Design and Optimization of Ramjet Engine

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SPC 410 Gas Dynamics

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Introduction

It is required to design the ramjet rocket shown in the schematic. The engine intake comprises double-angle wedges to maximize total pressure recovery. The flow then is diffused to a lower Mach number to facilitate the heat addition process. The heat is added in the combustion chamber and then the flow rushes out of the supersonic nozzle producing thrust by expanding it to the atmospheric pressure.

The design point flight conditions are: P=12.11kPa, T= 216.5K, and Mach is 2.75. The engine has a square cross-section with a side length of 25 cm. The maximum combustor temperature is 2200K. The design process generally exhibits an iterative scheme for the supersonic intake, the diffuser, the combustion chamber, and the supersonic nozzle.

The main objective is to maximize the produced thrust. This objective is achieved by acquiring maximum pressure recovery in the intake, increasing heat addition capacity through the combustion chamber, and optimizing the nozzle exit to throat area ratio. The intake design requires multivariable optimization of the intake parameters ($\theta 1$ and $\theta 2$) to obtain maximum total pressure recovery after two obliques and terminal normal shock waves.

A two-dimensional flow model will be implemented to model the intake wedges and one-dimensional flow for the terminal normal shock wave. The combustion chamber section will be modeled as one-dimensional flow with heat addition assuming that total pressure at the exit of the combustor is reduced by 5% due to friction added to pressure drop due to heat. The diffuser and the supersonic nozzle will be modeled as quasi-one-dimensional flow.

Assumptions

- A two-dimensional flow model for the intake wedges
- A one-dimensional flow model for the terminal normal shock wave
- A one-dimensional flow with heat addition model for the combustion chamber
- The combustor exit total pressure is reduced by 5% due to friction added to pressure drop due to heat addition
- A quasi-one-dimensional flow model for the subsonic diffuser and the supersonic nozzle

Design Flow Chart

The flow chart

Design Procedure

The ramjet design implemented model is illustrated in fig.1 below.

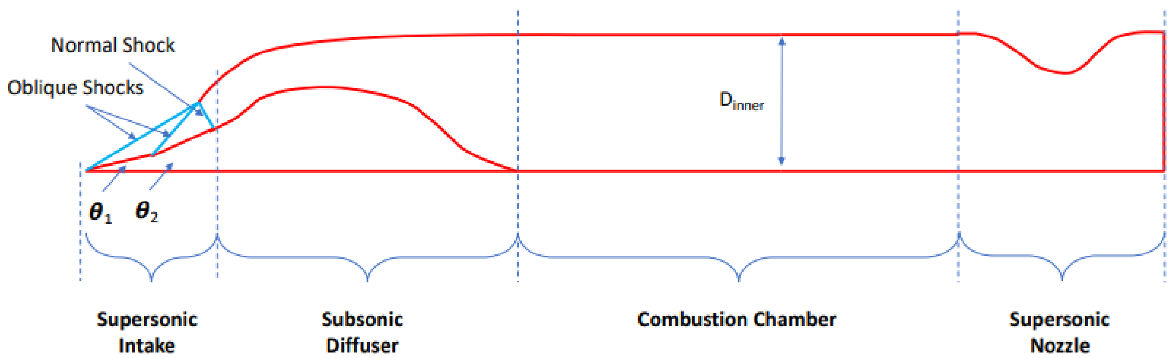


Figure 1. The ramjet engine cross-sectional view

Intake Design

The intake is designed to achieve an external compression with two oblique shock waves then a terminal normal shock wave, as shown in fig.2.

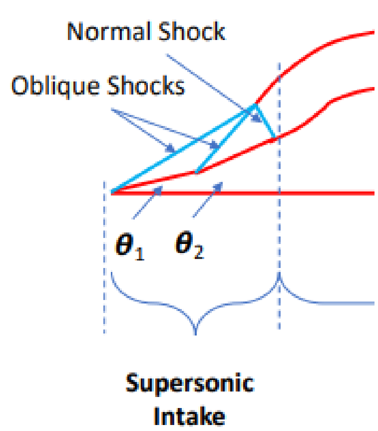


Figure 2. The intake sketch

With an upstream Mach number of 2.75, an iterative solution is applied to determine the wedge angles θ_1 & θ_2 such that a maximum pressure recovery is achieved after two oblique shock waves and a terminal normal shock wave.

$$\frac{IntakeSide}{sin(\beta_2-\theta_2)} = \frac{wedgeLength2}{cos(\beta_2-\theta_2)} = obliqueLength2$$

$$\frac{obliqueLength2}{sin(\beta_1-\theta_1)} = \frac{wedgeLength1}{sin(\theta_1+\beta_2-\beta_1)} = \frac{obliqueLength1}{sin(\beta_2)}$$

Using Matlab code (last section)

- Wedge angles of $\theta_1 = 12^o$ & $\theta_2 = 14^o$
- Pressure recovery of 14.92

The maximum cowl height is $125\ mm$ and hence maximum intake side of $54.18\ mm$ (from the geometry) which makes a maximum intake area of $0.0135\ m^2$.

Iterating the intake area to the maximum area and recording the thrust for each area to optimize the design.

Subsonic Diffuser

The flow enters the subsonic diffuser with a mach number $M_4 = 0.648$ and inlet area varying from $0.013\ m^2\ to\ 0.0313\ m^2$ and then diffused till the combustion chamber entrance cross-sectional area $A_5 = 0.0313\ m^2$. A^* could be calculated then. Knowing A_5/A^*, $M_5$is calculated and the flow properties (T_5, To_5, P_5, Po_5) are evaluated at that point for each inlet area, too.

Combustion Chamber

The flow enters the combustion chamber with a mach number M_5. Using M_5 & T_5, T^*_5 is evaluated. If T^*_5 is greater than the combustion chamber maximum temperature $2200\ K$, then $T_6 = 2200\ K$ and M_6 is to be evaluated accordingly. Otherwise; if T^*_5 is less than the combustion chamber maximum temperature $2200\ K$, then $T_6 = T^*_5$ and M_6 is to be evaluated accordingly. Following that, the flow properties (T_5, To_5, P_5, Po_5) are evaluated at that point for each inlet area, too.

Supersonic Nozzle

The flow enters the combustion chamber with a mach number M_6 & Po_6. Getting A_6/A^* and form knowing A_6, $A^*$is evaluated which is the throat area A_t too. Now evaluating Pe/Po_6 and the corresponding mach number M_e & A_e/A^*. A_e is evaluated then and compared with A_{max}. If A_e is greater than A_{max}, A_7 is set to A_{max}. Otherwise, A_7 is set to A_e.

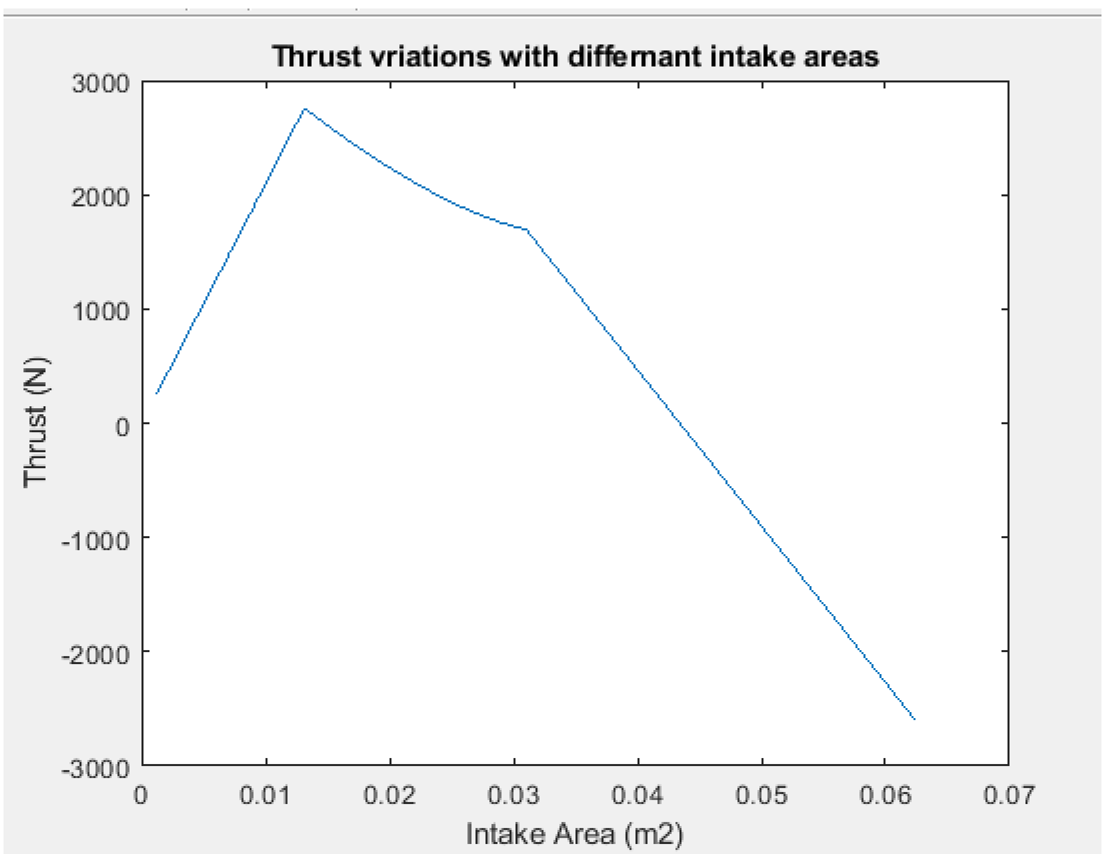
Finally the thrust for that inlet area is calculated and recorded to be plotted versus the various inlet areas after the iteration loop is executed entirely.

Temperature of Maximum Thrust

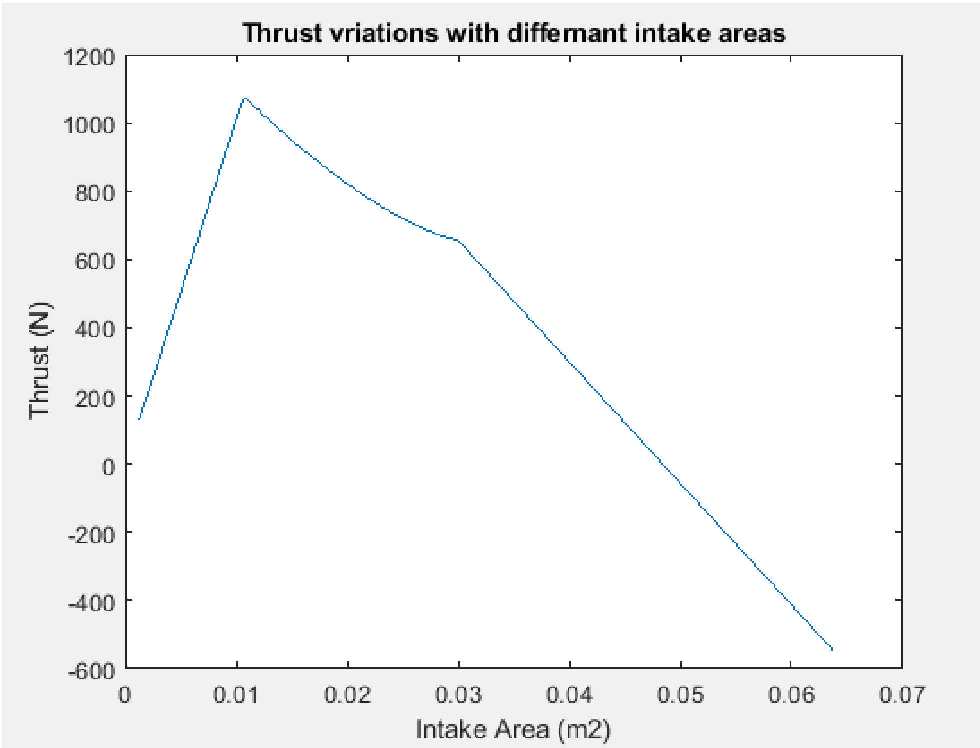
It is observed that the maximum corresponding combustion temperatures is always $2200\ K$ which is the maximum temperature of the combustion chamber. The same temperature is observed even with different flight conditions. Which does make full sense and should be very expected; as the actual energy given to the flow is only taking place in the combustor so, intuitively, the greater the amount of energy (heat added) given to the flow, the greater the thrust. Hence the maximum combustion chamber temperature corresponds to the maximum value of thrust.

Results

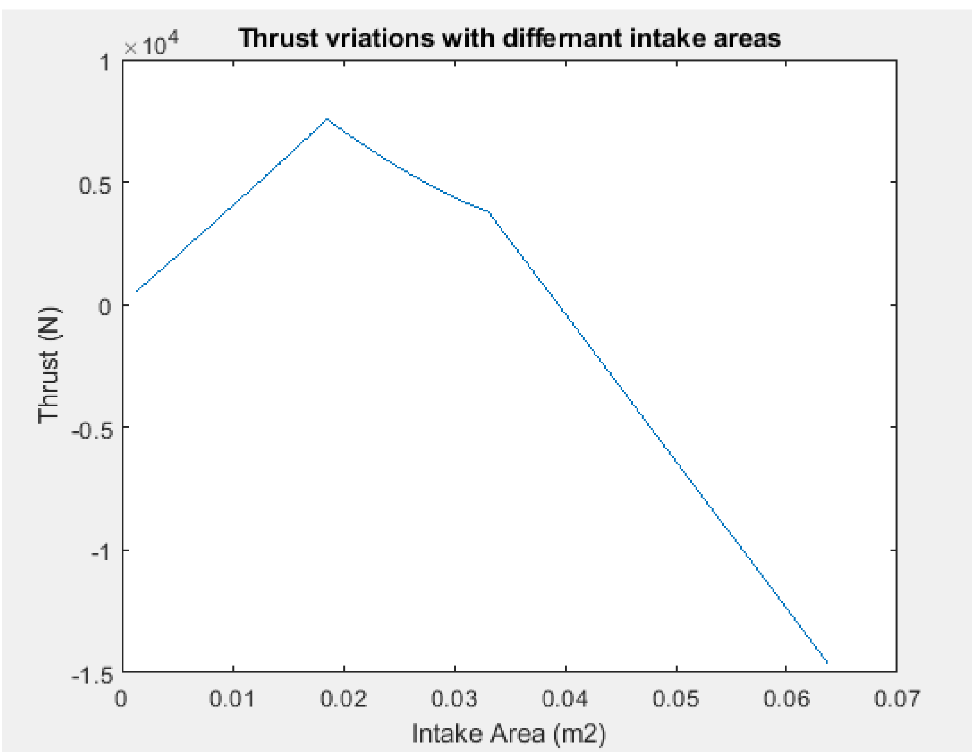
M = 2.75



M = 2


Thrust vriations with differnant intake areas
1200
1000
800
600
400
200
0
-200
-400
-600
Thrust (N)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Intake Area (m2)

M = 4


Thrust vriations with differnant intake areas
× 10^4
1
0.5
0
-0.5
-1
-1.5
Thrust (N)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Intake Area (m2)

Matlab code

```
clear all; clc;
%% Constants
k = 1.4;
R = 287;
Amax = 250;
M1 = 2.75;
P1 = 12110;     % Pa
T1 = 216.5;     % K
pho1 = 0.193;   % Kg/m3
To1 = T1 * (1+(k-1)/2*M1^2); % To1 = To2 = To3 = To4 = To5
Po1 = P1 * (To1/T1)^(k/(k-1));
BestP4P1 = 1; % dummy
IntakeArea = 1:50;
Thrust = 1:50;

%% Determining the intake angles
for theta = 1:0.05:30
  % from 1 to 2
  [M2,beta1,P2P1,T2T1,Po2Po1] = OSW(M1,theta);

  % form 2 to 3
  for theta2 = 1:0.5:30
    [M3,beta2,P3P2,T3T2,Po3Po2] = OSW(M2,theta2);
    if ~isreal(M3)
      break;      % if theta2 exceeds the maximum, break
    end
    P3P1 = P3P2 * P2P1;
    Po3Po1 = Po3Po2 * Po2Po1;
    T3T1 = T3T2 * T2T1;

    % from 3 to 4
```

```
    [M4,T4T3,P4P3,Po4Po3] = NSW(M3);

    P4P1 = P4P3 * P3P1;
    Po4Po1 = Po4Po3 * Po3Po1;
    T4T1 = T4T3 * T3T1;

    if P4P1 > BestP4P1
      BestP4P1 = P4P1;
      BestPo4Po1 = Po4Po1;
      BestT4T1 = T4T1;
      BestM2 = M2;
      BestM3 = M3;
      BestM4 = M4;
      BestTheta1 = theta;
      BestTheta2 = theta2;
      BestBeta1 = beta1;
      BestBeta2 = beta2;
    end
  end
end
% clearing dummy loop data
clear beta1 beta2 M2 M3 M4 P2P1 P3P1 P3P2 P4P1 P4P3 T2T1 T3T1 T3T2 T4T1 T4T3 pho4pho3 theta theta2;

i = 1;
for IntakeSide = 5:1:250
  %% Intake Design (1-2-3-4)
  % the maximum cowl height is 125mm and hence maximum intake side of 54.175mm
  % taking IntakeSide = 50;
  IntakeArea(i) = IntakeSide * Amax * 10^-6;
  [wedgeL1,wedgeL2,obliqueL1,obliqueL2,cowlHeight] =
IntakeDesign(IntakeSide,BestTheta1,BestTheta2,BestBeta1,BestBeta2);
  A4 = IntakeSide * Amax * 10^-6; % Intake Area in m2
  T4 = BestT4T1 * T1;
  P4 = BestP4P1 * P1;
```

```
To4 = To1;
Po4 = P4 * (To1/T4)^(k/(k-1));
pho4 = P4/(R*T4);
mDot = pho4 * A4 * BestM4 * sqrt(k*R*T4);


%% The Subsonic Diffuser (4-5)
A5 = 0.0313;    % the combustion chamber maximum cross-sectional area
A4Astar = sqrt(1/BestM4^2 *(2/(k+1)*(1+(k-1)/2*BestM4^2))^((k+1)/(k-1)));
Astar4 = A4/A4Astar;
A5Astar = A5/Astar4;
M5 = 0.6479; err1 = inf;
while err1 > 10e-3
    M5 = M5 - 0.001;
    err1 = A5Astar - sqrt(1/M5^2 *(2/(k+1)*(1+(k-1)/2*M5^2))^((k+1)/(k-1)));
end
T5 = T4 * (1+(k-1)/2*BestM4^2)/(1+(k-1)/2*M5^2);
P5 = P4 * (T5/T4)^(k/(k-1));
To5 = To1;
Po5 = Po4;


%% The Combustion Chamber (5-6)
Tstar5 = T5 * 1/M5^2 * ((1+k*M5^2)/(1+k))^2;
if Tstar5 > 2200     % the max T at the combustion chamber
    T6 = 2200;
else
    T6 = Tstar5;
end

if i == 48   % max thrust iteration
    BesttComustionTemp = T6;
end
```

```
% Tostar5 = To1 * (1+k*M5^2)^2/((k+1)*M5^2)*(2+(k-1)*M5^2);
T6Tstar5 = T6 / Tstar5;
M6 = M5; err2 = inf;
while err2 > 10e-3
   M6 = M6 + 0.001;
   err2 = (M6^2 *((k+1)/(1+k*M6^2))^2) - T6T star5;
end
P6 = P5 * (1+k*M5^2)/(1+k*M6^2);
To6 = T6 * (1+(k-1)/2*M6^2);
Po6 = 0.95 * P6 * (To6/T6)^(k/(k-1)); % 0.95 due to the 5% friction loss


%% The Nozzle
A6 = 2*A5;
Astar6 = A6 * 1/(sqrt(1/M6^2 *(2/(k+1)*(1+(k-1)/2*M6^2))^((k+1)/(k-1)))); % Astar6 is At

PePo6 = P1/Po6;
M7 = 1; err3 = 10;
while err3 > 10e-3
   M7 = M7 + 0.001;
   err3 = PePo6 - (1+(k-1)/2*M7^2)^(-k/(k-1));
end
A7 = Astar6 * sqrt(1/M7^2 *(2/(k+1)*(1+(k-1)/2*M7^2))^((k+1)/(k-1)));
if A7 > Amax
   A7 = Amax;
end

T7 = To6 * 1/(1+(k-1)/2*M7^2);
P7 = Po6 * (T7/To6)^(k/(k-1)); % Pe
Po7 = P7 * (To6/T7)^(k/(k-1));
To7 = To6;
PePo = P7/Po6;
pho7 = P7/(R*T7);
mDote = pho7 * A7 * M7 * sqrt(k*R*T7);
```

```
    %% The Thrust
    Ve = M7 * sqrt(k*R*T7);
    Vi = M1 * sqrt(k*R*T1);
    Thrust(i) = mDot*(Ve-Vi) + A7*(P7-P1);
    i = i + 1;
end

plot(IntakeArea,Thrust)
xlabel('Intake Area (m2)')
ylabel('Thrust (N)')
title('Thrust variations with different intake areas')
```

References

1. Smart, M.K. Scramjet Inlets; RTO-EN-AVT-185; NATO Science and Technology Organization: Neuilly sur Seine, France, 2010; pp. 1–24.
2. Kotteda, V.M.K.; Mittal, S. Instabilities in Air Intakes of Supersonic Air Vehicles. Directions. Available online: https://www.iitk.ac.in/aero/research-areas (accessed 8 February 2022).
3. Hall, N. Ramjet/Scramjet Thrust. NASA Glenn Research Center, 2017. Available online: https://www.grc.nasa.gov/www/k-12/airplane/ramth.html (accessed 8 February 2022).