

# Performance Optimization of Mini-Jet Engine

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**Abstract** - This paper describes optimization of specific fuel consumption (SFC) of mini-jet engine with two parameters: inlet Mach number ( $M_1$ ) and compressor pressure ratio ( $Pr$ ). And also optimum design line is described. The designated mini-jet engine is 47 N in thrust, 62700 rpm in revolution, and 100 mm in diameter, 180 mm in length. The maximum thrust (F) is 75 N, maximum revolution (N) is 120000 rpm and maximum turbine inlet temperature (TIT,  $T_{05}$ ) is 900 K.

**Keywords** - mini-jet engine, optimization, optimum line, SFC, thrust, TIT

## I. INTRODUCTION

### A. Basic Principles

The study of propulsion is needed to explain mini-jet engine theory. Jet propulsion is a practical application of Sir Isaac Newton's third law of motion which states that, "for every force acting on a body there is an opposite and equal reaction". The verb propel is defined as "to drive, or cause to move, forward or onward". Propulsion involves an object to be propelled plus one or more additional bodies, called propellant [1].

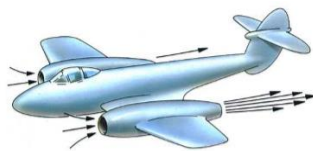
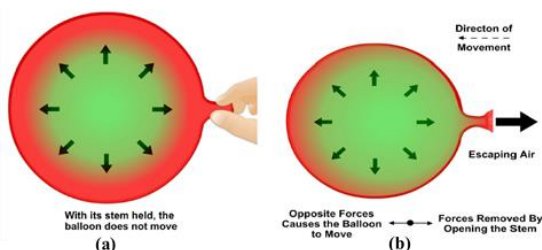


Fig. 1 Aircraft propulsion [2]

Jet propulsion is the propelling force generated in the direction opposite to the flow of a mass of gas or liquid under pressure. The mass escapes through a hole or opening called a jet nozzle. A familiar example is the nozzle at the end of a fire hose. An example of the theory of jet propulsion is an inflated balloon. With the opening in the balloon closed Figure 2a, there is no action because the pressure of the gas inside the balloon is equal in all directions. When you allow



the opening to release the air Figure 2b, the balloon moves. Its movements appear to be in all directions. However, it is always moving in the opposite direction from the open end where the air is exiting [3].

Fig. 2 Basic principle of jet propulsion [3]

Jet propulsion systems can be subdivided into two broad categories: airbreathing and non-airbreathing. Airbreathing propulsion systems include the reciprocating, turbojet, turbofan, ramjet, turboprop, and turboshaft engines. Non-airbreathing engines include rocket motors, nuclear propulsion systems, and electric propulsion systems [1].

### B. Gas Generator

The "heart" of a gas turbine type of engine is the gas generator. A schematic diagram of a gas generator is shown in Fig. 3. The compressor, combustor, and turbine are the major components of the gas generator which is common to the turbojet, turbofan, turboprop, and turboshaft engines. The purpose of a gas generator is to supply high-temperature and high-pressure gas [1].

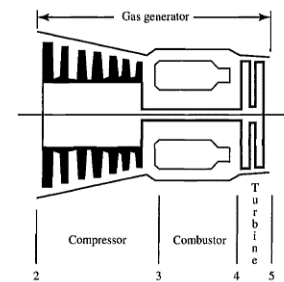
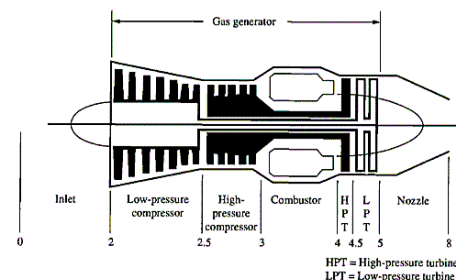


Fig. 3 Schematic diagram of gas generator [1]



### C. Turbojet Engine

The turbofan, turboprop, and turboshaft engines are adaptations of the turbojet to supply thrust or power through

the use of fans, propellers, and shafts. By adding an inlet and a nozzle to the gas generator, a turbojet engine can be constructed. A schematic diagram of a simple turbojet is shown in Fig. 4.

Fig. 4 Schematic diagram of a turbojet [1]

The thrust of a turbojet is developed by compressing air in the inlet and compressor, mixing the air with fuel and burning in the combustor, and expanding the gas stream through the turbine and nozzle. The expansion of gas through the turbine supplies the power to turn the compressor. The net thrust delivered by the engine is the result of converting internal energy to kinetic energy [1].

#### D. Mini-Jet Engine

The working principle of mini-jet engine is similar to full-sized turbojet 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 [4].

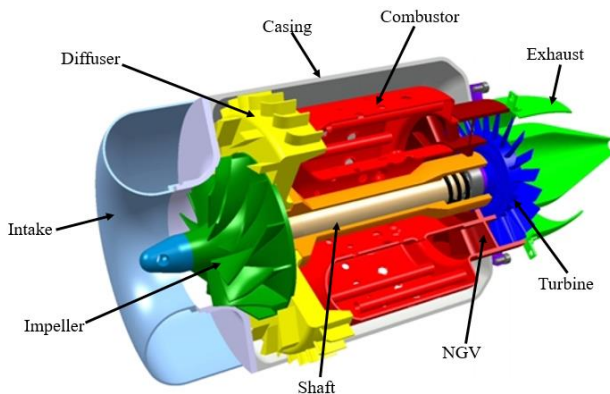


Fig. 5 Mini-Jet Engine

#### E. Uses

Small turbojet engine are developed for use in cruise missiles, target drones, and other small unmanned air vehicles (UAVs) [5]. Examples are Microturbo TRI 60 which different types (TRI 60-1, 60-2, 60-3, 60-5, 60-20, and 60-30) produce a thrust force ranging from 3.5 to 5.3 kN. This engine is a single spool, having a length of 851 mm (33.5 in), diameter of 348 mm (13.7 in), and dry weight of 61.2 kg (135 lb). March 20, 1983, represents the first-ever flight of a micro-turbojet powered model aircraft, which had a three-minute flight. This engine measured 4¾" in diameter

and 13½" long and weighed 3¾ pounds. At 85000 rpm it produced over 9 lb of thrust and had a top speed of 97000 rpm. Twenty years later, commercial engines of roughly similar dimensions and weight are in the 30 lb thrust class when running at 120000 rpm. The airframe, with its twin-boom hightail configuration, is remarkably, perhaps inevitably, similar to many of today's trainer aircraft. The first commercial micro-turbines were made available by JPX in the early 1990s [6]. Shortly after, Germany and the Netherlands sought out to develop a powerful, lightweight, liquid-fueled micro-turbine [5]. Other applications of mini-jet engines are auxiliary power unit (APU), Jet-man, flying hoverboard etc.

#### F. Modern Trends and Current Challenges

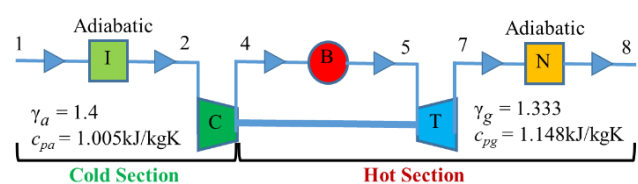
Research works studied the effects compressor pressure ratio on thrust and other performance parameters [7]. In military applications there were special studies on the factors which determine the proper choice of engine cycle for a combat aircraft to suit the requirements of the designed mission [8]. Some researchers used energy and energy analyses with a turbojet engine over flight altitudes ranging from sea level to 15000m to determine the relative effects of operating variables [9]. In mini-jet engine, air as the working fluid is used to produce thrust based on the variation of kinetic energy of burnt gases after combustion [10], [11]. Performance typically focuses on use of cycle efficiency, specific thrust, and specific fuel consumption [12], [13]. In addition, Pilavachi [14], Kaikko et al. [15], Katsigiannis and Papadopoulos [16], Nikpey et al. [17] and Caresane et al. [18] studied the use of mini-jet engine in typical cogeneration applications for heat production.

In aviation, engine fuel consumption and aircraft impacts on the environment are two important areas of research. From an environmental perspective, using energy with high efficiency reduces pollutant emissions and harm to ecological systems. For a given output, less fuel is needed when efficiency increases and less waste is released. These benefits lead to increased life times for energy resources and greater sustainability. [19], [20].

## II. DESIGN METHODOLOGY

### A. Working Cycle

Mini-jet engine 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 [21]. 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. 7 and Fig. 8 respectively.

Fig. 7 Block diagram of mini-jet engine

Fig. 8 Brayton cycle

From Fig. 7 and Fig. 8, section 1 and 8 are the static condition. In the intake section total temperature ( $T_{01}$  and  $T_{02}$ ) are equal because of adiabatic process and also the nozzle section of the two total temperature ( $T_{08}$  and  $T_{07}$ ) are also equal. At the compressor section, the compression takes place by the isentropic process that rises the pressure from  $P_{02}$  to  $P_{04}$ . The combustion is done by isentropic expansion which increase the temperature from  $T_{04}$  to  $T_{05}$  and that loss the pressure by ( $P_{05}-P_{04}$ ) which called the combustion pressure loss. Turbine section also occurs isentropic expansion.

### B. Modelling

The mini-jet engine was modelled by the following steps namely, intake, compressor, combustion chamber, turbine and nozzle sections the shown in Fig. 7 to get the performance parameters of specific fuel consumption and specific thrust.

1) *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 [22].

$$A_1 = \frac{\pi D_1^2}{4}$$

$$T_{01} = T_1 + \frac{c_1^2}{2c_{pa}}$$

$$P_{01} = P_1 \left[ \frac{T_{01}}{T_1} \right]^{\gamma_a/\gamma_a-1}$$

$$T_{02} = T_{01}$$

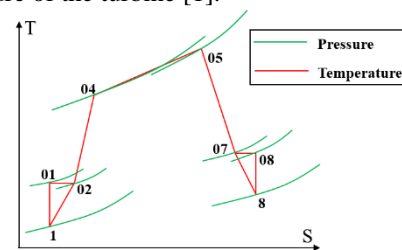
$$P_{02} = P_1 \left[ 1 + \eta_i \frac{\gamma_a - 1}{2} M_1^2 \right]^{\gamma_a/\gamma_a-1}$$

2) *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.

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

$$P_{04} = Pr P_{02}$$

3) *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 [1].



$$f = \frac{c_{pg} T_{05} - c_{pa} T_{04}}{\eta_b LHV - c_{pa} T_{05}}$$

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

4) *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 [1].

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

$$P_{07} = P_{05} \left( 1 - \frac{T_{05} - T_{07}}{\eta_t T_{05}} \right)^{\gamma_g/\gamma_g-1}$$

5) *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 [1]. The nozzle is needed to consider that is whether choked or not that depends on design consideration. However, most of mini-jet engine nozzles are unchoked.

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

if  $P_c < P_1$  (Unchoked Nozzle)

$$P_8 = P_1$$

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

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

if  $P_c > P_1$  (Choked Nozzle)

$$P_8 = P_c$$

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

$$c_8 = \sqrt{\gamma_g R_g T_8}$$

6) *Performance Parameters:* The main engine performance parameters are specific thrust  $F_s$ , specific fuel consumption SFC, thermal efficiency  $\eta_T$ , propulsive efficiency  $\eta_P$ . These parameters were done by the following equations.

$$F_s = a_1 \left[ (1+f) \frac{c_8}{a_1} - M_1 + (1+f) \frac{R_g T_8 / T_1}{R_a c_8 / a_1} \frac{1 - (P_1 / P_8)}{\gamma_a} \right]$$

$$\dot{m}_a = \rho_1 A_1 c_1$$

$$F = \dot{m}_a F_s$$

$$SFC = \frac{f}{F_s} \times 3600$$

$$\eta_T = \frac{a_1^2 \left[ (1+f) \left( \frac{c_8}{a_1} \right)^2 - M_1^2 \right]}{2f \text{ LHV}}$$

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.). From parametric cycle analysis, we can easily determine which engine type (e.g., turbofan) and component design characteristics (range of design choices) best satisfy a particular need.

#### D. Inputs and Assumptions

Engine's inlet Mach number ( $M_1$ ) and compressor's pressure ratio ( $Pr$ ) are chosen as important parameters because the performance of engine is changing at different inlet conditions ( $M_1, P_1, T_1$ ), values of design choice ( $Pr$ ), design limit ( $T_{05}$ ).

The range of  $M_1$  is between 0.1-0.4 (0.4 is maximum value in mini-jet engine). And the range of  $Pr$  is 1.2 to 4 (the small amount of thrust is produced at  $Pr=1.2$  and 4 is maximum value for single stage centrifugal compressor).

Inlet static pressure and temperature are not considered as changing parameters at sea level and room temperature. The turbine inlet total temperature is chosen 900K because of materials limit. Also the sizing of inlet diameter is chosen as an input to know air mass flow rate. The fuel low heating value is also selected from type of used fuel.

After that, components' efficiency, combustor total pressure loss, and specific values are assumed. The intake efficiency is 1 to neglect intake effect. The ranges of compressor and turbine efficiencies are normally between 0.8-0.87. Although the efficiencies of compressor and turbine are used as the lowest values because of technology availability. The 15% loss in combustor, 5% mechanical loss and 10% loss in nozzle are assumed. The values of parameters, inputs and assumptions are shown in Table 1.

TABLE I  
INPUTS OF PARAMETRIC CYCLE ANALYSIS

Parameters	
Inlet Mach number ( $M_1$ )	0.1-0.4
Compressor pressure ratio ( $P_{04}/P_{02}$ )	1.2-4
Inputs	
Inlet temperature ( $T_1$ )	298 K
Inlet pressure ( $P_1$ )	101325 Pa
Turbine inlet temperature ( $T_{05}$ )	900 K
Assumptions	
Intake efficiency ( $\eta_i$ )	1
Compressor efficiency ( $\eta_c$ )	0.8
Turbine efficiency ( $\eta_t$ )	0.8
Exhaust efficiency ( $\eta_j$ )	0.9
Mechanical efficiency ( $\eta_m$ )	0.95
Combustor efficiency ( $\eta_b$ )	0.85
Combustor pressure loss ( $\Delta P_b/P_{04}$ )	0.06
Fuel low heating value (LHV)	45.277 MJ/kg (Butane)

$$\eta_P = \frac{2 c_1 F_s}{a_1^2 \left[ (1+f) \left( \frac{c_8}{a_1} \right)^2 - M_1^2 \right]}$$

$$\eta_o = \eta_T \eta_P$$

#### C. Parametric Studies

Parametric cycle analysis is also called *design point analysis* or *on-design analysis* because each plotted engine is operating at its so-called design point. The main objective of parametric cycle analysis is to relate the engine performance parameters (primarily thrust  $F$  and thrust

### III. RESULTS AND DISCUSSION



A. Variation of Thrust

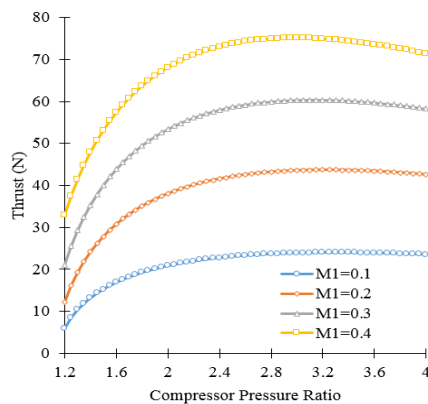


Fig.9 Variation of Thrust with pressure ratio and Mach number

The variation of compressor pressure ratio (1.2-4), Mach number (0.1-0.4) and Thrust is shown in Fig. 8. Thrust increases when Mach number and pressure ratio are increased. But thrust decreases after the optimum pressure

M <sub>1</sub>	Pr	F (N)	SFC (kg/N.hr)
0.1	3	23.9518	0.1875
0.2	3.1	43.6633	0.2064
0.3	3.2	60.3606	0.2241
0.4	3.3	75.0704	0.2397

ratio is reached. The optimum compressor ratio is 3, the maximum thrust is 75.0804N at M<sub>1</sub>=0.4.

B. Variation of SFC

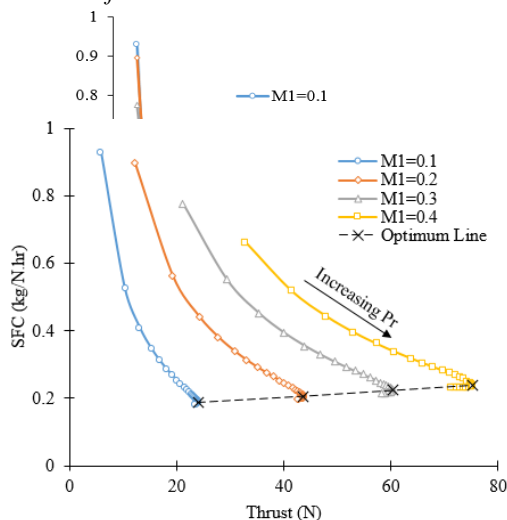
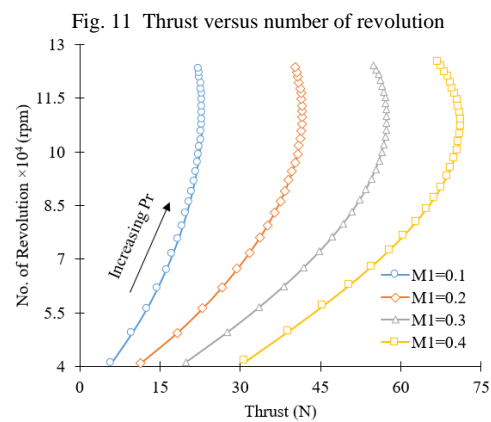


Fig. 10 Variation of SFC with pressure ratio and Mach number

Fig. 10 shows the SFC variation with compressor pressure ratio and inlet Mach number. In this figure SFC decreases when pressure ratio is increased, and Mach number is fixed. When the pressure ratio is fixed and changing Mach number, the SFC increases. The minimum SFC is found at maximum pressure ratio and minimum Mach number.

C. Variation of Thrust and RPM



This Fig. 11 is achieved by parametric cycle analysis and impeller design calculation. The number of revolution is calculated impeller design. The effect of pressure ratio and Mach number on thrust and number of revolution is shown in Fig. 11. By increasing Mach number, increasing thrust and rpm. By increasing pressure ratio, increasing thrust and rpm until optimum pressure ratio points. Beyond this points, increasing rpm but decreasing thrust.

D. Performance Optimization

The optimization of engine performance is the investigation of maximum thrust and optimum SFC for every operating conditions. This investigation is done with four parameters (M<sub>1</sub>, Pr, F, SFC). This engine performance optimization is a part of parametric cycle analysis.

Fig. 12 Variation of SFC and thrust with Mach number and pressure ratio

Fig. 12 shows the variation of SFC and thrust with Mach number and compressor pressure ratio. When the Mach number is increased, both SFC and thrust increase. By increasing pressure ratio, SFC decreases and thrust increases. For each Mach number, there have an optimum pressure ratio that is the point of maximum thrust and optimum SFC. When the optimum points for every Mach number are connected, the optimum pressure ratio line was achieved. This is the optimization method of mini-jet engine for maximum thrust and optimum SFC. The optimum points are shown in Table 2.

TABLE III  
OPTIMUM POINTS OF MAXIMUM THRUST AND OPTIMUM SFC

IV. CONCLUSIONS

Firstly, variations of performances were investigated with inlet Mach number (M<sub>1</sub>) and compressor pressure ratio (Pr). From these investigations, optimum pressure ratio was found with different conditions. The optimum point was designated

for maximum thrust and optimum SFC at a flight condition. When the optimum points were connected, the optimum line was achieved at different flight conditions. This optimization method is very useful and helpful for better engine performance.

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