<u>Introduction to Propulsion Theory and Applications</u>

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MAE 563: Aircraft Propulsion

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Fall 2019

Introduction

In this project, a tool was developed that allows the user to calculate the Thermodynamic states for a ram/scramjet propulsion system at 5 points in the flow path:

- 1) The Free stream
- 2) Diffuser exit
- 3) Combustor exit
- e) Nozzle exit
- 4) Exit stream

The inputs given to the tool are:

1) Flight altitude, z (meters)
2) Flight Mach no, M1
3) Diffuser efficiency, ηd
4) Mach no at diffuser exit, M2
5) Nozzle efficiency, ηn
6) Nozzle exit area, Ae (m^2)

At all the 5 slow points, the Total and static pressure and temperature, Change is entropy, Flow speed, Specific heat capacity and Mach number is calculated.

At the end of the flow the following results is calculated:

1) Thrust, T (N)
2) Propulsive Power, P (W)
3) Overall efficiency, ηo
4) Exit mass flow rate, $\dot{m}_e$ (kg/s)
5) Fuel mass flow rate, $\dot{m}_f$ (kg/s)
6) Specific impulse, I_{sp} (s)
7) Thrust Specific Fuel Consumption, TSFC (kg/hr/N)

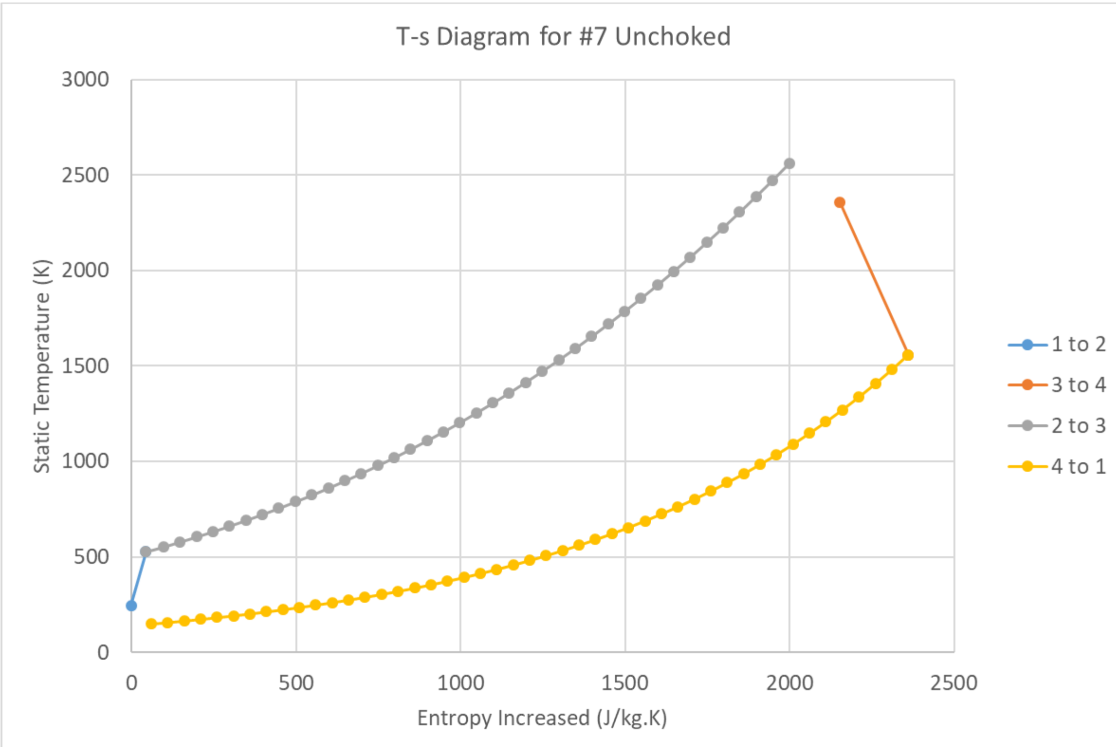
A main code with 6 modules is used to do the calculations, while a secondary code calls the main code as a function to iterate over the necessary changing inputs.

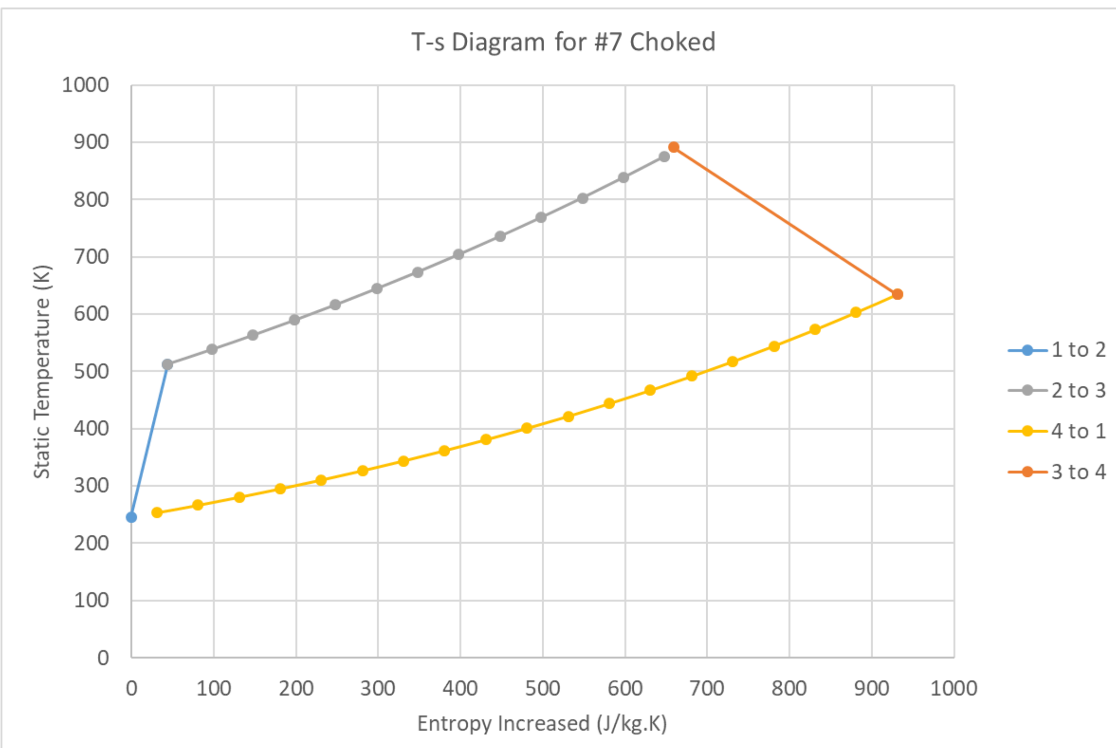
The <u>Unchoked</u> conditions are used extensively when the tool is used to determine the effects of varying a parameter. The input parameters are held constant in the analysis unless stated.

The conditions are: z=4300m, M1=2.4, z = 4300 m, M1 = 2.4, ηd = 0.92, M2 = 0.15, qf = 43.2 MJ/kg, Tt3max = 2400 K, ηn = 0.94, and Ae = 0.015 m2.

PART A:

The following graphs show the computed T-s diagrams for the cycles, both unchoked and choked conditions are shown:

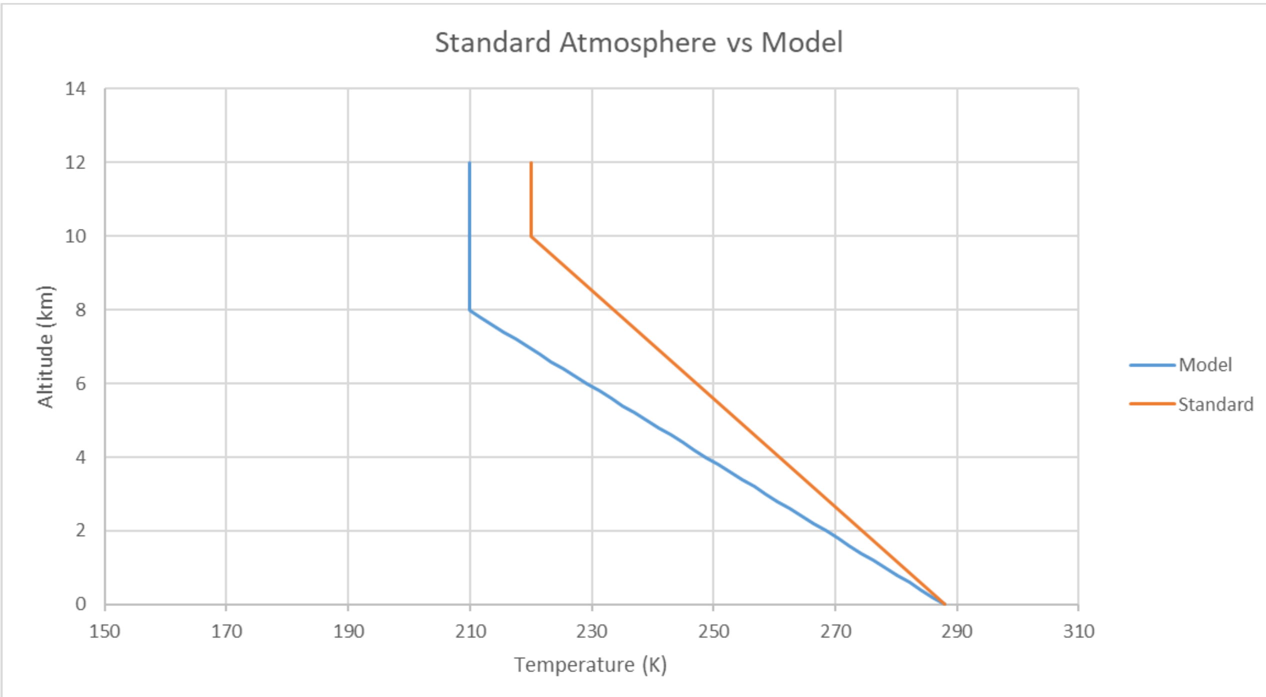




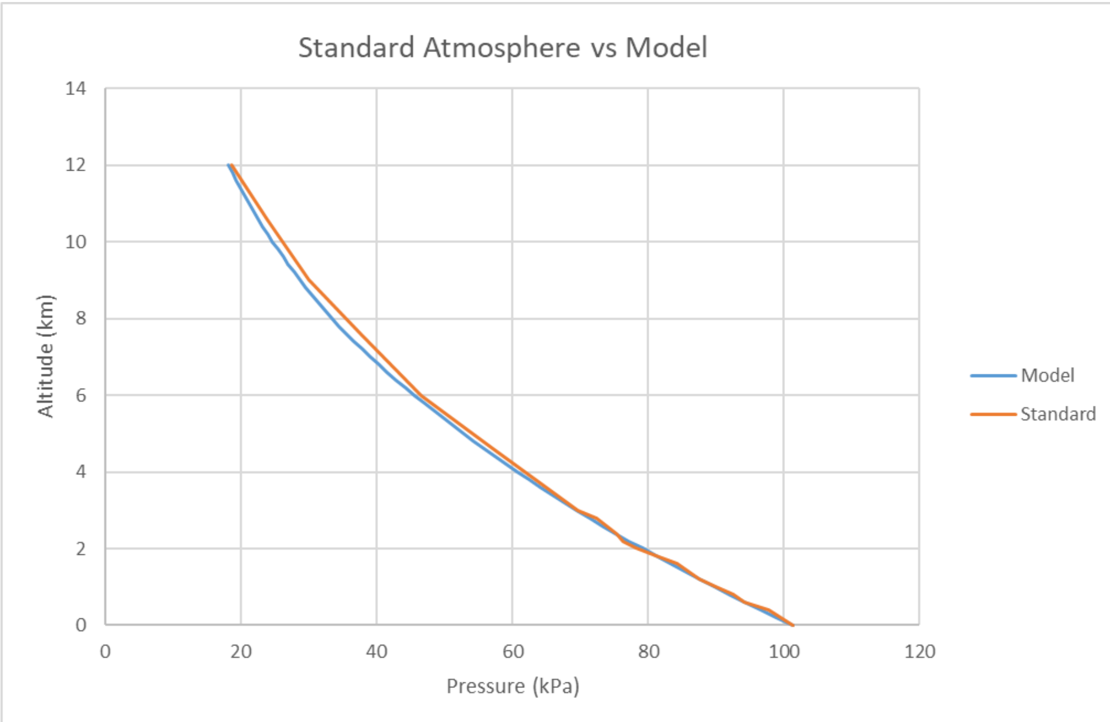
These curves are do not exactly connect because the approximate formula used to calculate the value of C_p leads to inaccuracies.

PART B

The calculated static pressure and temperature conditions at given flight altitude ‘z’ is compared to the Standard Atmospheric data to check for accuracy.



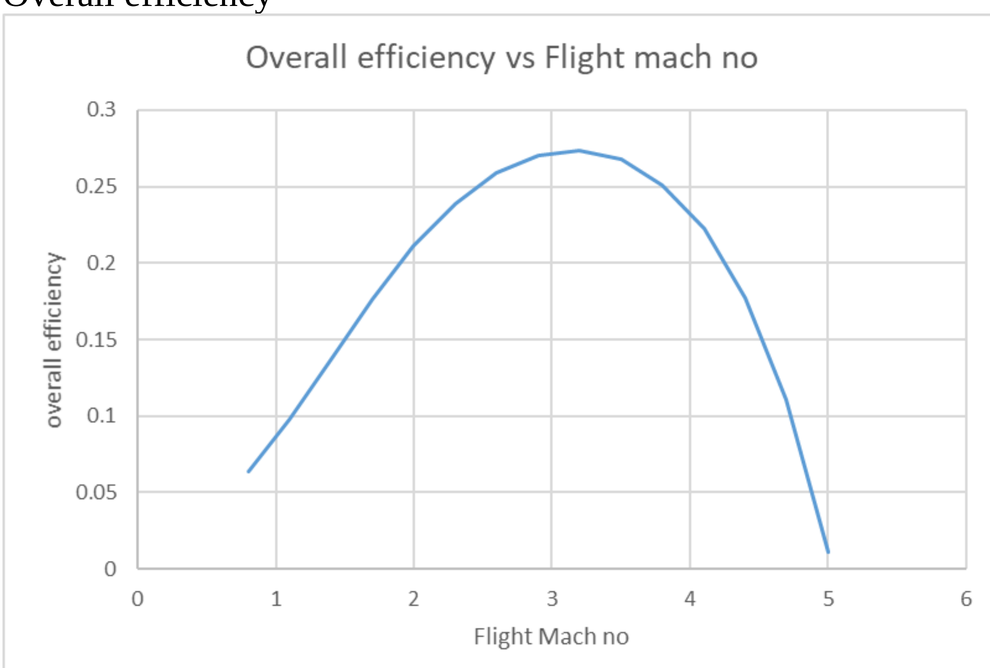
We can see that the calculated(model) temperature is lower than the actual temperatures recorded at these altitudes. This is likely due to the used formula being a rough approximation.
The pressure curve shows an excellent agreement with the recoded data.



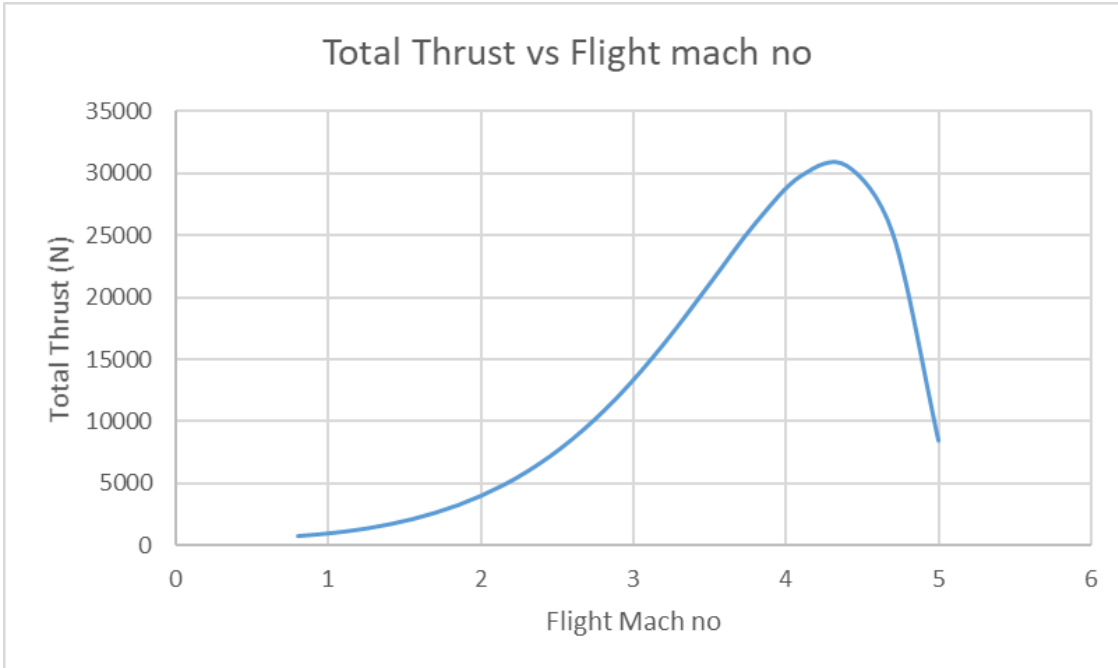
PART C

The flight Mach number M1 is varied in sufficiently small steps from $0.8 \leq M1 \leq 5.0$ to determine the following:

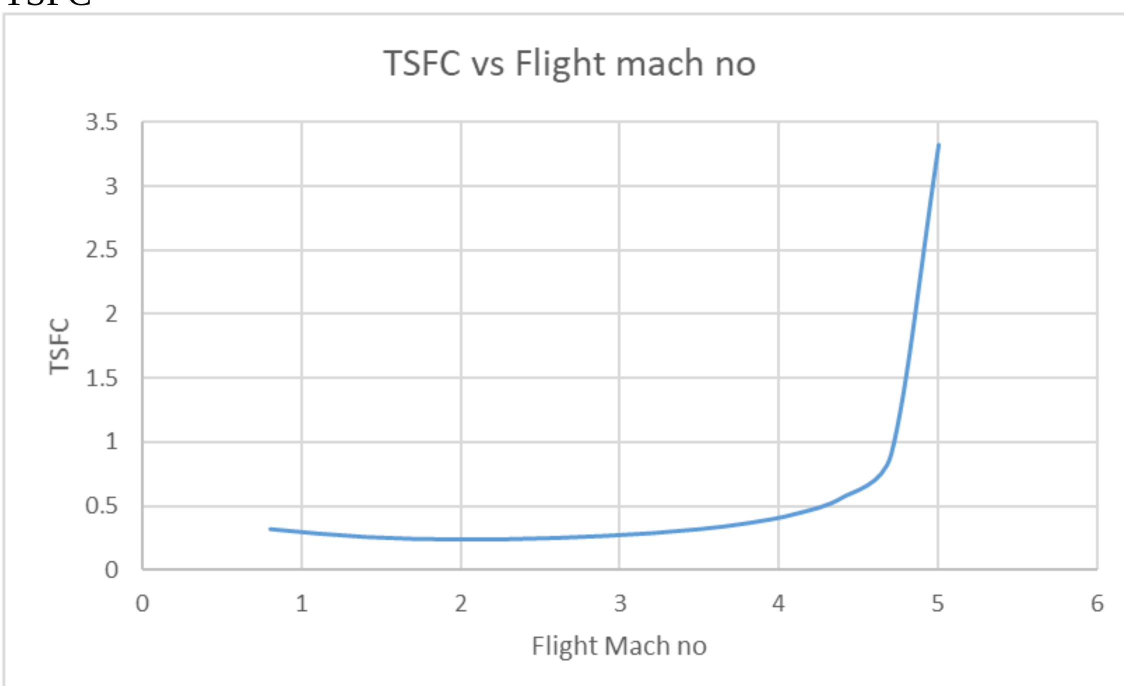
i. Overall efficiency



ii. Thrust



iii. TSFC



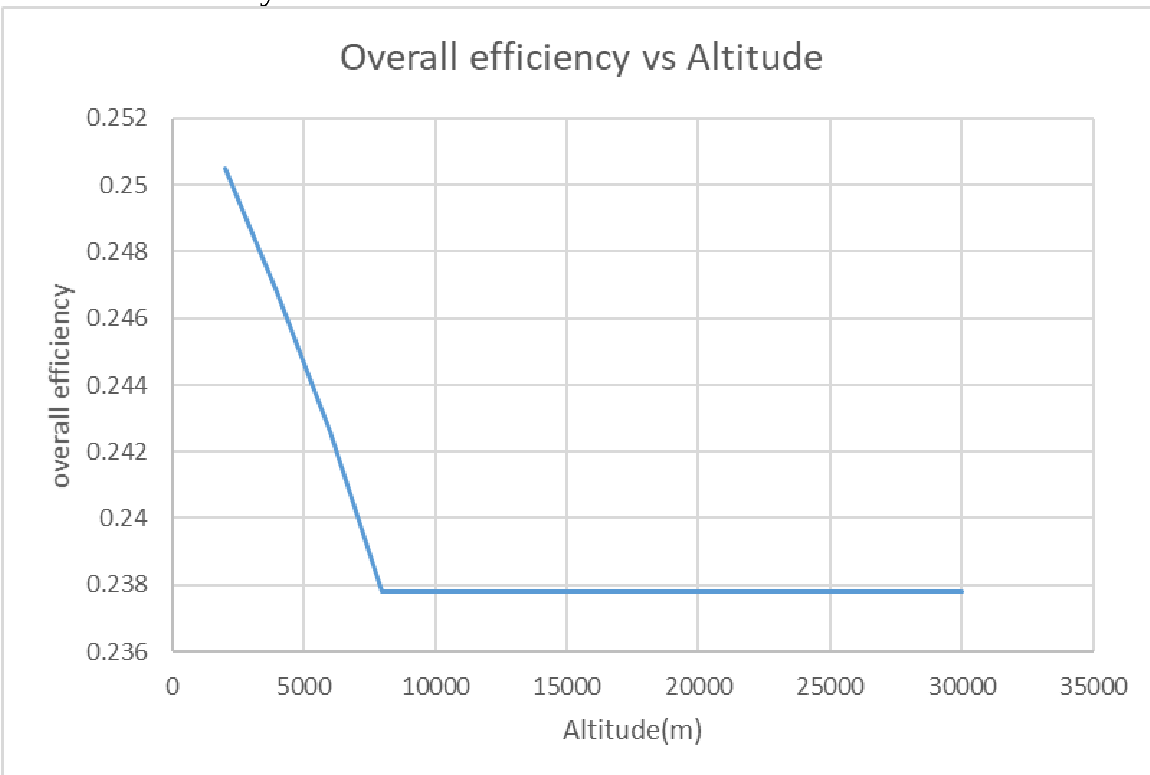
Here we see that we get best overall efficiency at a Flight Mach no of slightly over 3, and for that range the TSFC is low. The Thrust on the other hand is much lower that this Mach number than its peak at Mach number of 4.4

This means that it there is a tradeoff between maximum thrust and fuel efficiency that needs to be considered when deciding the flight Mach number.

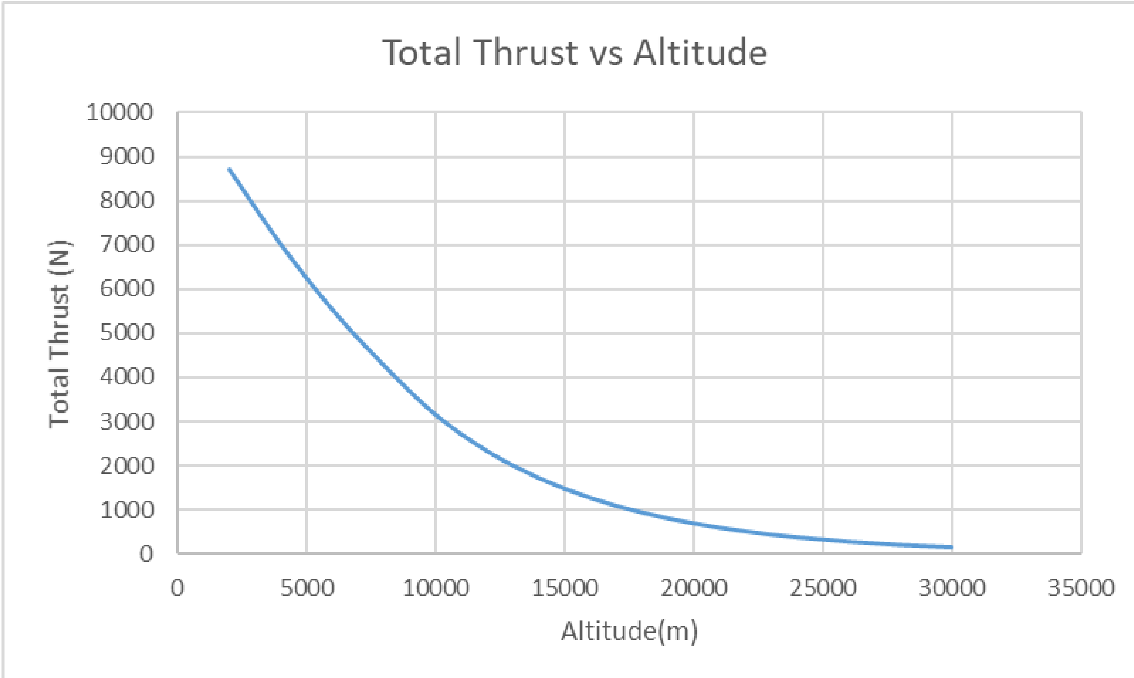
PART D

The flight altitude ‘z’ is varied in sufficiently small steps from 2000m≤ z ≤30000m to determine the following:

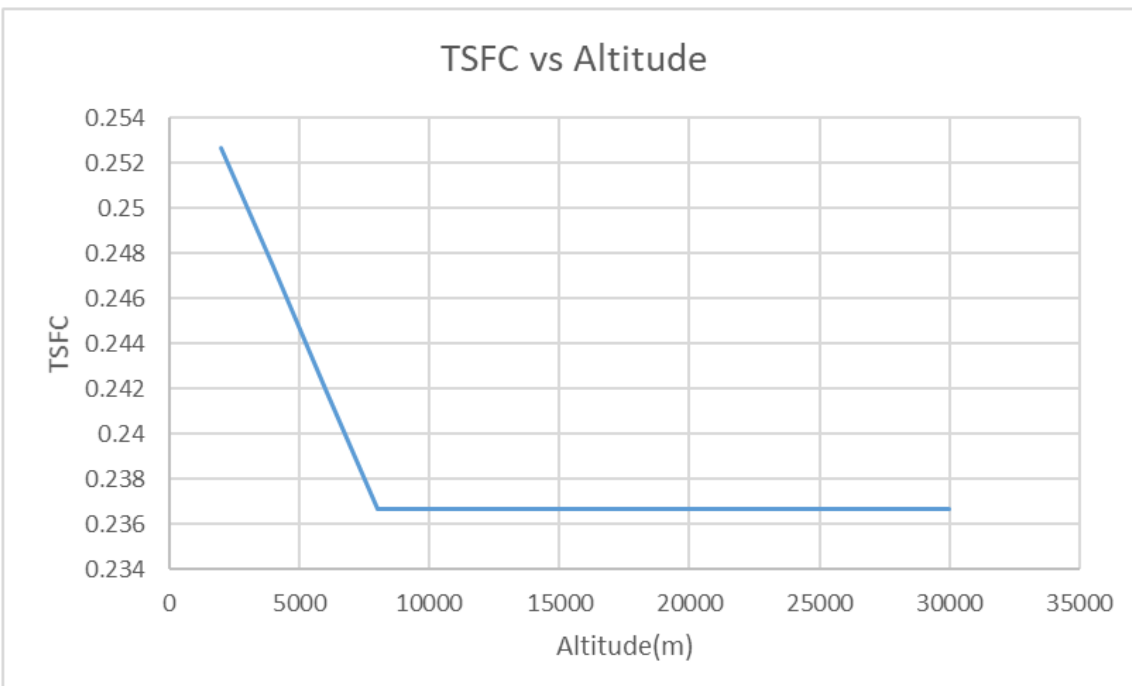
i. Overall Efficiency



ii. Thrust



iii. TSFC



We can see that all 3 parameters reduce with increased in Altitude.

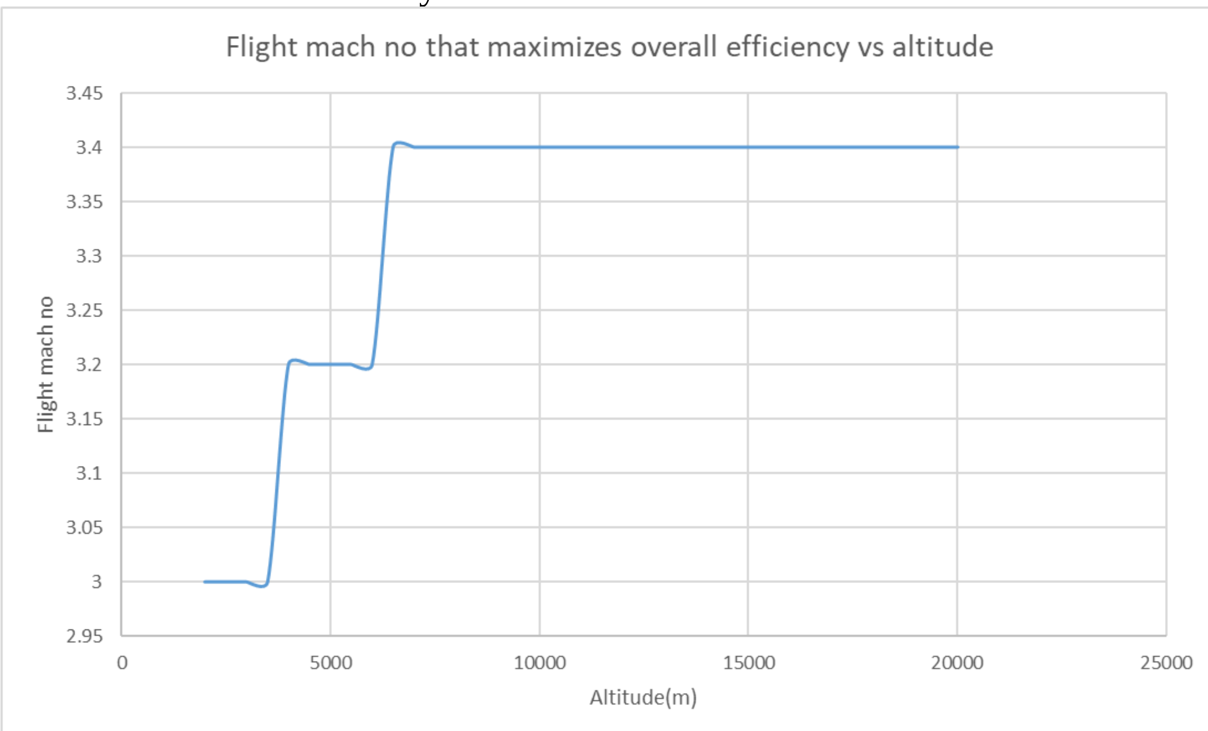
This makes sense logically as the density of air decreases drastically with altitude.

It is interesting to note that both TSFC and Overall efficiency plateau at a similar altitude. This is because of the constant temperature assumed in the model used.

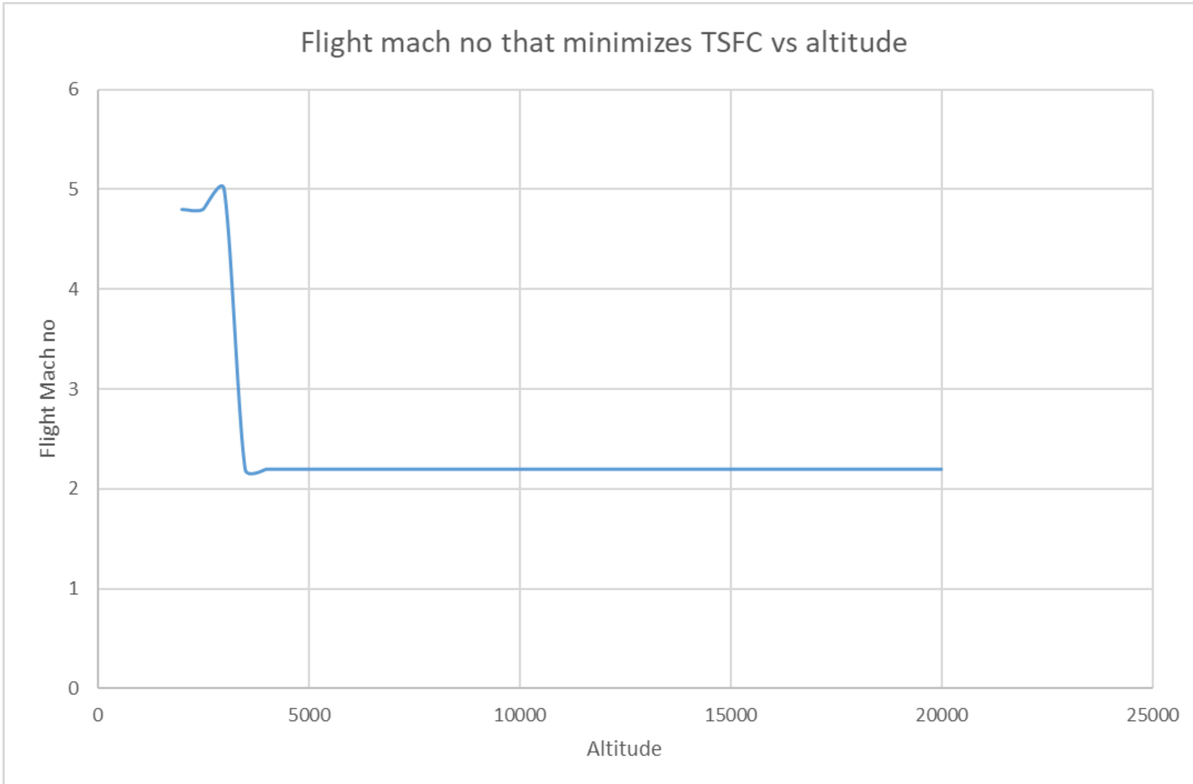
PART E:

Taking 2000 m $\leq z \leq$ 20,000 m in steps of 500 m and for each z value systematically vary M1 to find the flight Mach number that:

i. Maximizes overall efficiency



ii. Minimizes TSFC

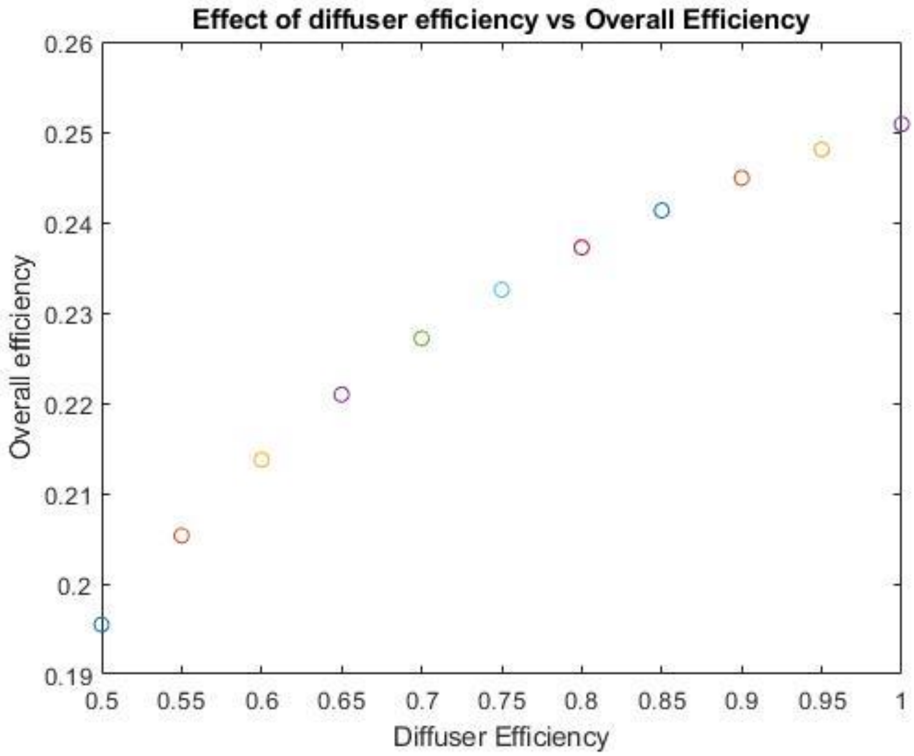


We see that the higher we travel, the higher the necessary Mach no to maximize the efficiency and lower the Mach no to minimize TSFC. This is because of the reduction in density of air having adverse effects on the combustion inside the engine. Both these plateau as expected with constant temperature.

PART F

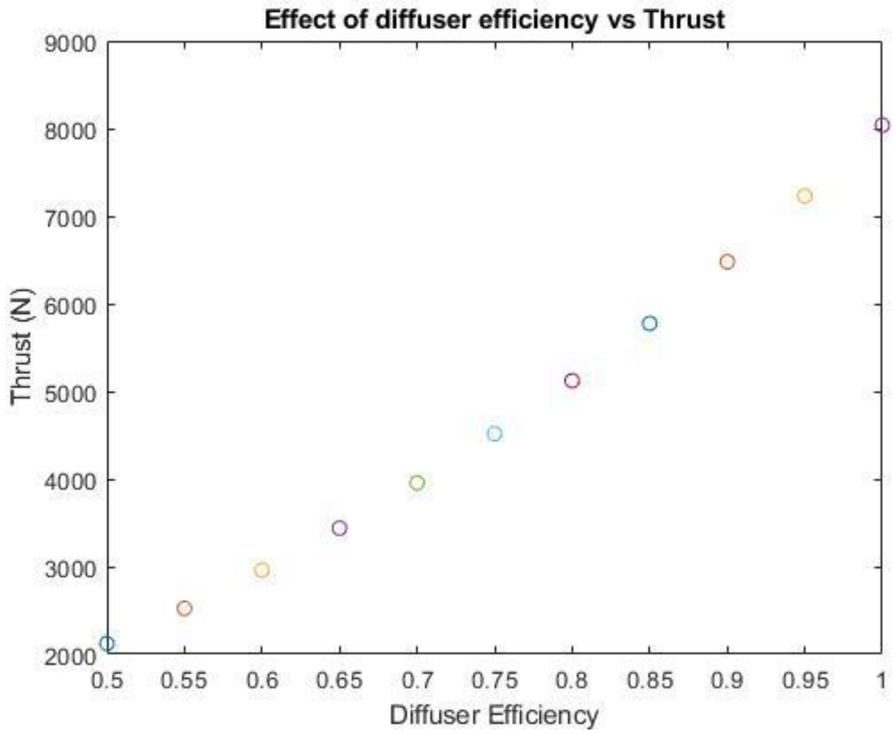
The inlet/diffuser efficiency from $0.5 \leq \eta d \leq 1.0$ is varied in steps of 0.05 to compute the resulting:

i. Overall efficiency:

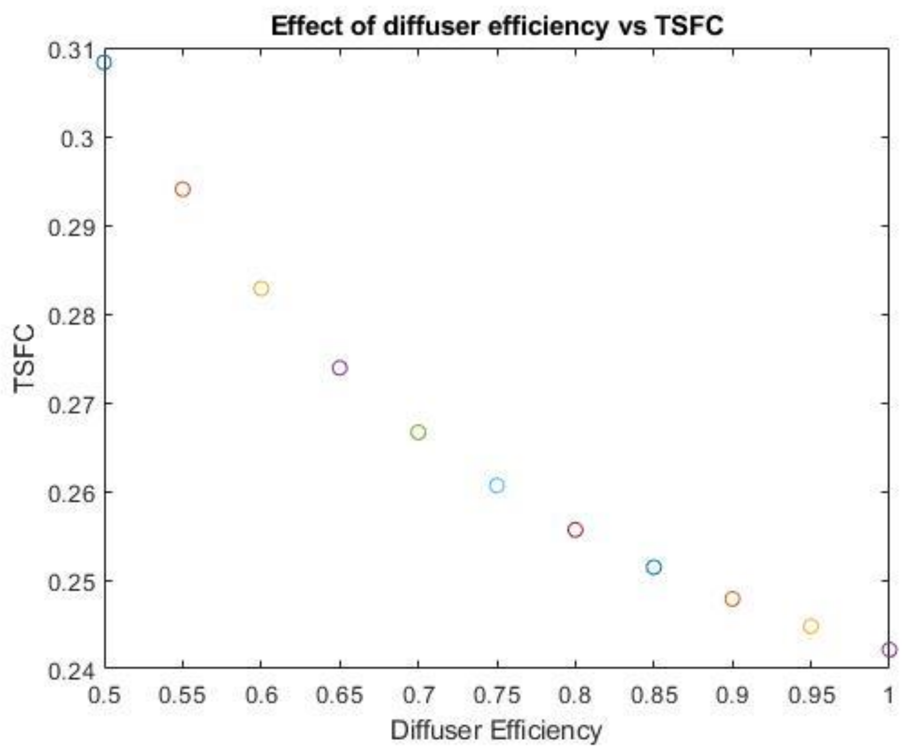


The results are as expected. With increased in efficiency, we have lower irreversibilities, meaning more Thrust, Overall efficiency and lower TSFC.

ii. Thrust:



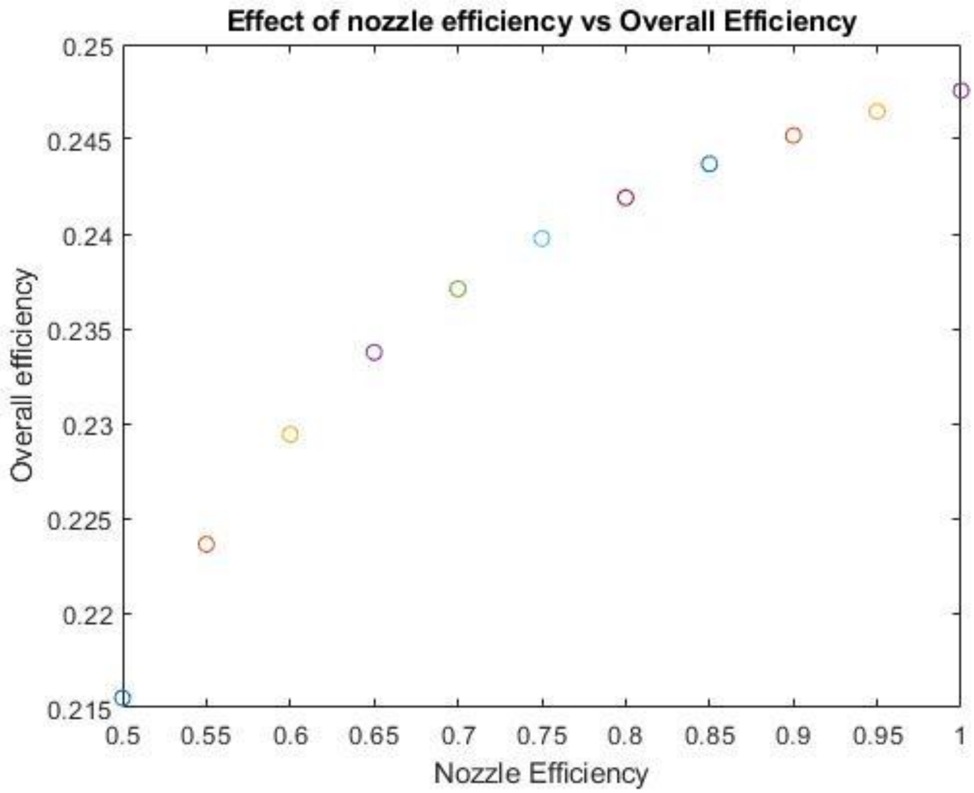
iii. TSFC:



PART G:

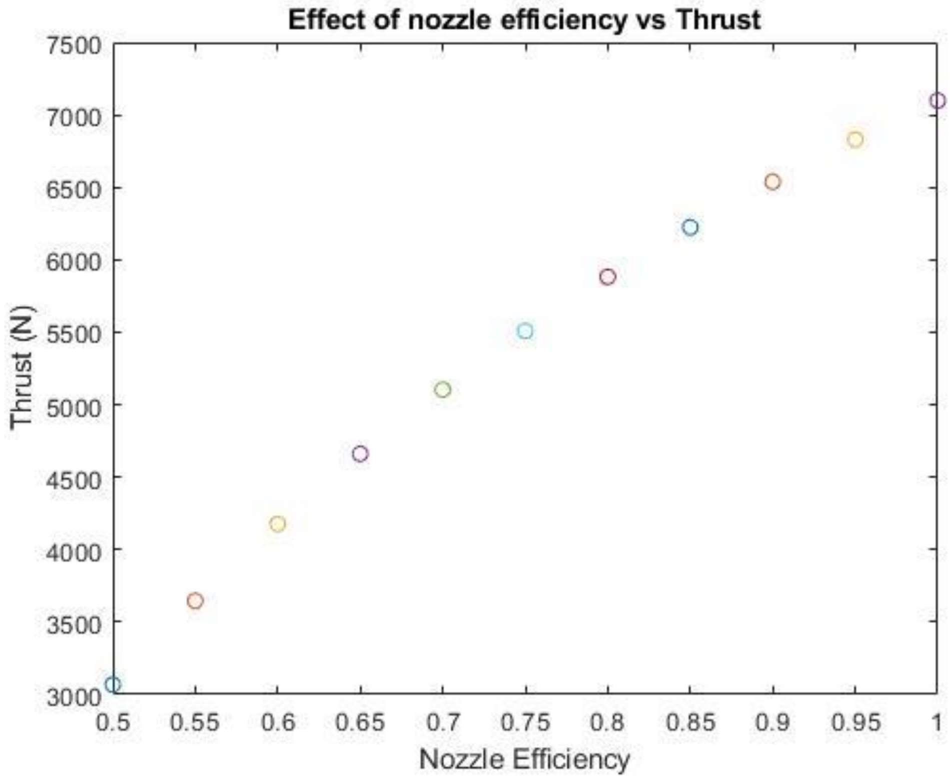
The nozzle efficiency from $0.5 \leq \eta n \leq 1.0$ is varied in steps of 0.05 to compute the resulting

i. Overall efficiency

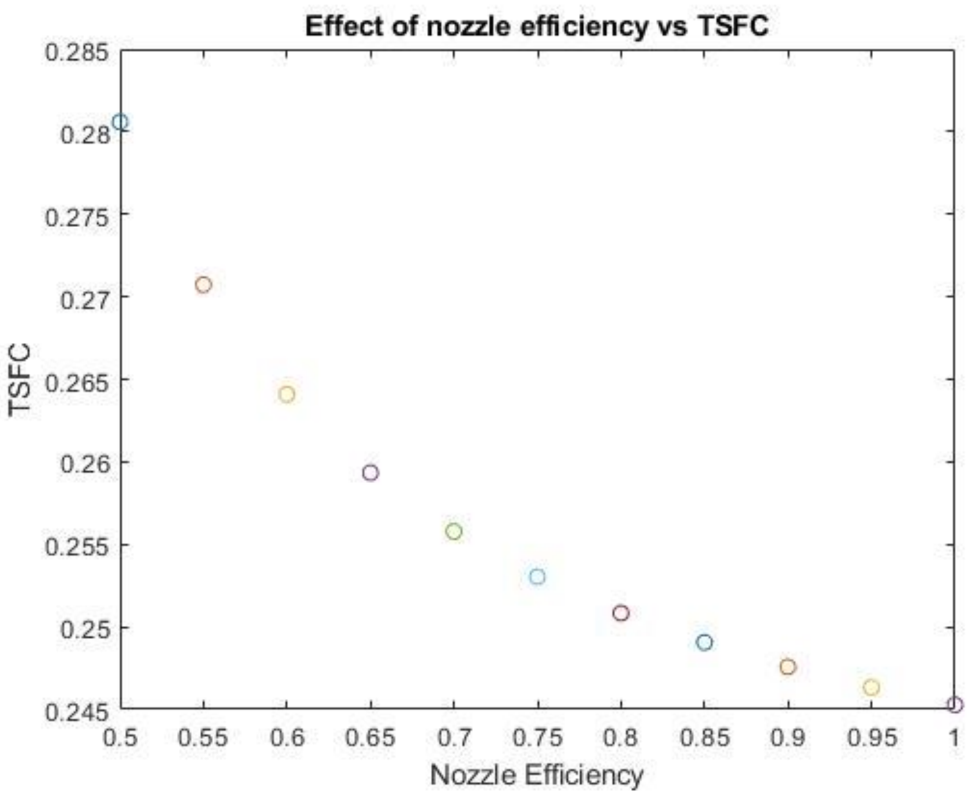


The results are, once again, as expected. With increased in efficiency, we have lower irreversibilities, meaning more Thrust, Overall efficiency and lower TSFC

ii. Thrust



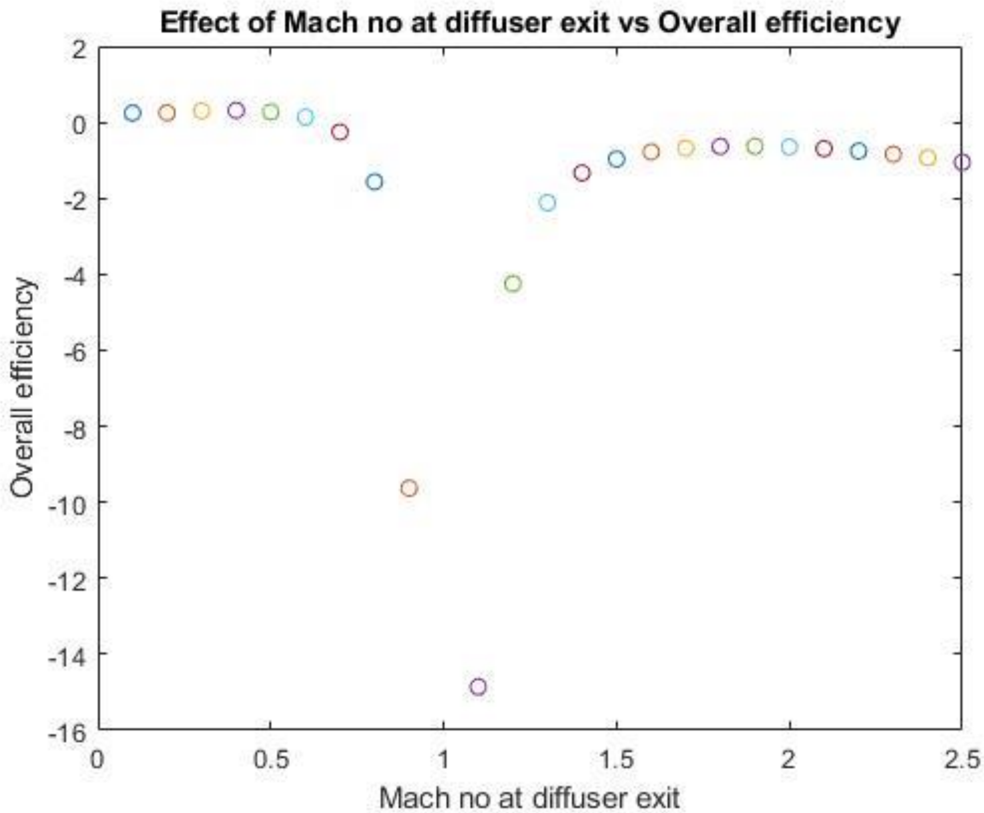
iii. TSFC



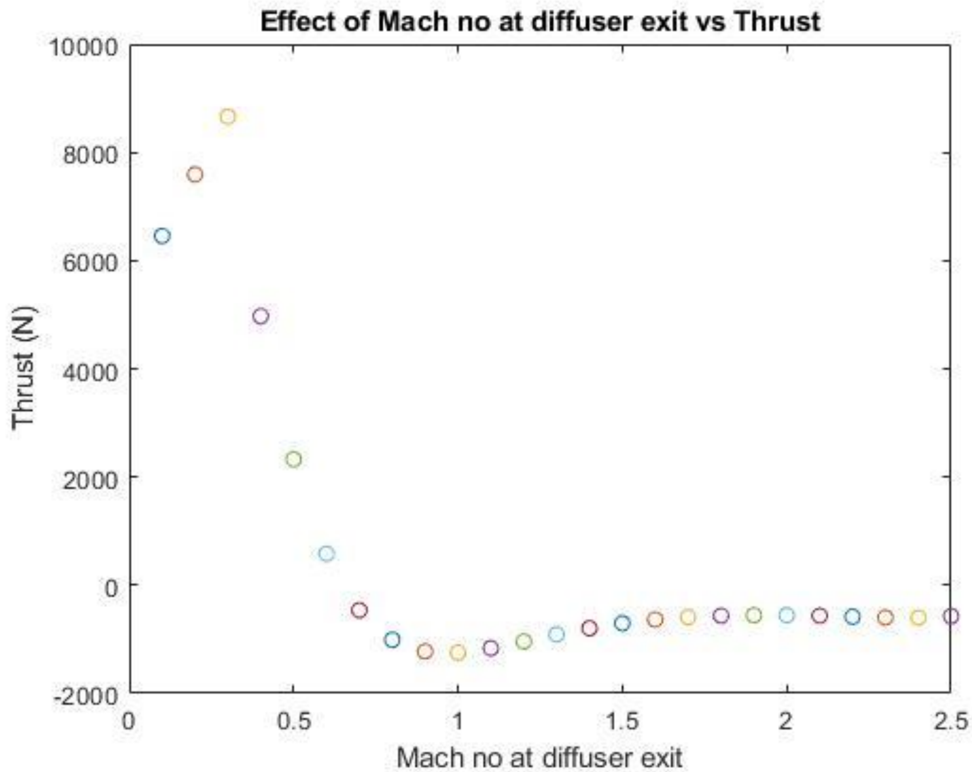
PART H

The Mach number M2 is varied from $0.1 \leq M2 \leq 2.5$ in steps of 0.1 to compute the resulting:

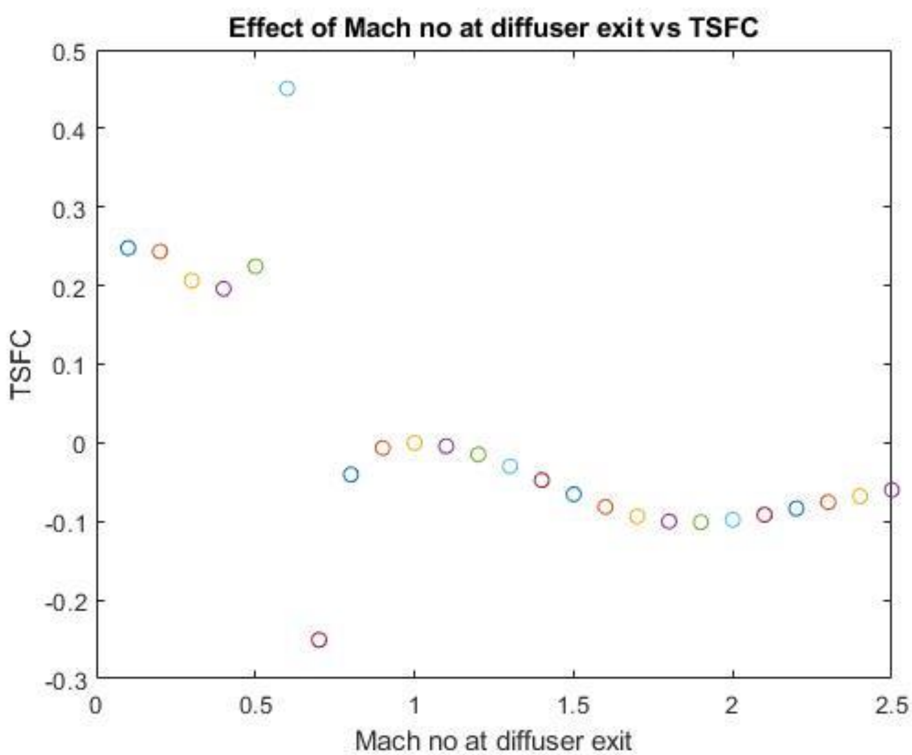
i. Overall efficiency



ii. Thrust



iii. TSFC



We have several resulting points which are invalid as they are negative, showing that there is a very small range of allowable Mach no at diffuser exit.

The limiting number is around 0.6 to 0.7

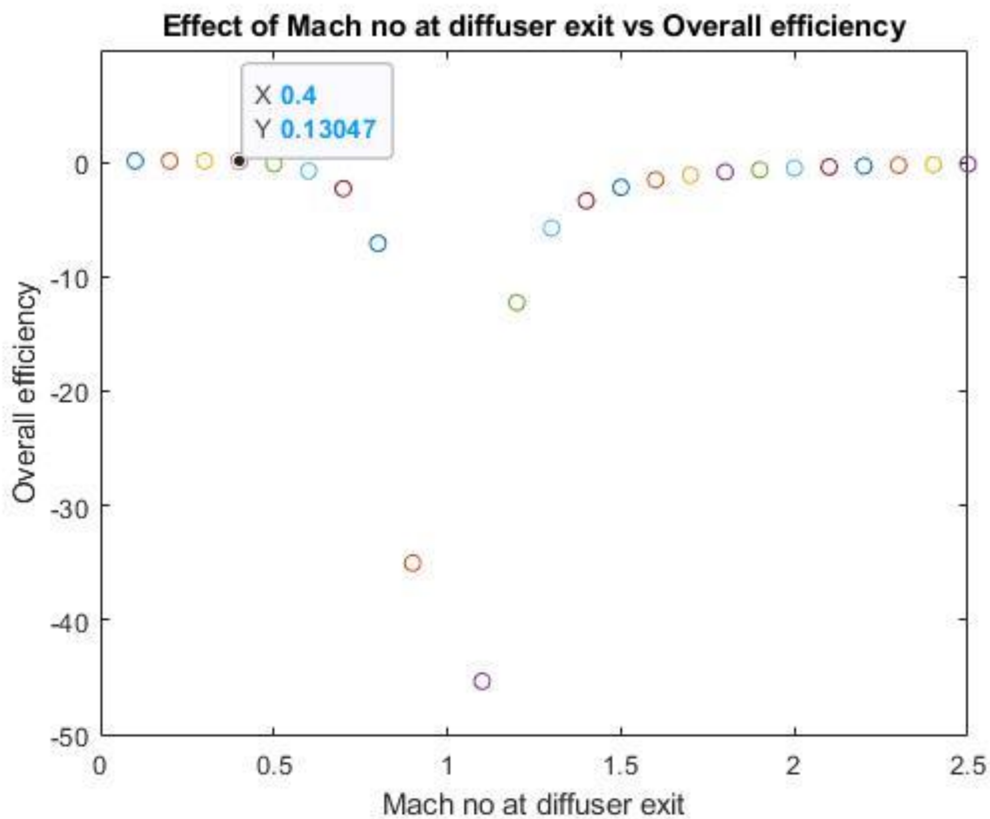
All performance parameters decreased beyond M2=0.3, showing that it's likely that at Mach no above that the engine becomes thermally choked, reducing performance.

PART I

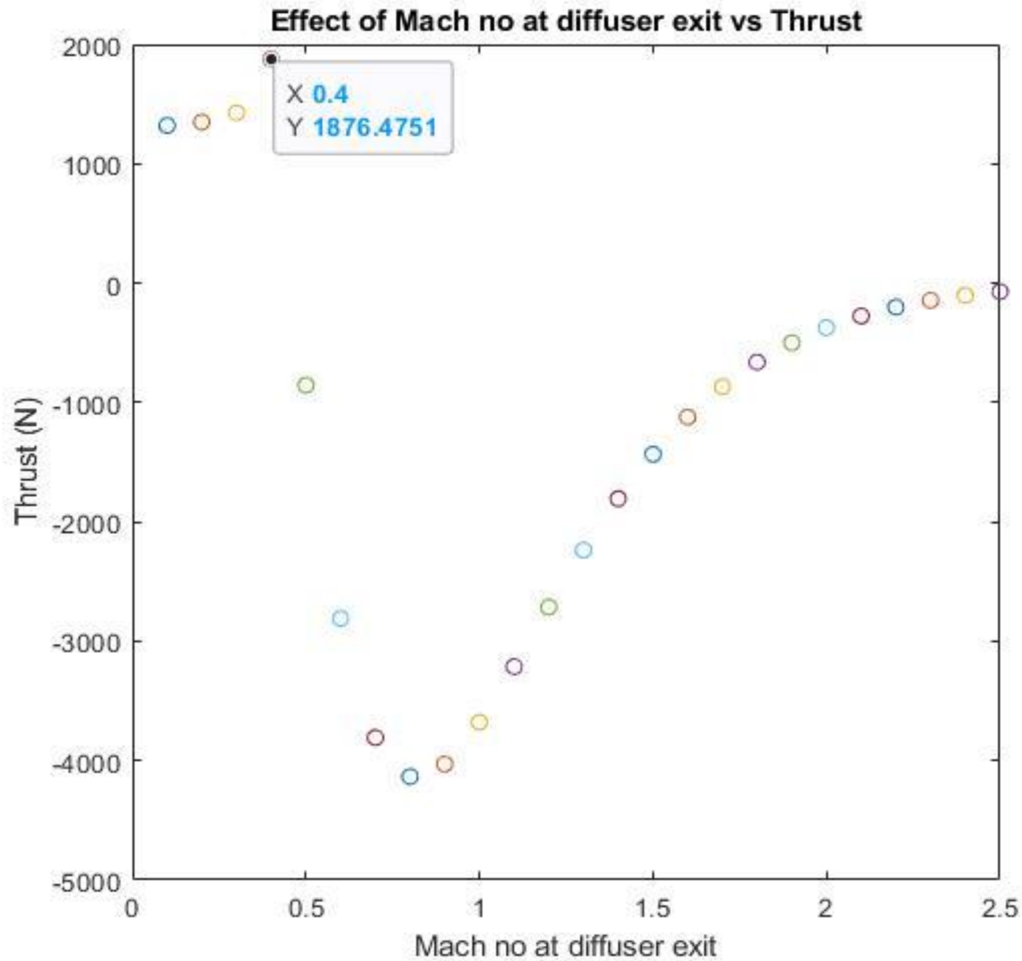
The tool was used to design a ram/scramjet system with Hypersonic fight Mach no of 5, and an altitude of 27,400m. The goal was to find the maximum Thrust and Overall efficiency for combustor exit total temperature limited to 2400K and varying the diffuser exit Mach no M2. The remaining parameters are kept same as unchoked conditions.

By varying M2 from 0.1 to 2.5 in steps of 0.1, we obtain the following results:

i. Overall efficiency:



ii. Thrust



For both parameters, we see that parameter increases till M2=0.4, then goes into the negative values, meaning they are not applicable.

This shows that the Optimal value for M2 is 0.4

At this M2, we have Overall Efficiency of 0.13

Thrust for M2=0.4 is 1876.48 N.

APPENDIX:

The MATLAB Code used:

Main code for solver function

```
%%
%Module 1: Free stream conditions
function output=Moudgalya_Sandeep_Project(m2)

%Accepting all inputs
% z=input("Enter flight altitude: ");
% m1=input("Enter flight Mach no: ");
% nd=input("Enter inlet/diffuser efficiency: ");
% m2=input("Enter Mach no at diffuser exit: ");
% Tt3max=input("Enter maximum allowable total temperature at combustor exit:
");
% qf=input("Enter heating value of the fuel: ");
% nn=input("Enter nozzle efficiency: ");
% Ae=input("Enter nozzle exit area: ");
%Value for iteration
%z=4300;
%Values for validation:
% z=4300;
% m1=2.4;
nd=0.92;
% %m2=0.15;
% %m2=0.4;
Tt3max=2400;
qf=43.2*1000000;
nn=0.94;
Ae=0.015;
%Hypersonic Flight:
m1=5;
z=27400;

%Given values:
Ts=288;
ps=101.3*1000;
gamma=1.4;
zstar=8404;
R=286.9;
a=986;
b=0.179;

%Finding conditions:
if(z<7958)
    T1=Ts*(1-((gamma-1)/gamma)*(z/zstar));
    p1=ps*(1-((gamma-1)/gamma)*(z/zstar))^(gamma/(gamma-1));
else
    T1=210;
    p1=1000*33.6*exp((7959-z)/6605);
end
Tt1=T1*(1+m1^2*(gamma-1)/2);
pt1=p1*(1+m1^2*(gamma-1)/2)^(gamma/(gamma-1));
a1=sqrt(gamma*R*T1);
```

```
v1=m1*a1;
Cp1=a+b*T1;
%End of module 1
%%
%Module 2: For inlet/diffuser
gamma=1.4;
Tt2=Tt1;
T2=Tt2/(1+m2^2*(gamma-1)/2);
pt2=p1*(1+nd*m1^2*(gamma-1)/2)^(gamma/(gamma-1));
p2=pt2/(1+m2^2*(gamma-1)/2)^(gamma/(gamma-1));
Cp2=a+b*T2;
s12=Cp2*log(Tt2/Tt1)-R*log(pt2/pt1);
a2=sqrt(gamma*R*T2);
v2=m2*a2;
%End of module 2
%%
%Module 3: For combustor
gamma=1.3;
Tt3choked = Tt2*((1/(2*(gamma+1)))*(1/(m2^2))*((1+gamma*m2^2)^2)*(1+((gamma-
1)/2)*m2^2)^-1);
%Checking thermal choking:
if(Tt3choked < Tt3max)
    m3=1;
    Tt3 = Tt3choked;
else
    Tt3 = Tt3max;
    C=(Tt3/Tt2)*(m2^2)*((1 + ((gamma - 1)/2)*m2^2)/((1 + gamma*(m2^2))^2));
    A=C*gamma^2-(gamma-1)/2;
    B=2*C*gamma-1;
    m3=sqrt((-1*B+sqrt(B^2-4*A*C))/(2*A));
    if(m3>m2 && m2<1 && m3<=1)

    else
        m3=sqrt((-1*B-sqrt(B^2-4*A*C))/(2*A));
    end
end
q23=a*(Tt3-Tt2)+0.5*b*(Tt3^2-Tt2^2);
p3=p2;
T3=Tt3/(1+m3^2*(gamma-1)/2);
pt3=p3*(1+m3^2*(gamma-1)/2)^(gamma/(gamma-1));
Cp3=a+b*T3;
a3=sqrt(gamma*R*T3);
v3=m3*a3;
s23=Cp3*log(Tt3/Tt2)-R*log(pt3/pt2);
%End of module 3
%%
%Module 4: Converging nozzle
gamma=1.3;
mtest=sqrt((2/(gamma-1))*(nn*(1-(p1/pt3)^((gamma-1)/gamma))/(1-nn*(1-
(p1/pt3)^((gamma-1)/gamma)))));
if(mtest<1)
    me=mtest;
    pe=p1;
else
    me=1;
    pe=pt3*(1-nn^-1*((gamma-1)/(gamma+1)))^(gamma/(gamma-1));
end
```

```
Tte=Tt3;
Te=Tte/(1+me^2*(gamma-1)/2);
pte=pe*(1+me^2*(gamma-1)/2)^(gamma/(gamma-1));
ae=sqrt(gamma*R*Te);
ve=me*ae;
Cpe=a+b*Te;
exmassflux=pe*ve*Ae/(R*Te);
s3e=Cpe*log(Tte/Tt3)-R*log(pte/pt3);
se1=s3e+s23+s12;
%End of module 4
%%
%Module 5: External Flow
gamma=1.3;
%Checking nozzle choking condition:
if(mtest<1)
    nnext=1;
else
    nnext=mtest^(-0.3);
end
%Calculations
Tt4=Tte;
T4=Tt4*(1-nnext*(1-(p1/pte)^((gamma-1)/gamma)));
m4=sqrt((2/(gamma-1))*(Tt4/T4-1));
p4=p1;
pt4=p4*(1+m4^2*(gamma-1)/2)^(gamma/(gamma-1));
a4=sqrt(gamma*R*T4);
v4=m4*a4;
Cp4=a+b*T4;
s4e=Cp4*log(Tt4/Tte)-R*log(pt4/pte);
s41=se1+s4e;
%End of module 5
%%
%Module 6: Performance parameters
inmassflux=exmassflux/(1+q23/qf);
fuelmassflux=(exmassflux-inmassflux);
f=fuelmassflux/inmassflux;
jThrust=inmassflux*((1+f)*ve-v1);
pThrust=(pe-p1)*Ae;
totThrust=jThrust+pThrust;
TSFC=(fuelmassflux*3600)/totThrust;
Isp=totThrust/(fuelmassflux*9.8);
veq=ve+((pe-p1)*(Ae/exmassflux));
nth=((exmassflux*veq*veq/2)-(inmassflux*v1*v1/2))/(inmassflux*q23);
nprop=2/(1+(veq/v1));
noverall=nth*nprop;
propP=totThrust*v1;
output=totThrust;
end

%End of module 6
```

Iterating function

```
%For calling the main function
clc
clear
for n=0.1:0.1:2.5
    n
    o=Moudgalya_Sandeep_Project(n)
    plot(n,o,'o')
    hold on
end
title('Effect of Mach no at diffuser exit vs Thrust')
xlabel('Mach no at diffuser exit')
ylabel('Thrust (N)')
```

EXCEL SHEETS USED:

Unchoked T-s Diagram:

s	T		
0	245.8976	1	
43.951	526.801	2	
2152.451	2354.3	3	
2360.059	1557.7	4	11.9606
			195.647

2 to 3		4 to 1	
43.951	526.801	2360.059	1557.7
98	553.1577	2310.059	1480.125
148	578.6485	2260.059	1406.414
198	605.2023	2210.059	1336.373
248	632.854	2160.059	1269.821
298	661.6389	2110.059	1206.583
348	691.5926	2060.059	1146.494
398	722.7512	2010.059	1089.398
448	755.1508	1960.059	1035.145
498	788.8276	1910.059	983.5938
548	823.8182	1860.059	934.61
598	860.1589	1810.059	888.0657
648	897.8862	1760.059	843.8393
698	937.0364	1710.059	801.8155
748	977.6454	1660.059	761.8844
798	1019.749	1610.059	723.942

848	1063.383	1560.059	687.8891
898	1108.581	1510.059	653.6316
948	1155.379	1460.059	621.0803
998	1203.81	1410.059	590.15
1048	1253.907	1360.059	560.76
1098	1305.702	1310.059	532.8337
1148	1359.227	1260.059	506.2982
1198	1414.511	1210.059	481.0841
1248	1471.585	1160.059	457.1258
1298	1530.476	1110.059	434.3605
1348	1591.211	1060.059	412.729
1398	1653.816	1010.059	392.1748
1448	1718.316	960.0586	372.6442
1498	1784.733	910.0586	354.0862
1548	1853.089	860.0586	336.4524
1598	1923.405	810.0586	319.6968
1648	1995.697	760.0586	303.7757
1698	2069.985	710.0586	288.6474
1748	2146.282	660.0586	274.2725
1798	2224.603	610.0586	260.6135
1848	2304.959	560.0586	247.6348
1898	2387.363	510.0586	235.3024
1948	2471.821	460.0586	223.5841
1998	2558.342	410.0586	212.4495
		360.0586	201.8693
		310.0586	191.8161
		260.0586	182.2635
		210.0586	173.1866
		160.0586	164.5618
		110.0586	156.3665
		60.0586	148.5793
		10.0586	141.1799

Choked
TS

s	T	
0	245.8976	1
43.951	512.7632	2
658.6885	890.953	3
930.8228	634.5804	4

11.9606
260.1737

2 to 3		4 to 1	
43.951	512.7632	930.8228	634.5804
98	538.4774	880.8228	602.9778
148	563.3519	830.8228	572.949
198	589.2689	780.8228	544.4157
248	616.2629	730.8228	517.3034
298	644.3691	680.8228	491.5412
348	673.6229	630.8228	467.0621
398	704.0601	580.8228	443.802
448	735.7167	530.8228	421.7003
498	768.629	480.8228	400.6993
548	802.8333	430.8228	380.7442
598	838.3662	380.8228	361.7828
648	875.2639	330.8228	343.7657
		280.8228	326.6459
		230.8228	310.3787
		180.8228	294.9216
		130.8228	280.2343
		80.8228	266.2784
		30.8228	253.0175

B) Temp

Standard Atmosphere

T	z
288	0
220	10
220	12

Model

T	z
288	0
286.0417	0.2
284.0835	0.4
282.1252	0.6
280.167	0.8
278.2087	1
276.2505	1.2
274.2922	1.4
272.334	1.6
270.3757	1.8
268.4175	2
266.4592	2.2
264.501	2.4
262.5427	2.6
260.5845	2.8
258.6262	3
256.668	3.2
254.7097	3.4
252.7515	3.6
250.7932	3.8
248.835	4
246.8767	4.2
244.9185	4.4
242.9602	4.6
241.002	4.8
239.0437	5
237.0855	5.2
235.1272	5.4
233.169	5.6
231.2107	5.8
229.2525	6
227.2942	6.2
225.336	6.4
223.3777	6.6
221.4195	6.8
219.4612	7
217.503	7.2

215.5447	7.4
213.5865	7.6
211.6282	7.8
210	8
210	8.2
210	8.4
210	8.6
210	8.8
210	9
210	9.2
210	9.4
210	9.6
210	9.8
210	10
210	10.2
210	10.4
210	10.6
210	10.8
210	11
210	11.2
210	11.4
210	11.6
210	11.8
210	12

Pressure

P	z
101.3	0
98.90966	0.2
96.55989	0.4
94.25026	0.6
91.98037	0.8
89.74979	1
87.55813	1.2
85.40496	1.4
83.28988	1.6
81.21248	1.8
79.17236	2
77.16911	2.2
75.20233	2.4
73.27161	2.6
71.37657	2.8

69.5168	3
67.69189	3.2
65.90147	3.4
64.14513	3.6
62.42249	3.8
60.73314	4
59.0767	4.2
57.45279	4.4
55.86102	4.6
54.301	4.8
52.77235	5
51.27469	5.2
49.80763	5.4
48.37081	5.6
46.96384	5.8
45.58635	6
44.23796	6.2
42.9183	6.4
41.62701	6.6
40.3637	6.8
39.12802	7
37.91961	7.2
36.73808	7.4
35.58309	7.6
34.45428	7.8
33.38702	8
32.39121	8.2
31.4251	8.4
30.48781	8.6
29.57847	8.8
28.69626	9
27.84036	9.2
27.00998	9.4
26.20438	9.6
25.4228	9.8
24.66453	10
23.92888	10.2
23.21517	10.4
22.52275	10.6
21.85098	10.8
21.19925	11
20.56696	11.2
19.95352	11.4

19.35838	11.6
18.781	11.8
18.22083	12

Standard

P	z
101.32	0
99.5	0.2
97.7	0.4
94.2	0.6
92.5	0.8
90	1
87.5	1.2
85.9	1.4
84.3	1.6
81.2	1.8
78.2	2
76.3	2.2
75.3	2.4
72.4	2.8
69.7	3
57.2	4.6
46.6	6
37.6	7.6
30.1	9
23.8	10.6
18.7	12

C)

M1	no	T	TSFC
0.8	0.0638	802.6864	0.3226
1.1	0.098	1155.7	0.2878
1.4	0.1373	1754	0.2609
1.7	0.1763	2679.4	0.2461
2	0.2109	4043.5	0.2412
2.3	0.2387	5978	0.2441
2.6	0.2587	8615.3	0.2535
2.9	0.2704	12052	0.2689
3.2	0.2736	16286	0.2913
3.5	0.2676	21115	0.3228

3.8	0.2512	25990	0.3688
4.1	0.2223	29803	0.4413
4.4	0.1775	30591	0.5736
4.7	0.1106	25147	0.9019
5	0.0109	8489.7	3.324

D)

z	no	T	TSFC
2000	0.2505	8708.2	0.2527
4000	0.2468	7008.7	0.2474
6000	0.2426	5530.3	0.242
8000	0.2378	4267.2	0.2367
10000	0.2378	3152.4	0.2367
12000	0.2378	2328.8	0.2367
14000	0.2378	1720.4	0.2367
16000	0.2378	1270.9	0.2367
18000	0.2378	938.9	0.2367
20000	0.2378	693.6	0.2367
22000	0.2378	512.4	0.2367
24000	0.2378	378.5	0.2367
26000	0.2378	279.6	0.2367
28000	0.2378	206.6	0.2367
30000	0.2378	152.6	0.2367

E)

z	m1 for max noverall	TSFC
2000	3	4.8
2500	3	4.8
3000	3	5
3500	3	2.2
4000	3.2	2.2
4500	3.2	2.2
5000	3.2	2.2
5500	3.2	2.2
6000	3.2	2.2
6500	3.4	2.2
7000	3.4	2.2
7500	3.4	2.2
8000	3.4	2.2

8500	3.4	2.2
9000	3.4	2.2
9500	3.4	2.2
10000	3.4	2.2
10500	3.4	2.2
11000	3.4	2.2
11500	3.4	2.2
12000	3.4	2.2
12500	3.4	2.2
13000	3.4	2.2
13500	3.4	2.2
14000	3.4	2.2
14500	3.4	2.2
15000	3.4	2.2
15500	3.4	2.2
16000	3.4	2.2
16500	3.4	2.2
17000	3.4	2.2
17500	3.4	2.2
18000	3.4	2.2
18500	3.4	2.2
19000	3.4	2.2
19500	3.4	2.2
20000	3.4	2.2