CONCEPTUAL DESIGN OF AN ULTRA-MICRO GAS TURBINE POWER PLANT FOR MULTI-COPTER AND SATELLITE APPLICATIONS

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ABSTRACT OF DISSERTATION

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CHAPTER 1 - BACKGROUND

1.1 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); Photovoltaic (PV) Cells; and Hydrogen Fuel (FC) Cells) have been used [4]. The Sterling 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 ultra-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 [6].

A major problem for both exploration and communication satellite is the Mass and Volume of the power sources. The collection of solar power in space and then transmitting them to nearby satellites or for powering their own needs is known as Space-based solar power they have wider application when they could be transmitted back to Earth via microwaves. This has a comparative advantage over the alternate method of collecting solar power at the earth's surface in terms of higher collection rate and minimizing transfer losses. Power systems in space or in orbit operation use solar power systems, however, numerous proposals are made using a combination of both thermal and solar power systems. In this research solar thermal power system uses parabolic solar heat collectors for generating steam.

The research focuses on the investigation of theoretical limits for performances of the gas turbine used as a power generation source for any satellites that would require about 6-10 kW... Based on the numerical simulation using a computer-aided system ASTRA developed at the Samara University Parametric Analysis is performed to optimize the best design conditions [6]. Numerical analysis is performed on Thermo-gas dynamics for cycle analysis to improve the overall gas turbine efficiency. This report contains the preliminary phase concept design and reveals findings, subject to revision as analysis proceeds. The research improves and optimizes both,

- Thermodynamic cycle efficiency along with the conversion of heat to mechanical work
- The total energy delivered in the form of mechanical work plus useful heat.

1.2 Ph.D. SCOPE

The main objectives and target of the Ph.D. research are to investigate the feasibility of conceptual design for micro gas turbines and its potential technology usage. The design objectives involve in understanding various configurations and how it affects the thermodynamic cycle parameters affects the results. This was done by developing mathematical models and tools that are sufficiently accurate to perform parametric analysis that doesn't require specific geometry and operating conditions. Analytical and empirical models were developed to run faster and simulate the required data convergence.

The problem has been addressed with the discrete number of assumptions that have been simplified to an analytical form where the boundary layer and operating conditions are stated. These assumptions are emphasized throughout the thesis. An alternate method of numerical estimation via Finite Element Analysis (FEA) was significantly enhanced to predict the structural weight approximately.

The Ph.D. uses an approach to compare the closed and open-cycle gas turbines of respective power output for their respective operating conditions. A parametric study would then enable us to estimate the most efficient design variables with given constraints to achieve target functions. The research evaluates the advanced theoretical concepts of estimating variables for rapid prototyping and testing that enables the improvement of the performance of the power plant. A comparison study of quantifying the benefits with alternative technologies is investigated.

Various concepts and cycle configuration of a micro gas turbine for both closed and open-cycle both were investigated. Diverse Micro gas turbine power plant configuration was optimized and designed to power a multi-copter, high altitude pseudo satellites and for space applications, as follows.

1. · *Open cycle micro gas turbine optimized at sea level.*

2. · *Open cycle micro gas turbine optimized at 5 km to power multi-copter.*
3. · *Closed cycle micro gas turbine optimized at space operating conditions.*

The power plant specification was to provide an uninterrupted power supply of 6 kW. This was derived by evaluating the power requirements for a multi-copter and communication satellite. The requirements of a multi-copter are to travel a minimum distance of 200 km and should have a minimum thrust capability of 100 kg. To reduce the noise a minimum of 100,000 rpm was capped. In order to model both, the power plant Samara University's Power plant CAE tool ASTRA was selected to match the power plant performance with the requirements by modeling in-house for the parametric studies. The theory is based upon the analytical and empirical formula for integrating any new designs with models. The Ph.D. aims to investigate the potential for use of micro gas turbine power plants for powering heavy lifting multi-copters and also even powering space-based systems. The final stage of the Ph.D. work was to investigate a comparison study between current existing systems. The concepts have been explored with the different technologies and the feasibility has been assessed on an initial basis and future recommendations are given.

1.3 AIM

The use of computer-aided optimization techniques used in preliminary design helps in identifying the critical performance parameters rapidly for prototyping and testing the power plant resulting in shorter design time at a reduced cost. Various algorithms and models are available for optimizing gas turbines of larger sizes but not for micro gas turbines especially for less than 10 kW. The aim of this project is to propose and develop a design optimization tool with novel analytical models that had been scaled down to investigate smaller gas turbine power plants both open and closed Brayton cycle configurations.

A modular toolbox was created to identify target functions under various critical constraints to study their performances by gradually changing required parameters through numerous iterations. To create a modular model along with the optimization library for achieving required performance criteria for batch processing and data handling for meeting the requirements of the target design with given set initial constraints. This thesis presents work carried out with the aim of optimizing the performance analysis of a micro gas turbine power plant. The work also examines the various constraints and environments where the performance of the turbomachinery components is investigated and recommendations are made for estimating the non-dimensional variables. A performance model was built using the turbomachinery characteristics proposed in order to test the robustness of the parameters with input variables. The effect of variables and engine input parameters have produced the thermodynamic cycle results are presented.

1.4 OUTLINE

The biggest problem that comes with Micro gas turbines in the size of a shoebox is the noise, and this prevents it from everyday application usage. The power plant could have a short duration of operation yet it requires higher efficiency that might be achieved with low specific fuel consumption. In smaller power plants the diameter for the flow working fluid is small and understanding such flow in miniature level is important. Any leakage would cause substantial degradation in the performance of the power plant. The problems could be listed as follows,

1. High fuel consumption and low efficiency

2. Restriction on size and materials
3. High noise
4. Higher emissions when compared to engines of the same capacity.

Particularly, pressure losses between the compressor outlet and the turbine inlet are a major issue of overall efficiency and system stability. To power satellites based on a closed-loop Brayton cycle has a huge positive impact particularly after the introduction of electric propulsion system faces key challenges such as requirement of high energy density and electric energy storage capabilities with less electric system weight and less heat generated by components for safety and reliability.

Firstly, a detailed description of the gas turbine components preliminary design phase is presented in order to highlight its specific requirements and challenges. This is followed by a description of the design of the optimization toolbox. The toolbox theory behind the optimization algorithm technique will be presented. This will be followed by a description of the improvements made to the design in order to attain increased net efficiency with the comparative models of the Jet CAT engines. The addition of a quantum chemistry-based engineering design tool is adapted to increase the optimization for the combustion process is presented. Conclusions for the present work and proposals for future work are given at the ending.

CHAPTER 2 - WHY A 6-10KW ULTRA-MICRO GAS TURBINE?

2.1 PROBLEM STATEMENT

The data published by the gas turbine manufacturers is for business reasons with certain exclusions and thus provides information only related to the data needed for the interfaces of a gas turbine. However, the important data allowing judging the thermodynamic quality of the machines remain hidden. This work highlights the fact that the user likes to get more information to be able to judge the performance of the gas turbine in a power plant. The missing data that should be determined using certain assumptions include mainly firing temperature, polytrophic efficiencies of compressor and turbine blading and others. These parameters must be accurately evaluated for UMGTP performance for carrying out the present investigation.

In order for the proper functioning of the application i.e., multi-copter or a satellite a continuous operation of the power system is required. It is vital to design and fabricate its power systems to meet various requirements. Otherwise, the systems could stop functioning and could cause a potential catastrophe.

2.2 RESEARCH OBJECTIVES

To optimize and improve the overall efficiency of a conceptual Design Ultra-Micro Gas Turbine Power Plant by developing a detailed mathematical model for simulating the

micro gas turbine at various operating conditions for Multi-copter and Satellite Applications.

The study comprises two comparison studies both producing an electrical power output of 6kW. The objectives of the research have two main goals as follows,

1. Open cycle 6kW UMGTP for powering multi-copter vs. alternate power source.
2. Closed cycle 6kW UMGTP for powering satellite vs. alternate power source.

The multi-copter with UMGTP of open cycle gas turbine acts as a power source and its optimization is performed and later compared with the existing battery system. This research proposes a new method and possible configurations to extend the flying capabilities of a multi-copter. To resolve the current limitations, we propose the hybrid approach for extending drone flight duration along with the battery pack.

In the second part of the research, a closed cycle UMGTP is proposed for powering a satellite compared to the existing solar array of panels, Solar and Battery packs. In both cases following tasks were considered to reach the objectives specified. The main objective of this research is to create and simulate the mathematical model to evaluate the thermodynamic performance of a micro gas turbine. It is hard to find literature on micro gas turbine performance analysis using published data by manufacturers. The gas turbine performance in this work for the gas data functions is evaluated using Astra. Problems with more than one iteration variable can be solved with nesting iteration loops.

- To optimize micro gas turbines for variable applications.
- To evaluate the performance of gas power cycles in which the working fluid is always gas throughout the entire cycle.
- To determine, innovative thermodynamic cycle.

- To develop simplified assumptions.
- To analyze both open and closed gas cycles.
- Solve the problem based on the Brayton cycles with a regenerator.
- To consider various configurations and other viable power sources available as threat technology for the proposed solutions.

2.3 TASKS PERFORMED

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- To perform a literature review of the current Micro gas turbines power plant available.
- To model and validate the baseline power plant similar to the Jet cat PHT3 and Jet cat SPT 15 RT models, using Samara University's performance tool ASTRA.
- Built a robust conceptual power design tool capable of modeling a range of thermodynamic cycles by modifying the baseline curves.
- Validated the conceptual power plant model using specification data available from Jet CAT and another public domain literature.
- Model the following chosen concepts using the ASTRA for Optimization of the thermodynamic cycle for both Open and Closed Brayton Cycle.
- To optimize open cycle micro gas turbines for variable applications.

  Fn {TiT, Pr} = < 10 kw ; η > existing system @ sea level, 5 & 22 km.
- To analyze closed gas cycles, from the same variables as constraints for open-cycle gas turbines.

  Output [Open cycle Variables] = Input [Input cycle Variables]
- To evaluate the performance of gas power cycles in which the working fluid is always gas throughout the entire cycle.

  (Co2 working fluid was eliminated, He & Ar was considered for closed cycle)
- To determine, innovative thermodynamic cycle.

  (Modifications to Baseline systems)

- To optimize the ratio of Compressor and Turbine work.
- To perform comparative technology feasibility study with alternate power sources.

CHAPTER 3 – PERFOMANCE ANALYSIS

3.1 PERFORMANCE MODEL

Gas turbine performance modeling can be described from a various literature review of how the mathematical constraints were used to define the system for steady-state modeling. Some assumptions considered were the Flow continuity equations, turbines and compressors were mounted on the same shafts operate at the same speed. Compressor work is equal to turbine work along with the reduction of the required power outputs and the mechanical losses, Conservation of momentum equations and various Component characteristics was used. Extrapolation of components characteristics data is mapped based on the mode of operation for specific performance calculations. At times there is a problem that raises the iterative non-convergences when modeling the micro gas turbine power plants.

Table 1 Comparison between existing vs developed model

Functions	**Existing models**	**Developed model**
Unknown variations in components performance parameters are computed	Physics based mathematical modeling Data based modeling	Hybrid scheme that combine both physics-based and data-driven approaches
Applications	Performance deterioration in a gas turbine, Diagnostics of Gas turbine, Material determination for erosion, corrosion, surface cracking, increase in tip and seal clearance.	Unknown variations in components performance parameters are computed.
Operations	Part or full load, start-stop cycles, and fuel type	High altitude investigations & Fuel optimization using Quantum Chemistry
Methodology	A compressor map adaptation technique to enhance the accuracy of performance-based diagnostics of a heavy-duty gas turbine	Micro gas turbines have higher accuracy with this methodology.
Weight Estimation	Weight estimation models for micro gas turbines are not validated	Weight estimation models for micro gas turbines are validated.

CHAPTER 4 - THERMODYNAMIC OPTIMISATION

4.1 Design optimization

The power plant system components have integrated empirical design rules that support the correlations with variable parameters at required constraints to meet the target functions as specified by the designer. Any designer has to start with a traditional system approach of trial and error to optimize and tune the parameters. The process of tuning numerous design variables until the system achieves the required parameters is called design optimization. The main drawback of this method when dealing with multi-dimensional, nonlinear and complex problems the selection process is trivial. The goal is to generate the best possible solution to improve the design requirements for the given constraints.

4.2 Astra

Modeling of accurate gas turbine performance and simulations leads to the faster robust design of the required gas turbine. The software that Samara University has built for performance simulation is ASTRA. This has a graphical user interface (GUI) and performs thermodynamic calculations [9]. The computer-aided system ASTRA developed at Samara University used for Parametric Analysis and optimization for the required gas turbine power-plant and the depiction of software as shown in figure 1.

Figure 1: Logo of the power plant simulation software ASTRA, developed at Samara University

Parametric Analysis of our Micro Gas turbine engine cycle analysis was a performance for different engine cycles to predict and study their performance and their effects on losses in real conditions. The one-dimensional flow was considered for performing a variety of specific heats, components losses were considered at mass flow at various components. The exhaust pressure need not be equal to atmospheric pressure.

CHAPTER 5 REQUIREMENTS

5.1 Requirements for a multi-copter electrical propulsion system.

A multi-copter specified here needs to lift a mass of 200 kg and should be able to produce 400 kg of thrust for hovering capabilities. Additional requirements of the multi-copter should be able to carry the payload to a distance of 300 km without refuelling. The vehicle is expected to have a maximum speed of 145 km/s. 400 kg of lift thrust could be generated by using 8 motors of 4 kW each producing about 50 kg of thrust. The propeller size and the motor stator correlates to each other so specific iterations need to be performed. Apart from this, the selection of motor also includes factors such as weight efficiency power and torque. However, the scope of this paper does not study or design the quadcopter. These performance requirements cannot be matched by an Electric Drones with current battery mass technologies, thus comparison studies of Gas turbine powered multi-copter Vs Electric Gas turbine of the same configuration cannot be performed.

All parameter configurations needed to be under certain geometrical requirements. The designs should be easy assembling using the available parts mentioned. The propeller considered was G40x13.1 Prop-2PCS/PAIR developed by T motors 237grams and could produce a thrust of 60 kg. The T-Motor U15 II KV80 engine is suitable for use in super-heavy multi-copters and could produce a thrust of 36kg at 8.6 kW and has a mass of 1640 g. The motor requires a recommended battery of 12-24S.

5.3 Requirements for a Pseudo Satellite.

High altitude pseudo satellite also known as HAPS could float or would fly above conventional aircraft thus having a continuous coverage of the underlying territory at all times of 24*7. Some of the target applications include search and rescue missions, disaster relief, environmental and agriculture monitoring assistants. HAPS offers complimentary solution to overcome the difficulties faced by satellites and drones system by offering a reliable platform. In recent times, HAPS are used extensively to provide internet services and data activities in remote areas. At high altitudes temperatures could reach minus 184 degrees Fahrenheit in the stratosphere. At an altitude of 20 km, despite the roundness of the Earth, a HAPS could function over a radius of 200 km.

AZTROS-I was the first stratospheric space mission to support the Sustainable Development Goals (SDG) of the United Nations, in order to test five Nano Satellites KALAM SAT | AGNI SAT | ANITHA SAT | NASO-APRS SAT on board Aztratos Stratospheric Platform by Aztra Labs in partnership with Aztra Labs Space Technology to the Earth - Leader of Initiative 1. Universidad Nacional Autonoma de Mexico (UNAM) 2. Facultad de Ciencias - UNAM 3. Samara University 4. The Valles Marineris 5. Team Synergy Moon 6. Space Kids 7. Kosmos sp 8. NASO 9. KSF Morocco 10. Pioneers 11. Confederation of Industrial Chamber of Mexico (CONCAMIN), was sent to the edge of the space with the commitment and responsibility to contribute awareness and monitoring the effects of climate change.

Figure 2 Logo of the mission dedicated to the SDG UNOOSA

CHAPTER 6 – MODEL VALIDATION

The engine characterization uses the following parameters for output power, overall dimensions, and 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 to various turbine inlet temperatures .

To predict the gas turbine power-plant performances an analysis tool was developed based on physics that uses multivariate optimization method to solve the gas turbine thermodynamic equations. For validating this approach JET CAT PHT3 and JET CAT SPT 15 RT with various operating points were calibrated. During the cross-validation method almost all the key thermodynamic parameters were estimated to be accurate as predicted accurately.

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. The net power of the gas turbine power-plant of the open cycle gas turbine power-plant is given by the following expression along with the net overall efficiency.

$$\eta_{(net)} = \frac{Output\ power\ generated\ (kW)}{Rate\ of\ chemical\ energy\ consumed} = \frac{6kW}{Heat\ of\ reaction\left(4.3 * \frac{10^7 J}{kg}\right) * Fuel\ flow\ rate} \qquad (1)$$

$$\eta_{Overall} = \eta_{mechanical} * \eta_{combustion} * \eta_{energyconversion} \qquad (2)$$

To accomplish this goal, an existing system were used to validate the results. The influence of several effective parameters (such as the pressure ratio of the compressor, the inlet temperature of turbine, altitude of the flight, working fluid, choice of working fuels) are presented at the section thermodynamic results and discussion. The theoretical model was compared with the existing power-plant families with similar output power and operating conditions. These are shown in the table 2 as follows.

Table 2 : Model Validation with existing power plant families

Data validation	**Computed Value @ 5.5 kW**	**Jet Cat PHT3**	**Computed Value @ 15 kW**	**Jet Cat SPT 15 RT**
Output power (kW)	5.5	5.5	15	15
Pressure ratio	1.8	1.8	3.5	3.5
Mass Flow rate (Kg/s)	0.167	0.15	0.382	0.37
Turbine inlet Temperature (K)	1325	1325	1325	1325
Fuel consumption (ml/min)	240	270	480	550
Exit Gas Temperature (K)	744	730	775	730

8.1 Concept schematic

8.5 Novel Innovative cycles concepts

Various cycles were investigated for both closed and open cycle gas turbine with a function of power and altitude and TiT as constraints. The mathematical model comprises 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.

$$P_{GT} = P_{Turbine} - P_{Compressor} \qquad (3)$$

$$P_{electric} = \eta_{Electric} * \eta_{mech} * \mathrm{M}_{dry\ air} * \mathrm{P}_{GT} \qquad (4)$$

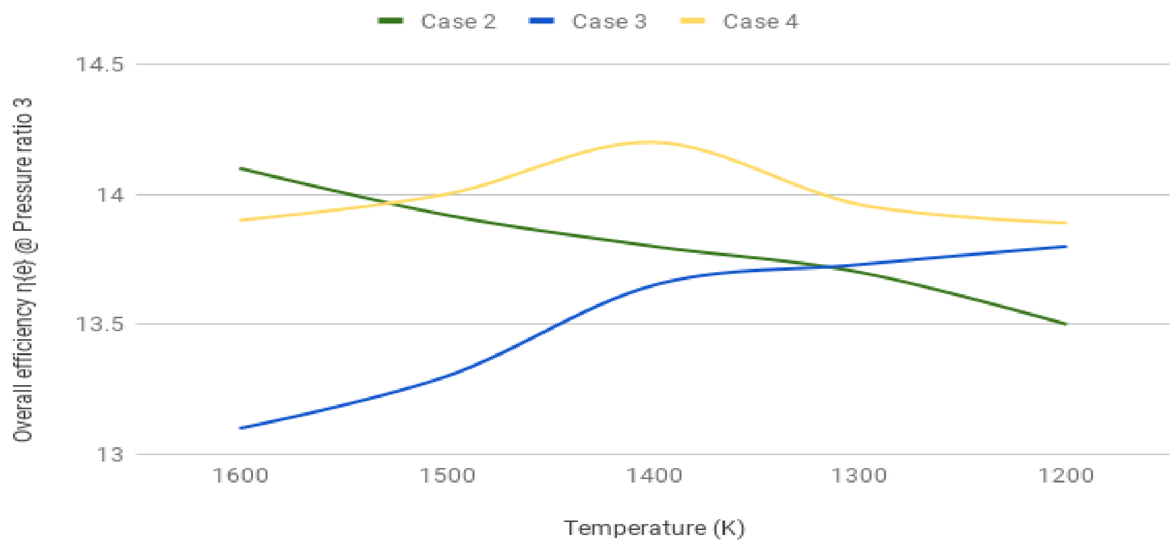

Figure 2 Investigating three cases Conventional re-heater – case 2, Alternative re-heater – case 3 and Solar based combustor case 4 for their overall efficiency at 22km altitude.

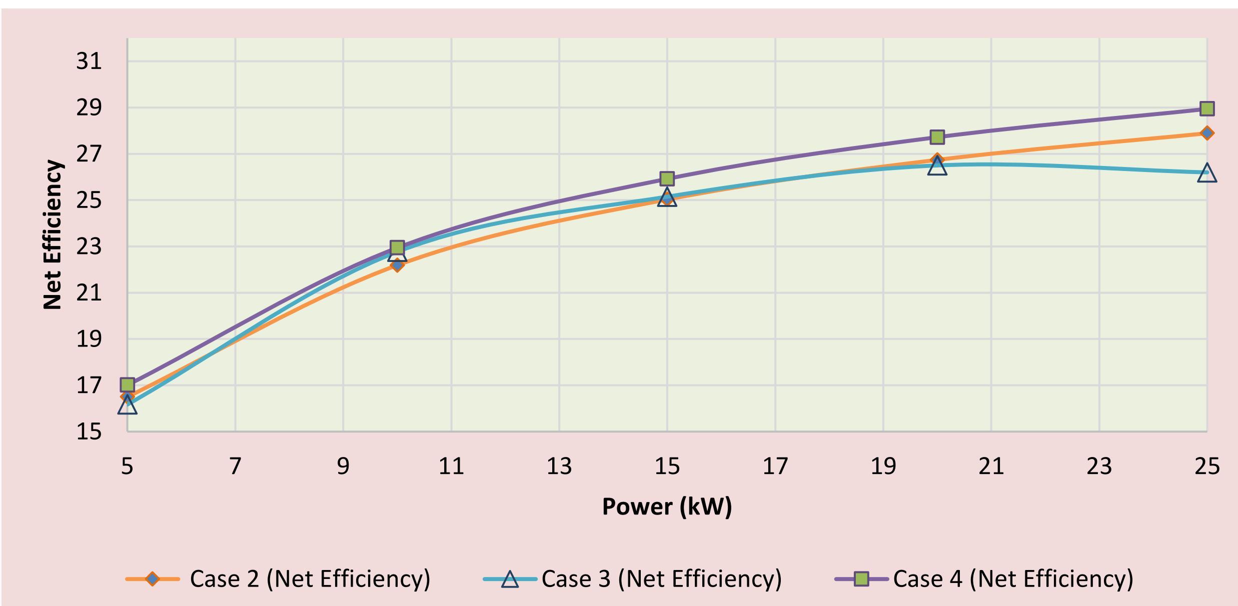

Figure 3 Investigating three cases Conventional re-heater – case 2, Alternative re-heater – case 3 and Solar based combustor case 4 for their overall efficiency based on power requirement.

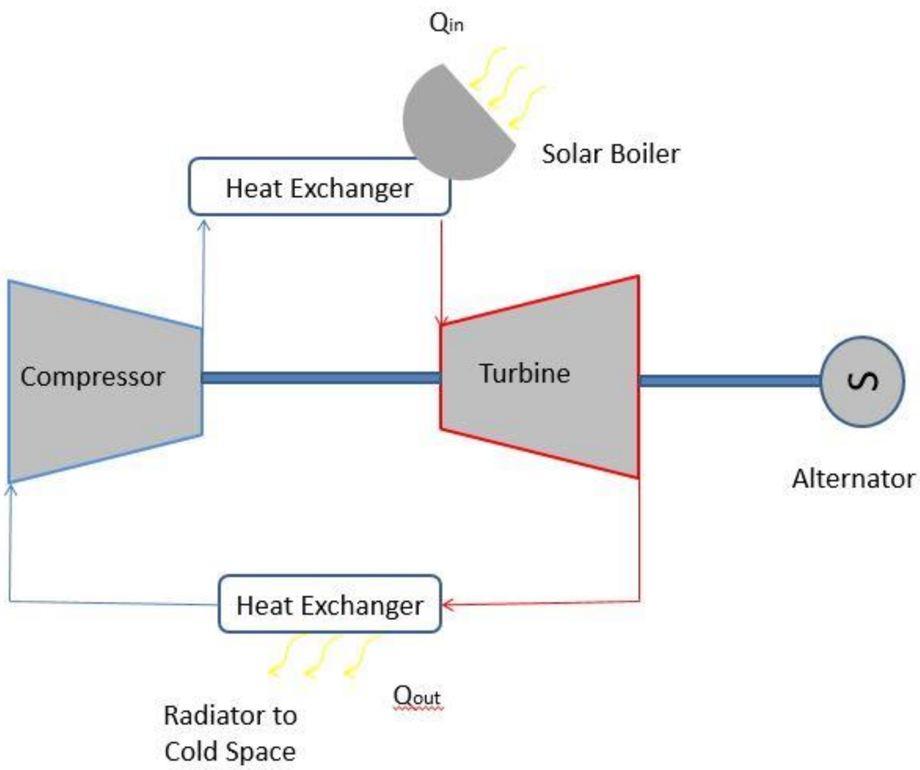

Figure 5 Architecture to simulate closed cycle gas turbine

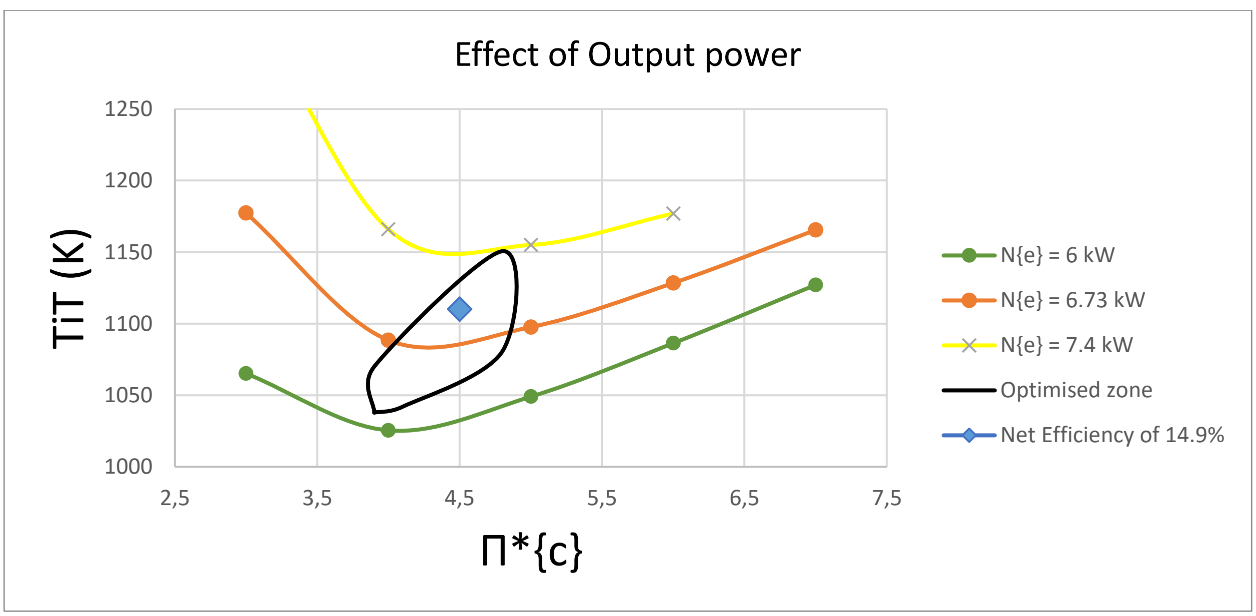

Figure 6: Effect of output power wrt to pressure ratio and turbine inlet temperature (K) for closed cycle.

CONCLUSIONS

The following conclusions are drawn from this work:

i) A detailed computational model for gas turbine thermodynamic analysis has been presented and applied to 4 cases of open cycle gas turbines and 1 case of closed cycle micro gas turbine.

ii) The model conforms with the efficiency and output with existing similar gas turbines in the market very closely thus validating the model.

iii) Based on the values of (Altitude, sink temperatures, TiT, pressure ratio, power output and efficiency) parametric study has been carried out for all configurations of the micro gas turbine power plant.

IV) The open cycle gas turbine power plants have higher efficiency at higher altitudes due to the advantage in the ambient conditions, however the size of the compressor blades tends to become massive to compress the rarefied gases.

v) The open cycle gas turbine at TiT < 1150 K a solar heater adds advantage to the system. There exists an optimum overall compressor pressure ratio and turbine inlet temperature in all the various configurations that were examined.

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