Micro Gas Turbine Performance Evaluation*

[1]F. Oppong, [1]S.J Van Der Spuy, [1]T.W. Von Backstrṑm, and [2]A. Lacina Diaby
[1] Stellenbosch University, South Africa
[2]University of Mines and Technology, P.O. Box 237, Tarkwa, Ghana

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Abstract

The deployment of Micro Gas Turbine (MGT) engines in unmanned aerial vehicles, hybrid electric vehicles, and small power plant applications is increasingly becoming popular due to their high power to weight ratios. In this paper, MGT performance evaluation is investigated for the Baird Micro Turbine 120 Kerosene Start engine (BMT 120 KS). This investigation involves component matching of the engine and its modifications. Analytical and numerical approaches were employed to review the thermodynamic cycle of the engine. The performance predictions of the engine and its modifications were found to correlate well with available engine experimental data.

Keywords: Simulation, GasTurb, Flownex, Component Matching

1 Introduction

Micro Gas Turbine (MGT) engines have evolved as a popular technology in the commercial aviation and hobby industry (Verstraete *et al.* 2014). They are used in unmanned aerial vehicles (UAVs), hybrid electric vehicles, and small electricity generation applications (Simon & Jiang 2003). They are also used as auxiliary power units (APU) for modern aircraft (Trebunskikh *et al.* 2012). They are suitable for these applications due to their high power to weight ratios. MGT individual component performance dictates the engine overall performance (Bakalis & Stamatis, 2011).

As such, considerable research efforts have been directed towards improving the performance of individual components of the Baird Micro Turbine 120 Kerosene Start engine (BMT 120 KS) to increase its thrust (Krige, 2013; Van der Merwe, 2012; De Villiers, 2014; Basson, 2014; Burger, 2015). Despite the improved component performance, the engine suffers from high exhaust temperature, inability to reach design rotational speed, and high fuel consumption, possibly due to component mismatch. In this paper, the component matching for the BMT engine is investigated. On this basis, both analytical and numerical analyses are performed to review the BMT thermodynamic cycle as a basis for better component matching.

1.1 BMT 120 KS Engine

The BMT 120 KS engine depicted in Fig. 1 is a single spool engine. It consists of a centrifugal compressor, with a radial wedge diffuser, a straight through annular combustor, an axial flow turbine, and a fixed convergent nozzle. Air is induced and compressed in the compressor. The compressed air then mixes with fuel in the combustion chamber where it is ignited to increase the temperature. The turbine expands the hot gas from the combustor to produce mechanical power to drive the compressor. The nozzle accelerates the hot gas from the turbine to increase its kinetic energy to produce thrust for propulsion.

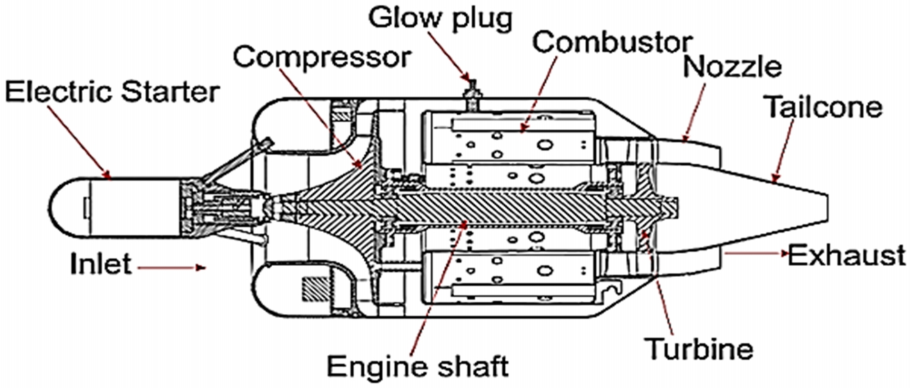

Fig. 1 BMT 120 KS Engine

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2 Resources and Methods Used

2.1 Analytical Approach

The Brayton open-air cycle determines the thermodynamic conditions at the interface between the components of the engine. Fig. 2 shows the thermodynamic representation of the Brayton open-air cycle with the various station points. Each component of the engine is treated as a separate control volume. Table 1 depicts the engine parameters used for the calculations. Some of the values were assumed while others were acquired from literature and manufacturers data (Baird, 2011). All calculations performed iteratively in a Python programming code. The total conditions at the inlet of the compressor are used to determine an estimated value for the inlet velocity of air into the engine; hence, an iterative method is used to determine the actual static temperature, static pressure as well as the velocity. Engine intake conditions are assumed as standard sea level.

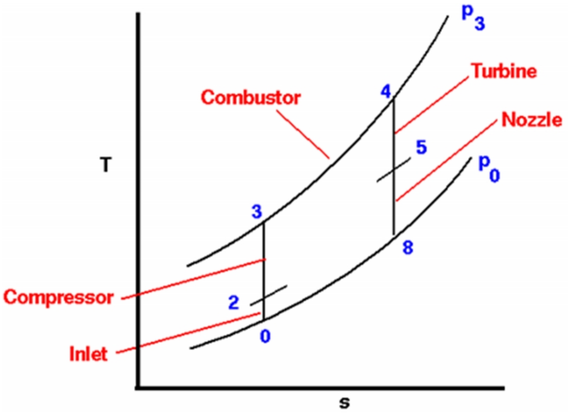

Fig. 2 T-S Diagram

Table 1 BMT 120 KS basic engine parameters

Parameter	Name of Parameter	Value
Ambient conditions	Ambient temperature	288 K
	Ambient pressure	101 kPa
BMT parameters	Compressor pressure ratio	3.15
	Compressor efficiency	81.6%
	Turbine efficiency	85%
	Combustion efficiency	90%
	Combustion pressure loss	10%
	Mechanical efficiency	98%
	Mass flow	0.288 kg/s
	Rotational speed	120000 rpm
Other parameters	Air specific heat	1005 J/kgK
	Hot air specific heat	1148 J/kgK
	Air specific heat ratio	1.4
	Hot air specific heat ratio	1.333
	Fuel heating value	43.1 MJ/kg

The cycle calculation Equations are presented as follows:

1. *Compressor inlet and exit parameters*
Compressor inlet velocity is given by,

$$C_2 = \frac{\dot{m}_a}{\rho_{02} A_2} \tag{1}$$

Equations (2) and (3) are used to calculate the compressor discharge total pressure and temperature, respectively.

$$P_{03} = P_{02} \times \pi_c \tag{2}$$

$$T_{03} = T_{02} + \frac{T_{02} - T_{03}}{\eta_c} \tag{3}$$

where,
$\dot{m}_a$ is the mass flow rate of air
ρ_{02} is the air density
A_2 is the compressor inlet area
P_{02} is the compressor inlet total pressure
π_c is the compressor pressure ratio
T_{02} is the compressor inlet total temperature
T_{03} is the compressor outlet stagnation temperature
η_c is the compressor efficiency

2. *Combustion chamber parameters*
Turbine total inlet temperature, T_{04}, is dependent on T_{03} and given by:

$$T_{04} = T_{03} + \frac{\eta_{cc} fHV}{c_{pg}} \tag{4}$$

where,
η_{cc} is the combustion efficiency
f is the fuel-air ratio
HV is the fuel heating value
c_{pg} is the hot air specific heat

3. *Turbine stage parameters*
Turbine total discharge temperature is estimated from Equation (5):

$$T_{05} = T_{04} - \frac{c_{pa}(T_{03} - T_{02})}{c_{pg}\eta_m(1+f)} \tag{5}$$

Equations (6) and (7) are used to evaluate the turbine total inlet and outlet pressures respectively:

$$P_{04} = P_{03} \times (1 - \Delta p) \tag{6}$$

Turbine total outlet pressure

$$P_{05} = P_{04}\left(\frac{T_{05}}{T_{04}}\right)^{\frac{k_g}{k_g-1}} \tag{7}$$

where,
Δp is the combustion pressure loss
T_{05} is the turbine outlet stagnation temperature
k_g is the gas specific heat ratio
c_{pa} is the ambient air specific heat

4. *Nozzle parameters*
Exhaust static temperature is given by

$$T_8 = T_{05}\left(\frac{P_8}{P_{05}}\right)^{\frac{k_g-1}{k_g}} \tag{8}$$

Nozzle exhaust velocity is estimated from Equation (9)

$$u_e = \sqrt{2c_{pg}\left(T_{04} - T_8\right)} \tag{9}$$

where,
P_8 is the nozzle exit static pressure
P_{05} is the nozzle inlet stagnation pressure

5. *Engine performance parameters*
Engine thrust is defined as:

$$F = \dot{m}_a\left(u_e - u_o\right) \tag{10}$$

Thrust specific fuel consumption is calculated using Equation (11)

$$TSFC = \frac{\dot{m}_f}{F} \tag{11}$$

where,
$\dot{m}_f$ is the fuel flow rate
u_o is the free stream velocity of air
u_e is the free stream velocity of air

2.2 Numerical Analysis

GasTurb 12 (Kurzke, 2012) and Flownex SE (M-Tech, 2015) software are used for the BMT numerical analysis. The numerical simulations were performed to validate the analytical results.

2.2.1 GasTurb Simulation Environment

GasTurb is a simulation program designed specifically for both aircraft and industrial gas turbines performance analysis. It is easy and flexible to evaluate thermodynamic parametrs at both on-design and off-design conditions. GasTurb can handle different engine configurations such as single or two spool turbojets, turboprops, turbofans, and turboshafts. Fig. 3 displays the schematic layout of a single spool turbojet engine such as the BMT micro gas turbine in GasTurb. Although, GasTurb uses the axial compressor, it can be used for radial compressor gas turbines such as the BMT. The station point (2-3) denotes the compressor intake, outlet, section (31-4) is the combustor inlet and outlet, station (41-5) shows the turbine upstream, and downstream, and station (6-8) represents the nozzle inlet and outlet.

The BMT parameters presented in Table 1 and 2 were used for GasTurb simulation. They were used to determine the baseline steady state performance model. These parameters are established from the analytical calculation, literature, and manufacturer's data.

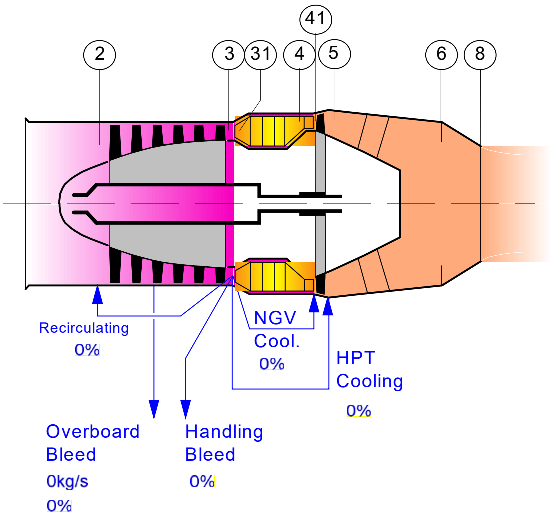

Fig. 3 GasTurb Generic Single Spool Turbojet Engine

Table 2: GasTurb model parameters

Name of Parameter	**Value**
Burner exit temperature	984.88 K
Turbine exit duct pressure ratio	0.999
Number of turbine stages	1
Burner pressure ratio	0.90
Compressor intake pressure ratio	1

2.2.2 Flownex Simulation Environment

Flownex SE is a thermodynamic and computational fluid dynamics (CFD) network simulation, design and optimization program. The software is suitable for design and simulation of aerospace and other related industry thermodynamics and turbomachinery network problems. Flownex SE is well suited for modelling and simulation of gas turbine engines. Fig. 4 describes the BMT setup in Flownex. The engine consists of inlet boundary conditions, source of fuel, combustor, adiabatic flame, axial turbine, thrust nozzle and exhaust boundary conditions connected together with connecting nodes. The BMT Flownex combustion system employs the adiabatic flame method, thus 100% combustion (M-Tech, 2015).

The initial modelling and simulation were executed for the baseline engine followed by the modified compressor stages by (Burger, 2015; De Villiers, 2014). The BMT network module served as the standard/baseline engine for the subsequent modules. The baseline engine compressor and turbine characteristic maps established by (Krige, 2013; Basson, 2014) were introduced into the program for the simulation. The turbine stage of the baseline engine was replaced with the new turbines designed by Basson.

The Flownex design functionality was used to attain component matching for the baseline engine. The design functionality tool does the component matching using an equal number of constraints and independent variables. The engine shaft excess power and turbine mass flow were set as the equality constraints while the independent variables were set as the turbine geometry and the compressor rotational speed.

3 Results and Discussion

Table 3 summarizes the correlation between the experimental results measured by Krige and the analytical results. The thrust output and the turbine inlet temperature present percentage difference of 6-9% with the exhaust gas temperature (EGT) showing deviation of almost 12%. The fuel flow was adjusted in the analytical calculations to match the engine manufacturers and experimental thrust value. This is attributed to the fact that part of the total system fuel consumption is used for lubrication. It was assumed that 10% of the total mass of the fuel is for engine lubrication and 90% for combustion. This produced a thrust of 128 N for the fuel flow of 0.00477kg/s. The thrust was over predicted by 0.8%. Fig. 5 and Fig. 6 show the GasTurb parametric analyses result for the BMT engine at varying compressor pressure ratios and combustor exit temperatures. It was found that the engine thrust output increases with increasing pressure ratio and decreasing specific fuel consumption. As shown in Table 4 the GasTurb output thrust simulated at the design point show good agreement with the Flownex and experimental data.

Good correlation was established between the Flownex simulation and the experimental data as shown in Table 4. The engine numerical simulations obtained maximum percentage difference in between 3-8% for the thrust outputs. However, Flownex showed the maximum thrust deviation. This is attributed to the fact that the Flownex simulation assumes an efficiency of 100% for the combustion process. The EGT showed deviation in between 12-18%. The baseline engine simulated results with Basson’s turbines show good correlation with the experimental results. Table 5 depicts the Flownex simulation results for the Basson’s turbines with the baseline engine compressor stage. The turbines are named as turbine 1, 2 and 3. The turbines were designed with work coefficient of 95% (Turbine 1), 100% (Turbine 2), and 105% (Turbine 3).

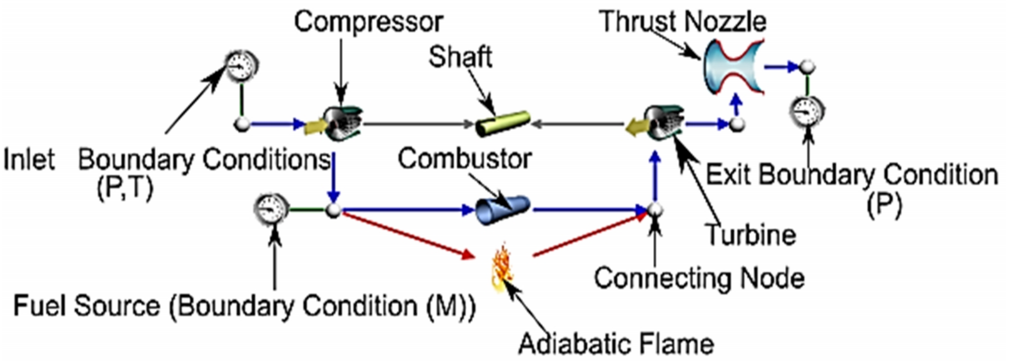

Fig. 4 Engine Schematic in Flownex SE

Table 3 BMT Experiment and Analytical Data

Parameter	Analytical	Experiment	Percentage error (%)
Thrust (N)	138	127	8.7
Turbine inlet temperature (K)	1047	1112	5.8
EGT (K)	926	1051	11.8

Table 4: BMT Simulation and Experimental Results

Parameter	GasTurb	Experiment	Percentage error (%)	Flownex	Experiment	Percentage error (%)
Thrust [N]	130	127	2.3	137	127	7.8
EGT [K]	864	1051	17.7	927	1051	11.7

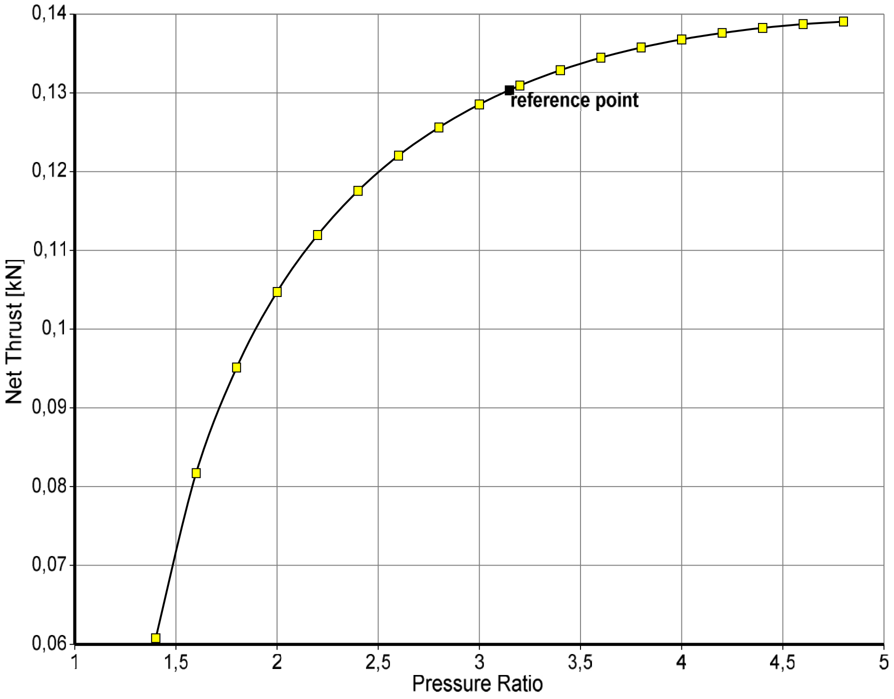

Fig. 5 Thrust vs Pressure Ratio

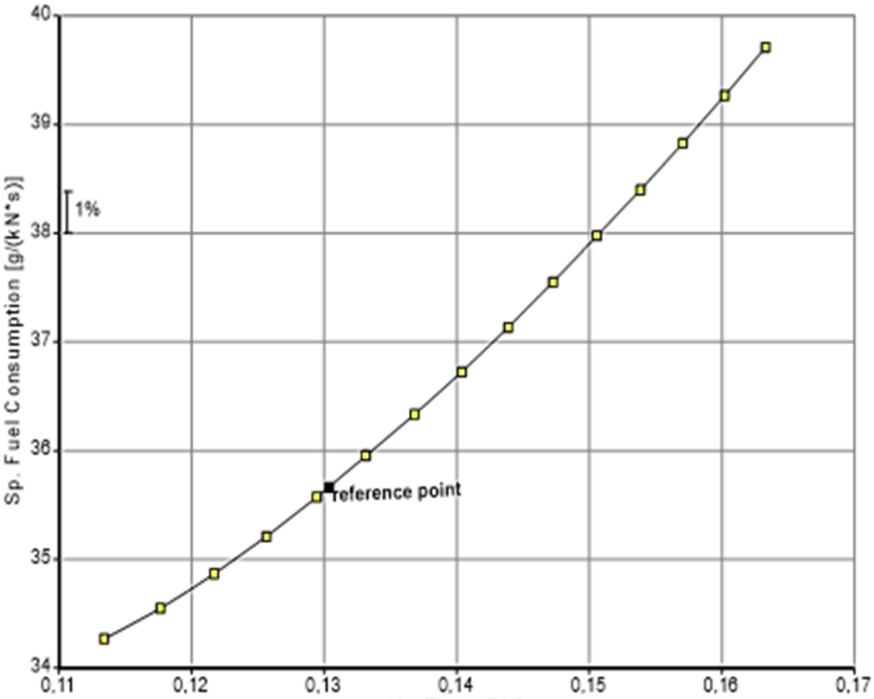

Fig. 6 Specific Fuel Consumption vs Thrust

Table 5 Simulation Results for Baseline Engine Compressor and Basson's Turbines

Parameter	Turbine 1 simulation	Experiment	Turbine 2 simulation	Experiment	Turbine 3 simulation	Experiment
Thrust [N]	118	99	125	117	120	112

Fig. 6 shows the comparative results for Burger's modified compressor stage and the experimental test. Good agreement was established for the experiment and the simulation. A percentage difference of 8.2% was achieved for the thrust output. The engine showed higher temperatures and excessive fuel consumption at higher speeds. The simulated results for the engine with Bassons turbines and Burger's compressor established good correlation as shown in Table 6. Turbine 2 which over predicted the thrust by 3.93% presented the maximum thrust deviation. Fig. 7 presents the results obtained for a component match analysis performed for the original BMT axial flow turbine and a modified compressor stage by De Villiers. The results correlate well. The simulation predicted higher exhaust temperature at high rotational speeds for the engine configuration with the De Villiers' compressor. The experimental test performed by the author suffered the same complexities. Hence, the Flownex simulation agrees well with the experimental test. The performance analyses with Basson's turbines and De Villiers' compressor is summarized in Table 7. The results show good agreement. Maximum deviation in the range of 9-11% was attained.

Table 6 Simulation Results for Burger's Compressor and Basson's Turbines

Parameter	Turbine1	Turbine 2	Turbine 3
Thrust [N]	129	132	128
EGT [K]	826	861	826

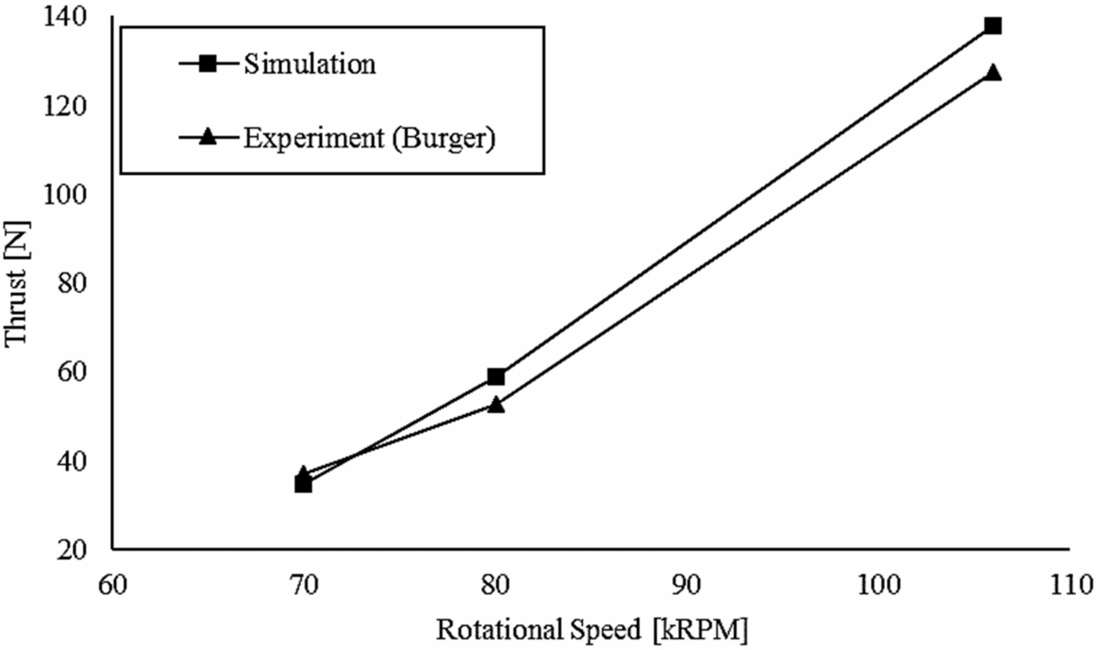

Fig. 7 Thrust vs Rotational Speed for Burger's Modified Compressor Stage Compressor

Table 7 Results for De Villiers' compressor and Basson's turbine

Parameter	Turbine1	Turbine 2	Turbine 3
Thrust [N]	119	120	117
EGT [K]	818	850	822

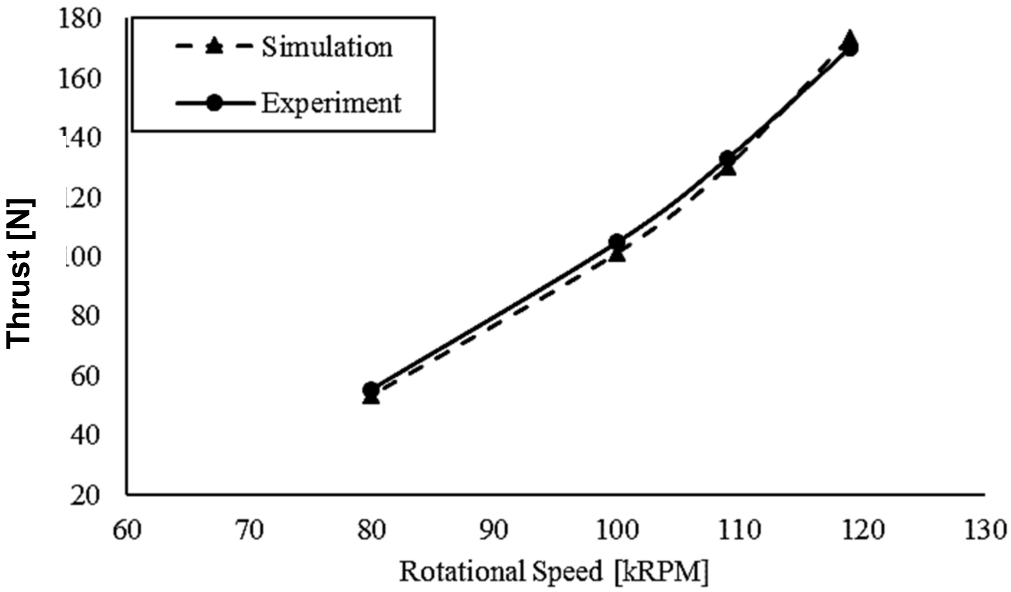

Fig. 8 Thrust vs Rotational Speed for Basson's Turbines and De Villiers' Compressor

4 Conclusion

A performance analysis was performed for the BMT 120KS micro gas turbine engine, making use of analytical and numerical calculations. GasTurb and Flownex simulation programmes were used for component matching investigation and evaluation of the engine. Good agreement between experimental results and simulation results obtained from Flownex was established for the baseline engine and its modifications. In particular, it was found that Flownex can be used to investigate the effect of modifications to the compressor stage on the performance of a gas turbine engine. The results from the above investigation will be used to further investigate the successful integration of modified compressor stages into the existing engine.

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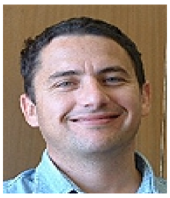
Authors

Francis Oppong holds MEng in mechanical engineering from the University of Stellenbosch, South Africa. He is currently a freelance mechanical engineer. His current research interests include turbomachinery, heat exchangers, solar energy, biomass combustion, and CFD analysis.

Theo von Backström is Emeritus Professor and a Senior Researcher at the Thermofluids Division, University of Stellenbosch, South Africa. He holds Ph.D Eng and D.Eng from the University of Stellenbosch. His current research interests involve turbomachinery, solar, ocean and wind energy. He is a member of ECSA and SAIMech.



Johan van der Spuy is an Associate Professor and a Senior Lecturer at the Thermofluids Division, University of Stellenbosch, South Africa. He holds Ph.D Eng from the University of Stellenbosch. His current research interests include turbomachinery, aerospace, and heat exchangers. He is a member of ECSA and SAIMech.

Abdullatif Lacina Diaby is a lecturer at the Department of Mechanical Engineering, University of Mines and Technology (UMaT), Tarkwa, Ghana. He received his PhD from the School of Engineering, University of South Australia (UniSA), Australia, after graduating from UMaT with a BSc (Hons.) Mechanical Engineering. His research interest involves modelling, simulation and optimisation of large heat exchanger networks (HENs) undergoing fouling/ageing in petrochemical and chemical industries using evolutionary computational techniques.