

## ENERGY AND ENTROPY ANALYSES OF AN EXPERIMENTAL TURBOJET ENGINE FOR TARGET DRONE APPLICATION

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### ABSTRACT

This study investigates energy and entropy analyses of an experimental turbojet engine build in Anadolu University Faculty of Aeronautics and Astronautics Test-Cell Laboratory. Law of motions and Brayton thermodynamic cycle model are used for this purpose. The processes (that is, compression, combustion, and expansion) are simulated in P-v, T-s and h-s diagrams. Furthermore, the second law of thermodynamics is applied to the cycle model to perform the entropy analysis. A distribution of the wasted and thrust power, the overall (energy-based the first law efficiency), and the specific fuel consumption and specific thrust of the engine were calculated during the analyses as well. The results of the study also show the entropy changing value in engine components due to irreversibilities and inefficiencies. As a conclusion, it is expected that this study is useful to study future design and research work similar aircraft turbojets, auxiliary power units and target drone power systems.

**Keywords:** Turbojet, Target Drone, Entropy, Energy, UAV

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### 1. INTRODUCTION

Unmanned air vehicles (UAVs)-commonly known as drones-have become a staple of military reconnaissance and weapons. They include all classes of airplanes, helicopters, airships, and translational lift aircraft that have no onboard pilot. Design of a UAV systems are complex, similar to regular military or commercial aircraft. UAVs are characterized according to range, endurance, altitude, speeds, and payloads [1-3].

Turbomachinery is candidate propulsion and power systems for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (UAV) and Auxiliary Power Systems (APU) for aircrafts [4]. So, aircraft conceptual design tools need a propulsion model. In other words, aircraft designers need a data set of an existing engine or a detailed engine model for propulsion calculations. Better propulsion models increase the accuracy of this kind of tools. Propulsion models can be created by employing engine thermodynamic cycle analysis. During recent years, interest on small-sized gas-turbine engines (SSGT) has increased for both ground-based and aircraft uses. SSGT, in particular, are becoming attractive for their potential application on remote-control airplanes or on unmanned aerial vehicles (UAVs) because of their extremely-high thrust-to-weight ratio.

The performance of a turbojet engine has increased through by engine efficiency and improved material properties. A number of works exist to define optimum engine parameters for minimizing specific fuel consumption. Guha [5,6] investigates gas turbine cycle optimization including real gas effects. Energy and entropy methods are important to gain a deeper understanding of fuel efficiency of an aero vehicle and its power systems. So, thermodynamic analyses have been applied to some aircraft systems in the last 10–15 years [7-14].

The main goals of this study are yielding following performance parameters of the TRS 18 experimental turbojet engine:

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- entropy of the engine components such as inlet, reverse flow combustion chamber, axial-flow turbine and exhaust nozzle,
- unmeasured pressure and temperature at engine stations,
- T-s, P-v and h-s diagrams
- Specific thrust and specific fuel consumption
- propulsive, thermal and overall efficiency
- thrust and wasted power

Through a literature review, it is noticed that any studies on the energy and entropy analyses of the TRS18 turbojet engine have not appeared with the aid of experimental test to the best of the authors' knowledge. So, the results in this study provides the first attempt to show experimental performance of the TRS 18 turbojet engine by taking into account test-cell set-up and experiment data. Lack of these makes this study original and becomes main motivation for the turbojet engine for target drone applications.

## 2. Performance Parameters of Aero-Engines: General Equations

### 2.1. Generic Thrust Expression

Aero-engines are designed to produce thrust force. In these engines, momentum of air, mass flow rate of air and fuel is main source of creating thrust force. Figure 1 is schematic drawing of such basic turbojet engine. The air is brought in through the air intake, or inlet, system, where station 0 designates the free flight condition, station 1 is at the inlet lip, and station 2 is at the exit of the inlet, which corresponds to the inlet of the compressor [15].

The compression process from stations 2 to 3 is composed of a low-pressure, compressor (LPC) spool and a high-pressure compressor (HPC) spool. The exit of the LPC is station 2.5 and the exit of the HPC is station 3. The HPC drives at a higher shaft rotational speed than the LPC spool. The compressed gas enters the main burner at 3 and is combusted with the fuel to produce hot high pressure gas at 4 to enter the high-pressure turbine (HPT).

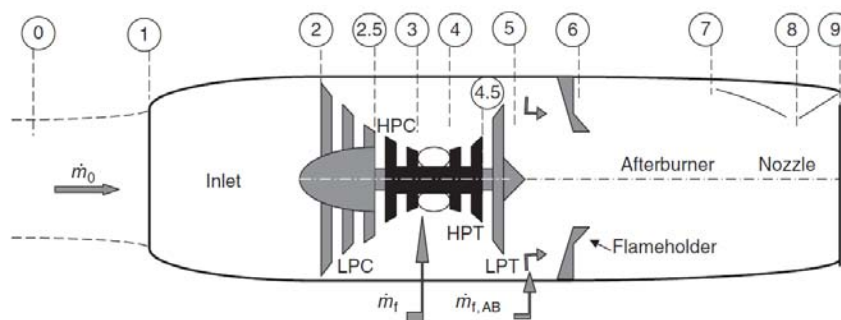


Figure 1. Stations for an afterburning turbojet engine [15]

Flow expansion through the HPT and the low-pressure turbine (LPT) produces the shaft power for the HPC and LPC, respectively. An afterburner is designated between stations 5 and 7, where an additional fuel is combusted with the turbine discharge flow before it expands in the exhaust. Station 8 is at the throat of the nozzle and station 9 is the exhaust nozzle exit [15].

To drive an expression for the engine thrust, control volume must be described and momentum principle must be applied to the fluid flow crossing the boundaries of the control volume. Figure 2 depicts a control volume of the engine.

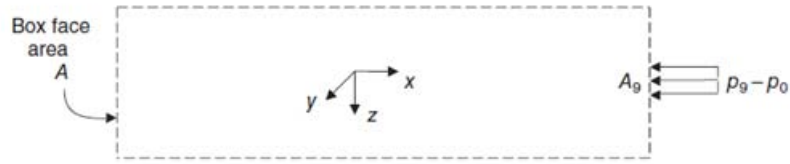


Figure 2 (a)

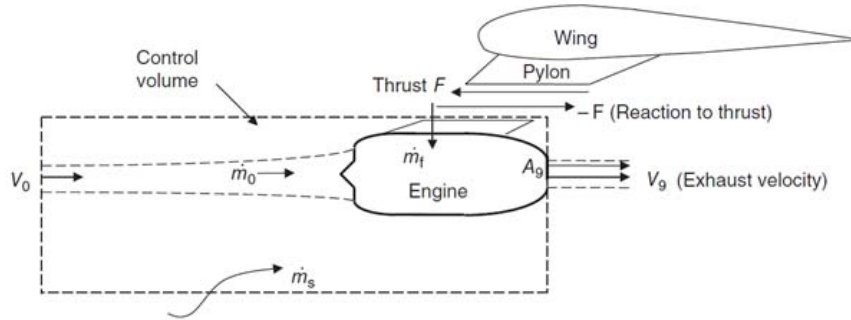


Figure 2. (b)

Figure 2. a) Simplified model of the static pressure force acting on the control surface b) Schematic drawing of an aero-engine with a control volume [15]

Assuming steady state, uniform flow, the momentum equation can be written as following:

$$\sum(\dot{m}V_x)_{out} - \sum(\dot{m}V_x)_{in} = \sum(F_x)_{fluid} \quad (1)$$

The difference between the fluid momentum out and into of the control volume is equal to the net forces acting on the fluid in the x-direction [15].

$$\sum(\dot{m}V_x)_{in} = (\rho_0 V_0 A) V_0 + \dot{m}_s V_0 \quad (2)$$

$$\sum(F_x)_{fluid} = (-F)_{fluid} - (p_g - p_0) A_g \quad (3)$$

From above four equations, we get

$$(\dot{m}_0 + \dot{m}_f) V_g + [\rho_0 V_0 (A - A_g)] V_0 - (\rho_0 V_0 A) V_0 - (\dot{m}_0 - (\rho_0 V_0 A_g)) V_0 = (-F)_{fluid} - (p_g - p_0) A_g \quad (4)$$

Eq.5 simplifies to

$$(\dot{m}_0 + \dot{m}_f) V_g - \dot{m}_0 V_0 = (-F)_{fluid} - (p_g - p_0) A_g \quad (5)$$

From above equations, engine thrust ( $F$ ) expression can be get as following,

$$F = (\dot{m}_0 + \dot{m}_f) V_g - \dot{m}_0 V_0 + (p_g - p_0) A_g \quad (6)$$

## 2.2. Aero-Engine Performance Parameters

Aircraft propulsion system figures of merit includes performance parameters such as engine thrust, mass flow rates of air and fuel, the rate of kinetic energy, mechanical/shaft power output, specific thrust, engine efficiencies and specific fuel consumption [15].

### 2.2.1. Specific Thrust (ST)

In case of aircraft propulsion engine, the specific thrust is the ratio of thrust to air mass flow, that is

$$ST = \frac{F}{\dot{m}_0} \quad (7)$$

ST is usually to be maximized in cycle analysis to get thrust with the least quantity of air flow rate, or equivalently to produce thrust with a minimum of engine inlet area.

### 2.2.1 Specific fuel consumption (SFC)

For an aero-engine, the ratio of fuel flow rate per unit thrust force is called specific fuel consumption (SFC), or sometimes just the thrust specific fuel consumption (TSFC) is defined as

$$SFC = \frac{\dot{m}_f}{F} \quad (8)$$

SFC is to be minimized, in a cycle analysis, that is, to produce thrust with a minimum of fuel flow rate.

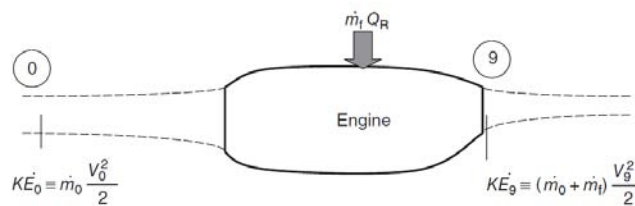
### 2.2.2. Thermal Efficiency ( $\eta_{th}$ )

The ability of an aero-engine to convert the thermal energy inherent in the fuel to a net kinetic energy called the engine thermal efficiency [15].

$$\eta_{th} = \frac{\Delta KE}{\dot{Q}_{thermal}} = \frac{\dot{m}_9 \frac{V_9^2}{2} - \dot{m}_0 \frac{V_0^2}{2}}{\dot{m}_f Q_R} = \frac{(\dot{m}_0 + \dot{m}_f) V_9^2 - \dot{m}_0 V_0^2}{2 \dot{m}_f Q_R} \quad (9)$$

Where  $\dot{m}$  denotes mass flow rate corresponding to each stations 0 and 9, subscript “f” denotes fuel, and  $Q_R$  is the fuel heating value.

Figure 3 is a definition about thermal efficiency definition, as it graphically shows the energy sources in an aero-engine. The thermal energy production in an engine is not actually “lost,” as it shows up in the hot jet exhaust stream, rather this energy is “wasted” that is not to convert it to a useful power.



**Figure 3.** Power input and output of the engine [15]

Wasted power of the engine ( $WP$ ) can be expressed as following,

$$WP = \frac{(\dot{m}_0 + \dot{m}_f)(V_9 - V_0)^2}{2} \quad (10a)$$

Total power of the engine ( $TP$ ) can be expressed as following,

$$TP = KE_9 - KE_0 \quad (10b)$$

### 2.2.3. Propulsive efficiency ( $\eta_p$ )

The fraction of the net mechanical output of the engine which is converted into thrust power is called the propulsive efficiency [15].

$$\eta_p = \frac{F.V_0}{\Delta K\dot{E}} = \frac{F.V_0}{\dot{m}_9 \frac{V_9^2}{2} - \dot{m}_0 \frac{V_0^2}{2}} \quad (11)$$

### 2.2.4. Overall efficiency ( $\eta_o$ )

The product of the engine thermal and propulsive efficiency is called the engine overall efficiency [15].

$$\eta_o = \eta_{th} \cdot \eta_p = \frac{F.V_0}{\dot{m}_f Q_R} \quad (12)$$

## 3. Aerothermodynamics and Cycle Analysis of Aero-Engines: A Simple Overview of Turbojet

### 3.1. The Turbojet Engine

An aircraft turbojet (TJ) engine is basically a gas generator (i.e. compressor, combustion chamber and turbine) fitted with an inlet and exhaust as shown in Figure 4.

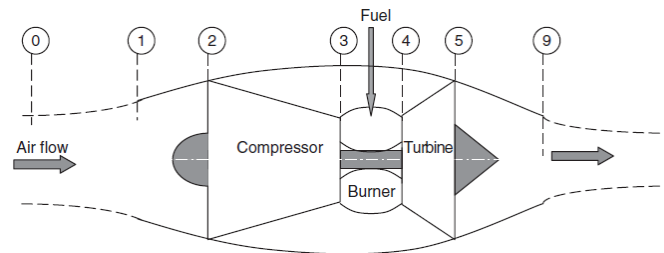


Figure 4. Stations of turbojet engine [15]

The station numbers in a TJ are defined at the flight condition (0), inlet lip (1), compressor face (2), compressor exit (3), burner exit (4), turbine exit (5), and the nozzle exit plane (9).

#### 3.1.1. Inlet

The basic function of the inlet is to deliver the air to the compressor at the right Mach number  $M_2$ . Behind, it diffuses the flow as well. An ideal inlet is considered to provide a reversible and adiabatic, that is, isentropic, compression of the captured flow to the engine.

The process of compression in a real inlet can be shown on the h-s diagram of Figure 5. The entropy rise in an adiabatic process leads to a total pressure loss  $\Delta p_t$ , following the combined first and second law of thermodynamics, that is, Gibbs equation, according to [15]

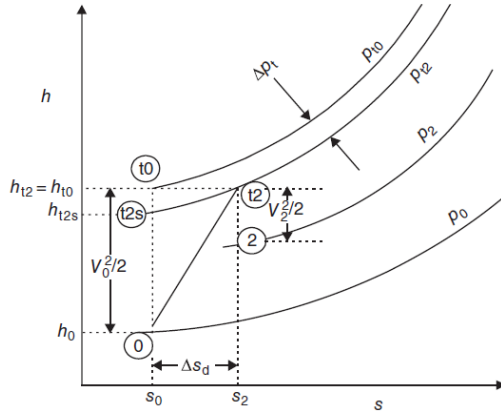


Figure 5. h-s diagram for an inlet under ideal and real condition [15]

$$\frac{p_{t2}}{p_{t0}} = e^{\frac{s_2 - s_0}{R}} = e^{\frac{\Delta s}{R}} \quad (13)$$

We use the fictitious state (t2s) in a definition of inlet efficiency (or a figure of merit) known as the inlet adiabatic efficiency ( $\eta_d$ ). Symbolically, the inlet adiabatic efficiency is defined as

$$\eta_d = \frac{h_{t2s} - h_0}{h_{t2} - h_0} = \frac{(V^2/2)_{ideal}}{(V_0^2/2)} \quad (14a)$$

Another

of merit for an inlet is the total pressure ratio between the compressor face and the flight condition ( $\pi_d$ ). It is often to as the inlet total pressure recovery:

$$\pi_d = \frac{p_{t2}}{p_0} = \frac{\left[ 1 + \eta_d \frac{\gamma - 1}{2} M_0^2 \right]^{\frac{\gamma}{\gamma - 1}}}{\pi_r} \quad (14b)$$

### 3.1.2. Compressor

The measure of irreversibility in a compressor is defined with the aid of compressor efficiency definitions. These are i) compressor adiabatic efficiency ( $\eta_c$ ) and ii) compressor polytropic efficiency ( $e_c$ ).

The compressor adiabatic efficiency is the ratio of the ideal power required to the power consumed by the compressor as shown in Figure 6, that is [15],

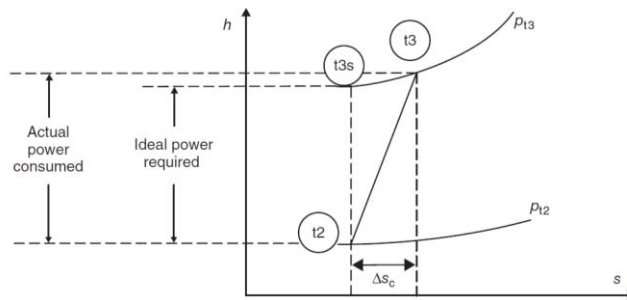


Figure 6. h-s diagram for a compressor under ideal and real condition [15]

$$\eta_c = \frac{\Delta h_{t,isentropic}}{\Delta h_{t,actual}} = \frac{h_{t3s} - h_{t2}}{h_{t3} - h_{t2}} = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\tau_c - 1} \quad (15)$$

The polytropic efficiency ( $e_c$ ) is actually the adiabatic efficiency of a compressor with small pressure ratio. Consequently, compressor polytropic efficiency is also called small stage efficiency [15].

$$e_c \equiv \frac{dh_{ts}}{dh_t} = \frac{\frac{dp_t}{p_t}}{\frac{\gamma}{\gamma-1} \frac{dT_t}{T_t}} \quad (16)$$

### 3.1.3. Combustion Chamber

In a real combustor, due to wall friction, turbulent mixing and chemical reaction at finite Mach number, the total pressure drops, that is [15],

$$\pi_b = \frac{p_{t4}}{p_{t3}} < 1 \text{ "real combustion chamber"} \quad (17)$$

$$\pi_b = 1 \text{ "ideal combustion chamber"}$$

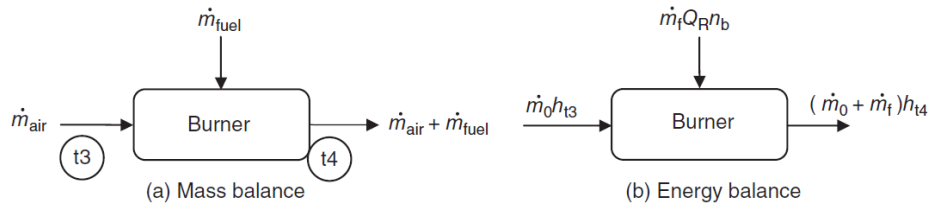


Figure 7. Mass and energy balance of combustion chamber [15]

Figures 7a and 7b are the steady-state mass and the energy balance applied to the combustion chamber, that is [15],

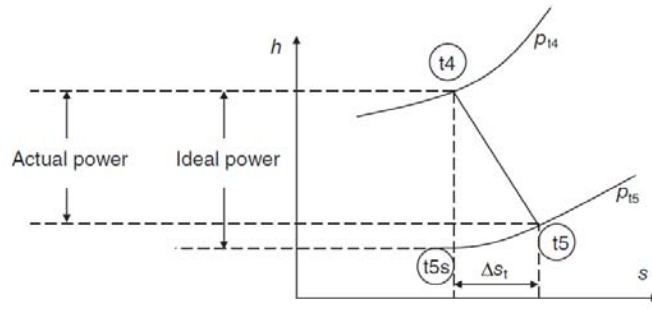
$$\dot{m}_0 h_{t3} + \dot{m}_f Q_R \eta_b = \dot{m}_0 (1 + f) h_{t4} \quad (18)$$

The fraction that can be realized is called burner efficiency ( $\eta_b$ ) and

$$\eta_b \equiv \frac{Q_{R,actual}}{Q_{R,ideal}} \quad (19)$$

### 3.1.4. Turbine

The thermodynamic process for an uncooled turbine flow may be shown in an h-s diagram (Figure 8). The actual expansion process in the turbine is depicted by the solid line connecting the total (or stagnation) states t4 and t5 in Figure 8.



**Figure 8.** Expansion process in an uncooled turbine [15]

Turbine adiabatic efficiency ( $\eta_t$ ) can be defined as following:

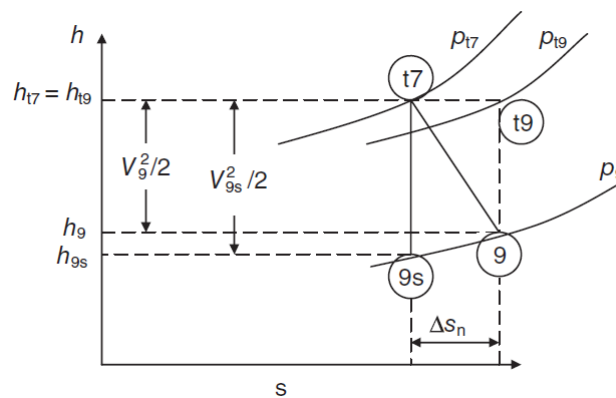
$$\eta_t = \frac{\Delta h_{t,actual}}{\Delta h_{t,isentropic}} = \frac{h_{t4} - h_{t5}}{h_{t4} - h_{t5s}} = \frac{1 - \tau_t}{1 - \pi_t^{\frac{\gamma-1}{\gamma}}} \quad (20)$$

Turbine polytropic efficiency ( $e_t$ ) is defined as a small-stage efficiency for a turbine, and can be express as following:

$$e_t \equiv \frac{dh_t}{dh_{ts}} = \frac{dh_t}{\frac{dp_t}{\rho_t}} \quad (21)$$

### 3.1.5. Exhaust nozzle

The main function of an aero-engine exhaust system is to accelerate the gas efficiently. To examine the efficiency of a nozzle in expanding the gas to an exit (static) pressure  $p_9$ , we create an enthalpy–entropy diagram, very similar to an inlet as shown in Figure 9.



**Figure 9.** h-s diagram for an exhaust nozzle [15]

We may also define a nozzle adiabatic efficiency ( $\eta_n$ ) very similar to the inlet adiabatic efficiency, as

$$\eta_n = \frac{h_{t7} - h_9}{h_{t7} - h_{9s}} = \frac{(V_9^2 / 2)}{(V_{9s}^2 / 2)} \quad (22)$$



## 4. SYSTEM DESCRIPTION AND TEST-CELL SETUP OF THE EXPERIMENTAL TURBOJET

### 4.1. System Description

Experimental turbojet engine shown in Figures 10 and 11 for use air as the working fluid and provide thrust force based on the variation the kinetic energy of burnt gases after combustion. The study of the cycle of the turbojet engine involves components inlet and outlets temperatures, pressures, mass flows and thermo-mechanical features of the engine such as overall efficiency, specific fuel consumption and thrust. The description of thermodynamic equations can be found in any number of texts [13,14]. Figure 12 also shows thrust evolution of the engine class.

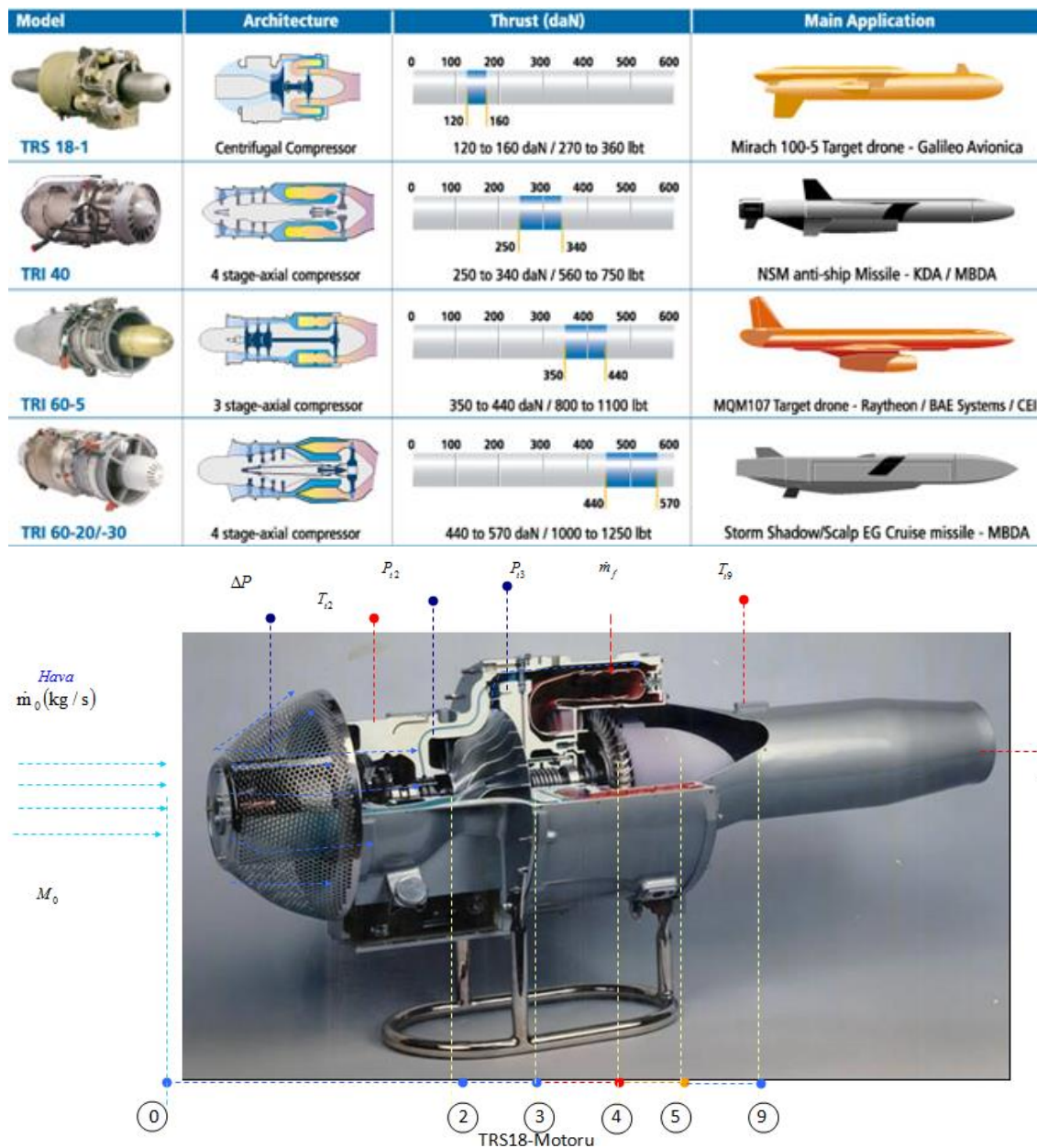


Figure 10. Turbojet engine target drone applications and stations location [16]

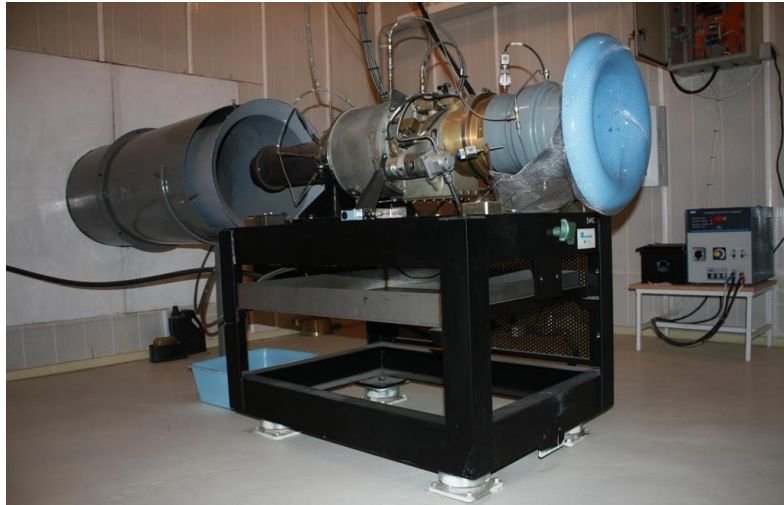


Figure 11. Turbojet engine overview in the test-cell [16]

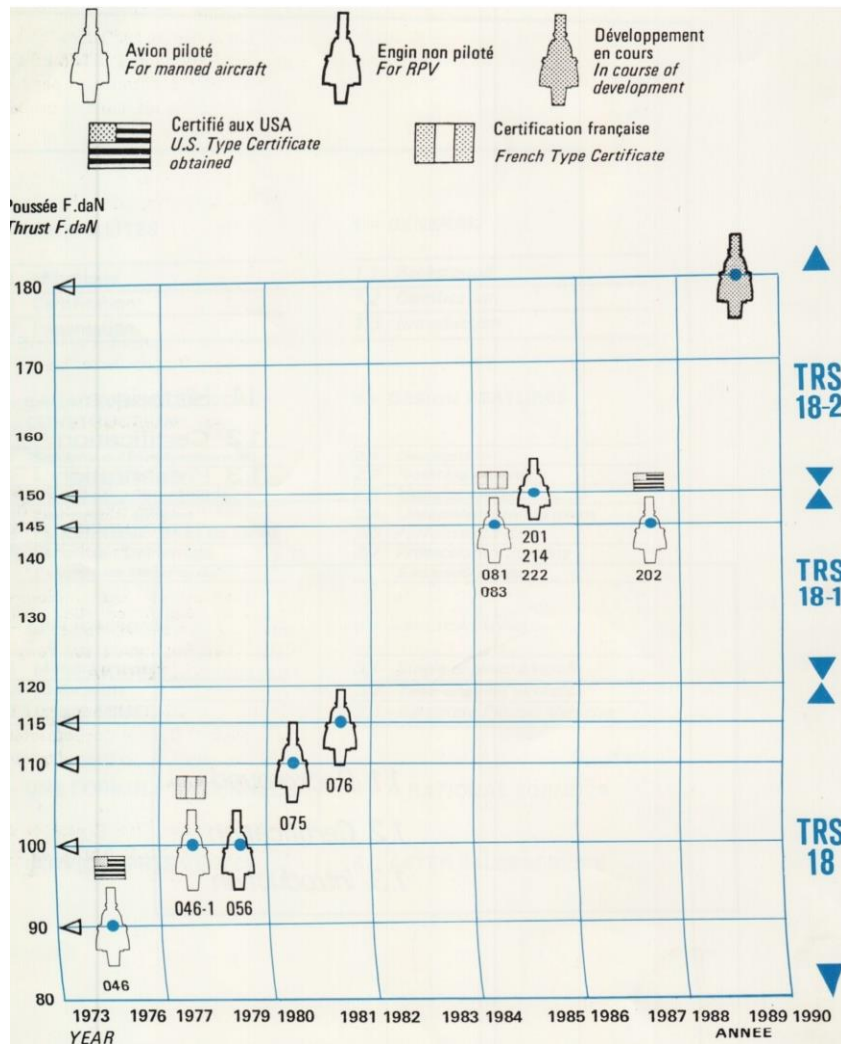


Figure 12. Turbojet engine thrust level improvement [16]

**Table 1.** Microturbo TRS18 turbojet engine general specifications [15]

<b>Power output</b>	<b>Up to 1,500 N thrust depending on version</b>
<b>RPM</b>	44,000-47,000 estimated maximum
<b>Compressor</b>	Centrifugal impeller
<b>Combustion chamber</b>	Reverse flow annular with 10 spill type burners
<b>Turbine</b>	1 stage axial flow
<b>Layout</b>	Single spool with accessory gearbox in nose
<b>Starting</b>	Air impingement
<b>Fuel system</b>	Engine driven fuel pump or electric pump, electronic control
<b>Lubrication</b>	Return system
<b>Oil spec</b>	MIL-L-7808
<b>Weight</b>	38 kg
<b>Application</b>	BD5J, Single seat jet, microjet and target drones

## 4.2 Engine Test-Setup and Testing

The engine testing is starting to install engine on chasis and secure by attaching lugs. Then, the procedure is carrying out the following measurement connections and couplings:

- Oil pressure pipe to oil pressure line
- Compressor air pressure pipe to line
- Removing oil filter plug, installing tool
- Air intake temperature pipet to line
- Combustor manifold inlet and outlet pressure pipe to lines

Engine test is starting to press START pushbutton three seconds. In relation to requirement for speed (idle, full power) and starting mode (electrical, air), it needs to check the parameters which should comply with technical specifications on the test sheets.

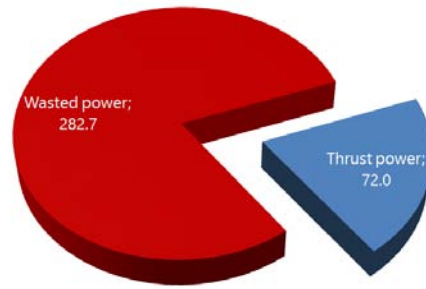
In idle speed, duration is 3 minutes. In this mode, engine is shutting down and checking for leakage. In full power mode, maximum duration is 5 minutes.

## 5. RESULTS

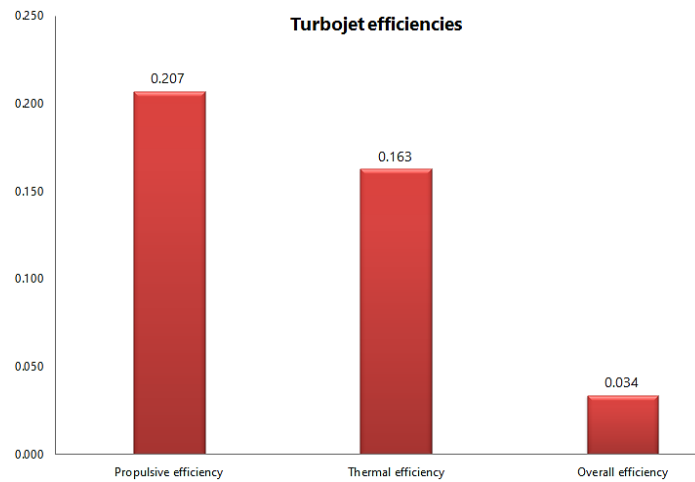
The common thought process with respect to analysis of aero-engines focuses heavily on the flow of air through the engine. In point of fact, the ultimate aim of any aero-engine is to efficiently convert energy stored in the chemical bonds of a fuel into useful thrust power. Energy, entropy and cycle analyses for the turbojet engine in this study allow to get engine behavior and to measure energy destruction and wasting energy of the engine to the environment and to introduce the engine and component efficiencies, engine powers and cycle diagrams as parameter for evaluating the thermodynamic performance together with first and second law of thermodynamics and physics law of motion.

In Figure 13, wasted and thrust power are shown. According to measured engine data and related power equations, wasted and thrust power are calculated to be 282.7 kW and 72 kW, respectively. While thrust power is imparted the energy rate to the engine test bench or aircraft, waste power is discharged to the environment.

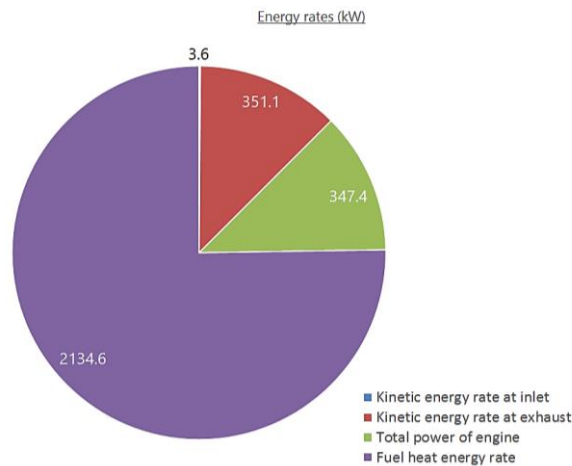
Efficiencies of the turbojet engine are given in Figure 14 as well. In this figure, overall efficiency of the engine is calculated to be 3.4%, while propulsive and thermal efficiency of the turbojet are 20.7% and 16.3%, respectively. Due to high level wasted energy to the environment, these efficiency values, as expected, are very low compared to turbofan engines.



**Figure 13.** Thrust power and wasted power of the turbojet engine (kW)

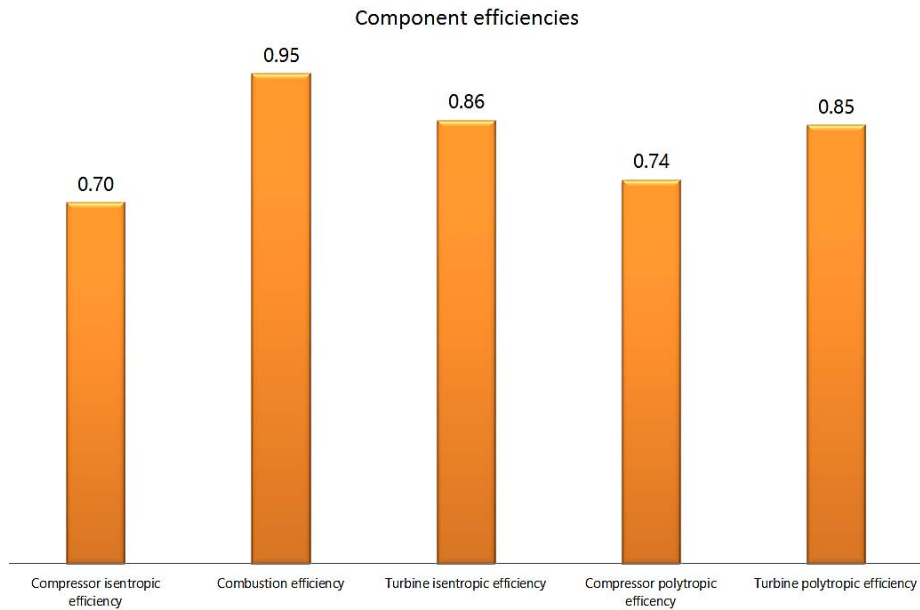


**Figure 14.** Propulsive, thermal and overall efficiencies of the turbojet engine



**Figure 15.** Power distribution of the turbojet engine (kW)

Figure 15 shows kinetic energy rate at inlet (station 0) and outlet (station 9) of the engine, fuel heat rate and total power of the turbojet engine. Fuel heat rate increases with increasing fuel flow rate and fuel heating value. According to Figure 15, the greatest power value is found to be 2134.6 kW in fuel heat rate. At stations, 0 and 9, kinetic energy rates are calculated to be 3.6 kW and 351.1 kW, respectively.



**Figure 16.** Component isentropic efficiencies of the turbojet engine

The measure of irreversibility in rotary part of turbomachinery (i.e., compressor and turbine) may be thermodynamically defined through some form of isentropic and polytropic efficiencies. As might be expected, adiabatic and polytropic efficiencies are related. In Figure 16, isentropic and polytropic efficiencies for the compressor and turbine are shown with their values between 0.70-0.86. In same figure, burner efficiency is given with the value of 0.95.

To understand how an aero-engine works, basic thermodynamics of gases must be known. Gases have various properties, including the gas pressure  $p$ , temperature  $T$ , mass, and volume  $v$ . A thermodynamic process, such as heating or compressing the gas, changes the values of the state variables in a manner, which is described by the laws of thermodynamics. A series of processes is called a cycle and forms the basis for understanding engine operation. A T-s diagram is the type of diagram frequently used to analyze energy system cycles. By the definitions of entropy, the heat transfer transferred to or from the system equals the area under the T-s curve. Mollier's h-s diagram was a logical extension of the T-s diagram first proposed by Gibbs. The advantages of such a diagram are that vertical lines represent reversible processes and horizontal lines represent lines of constant energy. In this study, P-v, T-s and h-s diagrams are drawn for experimental turbojet TRS18 engine with GASTURB program according to experimental parameters as shown in Figures 17, 18 and 19, respectively.

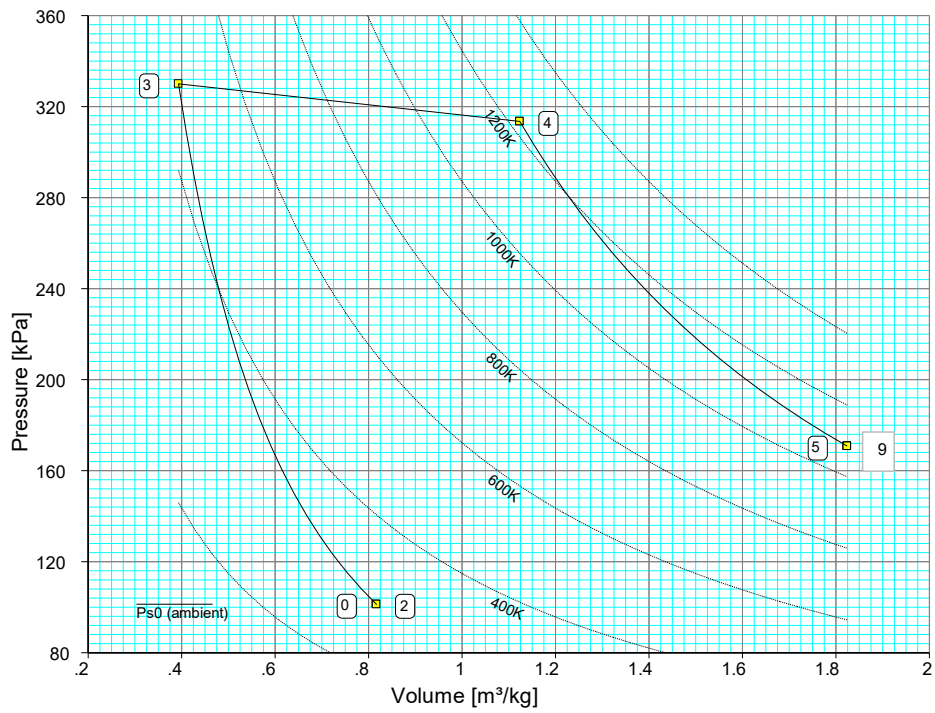


Figure 17. P-v diagram of the engine

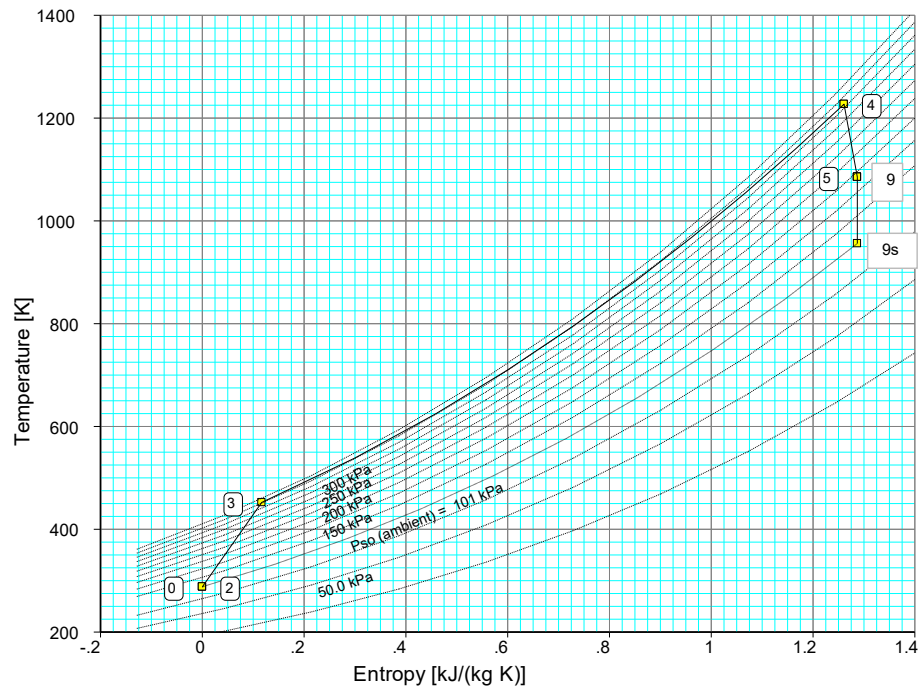


Figure 18. T-s diagram of the engine



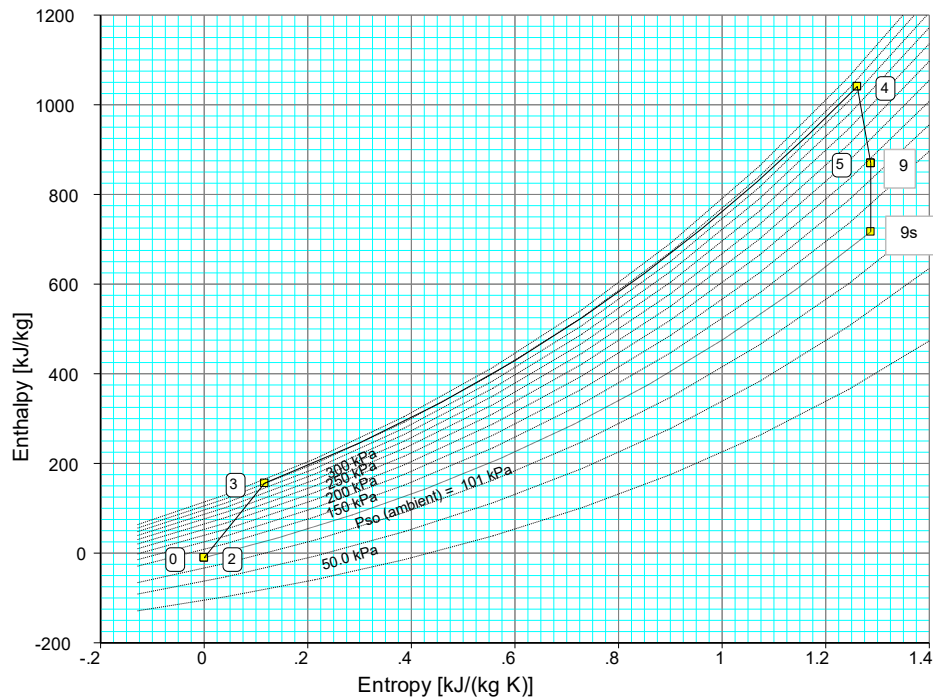


Figure 19. h-s diagram of the engine

## 6. CONCLUSION REMARKS

The detailed thermodynamic analysis of the experimental turbojet engine presented in this paper is well suited for furthering the goal of more effective energy resource use, for it enables the location, cause and true magnitude of waste to be determined. The main conclusions can be drawn from the results of energy and entropy analysis of the turbojet engine are as follows:

- The overall energy efficiency of the turbojet engine has been calculated as 3.4%. It looks like low value because of low flight speed in ground test-cell experiments.
- Wasted energy of the engine discharging to the atmospheric environment is found to be 282.7 kW due to low efficiency and yielding high thrust.
- Thrust force and specific thrust are found to be 1,270 N and 564.36 m/s, respectively.
- Specific fuel consumption of the engine is calculated to be 160 g/kN.s
- P-v, T-s and h-s diagrams are shown graphically due to thermodynamic behavior of the turbojet engine. Unmeasured pressure and temperature values are seen in these diagrams easily. Behind, entropy changes in engine component stations seen in these diagrams as well.

This paper also discusses the energy and entropy analysis of the turbojet engine through the use of experimental testing. Such information can be used in the design of the similar turbojet engine efficient systems and for increasing the efficiency of existing systems.

As a conclusion, this detailed analysis provides a powerful and systematic tool for identifying all cost sources and for optimizing the design of turbojet engine powered target drones, auxiliary power units and aircrafts. The results from this study will be used in the optimization of small gas turbine engine and ground gas turbine power systems. This is a first study for first and second law performance comparison of the TRS18 turbojet engine. The results should provide a realistic and meaningful in the performance evaluation of target drone power systems, which may be useful in the analysis of similar turboprop, turboshaft and industrial gas turbines.

In a future study, we will focus on exergy and emission analysis of the turbojet engine in the engine-test cell laboratory in Anadolu University Faculty of Aeronautics and Astronautics.

## Nomenclature

A	Area (m <sup>2</sup> )
$C_p$	Specific heat ratio (kJ kg <sup>-1</sup> )
e	Polytropic efficiency
E	Energy (kJ)
f	Fuel-air ratio
F	Thrust (N)
h	Specific enthalpy (kJ kg <sup>-1</sup> )
HPC	High pressure compressor
HPT	High pressure turbine
KE	Kinetic energy, kJ kg <sup>-1</sup>
LPT	Low pressure turbine
M	Mach number
$\dot{m}$	Mass flow rate (kg s <sup>-1</sup> )
N	Shaft speed
P	Pressure (Pa)
pe	Potential energy (kJ kg <sup>-1</sup> )
$Q_R$	Fuel heat rate (kJ kg <sup>-1</sup> )
R	Ideal gas constant (J·K <sup>-1</sup> mol <sup>-1</sup> )
T	Temperature (K)
TP	Thrust power (W)
s	Entropy; isentropic state; surface
SFC	Specific fuel consumption ( kg N. s <sup>-1</sup> )
ST	Specific thrust (m s <sup>-1</sup> )
V	Velocity (m s <sup>-1</sup> )
$\dot{W}$	Work (kJ s <sup>-1</sup> )
WP	Wasted power (W)

### Greek Letters

$\gamma$	Specific heat ratio
$\eta$	Efficiency
$\pi$	Pressure ratio
$\rho$	Density (kg m <sup>-3</sup> )
$\tau$	Temperature ratio

### Subscripts

b	Burner
c	Compressor
ch	Chemical
d	Diffuzer
f	Fuel
in	Input
n	Nozzle
O	Overall
out	Output
p	Propulsive
t	Turbine
th	Thermal



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