Design of a Novel Gas Turbine Generator for South African International Airports

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Abstract

South Africa (SA) is highly dependent on the state utility ESKOM for electric power supply. This includes big companies and tourism sectors in SA. For the very first time in history, SA has had the OR Tambo international airport (one of the busy airports in SA) switch off to darkness. This was due to the boiler failures at the power stations owned by the state utility ESKOM. These types of boilers are fired with the use of coal and they produce a reasonable amount of Carbon dioxide (CO_2) and soot to the atmosphere. This paper details the design of a gas turbine that can drive an electric generator to produce electricity for the OR Tambo international airport in Johannesburg, the King Shaka international airport in Durban and the Cape Town international airport.

Specifications of the design were made and are as follows: the gas engine aims to have a mass of 1 000kg or less, the work produced is specified to be more than 500 kW with an efficiency of 35 % or more. The mass of the engine after preliminary analysis is determined to be 1 180.965 kg (i.e. 18 % more than the specified mass), the work that can be produced by the engine is calculated to be 811.59 kW with an efficiency of 40.34 %. The material cost is analyzed to be R 107 787.77 or $ 7000.

Safety considerations, maintenance and repair of the designed gas turbine are also documented in this paper. The social, economic, heath, and environment impacts of the design are clearly stated. The gas turbine generator aims to use natural gas as fuel. Natural gas power generation has almost no emission of CO_2 and soot. The gas turbine design has the significant potential to decrease the expenditure on ESKOM electricity demand.

Keywords
Power, Gas Turbine Engine (GTE), Carbon dioxide (CO_2), Efficiency, Airport, Natural gas, Energy.

1. Introduction

Electricity is the most important part of the airport's operation; however, the sector is currently underperforming due to South Africa's main utility not meeting the demand arising from regular failures at power plants owned by the state utility ESKOM. Consumers have been paying higher prices for electricity as electricity has become more expensive over the past few years and continue to climb at an estimated increase of more than 8% for 2020 [1], approved by the National Energy Regulator (NERSA) of South Africa. Keeping the country stable is still not enough. For the first time in history South Africa's most important Airport (OR Tambo International Airport) has been plunged into darkness, posing the greatest threat to the country's gateway (international porter) security. Although electricity is a way of life, the current power generation also poses threats to the ozone layer, because ESKOM runs boilers which emits high levels of carbon dioxide (CO_2) causing global warming. Coal-fired boilers used in most power plants in South Africa produce a fair amount of emissions and heat. There is a need to find better alternatives to back up ESKOM, other technologies which can work in the airport environment. Renewable energy installations in some affluent countries have reduced the impact of airport operations on climate and led to significant cost savings.

It is estimated that the operational cost savings at 6 regional airports in South Africa because of the use of solar energy will be around R7.85 m/b [2]. However, the implementation of solar technology at the three (3) international airports in South Africa is hampered by many requirements such as space constraints. An energy mix technology should be introduced to the airport environment as a cost-effective alternative to satisfy electricity demand and carbon footprint reduction. Therefore, there is a need for gas technology that has the potential to significantly reduce the cost of ESKOM electricity demand through internal power generation at OR Tambo International Airport (ORTIA), Cape Town International Airport (CTIA) and King Shaka International Airport (KSIA) with the use of natural gas, which is abundant in our neighboring country (Mozambique) as well as pipelines to South Africa. Natural gas power generation has many benefits. Emissions of CO_2 and soot are almost non-existent in natural gas production. Nitrogen oxide emissions are low, with high environmental value, with an increase in domestic natural gas exploration and development efforts.

These bring with it the need to design a gas turbine generator that can produce enough power to run the airport without any external electricity. Therefore, the purpose of this project is to design a gas turbine generator that can generate electricity locally at each of the three international airports. The design should produce low noise and emissions, have high performance, and be environmentally friendly, safe, easy to service and easy to install and commission. This design will help reduce carbon and nitrogen monoxide emissions and will also positively affect electricity costs. Greenhouse gases such as CO_2 are a major cause of climate change. Reducing these emissions is important to prevent global warming. At the same time the energy industry, transportation and various types of transport all emit significant amounts of CO_2.

1.1 Historical Development of Gas Turbines

The technologies of the Gas Turbine Engine (GTE) and the reaction engine have overlayed a great deal throughout recent years. A great deal of engineers and scientists have worked in these fields, and the same sciences and technologies are applied to many types of engines. In the past, the reaction engine has been utilized a lot of in flights. The GTE has been utilized for mechanical drives like electrical generation, ship propulsion, and in experimental automobile propulsion [3].

Some operational turbine engine power plants use a by-product of aircraft reaction engine as a gas generator (GG). Once used in and of itself, the engine should be changed by the addition of a power turbine (PT) and reduction gear to complete the plant.

In nature, the squid was utilizing reaction propulsion before researchers thought of it. Cases of the response guideline (Newton's third law) existed in early history. Be that because it might, the right down to earth application of the response guideline, occurred solely recently. This delay is because of the slow progress of technical accomplishment in engineering, fuels, and metallurgy (the science of metals). In the 1680s Sir Isaac Newton delineated the laws of motion. All devices that use the idea of reaction propulsion are supported by these laws. Newton's steam wagon is an example of the reaction principle, Figure 1a. In history there are several other examples of scientists who used the principle of expanding gases to do work. Among these scientists, the Egyptian scientist from Alexandria who was on earth between the first and third centuries, described the first jet engine (the aeolipile). The aeolipile, Figure 1b, is traced back as far as 250 B.C., and several sources are considering Hero as the inventor [3].

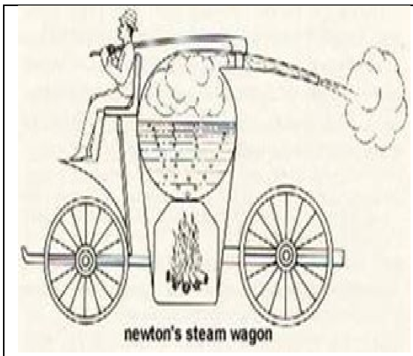	
a) Newton's steam wagon	b) Hero's aeolipile

Figure 1: Newton's steam wagon and Hero's aeolipile [3].

In 1791 John Barber, an Englishman, submitted the primary patent for a style that used the physics cycle of the trendy GTE. This style was additionally prompt for reaction propulsion. The proprietary application for the GTE as we all know it these days was submitted in 1930 by an Englishman, Sir Frank Pare. His patent was for a jet engine. Pare used his own ideas at the side of the contributions of different scientists. After many failures, he came up with an operating GTE [4]. The United State (US) did not enter the GTE field till 1941. General electrical was then awarded a contract to create a yank version of the British-designed Pare engine. The engine and framing were each built in one year. The primary jet craft was flown during this country in October 1942. In late 1941 artificer Corporation was awarded a contract to style and build the very first American GTE. Their engineers designed the primary axial-flow compressor and annulate combustion chamber [4].

2. Brief Theory of Gas Turbine Operation

Several pressure, volume, and speed changes occur at intervals within a GTE throughout its operation. The convergent-divergent method associated with the Bernoulli's principle: if a fluid flowing through a tube reaches a constriction or narrowing of the tube, the speed of the fluid flowing through the constriction will increase and therefore the pressure decreases. The reverse is true once the fluid leaves the constriction, speed decreases and pressure increase. Boyle's law and Charles's law conjointly play throughout this method. Figure 2 shows these laws applied to the GTE.

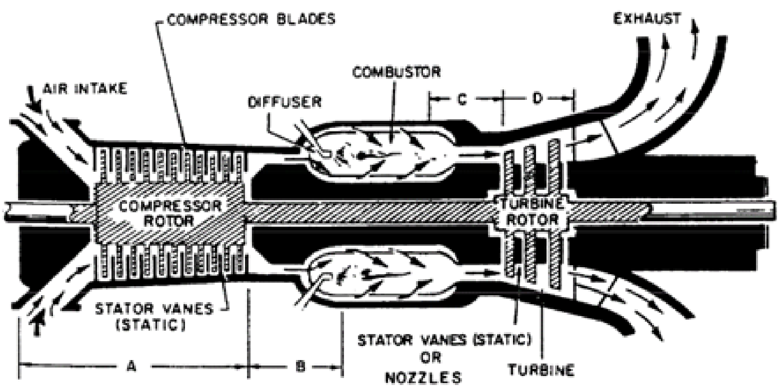

Figure 2: A typical gas turbine [5].

Air is drawn into the front of the mechanical device (compressor). The rotor is therefore created such that that the realm decreases toward the rear. This tapered construction provides a convergent area (area A). Between every rotating stage there is a stationary stage or stator. The stator converts high speed to pressure and directs the air to consecutive set of rotating blades. Owing to its high motion speed and therefore the mechanics form of its blades, the rotor will increase the speed of the air. Every combination of rotor and stator blades constitutes a pressure stage. Both pressure increase and reduction in volume takes place at each stage (Boyle). (GE Gas Turbine Design Philosophy).

This operation continues at every stage till the air charge enters the diffuser (area B). There is a short space within the diffuser where no additional changes manifest itself. Because the air charge approaches the tip of the diffuser, it may be noticed that the gap flares diverges outward. At this stage, the air loses speed and will increase in volume and pressure. The speed energy becomes pressure energy, whereas pressure through the diffuser remains constant. The reverse of Bernoulli's principle and Boyle's law is noted to be taking place, the compressor unceasingly forcing additional air through this section at a relentless rate maintaining constant pressure. Once the air is within the combustor, combustion takes place at constant pressure leading to an oversized increase within the volume of the air and combustion gases (Charles's law). The combustion gases go rearward to space C. This happens by speed imparted by the compressor and partially because area C is a lower pressure space. The tip of space C is the turbine engine nozzle section. Here a decrease in pressure and a rise in speed are noticed. The high speed, high-temperature, low-pressure (LP) gases are then directed through the inlet nozzle to the primary stage of the rotary engine (turbine) rotor (area D). The high speed, high-temperature gases cause the rotor to rotate by transferring speed energy and thermal energy to the rotary engine blades. Space D may be a divergent space. Between every rotating turbine stage there is a static stage or nozzle. The nozzles perform a similar function as the stators within the compressor.

A turbine nozzle is a stator ring with a series of vanes. The vanes direct the combustion gases uniformly and at the right angle to the rotary engine blades. The passages between the vanes are designed as branching nozzles. Every succeeding stage imparts speed to the gases as they go through the nozzle, where every nozzle converts heat and pressure energy into speed energy by managing the expansion of the gas. Every stage of the turbine is larger than the preceding one. The decrease in pressure is sort of rapid; consequently, every stage should be larger to use the energy of a lower pressure, lower temperature, and larger volume of gas. Ambient air is raised in pressure and speed and reduced in volume space. Every stage will solely compress air about 1.2 times within the turbine rotor (area D), the gases give up thermal, pressure energy and increase in volume through 3 stages - if this did not happen apace, back pressure from space D would cause space C to become clogged. The gases within the combustor would back up into the compressor. There they would disrupt flowing and cause a condition referred to as surge, or compressor stall. This condition can destroy the engine in a matter of seconds [5]. (PEREZ ZUÑIGA, Y.S.)

The gases from the last engine stage enter the exhaust duct where they are sent to the atmosphere. The leading part of the exhaust duct is a component of a divergent space. Additional divergence reduces the pressure and will increase the volume of the warm gases and aids in lowering the speed. The exhaust gases enter the atmosphere at or slightly higher than the ambient pressure of the air, but this relies on the length and size of the exhaust duct.

Air enters the intake at constant pressure (as shown in Figure 2), is compressed because it passes through the compressor (space A in Figure 2). Between the tip of area B and therefore the starting of area C in Figure 2, combustion takes place, and the volume will increase. Because the gases go through area D (Figure 2), the gases expand with a decrease in pressure and a rise in volume. The gases discharged to the atmosphere through the exhaust duct at constant pressure (Figure 2, exhaust).

3. Development of Novel Gas Turbine Model

The final design shown in Figures 3 and 4 has a length of 1 737.57 mm (excluding the air inlet guide). The total length of the model is 2 052.22 mm (including the air guide) and has a total height of 804 mm. The gas turbine rotates at a speed of 5000 rpm and produces a predicted power of 811.59 kW. The torque developed by the rotating shaft is 1.55 kNm. The compressor works at a pressure ratio of 1:15 and the combusted gases enters the turbine at a temperature of 1 800 K and discharged at a temperature of 897.4 K. The heat added by the fuel is 845.3 kW and the net work done by the turbine engine is 341 kW. The model operates in a Bryton simple cycle and has an efficiency of 40.34 %. The mass flow rate is constant during full operation of the engine and has a value of 50 kg/min. The model has a total mass of 1 180.965 kg (resulting to a weight of 11.585 kN).

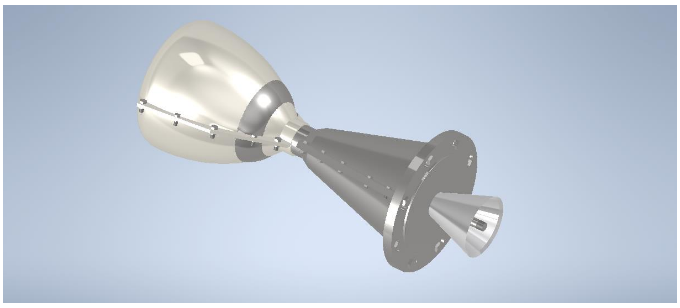

Figure 3: 3D CAD model.

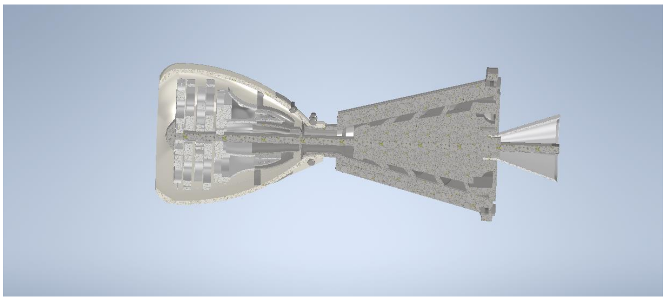

Figure 4: 3D CAD (section view).

The compressed air from the compressor enters the combustion chamber at a temperature of 859.9 K and a pressure of 15.2 bar. The air that enters inside the combustor is approximately 10 % of the compressed air. Fuel is added in the combustor to mix up with the air, the air and fuels mixes at a ratio of 1:17.2. After the mixing of the air and fuel, ignition takes place via a spark plug. The chemical energy added by the fuel is converted to mechanical work during the expansion of the combusted gases through the turbine blades. The mechanical work is produced by the rotating turbine caused by the expanding of the hot gases through the turbine. By coupling a grid electric generator at the end of the shaft on the cold side of the engine, electricity could be produced.

4.1 Subcomponents

Figure 5 shows the rotor parts of the compressor (impeller and screw type body). The impeller has 16 blades (12 of which are shorter and the remaining 4 are long, exiting the impeller rim). The cone type body has the same diameter with the impeller of 400 mm and it reduces to the output end to a diameter of 150 mm. This cone body has 4 helical vanes which meet up with the longer blades of the impeller and they make one revolution.

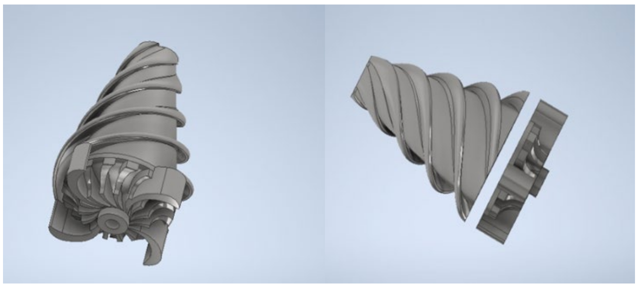

Figure 5: Compound compressor rotor.

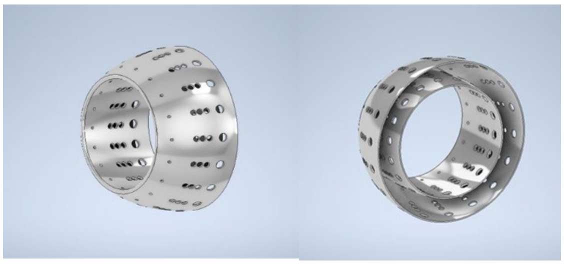

Figure 6: Combustor.

4.1.1 Combustor

The combustor (see Figure 6) is a ring type single combustor (not common in the gas turbine technology). It has a length of 139 mm, outside diameter of 291 mm and an inner diameter of 206.5 mm (these are the diameters at the output of the combustor). The combustion space has a height of 40 mm, reducing to the rearward of the compressor to a height of 10 mm at a length of 139 mm from the exhaust side of the combustor. Figure 7a, shows the combustor-can that fit in the combustor. Figure 7b, represent the first stator blade of the turbine and Figure 8 shows the last rotor blade of the engine.

	
a) Combustor can	b) Combustor-stator blade

Figure 7: Combustor can and Combustor-stator blade.

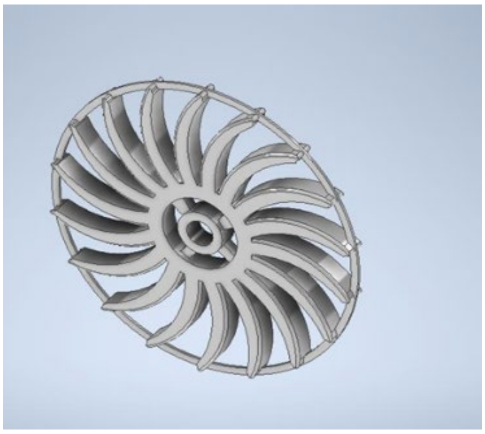

Figure 8: third rotor part (last rotor in the turbine section).

5. Model Testing

The performance of the engine, in terms of power produced and cycle efficiency, can be predicted for a particular operating condition. This is carried out with the use of thermodynamic equations and knowledge or assumption of the performance of components in the engine. The gas turbine engine conditions and component efficiencies assumed for the compressor and turbine are given here:

- Ambient temperature (T01 = 298K)
- Turbine entry temperature (T03 = 1800K)
- Pressure ratio (P1/P2 = P4/P3 = 1/25)
- Compressor isentropic efficiency (= 0.80)
- Turbine isentropic efficiency (= 0.85)
- Mass flow rate (= 50kg/min)

One of the main concerns for this concept is that an adequate power output would be available during operating conditions of the gas turbine generator. Based on the assumptions made. For this purpose, calculation of the heat addition by the natural gas, the work done by the turbine (or the power output) and the cycle efficiency as well as the torque developed are carried out. The efficiency determination is summarised here.

$$W_T = \dot{m}C_{p-mix}(T_{03} - T_{04})$$

$$W_T = 0.833 \times 1.079(1800 - 897.4)$$

$$= 811.59\ KW$$

$$W_C = \dot{m}C_{p-air}(T_{02} - T_{01})$$

$$W_C = 0.833 \times 1.005(859.9 - 298)$$

$$= 470.59\ KW$$

$$\eta_{cycle} = \frac{W_{net}}{Q_{in}}$$

$$\eta_{cycle} = \frac{341}{845.3} \times 100$$

$$= 40.34\%$$

5.1 Cost Analysis

The cost of materials is shown in the Table 1. The mass of each components was investigated using CAD software and the cost of material per kilogram was also investigated. The total cost of material is R 107 787.77. The cost for machining (using multi-axis CNC machine) the subcomponents is estimated to be R 540 000 ($ 36 000) and the cost of assembling is estimated to be R 91 619.60 ($ 6 107.97).

5.2 Other Design Considerations

The gas turbine will be equipped with accessories to provide safe and reliable operation:

- Inlet air filters
- Metal acoustical enclosures
- Double lube oil coolers
- Dry low NOx combustion system
- Compressor wash system
- Fire detection and protection system

The gas turbine designed for ease of maintenance and service. Both casing of the engine (compressor and turbine casing) may disassemble into two separate symmetric parts. Components such as fuel nozzles, induction valves, wiring, bearings, and sensors replaced by buying new ones from the gas component sellers.

The potential ecological impacts identified in the operation of the gas turbine generator are: (i) water pollution from oil wastes and/or spills used for the maintenance of apparatus, (ii) noise resulting from the operation of the turbine, (iii) air pollution resulting from the stack emissions during power generation. All these wastes with possible influences on the surroundings are handled with latest technology available in accordance with the relevant country wide and global legal framework.

Table 1: Bill of materials

Components	Material	Mass(kg)	Cost (Rands)
1.Turbine casing	Titanium alloy	156.218	39 574.24
2.Rotor 1	Nickel alloy	27.288	2 595.09
3.Turbine lock	Stainless steel	03.448	145.16
4.Stator 3	Nickel alloy	36.135	3 436.44
5.Shaft	Stainless steel	30.434	1 281.27
6.Rotor 3	Nickel alloy	40.194	3 822.45
7.Rotor 2	Nickel alloy	13.827	1 314.95
8.Stator 2	Nickel alloy	36.135	3 332.78
9.Combustor-stator	Nickel alloy	43.377	4 125.15
10.Combustor	Nickel alloy	06.09	579.25
11.Compressor casing	Steel alloy	349.79	19 088.04
12.Compressor cover	Steel alloy	82.379	4 495.42
13.Air guide	Aluminum alloy	06.868	192.72
14.Combustor can	Steel alloy	14.682	801.20
15.Combustor holder	Steel alloy	19.312	1 053.86
16.Compressor rotor parts	Steel alloy	402.231	21 949.75
TOTAL COST			**107 787.77**

6. Conclusion

The paper discusses the problem encountered by South African international airports with shortage of electric power supply. The three airports are named as follows, the OR Tambo, the King Shaka, and the Cape Town international airports. These airports depend on the ESKOM electricity supply which faces enormous challenges to supply the country with enough power.

The current generation of electricity with the use of coal-fired boilers produces a reasonable amount of CO_2 and soot emissions. The initial cost of this type of power station is quite high as well as its operating cost. A lot of construction is needed to complete such power plant, thus more space is required to build this kind of project. The construction and operating of this plant have great negative impact on the environment, ecosystem and to the health of people.

From preliminary analysis of the compound compressor concept, the power produced by this model was found to be 811.59 kW. Thus, the output power is much greater than the minimum power of 500 kW that was specified in the beginning of the project. The model operating on a simple Bryton cycle was determined to have an efficiency of 40.34 %. The minimum efficiency that was specified is 35 %, and therefore the efficiency of the gas turbine model meets the efficiency requirement. The mass of the gas turbine assembly is 1 180.965 kg, which is greater than the specified mass by 18%.

Thermal stress analysis and flow simulation must be taken into consideration to assure the performance of the gas turbine engine. These simulations can be done by CAD software or other software such as CFD. If this design is to be modified in the future, the simulations must be taken into consideration to assess the performance of materials and components. A prototype can then be built after the simulations of the design. A room for the gas turbine must also be designed for the protection of the gas turbine and the grid generator. The room of the engine should have the following: air filters, air conditioners (for high performance without depending on the surrounding weather), and proper ventilation.

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Biographies

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