Performance computing of an open cycle micro gas turbine powerplant using data aided modeling and simulation

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Abstract. In this paper the study of the thermodynamic performance for a 6kW micro gas turbine power plant has been optimized by considering Air-fuel ratio at various altitudes along with fuel inlet temperature. The parametric analysis was performed to improve the overall efficiency of the power plant to obtain the required power needed by a multi-copter. The research deals with parametric optimization for determining realistic and practical combinations for improving the specific fuel consumption and overall efficiency of the Micro gas turbine power plant. The use of recuperators has not been beneficial for the micro gas turbine power system due to the increase in the total volume and weight of the engine. The fuel inventory should be decreased significantly to justify the addition of a recuperator system. The addition of heat exchangers improves the Specific fuel consumption that results in environmental friendly micro gas turbine engines. The result of this work helps to develop and design the micro gas turbine with high efficiency and at the optimized output. A model for a 6 kW micro gas turbine power plant was optimized for the application of primary power units for multi-copter or drones at low altitude conditions. To validate the model, JET CAT PHT3 shaft turbine design parameters were used and the results are compared with the experimental tests on this engine.

1. Introduction
Multi-copters have a wide range of applications in photography, disaster response, search and rescue operations, hazard mitigation, and geographical 3D mappings. The civilian uses are increasing rapidly and thus there is a rise in the need of multi-copters that needs to cover a long distance and lift heavy objects. The current battery systems are considered massive for take-off thus restricting the functionality and operating time for such multi-copters to 20 minutes of flying duration at maximum speed for 150 -250 km/hr. Large drones such as DJI Phantom 4 have a maximum flight time of 28 minutes however the Power consumption for drones depends on dynamic environments such as winds at various altitudes and operating temperatures. Very few researches have been conducted on the power consumption of drones at various altitudes [1-3]. The European Unmanned Vehicle Association identifies five main categories of UAVs and has been tabulated as follows in Table 1. To attain endurance flight, an effective on-board power supply unit is necessary that is capable of producing a high power density. In today’s technology only, energy storage systems (Lithium Polymer (Li-Po) Batteries; Super Capacitors (SC); Photo Voltaic (PV) Cells; and Hydrogen Fuel (FC) Cells) have been used [4]. The Stirling engine technology for micro-scale suffers from technical problems that affect life and reliability which is an outcome of the issues related to cylinder seals, heater hot spots and load...
control difficulties. The fuel cells though they are novel commercialization of such systems were never done due to the high cost of technology [5]. In this research, a novel method of using a 6kW micro gas turbine power plant is optimized for powering a multi-copter to improve its long endurance of operability. To convert mechanical to electrical energy gas turbines are the most efficient means of power conversion that is presently functional.

| Flight Path         | Distance (km)     |
|---------------------|-------------------|
| Close range         | < 25              |
| Short-range         | 25 - 100          |
| Medium range        | 100 - 200         |
| Long-range          | 200 - 500         |
| Endurance           | 500 < or 20 hours of continuous flight |

The initial constraint was considered from the flying regulation that the drone must operate not more than its peak altitude of 6 km and optimum operating altitude should be less than 5 km [6]. Micro-gas turbines are single-stage, radial flow devices that have power output in between 30 kW to over 200 kW can reach efficiency up to 30% and can have rotating speeds of 90 000 to 120000 rpm [7]. To sustain high rotation, they use oil/air-based bearings [8].

2. Design Configuration

A design solution to the technology adopted for a simple micro gas turbine cycle was analyzed on the following parameters 1) low-pressure ratio 2) low turbine inlet temperature 3) low exhaust temperature and various altitudes up to 8 km... The design solution comprises a single-stage radial compressor, Two-stage axial turbines, and a recuperator as shown in the schematic in figure 1. The schematic representation of the Micro gas turbine is shown in figure 1, parts of the engine on schematic needed to be co-coordinated for representing corresponding parts to all the designers, suppliers and for conducting tests. To reduce the complexity in understanding aircraft propulsion engineers, assign station numbers. The labeling of stations is as follows, The Freestream conditions are numbered 0, the entrance to the Inlet of the engine as station 1. The exit of the inlet/inlet to compressor numbered as station 2. The compressor exit /combustion chamber entry is numbered as station 3. The combustion chamber exit / Turbine entrance is numbered as station 4. The turbine exit is numbered as 5. Nozzle Downstream of the throat is numbered as 9. The power plant input parameters for this study are shown in table 2. The gas turbine power plant uses single-stage radial designs for the compressor as the small size power plant cannot support large size blade lengths while the axial two stages are used for the turbine as they are commonly more efficient. This would allow high efficiency and compact design. Air bearing systems are chosen due to its simplicity in design solutions for micro gas turbines. The radial turbo-machinery has more efficiency for generating up to 100 kW [15].

![Figure 1. A Schematic of the baseline configuration for a 6kW micro gas turbine power plant. C – combustor, hpt – high-pressure turbine, fpt – free power turbine.](image-url)
The recuperator has a significant portion in contributing to the overall efficiency of the power plant. To improve performances and efficiency two parameters are considered increasing the turbine inlet temperature and (ii) higher recuperator effectiveness. The recuperator increases thermal efficiency but reduces the pressure. This pressure drop has an impact on the final output power negatively. The material of recuperator should be resistant to oxidation thus stainless steels or nickel-based alloys are used extensively for this purpose. [16]. The modeling technique was a component level cycle that allows for transient effects. The key relationships that were satisfied are the Power-balance equation, Continuity equation, heat transfer of each component and static pressure balance for core flows at a surface boundary where working fluid mixes with the fuel. The novel method of modeling of the gas turbine is shown in figure 2. The engine model here calculates transient clearances as a function of rotor speed, pressure differences and peak cycle temperatures. The power output in gas turbines depends on the thermal efficiency and development in recuperators plays an important role. Operating at high turbine inlet temperatures improve the thermal efficiency but has a metal permissible limit. The study focuses on calculating and evaluating 6 kW micro- gas turbine powerplant performances to different altitudes and air-fuel mix ratios to determine the optimized acceptable maximum temperature and improve the overall efficiency.

| Parameters                                  | Value       |
|---------------------------------------------|-------------|
| Compressor type                             | Centrifugal |
| Turbine type                                | Axial       |
| The overall pressure ratio of the compressor| 3           |
| Peak stagnation temperature at the turbine inlet | 1280 k     |
| Fuel injection temperature                  | 293.15 K    |
| Composition and properties of a fuel        | Kerosene A1 |
| Excess power capacity on the rotor shaft for generator output | 6 kW       |

Gas turbines have undergone a rapid evolution in terms of improvement in thermal efficiencies [17]. The recuperator can increase efficiency by 70%. The power flow from the micro gas turbine to the battery can be denoted as PB. The energy flow can be given by equation 1, [10]. The variables that are enabled in the models are vertical climb angle $\gamma$, the roll angle $\phi$, the velocity $v$, and the acceleration $a$. This makes the model very simple, fast and reliable. To find the parameters for a given aircraft we use machine learning techniques. The proposed power model presented in equation 1 has been validated by comparing measured energy consumption with estimated consumption.

$$P_B = A \frac{\cos^2 \gamma}{\cos^2 \phi} + Bu^2 + C(g \sin \gamma + a)v$$ (1)

3. Methodology
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with estimated consumption. [11]. Heat exchangers and the Turbine was per-formed. At various altitudes, a comparison was made with Air to Fuel Mix Ratio for component efficiencies. High altitudes, compressor and turbine efficiency, mass flow capacity along with pressure drops and effectiveness for recuperator were analyzed using parametric analysis. The model generates sufficient data to create patterns for design optimizations. The working parameters such as Overall Pressure Ratio and Turbine inlet temperature were investigated with thermo gas dynamic calculation for designing an optimized power plant.

A micro gas turbine steady-state model was developed for the high altitude specifications. The optimization was performed for Specific fuel consumption to derive valuable power output in the function of altitude and compressor rotational speed. The model was validated against the experimental performance data from sea level equivalent system JET CAT PH3 [12]. Parametric value optimization of the micro gas turbine includes compressor pressure; turbine inlet temperature and exhaust stream temperature; fuel volumetric flow rate; compressor inlet air mass flow rate; output power. The values were simulated for high altitude ambient temperature, pressure, and relative humidity for validating the model. The results of the modeling indicated the most efficient design values for operational performance with maximum overall efficiency.

Figure 2. A novel pipe-based simulation for a micro gas turbine powerplant.

Component matching helps in analyzing engine performance that helps to evaluate thermal efficiency and pressure ratio performances. Some methods of the component matching method are nested loop, a matrix iteration method and genetic algorithm. The matrix iteration method is used for advanced gas turbine off-design performance situations. In this research, the procedure is iterated repeatedly until convergence is reached [13-14].

4. Results and discussions
The investigated cycle which is the baseline cycle for the micro gas turbine power plant is briefly described and their configurations are shown in figure 3. The single shaft power plant incorporates a high-speed generator and the loss of such a system is not considered. At a full charging load of 6 kW, the nominal pressure ratio and turbine inlet temperature (TIT) are 3 and 1270 k respectively. At ISO ambient environment condition the JetCat PH T3 generates 6 kW power, in terms of our simulated model, the micro gas turbine power plant could produce about 6.1 kW of electricity with an overall efficiency of electrical efficiency of approximately 19% which is 4-5% higher than the existing models, at this range of power. Given the high recuperator outlet temperature on the exhaust gas is has little or no differences, which is approximately 620°C [15-18].

Numerical predictors for net power output were evaluated by studying the effects of hot fluid mass flow rate and drop in pressure drops. The Parametric value obtained after the thermodynamic cycle
optimization. The results of the simulation are depicted in the following graphs from Figure 4-6. Sensitivity analysis was carried out to study the effects of the variable pressure ratio on the system in comparison with the turbine inlet temperature, specific fuel consumption for the optimizing the overall efficiency of the system. When the inlet temperature decreased, the overall efficiency is proportionally increased while in figure 5 the specific fuel consumption increases with the increase in pressure ratio observing that the thermal efficiency is higher for the regenerative cycle.

Table 3. System Validation comparison with the specification

| Parameters                  | Our model | Jet Cat PhT3 |
|-----------------------------|-----------|--------------|
| Compressor pressure ratio   | 3         | 3            |
| Power output at shaft       | 6.1       | 5            |
| Average shaft speed         | 98 000 rpm| 103,000 rpm  |
| Exhaust temperature         | 593 K     | 895 K        |
| Fuel consumption            | 45 ml/min | 230 ml/min   |

This indicates that inlet pressure at the combustor and the exit temperature of the combustion have a strong impact on the optimal value of objective and target functions of mass flow rate and the effectiveness of heat exchangers. Multi-criteria optimization and a parametric study showed the performances of design criteria at the optimal working condition assumption made for the base case. The fuel inlet temperature does not improve the quality of the system efficiency significantly but it is improving the overall efficiency 3% when considering alternate pressure ratio as shown a comparison of the temperature changes impacting the overall efficiency for the fixed power output of 6kW on all the various approaches of the baseline system [19-21].

Figure 3. Schematic of the optimized 6kW micro gas turbine power plant for aviation application. Overall Efficiency = 17% and Pressure ratio =3.

According to Figure 6, the values for the recuperator effectiveness has greater significances than any other functional values for a micro gas turbine less than 10 kW. The initial temperature is the ambient conditions at sea level for all parametric analysis (286.15 K). Furthermore, the maximum amount of waste or unused heat is plotted in figure 6 the higher the pressure ratio the more inefficient the engine for the smaller intake engines. The heat waste gets saturated after an increase of about +100 K for any pressure ratio chosen for a fixed inlet turbine temperature. Figure 11 shows how the material technology can help Micro gas turbine overall efficiency to be above 25% if the effectiveness is more than 90%.
Figure 4. Impact of the temperature of inlet fuel.
Specific Fuel consumption (kg/hour) Fₚ (Recuperator effectiveness θₑ (%) vs. TᵢT (K))

Figure 5. Impact of recuperator effectiveness on Turbine inlet temperature.
Overall Efficiency ηₑ (%) vs. Recuperator effectiveness θₑ (%)

Figure 6. Impact of recuperator effectiveness.
5. Conclusion
The Parametric value obtained after the thermodynamic cycle optimization. The research focuses on optimization for a 6 kW micro gas turbine powerplant with validating the model with Jetcat PhT 3 specification chart. By studying parametric evaluation on the thermodynamic cycle, the expected results obtained provide us the parameter insight on the efficiency of diverse components (Pressure Ratio, Turbine inlet temperature, Compressor work, Specific fuel consumption and output power generated) at Sea level testing. The overall cycle efficiency depends on thermal efficiency and the effectivenes every 5% increase in the efficiency of recuperator could save 200 ml/hour consumption of fuel. The research signifies the importance of the addition of a heat recovery cycle to the baseline cycle for improving the overall efficiency of the power plant even for a micro gas turbine power plant with less than 10 kW of power output since the effectiveness of the recuperator massively influences the thermal efficiency. The design concepts were based on the parametric values obtained using the computer program ASTRA and the program has design experiences by incorporating past experimental data and high end sophisticated mathematical models. The schematic of the gas turbine power system presented in this article along with results shows a value increase in Overall efficiency. The micro gas turbine under 10 kW has the potential to reach more than 30% in overall efficiency if the recuperator has an effectiveness of more than 95%. Thus, the importance of recuperator design and innovation would pave the wave for the next set of ultra micro gas turbines power plants.

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