Parametric study and efficiency optimization of the solar coupled hybrid micro gas turbine power plant for high altitude flight.

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Abstract. The performance and feasibility study of a hybrid system designed by combining solar micro gas turbine for power generation process during high altitude flight were explored. The high altitude flight could be defined as long duration stratosphere balloon. Payloads in this high altitude balloon flight could be remote sensing satellites or communication satellites which require a continuous high-density power supply that cannot be provided by solar panels. To reduce greenhouse gas emission, the hybrid method was chosen and studied for its effectiveness in a gas turbine power plant. A thermodynamic cycle analysis for high altitude gas turbine power generator was analyzed along with various power conversion systems and recuperator placement configurations were investigated. The working parameters such as Overall Pressure Ratio and Turbine inlet temperature was investigated with the thermo gas dynamic calculation for designing an optimized power plant. Parametric optimization for determining the realistic and practical combination of recuperators for improving the specific fuel consumption and overall efficiency of the Micro gas turbine power plant was performed. The recuperators could be positioned either in the exhaust of a high-pressure turbine or at the exhaust of the free turbine. The recuperator position and heat extraction are explored and the resulting data depicts the recuperator surface area increases the effectiveness thus the fuel consumption decreases but the recuperator increases the overall mass and volume of the power plant size. A comprisable trade-off was made between the recuperator performance and its size and the results are optimized for high overall efficiency of the power plant. A short trade-off between the selected system and existing systems were made. The system performance, Efficiency optimization and the component size and weight characteristics were performed to deliver maximum payload capabilities.

1. Introduction
Micro gas turbine provides the most powerful, compact and high-density power source suitable for powering vehicles in transportation sectors. The micro gas turbines benefit from its air-breathing capabilities that have better eco-friendly emissions when compared with other fuel consuming engines. The gas turbine power plant technology has reached a high level of maturity [1-2]. The micro gas turbine engine has high heat wastage and Noise, thus numerous research works have been dedicated to reusing the waste heat and reduction of noise. The most conventional method uses the recuperator or heat exchanger that acts as a preheater to combustor inlet. In this research at high altitude applications noise is not considered as an emerging problem thus focuses mainly on the positioning of recuperator for determining the most efficient micro gas turbine. Depletion of fuel and environmental concern has raised a need for alternate or hybrid fuel technology. Various researches have been conducted from solar, solid fuel cells and even algal biomass promises to be sustainable, renewable and effective biofuels [3-5].
The micro gas turbine has engineering challenges both in terms of theoretical and practical implications. Certain parameters when scaled down has significant losses, for instance, the Compressor pressure ratio, Turbine inlet temperature and heat exchangers designed for a micro gas turbine requires low volumetric flow causing losses in pressure and also low heat transfer surface area creating a great constraint [6]. Improving the overall efficiency of the micro gas turbine faces a challenge due to the lack of high-temperature materials. The use of recuperators has not been beneficial for micro gas turbine power system due to the increase in total volume and weight of the engine. The fuel inventory should be decreased significantly to justify the addition of a recuperator system. Addition of heat exchangers helps to decrease Specific fuel consumption that results in environmental friendly micro gas turbine engines.

The design and manufacturing process for a micro gas turbine usually takes 6-8 years. The first stage of design is conceptual design phase that emphasis on the core power plant architecture and optimizing its working process parameters. Optimization of the power plant parameters is solved using the multi-criteria modeling of optimization. For micro gas turbine power plant the size has to be kept minimum thus recuperator technology plays a crucial role in the design phase. The decrease in the size of the power plant also reduces the compressor choice of technology (i.e axial or centrifugal compressors) this changes the Reynold number and also the mass flow rate of the working fluid. All these parameters influence on the thickness and boundary walls of the gas turbine which enables us to calculate the geometry of the power plant. To obtain parameters for turbomachinery efficiency Power output is necessary. In this research a novel 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 [REF 9]. 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. The research does not present a detailed study on the need for downscaling gas turbine engines.

2. Methodology
The program ASTRA simulates the thermodynamic cycle of the micro gas turbine power plant. Performances optimization for parameter characteristics for components such as Compressor, Heat exchangers and Turbine was performed. At high altitudes, compressor and turbine efficiency, mass flow capacity along with pressure drops and effectiveness for recuperator was 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 was investigated with thermo gas dynamic calculation for designing an optimized power plant. Parametric optimization for determining the realistic and practical combination of recuperators for improving the specific fuel consumption and overall efficiency of the Micro gas turbine power plant was performed. The recuperators could be positioned either in the exhaust of a high-pressure turbine or at the exhaust of the free turbine. The recuperator position and heat extraction are explored for flight systems. The data shows The resulting data depicts the recuperator surface area increases the effectiveness thus the fuel consumption decreases but the recuperator increases the overall mass and volume of the power plant size that increases drag causing high fuel consumption. A comprisable trade-off was made between the recuperator performance and its size and the results are optimized for high overall efficiency of the power plant [7-8].

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 [REF 9]. 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
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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 simulations. In this research, the procedure is iterated repeatedly until convergence is reached [10-12].

3. Design Configuration

A design solution to technology adopted for a simple micro gas turbine cycle was analyzed on two parameters 1) low-pressure ratio and 2) turbine inlet temperature. The design solution comprises of

- A single stage radial compressor
- A single stage radial turbine
- Use of a recuperator to avoid efficiency penalty.

The 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 are 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 basic configuration of the micro gas turbine cycle was investigated in this research in 4 different cases, based on their configurations. CASE 1 is a simple cycle micro gas turbine as shown in figure 1, CASE 2 & 3 have additional recuperator, the difference between the two cases is the position of the heat exchanger. In CASE 2 the heat exchanger reuses only the waste heat from the exhausts, however in CASE 3 the heat is used before being used by the free turbine, this CASE was interesting to study as the oxygen content at the high altitude was too low for complete combustion. In CASE 4 the fuel is heated using a solar heater before entering the combustion chamber to improve the specific fuel consumption.

![Figure 1. CASE 1, basic gas turbine power plant.](image1)

![Figure 2. CASE 2, gas turbine power plant with heat recuperator.](image2)

The multitudinal position of recuperator was implemented as shown in Fig 2, 3, 4. Comparing of generated data for the different schematics resulted in solving the most efficient power plant that determines the most optimized heat exchanger position. The analyzed cycles provide novel and valuable insights for improving the performances of the thermodynamic cycles. Recuperator, usually placed after free turbine acts as the best scenario of using waste heat, however, altitude due to a decrease in oxygen content at high altitude heat recuperation from the first turbine seems reasonable. The recuperator influences the performance characteristics for a micro gas turbine turbo power plant the working parameters such as Overall Pressure Ratio and Turbine inlet temperature was investigated with thermo gas dynamic calculation for designing an optimized power plant. Parametric optimization
for determining the realistic and practical combination of recuperators for improving the specific fuel consumption and overall efficiency of the Micro gas turbine power plant was performed. The recuperators could be positioned either in the exhaust of a high-pressure turbine or at the exhaust of the free turbine as shown in figure 2 and 3.

The engine characterization uses the following parameters for output power, overall dimensions, the overall mass flow rate for Optimization of working process parameters for the required power plant. It could be noted the Reynold number influences the efficiency for micro gas turbines at high altitudes less than that of large turbines. To calculate the overall mass and volume of the micro gas turbine power plant proposed model use flow areas summation at the compressor inlet and turbine outlet flow areas. Some ASTRA advanced model includes pressure loss coefficients. An iterative process for the isentropic efficiency of both compressor and turbine was calculated in relation with various turbine inlet temperatures [13].

The mass and volume of the power plant could be derived from the following parameters
- The diameter of the inlet.
- The diameter of the compressor exit
- The diameter of the turbine and
- The diameter of the exhaust.

In most of the research and modeling, the only the Diameter of the inlet/Diameter of the compressor exit and Diameter of the turbine are used [14]. However, the model used all 4 parameters along with losses are considered. The losses considered for calculating mass and volumes of the power plant are as follows,
- Pressure drop losses in the intake, compressor, regenerator, turbine, combustion chamber, and mass flow process.
- Heat transfer losses to the ambient environment.
- Losses due to irreversible compression and expansion in the compressor and the turbine.

4. RESULTS AND DISCUSSIONS
The compressor pressure ratio optimized for the scenario CASE 1 was identified as pressure ratio 3. In addition to increasing design performance calculation and prediction, physical problems cause changes in the characteristic parameters (component efficiency and flow capacity). In this study, a program to simulate the operation of a micro gas turbine was constructed. The mathematical model comprises of the Total pressure, Mass flow rate and Peak Temperature. The turbomachinery components consist of the Compressor, Combustor, Turbine and Free Turbine. A hot flow process through a pipe is considered to determine the relationship between Thermal Efficiency, Compressor Pressure ratio, and Power Output. Numerical predictors for net power output were evaluated by studying the effects of hot fluid mass flow rate and drop in pressure drops. In figure 5, it is denoted clearly that there is a need for a heat exchanger as it almost doubles the overall efficiency from 7.3% to 14 %. This reduces the Specific fuel consumption by 83% in CASE 2, 3 and 4 compared to CASE
1. In figure 6, only CASE 2, 3 and 4 were considered. CASE 4 the solar assisted fuel heater has better overall efficiency than CASE 2 and 3 until 1500 k for turbine inlet temperatures due to the extra heat boost from the solar heater however after 1550 k the heat from the solar heater is not significant enough to improve the efficiency thus CASE 2 has significant efficiency improvement over 1600 k of TiT but it requires additional power source for active cooling system for the combustor and the turbines also increasing the overall mass of the system. CASE 3 is interesting than CASE 2 because of the reheating capability and use of high percentage of oxygen that is necessary for high altitude combustion. The CASE 3 is also significant only at turbine inlet temperatures less than 1300 k.

![Figure 5. Overall Efficiency improvement and importance of recuperator.](image)

![Figure 6. Nonlinear Overall Efficiency improvement over turbine inlet temperature.](image)

The obtained results are presented and analyzed for all the CASEs (1, 2, 3 and 4). CASE 1 seems to be the least reasonable configuration to be used in high altitude flights as the efficiency is less than 8% even with maximum optimization methods. Less than 1300 K CASE 3 with oxygen priority heat exchanger is better than CASE 4. CASE 4 is efficient at very high operating TiT but requires an active or passive coolant thus increasing the mass and volume of the overall micro gas turbine. Increasing the cycle peak temperature ratio and total pressure ratio can still improve the performance of the gas turbine cycle. CASE 4 has been simulated and predicted to have better-operating capabilities and overall efficiency when compared with all other CASEs.

![Figure 7. Power=1 at 0 km; Power = function (Altitude)](image)
Specific fuel consumption could be defined by the ratio of fuel mass to that of the output power of the power plant. For every 1% of Specific Fuel Consumption lower for generating the required power output .05 kg/s of fuel will be reduced in the total engine mass and $2.5 USD of the fuel cost/hr.

Power optimization along with altitude was performed from Sea Level to an altitude of 22 km. Figure 7 shows that there is a very rapid decrease in power output up to 15 km after which the power stabilizes. The micro gas turbine power plant power output is not impacted heavily after 15 km. Thus the power plant optimum performances range between 0-5 km for low altitudes and 15-22 km for high altitudes.

The same iteration was also performed on Specific fuel consumption (SFC) along the altitude which results in Figure 9. The graph represents the same linearity with the Power output stability. Below 10 Km there is a huge potential positive benefit for Specific fuel consumption along vs the altitude performances The lower the altitude the higher the performances. The Specific fuel consumption, however, stabilizes after 15 km to 22 km no significant changes are noticed.

![Figure 8](image1.png)  **Figure 8.** Specific fuel consumption; SFC = function (Altitude).

![Figure 9](image2.png)  **Figure 9.** Solar fuel; SFC = function fuel temperature.

The output of the micro gas turbine power plant is characterized by the output power, specific fuel consumption, thermal efficiency, and overall efficiency. The results are compared with experimental data those obtained in [9] for CASE 1 and CASE 2 micro gas turbine power plant with conventional analyses. The thermal efficiency of the cycle increases with the increase in the effectiveness of the regenerator. The results suggest a preliminary turbine stage design improvement.

5. **Conclusion**

The Parametric value obtained after the thermodynamic cycle optimization. A mathematical model was created and the steady state parametric simulation was performed on a micro gas turbine power plant capable of producing 1 kW using ASTRA a software program developed to investigate and simulate the thermodynamic cycle calculation. The software helps in the simulation process by integrating the user-defined models with the user interface tools for calculating chemical kinetics and thermodynamic models. In this study, the ideal gases operating at high altitude was assumed for the chemical kinetics while for the thermodynamic model it uses the standard fundamental equations of modified for specific components such as compressors, recuperators, combustor, and turbines.

The research focuses on optimization of recuperator positioning for a 1 kW micro gas turbine 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 high altitude flights similar to the required operating conditions.

Thermal Efficiency is the ratio of the mechanical power output produced by the engine to the heat energy input. The thermal efficiency of a gas turbine is increased by increasing the compression pressure ratio and the turbine inlet temperature. The overall cycle efficiency depends on thermal
efficiency. 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 and efficient positioning of the heat exchangers position. 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 model. The schematic of the gas turbine power system presented in this article along with results shows a value increase in Overall efficiency.

6. References

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