An overview of micro gas turbine engine performance investigation.

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An overview on the performance investigation and improvement of micro gas turbine engine

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Abstract

Micro gas turbine (MGT) engines has become popular technology in Remote Control (RC) jets. They are are also used in small electrical power generation plants, hybrid electric vehicle applications and as auxilliary power units (AUPs) for modern aircrafts. As at present, a substantial number of research and papers have been published in this area to assess and improve the performance of MGTs. This paper intends to present an outlook of MGTs system performance analysis and improvement evaluation-based methods available in open literature.

Additional keywords: MGT,Compressor

Nomenclature

APU	auxiliary power unit
UAV	unmanned aerial vehicle
kW	kilowatt
rpm	revolution per minute
BMT	baird micro turbine
KS	kerosene start
N	newton
TIT	turbine inlet temperature
CFD	computational fluid dynamics

Greek

η	efficiency [%]
γ	heat ratio [-]
π	pressure ratio [-]

Subscripts

a	air
c	compressor
cc	combustion chamber
m	mechanical
0	total

1 Introduction

The use of micro gas turbine (MGT) engine is increasingly becoming popular technology in the commercial aviation and hobby industries. They are employed in unmanned aerial vehicles (UAVs) applications used in missions such as national security, telecommunications, real-time reconnaissance, remote sensing, crime fighting, disaster management, agriculture and election monitoring[65].[13] MGTs are also used in hybrid electric vehicles and small electricity generating plant (combined heat and power) applications and as auxiliary power units (APUs) for modern aircraft[43].[7] They are suitable for such applications due to their high density to weight ratio, multi-fuel capability and simple design, low energy costs and emissions[82].[1] MGTs can be regarded as a prospective and compact competitor to the other propulsion system power supplies such as battery cells.[5] These engines have interrelated components which have non-linear characteristics. Therefore, the overall engine performance depends on the individual engine element's performance.

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2 Micro Gas Turbine Engine

A micro gas turbine engine (shown in Figure 1) is a single spool (shaft) rotary engine that extracts energy from a flow of micro combustion gas. The engine is a miniature replica of larger conventional gas turbine engines. They have thermal efficiency varying between 10% and 25% and power and thrust capacity in the range of 15-300 kW and 30-200 N at a rotational speed of 20 000-150 000 rpm[51030].[18] The engine is made up of a centrifugal compressor with either a radial or crossover vanned diffuser, an annular straight through or reverse flow combustor, axial flow turbine and a fixed convergent propelling nozzle at the downstream of the engine.

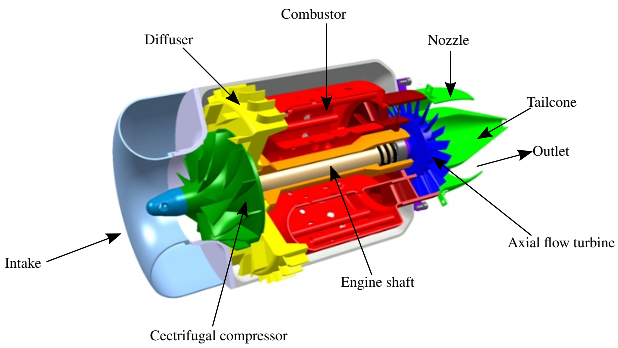

Figure 1 Micro gas turbine engine.

During operation the engine centrifugal compressor draws in air from its environs into the engine. The air is then compressed to increase its total pressure and temperature. The compressor diffuser increases the static pressure of the air and lowers its velocity as it passes through the diverging passages (vanes). The low velocity air mixes with fuel in the combustion chamber to burn continuously to produce high temperature, high pressure and velocity gas. The turbine expands the high temperature gas from the combustion process to produce mechanical shaft power to drive the compressor. The convergent exhaust propelling nozzle accelerates the exhaust gases from the turbine to create thrust for propulsion.

3 MGT Thermodynamic Working Cycle

Micro gas turbine operates on the principles of Brayton open gas/air cycle. The cycle is represented in temperature-entropy (T-s) and pressure-volume (p-v) diagram as shown in Figures 2 and 3. In Brayton open cycle the engine working fluid exit/exhaust into the atmosphere after expansion in the turbine and/or the exhaust propelling nozzle.

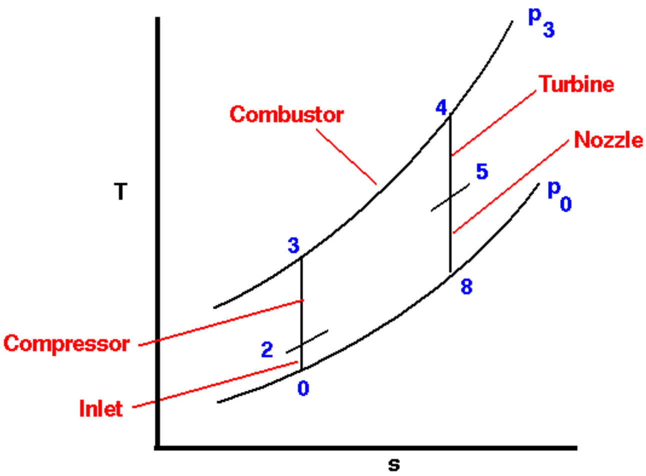

Figure 2 T-s diagram.[9]

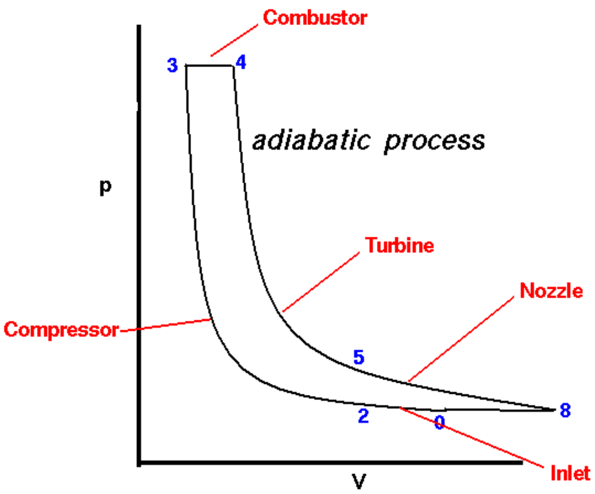

Figure 3 p-v diagram.[9]

The cycle is assumed to have isentropic air compression, constant pressure heat addition, isentropic gas expansion and constant pressure heat rejection. In practice, these processes are not isentropic. As shown in Figures 2 and 3 isentropic compression occurs at point 0-3 in the compressor, constant pressure heat addition at 3-4 in the combustion chamber, isentropic expansion at position 4-5 in the turbine, isentropic workdone at station 5-8 in the nozzle and finally constant pressure heat rejection from 8-0 into the atmosphere.

3.1 MGT Cycle Analysis

Micro gas turbine engine as any turbomachinery can be evaluated using the transport equations, thus mass, momentum and energy equations. The engine cycle analysis starts at the cold section (compressor inlet to combustor upstream) of the engine to the hot section (combustor upstream to nozzle outlet/downstream) of the engine. These equations are used to determined the stage and/or engine station thermodynamic parameters.

From Figures 2 and 3 the compressor ratio and efficiency are determined as using these relations:

$$\pi_c = \frac{p_{03}}{p_{00}} \tag{1}$$

$$\eta_c = \frac{T_{00}(\pi_c^{\frac{\gamma-1}{\gamma}} - 1)}{T_{03} - T_{00}} \tag{2}$$

Knowing the compressor parameters the combustion thermodynamic properties or values are found. The combustion pressure loss/drop is usally expressed as a percentage of the compressor downstream stagnation ppressure. The maximum engine cycle temperature is estimated as:

$$T_{04} = T_{03} + \frac{\eta_{cc} f LHV}{c_{pg}} \tag{3}$$

Applying the principles of work and speed compatibility the turbine upstream temperature is computed.

$$T_{05} = T_{04} - \frac{\dot{m}_a c_{pa}(T_{03} - T_{00})}{\dot{m}_g c_{pg} \eta_m} \tag{4}$$

With known turbine parameters the nozzle thermdynamic values are determined. Having estimated the nozzle exhaust velocity the engine thrust is found, thus for propulsion purposes.

$$F_{net} = \dot{m}_a(u_e - u_0) \tag{5}$$

Similarly, for electrical power generation application the power can be determined using the required formula.

4 MGT Performance modelling

The performance of an engine at the design and off-design points can be obtained from gas turbine performance modelling. Off-design evaluation is required to model the operating range of gas turbines due to the engineâĂŹs nonlinear thermodynamic behaviour. Off-design behaviour is also used to examine the impact of a change in engine component characteristics on engine output. Cumpsty (2003) agrees that a gas turbineâĂŹs performance at off-design conditions should be satisfactory and safe irrespective of its non-linear behaviour. El-Sayed (2008) emphasises that although gas turbines are designed to operate effectively at specific design points, the engine should also work acceptably at off-design conditions. According to Asgari (2014), off-design modelling is the most suitable means of optimising, maintaining and predicting the performance of a gas turbine. The off-design performance of a gas turbines involves performance predictions, condition monitoring and degradation analysis. The engine diagnosis and degradation analysis are normally executed based on the performance predictions (Suraweera, 2011). The off-design performance of gas turbines can be evaluated using the following methods: component matching, stage stacking, gas path analysis, computational fluid dynamics and the Wittenberg method (Thirunavukarasu, 2013). These modelling methods are mathematically formulated with linear and nonlinear equations into computer programs for performance simulations.

5 MGT Performance Challenges

Although MGTs have outstanding advantages over its competitors in the propulsion and power environment, they are faced with the drawbacks of limited or lower overall (peak) or turbine inlet temperature of the system due to ineffective cooling.[15] They have turbine inlet temperatures (TIT) in between 600 and 900 K. Additionally, miniaturization of these engines create problems such as lower engine Reynolds Numbers, poor engine heat transfer, larger tip clearances, and other mechanical and geometrical limitations.

Reynolds Number: Reynolds number play a critical role in turbomachinery designs, therefore it should be much considered when designing MGTs. Small gas turbine engines operate in a highly viscous environment, hence having low Reynolds Number[5].[8] The viscous force dominates the inertia forces, therfore, slowing down the mixing of fuel and air, hot and cold gasses in the combustor.[8] Hence, the combustion residence time is reduced.[14] The highly dominant viscous forces between engine components increase the pressure and temperature losses and other thermodynamic variation in the engine.[8] Lower Reynolds numbers decreases the compressor efficiency as a result of transition and separation effects in the compressor.[6]

Heat transfer: Internal heat transfer in the engine have an essential influence on the engine efficiency and power output. The engine has a higher surface to volume ratio and this creates heat transfer complexities in the engine[68].[5] Higher thermal losses decreases combustor efficiency and flammability.

Higher tip clearance: Higher tip clearance losses are inherent in MGTs due short compressor and turbine blade heights. The higher the tip clearance the higher performance deterioration and higher fuel consumption of gas turbines.[30] MGTs compressor have low-pressure ratios due to smaller blade heights. The compressor efficiency decreases due high tip clearance.[30]

Lower cycle peak temperature: Effective and efficient cooling significantly increases the turbine inlet temperature (TIT) of the engine. Larger gas turbines use bled air from the compressor to cool the turbine blades. Micro gas turbines hardly accommodate this cooling technique and are susceptible to lower turbine inlet temperature.

Mechanical and geometrical restrictions: The manufacturing of smaller gas turbine is similar to that of a larger gas turbine. The manufacturing accuracy attained for larger gas turbines is impossible for MGTs, hence the engine wouldn't perform as expected. They have high relative surface roughness from the design process, therefore having high engine losses. In addition, excessive frictional losses in the engine bearings have an adverse effect on the engine cycle efficiency.

6 MGTs Performance Studies

Different academic research projects have been undertaken on micro gas turbines with the purpose of improving the performance. This includes MGTs compressor and turbine stage design improvements (new designs and flow physics analyses), new combustor designs and combustion analysis. The intent of these researches was to optimise the engine performance parameters such as the specific fuel consumption, pressure ratio, cycle peak temperature, system pressure losses, turbine and compressor efficiencies and the engine thrust and power. Some of the techniques considered for the performance improvements are discussed.

6.1 Compressor Stage Investigations

Compressor is a turbo machinery device that increases the pressure of a fluid. It provides high pressure and high volume air. Centrifigal compressors is an aerodynamic compressors. It is used for low power applications such as micro gas turbine applications. The compressors used in MGT applications incorpoartes radial or crossover (curved) diffusers to reduce the velocity of the airflow and increase the pressure. Figure 4 shows the compressor stage of a micro gas turbine engine.

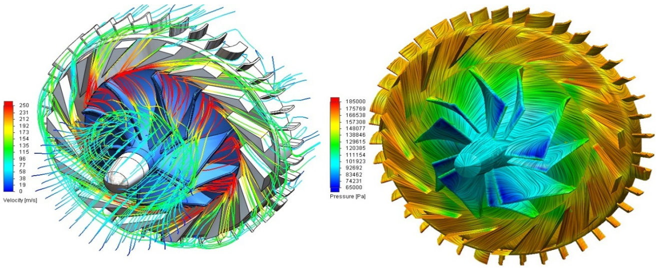

Figure 4 Compressor stage performance analysis.

Centrifugal compressors are inherent with low efficiencies due Reynolds Number, blade tip leakage, growth of boundary layer and separation on the blades, therefore having adverse effect on the engine performance output. In recent years, reseaches have been directed towards increasing the performance of MGT compressors through redesigning and reconfiguration of the compressor impeller and diffuser as well computational modeling and simulations.

Ling et al[18] designed and improved the compressor stage of the KJ66 micro jet engine using ANSYS CFX. The intent was to improve the efficiency and performance otuput of the engine. They increased the pressure ratio of the centrifugal compressor at a lower mass flow rate. They contend that the new design outperformed the baseline/standard compressor.

Aghaei and Mesgharpoor[20] deals with the design and computational fluid dynamics analysis of micro gas turbine comppressor. Their design involved 1D, 3D theoretical and computational fluid dyanmics(CFD) using ANSYS FLUENT to model the compressor stage. A pressure ratio of 4 was obtained for the new compressor.

Jie and Guoping[19] discussed the re-designed of a 11 cm MGT diffuser of a compressor stage. They sought to investigate the effect of cross-sectional area distribution along the flow path of the new diffuser's performance. The newly design diffuser configuration was equipped with main and splitter blades. The computational fluid dynamics (CFD) and the experimental predictions showed that the pressure coeffiecient and pressure recovery coefficient improved by 0.65 and 0.9. It was found that the thrust of the engine increase by 11% and the specific fuel consumption decreased by 9% decrease.

Tough et al.[21] improved the performance of MGT compressor impeller using differnt inlet blade angles. They sought to study the effects of different blade inlet angle and backward sweep on the compressor performance. The writers concluded that reducing the backsweep and the inlet blade angle by 3° and 2° produced stable operating range, high pressure ratio and efficiency.

Krige[7] redesigned the BMT 120 KS engine vaned diffuser.

He aimed to maximise the compressor stage pressure recovery in order to increase the engine's total-to-static pressure ratio, mass flow and thrust output. The experimental and numerical examination showed that the diffuser pressure recovery increased from 0.48 to 0.73. The static-to-static pressure ratio across the diffuser increased from 1.39 to 1.44.

Van Der Merwe[22] designed and optimised a centrifugal compressor impeller of the BMT engine. The author pursued to achieve a total-to-total pressure ratio of 4.72 and an isentropic compressor efficiency of 79.8% at a mass flow rate of 0.325 kg/s. The new impeller performance was validated by comparing its mean-line, experimental and CFD results. He showed that the experimental and numerical data correlated well.

De Villiers[17] employed a 1D (1-dimensional) mean-line code and CFD software codes FINETM/Turbo and FINETM/Design3D to design a centrifugal compressor stage for the BMT engine. According to the author, the new compressor stage yielded a total-to-static pressure ratio of 3.0, and efficiency of 76.5% and a thrust of 170 N at a rotational speed of 119 000 rpm compared to the origininal BMT engine. Burger (2016) designed and optimised a crossover diffuser for the BMT engine. The crossover diffuser combined with Van der Merwe's impeller improved the compressor stage total-to-static pressure ratio from 2.62 to 3.65.

6.2 Combustor Analysis and Improvement

The main function of a combustion chamber is to increase the maximum allowable temperature of the gas turbine working fluid. The fuel mixes with air and undergoes exothermic chemical reaction to release thermal energy.[29] Figure 5 depicts a microjet engine combustor. It consist of inner and outer liners with dilution holes, vaporizing tubes and fuel injection needles.

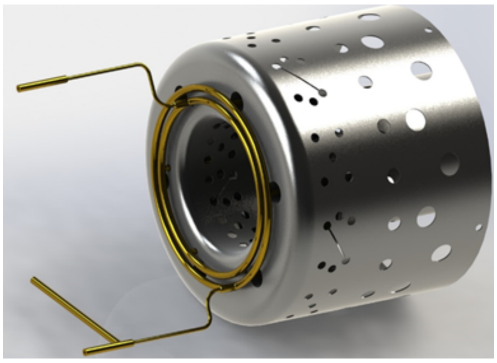

Figure 5 Combustor.

Combustor design is the most complex among MGT components, hence the design of effective and efficient combustor is indispensable for the performance of the engine. Previous combustor design procedures were based on experimental results and empirically derived design rule. Micro gas turbines to date uses constant pressure combustor. They are are simple to implement and provide a relatively steady, uniform gas flow to the turbine. Although, they have practical benefits the flow behaviour in the combustor is complex due compactness and high viscous environment. The combustion efficiency, flame stability and ignition, wall cooling, prssure loss and emission control are some of the common challenges faced in the design and performance of a small jet engine combustors.[27] These parameters ascertain the engine operational range, durability, cost, maintainability and emissions characteristics.[28]

Jaafar et al.[25] analysed a micro combustor aerodynamic flow using FLUENT. Their focus was on the effects of swirl on the flow inside the combustor. They employed four axial vane swirlers in the order of 20°, 30°, 45° and 60° with swirl numbers of 0.27, 0.42, 0.74, and 1.285 respectively. The investigation showed that high swirl vane angles increases swirling in combustion chambers, therefore increasing turbulence strength, recirculation zone size and the amount of recirculation mass at increasing pressure loss in the combustor.

Guidez et al.[23] described the studies performed on combustion characteristics of a miniature combustor. The aim was to examine combustion stability and efficiency.Raman spectroscopy and 1D Rayleigh scattering and standard thermodynamic measurements were used to estimate the temperature profile and main species concentration at the combustor outlet. They measured combustion efficiency of 80%.

Chaudhari et al.[24] report the design and simulation of a miniature annular combustion chamber applying ANSYS CFX. They evaluated the impact of flow patterns and temperature distributions on the combustion chamber liner walls. The numerical results showed that the combustion chamber walls were significantly affected by combustion flames which can cause combustor failure.

Gieras[4] performed computational modeling of the aerodynamic flow in the GTM-120 micro jet engine combustor. They considered the effect of engine downsizing on the mass flow, pressure losses and heat transfer in the combustor. The aim of their research was to maximise thermal efficiency by minimising fuel consumption and controlling emissions. A combustion pressure loss of 10% was obtained. Combustion pressure drop 4-8% are usually obtained for miniature combustors. They emphasised that the size and shape of diffuser channels (vanes) give rise to high speed and non-uniformity of a flow, which are an important source of pressure loss in the combustor. The consequence of excessive flow velocity in the diffuser and the annulus may also restrict the flow through the first row of holes in the combustion chamber. Therefore, deteriorating the process of mixing fuel with air.

Krieger et al.[26] presented the design, computational and experimental evaluation of a microjet engine combustion chamber. They analysed the flow physics of heat transfer and temperature patterns in the combustion chamber. The numerical study was carried out with CFD commercial software ANSYS FLUENT, using the RANS turbulent model for the simulation. The authors argued that the numerical and experimental results correlate well.

According to Armstrong and Verstraete (2014), a semi-constant volume combustor increases the pressure in the combustor and reduces engine fuel consumption. The authors redesigned a constant volume combustor for a micro jet engine. Their proposed design consist of a choked first stage nozzle guide vane, which functions as a flow restrictor, combined with a mechanical valve at the combustion chamber upstream. They contend that the new design could possibly improve the specific fuel consumption and thrust by 27% and 35% for a combustiona pressure ratio of 1.1.

6.3 Wave Rotor Approach

The wave rotor technique employs a pressure exchanging device which uses pressure waves to transfer energy between a gas turbine engine's working fluids (Akbari and Müller, 2003). The pressure and temperature of the low working fluid of the gas turbine GT is then increased. This tool can either be a rotating drum or disc attached to the compressor/turbine or the combustor of the engine. The wave rotor concept can either be in radial or axial form.

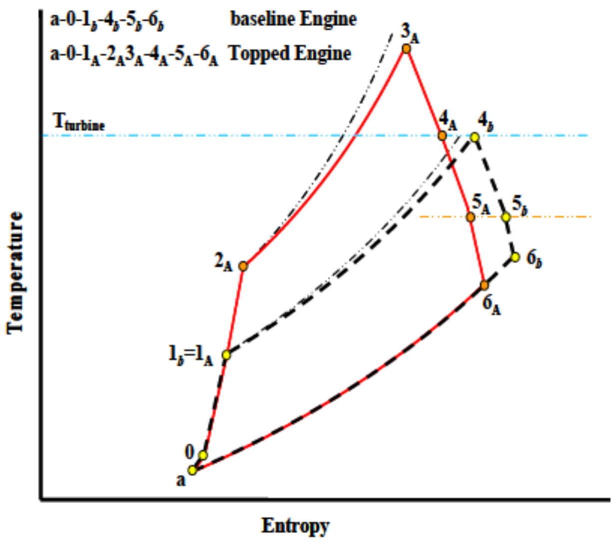

Figure 6 Wave Rotor T-s diagram.

Akbari and Müller (2003) suggest that the wave-rotor technique is the efficient approach to improve small jet engine thermodynamic cycle performance. The authors investigated and evaluated the performance of a small turbojet engine at different thermodynamic conditions with a four-port wave rotor. According to the authors, the outcome of their investigation showed significant improvement in the combustion pressures and temperatures compared to the baseline engine.

Wilson and Paxson (1993) investigated the performance of a simple turbojet engine with the wave-rotor enhanced technique. They obtained an increase of 1 to 2% for the engine thermal efficiency and 10 to 16% for the specific power.

Snyder and Fish (1996) evaluated the performance benefits of the wave rotorcycle in a small turboshaft engine. The engine topped with wave rotor showed a considerable reduction of 22% in specific fuel consumption (SFC) compared to the baseline engine.

According to Iancu et al. (2005), the wave-rotor cycle increases the overall gas turbine compression and expansion ratio. They argued that the waverotor technique can achieve a 50 to 83% increase in compression efficiency for ultra-micro and small gas turbines.

6.4 Axial Flow Turbine Assessment

Bar and Czarnecki (2009) performed a mean line and CFD analysis of a micro jet axial turbine. The Concept NREC AXCENT code was used for aerodynamic computations to develop 2D and 3D entropy performance contours for the turbine. The authors assert that a lower tip clearance, higher Reynolds Number, and specific speed coefficient boost turbine efficiency and overall engine performance.

Verstraete et al. (2010) investigated and improved the overall performance of the KJ66 turbojet engine. A spherical dimple vortex turbine blade profile was adapted for the axial turbine stage in order to obtain the required performance improvement. The authors claim that the improved engine showed an efficiency increase of 2 to 6% compared to the baseline engine.

Basson (2014) designed new turbine stages as the replacement for the existing turbine of the BMT 120 KS engine. He performed 1D and 3D numerical analyses on the new turbines.

6.5 Overall System Analysis

Pachidis et al. (2006) performed turbofan engine performance analysis with ANSYS FLUENT. They concluded that good correlation was established between the baseline engine PYTHIA simulation and the CFD results.

Jong et al 2007 studied the performance of miniature gas turbine engine measuring its thermodynamic or engine performance parameters.

Amirante et al. (2007) optimised the intake of the Pegasus small jet engine. They analysed and improved the effects of boundary layer on the engine intake nozzle and velocity profile using ANSYS FLUENT combined with the progressive optimisation technique. They conclude that the numerical and experimental data match well.

Trebunskikh et al. (2012) examined the performance of the KJ66 micro turbine engine with the FloEFD, CFD software code. The authors concluded that the numerical results correlate well with the experimental test results. However, they reported that non-uniform fluid temperature distributions at the combustor outlet, and wedge diffuser inefficiencies contribute towards poor performance of the engine.

Badami et al. (2013) used ANSYS FLUENT to analyse the performance of the SR-30 micro jet engine. The intent was to investigate the engine thermodynamic cycle performance. According to the authors, the CFD data showed consistent matching with the experimental values. The nozzle and turbine pressure ratios showed differences of less than 5% and the mass flow rate and thrust values showed differences close to 2% and 10% respectively.

Krivcov et al. (2014) studied the performance of a micro gas turbine engine with ANSYS CFX. The authors claim that good agreement was established between the computational results and the thermodynamic 1D code for the engine.

Oppong (2016) investigated the performance of the BMT 120 KS engine using theoretical (numerical and analytical) and experimental measurements of thermodynamic properties. He examined matching of the engine components using Flownex SE and GasTurb simulation softwares. It was found that

7 Conclusion

8 Acknowledgement

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