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Design of an Experimental Turbo Shaft Gas Turbine

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Abstract - *This project aimed to design, manufacture, and evaluate for performance an experimental assembly of a turbo shaft gas turbine engine, capable of demonstrating the physical effect of novel technologies to the combustion process (such as the injection of water into the combustion zone) on a variety of overall performance parameters. In particular, the project considered the reduction of the production of greenhouse gasses such as oxides of nitrogen, with a negligible effect on system performance.*

The drive to conduct this design exercise was to create a facility that could be used to aid the development of combustion control technologies that reduce the release of emissions from gas turbines, which are known to be harmful to human and environmental health on a global scale. The technology developed was designed to be suitable to give a physical representation of a variety of gas turbine technologies at a laboratory scale. The main challenges of workshop manufacturability and financial limits have been adhered to with the successful manufacture of a design that is considered valid – to the extent of investigations that have taken place to date.

The design of the experimental turbo shaft gas turbine engine that has been presented in this project is capable of functioning as prescribed and is suitable for its intended use; with all design evaluation methods generating coherent data, which has been validated by comparison or review against the theories explored during the initial research process.

1. Introduction

It is argued that the increased presence of greenhouse gases such as carbon dioxide (CO2), oxides of nitrogen (NOx) and chlorofluorocarbons (CFCs), all of which have been produced at an increased rate as a result of human activity, are contributing towards the phenomenon known as Climate Change. This process, as a result of changes in the planet's obliquity, constantly alters the climate of Earth, with the pattern being described as a Milankovitch cycle (Hyun, 2005). Despite the fact that this progression happens regardless of advancements in civilization, there is strong evidence to suggest that the combustion of fossil fuels has been the biggest contributing factor to the rate at which climate change is occurring, as shown in Figure 1.

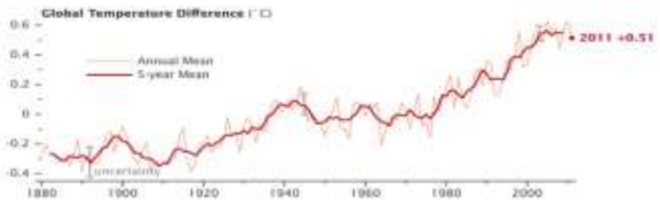

Fig. 1 Rise in global temperature over time [NASA, 2012]

As a part of the EU 2020 targets to reduce the rate of Climate Change, reduction of emissions was agreed upon. An example of this ten-year plan, specific to emissions from aviation turbojet engines, focused on reducing NOx emissions by 80% and cutting the emission of CO2 and perceived noise in half by 2020. It was indicated by the Project Supervisor that improving the design of the gas turbine combustor was an area of development that had the potential to help meet these targets.

This project focuses on gas turbine technology, with gas turbines being one of the most commonly used techniques for the generation of electrical power. Figure 2 shows a simplified gas turbine layout. Gas turbines work by passing air and fuel through a combustion chamber, where the combustion process produces extremely hot compressed gases, which then generates power via the spinning of an internal turbine [Wartsila, 2016] - this is known as the Brayton cycle. Gas turbines produce several different types of harmful emissions, namely CO2, CO, NOx and unburned Hydrocarbons. As mentioned above, gas turbines are abundant in the field of electrical power generation, with a variety of alternative applications in the energy and avionics industries. As a result of being used on such a large scale, it is essential that methods by which to reduce the amount of greenhouse gases produced during their operation are explored. This theme has formed the basis of this project.

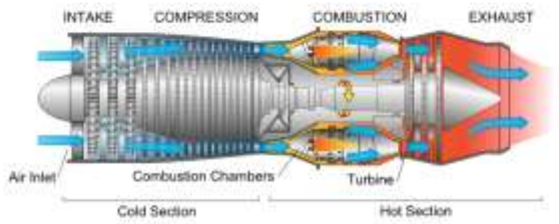

Fig. 2 Gas turbine layout [Minnesota State University]

2. Project Aim

There exists to this day numerous technologies to reduce or minimise the amount of greenhouse gas emissions from such turbines, many of which, however, are still experimental. Whilst computational fluid dynamic approaches are commonly used to investigate and further develop these technologies, the existence of a physical apparatus to validate the computational results and expand the scope of the investigation is uncommon.

This project aims to: design, manufacture, and evaluate for performance an experimental assembly of a turbo shaft gas turbine engine capable of demonstrating the physical effect of novel technologies particular to the combustion processes (such as the injection of water into the combustion zone) on a variety of overall performance parameters, with a focus on considering the effect of these technologies on the reduction of the production of greenhouse gasses such as oxides of nitrogen, whilst having a negligible effect on system performance.

After scrutinising the various technologies available, the design and manufacture of a testing-rig that models the combustion chamber of a gas turbine was conducted.

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3 Design

While a gas turbine usually comprises of a few principal components (i.e. compressor, combustion chamber and turbine), the design described here focuses solely on the combustion chamber. However, from a practical point of view, for the engine to function it must feature a compressor and turbine component. The main challenges faced in this project, which essentially constitutes the main engineering problems are:

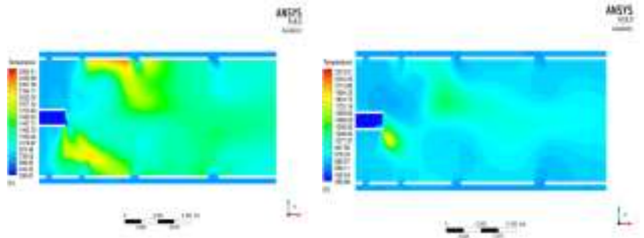

Fig. 3 Temperature distribution illustrating flame position with the minimum and maximum air fuel ratios

Achieve simple manufacturability that falls within the capacity and availability range of the facilities of the Faculty of Engineering. The design of a gas turbine combustion chamber at relatively low cost while permitting as reliable as possible mimicking of state-of-the-art gas turbines and while taking the appropriate measures in ensuring that the engine is safe to operate. Additionally, the design of a modular (to some extent) engine was a challenge, which was met for the purpose of allowing the engine to be used for the testing of a wider range of technologies revolving around the reduction of pollutants such as greenhouse gases.

A cost-effective way of replacing the compressor and turbine components typically used in gas turbines was found by using a turbocharger instead. A turbocharger (or turbo) is a device usually used in cars, and essentially comprises of two sections: a compressor and a turbine, coupled with a shaft that transfers kinetic energy from the turbine to the compressor. When used in cars, the compressor compresses the air entering the engine's cylinders before combustion. After combustion, the exhaust gases enter the turbine and expand generating kinetic energy. This kinetic energy is transferred through the connecting shaft that drives the compressor, which in turn compresses more air. The cycle repeats, as schematically depicted in Figure 4. Because of its low cost, availability and suitability for compressing air and expanding high-temperature exhaust gases, a turbocharger is an ideal replacement for the compressor and turbine in a small-scale gas turbine engine.

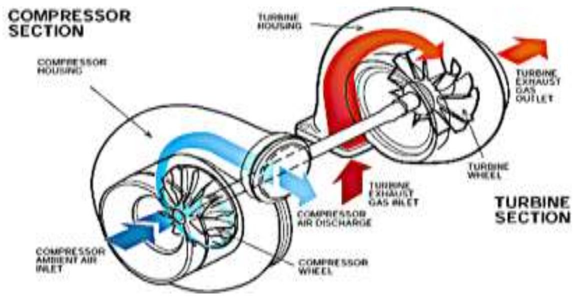

Fig. 4 Diagram of turbocharger mechanism of operation [Bright Hub Engineering, 2017]

As in the present case, ease of manufacturability is a main objective and so a single can-type combustor constitutes the best configuration to adopt. This is because it will be easier to source the parts and run computational and experimental analyses for a single can. Additionally, a single-can type combustor will have less interfacing issues than an annular or cannular type, making it easier to manufacture an experimental rig and mount measurement devices on it.

The design process was divided into two parts:

1. The preliminary design phase was aimed at gaining a comprehensive understanding of the design procedure behind each component of the combustor and the role played by each in the combustion process.
2. The final design phase built upon the preliminary phase and attempted to scale-down, simplify, but also elaborate and refine the final design while achieving a more easily manufacturable, testable and operable test-rig.

Below is a summary of the design decisions that were made at the beginning of the project, which formed the basis of the preliminary and primary design processes:

- A turbocharger will be used to replicate the processes provided by turboshaft gas turbine's compressor and exhaust facilities.

- The combustion chamber will be manufactured in the faculty workshop, permitting a greater amount freedom during the design.

- The engine will be fuelled by propane, as propane has one of the highest calorific values of any of the commercially available gaseous fuels (Natural Gas: 43,000 kJ/kg, Methane: 39,820 kJ/kg, Propane: 101,000 kJ/kg) (Engineering Toolbox, 2017). A higher calorific value for the fuel will allow the combustion chamber to remain compact, thus resulting in less thermal losses that are likely to occur due to the scale of the engine. A gaseous fuel will reduce the amount of auxiliary equipment required as it will be supplied in a pressurised canister.

4. Results

The temperature contours below in Figure 3 show the simulations run for minimum and maximum air-fuel ratios. This was done to validate our design over a range of operating conditions. The temperature contour with minimum air-fuel ratio of 80 (left) shows that the flame is still contained within the primary zone. The flame has not moved further down and hence there is no risk of damage to the turbine, allowing it to operate without failure. The temperature contour with maximum air-fuel ratio of 320 (right) shows that the flame has not blown out at low fuel flow rate.

5. Water Injection Analysis

To validate the MATLAB® results, combustion simulations were carried out with increased water content of the air. The amount of water was increased in increments of 20% of the fuel mass flow-rate. The table below shows the configuration parameters and the results.

Water Mass%	Air Flow Rate (kg/s)	Fuel Mass Flow Rate (kg/s)	Peak Temperature (K)
0	0.2	0.00125	2085.54
20	0.2	0.00125	2080.93
40	0.2	0.00125	2077.07

Table. 1 Results from CFD investigation into the reduction of peak temperature using the water injection method

The effect of water injection can be seen in the temperature contours, and the decrease in peak flame temperature and average temperature indicates a reduction in NOX emissions. This is further verified by the results from the NOX model, which show an overall reduction in NOX mass fraction, as seen in Figure 5. The peak temperature has reduced from 2085.54K to 2077.07K over a water-fuel ratio range of 0% to 40%. The theory that a reduction in peak temperature reduces the formation of NOx in the combustion chamber was also validated, and this effect can be observed clearly in Figure 5.

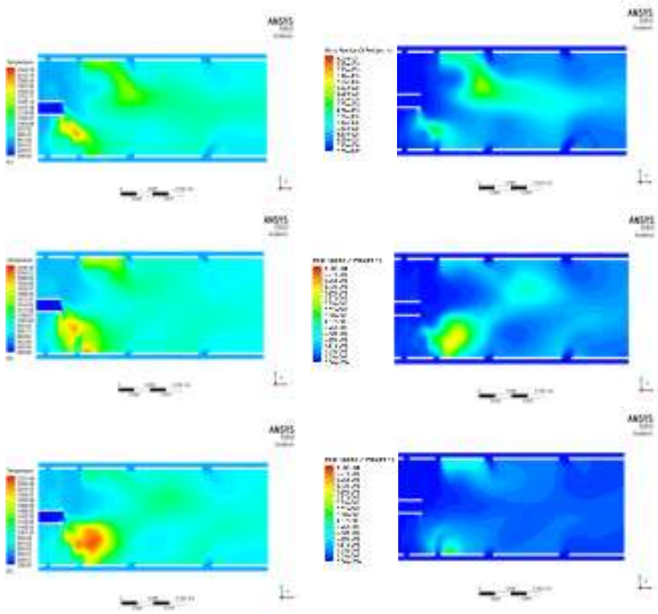

Fig. 5 Temperature (left) and NOx (right) distribution patterns that can be observed in the combustion chamber with increasing water/fuel ratios (0%, 20%, and 40% moving downwards)

6. Conclusion

The design of the experimental turbo shaft gas turbine engine that has been presented is capable of both functioning as prescribed and is suitable for its intended use. Although physical testing has not been undertaken at this stage, the two computational models of the gas turbine agree with ideas expressed in the literature, leading to the evaluation that the design is valid up to the current stage of investigation. A physical investigation into the functionality of the gas combustion turbine has been prescribed, allowing execution of such a test to take place – thus further evaluating the design.

The method used to design the combustion chamber has proved successful. A thorough investigation into the thermodynamic processes and functions of components within a 'state-of-the-art' gas turbine allowed the simplification for manufacturability of the design to incorporate all the desired characteristics. The use of computational fluid dynamics using ANSYS ®allowed an accurate iterative process to ensure that certain design criteria (such as swirl and airflow distribution) were met.

The project is currently running to schedule, with physical testing remaining the only outstanding task of the project. Efforts to design a turboshaft gas turbine that can be manufactured within the faculty workshop, and permit modifications to the combustion chamber, have been fulfilled, with the completion of the manufacturing occurring on May 25th, 2017. The design is presented with a valid MATLAB® script to allow the prediction of experimental results using the design under specific circumstances, and a method of verifying any results obtained by making simple modifications to align the operating parameters of the engine with the program.

Accompanying the design, is an example testing procedure, a breakdown of the equipment that has been deemed suitable for use with the rig, a risk assessment, and expected results for design verification purposes.

The facility presented is a complete 'package' and the project has been completed significantly under budget with the money remaining available to undertake a certain level of design modification if necessary.

Future work for this project immediately involves the physical testing of the experimental rig for evaluative purposes. Further to this, the rig will hopefully be deemed as suitable for the exploration of novel technologies for the reduction of the formation of oxides of nitrogen within the combustion chamber (such as the injection of water into the combustion zone). This will hopefully thus create a facility for future investigations into the reduction of pollutants being formed in the combustion chambers of gas turbines, working towards reducing the environmental impacts of such technologies.

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