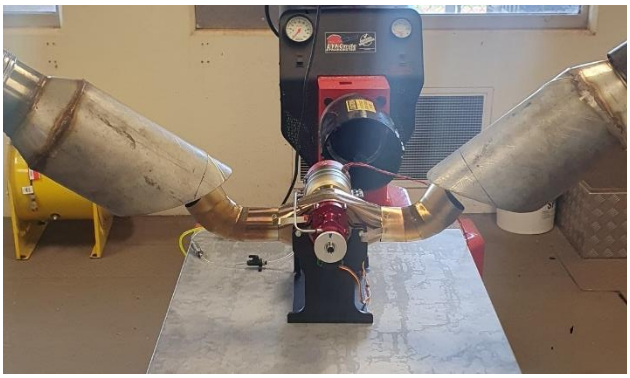

Figure 21 - Engine Exhaust tips installed with exhaust extraction system positioned

3.4.1 Emissions Testing Allowance

Emissions testing was a key aspect of the procedure, requiring precise placement of the emissions testing probe within the exhaust stream. To facilitate this, a hole was drilled into one of the exhaust duct air inlet attachments. This modification created a stable and accurate position for the probe, as illustrated in Figure 22.

Figure 22 - Emissions sample probe placement

3.5 Initial Testing and Issues

With the engine, auxiliary components and air extraction system fully assembled, it was time to attempt to operate the engine. For the first test runs, diesel was used as the fuel source as the baseline fuel for future testing. The *'KingTech Turbine BDT GSU'* application was installed onto a mobile device for both engine control and monitoring. Before and during the initial runs, several problems were identified and subsequently addressed. This section provides a detailed explanation of these issues.

3.5.1 GSU and Receiver Power

The first issue encountered was that the GSU display failed to power on. According to the instruction manual, 'The GSU is powered by the receiver and requires a voltage between 5.7 – 8.4' (KingTech 2023). Although the ECU battery was installed, it was only supplying power to the starter, glow plug, ECU, and fuel pump. A separate power source was needed to power the GSU.

An interim solution was provided by the UniSQ electrical engineering department, who supplied a 12 Volt power supply with a voltage regulator. This allowed the GSU and Bluetooth module to be powered, subsequently enabling the first successful start and operation of the turbine. The final power solution is described in Section 3.5.5.

3.5.2 Bluetooth Connectivity.

Initial testing was conducted using the *'KingTech Turbine BDT GSU'* application; however, it was discovered that the Bluetooth connection dropped out when moving to the control room. This caused an uncommanded termination of the start sequence, as the built-in safety logic automatically shuts down the engine if no throttle command signal is detected.

To initially address this issue, the Bluetooth module was relocated back to the test bench (refer to 3.3.3.2 Electrical Components for the original location). While this adjustment provided a more secure connection, it still lacked reliability. Measurements were taken of both the GSU and the Bluetooth module with the intention of creating a 3D-printed model. These dimensions were provided to a specialist in 3D design and manufacturing, who subsequently produced a structure to hold the Bluetooth module in an elevated position, thereby improving its connectivity range. This stand also served the dual purpose of positioning the GSU in a more ergonomic location for the engine operator. The stand was then securely mounted to the bench, carefully positioned away from the engine inlet and fuel systems as seen in Figure 23.

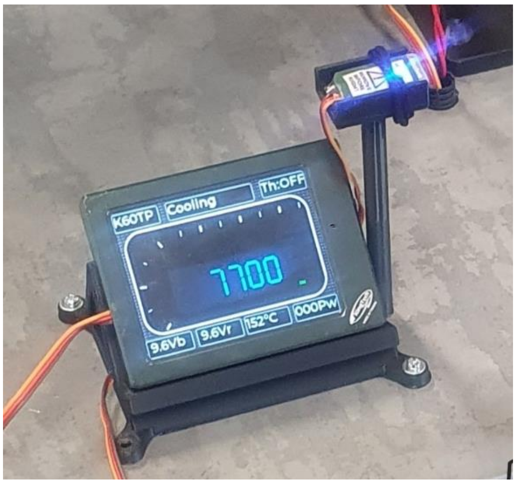

Figure 23 - GSU and Bluetooth module on 3D printed stand

3.5.3 Fuel Usage and Storage

During the initial test runs, a small plastic fuel container with a capacity of approximately 500 mL was used to store the diesel. The K60TPG4 engine can burn up to 280 mL's per minute, which led to one of the initial runs ending prematurely when the fuel supply was depleted. The limited capacity of the vessel was further problematic as the remaining fuel level could not be monitored from the control room. To mitigate this issue, larger 4L fuel tanks were used for all subsequent tests (refer to Section 3.7).

3.5.4 Battery Discharge Rate

In accordance with the engine manual, power for the electrical components requires either a 3S Lithium Iron (LiFe) pack or a 7-cell Nickel Metal Hydride (NiMH) battery with a capacity ranging from 2000mAh to 5000mAh for the ECU. While it was attempted initially to purchase a LiFe battery pack, none of the retailers contacted had them in stock.

Consequently, a NiMH battery was opted for, which still met the specifications outlined in the engine manual.

The NiMH battery performed adequately but discharged its voltage faster than anticipated, allowing for only 2-4 engine starts before needing a recharge. This proved inefficient, as it led to downtime while waiting for the battery to recharge.

Ultimately, through the assistance of the FSR, a suitable LiFe battery was able to be sourced, which resolved this issue (see Section 3.5.5.1).

3.5.5 Field Service Representative Visit

During the assembly and initial test runs, occasional information was required from the Original Equipment Manufacturer (OEM). Although KingTech is based in Taiwan, they have an Australian-based Field Service Representative (FSR). After ongoing phone based commincations, the FSR arranged a site visit to assess our progress.

The visit proved to be highly productive, particularly in advancing the K60TPG4 test bench to its final operational state. The FSR addressed any remaining knowledge gaps the team had regarding the safe operation of the engine.

Additionally, the FSR brought along a receiver module and battery pack to power the GSU and Bluetooth module, as mentioned in Section 3.5.1. This setup (Figure 24) was significantly more compact and user-friendly compared to the previous method of using a power supply and voltage regulator.

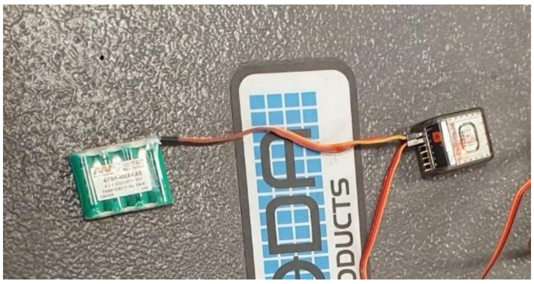

Figure 24 - Battery Pack and Receiver, more compact than the initial iteration involving a power supply and voltage regulator

3.5.5.1 Recommendations

While stating the general setup of the K60TPG4 test bench was sufficient, the FSR provided some recommendations for enhancing the safety and efficiency of future engine runs.

- **Purchase a Specialised Controller**

Although the mobile device using the 'KingTech Turbine BDT GSU' app was functional, relying on a Bluetooth connection for engine operation was not ideal. A specialised radio controller would eliminate any Bluetooth connectivity issues and offer more precise throttle control.

This recommendation was taken on board, and a controller was purchased for future engine operations (Section 3.6).

- **Purchase a Smaller Amperage, Higher Voltage LiFE ECU Battery**

As discussed in 3.5.4 Battery Discharge Rate, the NiMH battery met the engines manual specifications, however it was inferior to the alternative recommended by the FSR. A smaller amperage, higher voltage LiFE battery would be more reliable for the projects needs.

The recommendation was also implemented with the purchase of a new battery. It was mentioned that difficulties were encountered sourcing this type of battery, however, the FSR was able to leverage his industry connections to locate a suitable LiFE battery for the

K60TPG4 test stand. As predicted, this new battery significantly increased the number of starts before requiring recharging, with Table 1 displaying initial vs recommended battery specifications.

	mAh	Volts	Composition
Initial Battery	3300	8.4	NiMH
Recommended Battery	2100	9.9	LiFE

Table 1 - Initial vs Recommended battery specifications.

3.6 Control System

The ultimate objective for the test bench control system was to allow the engine to start, operate, and shut down safely from within the control room. Initially, it was thought that this could be achieved using a mobile device via a Bluetooth connection, but early testing revealed that this method was unreliable. Based on recommendations from the KingTech FSR, a specialised radio controller was purchased, which proved to be a significant improvement.

The control system is made up of the following components,

- Controller
- Receiver
- Bluetooth module
- Engine Dashboard

3.6.1 Controller

Officially referred to as a ‘transmitter,’ this controller acts as the interface for starting, operating, and shutting down the engine from a safe distance. Based on the recommendation from the KingTech FSR, a Spektrum 6-Channel transmitter was purchased to meet the projects needs. As it is primarily designed for operating fully functional model aircraft, many of its switches and settings were unnecessary for the operation of the K60TPG4 test bench. Throughout both initial and final engine testing, the controller performed reliably, providing precise throttle control as required.

Figure 25 – Spektrum 6-Channel Transmitter, utilised for K60TPG4 engine control.

3.6.2 Receiver

As the name suggests, the receiver captures the transmission from the controller and relays the commands through the ECU (via the DRM) to control the engine. The Spektrum AR620 receiver was recommended by the FSR due to its compatibility with the Spektrum controller, its compact size, and inherent reliability. The receiver required a separate power supply from the ECU, which was provided by a small 4.8V 400mAh NiMH battery, as shown in Figure 24.

3.6.3 Bluetooth Module

Originally intended to serve as the medium for controlling and monitoring the engine, the Bluetooth module encountered connectivity issues that necessitated the purchase of radio-controlled components, as mentioned in Sections 3.6.1 and 3.6.2. Under normal circumstances, the Bluetooth module would have been sufficient, as the engine could be operated with the operator in close proximity. However, due to UniSQ safety regulations and the increased risk associated with operating on alternative fuels, the need to operate from a separate control room was incompatible with using Bluetooth for control.

Despite this, the Bluetooth module was still necessary for transmitting engine operating parameters to the operator (via the *'KingTech Turbine BDT GSU'* application), allowing them to monitor engine inputs and subsequent performance metrics. As mentioned in Section 3.5.2, a 3D-printed structure was created to elevate the Bluetooth module and enhance its connectivity.

3.6.4 'KingTech Turbine BDT GSU' application

The *'KingTech Turbine BDT GSU'* application enables the parameterisation and control of the engine and its associated components. On the control system side, its primary function was to provide a real-time visual reference for critical engine operating parameters. Vital operating metrics such as Engine RPM, EGT (Exhaust Gas Temperature), and ECU status could be monitored by the operator in the control room, as displayed in Figure 26. This meets the objective of safely operating the turbine from the control room, as the application dashboard can be viewed on a mobile device brought into the room with the operator.

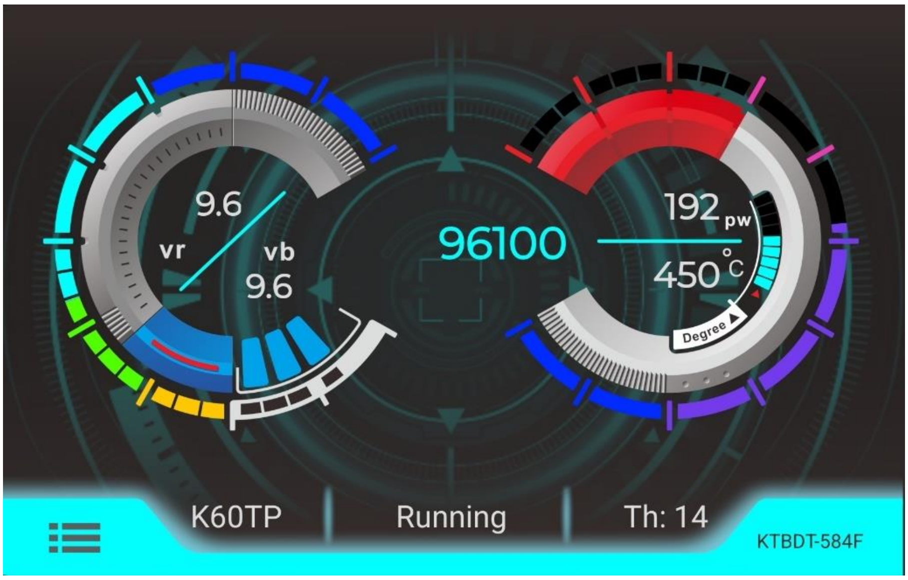

Figure 26 - Engine operation parameters displayed on application

3.7 Fuel Storage

The fuel supply for continuous operation needs to be positioned as close as reasonably practicable to the engine while also ensuring sufficient storage capacity. As mentioned in Section 3.5.3, the K60TPG4 can consume up to 280 mL of diesel per minute. To meet this requirement, three 4L fuel tanks from a previous project were repurposed and attached to the test bench. These tanks were mounted towards the front of the bench, away from the hot sections of the engine, as per Figure 27. Additionally, a new fuel line was purchased and installed to bridge the distance from the tanks to the fuel pump.

Figure 27 - Fuel tanks as installed to test bench

3.7.1 Fuel Line Weight Addition

During the initial test runs, there was an instance where the engine shut down prematurely for an unknown reason. Upon further investigation, it was discovered that the fuel line was ‘dry’, despite a substantial amount of fuel remaining in the tank. The root cause was determined to be that the fuel lines were ‘floating’ in the tank, leading to air being sucked into the line and causing premature engine shutdown due to fuel starvation, despite ample fuel still available in the feed tank.

To resolve this issue, the fuel line was fed through a piece of rubber tubing, which kept the hose straight and at the bottom of the tank (Figure 28). This solution not only prevented the line from floating but also provided the added benefit of acting as an uncalibrated ‘dipstick,’ offering a quick visual reference to the remaining fuel in the tank.

Figure 28 - Fuel weight tubing installed to fuel feed line

3.8 Load Application

One of the primary reasons for selecting the K60TPG4 turbo prop jet engine was its capability to accommodate a load application on its propeller shaft. This feature would enable a deeper understanding of how the properties of alternative fuels affect engine performance and emissions under load. Although time constraints prevented the installation of a suitable load application system on the test bench, high level analyses have been conducted, and recommendations for potential systems that could be used in future projects have been provided as follows.

3.8.1 Eddy-Current Dynamometer

An Eddy Current Dynamometer is a specialised device used for testing and measuring the performance of engines and other rotating machinery by applying a controlled load. It operates on the principle of eddy current braking, where a magnetic field is generated to produce resistance against the rotational movement of the engine being tested. Magtrol manufactures many eddy current models depending on the application requirements, of which the WB series best suits the needs of the K60TPG4 test bench.

Figure 29 - Magtrol Eddy Current Dynamometer (Magtrol 2022)

Advantages

- Specifically designed for high RPM applications, up to 65000 RPM.
- Small footprint.
- Designed for test bench and application such as gas turbines.

Disadvantages

- Cost – Quotation for the dynamometers was $50,000 AUD; this did not include the required controller.
- Cooling – The unit requires water cooling, adding an additional layer of complexity to setup.

Summary

In terms of technical specifications, the Magtrol Eddy Current Dynamometer stands out as the best option for applying a load control to the K60TPG4. Unlike other options, it can handle the high RPM output of the engine while still maintaining a compact footprint suitable for the test bench. Although its water-cooling requirements could be managed with relative ease, the high initial purchase cost makes it an economically unfeasible choice for the desired application.

3.8.2 High Speed Hydraulic Motors

High speed hydraulic motors are advanced motors designed for applications requiring high rotational speeds and significant power output. These motors could be attached as a load on the K60TPG4 shaft, with the hydraulic pressure increased or decreased to enable load control. Parker high speed hydraulic motors are what the following analysis is based on.

Figure 30 - Parker high speed hydraulic motor (Parker 2023)

Advantages

- Compact – The biggest model still comes in at under 300mm in length and a touch over 150 mm (152.5mm).
- Simple Operation – As it is a pump, no complex components or software required.
- RPM– The RPM Range tops out at 7500 RPM, the same max speed of the K60TPG4 Propellor shaft.

Disadvantages

- Oil Requirements – Runs off specific oil (Mobile DTE-26 Spec), of which quality must remain high for continued reliability.
- Oil Cooling – The oil may require a cooling system/medium to keep its temperature at recommended levels.
- Cost – Each pump is $5000 AUD; it is likely we would need two for our application. Oil and subsequent cooling system costs will also add an ongoing cost.

Summary

A promising load application option, the Parker high speed hydraulic motor presents potential; however, concerns about the storage, monitoring, and cooling of the required oil reduce its practicality. Additionally, the relatively high cost per pump further limits its viability, making it a possible but not the most likely choice for the test bench.

3.8.3 Magnetic Powder Brake System

Magnetic powder brake systems, also known as particle magnetic brakes, work by using magnetic particles suspended between a rotating shaft and a stationary housing to generate braking force. This force is regulated by adjusting the current supplied to the system, with the braking power directly proportional to the strength of the magnetic field. This mechanism allows for highly precise control of the applied load, making it ideal for applications requiring fine-tuned load application performance. For the following analysis, brakes and relevant components from the manufacturer Daysensor were used. This company specialises in producing high-quality magnetic brake systems, and their products were chosen for their reliability and suitability for precision load applications. It is of note that a separate torque sensor is required to be installed as part of a fully functioning load application assembly.

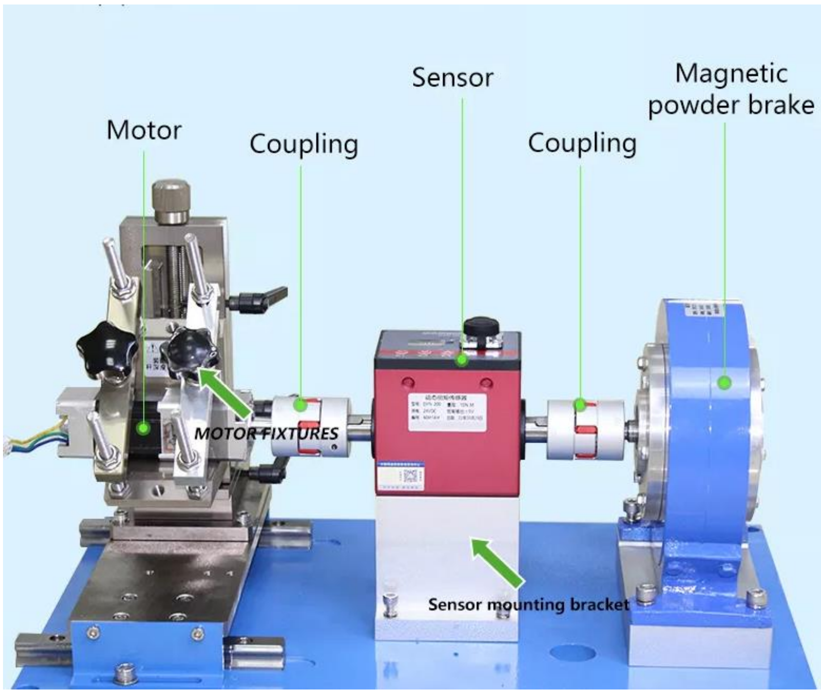

Figure 31 - Magnetic Powder Brake Assembly Setup (Daysensor 2024)

Advantages

- Compact – Even when paired with a torque sensor, the total load application assembly is only about 200mm, making it ideal for fitting within the available 300mm space.
- Control – The system allows for high precision load control due to the adjustable current applied to the brake. This variability enables fine-tuned adjustments, ensuring accurate and smooth control of the braking force.
- Cost – The magnetic powder brake and torque sensor can be purchased for approximately $500, much cheaper than alternative options.

Disadvantages

- Hardware – Couplings are required to connect the motor, torque sensor, and brake components, adding complexity to the assembly. Additionally, custom stands must be manufactured to ensure all components are aligned at the correct height, which increases setup time and effort.
- Power Supply – The need for a dedicated power supply and the necessary connections to power both the torque sensor and the magnetic brake. Although it is likely that UniSQ has the required equipment and expertise to handle this, the exact costs and time involved in setting up this system remain uncertain.

Summary

A magnetic powder brake system offers a balanced mix of economic and technical practicality for providing a controllable load application to the K60TPG4 test bench. While additional work is required, such as manufacturing stands and configuring the power supply, it is expected that UniSQ personnel and available equipment can handle these tasks. This approach will help minimise extra costs while ensuring the system remains functional and sustainable over time.

3.9 Chapter Summary

The K60TPG4 turbine jet engine test bench was fully assembled and capable of running the engine on alternative fuels. Through design and integration of the K60TPG4, auxiliary components, required controls and fuel storage systems, the test bench allows for safe and efficient operation from within the designated control room. The challenges encountered during the initial testing phases were effectively addressed, resulting in a robust and reliable setup. With the test bench now fully operational, it is well-equipped to facilitate in depth analysis of engine performance and emissions under various fuel sources, laying the groundwork for future research and development in alternative fuel applications. A comprehensive instruction manual, titled the ‘KingTech K60TPG4 Test Bench Operation Manual’, was developed as part of the project and can be found in Appendix A.

Chapter 4

Methodology

4.1 Chapter Overview

This chapter outlines the systematic approach used to test alternative fuels on the K60TPG4 turbine jet engine, focusing on evaluating performance and emissions. The process started with the design and assembly of a test bench to ensure the safe and consistent operation of the K60TPG4 in alternative fuel sources. Baseline tests using diesel were conducted to establish reference points for comparison. The procedure involved operating the engine, switching between fuels, and collecting data under controlled conditions. Safety was a top priority throughout the process, with the corresponding risk assessment provided in Appendix B.

4.2 Equipment and Materials

4.2.1 K60TPG4

The micro turbine propeller engine that all experiments will be conducted on is a KingTech Model K-60TPG4. KingTech is a respected small turbine jet engine manufacturer who have supplied their high-quality product to the industry since 2009. Building on their experience and technology, the ‘G4’ in the model numbers signifies the fourth generation of their engines.

The K-60TPG4 was chosen due its

- **Reliability:** KingTech Turbines are renowned for their durability and dependable performance.

- **Customer Service:** A field service representative was available to assist with any technical issues.
- **Multi-Fuel Capability:** The existing capability to run on three different fuel types provided strong confidence it could handle alternative fuel mixes.
- **Engine/ECU Integration:** Enables all operating parameters, including run time, to be recorded and later reviewed and analysed after testing.
- **Load Attachment Capability:** The propellor shaft offers a means to attach a controllable load to the engine, facilitating further performance testing and analysis.
- **Bluetooth Module:** Allows for wireless mobile app connectivity to monitor engine operating parameters form a safe distance.
- **Fuel Pump:** External to the engine, the digital brushless pump is capable of handling alternative fuel with varying viscosity, ensuring consistent fuel delivery.
- **Internal Lubrication:** Lubrication of the reduction gearbox is accomplished by siphoning a portion of the fuel supply, eliminating the need for a separate lubrication oil and storage system.
- **Cost:** At the time of purchase, the K-60TPG4 engine and its associated components totalled $4,500.

KingTech K60TPG4 technical specifications.

- Length: 362 mm
- Weight: 2400g
- Max RPM (Core): 160000
- Max RPM (Propellor Shaft): 7500
- EGT: 700°C Max
- Fuel Pump: Digital SBUS Brushless Pump

- Fuel Consumption: 240g/min
- Fuel: Diesel, Jet A1, Kerosene
- Lubrication: 5%

No modifications were made to the engine to accommodate running on alternative fuel mixes. Based on insights from the literature review, it was recommended to perform a ‘clean out’ run using the baseline fuel (diesel) after operating on alternative fuels. This process helps to burn off any residue from the more viscous alternative fuel mix, ensuring the internal components remain clean and the engine remains serviceable for continued use.

4.2.2 Fuels

For this set of experiments, three different fuel mixes will be utilised for emission and performance analysis.

The K60TPG4 specifications list three primary fuels that the engine can operate on: Diesel, Jet A1, and Kerosene. Diesel has been selected as the primary baseline fuel for testing due to its wide availability and affordability.

As there is no separate lubrication system on the engine, 5% (by volume) of suitable oil is to be added to every fuel mix to be used for engine operation. This is to ‘aid in reduction of friction in gas turbine engine, safeguarding rotating components like turbine blades and bearings from wear and tear caused by the extreme temperatures and high rotating speeds’ (Silmid 2024).

The engine manual recommends using a turbine oil that meets MIL-PRF-23699 specifications and provides a list of oils deemed suitable for optimal performance (Figure 32). KingTech oil was selected to be used for all tests, as it was advised to offer the best lubrication and non-coking properties, which are crucial when operating the engine with alternative fuels.

Engine Oil Comparison from KingTech Turbines

	Lubrication	Non-Coking	Non-carcinogenic	Eligibility for 25 hr I.S.	Full Lifetime Warranty	No additional labor required
2 Stroke oils	★☆☆☆☆	★☆☆☆☆	√		*	
Aeroshell 500	★☆☆☆☆	☆☆☆☆☆			*	
Aeroshell 560	★★★☆☆	★★★☆☆		√	√	***
BP 2197	★★★☆☆	★★☆☆☆		√	√	***
BP 2380	★★★☆☆	★★★☆☆		√	√	***
JetCat oil	★★★☆☆	★☆☆☆☆	√	√	√	***
KingTech oil	★★★★★	★★★★★	√	√	√	√
Mobil DTE	★★☆☆☆	★★★★☆	√	**	√ **	√
Mobil Jet II	★★★½☆	★☆☆☆☆		√	√	***
Tellus 32	★★☆☆☆	★★★★☆	√	**	√ **	√

* The use of Aeroshell 500 and 2 Stroke oil will void warranty.

** Running Mobil DTE, Tellus 32 or their equivelent would cause excessive bearing noise and failure, recommended to be sent in for service between 15 to 20, hours. Warranty voids beyond 20 hours.

*** Due to excessive coking, up to 1 hour extra labor charge may apply to the use of Aeroshell 560, BP 2197, BP 2380, JetCat oil and Mobil Jet II

Figure 32 - Oil Comparison for KingTech Turbines (KingTech 2023)

A batch of 100% biodiesel blend (B100) was generously donated by Eco Tech Brisbane for use in testing. This biodiesel consists of methyl esters derived from fatty acids. A detailed chemical analysis of the biodiesel can be found in Appendix C of this report, which provides key insights into its composition and suitability for use in the experiment.

With the availability of this alternative fuel source for testing, the following mixes were selected for comparative analysis.

- **Diesel** – 100% diesel
- **B25** – Diesel with 25% biodiesel (B100)
- **B100** – 100% biodiesel

All fuel blends will have the required volumetric 5% turbine oil mixed in.

4.2.3 Emissions Testing

A vital part of testing was accurately capturing and analysing the exhaust emissions from the different fuel mixes. This required the use of specialised test equipment, specifically the EMS Model 5002 exhaust gas analyser. The gases measured by this analyser are as follows:

- HC – Hydrocarbons, measured in Parts Per Million (PPM)
- $C0_2$ – Carbon Dioxide, measured in percentage (%)
- NOx – Nitrogen Oxide, measured in Parts Per Million (PPM)
- CO – Carbon Monoxide, measured in percentage (%)
- O_2 – Oxygen, measured in percentage (%)
- AFR- Air to Fuel Ratio (Not relevant for the purposes of this testing)

The sample probe will be inserted into the exhaust stream through an access hole created in the air extraction duct inlet attachment as per Figure 22. This setup allows for accurate sampling of exhaust gases for analysis during engine operation. Figure 33 shows the EMS Model 5002 exhaust gas analyser connected to the exhaust extraction duct. The setup enables precise measurement of exhaust emissions by directly sampling the gases as they pass through the extraction system, ensuring reliable data collection for emissions analysis.

Figure 33 - EMS Model 5002 exhaust gas analyser connected to exhaust extraction duct

The EMS Model 5002 will enable comprehensive, accurate, real-time data analysis for the emissions portion of the tests. Figure 34 illustrates the accuracy levels to which the Model 5002 is calibrated.

Gas species	Sensor	Accuracy
CO_2	NDIR sensor	0.3%
CO		0.06%
HC		4 ppm
NO	Electro-chemical sensor	25 ppm
O_2		0.1%

Figure 34 - Accuracy Specifications of EMS5002/5002 Gas Analyser (Huang et al. 2019)

4.2.4 Engine Performance Testing

Engine performance parameters will be captured by the K60TPG4's ECU. At the end of each specific fuel blend run, the data will be downloaded via the *'KingTech Turbine BDT GSU'* application for subsequent analysis.

The engine operator will monitor real-time operating parameters through the dashboard on the *'KingTech Turbine BDT GSU'* application. This ensures they can safely adjust the throttle or shut down the engine if the fuel mix appears to be causing adverse effects that could potentially lead to permanent engine damage.

A stopwatch or device with a timer function is also required to ensure accurate timing of engine operation at each specified throttle setting.

4.3 Preparation

Properly preparing the engine, associated components, and fuel source is essential for achieving consistent and successful testing outcomes. Some topics in this section are explored in greater detail in Appendix A - KingTech K60TPG4 Test Bench Operational Manual.

4.3.1 Engine and Auxiliary Components

Batteries

The ECU and receiver batteries shall be fully charged before any engine operations commence; this ensures no time is wasted in charging the batteries. This may allow the engine to cool down and possibly enable variations in results.

Controller

Ensure the controller is functional and communicating effectively with the engine.

Bluetooth Connectivity

Ensure the Bluetooth connection is secure and the dashboard on the *'KingTech Turbine BDT GSU'* is displaying all relevant data.

4.3.2 Fuel Blends

The fuel mixes must be measured as accurately as possible to ensure that the data can be analysed fairly. This task will be conducted by the Senior Technical Officer, who has the necessary qualifications, training and experience to use the fuel mixing room and its associated measuring equipment. KingTech turbine oil will be the only oil added to the relevant fuel mixes. Each fuel tank will be filled with 3 litres of fuel, ensuring the tank is not overfilled while providing at least 12 minutes of engine operation per fuel mix. The 3-litre fuel requirements for each fuel mix are outlined in Table 2.

Fuel blend	Diesel (mL)	B100 (mL)	Turbine Oil (mL)	Total (mL)
Diesel	2850	0	150	3000
B25	2100	750	150	3000
B100	0	2850	150	3000

Table 2 - Fuel blend specifications

Once all the fuel tanks are filled, the fuel shut-off valve will be switched to the open position. If the fuel lines are dry, priming will be necessary, this process is explained in detail in Appendix A.

4.3.3 Emissions Tester

The exhaust gas analyser performs a self-calibration, known as 'zeroing', upon startup. This process sets all gas readings to zero (except for O_2) to ensure that measurements are taken from the same baseline. The sample probe will be installed in the allocated access hole in the extraction duct during both the warmup and zeroing process. The zeroing process takes between 5 and 10 minutes, and this time should be accounted for before starting the engine. While the gas analyser is performing these pre-checks, the direct exhaust ducting must be positioned centrally over both engine exhaust tips. This ensures that no exhaust escapes from the duct and that the analyser consistently receives similar exhaust flow during every engine operation and fuel mix test.

Once the zeroing is complete, the display will show 'SAMPLING', as depicted in Figure 35. This indicates that the exhaust gas analyser is now sampling and analysing the airflow through the probe, and the engine can be started, allowing the analyser to take emission readings from the exhaust flow.

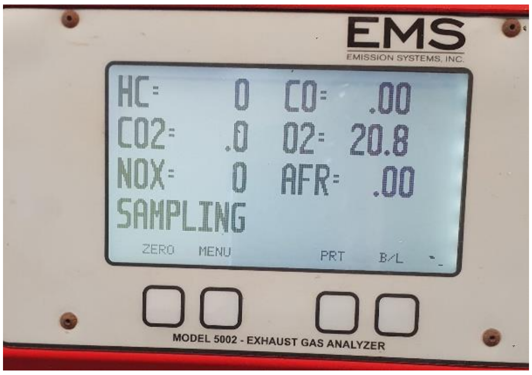

Figure 35 - Gas analyser ready for sampling

4.4 Testing Procedure

With the engine test bench preparation complete, the engine testing can begin. The testing procedure follows a simple step by step procedure, commencing with engine start; followed by engine operation; engine shut down; and data collection. This sequence is carried out each time per fuel mix and is designed to be repeatable to verify the consistency and reliability of results. The following section gives a summary-level description of this sequence, a more in-depth operation sequence of the engine and components is covered in Appendix A - KingTech K60TPG4 Test Bench Operational Manual.

4.4.1 Engine Operation

1. Turn on the air extraction system upon entering the control room post engine start preparation.

2. Using the controller and monitoring the dashboard, commence the start sequence of the engine.
3. Start the stopwatch/timer once the ECU state reads 'Running'. The ignition sequence is shown in Figure 36.

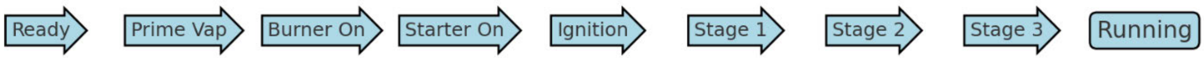

Figure 36 - K60TPG4 Ignition Sequence

4. Operate the engine for 2 minutes at each power setting, as illustrated in Table 3. This duration provides sufficient time to assess engine performance with the respective fuel and collect emission data.

Time	Engine Setting	Notes
0 - 2 Minutes	Idle	Circa 55,000 turbine RPM
2 -4 Minutes	Mid power	Circa 75,000 turbine RPM
4-6 Minutes	High Power	Circa 1000,000 turbine RPM
6 - 6.5 minutes	Idle/Cool down	Idle/Cooldown
6.5 minutes	Off	Shutdown

Table 3 - Operation Time vs Throttle Setting

4.4.2 Emissions Data Collection

During the 2-minute interval at each engine setting, the Senior Technical Officer will take note of the exhaust gas analyser outputs to capture the emissions data.

4.4.3 Engine Performance Data Collection

After the engine is shut down, the engine operator will transfer the most recent run data to their mobile device using the functionality built into the *'KingTech Turbine BDT GSU'* application.

4.4.4 Fuel Switching

The fuel lines will be pulled from the fuel mix tank used for the previous engine run, dried off with a suitable cloth to avoid cross contamination, and placed into the next tank containing the new fuel mix for testing.

4.4.5 Replicate

Following the same set of steps (4.41 – 4.4.4) to test and gather emissions and engine performance data for the next fuel mix.

4.5 Analysis and Reporting

Emissions data collected during testing will be entered into an Excel table, allowing for comparisons from the baseline diesel fuel to the bio diesel mixes. Graphs of each gas analysed by the exhaust gas analyser will be created from these tables to visually represent any identified trends. The gases analysed are detailed in 4.2.3 Emissions Testing.

The engine operation data will also be displayed graphically, as shown in Figure 37, providing a high-level visual overview of the engine parameters throughout the testing phase.

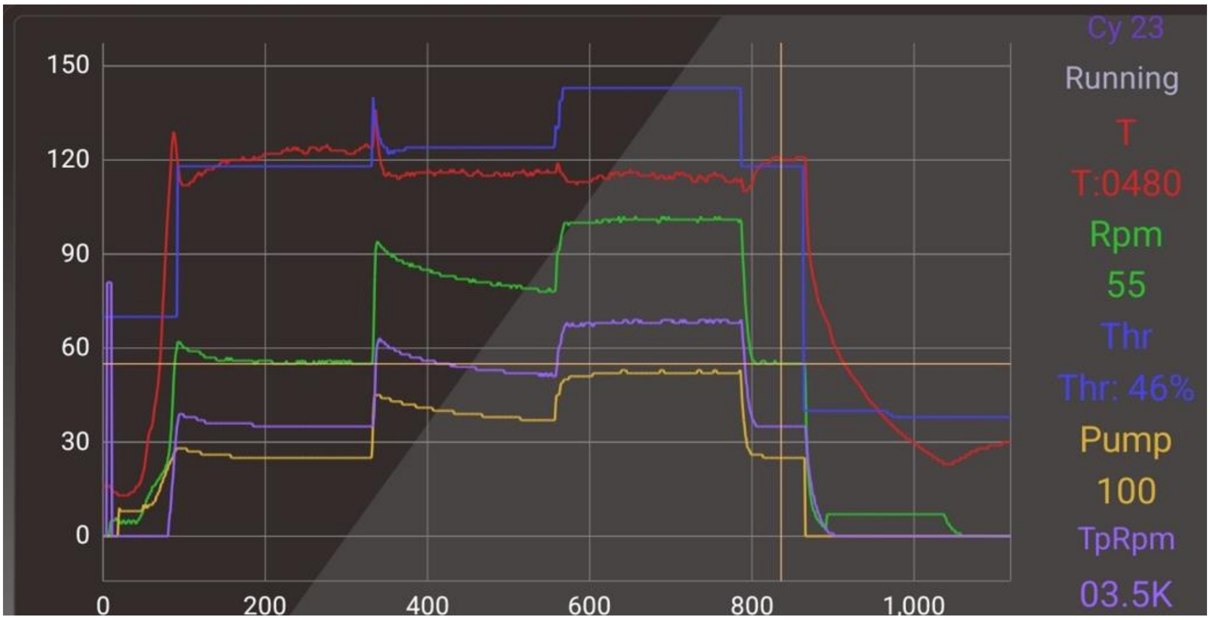

Figure 37 - K60TPG4 turbine log data.

The graph (Figure 37) displays six main parameters as follows:

- Cy – Engine Cycle, refers to the number of complete operations the engine has undergone. One cycle consists of a full start-up and shut-down sequence.
- T (Red line) – Exhaust Gas Temperature (°C).
- RPM (Green line) – The RPM (10^3) of the core engine, this comprises of the compressor and turbine assembly.
- Thr (Blue line) – Throttle, what percentage level the throttle is at.
- Pump (Yellow line)– The pump Pulse Width Modulation reading (Hz).
- TpRPM (Purple line) – The RPM (10^3) of the propellor shaft

The graph X and Y axis values are as follows.

- X Axis – Increments of 200 and units of 0.5 seconds. For example, a value of 600 on the X axis equals 3 minutes (600 * 0.5 / 60)
- Y Axis – Displays the core engine RPM, with all other metrics shown relative to the RPM value.

4.6 Safety Considerations

Operating a turbine engine in a test environment inevitably involves certain safety considerations.

Some hazards identified are.

- Exposure to high noise levels
- Mechanical moving parts
- Hot surfaces

- Fuel handling
- Exhaust fumes

These hazards can be sufficiently mitigated to keep the overall risk factor at ‘Low’. See Appendix D for the approved risk assessment for ‘Research Activities Involving KingTech K60TPG4 test stand in Building P7’.

4.7. Challenges and Limitations

4.7.1 Challenges

Load Application

Section 3.8 outlines options for applying a controllable load to the engine via the propeller shaft. While the magnetic brake was deemed the most viable option, several challenges remain regarding its integration onto the K60TPG4 test bench.

Custom connections between the propeller shaft, torque sensor, and magnetic brake must be manufactured to withstand the RPM and torque requirements. Additionally, suitable support stands are needed to align the components with the shaft at 150mm above the bench. A control system must also be developed to precisely regulate the current applied to the magnetic brake.

Although these challenges are all technically solvable, time constraints prevent them from being adequately addressed within the scope of this project.

Fuel Compatibility

While the K60TPG4 can operate on various fuels (Diesel, Jet A1, Kerosene), there is no literature or evidence supporting its ability to run on high-percentage alternative fuels. The engine may not start or function as expected. As a turboprop engine, it utilises a reduction gearbox to drive the propeller shaft, and as mentioned in the literature review, the gearbox lubrication is provided by diverting a portion of the fuel supply. There is no available evidence on how biodiesel might affect the lubrication of the reduction gearbox.

4.7.2 Limitations

Controlled Environment

The test bench operates within the controlled environment of Building P7, where conditions are tailored to ensure the safe and continuous operation of the engine on alternative fuels. However, this setup does not account for the real-world conditions a turbine engine would experience, particularly in airborne applications.

Weather, including temperature, humidity, and wind, significantly impacts engine performance and fuel consumption. Modern engines, including the K60TPG4, are equipped with ECUs to monitor these conditions and adjust engine parameters accordingly. While the K60TPG4 has this capability, its performance and emissions analysis on the test bench are somewhat limited, as it is not exposed to such environmental variables.

The controlled environment not only imposes limitations on the engine but also on the fuel sources. Both the diesel and biodiesel fuel mixes are stored in a room-temperature tank securely attached to the test bench, which does not reflect the varying movements and temperature fluctuations that fuels experience in real-world ground or aviation applications. Biodiesel, in particular, is susceptible to freezing at low temperatures, although additives can be used to prevent this. However, these additives may affect engine emissions and performance—factors that remain hidden in the controlled test bench environment.

Scale of Engine Operation

Each test operation for the K60TPG4 is scheduled to last 6.5 minutes, a much shorter duration than what would be expected in an operational setting. This limits the ability to assess the long-term wear and tear the engine may experience when using alternative fuels. Over time, engine wear contributes to degradation in performance and emissions—factors that are unlikely to be observed within the short testing duration and controlled environment of the test bench.

4.8 Chapter Summary

In conclusion, the methodology was designed to ensure a controlled and systematic approach to evaluation the emissions and performance of the K60TPG4 engine using alternative fuels. By carefully managing fuel mixes, accurately capturing emissions data and adhering to safety considerations, the test bench is envisaged to provide valuable insight into engine behaviour. While challenges and limitations exist, the methodology offers a solid foundation for future testing and refinement in real world applications.

Chapter 5

Results

5.1 Chapter Overview

The results section presents findings from testing the K60TPG4 on alternative fuels using the test bench. Tables and graphs illustrate the impact of the three different fuel mixes on the engine. The results are divided into two categories: Emissions and Engine Performance outputs.

5.2 Emissions

For emissions testing, two separate run cycles were performed to collect data, ensuring the accuracy of the emissions tester and verifying any potential trends. The average of these results was calculated, allowing for the creation of a single graph that visually illustrates how emissions varied across different fuel mixes and throttle ranges. All tables that comprise the dataset for the graphs presented in this section can be found in Appendix B - Experiment Results Tables. These tables provide the raw data used for plotting the results, offering a detailed view of the measurements and calculations that support the graphical analysis.

The colour coding of the following graphs is as follows.

- Diesel – Pure diesel in in Blue
- B25 – 25% biodiesel mix in Orange
- B100 – 100% biodiesel Grey

As mentioned in the Chapter 4, 5% KingTech Turbine oil is part of each fuel blend.

5.2.1 Hydrocarbon Emissions

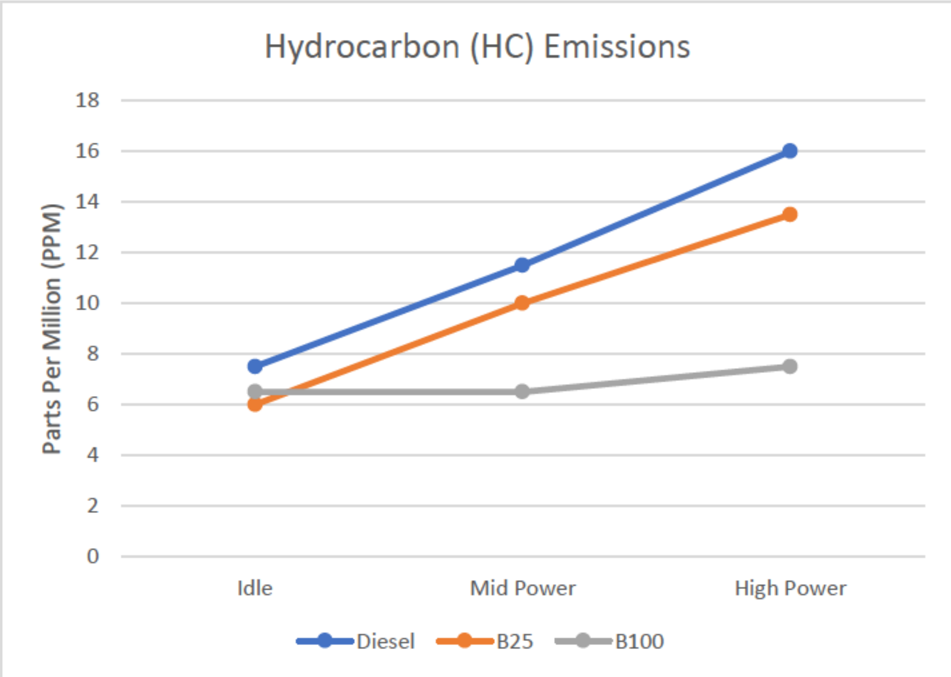

Figure 38 - Hydrocarbon emissions results

Diesel

The diesel fuel mix exhibited the highest HC emissions from idle to high power, with levels rising at a linear rate. Emissions increased by approximately 113% from idle to high power, indicating a clear trend of rising HC emissions as engine output increases.

B25

The B25 fuel mix follows a similar trend line to diesel, though at slightly lower HC levels. The emissions increase linearly, rising approximately 125% from idle to high power. This mix also shows a clear pattern of increasing HC emissions with higher engine output.

B100

The B100 fuel mix behaves quite differently from the Diesel and B25 mixes. Although emissions at idle are comparable, HC levels remain low across all throttle settings. With only a 25% increase in HC emissions from idle to high power, this mix shows no significant rise in HC emissions as engine output increases.

Summary

The Diesel fuel mix showed the highest increase in HC emissions, while the B25 mix followed a similar pattern at slightly lower levels. In contrast, the B100 mix maintained stable HC emissions across all throttle settings, with only a minimal increase. This highlights the B100 mix's advantage in maintaining lower HC emissions compared to Diesel and B25.

5.2.2 Carbon Dioxide Emissions

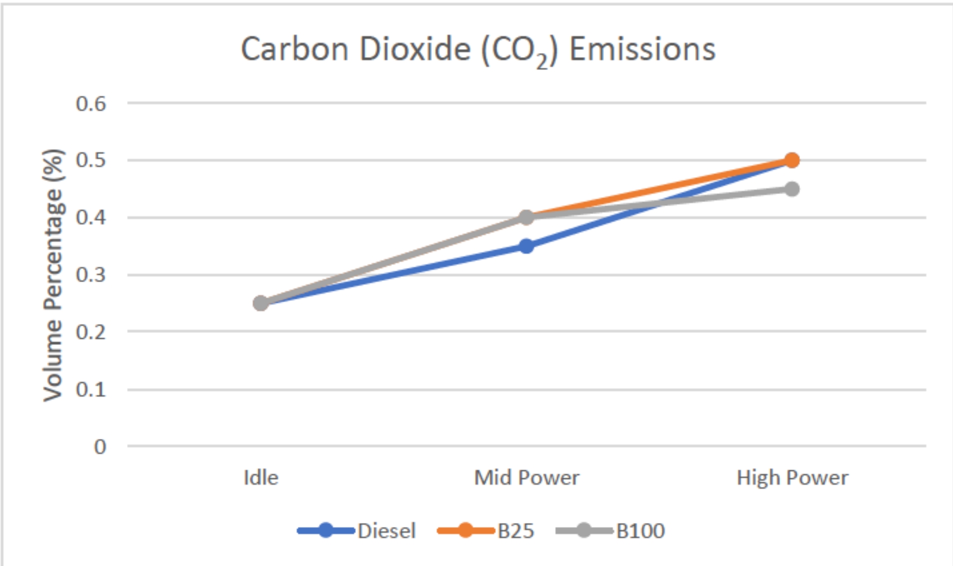

Figure 39 - Carbon Dioxide emissions results

Diesel

The diesel fuel exhibits a relatively linear trend in CO_2 emissions as engine output increases. Notably, it reaches the (comparatively) lowest value at the mid power mark before ending with the highest CO_2 emissions at high power. There is a 100% increase from idle to high power ; however, it's important to note that these are small, recorded values, so even minor numerical changes result in significant percentage increases.

B25

The B25 fuel mix also shows a relatively linear trend, starting at the same CO_2 level as the diesel mix at idle but emitting higher CO_2 levels across the other throttle ranges. Like diesel, it experiences a 100% increase in emissions from idle to high power.

B100

B100 CO_2 emissions are nearly identical to those of the diesel and B25 mixes. Only at higher engine outputs do CO_2 levels fall below those of diesel. This final drop results in an 80% increase in emissions from idle to high power.

Summary

The diesel and B25 fuel mixes show a linear increase in CO_2 emissions, both doubling from idle to high power. The B25 mix emits slightly higher CO_2 levels than diesel at most throttle settings. In contrast, the B100 mix closely mirrors the CO_2 emissions of diesel and B25, with a smaller increase of 80%, particularly dropping off at higher engine outputs. This suggests that B100 may offer a slight advantage in reducing CO_2 emissions at maximum power levels.

5.2.3 Nitrous Oxide Emissions

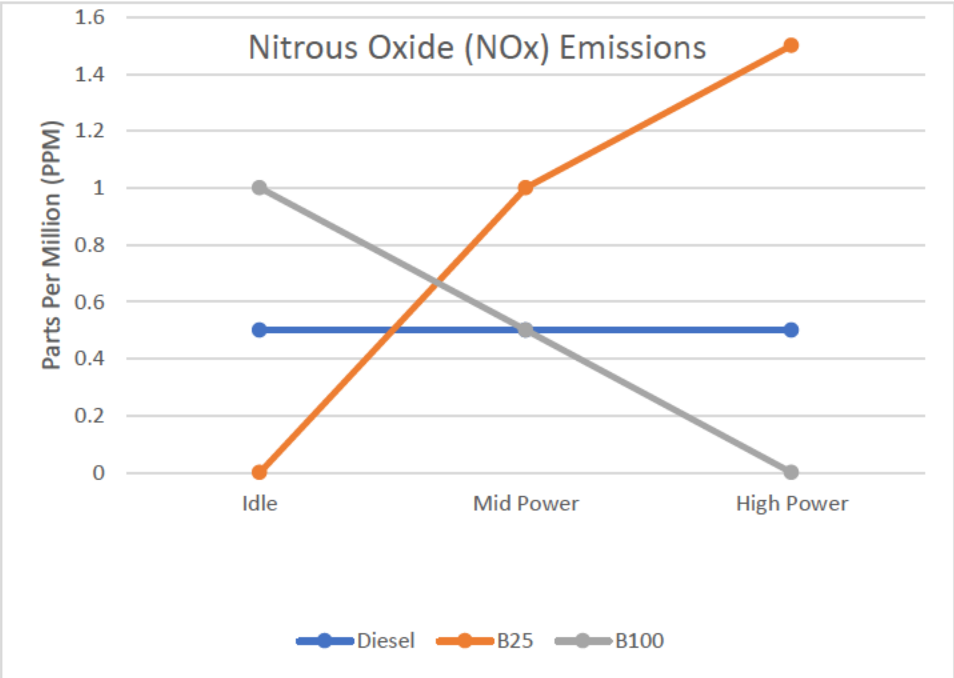

Figure 40 - Nitrous Oxide emissions results

Diesel

The NOx emissions for the diesel fuel remained steady at all throttle levels. There was a 0% change in the NOx levels, displaying that diesel does not emit an increasing amount of NOx even with increase engine output.

B25

Initially showing zero NOx emissions at idle, the B25 mix sees a dramatic increase as throttle settings rise. By the mid power setting, NOx levels are 100% higher than Diesel, escalating to a 200% difference at high power. This indicates a significant and sharp rise in NOx emissions with increased engine output.

B100

Initially producing the highest NOx emissions at idle, the B100 mix follows a perfectly linear decrease towards zero emissions at the high power mark. At idle, B100 emits 100% more

NOx than Diesel, but by the high power throttle setting, it reverses to emitting 100% less. This indicates that NOx emissions from B100 decrease as engine output increases.

Summary

The Diesel and B100 fuel mixes show contrasting trends in NOx emissions. Diesel maintains steady levels throughout, while B100 sees a consistent decrease, starting with the highest NOx emissions at idle and dropping to zero by the high power setting. In contrast, the B25 mix displays a sharp increase, with NOx levels rising from zero at idle to 200% higher than Diesel at high power. This makes B25 an outlier, as it defies expectations—one would not anticipate such a drastic increase when Diesel remains stable and B100 decreases with engine output. It is challenging to explain why B25 behaves this way in the data set. The literature review indicated that NOx levels typically increase with higher blends of biodiesel, making the fact that our results show the opposite somewhat concerning. This, combined with the erratic NOx readings for the B25 blend, raises questions about the accuracy of the NOx emissions data from the gas analyser.

5.2.4 Carbon Monoxide Emissions

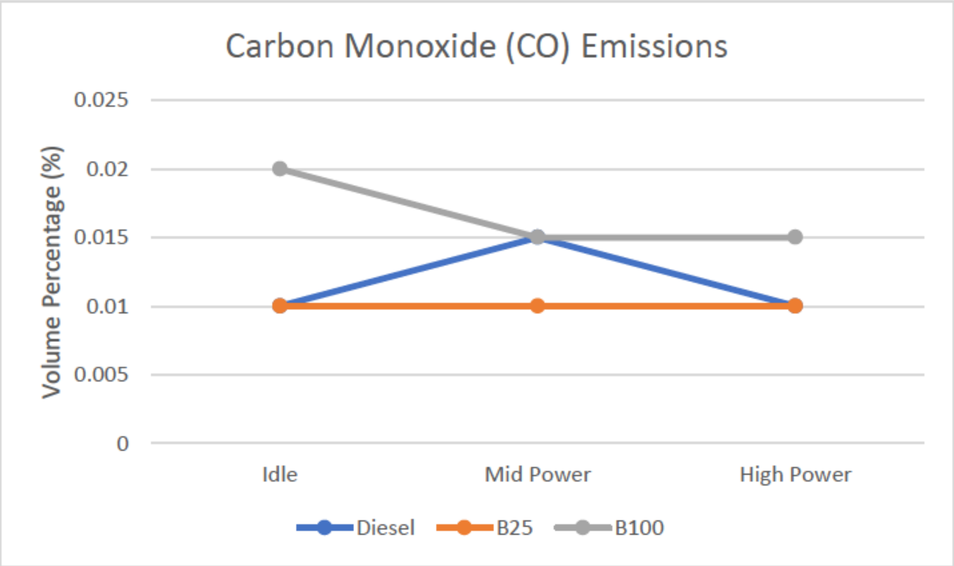

Figure 41 - Carbon Monoxide emissions results

Diesel

The diesel fuel mix CO emissions exhibited a 'pyramid shaped' trend, with CO levels being identical at both the idle and higher power throttle positions and showing a slight increase at the mid power setting.

B25

The CO emissions for the B25 fuel mix remained consistent across all throttle levels, with a 0% change observed. This indicates that the B25 mix does not produce higher CO emissions, even as engine output increases.

B100

At idle, the B100 fuel mix recorded the highest CO emissions at 0.02. However, these levels dropped by 50% at both the mid and high power throttle settings. Despite the decrease, B100 consistently had the highest CO emissions, indicating that using B100 results in higher CO emissions compared to diesel fuel.

Summary

As a volume percentage, CO emissions are relatively low compared to other emission compositions analysed in the testing, resulting in minimal variation across all fuel mix trend lines. Emissions for all fuel mixes fell within a narrow volumetric range of 0.01% to 0.02%. The diesel mix showed a peak in CO emissions at mid power, while B25 remained steady across all throttle settings. B100 consistently had the highest CO emissions, despite a decrease at higher throttle levels, indicating that it produces more CO than both diesel and B25.

5.2.5 Oxygen Emissions

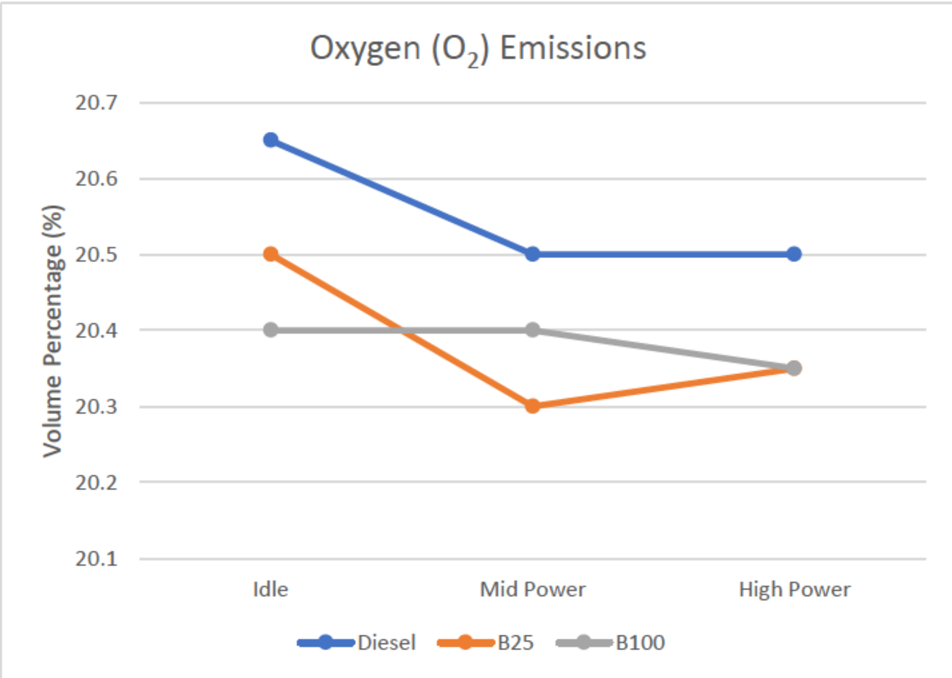

Figure 42 - Oxygen emissions results

Oxygen levels at ground level typically constitute 20.9% of the atmosphere. Hence, in the subsequent analysis, values closer to 20.9% are considered more favourable in terms of emissions.

Diesel

At idle, the diesel fuel mix was the closest what would be considered normal oxygen levels.

The Oxygen levels slightly dropped at the mid power throttle level and stayed at that level through to the high power setting.

B25

The O_2 emissions for the B25 mix decreased from 20.5% at idle to 20.3% at the mid power throttle setting. The oxygen content then slightly increased to 20.35% at the high power setting.

B100

The B100 fuel mix demonstrated the most consistency across all throttle ranges, maintaining an oxygen content of 20.4% from idle to the mid power setting, with a slight decrease to 20.35% at the high power throttle setting.

Summary

As expected, all fuel mixes showed lower oxygen content in exhaust emissions compared to the standard atmospheric level. The B25 mix experienced a slight drop in oxygen content from idle to mid power, followed by a small increase at high power. The B100 mix remained the most stable, with minimal variation in oxygen levels across all throttle ranges. Overall, the diesel mix remained closest to normal oxygen levels at idle, with minor decreases at higher throttle settings.

5.3 Engine Performance

For the engine performance analysis, data from only one run per fuel mix was used. This was due to the significant time required to figure out how to extract data from the ECU, a task that was only successfully achieved toward the end of the testing phase.

The turbine data graph features an interactive capability that allows users to select a specific point on the timeline to view the corresponding parameters for that exact moment. Data points were taken at the midpoint of each throttle setting across the three fuel mixes. The results were then tabulated and represented as bar graphs for comparison purposes. The tables utilised for the creation of the following graphs are in Appendix B - Experiment Results Tables.

5.3.1 Exhaust Gas Temperature

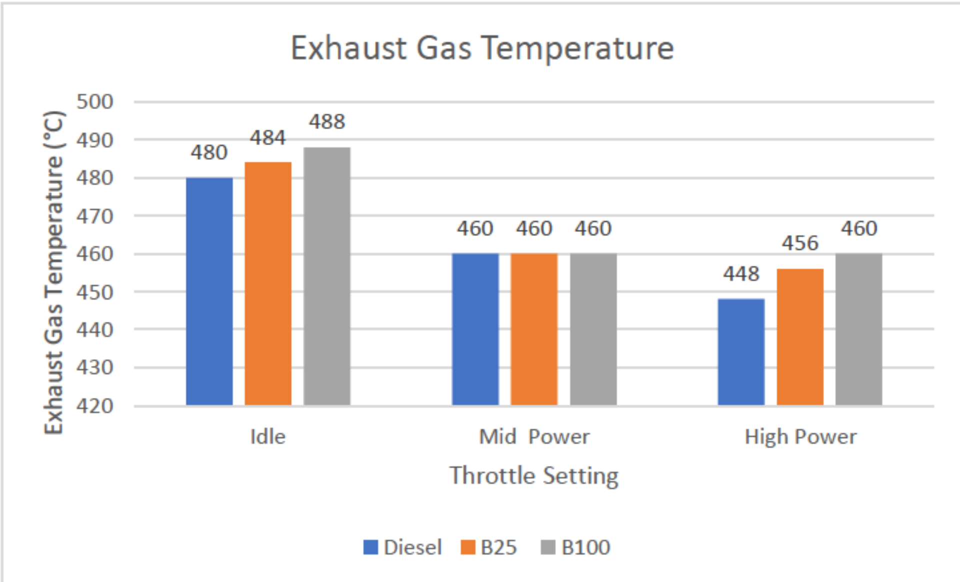

Figure 43 - Exhaust gas temperature results

Idle

There is a clear trend showing that EGT increases with the proportion of biodiesel in the fuel mix at the idle throttle setting. While the difference is not significant, diesel recorded an EGT of 480°C, which rose to 488°C with the B100 fuel mix.

Mid Power

Interestingly, the increasing trend observed at the idle power setting does not persist at the mid-power setting. All fuel mixes recorded the same EGT of 460°C at this throttle level.

High power

The increasing EGT trend with higher biodiesel content reappears at the high-power setting. This time, the difference is more noticeable, with the diesel fuel mix recording an exhaust temperature of 448°C, compared to 460°C for the B100 mix.

Summary

The general trend of decreasing temperature with increasing power settings aligns with typical 'unloaded' turbine operations, where improved combustion efficiency and airflow dynamics are more pronounced at higher RPMs. However, at both the lower and higher ends of the power spectrum, it is evident that higher biodiesel content in the fuel mix results in increased EGT.

5.3.2 Turbine RPM

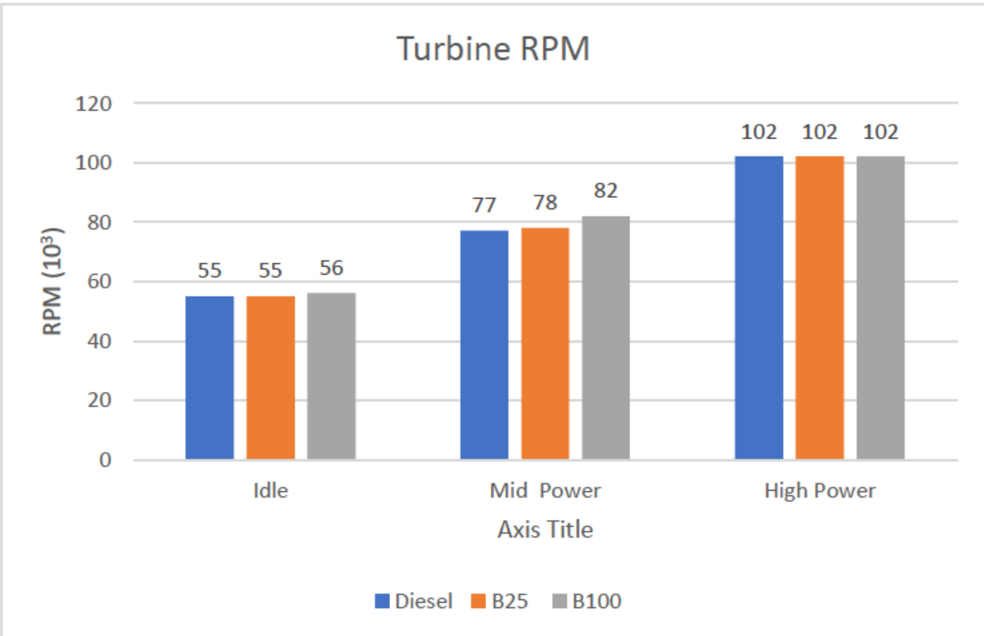

Figure 44 - Turbine RPM results

Idle

All fuel mixes maintained nearly the same RPM at the idle power setting. Both the diesel and B25 mix recorded 55,000 RPM, while the B100 mix showed a slight increase to 56,000 RPM.

Mid Power

Diesel exhibited the lowest RPM in the mid-power range at 77,000 RPM. The B25 blend showed a slight increase to 78,000 RPM, while B100 demonstrated a more pronounced rise, reaching 82,000 RPM at the same power setting.

High Power

RPM levels with all fuel mixes displayed the same RPM of 102,000.

Summary

This trend is essentially the opposite of what was observed for EGT, with RPM levels remaining almost identical at idle and high-power settings but increasing with higher biodiesel percentages at mid power. This suggests that the ECU prioritises maintaining RPM over EGT at low and high-power levels, while at mid power, EGT takes precedence.

5.3.3 Propellor Shaft RPM

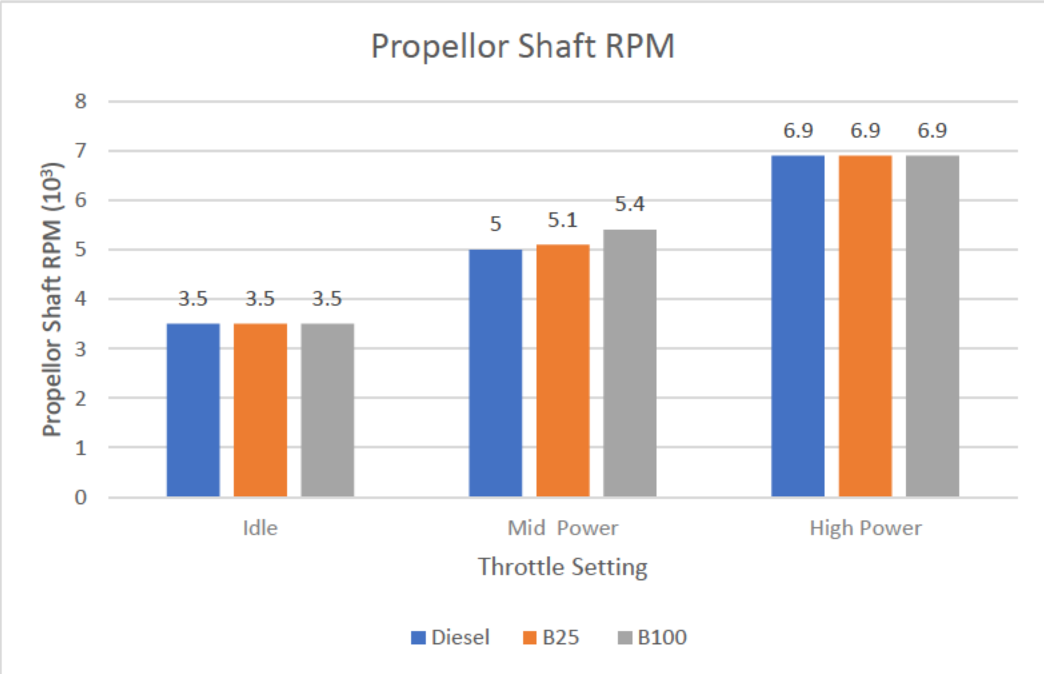

Figure 45 - Propellor Shaft RPM results

Idle

The Propellor Shaft RPM are all at 3,500 RPM at the Idle power setting, this is almost half the max RPM rate.

Mid Power

Diesel exhibited the lowest propellor shaft RPM in the mid-power range at 5000 RPM. The B25 blend showed a slight increase to 5,100 RPM, while B100 demonstrated a more pronounced rise, reaching 5,400 RPM at the same power setting.

High Power

RPM levels with all fuel mixes displayed the same propellor shaft RPM of 6,900. This is close to the maximum propellor shaft speed of 7,500 RPM, this is expected as there was no loading on the shaft during the experiments.

Summary

As expected, the propellor shaft RPM displayed the same characteristics as the turbine RPM.

With the ECU keeping both RPM levels steady at both low and high-power settings, while the high biodiesel percentage fuel mix correlated to a higher RPM at the mid power levels.

5.3.4 Fuel Pump Pulse Width

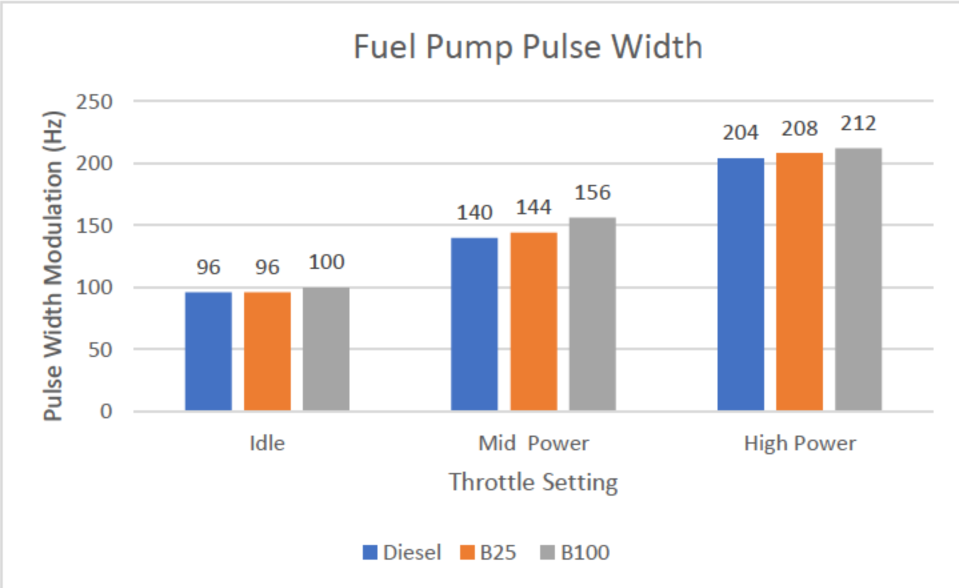

Figure 46 - Fuel pump pulse width results

Idle

Both the diesel and B25 fuel mix had a PWM reading of 96 Hertz (Hz) at idle, with the B100 mix having an increased reading of 100 Hz.

Mid Power

The was an increasing trend of PWM output in relation to the percentage of biodiesel in the fuel mix. The diesel mix gave a reading of 140Hz, which rose to 144Hz and 156Hz from the B25 to B100 mix.

High Power

The increasing trend of PWM Hz to biodiesel percentage continued in the high-power range, however it was in a more linear fashion. Each fuel mix increased in increments of 4Hz from the 3 fuel mixes at the high power setting.

Summary

There is a clear trend showing that as biodiesel percentage in fuel increases, the PWM of the fuel pump also increases. This suggests that the pump operates at a higher capacity when using biodiesel, which indicates more biodiesel is required to maintain optimal engine conditions as directed by the ECU. Additionally, the higher viscosity of biodiesel compared to diesel may cause the pump to work harder to deliver the necessary fuel flow.

5.3.5 Turbine Log Data

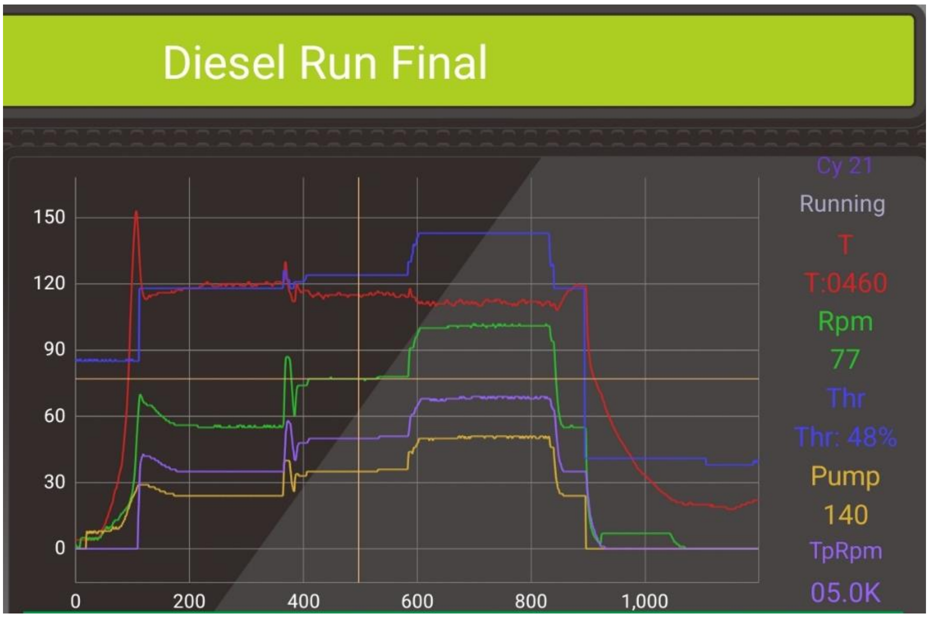

Figure 47 - Diesel mix turbine log data results

Figure 47 displays the baseline diesel fuel turbine log data, showing three distinct power levels where all parameters remain stable after an initial settling period at each setting. The initial spike in EGT is typical for a 'first start of the day', due to cooler internal components requiring more fuel to reach operating temperature quickly.

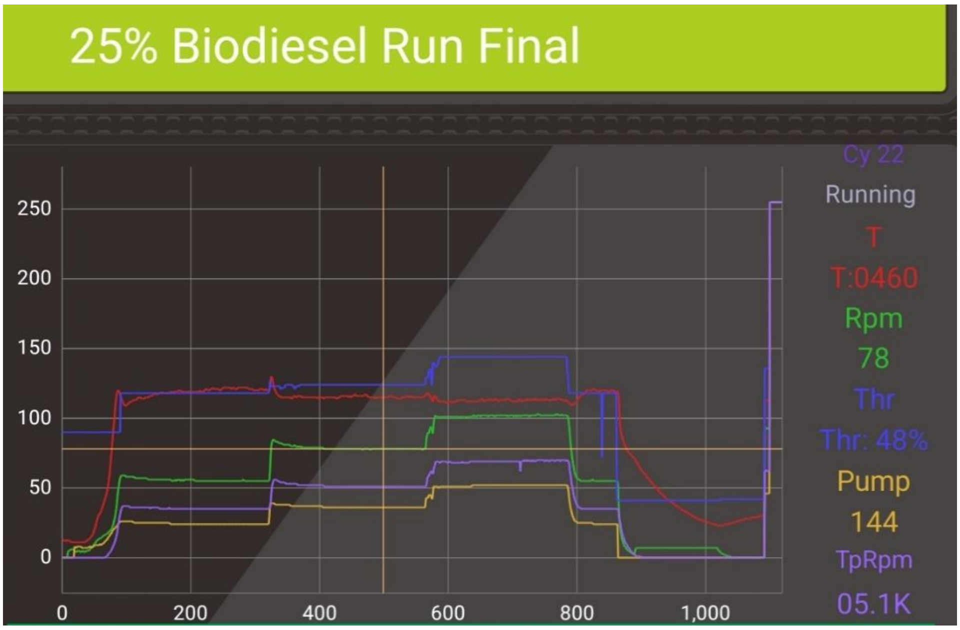

Figure 48 - B25 blend turbine log data results

The turbine log data for the B25 fuel mix, shown in Figure 48, displays minimal differences compared to the parameters of the diesel mix turbine log. It is observed that Figure 48 appears slightly compressed compared to Figure 47 and Figure . This is attributed to the TpRPM parameter recording an abnormally high value after engine shutdown, which caused the data log to compress other parameters to fit on the same graph. This anomaly is likely due to a random software glitch, as the reading reached approximately 25,000 RPM, far exceeding the maximum possible TpRPM of 7,500 RPM, especially considering that the engine was already shut down. This software glitch is considered an outlier and is not related to any characteristics of the B25 fuel blend.

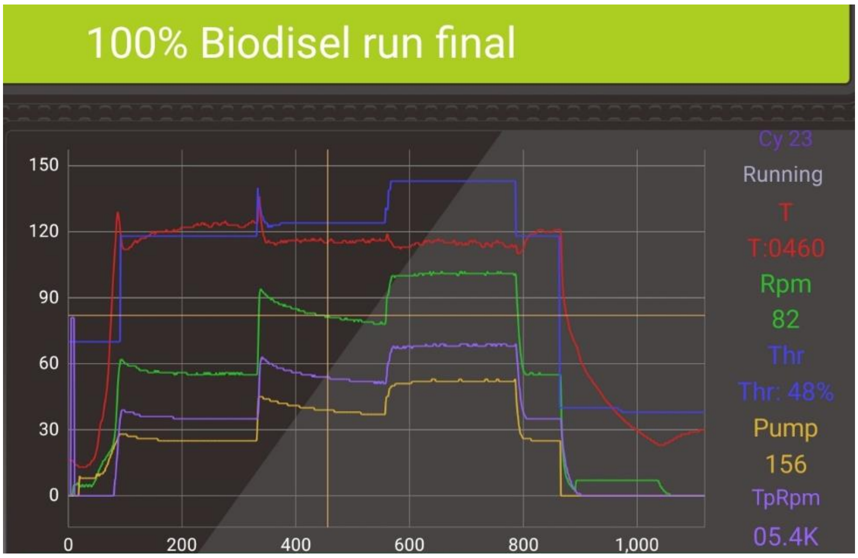

Figure 49 - B100 blend turbine log data results

Figure , which illustrates the testing cycle on B100, closely resembles the turbine log data for Diesel and B25. During the two minutes at mid-power, the RPM, TpRPM, and Pump values gradually decreased, with the intervals between changes lengthening toward the end, indicating that the values were stabilising. Notably, the EGT remained constant throughout the reduction in other parameters, and these changes went unnoticed by the operator during testing. This suggests that to maintain the EGT, the ECU appeared to adapt to the characteristics of B100, adjusting (lower) the fuel PWM and RPM accordingly. Data was collected from the midpoint, where B100 showed similarities to both diesel and B25 blends, though the parameters began at higher levels at the start of the mid-power testing and ended lower. Despite this anomaly in the mid-range setting, the B100 fuel blend followed a similar trend in engine parameters at both idle and high-power settings.

5.4 Chapter Summary

The testing procedure provided a substantial amount of data on emissions and engine performance. This data offered insights into how the three different fuel mixes affected the K60TPG4's operation. Key trends were identified in both emissions outputs, such as HC, CO, and CO_2 , as well as in engine performance metrics like EGT, RPM and fuel pump pulse width modulation. These results will be examined in more detail in Chapter 6.

Chapter 6

Discussion

6.1 Chapter Overview

This section further interprets the results from Chapter 5, providing a holistic analysis of emissions and engine performance. It also addresses certain issues related to the engine's use of B100 that were not covered in the results section, which primarily focused on quantitative analysis.

6.2 Emissions

The results aligned with existing literature, indicating that the use of biodiesel reduces pollutant emissions compared to diesel. This was primarily observed in the downward trend of HC emissions as the percentage of biodiesel in the blend increased. While most of the literature suggests CO_2 levels decrease with the use of biodiesel, the results of this study did not show a significant reduction, with all fuels emitting similar levels across all power settings. The consensus in the literature is that biodiesel increases CO emissions, and the results were consistent with this. However, it should be noted that the CO levels for all fuels were volumetrically low.

The NOx levels in the results diverged from previous studies and possibly from real-world expectations. While diesel emissions remained steady, the B25 blend showed an upward trend in NOx emissions, whereas the B100 blend exhibited a decrease. Most studies have reported an increase in NOx emissions with biodiesel blends, regardless of the blend percentage. The erratic NOx readings in these results raise concerns about the calibration of the specific sensor in the gas analyser used for testing.

6.3 Engine Performance

Similar to existing literature, the results found that the use of biodiesel had a negligible effect of engine parameters and performance. Upon analysing the data, it is evident that the K60TPG4 ECU prioritises maintaining engine RPM at idle and high-power settings, while focusing on EGT at mid-power. This was true regardless of the fuel blend, further demonstrating the engine's ability to handle alternative fuels. At low and high power, the results showed slightly higher EGT values with increasing biodiesel percentages. While other studies reported slightly lower EGT values with biodiesel, converging to base fuel levels at higher power settings. The difference in EGT in K60TPG4 testing between all fuel sources was a maximum of 2.6%, which can be attributed to the higher density and cetane number of the B100 biodiesel blend utilised.

Previous literature consistently found that biodiesel blends result in higher fuel consumption compared to base fuels. While fuel consumption was not directly measured, the fuel pump's pulse width modulation data was captured. PWM value increased as the percentage of biodiesel increased, indicating the pump was working at a higher duty cycle to deliver more fuel to the engine. This aligns with previous studies, confirming that biodiesel usage is higher compared to base diesel fuel.

While the K60TPG4 overall responded well to biodiesel as a fuel source, some issues were encountered during testing, as described in Section 6.4.

6.4 Engine Issues with B100

The results and subsequent discussion focused on the data gathered during the successful operation of the engine, without accounting for issues encountered in reaching those data points. This section addresses the few problems that the B100 blend seemingly induced on the engine during testing.

6.4.1 Fails to start

Unlike some other studies, difficulties were encountered in starting the engine when using the B100 blend. The possibility of a problematic start, discussed in Section 2.4.3, due to biodiesel's high flash point and viscosity, was realised during experimental testing. On two separate occasions, the engine failed to start with the B100 blend, with the ECU terminating the start sequence when ignition was not detected within the pre-set time frames. The system was primed to drain the B100 fuel from the lines and replaced with diesel which enabled initial ignition, after which the B100 was able to sustain combustion. The methodology called for B100 to be tested last, so subsequent successful starts can likely be attributed to the engine being warmed up from earlier operations. On these successful starts on B100, the increased time to ignition was noticeable, though no specific time delta was manually recorded. At no point was B100 used to attempt a start on a ‘cold engine’, and the results suggest that a successful start under such conditions is unlikely.

It is worth noting that some previous studies employed a fuel-switching mechanism to test alternative fuel blends. This approach allowed the engine to start on base fuel before introducing the alternative fuel blend, thus avoiding cold start issues. However this process was not followed for K60TPG4 testing as it is was not considered a realistic approach for fully assessing the engine’s performance with biodiesel blends.

6.4.2 Turboprop Seizure

During one of the initial startups on B100, a 'Check TPR' caution appeared, indicating an issue with the Turbo Propeller. Upon visual inspection from the control room, it was observed that the propeller shaft was not rotating, despite the core engine being at idle. Attempts were made to increase power and move the propellor shaft by advancing the throttle, but the engine's safety parameters prevented any power adjustment while the caution was active. Consequently, the engine had to be shut down, and the propeller shaft manually rotated to free it from its seized state. As discussed in the literature review, the propeller gearbox is lubricated by a portion of the fuel, which at the time of the seizure was B100. It is believed that the B100 blend lacks the same lubricating properties as diesel, even with the required 5% turbine oil blended in. Notably, after this initial seizure, no further occurrences were reported. There were no significant differences in TpRPM values when operating on B100 compared to other fuel blends, except for a slightly higher TpRPM at mid-power, which aligned with the core engine RPM. Previous studies did not employ a turboprop variant of micro turbines like the K60TPG4, so no direct comparative analysis was available.

6.5 Chapter Summary

The engine operational issues discussed in Section 6.4 were only apparent when the B100 fuel blend was utilised, the B25 blend displayed none of these issues. This points to a blend somewhere between B25 and B100 being the optimal fuel source to maintain all operating conditions alongside providing the environment benefits of using an alternative fuel.

Similar to previous studies, the tests were conducted over short durations, focusing on collecting the necessary data before ceasing operation on the alternative fuel blends. However, longer tests under more operationally realistic conditions are needed to fully assess the viability of these alternative fuels. Additionally, turbine maintenance reports following extended use of alternative fuel blends will be crucial in identifying any abnormalities or issues arising from their ongoing use.

Overall, the K60TPG4 micro turbine operated successfully on the alternative biodiesel blends, with no noticeable changes in engine behaviour and minimal differences in engine parameters. The emissions profile displayed a more environmentally friendly output when using biodiesel. These findings suggest fuel blends utilising renewable sources are feasible and should be explored further.

Chapter 7

Conclusions and Recommendations

7.1 Conclusion

The project successfully explored the effects of biofuel blends on the emissions and performance of the K60TPG4 micro gas turbine, demonstrating the viability of alternative fuels in micro turbine applications. Through hands-on experimentation and the design of a functional test bench, significant insights were gained regarding the environmental benefits and operational challenges of using high percentage biodiesel blends. The project achieved its primary objective of determining the impact of biofuel blends on microturbine performance and exhaust emissions.

The findings underscore the importance of continued exploration into sustainable fuel solutions, especially as industries seek to minimise environmental impacts while maintaining peak operational performance.

7.2 Further Research Recommendations

While the primary objective of the project was achieved, there are still opportunities for further research to deepen the understanding of alternative fuel use in micro turbines.

7.2.1 Load Application

Applying a load to the K60TPG4 engine would enable a more detailed analysis of alternative fuels, as it would require the engine to operate closer to real-world conditions. This increased load would force the engine to fully utilise the combustion properties of each fuel, allowing for a more comprehensive comparison of performance metrics, such as efficiency, emissions, and power output. This approach would highlight how each fuel blend performs when the engine is pushed closer to its operational limits, providing deeper insights into the practical applicability of alternative fuels in micro turbine systems.

Since completion of this project, there has been notable progress in this recommendation, with the magnetic powder brake system referenced in Section 3.8.3 being purchased. Initial planning for its integration onto the K60TPG4 test bench has begun, as shown in Figure 50.

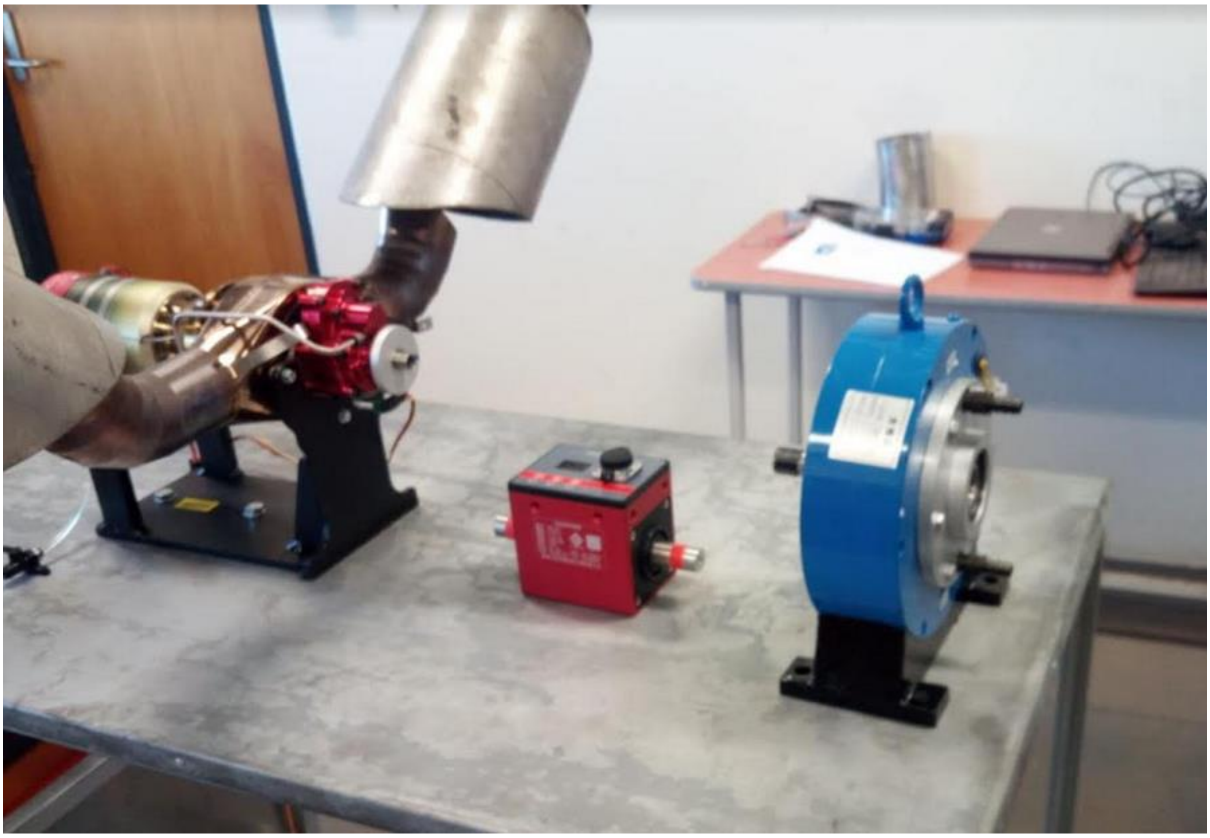

Figure 50 - Magnetic Powder Brake Load Application Incorporation

7.2.2 Alternate Fuels

While this study focused on biodiesel as an alternative fuel source, there are many other fuel blends suitable for micro turbine applications that warrant further exploration. These include ethanol, methanol, and other biodiesel source blends, each offering unique combustion properties and environmental benefits. Testing these alternative fuels could provide insights into efficiency, emissions, and overall performance under various operating conditions, furthering the understanding of sustainable fuel options for micro turbines.

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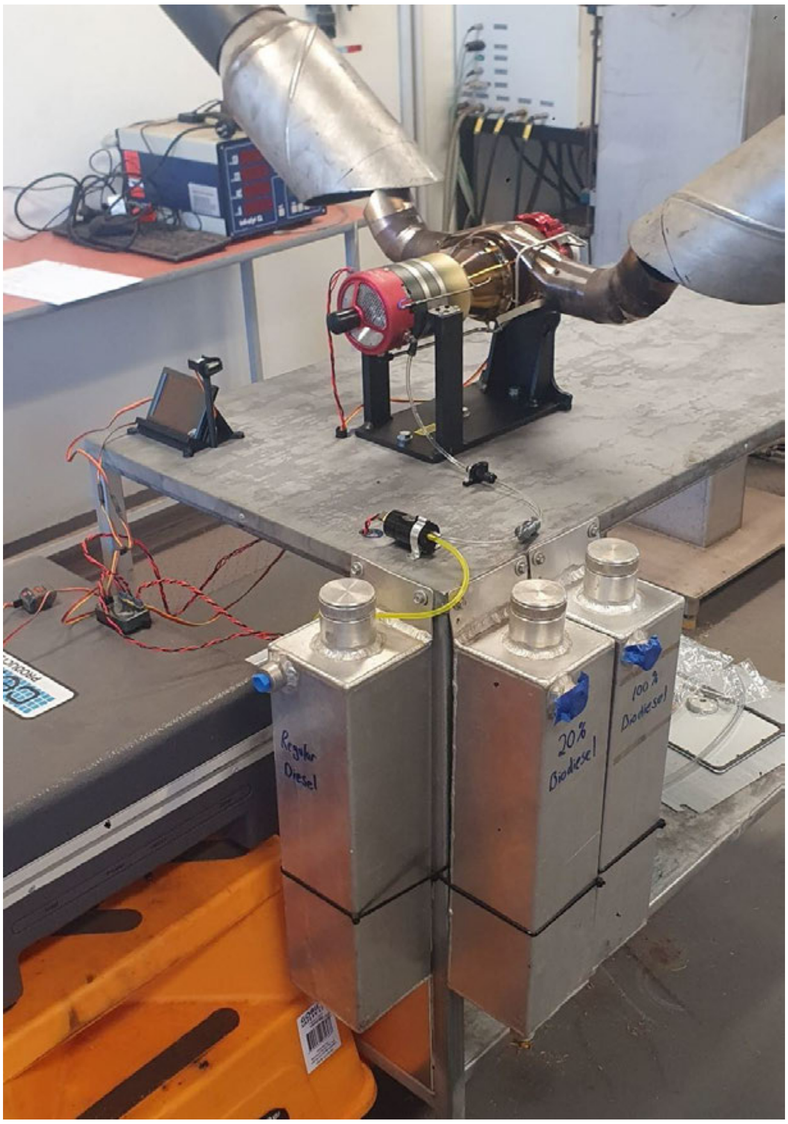
Appendix A - KingTech K60TPG4 Test Bench

Operational Manual

KINGTECH K60TPG4 TEST BENCH OPERATION MANUAL

When operated within Building P7, University of Southern Queensland, Toowoomba, QLD



Introduction

This operation manual provides detailed instructions on safely operating the KingTech K60TPG4 when installed on the test bench within the confines of Building P7 on the Toowoomba Campus of the University of Southern Queensland.

While this operation manual provides useful guidance to operate and conduct relevant testing with the K60TPG4 Turbine engine, it is to be used in conjunction with the official *KingTech Turbine Engine Manual*. Any new operator of the K60TPG4 Turbine shall first read the engine manual in its entirety before attempting any operation. Dr Khalid Saleh can provide the physical copy on request, alternatively it can be viewed at https://www.kingtechturbines.com/engine-manual-download (Under 'Manual for KingTech G4+ engines').

Safety

Building Induction

A building induction must be completed before continued access to P7 is permitted. This process is overseen by the authorised Senior Technical Officer, currently Brian Leske at the time of writing.

Test Bench Safety Measures

All critical safety aspects will have been covered in the building induction. However, the following points are emphasised specifically for working with and/or operating the K60TPG4 Turbine engine test bench.

- **Hearing Protection** – Even though turbine will be operated from the control room, it is highly recommended to have hearing protection on all persons.
- **Nitrile Gloves** – Whenever touching the engine post a run, especially pertinent if there is possible contact with any of the fuel sources (including any contact with the fuel tanks, lids etc).
- **Eye Protection** – Worn at all times within the confines of the workshop.
- **Safety Boots** – Worn at all times within the confines of the workshop.
- **CO_2 Fire Extinguisher** – Ensure the CO_2 fire extinguisher is in a serviceable condition and within its inspection dates.
- **Air Extraction System** – Ensure the Air Extraction System is fully functional, the turbine engine shall not be operated if there is any fault with this system.

Component List

Item	Picture	Function
K60TPG4		Micro turbine with turbo propeller gearbox
K60 Turbo Prop Exhaust Tips		Direct engine exhaust into air extraction system
Spektrum Controller		Enables control of engine throttle from a safe distance (the Control Room).
Ground Support Unit (GSU)		Displays Engine Parameters
Data Relay Module (DRM)		Relays data between Fuel Pump, ECU and (Propellor) Sensor
Fuel Pump		Supplies Pressure from applicable fuel tank to engine
Fuel Filter		Filters Fuel between the pump and engine
Fuel Shut Off Valve (SOV)		Manual shutoff Valve to prevent or allow fuel flow to engine

Receiver		Relays signal from Controller to Turbine
Receiver Battery		Provides Power for Receiver, GSU and Bluetooth module
ECU Battery		Provides Power for starter / glow plug / ECU / Fuel Pump / Fuel and gas valves
Bluetooth Module		Allows to the operator to view engine dashboard on the KingTech App
Fuel Tanks		3 x Tanks attached to stand to enable testing of different fuels

Ground Support Unit Application

The Ground Support Unit (GSU) displays all engine parameters, however due its close proximity to the engine, it is not able to be viewed from the control room. The operator is required to download the *'KingTech Turbine BDT GSU'* app. Instructions for downloading the application can be found on page 95 of the *KingTech Turbine Engine Manual*.

Once the app is installed, select the 'Dashboard' option. This will display a dashboard that mirrors the parameters shown on the GSU. While the parameters remain the same, the visual layout on the app is different. Figure 1 below shows the app's layout and details what each display represents.

Note: The throttle and stop button (highlighted withing the red box in Figure 1) will not be active on the app. This is because the controller has been deemed the primary throttle control authorisation. If the controller is not the primary control, this setting can be changed under the 'Turbine' option within the app.

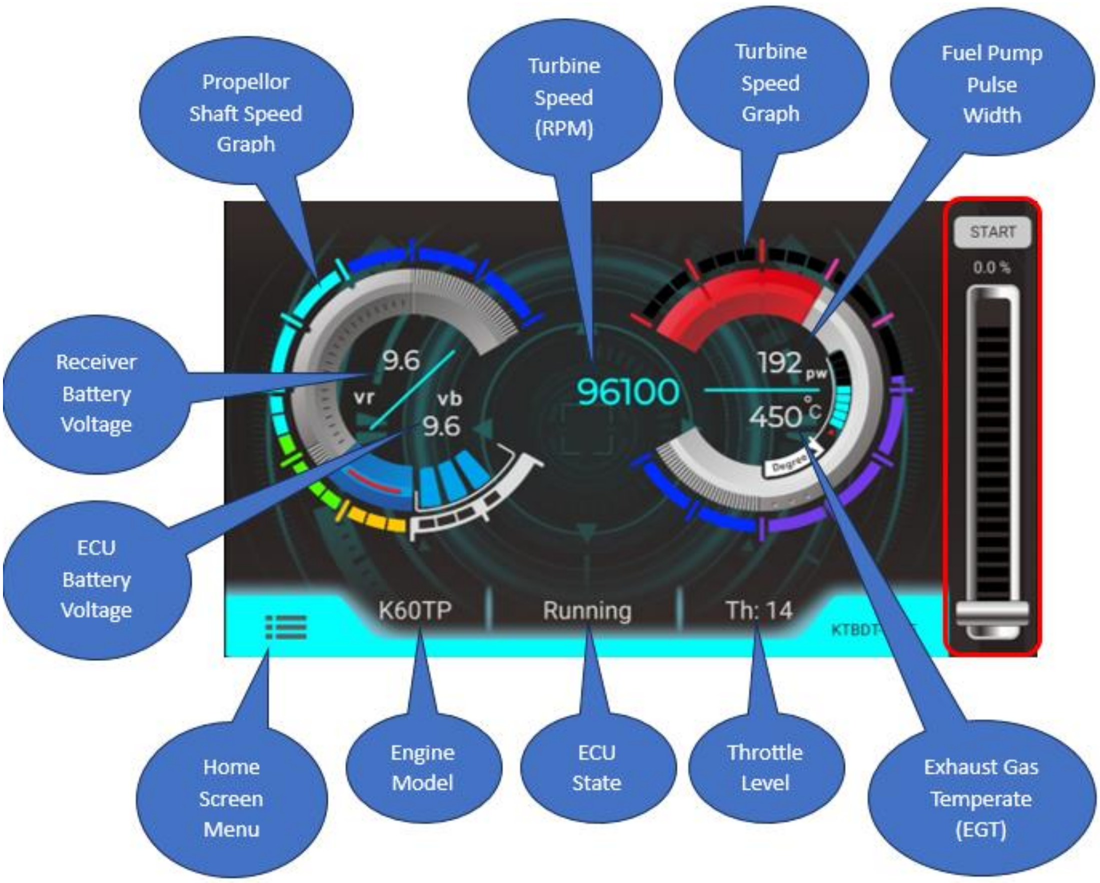


Figure 1 - Dashboard Display

Controller

Officially referred to as a 'Transmitter,' this controller serves as the interface for starting, controlling, and shutting down the engine from a safe distance. As its primary use is for operating fully functional model aircraft, there are a multitude of switches and settings which are not required for the operation of the K60TPG4 test bench. Although the other switches and buttons will not affect the engine, it is recommended not to alter their positions. The power button and throttle are the only components of the controller that should be required for test bench operation. A physical copy of the transmitter manual is available from Dr. Khalid Saleh upon request, or you can view it online under the 'Manuals & Support' section at https://www.spektrumrc.com/product/dx6e-6-channel-dsmx-transmitter-only/SPMR6655.html#.

Figure 2 - Controller for Engine Operation

- To turn Controller on, press the power button.
- To turn Controller off, press and hold power button for 4 seconds.

Pre-Start Checks

Battery Status	Ensure ECU and Receiver batteries are fully charged before commencing any engine runs.
Fuel Mixing	Ensure 5% of KingTech Turbine Oil is added and sufficiently mixed to the Fuel Source.
Full Tanks	Fill relevant fuel tanks (4L Capacity), insert line from fuel pump into source tank.
Direct Exhaust Ports	Ensure air extraction ducts are placed over turbine exhaust tips. Do not allow the ducts to rest on the turbine exhaust tips.
Battery Connection	Connect batteries to DRM and Receiver (ECU Battery has appropriate connections to provide power to both if required). Ensure GSU screen turns on.
Controller	Ensure Throttle Control is at the 'Stop' Position (full down). Turn on Controller.
Communication Check	Ensure Controller is talking to ECU by moving Throttle slightly up. GSU and/or Dashboard should change from 'Trim Low' to 'Ready' status. Move back to Stop and 'Trim Low' should display again.
Bluetooth Dashboard	Open KingTech 'BDT GSU' app and open the dashboard. Conduct previous 'Communication Check' on this display. Place Bluetooth Device in the Engine Room where it can be viewed from control room. (Can also be brought into control room if Bluetooth signal remains connected, another Communication Check will be required to confirm this.)
FOD Check	Ensure the Test Bench is clear of anything that may cause Foreign Object Debris (FOD) damage to the engine or turbo prop assembly.
Fuel SOV	Open Fuel Shut Off Valve (SOV) to ensure fuel delivery to engine. Prime if required (See Priming Instructions on Page 10)
Extraction System	Turn on the Air Extraction system via the 'Fresh Air Fans VSD Control Panel,' located in the control room. Turn 'Big Room' and 'Fume Exhaust' to the ON position.

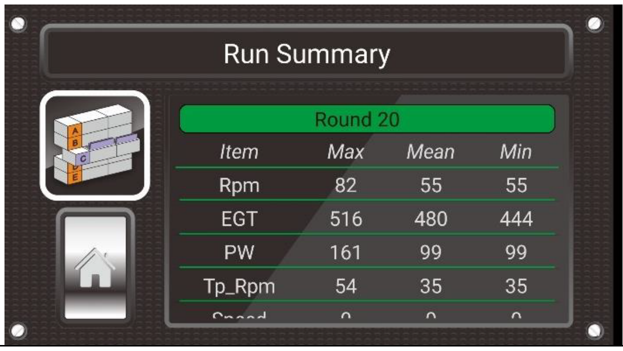
Turbine Start

Position	Ensure operator is stationed in the control room, with a clear view of both the turbine and the dashboard.
Start	Start the engine by moving the throttle beyond the halfway mark and then back to Idle. Do not bring all the way back to Stop as this will break the intended start sequence.
Monitor	The turbine will start to rotate, ensure the GSU and or Dashboard status displays ‘Prime Vap’, this indicates a successful start sequence initiation.
Timer	Start a timer once the ECU status reads ‘Start On.’
Ignition	This is where the ignitor will 'fire' to start combustion. There are three stages of Ignition, starting at Stage 1. If you are using a heavy percentage alternative fuel, ignition may take longer and even fail. If a failure occurs (The ECU has preset parameters to determine a failure and will read ‘Time Out’ if these are reached) the ECU will automatically stop the start sequence. You may need to prime the lines and try to start with Pure Diesel (with 5% Turbine Oil) to flush out the engine. See page 10 for priming instructions.
Warm Up	Ensure throttle level is at IDLE. Allow the engine to run at IDLE for at least 10 seconds before applying further throttle settings.
Conduct Testing	Conduct testing as required. **Note:** If there is no load on the Turboprop connection, do not run over 120k RPM at any time or 100k RPM for prolonged periods of time.

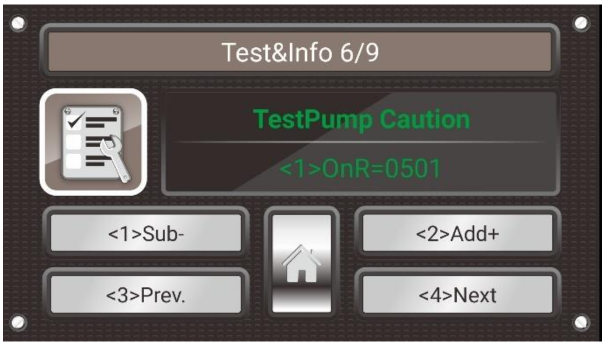
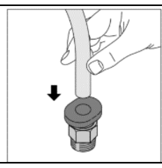
Turbine Shutdown

Cool Down	Return the throttle level to IDLE for 20 Seconds before shutting down turbine.
Shut Down	Move the throttle fully down to shut down the engine.
Timer	Stop timer and record run time
Extraction System	Turn off the Air Extraction system. Return the ‘Big Room’ and ‘Fume Exhaust’ switches to the OFF position.
Hot Surfaces	**Immediately after testing, the engine, exhaust tips, and extraction ducts will be hot. Exercise extra caution around these components to prevent injury.**
Cooling Cycle	The ECU will automatically cycle the starter motor until the EGT is below 100°C. Do not disconnect any batteries until the cooling cycle is complete.
Reset ECU	Once the Engine is shut down, the start sequence will not be operable again until the ECU is reset (Turbine Status will be stuck on ‘Stop’). This is achieved by disconnecting the ECU battery for a few seconds, then reconnecting. **Note:** ‘Heat Soak’ may have caused the turbine internal temperature to rise back above 100°C post initial cooling cycle, on reconnecting the battery the ECU may cycle the starter motor again to bring the temperature back down.
Data Collection	See Data Collection on Page 9.
Clean out Runs	**If alternative fuel mixes have been used throughout the day, ensure a final 'clean out' run is carried out with a pure diesel blend (with 5% Turbine Oil).** This will ensure any possible residue from the alternative fuel mix is cleaned out and allow continued internal engine serviceability. A duration of 30 seconds at a minimum of Throttle Level 5 shall be sufficient for this purpose.
Fuel SOV	Turn to OFF as per picture. 
Documentation	Fill out the UniSQ K60TPG4 Test Bench Operational Run Record (Page 13) to track Turbine usage
Batteries	Remove and charge as required.

Data Collection

Turbine Status	Ensure Turbine Status is in 'Trim Low', this is the only state that will allow data download. (ECU Battery will need to be disconnected and re connected to change status from ‘Stop’ to ‘Trim Low.’
Turbine Log	Select 'Turbine Log' on the *KingTech BDT GSU* App, or 'Log Turbine' on GSU.
Select	Select which 'Round' you want to view; the most recent run will be Round 1.
Download	Turbine Log will now download, this may take up to 30 seconds
View	Once loaded you will be able to view Log, it should appear as below. 
Save	Tap the save button to save file, ensure you give a proper naming convention to easily identify the run at a later date. NOTE: You will be able to view the logs later via the 'Read Log' option.
Run Summary	You may also view the Run Summary by selecting 'Run Summary' on the KingTech BDT GSU App, or 'Summary' on the GSU. The highest ‘Round’ number is the most recent Run Summary. 

Priming

PPE	Wear safety glasses and gloves to prevent direct exposure to fuel
Leakage Preparation	Place suitable absorbent material under the fuel lines as leakage may occur when fuel lines are disconnected
Fuel Container	Have a suitable container ready to catch the fuel during the prime procedure
Disconnect Lines	To disconnect the fuel lines, you must push the release ring to release the lock claws. 
	Gently remove the fuel line on Engine side from Fuel SOV, fuel should gravity feed from this line. Line may have to be removed from engine side also to ensure all fuel is released.
	Remove fuel line from fuel pump side of Fuel SOV.
Function Selection	Select Info/Tests and scroll through to section 6/9 'TestPump Caution', ensuring you have the fuel feed line in the Diesel Fuel Tank. 
Fuel Capture	Ensure open end of fuel line is placed over a suitable container
Start Pump	Select <1> on the test page. The fuel pump will now run, and diesel will replace any fuel that was previously in the lines.
Stop Pump	Select <2> to stop the Pump
Reconnect Lines	Reconnect fuel lines to both sides of the Fuel SOV. Push the tube into the fitting until resistance is felt, give a small tug to ensure it is properly fitted and locked into place. 
Prime Lines	Re-run the 'TestPump Caution' to prime the line from the Fuel SOV to the engine. This will take a matter of seconds, do not allow fuel to run into engine. This will 'flood' the engine, impeding the ability to start.

Troubleshooting

ECU status and diagnostic message codes are detailed on pages 55-56 of the official *KingTech Turbine Engine Manual*. The troubleshooting table below addresses issues encountered during the initial test bench setup that were not adequately covered in the manual.

ECU State	Description	Possible Cause	Options
CHK TPR	The ECU is not receiving an RPM reading from the propellor shaft, will not allow throttle setting to go past IDLE.	Propellor Shaft is seized/not rotating	Turn off turbine, manually rotate propellor shaft anti clockwise until minimal resistance is felt. If alternate fuel was used the priming procedure may be required to replace fuel in the Propellor Gearbox.
		Wire connection loose or incorrectly installed to DTU	Turn off turbine. Check wire integrity and connection at DTU.
OverVolt	The ECU has detected a high voltage and has prevented the start sequence from occurring to protect the glow plug.	ECU Battery is close to 12 Volts or above.	Disconnect the receiver battery and connect the ECU battery in its place. The ECU battery will now be the sole source of power, enabling a voltage drop. Re-attempt start sequence (Figure 3).

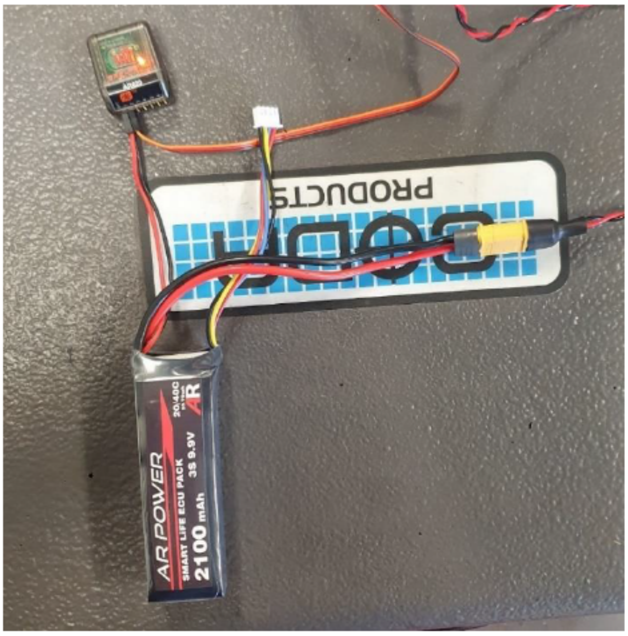


Figure 3 - ECU Battery Providing Both Receiver and ECU

K60TPG4 Test Bench Operational Run Record

See page 31 of the *KingTech Turbine Engine Manual* for instruction of how to view the Turbine Total Run Time. Ensure this operational run record matches that value recorded on the ECU.

Date	Operator	Fuel Type	Run Time	Total Run Time	Comments

Appendix B - Experiment Results Tables

Hydrocarbons Test 1				Hydrocarbons Test 2				Hydrocarbons Average			
	Idle	Mid Power	High Power		Idle	Mid Power	High Power		Idle	Mid Power	High Power
Diesel	7	11	17	Diesel	8	12	15	Diesel	7.5	11.5	16
B25	6	10	13	B25	6	10	14	B25	6	10	13.5
B100	6	7	8	B100	7	6	7	B100	6.5	6.5	7.5

Table 4 - Hydrocarbon Emissions Results Tables

Carbon Dioxide (CO2) Test 1				Carbon Dioxide (CO2) Test 2				Carbon Dioxide (CO2) Average			
	Idle	Mid Power	High Power		Idle	Mid Power	High Power		Idle	Mid Power	High Power
Diesel	0.2	0.3	0.5	Diesel	0.3	0.4	0.5	Diesel	0.25	0.35	0.5
B25	0.3	0.4	0.5	B25	0.2	0.4	0.5	B25	0.25	0.4	0.5
B100	0.3	0.4	0.5	B100	0.2	0.4	0.4	B100	0.25	0.4	0.45

Table 5 - Carbon Dioxide Emissions Results Tables

Nitrogen Oxide (NOx) Test 1				Nitrogen Oxide (NOx) Test 2				Nitrogen Oxide (NOx) Average			
	Idle	Mid Power	High Power		Idle	Mid Power	High Power	NOx	Idle	Mid Power	High Power
Diesel	1	1	1	Diesel	0	0	0	Diesel	0.5	0.5	0.5
B25	0	1	1	B25	0	1	2	B25	0	1	1.5
B100	1	1	0	B100	1	0	0	B100	1	0.5	0

Table 6 – Nitrogen Oxide Emissions Results Tables

Carbon Monoxide (CO) Test 1				Carbon Monoxide (CO) Test 2				Carbon Monoxide (CO) Average			
	Idle	Mid Power	High Power		Idle	Mid Power	High Power		Idle	Mid Power	High Power
Diesel	0.01	0.01	0.01	Diesel	0	0.02	0.01	Diesel	0.01	0.015	0.01
B25	0.01	0.01	0.01	B25	0	0.01	0.01	B25	0.01	0.01	0.01
B100	0.02	0.02	0.02	B100	0	0.01	0.01	B100	0.02	0.015	0.015

Table 7 - Carbon Monoxide Emissions Results Tables

Oxygen (O^2) Test 1				Oxygen (O^2) Test 1				Oxygen (O^2) Average			
	Idle	Mid Power	High Power		Idle	Mid Power	High Power		Idle	Mid Power	High Power
Diesel	20.8	20.7	20.7	Diesel	21	20.3	20.3	Diesel	20.65	20.5	20.5
B25	20.4	20.3	20.3	B25	21	20.3	20.4	B25	20.5	20.3	20.35
B100	20.4	20.4	20.3	B100	20	20.4	20.4	B100	20.4	20.4	20.35

Table 8 - Oxygen Emissions Results Tables

Idle Power Setting			
	Diesel	B25	B100
EGT	480	484	488
RPM	55	55	56
Throttle	46	46	46
Pump	96	96	100
TpRPM	3.5	3.5	3.5

Table 9 - Idle Power Setting Engine Parameters

Mid Power Setting			
	Diesel	B25	B100
EGT	460	460	460
RPM	77	78	82
Throttle	48	48	48
Pump	140	144	156
TpRPM	5	5.1	5.4

Table 10 - Mid Power Settings Engine Parameters

High Power Setting			
	Diesel	B25	B100
EGT	448	456	460
RPM	102	102	102
Throttle	56	56	56
Pump	204	208	212
TpRPM	6.9	6.9	6.9

Table 11 - High Power Settings Engine Parameters

Appendix C - ECOTECH B100 Certificate of Analysis

SpecCheck Laboratories

SPECCHECK LABORATORIES P/L
P.O.Box 835 Mittagong NSW 2575
Unit 4, 13 Lyell St
Mittagong NSW 2575
Phone/Fax: 4872 4590
Email: lab@speccheklabs.com.au

REPORT NUMBER: 24E43853
CUSTOMER NAME: ECOTECH BIODIESEL
CUSTOMER CODE: EB01

DATE: 12-Jun-24
CONTACT: [redacted]
ADDRESS:

Ph: 07 3204 0467   Fax: 07 3204 0497   Email:

CERTIFICATE OF ANALYSIS

SAMPLE ID: Biodiesel - B100 Batch 309 Tank 3
DATE SAMPLED: 07-Jun-24
DATE RECEIVED: 10-Jun-24

Sample matrix: Biodiesel
Tests commenced 10/06/2024
Tests completed 12/06/2024

TEST	RESULT	UNITS	METHOD	SPECIFICATION
Total contamination	13.8	mg/kg	EN12662	24 max
Free glycerol	0.006	% m/m	ASTM D6584	0.020 max
Total glycerol	0.102	% m/m	ASTM D6584	0.250 max
Monoglycerides	0.30	% m/m	ASTM D6584	0.40 max
Diglycerides	0.08	% m/m	ASTM D6584	0.20 max
Triglycerides	0.06	% m/m	ASTM D6584	0.20 max
Methanol content	0.05	% m/m	EN14110	0.20 max
Sulphated ash	<0.01	% m/m	ASTM D874	0.020 max
Ester content	96.9	% m/m	EN14103	96.5 min
Viscosity @40C	4.764	mm^2/s	ASTM D445	3.5 – 5.0
Filter blocking tendency (B100)	1.07	-	ASTM D2068	2 max
Cold soak filterability	104	sec	ASTM D7501	360 max
Density	0.8870	kg/l	ASTM D1298	0.860 - 0.900
Oxidation stability	>10	h	EN14112	8 min
Cold filter plugging point	-8	°C	ASTM D6371	-
Distillation temp @90% rec	357	°C	ASTM D1160	360 max
Appearance	Clear/bright	-	Visual	Clear/bright
Flash point	158.0	°C	ASTM D93	120.0 min
Total acid number	0.05	mg/KOH/g	ASTM D664	0.50 max
Moisture content	182	ppm	ASTM D6304	500 max
Carbon residue (10% res)	0.07	% m/m	ASTM D4530	0.30 max
Copper corrosion	1a	-	ASTM D130	1 max
Cloud point	-5	°C	ASTM D2500	-
Metals - Group I Na+K	<1	mg/kg	EN 14538	5 max
Metals - Group II Ca+Mg	<1	mg/kg	EN 14538	5 max
Phosphorus	<4	mg/kg	EN 14107	4 max
Sulphur	4	mg/kg	ASTM D5453	10 max
Derived cetane number	51.9	-	ASTM D6890	51.0 min

[redacted]

Signed: S.Brennan - Chief Chemist

Appendix D – Risk Assessment

NUMBER	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
5522	Research Activities Involving KingTech K60TPG4 test stand in Building P7		Low	Low

DOCUMENTS REFERENCED
KingTech Turbine Engine Manual Diesel Fuel SDS Bio Diesel Fuel SDS

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
David Coco	03/05/2024	27/08/2024	27/08/2025

RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER	DUE
Risk: Exposure to high noise levels Source: generated by K60TPG4 engine during operation. Potential Effects: Hearing loss, tinnitus, stress, fatigue, communication difficulties, reduced concentration, and overall reduced quality of life.	**Control:** The engine can be started, operated and shut down from the control room ,which provides a suitable Noise barrier . **Control:** Ear protection to be made available to members within the vicinity of the running engine	**Control:** Place Sign stating no Entry to Workshop when engine is in operation		16/08/2024
Risk: Moving Parts Source: Propeller Shaft Potential Effects: Risk of injury from contact or entanglement	**Control:** The engine can be started, operated and shut down from the control room ,which provides a physical barrier to rotating propeller shaft.	**Control:** Place Sign stating no Entry to Workshop when engine is in operation		16/08/2024

Risk: Hot Surfaces Source: Turbine and Extraction Ducts post engine Operation Potential Effects: Injury from contact with Hot Surfaces	**Control:** Engine is shutdown from control room, providing a physical barrier between operator and warm turbine and components **Control:** Warning placed in operation manual to be cautious of possible warm engine and extraction ducts	
Risk: Fire Source: Hard Turbine Failure resulting in Fire Potential Effects: Equipment and/or Building Damage	**Control:** Have a CO_2 fire extinguisher in close proximity to the room	
Risk: Exhaust Fumes Source: Turbine Exhaust Potential: Inhalation, causing headaches and nausea	**Control:** No personnel in the same room as the turbine when it is operating. **Control:** Room Exhaust: Air is extracted from the inside environment and exhausted into the outside environment **Control:** Direct Exhaust: Ducts are placed over Exhaust Tips and air is extracted to the outside environment. **Control:** Air Quality Warning System: Carbon Monoxide Detector is placed in the workshop, provides audible warning if high levels of Carbon Monoxide detected.	

	Control: Instructions in the operation manual state the engine cannot be operated unless the Direct and Room air extraction system is turned on.	
Risk: Fuel Handling Source: Fuel Source for Turbine Potential: Skin Irritation, respiratory issues, fire/explosion hazard.	**Control:** Fuel is to be mixed in the authorised mixing room within building P7. Access to this room and the fuel lockers is restricted to approve University Staff. **Control:** Fuel Sources for immediate turbine source are stored in sealed storage containers attached to the test bench **Control:** Nitrile gloves and Eye protection to be worn whenever fuel is mixed or poured into fuel containers attached to test bench. Wear a mask if required.	