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GAS TURBINE ENGINE: A SENIOR DESIGN PROJECT

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Abstract

This paper describes a senior design project conducted by two senior mechanical engineering students at the Virginia Military Institute. Completion of a capstone design project is a requirement for VMI's bachelor's degree in mechanical engineering. The objective, of this project was to design and build a radial flow gas turbine engine, that will be incorporated as part of an undergraduate energy laboratory program. A commercially available turbocharger was used for the compressor and turbine portions of the engine. As part of the design analysis the students developed the system of equations necessary to simulate the engine and used them in a computer model to predict the design and off-design performance of the engine. The results of these computer simulations were used to size and design the various engine systems and components. The engine systems and components designed by the students included a combustion chamber, fuel system, ignition system, lubrication system, starting system, instrumentation, and test stand. The combustion chamber was designed based on required air and fuel flow rates predicted by the engine simulation. The combustion chamber was fabricated from stainless steel using inert gas welding techniques. Instrumentation included gas temperature and pressure measurements, engine speed, and thrust measurements. The lubrication system was sized and fabricated from commercially available components, as were the fuel and ignition systems. The paper describes the sizing, fabrication, and operation of the completed engine.

Introduction

The objective of this design project was to design and assemble a fully functional gas turbine engine and to monitor the effect of a varying fuel flow rate on output and various operating variables. The gas turbine engine resembled a thermodynamic Brayton cycle[1] and consisted of a compressor and turbine connected by a common shaft and separated by a combustion chamber. In the combustion process, fuel was injected into the hot pressurized air stream from the compressor, burned in the combustion chamber at nearly constant pressure, and then expanded through a turbine to produce the work necessary to drive the compressor. The remaining energy of the gas stream was expanded through a nozzle to develop engine thrust. A turbocharger was used as the compressor and turbine for the engine.

A computer program was used to simulate the cycle. The results of the simulation were used to size the various engine components and to predict the output at a given fuel flow rate. In order to complete this project oil lubricating and cooling, ignition, and fuel injection systems had to be designed and fabricated along with a combustion chamber. The combustion chamber design required that the flame be stabilized inside the chamber to ensure a continuous combustion process. Instrumentation was also developed to measure oil system pressures and temperatures, combustion temperature, exhaust temperature, combustion chamber pressure, and turbine speed. An engine test stand was designed and assembled upon which the engine components and controls were mounted.

Computer Simulation

Prior to the design of any engine components the engine system was simulated using a Mathcad program. The engine simulation was developed by modeling the performance of each component in the engine using energy and mass balances with the performance characteristics provided for each component. The required equations, including the first and second laws of thermodynamics necessary to describe the various components and processes and the curve fits of the graphic component characteristics, and working fluid property data, were developed. The graphic data, representing components such as compressor ratio as a function of compressor speed and compressor flow rate, were curve fitted using multiple regression methods. The system simulation was accomplished by matching speeds, mass flow rates, pressure ratios, and work for each of the components in the engine, as described by Cohen[2]. The component models included a compressor model, a combustion chamber model, and a turbine model. The development of these models was described by Sexton[3]. The results of this simulation were used to determine required air and fuel flows. These flow rates were used as the basis for sizing and designing the various engine components.

Turbocharger

A Holset HX-35 turbocharger was used as the compressor and turbine for the engine. Complete compressor and turbine maps as well as other technical specifications for the turbocharger were available. The compressor-turbine combination was rated for 130,000 rpm and the turbocharger bearings require an oil flow rate of 2 L/min for cooling and lubrication. The casing for the compressor was aluminum, while the casing for the turbine was cast iron. The turbine blades were made of steel and the compressor blades were aluminum. The maximum pressure ratio for the compressor was 4, and the maximum pressure ratio for the turbine was 3. The compressor was capable of a larger mass flow than the turbine. Therefore, it was necessary to install a bleed valve after the compressor discharge as shown in Fig 1.

Combustion Chamber

The combustion chamber shown in Fig. 2 was designed with both an inside and an outside shell. The inside shell held the flame holder. The inside shell was drilled with 3/8” holes, 3” downstream of the injection nozzle to provide more flame stabilization and to ensure complete combustion within the combustion zone. Three sets of six, 1/2” dilution holes were drilled symmetrically around the circumference at the end of the inner shell to allow combustion chamber cooling air to mix with combustion products. The combustion chamber itself was oversized in length to ensure that the combustion process would not carry any flames into the turbine. The flame holding device came from an oil burner that contained a nozzle, pre-swirl

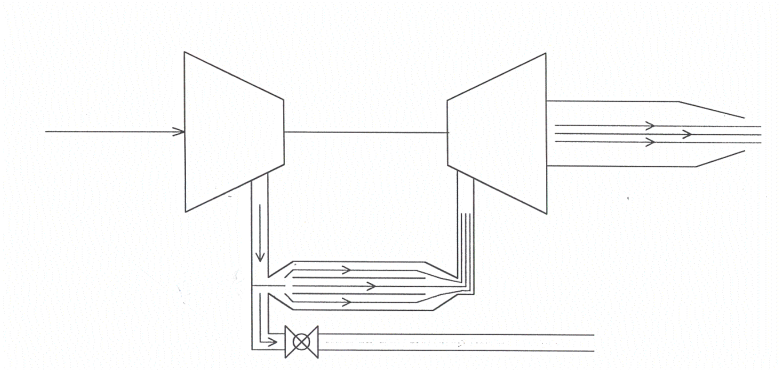

Fig. 1 Air Flow Diagram Showing Air Bleed Valve

guide vanes, and ignition electrodes. The purpose of the swirl vanes was to generate circumferential flow around the flame holder to ensure flame stability and to re-circulate burned and burning gases with the incoming air and fuel. The turbulent air aided in the complete combustion of the fuel because the air and fuel mixed more effectively. A diffuser was not used at the inlet to the combustion chamber because of the low-pressure ratio at which the turbine operated. A Plenum chamber was used at the inlet of the combustion chamber to slow airflow and to ensure a smooth transition from the compressor discharge duct into combustion chamber. This transition allowed equal velocities to exist in both the inner and outer shell of the combustion chamber. A convergent nozzle was used at the exit of the combustion chamber in order to reduce the flow area to the required flow area of the turbine inlet. As air entered the bottom of the combustion chamber from the compressor it was separated with a fraction of the air traveling through the outside shell of the combustion chamber to promote wall cooling. This air was mixed with the combustion products at the end of the inner shell. The cross-sectional area of the combustion chamber was designed to give an air velocity of 5 m/s in both shells. This velocity was the original velocity that the swirling vanes were designed for in the oil burner. The ratio of cross-sectional area of the inner liner to the outer liner was determined using the MathCAD simulation.

The combustion chamber was made from stainless steel in order to withstand the high temperatures that were generated by combustion. The sheet steel was fabricated into the 3.4" diameter inner shell using a slip-roll. The tube was then spot-welded using a Miller spot welder. Spacers were welded on the outside of this tube to fit tightly inside of the outer shell. The outer shell was also fabricated from the same stainless steel using the slip-roll to form a 5.5" diameter tube. This tube was TIG welded to ensure an effective seal. The convergent nozzle at the exit of the combustion chamber was fabricated from the same material and formed using methods similar to the outer shell. The plenum chamber was constructed from a 1/8" sheet of stainless steel. The stainless steel for the plenum chamber was cut using a plasma cutter and the dimensions were 4"x8"x8". The Plenum chamber was then arc welded using stainless steel rods. The bottom plate of the Plenum chamber was attached using twelve, 1/4" studs. Removal of this plate allowed access to the inner shell, swirling vanes, and nozzle. The completed combustion chamber was tested for leaks by pressurizing the chamber to 75 psi of air pressure.

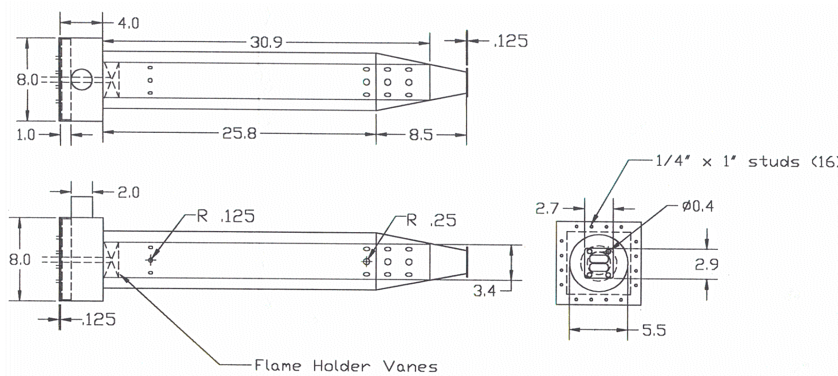

Fig. 2 Combustion Chamber

Fuel System

The fuel system consists of a standard propane tank connected to the flame holding nozzle with a throttling valve used for control. A 3/8" rubber fuel line was used to connect the fuel-throttling valve to the injection nozzle inside the combustion chamber. The original burner nozzle was designed to inject fuel through a single 1/8" hole in the direction of airflow. This design proved to be unsatisfactory as flames exited the combustion chamber and entered the turbine. This nozzle was replaced with one that had three holes symmetrically drilled in its walls to inject fuel perpendicular to the airflow. These holes were designed to initiate mixing of air and fuel earlier in the combustion chamber and to allow complete combustion before the hot gases entered the turbine. After testing, it was determined that the fuel regulator had to be removed from the propane tanks to increase the fuel flow rate needed for operation.

Electrical and Ignition System

The electrical system consisted of a single pole switch used to control the lubrication pump motor and an ignition switch wired in series with the lubrication pump switch to prohibit ignition prior to starting the lubrication system. The 10,000-Volt transformer used for ignition was obtained from an oil furnace ignition system. The coils on the transformer were connected to the electrodes on the flame holder using automotive spark plug lead wire. These leads passed through the plenum wall on the combustion chamber using fabricated Teflon connectors. A 3/4" spark was generated between the electrodes in front of the fuel nozzle.

Lubrication System

The purpose of the lubrication system, shown in Fig. 3, was to lubricate the turbocharger bearings and to aid in carrying away heat. The oil sump tank was constructed out of a 1/8" sheet of cold-rolled steel. The 12" square tank contained 12 quarts of 10W40 oil. The oil pump selected was the same as the type on the small block Chevrolet engine and was powered by a 2-hp electric motor. The oil pump shaft was connected to the motor shaft using a flexible coupling. From the pump the oil flowed through a pressure relief valve set at 60 psi. The oil flowed past pressure and temperature gauges mounted on top of the tank and through a flow control valve to the filter. The oil filter selected was a NAPA Gold 1607. The control panel oil pressure gauge was mounted to the filter housing. After flowing through the filter, the oil flowed

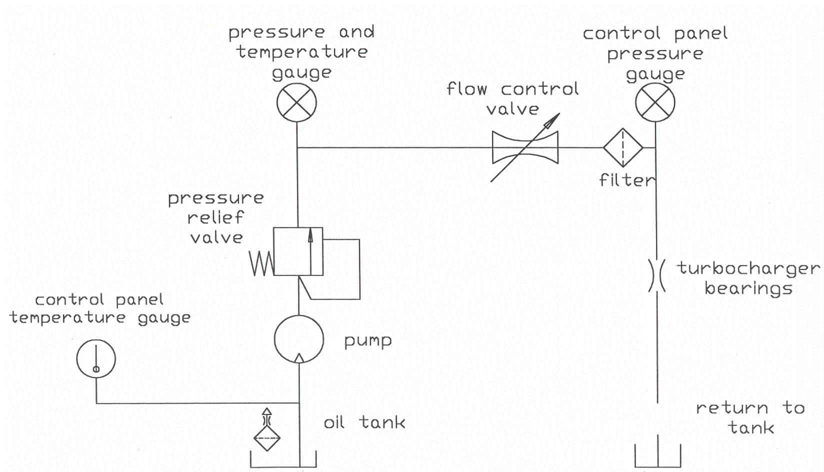

Fig. 3 Lubrication System

to the turbocharger bearings and then returned to the sump tank. The oil sump was equipped with a temperature gage mounted on the control panel. A dipstick was also installed in the oil sump to ensure that the oil level was always above the pump suction.

Starting System

Obtaining the start-up speed required for sustained operation posed a problem. Initially a 1/8" jet of compressed air was impinged directly onto the compressor blades to attain an ignition speed. Using a strobe-light tachometer, the compressed air spun the turbocharger up to about 4200-rpm. After failing to ignite the gas turbine at this speed, a standard leaf blower was attached to the air duct between the compressor and the combustion chamber to achieve ignition speed with this increased airflow. However, this ignition attempt also failed. Finally a 3/4" hose was bled off of a storage tank of an industrial air compressor and air was blown directly into the inlet of the compressor. This generated sufficient airflow to spin the compressor and provide adequate air for ignition. After ignition was achieved the engine came up to speed on its own.

Instrumentation

Instrumentation was required for the safe operation of the gas turbine engine and to confirm the predicted results from the Mathcad engine simulation. Oil temperature and pressure gauges were used to ensure proper lubrication and cooling of the turbocharger. These gauges were important to this design because a loss of oil pressure would cause the turbocharger bearings to seize resulting in catastrophic failure of the turbocharger rotor. A type K thermocouple was placed at the exit of the turbine to measure exhaust temperature. The exhaust temperature must be restricted to 1400 degrees Kelvin to ensure turbine blade and housing thermal stability. The combustion chamber pressure was monitored using a 30-psi Bourden gauge. This pressure was measured at the exit of the compressor. An optical tachometer was designed to measure the speed of the gas turbine. Some operational problems resulted due to electrical interference of the oil pump motor; alternate methods of measuring shaft speed are being investigated. The optical tachometer was designed to operate by shining an LED onto a disc attached to the turbocharger shaft. The disc was painted half flat black and the other half was polished aluminum. As the shaft turned the light from the LED was reflected from the polished half of the disc to a phototransistor. The output of the phototransistor produced a frequency that was measured using a frequency counter. The shaft speed was determined from this frequency.

For a complete comparison of actual operating data to the predicted results of the engine simulation additional instrumentation would need to be installed. This additional instrumentation would include: a turbine inlet thermocouple, a pitot-static tube to measure bleed air velocity, a pitot-static tube to measure duct air velocity at the inlet to the combustion chamber, a thermocouple to measure temperature at the compressor exit, and a flowmeter to measure the fuel flow rate.

Test Stand

A test stand, shown in Fig. 4, was design and assembled using 1" square, 15-guage, mild steel. The test stand has dimensions of 42"Hx32"Lx24"W. Adjustable legs were welded to the bottom corners of the stand to enable the stand to be leveled on most surfaces. The turbocharger was mounted on a ¾" shaft, and seated in to pillow block bearings bolted to the top of the test stand. A moment arm was welded to one end of the shaft, extending 24" vertically downward, and was connected to the test stand horizontally with a 3/8" all-thread shaft. Presently, this shaft holds the turbocharger in one position, however, at a later date this shaft could be removed and replaced by a load cell, which would enable the thrust of the engine to be measured. A control panel was bolted to the front of the test stand. This control panel contained oil pressure and temperature gauges, a combustion chamber pressure gauge, an oil pump switch, and an igniter switch for the transformer. The ignition transformer was mounted to the test stand underneath the control panel on the right side. The oil filter mount was directly below the transformer mount. The oil tank was mounted in the bottom corner of the test stand below the oil filter.

Starting and Running Procedure

The starting and running procedure of this engine had distinct steps that must be followed for safe ignition and operation. First, the fuel line must be hooked to a propane tank with the fuel throttling valve completely closed. Then the throttling valve on the lubrication system must be closed completely and the oil pump started to heat the oil. This preheating process was done to reduce the dynamic viscosity of the oil and to allow for higher startup speeds. Once the oil temperature reached approximately 140 degrees Fahrenheit on the tank mounted gauge; the oil valve was adjusted to maintain 35 psi of pressure at the turbocharger. This low pressure was used to reduce the drag on the bearings during starting. According to the turbocharger specifications this low pressure was safe for low load conditions. At this time, the ignition switch was turned to the on position and the high-pressure jet of air from the industrial compressor was blown directly into the compressor to spin the compressor up to self-sustaining speed. Next, the fuel valve was completely opened and ignition occurred in the combustion chamber. After the combustion process was self-sustaining the high-pressure jet of air was turned off and the turbine allowed to increase speed. Immediately after ignition the oil control valve was fully opened. Then the ignition switch was turned off and continuous combustion was

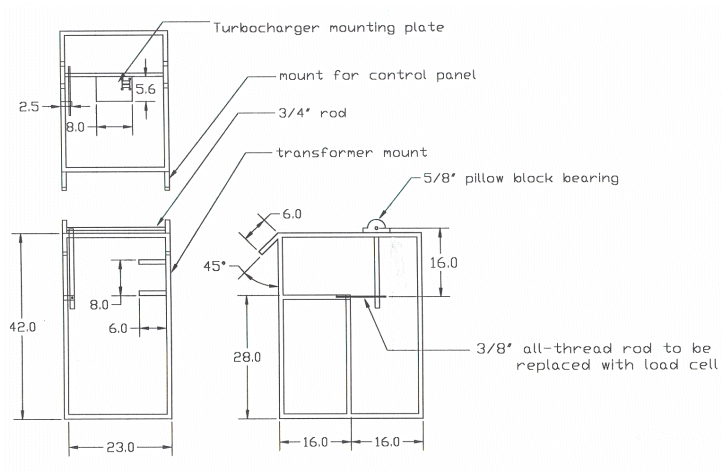

Fig. 4 Test Stand

maintained. During the testing of this engine, the ignition was turned off for only short periods because of safety reasons. To shut down the engine the fuel was turned off first with the ignition remaining on to ensure that all fuel in the combustion chamber was burned. After all the fuel was burned, the ignition was shut off. The oil pump was left running as the turbine coasted to a stop. The oil pressure was then adjusted to 20 psi and the oil flow allowed to continue providing cooling to the turbocharger. The oil pressure was reduced to ensure that oil was not forced past the bearing seals.

Summary

The design project described required relatively complex design, fabrication, research, testing, and simulation of a gas turbine engine. The completed engine will be used for demonstration and experimental purposes in future semesters. This project has laid the foundation for further work with either a free-power turbine to produce shaft power or a nozzle to produce thrust. An after-burner is also a possibility to enhance the thrust produced by the engine.

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