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OPERATIONAL OPTIMIZATION OF MICRO GAS TURBINE ENGINE FOR HIGHER PERFORMANCE

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Abstract - *This paper present the optimum operation of the Micro Gas Turbine Engine that is minimum specific fuel consumption and maximum specific thrust. In the turbojet engine, the main operating variables are: compressor pressure ratio and turbine inlet temperature. These variables affect the specific thrust and specific fuel consumption (SFC), which represent the main performance parameters. The analytical results show that the specific thrust and specific fuel consumption strongly depend on TIT and compressor pressure ratio (Pr). From the variation of TIT and Pr, the results show that the optimum running line (ORL) give while the engine is running at optimum (TIT) and (Pr) for higher performance.*

Keywords – *ORL, TIT, Pr, SFC, Fs, Performance*

Nomenclature

C_{pa}	= specific heat at constant pressure of air side
C_{pg}	= specific heat at constant pressure of gas side
c1	= inlet velocity
c8	= outlet velocity
f	= fuel air ratio
Fs	= specific thrust
HV	= fuel heating value
ORL	= optimum running line
P1	= ambient pressure
P01	= total pressure at the intake
P02	= total pressure at compressor inlet
P04	= total pressure at compressor outlet
P05	= total pressure at turbine inlet
P07	= total pressure at turbine outlet
P8	= static pressure at exhaust
Pc	= critical pressure at exhaust
Pr	= compressor pressure ratio
r_a	= specific gas constant at air side
r_g	= specific gas constant at gas side
SFC	= specific fuel consumption
T1	= ambient temperature
T01	= total temperature at inlet
T02	= total temperature at compressor inlet
T04	= total temperature at compressor outlet
T05	= total temperature at turbine inlet
T07	= total temperature at turbine outlet
T8	= static temperature at exhaust

I. Introduction

Jet Engine is a machine which converts chemical (Fuel) energy into Thrust. Jet engines are the power source for most of the aircrafts flying now [1]. And micro Gas Turbine (mGT) technology and deployment was initially welcomed with enthusiasm by the scientific community and industry [2]. They operate as a Brayton cycle that comprises a centrifugal compressor, a regenerator, a combustion chamber and a radial turbine connected to a permanent magnet alternator rotor. Their main features are that the high-speed generator is directly coupled to the turbine rotor and they use power electronics instead of a gearbox and a conventional generator to adapt the power produced to the grid power quality [3].

Research works studied the effects compressor pressure ratio on thrust and other performance parameters [4].In military applications there were special studies on the factors which determine the proper choice of engine cycle for a combat aircraft to suit the requirements of the designed mission [5]. Some researchers used energy and energy analyses with a turbojet engine over flight altitudes ranging from sea level to15000m to determine the relative effects of operating variables [6].

In Micro Gas Turbine (mGT), air as the working fluid is used to produce thrust based on the variation of kinetic energy of burnt gases after combustion [7,8]. Performance typically focuses on use of cycle efficiency, specific thrust, and specific fuel consumption [9,10]. In addition, Pilavachi [11], Kaikko et al. [12], Katsigiannis and Papadopoulos [13], Nikpey et al. [14] and Caresane et al. [15] studied the use of mGT in typical co-generation applications for heat production. Alternative integrations, like Bruno et al., using a mGT as power source in combination with a desalination plant, which absorbs the generated heat [16] and Ho et al., studying the performance of an mGT CHP system with absorption chiller, where the heat is used to provide cooling [17], are other typical examples of studies on mGT.

The main objective of this work is carrying out the performance analysis for the different components of the mGT. Consequently, optimum performance including minimum specific fuel consumption and maximum specific thrust are obtained.

II. MICRO GAS TURBINE ENGINE

A micro gas turbine engine 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. 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. 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. [18]

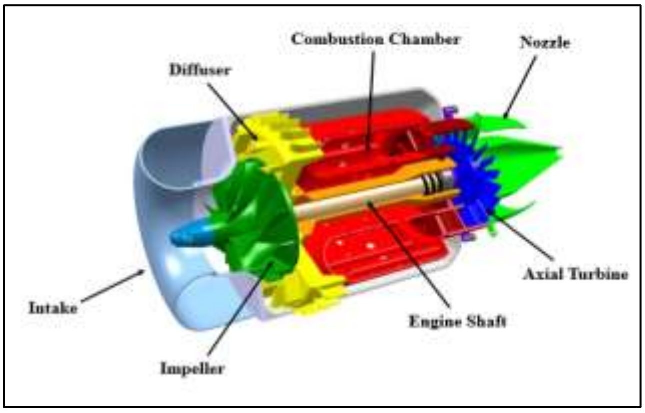

Fig. 1 Micro Gas Turbine Engine

A. Micro Gas Turbine Working Cycle

Micro gas turbine operates on the principles of Brayton open gas/air cycle. In Brayton open cycle the engine working fluid exit/exhaust into the atmosphere after expansion in the turbine and/or the exhaust propelling nozzle [18]. For analysis of real cycles, we will consider the behaviour of the realized turbojet engine including component losses, the mass flow rate of fuel through the components, and the variation of specific heats. Our analysis still assumes one-dimensional flow at the entrance and exit of each component. The variation of specific heats will be approximated by assuming a perfect gas with constant specific heat c_{pa} upstream of the main burner (combustor) and a perfect gas with different constant specific heat c_{pg} downstream of the main burner. Block diagram and real cycle of mGT is shown Fig .2 and Fig .3 respectively.

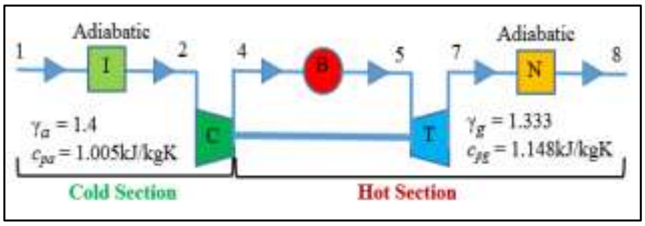

Fig. 2 Block Diagram Modelling

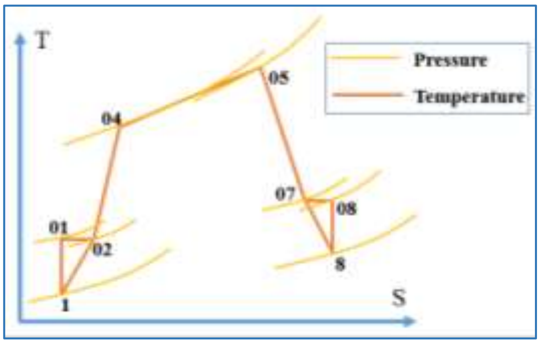

Fig. 3 Brayton Cycle

From Fig 2.and Fig 3. Section 1 and 8 are the static condition. In the intake section, total temperature (T01 and T02) are equal cause of Adiabatic process and also the nozzle section of the tow total temperature (T08 and T07) are also equal. At the compressor section, the compression takes place by the isentropic process that rises the pressure from P02 to P04. The combustion is done by isentropic expansion which increase the temperature from T04 to T05 and that loss the pressure by (P05-P04) which called the combustion pressure loss. Turbine section also occurs isentropic expansion that decrease the pressure and temperature to P07 and T07.

B. MGT Cycle Analysis

Cycle analysis studies the thermodynamic changes of the working fluid (air and products of combustion in most cases) as it flows through the engine. It is divided into two types of analysis: *parametric cycle analysis* (also called *design point* or *on-design)* and *engine performance analysis* (also called *off-design).* Parametric cycle analysis determines the performance of engines at different flight conditions and values of design choice (e.g., compressor pressure ratio) and design limit (e.g., combustor exit temperature) parameters. Engine performance analysis determines the performance of a specific engine at all flight conditions and throttle settings.[19]

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 of the engine to the hot section of the engine. These equations are used to determine the stage and/or engine station thermodynamic parameters. [18]

III. MGT MODELLING

MGT was modelled by the following steps namely, intake, compressor, combustion chamber, turbine and nozzle sections the shown in Fig. 2 to get the performance parameters of specific fuel consumption and specific thrust

A. Intake Section (1 -2)

An inlet reduces the entering air velocity to a level suitable for the compressor. The air velocity is reduced by a compression process that increases the air pressure. The operation and design of the inlet are described in terms of the efficiency of the compression process, the external drag of the inlet, and the mass flow into the inlet. [19] The intake efficiency of 0.8 was chosen because the efficiency is between 0.8 and 0.9 for subsonic. This section was done by

$$T_{01} = T_1 + \frac{c_1^2}{2c_{pa}} \qquad (1)$$

$$T_{02} = T_{01} \quad \text{(adiabatic)} \qquad (2)$$

$$P_{01} = P_1 \left[\frac{T_{01}}{T_1}\right]^{\frac{\gamma_a}{\gamma_a - 1}} \qquad (3)$$

$$P_{02} = P_1 \left[1 + \eta_i \frac{\gamma_a - 1}{2} M_1^2\right]^{\frac{\gamma_a}{\gamma_a - 1}} \qquad (4)$$

B. Compressor Section (2-4)

The function of the compressor is to increase the pressure of the incoming air so that the combustion process and the power extraction process after combustion can be carried out more efficiently. [19] The lowest efficiency of 0.8 was selected.

$$T_{04} = T_{02} + \frac{T_{02}}{\eta_c}\left[Pr^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right] \qquad (5)$$

$$P_{04} = Pr\, P_{02} \qquad (6)$$

C. Combustion Chamber Section (4-5)

The combustor is designed to burn a mixture of fuel and air and to deliver the resulting gases to the turbine at a uniform temperature. The gas temperature must not exceed the allowable structural temperature of the turbine. [19] Combustion efficiency (η_b) of 0.9 and combustion pressure losses (ΔP_b) of 4% were used.

$$f = \frac{c_{pg}\, T_{05} - c_{pa}\, T_{04}}{\eta_b\, HV - c_{pa}\, T_{05}} \qquad (7)$$

$$P_{05} = P_{04}\left(1 - \frac{\Delta P_b}{P_{04}}\right) \qquad (8)$$

D. Turbine Section (5-7)

Turbines are a class of turbo machinery used to convert the energy in a flowing fluid into mechanical energy by the use of rotor mechanisms. Turbines, in general, convert either thermal or kinetic energy of the fluid into work to drive compressors. The efficiency of a well-designed turbine is higher than that of a compressor. The main reason is that in compressors, the fluid undergoes a pressure rise and a flow deceleration accompanied by viscous losses and possible flow separation, while in turbines the flow is accelerated and thus boundary layer thickness/losses are minimized and flow separation is avoided. [19] The turbine efficiency of 0.8 was chosen.

$$T_{07} = T_{05} - \frac{c_{pa}\,(T_{04} - T_{02})}{c_{pg}\,\eta_m\,(1+f)} \qquad (9)$$

$$P_c = P_{07}\left(1 - \left[\frac{\gamma_g - 1}{\eta_j(\gamma_g + 1)}\right]^{\frac{\gamma_g}{\gamma_g - 1}}\right) \qquad (10)$$

E. Nozzle Section (7-8)

The purpose of the exhaust nozzle is to increase the velocity of the exhaust gas before discharge from the nozzle and to collect and straighten gas flow from the turbine. In operating, the gas turbine engine converts the internal energy of the fuel to kinetic energy in the exhaust gas stream. [19]

If the nozzle is unchoked,

$$P_8 = P_1 \qquad (11)$$

$$T_8 = T_{07}\left\{1 - \eta_j\left[1 - \left(\frac{P_8}{P_{07}}\right)^{\frac{\gamma_g}{\gamma_g - 1}}\right]\right\} \qquad (12)$$

$$c_8 = \sqrt{2\, c_{pg}\,(T_{07} - T_8)} \qquad (13)$$

If nozzle is choked,

$$P_8 = P_c \qquad (14)$$

$$T_8 = T_{07}\left(\frac{2}{\gamma_g - 1}\right) \qquad (15)$$

$$c_8 = \sqrt{\gamma_g\, R_g\, T_8} \qquad (16)$$

F. Performance Parameters

The main objective is to relate the engine performance parameters (primarily thrust F and thrust specific fuel consumption S) to design choices (compressor pressure ratio, fan pressure ratio, bypass ratio, etc.), to design limitations (burner exit temperature, compressor exit pressure, etc.), and to flight environment (Mach number, ambient temperature, etc.). [19] The objective is to minimize SFC and to maximize Fs as shown in eqn (17,18).

$$F_s = (1+f)\, c_8 - c_1 \qquad \text{(Maximize)} \qquad (17)$$

$$SFC = \frac{f}{F_s} \times 3600 \qquad \text{(Minimize)} \qquad (18)$$

IV. Operational Optimization Methodology

When considering the design of a turbojet, the basic thermodynamic variables at the disposal of the designer are the (TIT) and (Pr), which are used to get the optimum performance of a turbojet. Performance optimization is intended to find the maximum Fs and minimum SFC of the engine [20]. The method of optimization utilized here searches for the optimum compressor pressure ratio (Pr) at certain (TIT) for which the turbojet engine has optimum performance that gives maximum Fs and minimum SFC. For each (TIT) there is (Pr) that gives maximum Fs. hence, the optimum runningline (ORL) was formed over wide range of operating conditions, using the analytical model. The operational parameters, inputs and assumptions are shown in TABLE I.

TABLE II
OPERATIONAL PARAMETERS

Design Variables	
Pr	1.5 to 6
TIT	900K to 1100 K
Operation Condition (at Sea-Level)	
P1	101325 N/m^2
T1	288.16 K
M1	0.1
HV (fuel heating value)	43000 kJ/kg
Combustion Pressure Loss	4%
Isentropic Efficiencies	
Intake (ηi)	0.9
Compressor (ηc)	0.8
Turbine (ηt)	0.8
Exhaust (ηj)	0.9
Mechanical (ηm)	0.93
Combustor (ηb)	0.9
Objective	
SFC	Minimize
Fs	Maximize

To get the effects of the two design variables, firstly, turbine inlet temperature (TIT) of 900K and the operation condition that shown in TABLE II are used to get the effect of compressor pressure ratio (Pr) on the objective functions, specific fuel consumption SFC and specific thrust Fs. That shown in Fig .4. Secondly, compressor pressure ratio (Pr) of 4 and the operating values are used to analysis the effect of turbine inlet temperature (TIT) on the objective functions of specific thrust Fs and specific fuel consumption SFC as shown in Fig .5.

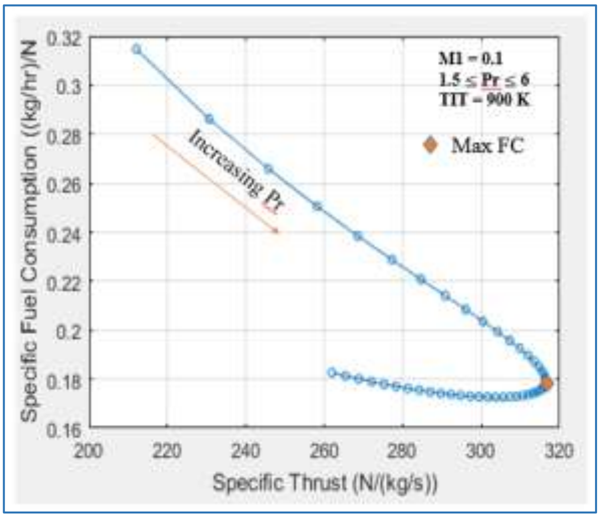

Fig. 4 Pressure ratio effect on Fs and SFC

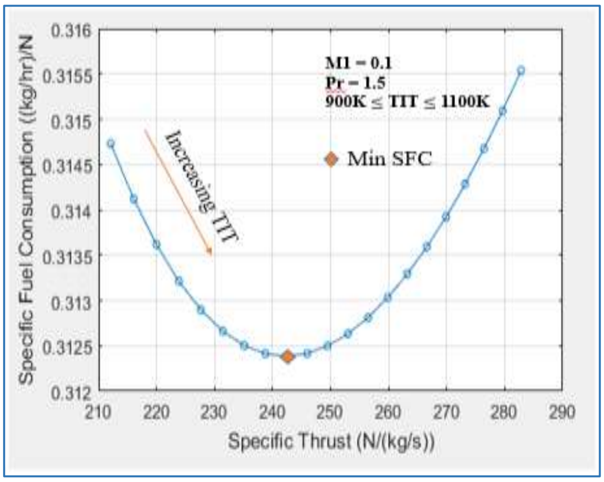

Fig. 5 Turbine inlet temperature effect on Fs and SFC

Thirdly, to get the operational optimum turbine inlet temperature (TIT) and optimum pressure ratio (Pr) for minimum specific fuel consumption (SFC) and maximum specific thrust (Fs), by varying the turbine inlet temperature (TIT) and pressure ratio (Pr) at the operation condition at sea level and inlet Mach number of 0.1. A performance carpet is produced for the determination of optimum condition, as shown in Fig. 6.

V. RESULTS AND DISCUSSION

From the Fig. 4, the compressor pressure ratio (Pr) strongly affects on both objective functions of specific fuel consumption (SFC) and specific thrust (Fs) at a design turbine inlet temperature (TIT) of 900K. At first,(Fs) increases and specific fuel consumption (SFC) decreases with increasing in pressure ratio (Pr) and then reduces after the optimum pressure ratio of 3.4 marked as in yellow drop. The optimum pressure ratio (Pr) of 3.4 was get at on operation condition for maximum specific thrust (Fs) of 316.4219 N/(kg/s) and specific fuel consumption of 0.1785 (kg/hr)N.

Fig .5, show that the specific fuel consumption (SFC) is highly affected by the variation of turbine inlet temperature (TIT). While increasing the TIT from 900k to 1100K at a constant pressure ratio of 1.5, (SFC) decreases and (Fs) increases directly but (SFC) increases after optimum temperature of 980K shown as in yellow drop. The result give that minimum specific fuel consumption (SFC) was found 0.3124 (kg/hr)N and the specific thrust (Fs) of 242 N/(kg/s).

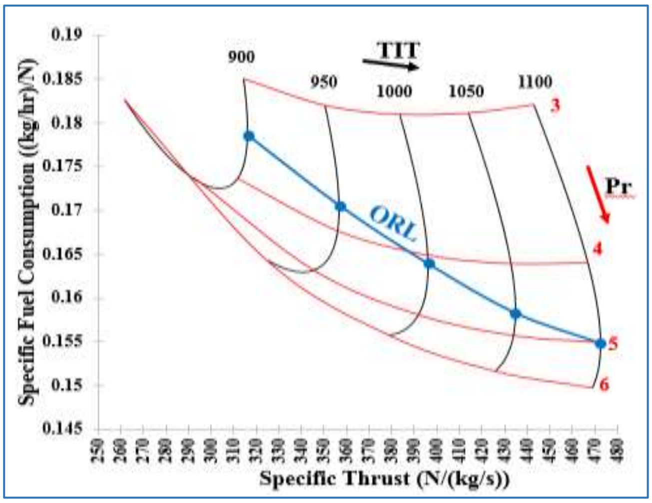

Fig. 6 Performance Carpet

A carpet of performance is produced as shown in Fig .6. This depicts the relation between Fs and SFC over wide range of operating conditions including Pr and TIT, while keeping (M1) and altitude at design conditions.

The pressure ratio (Pr) upper limit of 3 was selected instead of 1.5 because of the optimum condition cannot get between the limit of 1.5 and 3. From the (Pr) 1.5 to 3 cannot get the optimum operation condition, because the specific fuel consumption (SFC) decrease and specific thrust (Fs) increase directly with the rising of pressure ratio (Pr). From the performance carpet, the black line shown that at a constant temperature with the variation of pressure ratio and the red line shown that at a constant pressure with the variation of temperature on specific thrust and specific fuel consumption. From the blue line called optimum running line (ORL), every turbine inlet temperature (TIT) has an optimum pressure ratio (Pr) that give maximum specific thrust (Fs) and minimum specific fuel consumption (SFC) for higher performance at an operation condition. Fig .7 and TABLE II shown that the engine operation is optimum for maximum specific thrust and minimum specific fuel consumption for higher performance.

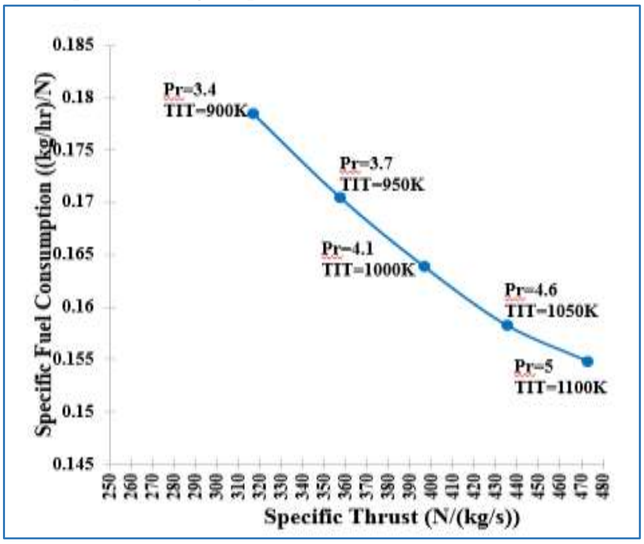

Fig. 7 Optimum running line

TABLE II
OPTIMUM OPERATION CONDITION

TIT (K)	Pr	Max Fs	Min SFC
900	3.4	316.4219	0.1785
950	3.7	356.9384	0.1705
1000	4.1	396.3456	0.1639
1050	4.6	434.7924	0.1583
1100	5	472.3684	0.1549

VI. CONCLUSION

The micro gas turbine engine (mGT) was selected as shown in Fig .1 to be an analytical model. Then one operation condition was used at sea level condition. At that operation condition, the nozzle was unchoked casue the critial pressure is Pc is lower than the nozzle outlet pressure P8. Then, the two variables parameters of TIT and Pr was chosen to analyse how sensitive effects on performance parameters of specifc thurst and specific fuel consumption. From that, every TIT and Pr not only minimize the SFC but also maximize the Fs.

The micro jet engine will meet higher performane if it operates with optimum running line that miximize the specific thrust and minimize the specific fuel consumption.

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