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THERMODYNAMIC ANALYSIS OF SCRAM JET ENGINE: EFFECT OF CYCLIC STATIC TEMPERATURE RATIO ON EFFICIENCIES

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ABSTRACT

This work studies the SCRAM jet engine using the First Law of Thermodynamics to analyse and study the effect of cyclic static temperature ratio and equilibrium heating value on the efficiencies of the engine. Thermal, cycle, propulsive and overall efficiencies were studied while a brief study of component efficiencies on their influence on overall efficiency was studied. It was seen that the optimum value of cyclic static temperature ratio was close to 7 and the overall efficiency depended upon the expansion efficiency the most. The study was conducted by the use of mathematical formulation and a rigorous excel code.

KEYWORDS: SCRAM Jet Engine, First Law of Thermodynamics, Cyclic Static Temperature.

INTRODUCTION

The jet engine operates a simple principles. Compression, combustion and expansion. In order to change the nature of the flow, different instruments such as turbines, nozzles are used in the jet engine. The ram jet engine is used when speed above Mach 2 need to achieved. Ram jet engines operate within the range of Mach 3 to Mach 6. Above which the dissociation effects at the end of compression make the engine inefficient. To overcome such a problem the combustion in a scram jet engine takes place at supersonic speeds. The working principle of the ram jet and the scram jet engine is the similar to that of jet engine. The processes are briefly explained below

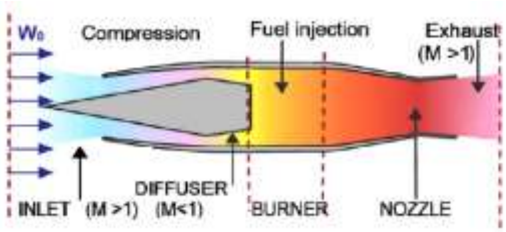

Figure 1 Ram Jet Engine [1]

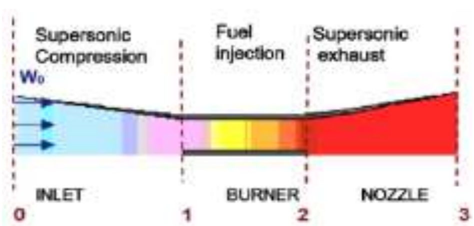

Figure 2 SCRAM Jet Engine [1]

1) Compression: This process in brought about by the use of a compressor turbine in a jet engine or a convergent geometric shape in a ram jet or a scram jet engine. The freestream flow is slowed to a desirable speed to facilitate combustion. In case of a ram jet engine, the flow at the end of the compression turns sub-sonic by the use of normal shock at the end of the compressor. In case of a scram jet engine, the normal shock is replaced by an oblique shock and the flow leaving the compressor is supersonic in nature.
2) Combustion: the addition and burning of fuel takes place within the combustion chamber. In case of the scram jet engine, the speed of the incoming flow is supersonic. The process of combustion adds energy to the flow by burning fuel, further accelerating it.

3) Expansion: Expansion takes place in a nozzle where the velocity of the flow is increased, while decrease in pressure according to the Bernoulli's principle. The pressure of the flow, in general, should match the freestream pressure. The velocity of the exhaust flow is many times faster than the intake flow. The difference in this velocity provides for propulsion.

The ram jet engine and the scram jet engine do not require the use of rotating parts, therefore they can be axisymmetric in nature. The scram jet engine can be built into the aircraft itself. Figures 1 – 2 show the configurations of a Ram jet and a Scram Jet engine.

Nomeclature

P_i	Pressure at reference station 'i'(mPa)	η_0	Overall efficiency
T_i	Temperature at reference station 'i' (K)	η_p	Propulsive efficiency
V_i	Velocity at reference station 'i' (m/s)	η_i	Efficiency of the 'i' component
F	Thrust(N)	M_i	Mach number at 'i' station
m_0	Inlet mass flow rate(kg/s)	ψ	Cycle static temperature ratio
m_f	Fuel flow rate(kg/s)	s_i	Entropy at 'i' station
g_0	Acceleration due to gravity(m/s^2)	C_p	Heat Capacity(kJ/K)
I_{sp}	Specific Impulse(s)	R	Gas constant(kJ/kgK)
h_{pr}	Heating value of fuel(kJ/kg)	f	Stoichiometric fuel/air ratio
T_{sp}	Specific Thrust(m/s)		

Component Modelling of SCRAM Jet

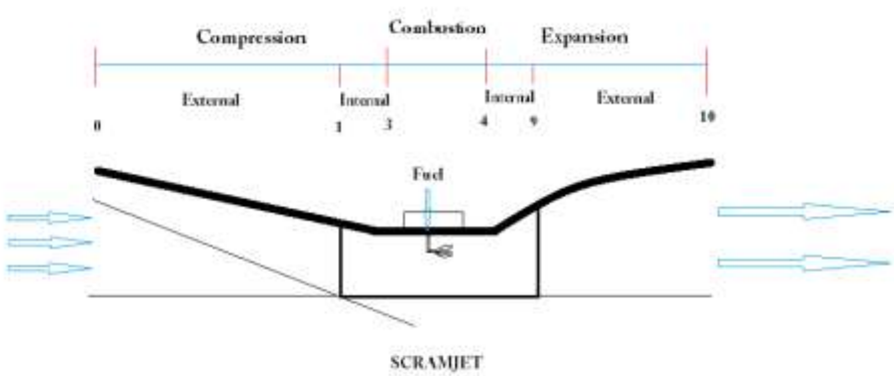

Figure 3 References stations in a SCRAM Jet Engine [1]

Reference station	Engine Location	Reference station	Engine Location
0	Free stream Conditions	4	Burner or combustor exit
	External compression begins		Internal expansion begins
1	External compression ends		Nozzle entry
	Internal compression begins	9	Internal expansion ends
	Inlet or diffuser entry		Nozzle exit

3	Inlet or diffuser exit		External expansion begins
	Internal compression ends	10	External expansion ends
	Burner or combustor exit		

Table 1 Stations in SCRAM Jet Engine

Ideal Brayton Cycle:

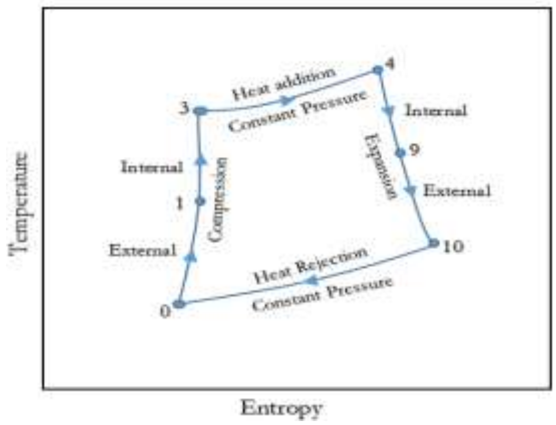

Figure 4 Ideal Brayton Cycle [1]

Figure.4 shows an ideal Brayton cycle. The processes of compression, combustion and expansion are taken as the paths in between the respective points within the cycle. The respective points represent the start and end of the processes.

Point 0-3 represents the compression in the engine cycle. As seen in reference [1], the cyclic static temperature, the ratio of the burner entry static temperature to the freestream temperature, was studied as a parameter with priority. The compression was taken to be adiabatic and isentropic.

Point 3-4 represents the process of heat addition. This process involved fuel addition without the addition of mass. This work considered heat addition at constant pressure.

Point 4-10 represents the process of expansion. The process was adiabatic and isentropic.

Point 10-0 represents the process of heat rejection. This fictional process was studied to maintain the equilibrium of the system.

Assumptions
The calculations in his work were done with some assumptions. The following are stated below.

a) The working fluid was a pure substance and it was always in an equilibrium state.[5]

b) The working fluid returns to its original state after the process.(Heat rejection process) [1][5]

c) The whole system was treated as a control volume without any interactions with the surfaces.[5]

d) Combustion takes place only at constant pressure and dissociation effects were neglected.[5]

MATERIALS AND METHODS

General Methodology:

The present work consists of thermodynamically analysing a SCRAM jet engine by using the mathematical formulation of the First law of thermodynamics [5] and studying its various parameters.

Previously [1] has done work using first law analysis and stream thrust analysis of a SCRAM jet engine at different altitudes. A simple Brayton cycle was used to study the performance parameters of the engine, including the study of efficiencies [6]. The system was divided into components and sub-systems to evaluate parameters at individual stations. More advanced methods such as treating the whole vehicle in terms of explicit second-law characteristics, considering the whole system as a stream tube have been studied [2]. The performance of the system in terms of thrust and propulsive losses in terms of entropy have also been studied [3].

In this work, the first law of thermodynamics was used to study the effect of cyclic static temperature over various efficiencies. The work also studies the effect of component efficiencies over other efficiencies.

Definitions

The following definitions play an important role in defining the performance of a SCRAM jet engine [1][5],

Overall Efficiency -Ratio of thrust power to chemical energy release rate of fuel.

$$\eta_0 = FV_0/m_f h_{pr} \qquad (1)$$

Propulsive Efficiency - Ratio of the thrust power to the engine mechanical power.

$$\eta_p = 2/((V_{10}/V_0) + 1) \qquad (2)$$

First Law Analysis

First law analysis was used to study variable parameters at different stations along the SCRAM jet engine. The parameters in study were temperature, pressure and entropy. The mathematical formulation was done using a rigorous excel program that followed the study of variables such as pressure, entropy etc. over the entire cycle. Due to the vast nature of the analysis, some assumptions on the values of variables were taken, one such value for the initial analysis was the cyclic static temperature which was used to determine the maximum allowable compression temperature. Equation 3 gives the definition of the ratio. An initial value was assumed during the first iteration after which the remaining variables were kept constant changing the ratio. The mathematical formulation for the analysis was taken from [5]

$$\psi = \frac{T_3}{T_0} \geq 1 \qquad (3)$$

1580 K was taken as the maximum allowable compression temperature in the first iteration [1][5]. The burner entry Mach number, which is a co-dependent variable on the cyclic static temperature, was formulated as

$$M_3 = \sqrt{\frac{2}{\gamma_c - 1}\{\frac{T_0}{T_3}\left(1 + \frac{\gamma_c - 1}{2}{M_0}^2\right) - 1\}} \qquad (4)$$

The primary way of studying the entropy change over the system was the Gibbs Equation.

$$Tds = dh - \frac{dp}{\rho} \qquad (5)$$

These relations were set because of practical limitations [5]. The following values were given as the initial input

M_0	5		n_e	0.9	
Gamma	1.4		C_{p0}	1000	J/kg K
Speed of Sound	298.663	m/s	C_{pc}	1090	J/kg K
V_0	1493.315	m/s	C_{pb}	1510	J/kg K
T_0	222	K	$C_{pc}.R_e/R_c.C_{pe}$	0.722	
T_3	1580	K	C_{pe}	1510	J/kg K
ψ	7.117117		$R_c(air)$	287	J/kg K
$n_b.fh_{Pr}/Cp_0.T_0$	16.78487		$R_e(air)$	287	J/kg K
n_c	0.9		fh_{Pr}	4140268	J/kg
n_b	0.9		$R_0(air)$	287	J/kg K
$\dot{m}_0$	300	kg/s			

Table 2 Initial Input Condtions

RESULTS AND DISCUSSION

This work discusses the effects of cyclic static temperature ratio on various efficiencies of the engine. The initial values were taken from Table - 2. The values of appropriate variable were changed to see their effect on other parameters without changing other values.

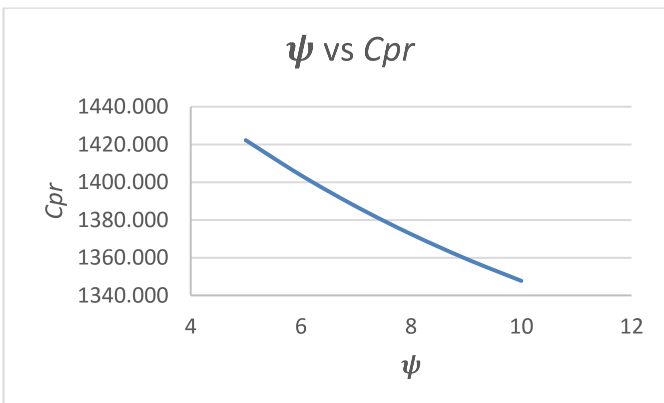

Figure 5 Cyclic Static Temperature VS Specific Heat

Effect of ψ on Cpr

Cpr is the equilibrium specific heat at constant pressure and is used as a parameters necessary to validate the mathematical process [5]. If the value of *Cpr* is not within range, then the process has to start with a change in the input conditions. Fig- 5 shows the graph pertaining to the change in *Cpr* with change in static cyclic temperature ratio. It was seen that with increase in the value of ψ there is a decrease in *Cpr*. Depending on the values of other variable, the value of *Cpr* can be taken as optimum for other calculations.

Effect of ψ on cycle and thermal efficiencies

The Fig - 6,7 shows the graph representing cycle and thermal efficiencies. Both the efficiencies are based on thermal concepts while other efficiencies may depend upon the velocity or the Mach number of the flow. It can be seen in Fig-6,7 that both efficiencies reach their highest values at cyclic static temperature of 7. Therefore this value was taken as the optimum value for other *Cpr* calculations as well. The values of cycle and thermal efficiencies do not change with velocity.

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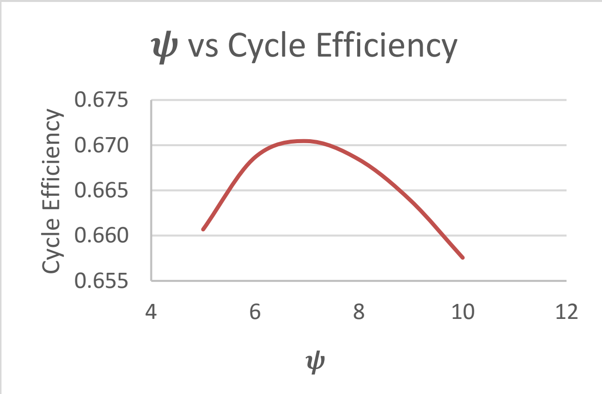

Figure 6 ψ VS Cycle Efficiency

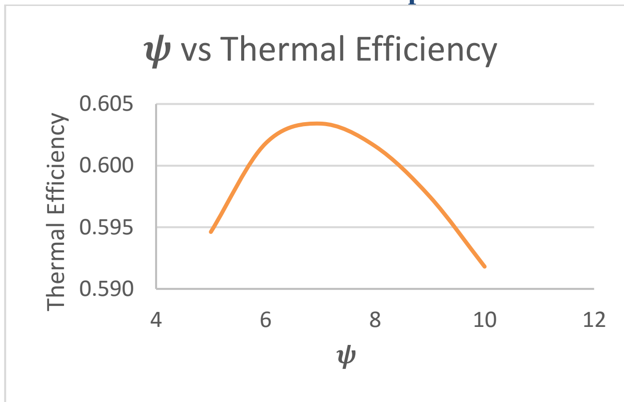

Figure 7 ψ VS Thermal Efficiency

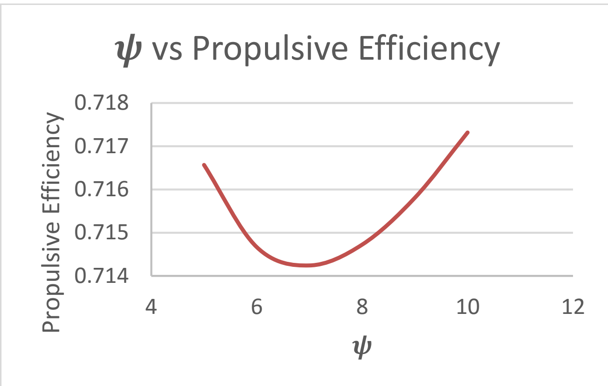

Figure 8 ψ VS Propulsive Efficiency

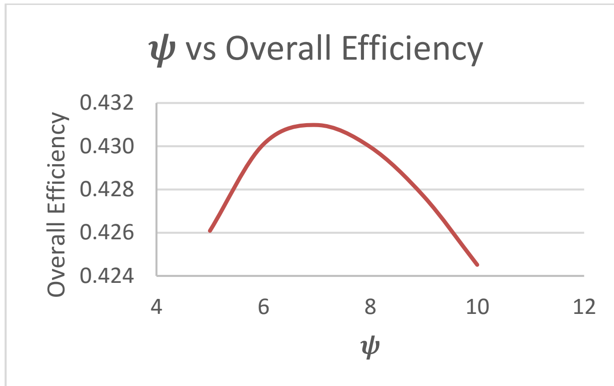

Figure 9 ψ VS Overall Efficiency

Effect of ψ on propulsive and overall efficiencies

Fig-8 is the graph that represents propulsive efficiency over cyclic static temperature ratio. It is see that the propulsive efficiency drops at the optimum value of ψ and climbs again as it increases. But the overall efficiency is maximum at optimum value of ψ and drops as it increases as shown in Fig-9. The overall efficiency is dependent upon the thermal efficiency of the system, while propulsive efficiency depends upon the velocity difference in intake and exhaust velocity. From the graphs studied above, it can stated that ψ effects mostly the thermal systems of the engine and temperature related parameters.

Effect of fuel-heating value on the overall efficiency:

Equilibrium heating value of fuel is represented by

$$\frac{\eta_b f h_{PR}}{C_{p0} T_0}$$

This term play an important role because it represents the heating value of the fuel. While the other terms are kept constant, $f h_{PR}$ is changed. The Fig-10 shows the graph representing fuel-heating value to the overall efficiency. The results showed an increase in efficiency with the increase in heating value.

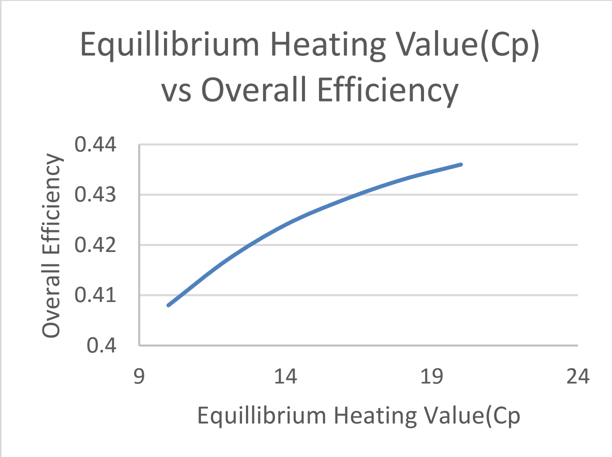

Figure 10 Cp vs Overall Efficiency

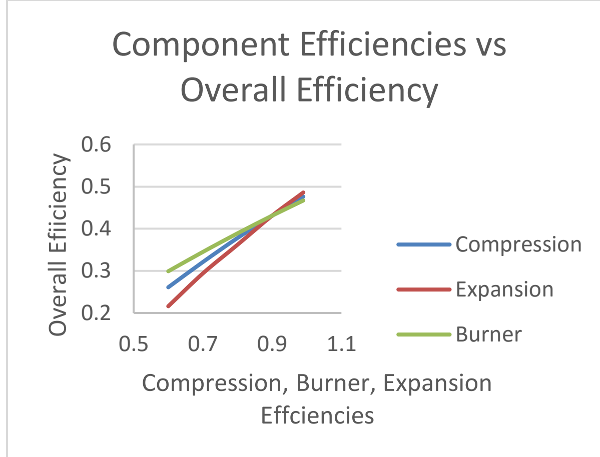

Figure 11 Component Efficiencies vs Overall Efficiency

Effect of Component efficiencies on the Overall efficiency

The components represent the processes, therefore η_c, η_b and η_e represent the efficiencies of compression, burning of fuel and expansion. The Fig-11 shows a graph representing the three efficiencies with respect to the overall efficiency. It was seen that with the increase in component efficiencies the overall efficiency increases. The expansion process influences the overall efficiency the most while compression and burner efficiencies show lesser influence. If the back pressure (pressure of outgoing flow) is not equal to the freestream pressure. A process called under expansion or over expansion takes places, decreasing the efficiency of the engine.

CONCLUSION

A simple analysis of the SCRAM jet engine using the First Law of Thermodynamics was done in this work. The most important parameters that was considered was the cyclic static temperature ratio. The analysis was conducted using mathematical formulation and a rigorous Excel code. It was seen that the optimum value of ψ was close to 7. This was concluded by studying the thermal, cycle, propulsive and overall efficiencies of the engine. A simple comparison between component efficiency showed the dependence of the overall efficiency on expansion efficiency. An in depth analysis would be required to arrive at conclusive results for the under-study parameters. This work provides a simple framework on which other learners may continue their work. More advanced methods such as using the second law may be used to validate and study the process of hypersonic propulsion.

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