RAMJET PROPULSION ANALYSIS PROJECT

MAE 563: AIRCRAFT PROPUSLSION

Dr. Werner Dahm

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ARYA NARASIMHARAJU

Introduction

In this project, we will develop an analysis tool using MATLAB programming language for parametric studies of ramjet propulsion performance and to examine performance variation across a range of key parameters. We will implement different sets of equation taught in lectures to analyze performance of a '*Non-Ideal Ramjet Propulsion System.'*

We will use following set of parameters in analysis tool to obtain detailed results:

Flight Altitude	Z
Flight Mach Number	M_1
Inlet/Diffuser Efficiency	η_d
Diffuser Exit Mach Number	M_2
Combustor Exit Max Allowable Temperature	$(T_{t3})_{max}$
Fuel Heating Value	q_f
Nozzle Efficiency	n_n
Nozzle Exit Area	A_e
Universal Gas Constant	R
Standard Gravity	g

Table 1: Analysis Tool Inputs

Total and Static Temperatures	T_t & T
Total and Static Pressures	P_t & P
Relative Change in Entropy	Δs
Flow Speed	V
Mach Number	M

Table 2: State Outputs

Below are the outputs of parametric analysis tool which are included in states of 1,2,3, e and 4.

Thrust	T
Propulsive Power	P
Thermal Efficiency	η_{th}
Propulsive Efficiency	η_p
Overall Efficiency	η_o
Required Fuel Flow Rate	$\dot{m}_f$
Thrust Specific Fuel Consumption	$TSFC$
Specific Impulse	I_{sp}

Before beginning parametric analysis, we must validate analysis tool by running it for two test cases which are:

1. Non-Thermally Choked Test Case
2. Thermal choked Test Case

Case # 1 Non-Thermally Choked	
Flight Altitude	4300 m
Flight Mach Number	2.4
Inlet/Diffuser Efficiency	0.92
Diffuser Exit Mach Number	0. 15
Combustor Exit Max Allowable Temperature	2400 K
Fuel Heating Value	46 MJ
Nozzle Efficiency	0.94
Nozzle Exit Area	0.015 m^2
R	286.9 $\frac{J}{kg*K}$

Table 4: Inputs for Validation Case (a)

Case # 2 Thermally Choked	
Flight Altitude	4300 m
Flight Mach Number	2.4
Inlet/Diffuser Efficiency	0.92
Diffuser Exit Mach Number	0. 4
Combustor Exit Max Allowable Temperature	2400 K
Fuel Heating Value	46 MJ
Nozzle Efficiency	0.94
Nozzle Exit Area	0.015 m^2
R	286.9 $\frac{J}{kg*K}$

Table 5: Inputs for Validation Case (b)

Note:

The gamma values of combustor upstream is 1.4 and downstream of combustor is 1.3.

Cp (t)= a+bt, where a=986 and b=0.170

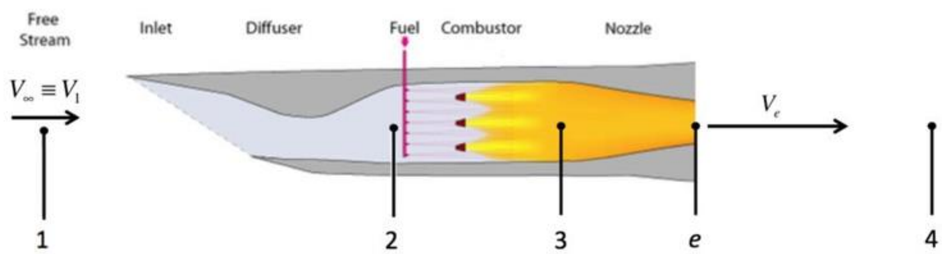

Fig1: Propulsion System Used

Problem A:

Below are graphs of two cases of thermally chocked and non-thermally chocked test cases. The T-S diagrams show net work of cycle and enclosed area shows net work done. Fig 2 represents a non-thermally chocked test case and fig 3 represents thermally chocked test case. The value of Cp is taken to be 1004 J/kg for 4-1.

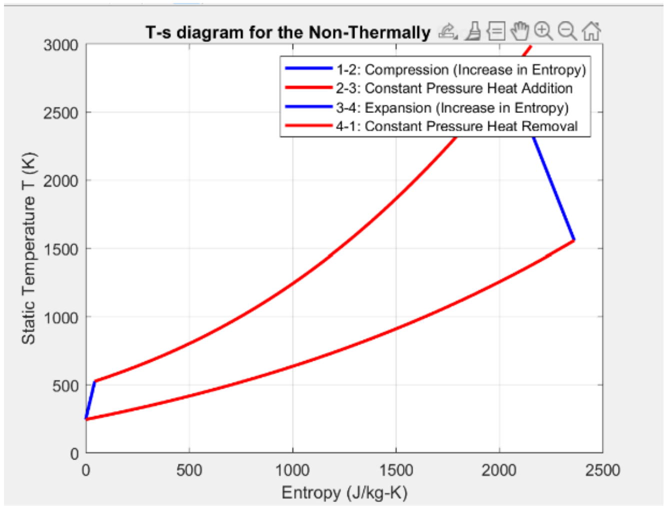

Fig 2: Non-Thermally Chocked Test case

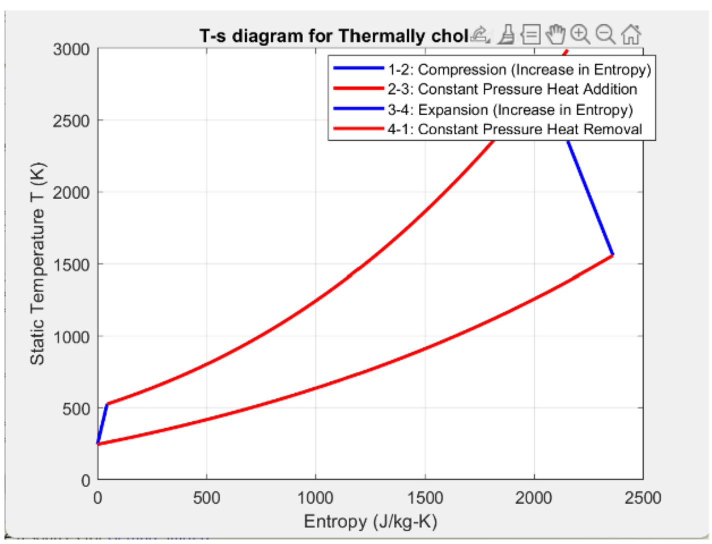

Fig 3: Thermally Chocked Test case

Problem B:

Comparing p(z) and T(z) from module1 with results from International Standard Atmosphere.

From module 1, we get equations:

Where Ts=288K, Ps=101.3kPa, Gamma=1.4 and z*=8404

$$\frac{T_1}{T_s} \equiv \frac{T(z)}{T_s} = \left[1 - \frac{\gamma - 1}{\gamma}(z / z^*)\right]$$

$$\frac{p_1}{p_s} \equiv \frac{p(z)}{p_s} = \left[1 - \frac{\gamma - 1}{\gamma}(z / z^*)\right]^{\frac{\gamma}{\gamma - 1}}$$

For Altitudes z<7958m:

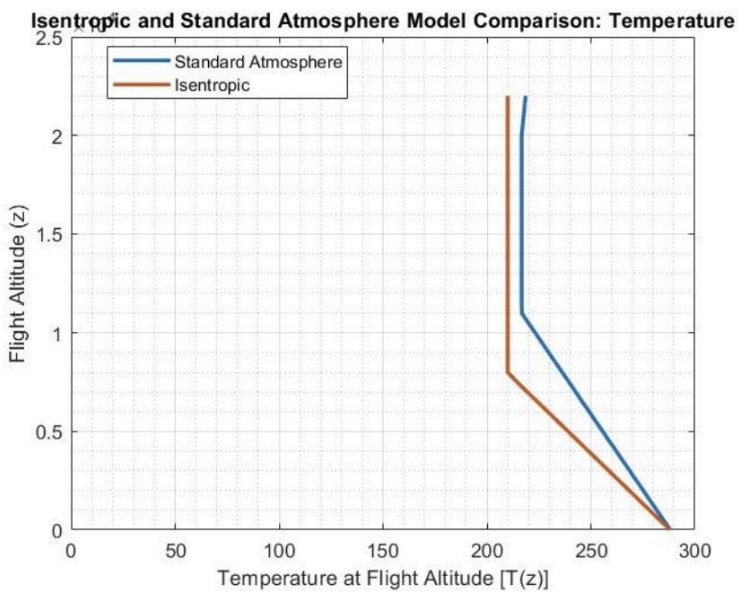

Fig 4 Isentropic VS ICAO model: Temperature

As seen in the graph, we can see temperatures exhibit comparable characteristics for altitudes above 1100m, and below 300m they exhibit strong association.

So, we can say that the isentropic model for temperature can be deemed suitable for analysis.

Based on the pressure comparison graph between the ICAO and Isentropic models, it is evident that these models exhibit a strong association, with only minimal variations. Therefore, with confidence, it can be asserted that the Isentropic model for pressure is suitable for analytical purposes.

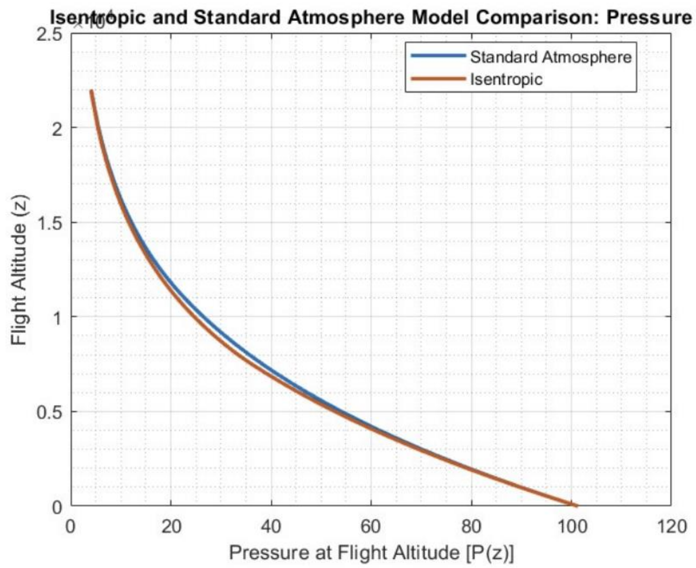

Fig 5: Isentropic Vs ICAO model : Pressure

Problem C

Using same input paramters as in unchocked validation case, we can vary 0.8<M1<5 in small steps we determine:

1. The Overall Efficiency ηo
   Given that this propulsion system is a RAMJET, it can be deduced that its efficiency is notably high only when the operational Mach number exceeds 1, indicating supersonic conditions. This heightened efficiency is attributed to the absence of a compressor, a feature absent in conventional jet engines designed for subsonic operations. To ensure optimal performance, the RAMJET requires inlet pressure ratios in the diffuser well surpassing 40. Achieving such ratios is contingent upon harnessing the "RAM" effect generated at speeds substantially exceeding sonic speed, specifically with Mach numbers greater than 1.5

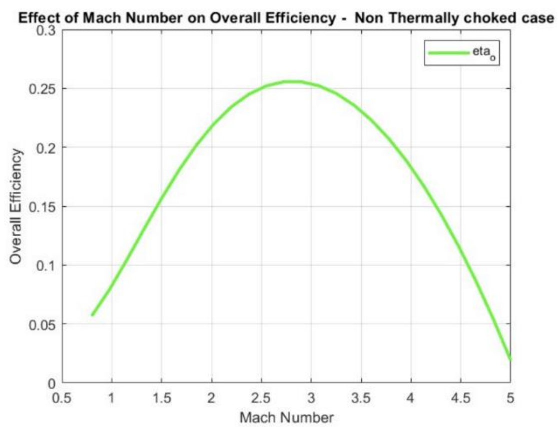

Fig 6 Mach # VS ηo

2. The Thrust T
   From graph we can see that thrust is proportional to mach mumber, as seen in mach number 4.5 the thrust is highest showing peak value at 39kN.

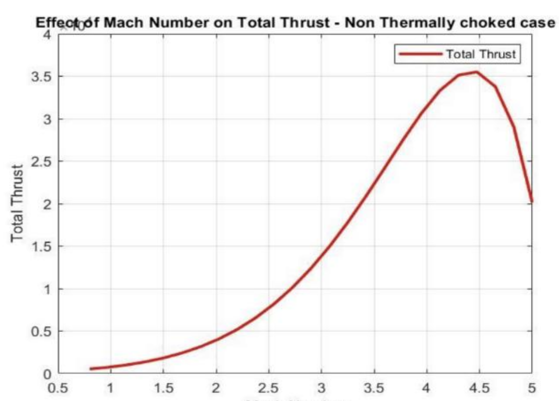

Fig 7 Mach 3 VS Thrust

3. TSFC

The graph indicates a low Thrust-Specific Fuel Consumption (TSFC) at low Mach numbers, demonstrating efficiency at lower speeds. As Mach numbers increase, the TSFC rises in a quadratic fashion, reaching a peak value at the highest Mach number, suggesting a notable change in efficiency with varying speeds.

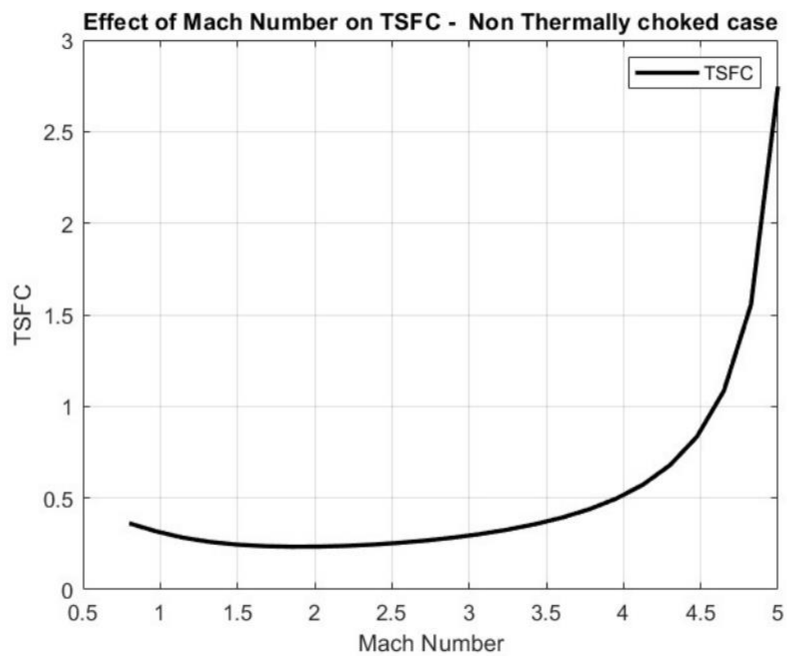

Fig 8 Mach # VS TSFC

Problem D

Using same inputs parameters used in unchoked case, varying flight altitude z in small strps from 2000m to 30000m to determine:

1. The Overhaul Efficiency ηo
   The highest overall efficiency is observed at the initial lowest altitude of z = 2000m. It experiences a continuous linear decline as the altitude increases until reaching z = 7958 m. Beyond this point, the overall efficiency remains constant despite further increases in altitude.

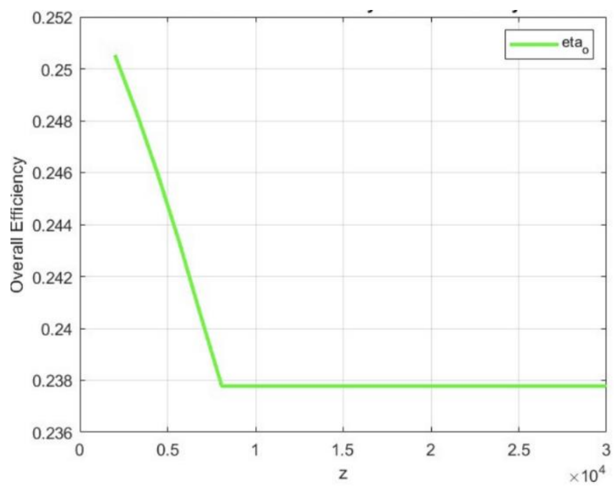

Fig 9 Altitude VS ηo

2. The total thrust (T)

exhibits a gradual decrease with the ascent of flight altitude (z). This phenomenon is likely attributed to the reduced air density at higher altitudes, resulting in a lower mass flow rate of ambient air into the diffuser.

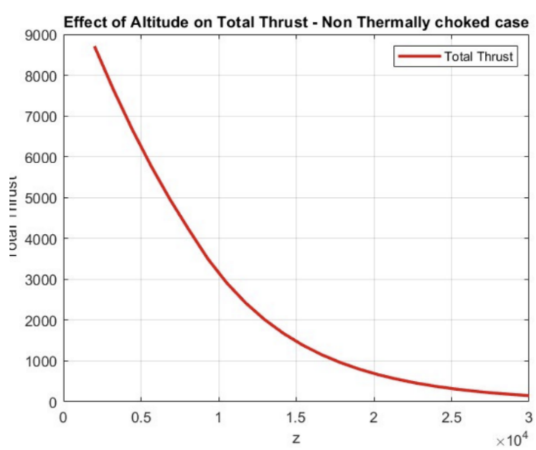

Fig 10 Altitude VS Thrust

3. TSFC
   We can see that TSFC is the same as overall efficiency.

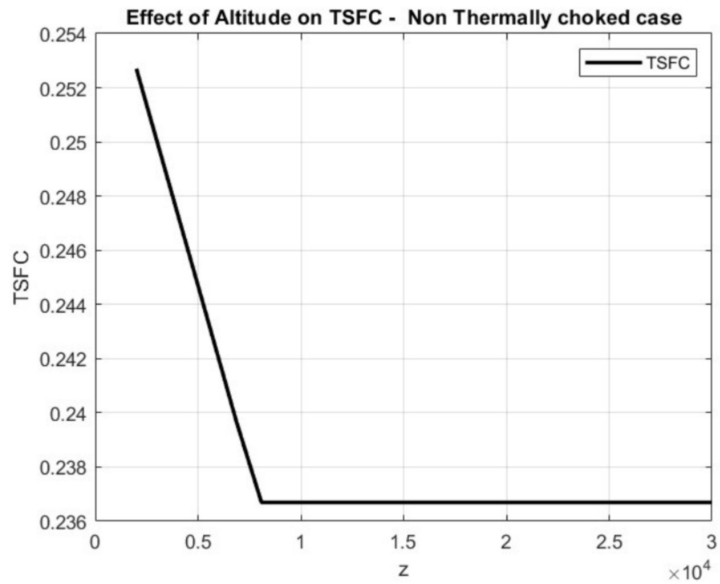

Fig 11 Altitude VS TSFC

Problem E

Using same input in unchoked case, where 2000m<z<20000m in steps of 500m and for each z value systematically vary M1 to find the flight Mach number that:

1. Maximizes the overall efficiency ηo
   The overall efficiency remains constant irrespective of altitude variation after z=7985m.

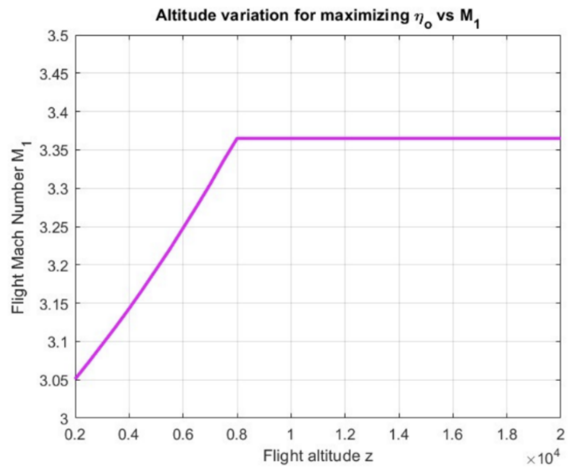

Fig 12 Altitude VS Mach # M1

2. Minimizes the TSFC
   As seen from the following graph, the flight Mach number that minimizes the TSFC has a steep decline at the altitudes ranging from 2000 m and 4000 m.

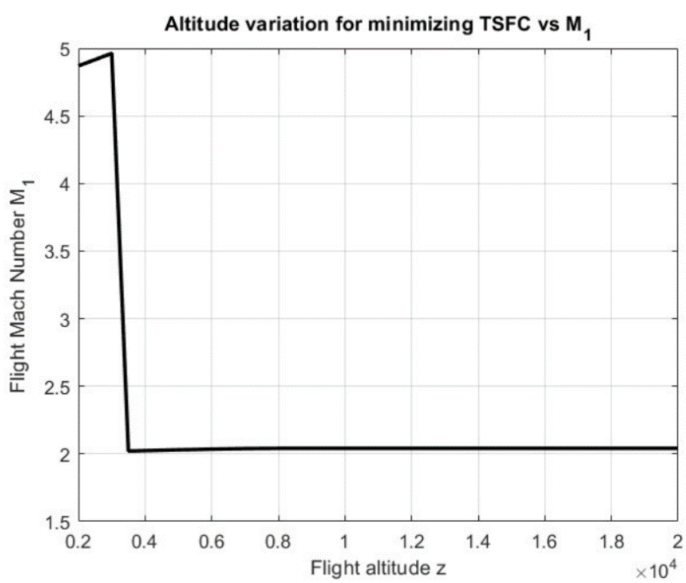

Fig 13 Altitude VS Mach # M1

Problem F

Using same parameters as in unchocked case, including z=4300m and M1=2.4, but systematically vary the inlet/diffuser efficiency from 0.5< ηd<1 in steps of 0.05 to compute:

1. The Overall Efficiency ηo
   As depicted in the graph below, the maximum overall efficiency, reaching 0.257, aligns with a diffuser efficiency of 1.0. This correlation is attributed to the presence of isentropic conditions at ηd = 1, signifying the absence of irreversibility's under these conditions.

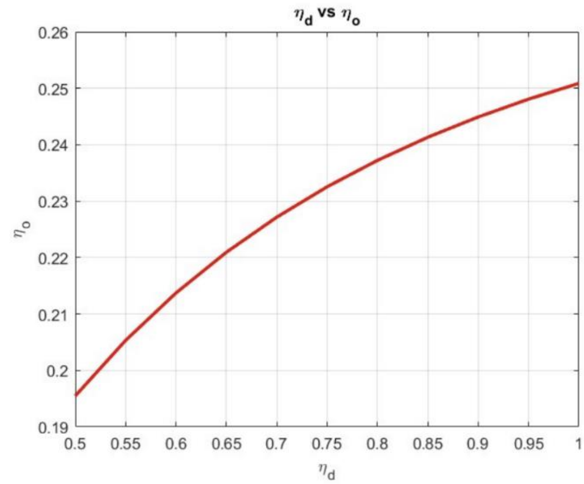

Fig 14 ηd VS ηo

2. The Thrust T
   The graph illustrates a notable rise in total thrust output as the efficiency of the diffuser (ηd) increases. Specifically, at the lowest specified efficiency of the diffuser (ηd = 0.5), the total thrust is recorded at 2000 N.

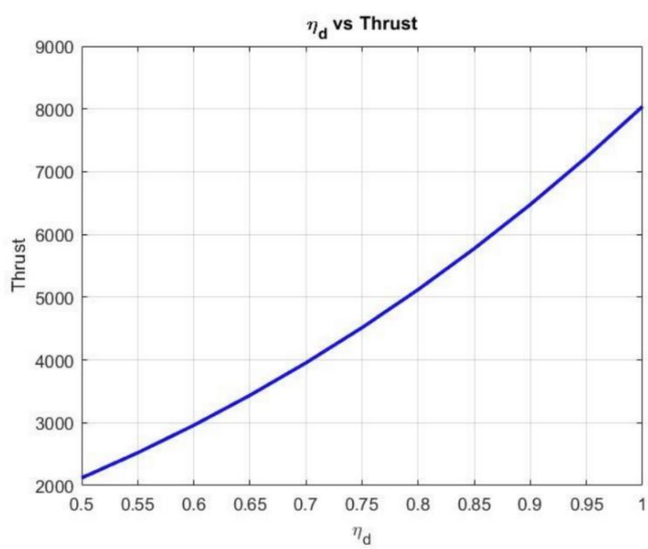

Fig 15 ηd VS Thrust

3. TSFC

   TSFC gradually decreases with increasing efficiency of diffuser.

   The value of TSFC is highest at efficiency of diffuser is 0.5 and lowest thrust at efficiency of diffuser at 1.

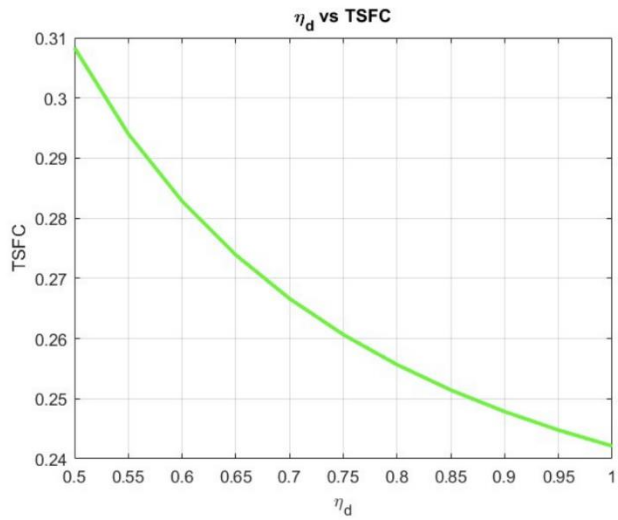

Fig 16 ηd VS TSFC

Problem G

We use same input parameters as in unchocked case, including z=4300m and M1=2.4, but now systematically vary the nozzle efficiency from 0.5< ηn<1 in steps of 0.05 to compute the resulting:

1. The Overall Efficiency ηo
   As we can see by examining the graph, the overall efficiency is largest when nozzle efficiency is equal to 1, this means irreversibility does not exist at isentropic conditions.

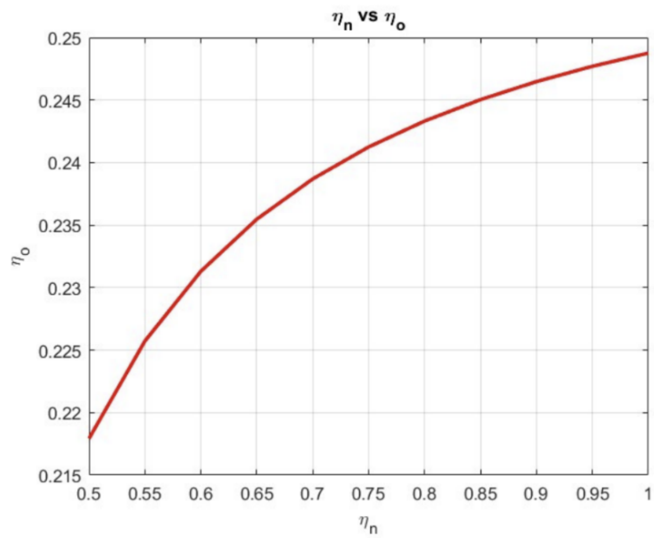

Fig 17 ηn VS ηo

2. The Thrust T,
   From the graph, we get to know that nozzle efficiency is highest at thrust 7500N and lowest thrust 3257N is at smallest nozzle efficiency 0.44.

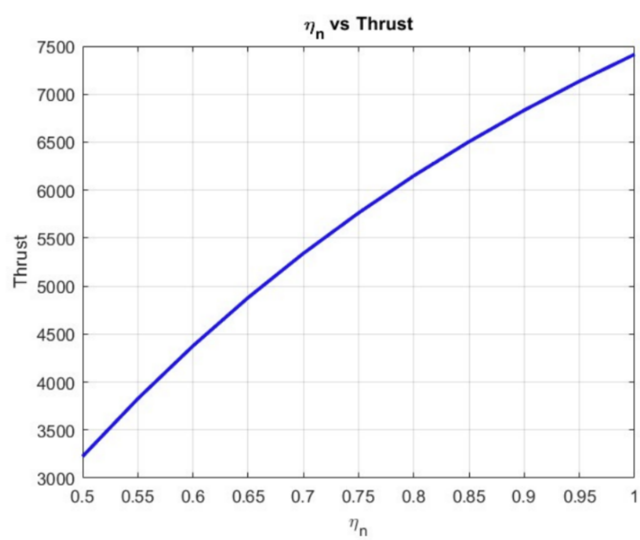

Fig 18 ηn VS Thrust

3. TSFC
   From the graph we know that TSFC at 0.28 is highest at nozzle efficiency 0.5 where it’s the lowest, and highest nozzle efficiency gives out lowest value of TSFC.

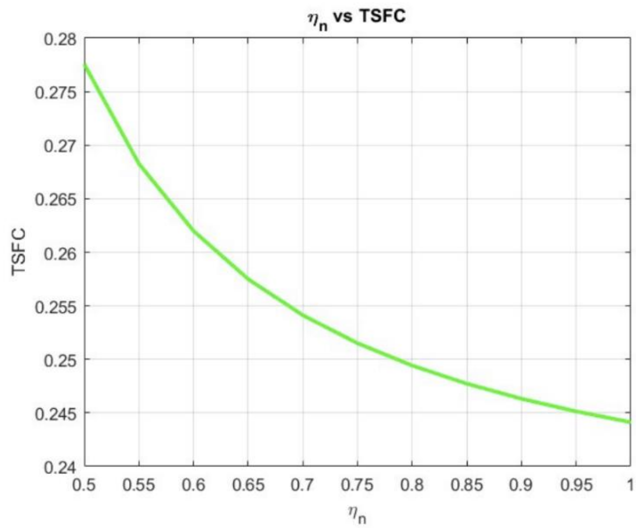

Fig 19 ηn VS TSFC

Problem H

Now using same input parameters as unchoked case, including z=4300 m and M1=2.4, but systematically vary Mach number M2 from 0.1<M2<2.5 in steps of 0.1 to compute the resulting:

1. The Overall Efficiency η_o
2. Observing the graph, it is evident that the overall efficiency experiences a steep decline and even turns negative as the combustor inlet Mach Number (M2) surpasses 0.6. This abrupt change may be attributed to the potential occurrence of engine flameout at supersonic speeds.

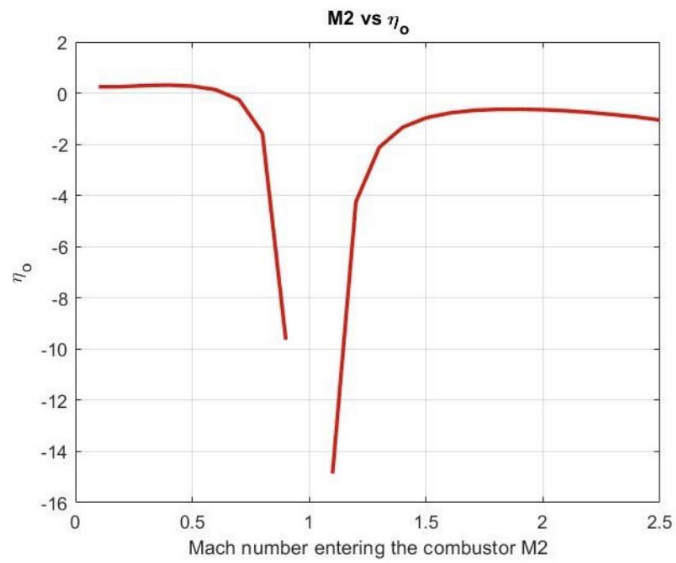

Fig 20 Variation of Overall Efficiency for M2

3. The Thrust T

   As seen on graph, the thrust spikes and decreases as combustor inlet Mach # goes after 0.3.

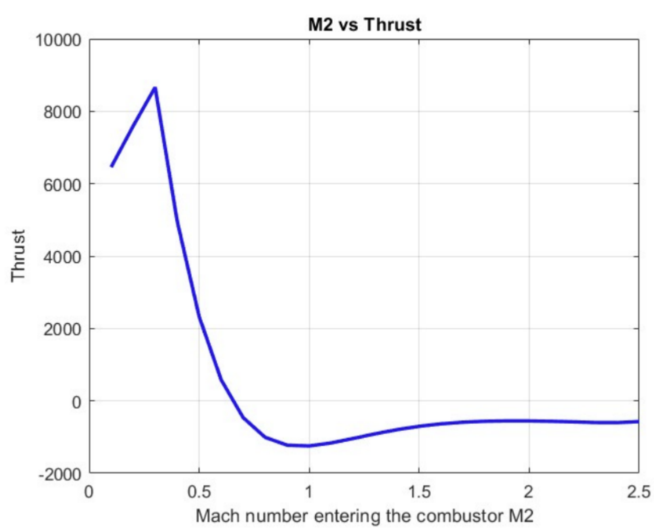

Fig 21 Variation of Thrust for M2

4. TSFC
   The graph depicting M2 vs. TSFC reveals a decreasing trend up to 0.45, followed by a steep increase beyond M2 = 0.5, and then a sharp decrease.

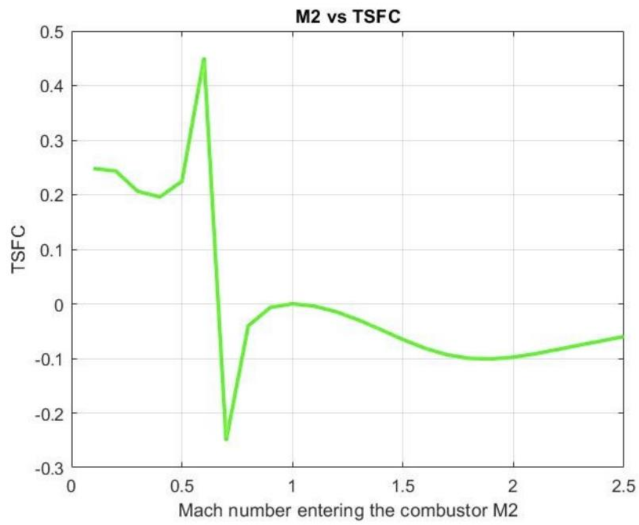

Fig 22 Variation of TSFC for M2

Problem I

Using parametric analysis tool developed to design ram/scramjet propulsion system, we need to develop for hypersonic flight at M1= 5 and z=90,000ft (27,400m) with same fuel heating value and inlet/ diffuser and nozzle efficiencies as in validation cases.

It is required that to limit combustor exit total temperature to Tt3max <2400K, it is to find two optimal design, one that produces the maximum positive thrust and second that maximizes the overall efficiency.

1. Determination of optimal system that maximizes the thrust:
   We get values:
   1.Diffuser exit Mach # = 0.41
   2.Tt3=2460K
   3.Thrust N = 1972.5 N

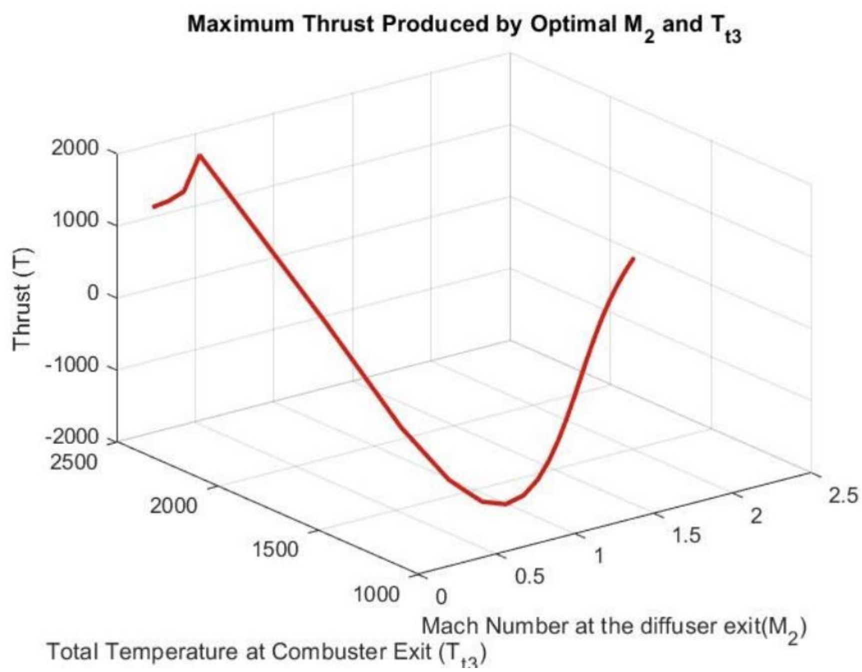

Fig 23 Optimized Thrust

2. Determination of optimal system that maximizes overall efficiency.
   We get values:
   1. Diffuser Exit Mach#= 0.40
   2. Tt3= 2439K
   3. Overall Efficiency=0.1401

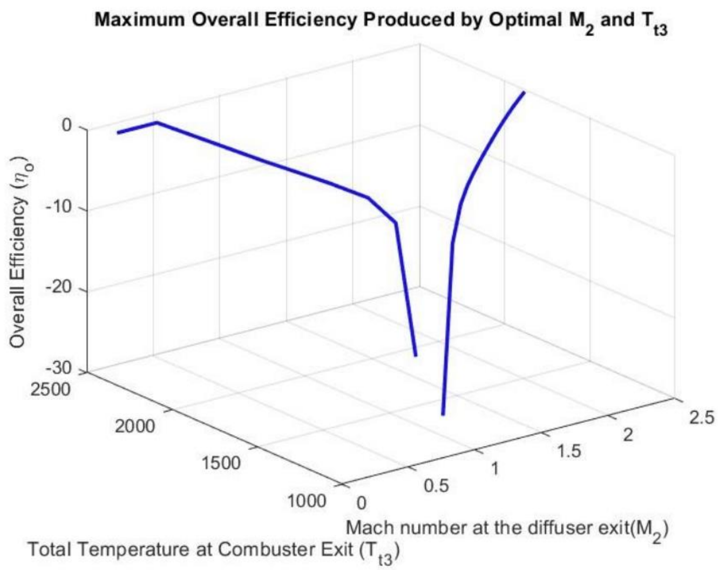

Fig 23 Optimized Overall Efficiency

Conclusion:

This research project delves deep into the intricate interplay between engine operating conditions and thermodynamic constraints, shedding light on the profound influence they exert on the performance of the RAMJET propulsion system. By meticulously analyzing key performance parameters like Overall Efficiency, Total Thrust, and Thrust-Specific Fuel Consumption (TSFC), we gain invaluable insights into the nuanced dynamics that shape the system's capabilities. The significance of these parameters varies, contingent upon the specific mission requirements, emphasizing the need for a nuanced and context-dependent evaluation.

Moreover, practical limitations further underscore the complexity of the RAMJET propulsion system. The imposed material constraint, for instance, acts as a critical factor preventing the maximum total temperature (Tt3_max) from surpassing 2400. This constraint introduces a unique set of challenges and restrictions, particularly when assessing the system's performance under exceptionally high Tt3 values. Navigating these limitations becomes integral to a comprehensive understanding of the RAMJET propulsion system's capabilities and feasibility in real-world applications.

Appendix:

Function statements used to derive each module:

Module 1

```
function [P1, T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1, z,z_star)
gamma = 1.4;
z=4300;
R=286.7;
Z_star=8404;
if z < 7958
    Ts = 288;
    Ps = 101.3;

    Cp1 = (gamma*R)/(gamma - 1);
    part1 = (1 - ((gamma - 1)/gamma)*(z/z_star));
    T1 = Ts * part1; % Temperature 1
    P1 = Ps * part1^((gamma)/(gamma - 1)); %  Pressure 1
    part2 = (1 + ((gamma -1)/2).*M1.^2);
    Tt1 = T1 * part2;
    Pt1 = P1 *  part2^ ((gamma)/(gamma - 1));
    a1 = sqrt(gamma*R * T1);
    V1 = a1 .* M1;

else
    Cp1 = (gamma*R)/(gamma - 1);
    T1 = 210 ;
    P1 = 33.6.*exp(-1.*((z-7958)./6605));
    Tt1 = T1.*(1+((gamma-1)/2).*M1.^2);
    Pt1 = P1.*(1+((gamma-1)/2).*M1.^2).^(gamma./(gamma-1));

    a1 = sqrt(gamma*R * T1);
    V1 = a1 .* M1;

end
```

Module2

```
function [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1, eta_d,Tt1,P1,Pt1)
gamma = 1.4;
Cp2 = R*gamma/(gamma-1);
Tt2 = Tt1;
T2 = Tt2/(1+((gamma-1)/2)*M2^2);
Pt2 = P1*(1+eta_d*((gamma-1)/2).*M1.^2).^(gamma/(gamma-1));
P2 = Pt2/(1+((gamma-1)/2)*M2^2)^(gamma/(gamma-1));
deltaS12 = Cp2*log(Tt2/Tt1)-R*log(Pt2/Pt1);
a2 = sqrt(gamma*R*T2);
V2 = M2*a2;
end
```

Module 3

```
function [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12)
gamma = 1.3;
Tt3_choked = Tt2*((1/(2*gamma+2))*(1/(M2.^2))*((1+gamma*M2.^2)^2)*(1+((gamma-1)/2)*M2^2)^-1);

if Tt3_choked < Tt3_max % Thermally Choked
    M3 = 1;
    Tt3 = Tt3_choked;
else % Thermally Unchoked
    Tt3 = Tt3_max;
    C = (Tt3/Tt2)*(M2^2)*((1 + ((gamma - 1)/2)*M2^2)/((1 + gamma*(M2^2))^2));

 % Solving quadratic
```

```
    a = C*gamma^2 - (gamma-1)/2;
    b = 2*C*gamma - 1;
    c = C;

    M3_1 = sqrt((-b+sqrt(b.^2-4*a*c))/(2*a));
    M3_2 = sqrt((-b-sqrt(b.^2-4*a*c))/(2*a));

        if M2 < 1 && M3_1 > M2 && M3_1 <= 1
            M3 = M3_1;
        else
            M3 = M3_2;
        end
end
% Find specific heats using specific heat model as given
A = 986;
B = 0.179;
q23 = A*(Tt3-Tt2)+0.5*B*(Tt3^2 - Tt2^2);

 % Constant Pressure Combustion
 P3 = P2;

 % Total to static relations
 T3 = Tt3/(1+((gamma-1)/2)*M3^2);
 Pt3 = P3*(1+((gamma-1)/2)*M3^2)^(gamma/(gamma-1));

 % Velocity at exit of combustor
 a3 = sqrt(gamma*R*T3);
 V3 = M3*a3;

 % Entropy Increase
 Cp = A + B*T3;
 Cp3 = Cp;
 deltaS23 = Cp3*log(Tt3/Tt2) - R*log(Pt3/Pt2);
 deltaS13 = deltaS12 + deltaS23;

end
```

Module 4

```
function [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test]
=module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23)
gamma = 1.3;
P_ratio = P1/Pt3;
M_Test = ((2/(gamma-1))*(eta_n*(1-(P_ratio)^((gamma-1)/gamma)))...
    /(1-eta_n*(1-(P_ratio)^((gamma-1)/gamma))))^0.5;
if  M_Test < 1
    Me = M_Test;
    Pe = P1;
else
    Me = 1;
    Pe = Pt3*(1-(1/eta_n)*((gamma-1)/(gamma+1)))^(gamma/(gamma-1));
end
 Tte = Tt3; % From First Law

 % Total to Static Relations
 Te = Tte/(1+((gamma-1)/2)*(Me^2));
 Pte = Pe*(1+((gamma-1)/2)*Me^2)^(gamma/(gamma-1));

 % Velocity
 ae = sqrt(gamma*R*Te);
 Ve = Me*ae;

 % Exit Mass Flow
 mdot_exit = Pe*Ve*Ae*1000/(R*Te);

 % Entropy Increase
 Cp = 986+0.179*Te;
 Cpe = Cp;
 deltaS3e = Cp*log(Tte/Tt3)-R*log(Pte/Pt3);
```

```
 deltaS1e = deltaS3e + deltaS23 + deltaS12;

end
```

Module 5

```
function [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e)

P4 = P1;% Because P4 = P1
Tt4 = Tte; % From the 1st law of thermodynamics
gamma = 1.3;

if M_Test < 1
    etan_e = 1;
else
    etan_e = M_Test^(-0.3);
end
T4 = Tte * (1 - (etan_e*(1 - (P1/Pte)^((gamma -1)/gamma))));
M4 = sqrt((2/(gamma - 1)) * ((Tt4/T4)-1));
Pt4 = P4 * (1 + ((gamma -1)/2)*M4^2)^(gamma/(gamma-1));
a4 = sqrt(gamma*R*T4);
V4 = a4 * M4;
Cp4 = 986 + 0.179*T4;
deltaS4e = Cp4*log(Tt4/Tte) - R*log(Pt4/Pte);
deltaS41 =  deltaS1e + deltaS4e;

end
```

Module 6

```
function [T,Tj,Tp,TSFC,Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o,Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae)
g = 9.81; % acceleration due to gravity
mdot_in = mdot_exit/(1+q23/qf);
mdot_f = mdot_exit - mdot_in;
f = mdot_f/mdot_in;
% Thrust
Tj = mdot_in*((1+f)*Ve - V1);
Tp = (Pe-P1)*Ae*1000;
T = Tj + Tp;
% Thrust Specific Fuel Consumption
TSFC = mdot_f*3600./T;
% Specific Impulse
Isp = T./(mdot_f*g);
% Equivalant Velocity
Veq = Ve + (Pe-P1)*1000*Ae/mdot_exit;
% Thermal Efficiency
eta_th = ((mdot_exit*0.5*Veq.^2) - (mdot_in*0.5*V1.^2))./(mdot_in*q23);
% Propulsive Efficiency
eta_prop = 2/(1+Veq/V1);
% Overall Efficiency
eta_o = eta_th*eta_prop;
% Propulsive Power
Propulsive_Power = T.*V1; % In Watts
end
```

MAIN CODE USED:

```
R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z_star = 8404;
eta_d = 0.92;
M1 = 2.4;
M2 = 0.15;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;
% Module. 1
% Determination of the quantities at the inlet of the diffuser
z = input('Please enter the flight altitude in meters');

%% Computation of the outputs for the module 1
[P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z,z_star);

%% computation of the outputs for the module 2

[P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1,eta_d,Tt1,P1,Pt1);

%% computation of the outputs for the module 3

[P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
%% computation of the outputs for the module 4

[Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
%% computation of the outputs for the module 5
[P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);

%% computation of the outputs for the module 6
 % heating value of the fuel
[T,Tj,Tp,TSFC,Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o,Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);
```

Problem A

1. *Non-Thermally chocked Test Case*

```
clear; close all; clc

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z_star = 8404;
eta_d = 0.92;
M1 = 2.4;
M2 = 0.15;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;
% Module. 1
% Determination of the quantities at the inlet of the diffuser
z = input('Please enter the flight altitude in meters');

%% Computation of the outputs for the module 1
[P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z,z_star);

%% computation of the outputs for the module 2

[P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1,eta_d,Tt1,P1,Pt1);

%% computation of the outputs for the module 3

[P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
%% computation of the outputs for the module 4

[Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
%% computation of the outputs for the module 5
[P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);

%% computation of the outputs for the module 6
 % heating value of the fuel
[T,Tj,Tp,TSFC,Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o,Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);



%% Part b

%% Part C
M1 = linspace(0.8,5,24);

for m = 1 : length(M1)
    [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1(m),z,z_star);
    [P2,T2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1(m),eta_d,Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,R,Tt2,M2,P2,Pt2,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(m),Tj,Tp,TSFC(m),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(m),Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);

end
figure(5)
    plot(M1, T,'Linewidth',2,'Color','r');
    grid ON
    xlabel('Mach Number');
    ylabel('Total Thrust');
    title('Effect of Mach Number on Total Thrust - Non Thermally choked case');
    legend('Total Thrust');
```

```
figure(6)
    plot (M1, eta_o, 'Linewidth',2,'Color','g');
    grid ON
    xlabel('Mach Number');
    ylabel('Overall Efficiency');
    title('Effect of Mach Number on Overall Efficiency -  Non Thermally choked case');
    legend('eta_o');
    figure(7)
    plot(M1, TSFC, 'Linewidth',2,'Color','k');
    grid ON
    xlabel('Mach Number');
    ylabel('TSFC');
    title('Effect of Mach Number on TSFC -  Non Thermally choked case');
    legend('TSFC');
```

2. *Thermally Chocked Test Case*

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z = 4300;
z_star = 8404;
eta_d = 0.92;
M1 = 2.4;
M2 = 0.4;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;

[P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z,z_star);
[P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1,eta_d,Tt1,P1,Pt1);
[P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
[Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
[P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
[T,Tj,Tp,TSFC,Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o,Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);

plot([0, deltaS12], [T1 T2], 'b-','LineWidth',2)
hold on

T23(1) = T2(1);
S23 = linspace(deltaS12,deltaS13,100000);
ds = deltaS13(1)/100000;
for n = 1:length(S23)
    if n + 1 == length(S23) + 1
        break
    end
T23(n+1) = T23(n) + (T23(n)/(986+0.179*T23(n)))*ds;
%     if T23(n) >= T3(1)
%         break
%     end
end
S23 = linspace(deltaS12,deltaS13,length(T23));
plot(S23, T23, 'r-','LineWidth',2);

plot([deltaS13 deltaS41], [T3 T4], 'b-','LineWidth',2)
hold on

T41(1) = T1(1);
S41 = linspace(0,deltaS41,100000);
ds = deltaS41(1)/100000;
for n = 1:length(S41)
    if n + 1 == length(S41) + 1
```

```
        break
    end
T41(n+1) = T41(n) + (T23(n)/1004)*ds;
    if T41(n) >= T4(1)
        break
    end
end
S41 = linspace(0,deltaS41,length(T41));
plot(S41, T41, 'r-','LineWidth',2)
hold on
grid on
title('T-s diagram for Thermally choked case')
xlabel('Entropy (J/kg-K)')
ylabel('Static Temperature T (K)')
legend('1-2: Compression (Increase in Entropy)','2-3: Constant Pressure Heat Addition','3-4: Expansion (Increase in Entropy)','4-1: Constant Pressure Heat Removal','Location','Best');
```

Problem B

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z_star = 8404;
eta_d = 0.92;
M1 = 2.4;
M2 = 0.4;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;

% defining the altitude
z = [0:500:20000 22000] ;

for i = 1:length(z)
    [P1(i),T1(i),Cp1(i),Tt1(i), Pt1(i), a1(i), V1(i)] = module1(R,M1,z(i),z_star);
end

data = readtable('Validation of Atmospheric Model.xlsx','Range','G14:H55');
T_z = table2array(data(:,1));
P_z = table2array(data(:,2));

figure(1)
plot(T_z,z,'LineWidth',2);
xlim([0 300]);
hold on;
plot(T1,z,'LineWidth',2);
title('Isentropic and Standard Atmosphere Model Comparison: Temperature')
legend('Standard Atmosphere','Isentropic','Location','Best')
xlabel('Temperature at Flight Altitude [T(z)]')
ylabel('Flight Altitude (z)')
grid on;
grid minor;

figure(2)
plot(P_z,z,'LineWidth',2);
hold on;
plot(P1,z,'LineWidth',2);
title('Isentropic and Standard Atmosphere Model Comparison: Pressure')
legend('Standard Atmosphere','Isentropic','Location','Best')
xlabel('Pressure at Flight Altitude [P(z)]')
ylabel('Flight Altitude (z)')
grid on;
grid minor;
```

Problem C

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z_star = 8404;
eta_d = 0.92;
M2 = 0.15;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;
z = 4300;
M1 = linspace(0.8,5,25);

for m = 1 : length(M1)
    [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1(m),z,z_star);
    [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1(m),eta_d,Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] = 
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(m),Tj,Tp,TSFC(m),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(m),Propulsive_Power] = 
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);
end

figure(1)
plot(M1, T,'Linewidth',2,'Color','r');
grid ON
xlabel('Mach Number');
ylabel('Thrust');
title('Effect of Mach Number on Engine Thrust - Thermally Unchoked Case');
legend('Total Thrust');

figure(2)
plot (M1, eta_o, 'Linewidth',2,'Color','b');
grid on
xlabel('Mach Number');
ylabel('Overall Efficiency');
title('Effect of Mach Number on Overall Efficiency- Thermally Unchoked Case');
legend('Overall Efficiency');

figure(3)
plot(M1, TSFC, 'Linewidth',2,'Color','g');
grid on
xlabel('Mach Number');
ylabel('TSFC');
title('Effect of Mach Number on TSFC- Thermally Unchoked Case');
legend('TSFC');
```

Problem D

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z_star = 8404;
eta_d = 0.92;
M2 = 0.15;
Tt3_max = 2400;
```

```
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;
M1 = 2.4;

z = linspace(2000,3e4,24);
for zz = 1 : length(z)
    [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z(zz),z_star);
    [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1,eta_d,Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] = 
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(zz),Tj,Tp,TSFC(zz),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(zz),Propulsive_Power] = 
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);
end

figure(8)
    plot(z, T,'Linewidth',2,'Color','r');
    grid ON
    xlabel('z');
    ylabel('Total Thrust');
    title('Effect of Altitude on Total Thrust - Non Thermally choked case');
    legend('Total Thrust');
figure(9)
    plot (z, eta_o, 'Linewidth',2,'Color','g');
    grid ON
    xlabel('z');
    ylabel('Overall Efficiency');
    title('Effect of Altitude on Overall Efficiency -  Non Thermally choked case');
    legend('eta_o');
 figure(10)
    plot(z, TSFC, 'Linewidth',2,'Color','k');
    grid ON
    xlabel('z');
    ylabel('TSFC');
    title('Effect of Altitude on TSFC -  Non Thermally choked case');
    legend('TSFC');
```

Problem E

```
R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z_star = 8404;
eta_d = 0.92;
M2 = 0.15;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;

% varying the Mach number M1
M1 = 0.8:0.001:5;

% varying the altitude from 2000 m to 20,000 m
z = 2e3:500:2e4;

for i = 1 : length(z)
    for j = 1 : length(M1)
        [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1(j),z(i),z_star);
        [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1(j),eta_d,Tt1,P1,Pt1);
        [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
        [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] = 
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
        [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
        [T(i,j),Tj,Tp,TSFC(i,j),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(i,j),Propulsive_Power] = 
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);
```

```
    end
end

for i = 1:length(z)
    [eta_o_max(i),I(i)] = max(eta_o(i,:));
end

figure(1);
plot(z,M1(I),'LineWidth',2,'Color','magenta')
ylim([3 3.5])
title('Altitude variation for maximizing \eta_o vs M_1')
xlabel('Flight altitude z')
ylabel('Flight Mach Number M_1')
grid on;

for i = 1:length(z)
    [TSFC_min(i),J(i)] = min(TSFC(i,:));
end

figure(2);
plot(z,M1(J),'LineWidth',2,'Color','k')
ylim([1.5 5])
title('Altitude variation for minimizing TSFC vs M_1')
xlabel('Flight altitude z')
ylabel('Flight Mach Number M_1')
grid on;
```

Problem F

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z = 4300;
M1 = 2.4;
z_star = 8404;
M2 = 0.15;
Tt3_max = 2400;
Ae = 0.015;
eta_n = 0.94;
qf = 43.2e6;

% Variation of the isentropic efficiency of the diffuser
eta_d = 0.5 : 0.05 : 1;

for i = 1 : length(eta_d)

    [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z,z_star);
    [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1,eta_d(i),Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(i),Tj,Tp,TSFC(i),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(i),Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);

end

figure(1);
plot(eta_d,eta_o,'LineWidth',2,'Color','red');
grid on
title('\eta_d vs \eta_o')
xlabel('\eta_d')
```

```
ylabel('\eta_o')
grid on

figure(2);
plot(eta_d,T,'LineWidth',2,'Color','blue')
grid on
title('\eta_d vs Thrust')
xlabel('\eta_d')
ylabel('Thrust')
grid on

figure(3);
plot(eta_d,TSFC,'LineWidth',2,'Color','green')
grid on
title('\eta_d vs TSFC')
xlabel('\eta_d')
ylabel('TSFC')
grid on
```

Problem G

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z = 4300;
M1 = 2.4;
z_star = 8404;
M2 = 0.15;
Tt3_max = 2400;
Ae = 0.015;
eta_d = 0.92;
qf = 43.2e6;

% Variation of the isentropic efficiency of the nozzle
eta_n = 0.5 : 0.05 : 1;

for i = 1 : length(eta_n)

    [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z,z_star);
    [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2,M1,eta_d,Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2,R,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n(i),P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(i),Tj,Tp,TSFC(i),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(i),Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);

end

figure(1);
plot(eta_n,eta_o,'LineWidth',2,'Color','red');
grid on
title('\eta_n vs \eta_o')
xlabel('\eta_n')
ylabel('\eta_o')
grid on

figure(2);
plot(eta_n,T,'LineWidth',2,'Color','blue')
grid on
title('\eta_n vs Thrust')
xlabel('\eta_n')
ylabel('Thrust')
```

```
grid on

figure(3);
plot(eta_n,TSFC,'LineWidth',2,'Color','green')
grid on
title('\eta_n vs TSFC')
xlabel('\eta_n')
ylabel('TSFC')
grid on
```

Problem H

```
clear; close all; clc;

% Defining the constants

R = 286.9; % gas constant in KJ/ Kg-K
gamma = 1.4;
z = 4300;
M1 = 2.4;
z_star = 8404;
Tt3_max = 2400;
Ae = 0.015;
eta_d = 0.92;
eta_n = 0.94;
qf = 43.2e6;

% Variation of the Mach number entering the combustor M2
M2 = 0.1 : 0.1 : 2.5;

for i = 1 : length(M2)

    [P1,T1,Cp1,Tt1, Pt1, a1, V1] = module1(R,M1,z,z_star);
    [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2(i),M1,eta_d,Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3,Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2(i),R,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(i),Tj,Tp,TSFC(i),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop,eta_o(i),Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve,V1,Pe,P1,Ae);

end

figure(1);
plot(M2,eta_o,'LineWidth',2,'Color','red');
grid on
title('M2 vs \eta_o')
xlabel('Mach number entering the combustor M2')
ylabel('\eta_o')
grid on

figure(2);
plot(M2,T,'LineWidth',2,'Color','blue')
grid on
title('M2 vs Thrust')
xlabel('Mach number entering the combustor M2')
ylabel('Thrust')
grid on

figure(3);
plot(M2,TSFC,'LineWidth',2,'Color','green')
grid on
title('M2 vs TSFC')
xlabel('Mach number entering the combustor M2')
ylabel('TSFC')
grid on
```

Problem I

```
clear; close all; clc
R = 286.9; % gas constant in KJ/ Kg-K
z = 27400;
z_star = 8404;
M1 = 5;
eta_d = 0.92;
M2 = 0.1:0.01:2.5;
qf = 43.2e6;
Tt3_max = 2400;
eta_n = 0.94;
Ae = 0.015;
% Variation of the Mach number entering the combustor M2
M2 = 0.1 : 0.1 : 2.5;

for i = 1 : length(M2)

    [P1,T1(i),Cp1,Tt1, Pt1, a1, V1(i)] = module1(R,M1,z,z_star);
    [P2,T2,Tt2,Cp2,Pt2,a2,V2,deltaS12] = module2(R,M2(i),M1,eta_d,Tt1,P1,Pt1);
    [P3,Pt3,T3,Tt3(i),Cp3,a3,V3,M3,q23,deltaS23,deltaS13] = module3(Tt3_max,Tt2,P2,Pt2,M2(i),R,deltaS12);
    [Pe,Pte,Te,Tte,Cpe,Me,Ve,ae,deltaS3e,deltaS1e,mdot_exit,M_Test] =
module4(Ae,eta_n,P1,Tt3,Pt3,R,deltaS12,deltaS23);
    [P4,Pt4,T4,Tt4,Cp4,a4,V4,M4,etan_e,deltaS4e,deltaS41] = module5(R,M_Test,Tte,P1,Pte,deltaS1e);
    [T(i),Tj,Tp,TSFC(i),Isp,mdot_f,mdot_in,f,Veq,eta_th,eta_prop(i),eta_o(i),Propulsive_Power] =
module6(q23,qf,mdot_exit,Ve(i),V1(i),Pe,P1,Ae);

end


figure(1)
plot3(M2,Tt3,T,'b-','LineWidth',2,'Color','r');
grid on;
xlabel('Mach Number at the diffuser exit(M_2)');
ylabel('Total Temperature at Combuster Exit (T_t_3)');
zlabel('Thrust (T)');
title('Maximum Thrust Produced by Optimal M_2 and T_t_3');

figure(2)
plot3(M2,Tt3,eta_o,'b-','LineWidth',2,'Color','blue');
grid on;
xlabel('Mach number at the diffuser exit(M_2)');
ylabel('Total Temperature at Combuster Exit (T_t_3)');
zlabel('Overall Efficiency (\eta_o)');
title('Maximum Overall Efficiency Produced by Optimal M_2 and T_t_3');
```