

Design and Fabrication of a Ramjet Inlet

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Design and Fabrication of a Ramjet Inlet

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In this report, the design and fabrication of the inlet to a ramjet engine is described. The inlet utilizes a single ramp and single sided three shock internal compression to slow the airflow from supersonic to subsonic speeds while providing maximum stagnation pressure to the combustor. The optimum angle for the inlet ramp is calculated to be 10° and it decelerates the airflow from Mach 3.3019 to Mach 0.5438. The stagnation pressure increases from 150 psi to 4.67 ksi. The material of the inlet is composed primarily of low carbon mild steel to accommodate the high pressure of the inlet.

Nomenclature

A	= cross-sectional area, in^2
A^*	= cross-sectional area of nozzle to choke the flow, in^2
a	= speed of sound, ft/s
C_p	= coefficient of pressure
C_p	= Heat Capacity, $Btu/lb R$
h	= height of cross section, in
f	= fuel air ratio, mass flow rate of fuel / mass flow rate of air
M	= Mach number, V/a
\dot{m}	= mass flow rate, $slugs/s$
\dot{m}^*	= mass flow rate of choked flow, $slugs/s$
P	= pressure, psi
R	= gas constant, $ft \cdot lb_f/lb_m \cdot R$
s	= entropy, $Btu/lb R$
T	= temperature, R
u	= velocity, ft/s
V	= velocity, ft/s
w	= width of cross section, in
ρ	= density, lb_m/ft^3
β	= wave angle
θ	= deflection angle
γ	= ratio of specific heats

Subscripts

∞	= freestream
o	= stagnation conditions
1	= section 1, the inlet
2	= section 2, after initial shock

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- 3 = section 3, combustion chamber
- 4 = section 4, after the combustion chamber at the nozzle face
- 5 = section 5, nozzle throat
- 6 = section 6, at the nozzle exit
- amb* = ambient atmospheric property
- cold* = signifies cold data, gas property before the inclusion of fuel and combustion
- hot* = signifies hot data, gas property after fuel and combustion
- n,1* = normal component of initial Mach number
- n,2* = normal component after initial shock
- STD* = standard atmospheric property

I. Introduction

The following paper details the team project to build a ramjet engine per the thesis of graduate student Harrison Sykes, "Baseline Performance of Ramjet Engine". The ramjet project is designed to be used for senior level labs and graduate level research. The working principle of the ramjet is to first decelerate high speed air flow to create high pressure and low speed, then mix and combust fuel, and finally expel hot air with burnt fuel out the converging-diverging nozzle. The ramjet engine in this work has a nominal operation point of Mach 3.3 for the inlet, a maximum static temperature of 953 Fahrenheit, and a maximum static pressure of 31.635psi.

The ramjet engine is mounted to the exit nozzle of the Supersonic Wind Tunnel (SSWT). The duct area dimensions of the ramjet engine are 4.937 inches wide by 4.785 inches high to match the exit nozzle of the Supersonic Wind Tunnel. The overall length of the ramjet engine is six feet long. The length is broken into three equal sections of two feet for the compressor, the combustor, and the nozzle, as shown below in Fig. 1.

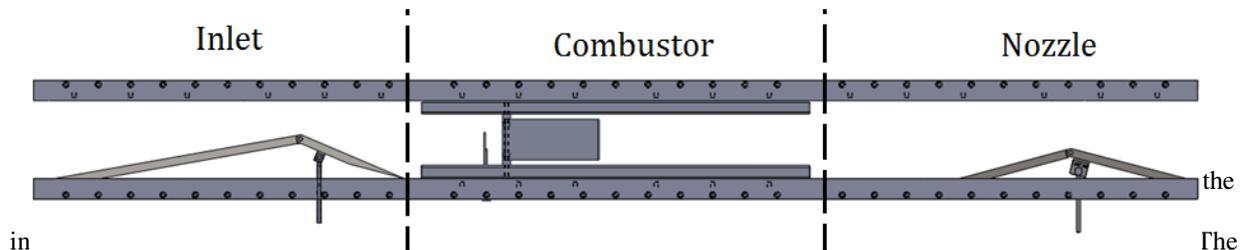


Figure 1. Ramjet engine diagram. The three sections of the ramjet are shown, the Inlet, the Combustor, and the Nozzle.

The combustor also requires the flow to be subsonic so that the fuel can be ignited by a spark and a controlled explosion created. The inlet ramp is single sided and the airflow is assumed to be two dimensional. The ramp angle and height of the inlet are designed to be adjusted by hand. This is to improve the range of input speeds for the inlet and account for any inconsistencies with the airflow.

II. Governing Equations of Inlet

To design the ramjet inlet, equations for supersonic flow and oblique shocks are used. For the ramjet inlet to be effective, it must have supersonic compression and deceleration to subsonic conditions. This is achieved as suggested in [1], by using single sided three shock internal compression. During the compression, there are three shocks in total. The first oblique shock is created by the ramp at the intake, the second oblique shock is created by the reflection on the ceiling, and finally, the last shock is a normal shock terminated at the crest of the ramp. The three shock internal compression is shown in Fig. 2. The arrows show the airflow from left to right, and the shocks are shown in the three stages. This method is preferred, because the oblique shocks slow the supersonic flow at a more gradual rate than a single normal shock, thus allowing a higher recovery of stagnation pressure. The ramp angle is adjustable in the design to ensure the second oblique shock lands at the crest of the ramp.

To find the optimum ramp angle for the inlet, incompressible gas equations are used. An initial guess is made for the ramp angle, and the pressure, temperature, and Mach numbers for the inlet exit are compared with the desired values to find the optimum ramp angle. The process is repeated until the desired values are found. The process starts with the following simple oblique shock equation to find the pressure and temperature downstream of the first oblique shock. The equation is shown below and it relates the wave angle, β to the deflection angle, θ as a function of the initial Mach number, M_1 and the ratio of specific heat, γ .

$$\tan(\theta) = 2 \cot(\beta) \frac{M_1^2 \sin^2(\beta) - 1}{M_1^2 (\gamma + \cos(2\beta)) + 2} \quad (1)$$

Where the desired β is easily found using the *fsolve* function in MATLAB. This equation assumes a weak oblique shock, since the flow is still supersonic.

To solve for air properties after the oblique shock, the normal component of the initial Mach number is required. It is calculated with the following equation,

$$M_{n,1} = M_1 \sin(\beta) \quad (2)$$

Where $M_{n,1}$ is the normal component of the initial Mach number. Using this value, the air properties after the oblique shock are calculated as follows,

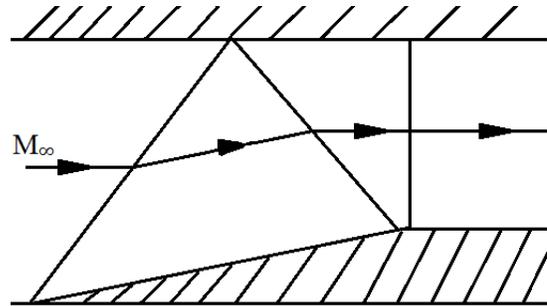


Figure 2. Three shock internal compression. *The first two oblique shocks are followed by a weak normal shock.*

$$M_{n,2}^2 = \frac{1 + (\frac{\gamma-1}{2})M_{n,1}^2}{\gamma M_{n,1}^2 - (\frac{\gamma-1}{2})} \quad (3)$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_{n,1}^2}{2 + (\gamma-1)M_{n,1}^2} \quad (4)$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_{n,1}^2 - 1) \quad (5)$$

Where $M_{n,2}$ is the normal component of the Mach number after the oblique shock, and ρ_2 , p_2 are the density and pressure after the oblique shock respectively. Using the outputs from Eqs. (3), (4), and (5), the Mach number and temperature ratio after the oblique shock are calculated.

$$M_2 = \frac{M_{n,2}}{\sin(\beta-\theta)} \quad (6)$$

$$\frac{T_2}{T_1} = \frac{p_2 \rho_1}{p_1 \rho_2} \quad (7)$$

Where M_2 is the Mach number after the oblique shock and T_2 is the temperature after the oblique shock.

To solve for the stagnation properties, the change in entropy across the shock is required. This is done with the following equation.

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \quad (8)$$

Where s is entropy, R is the gas constant, and c_p is found with the following relation,

$$c_p = \frac{\gamma R}{\gamma-1} \quad (9)$$

Assuming a specific heat ratio γ of 1.4, and a gas constant R of 1716 ft*lb/(slug*°R)

The change in entropy from Eq. (8) is used to find the ratio of the stagnation pressures before and after the oblique shock.

$$\frac{p_{02}}{p_{01}} = e^{-\Delta s R} \quad (10)$$

The previous equations for calculating air properties after the first oblique shock are used again for the second oblique shock reflected from the ceiling as shown in Fig 2. The same wave angle β is used for the reflected ceiling shock, since the ceiling is horizontal.

For the third and final shock, Eqs. (3), (4), (5), and (7) are used once again with the most recent normal Mach number for the inputted normal Mach number. The wave angle β would not exist in this case since the shock is completely normal. In this final shock, the air flow is made subsonic and the final values for the pressure, temperature, and Mach number are compared with the desired values.

To ensure the second oblique shock lands on the crest of the ramp and is reflected directly vertical or upstream, the following equations are used to calculate the required geometry of the ramp.

$$\text{—————} \quad \text{—————} \quad \text{—————} \quad (11)$$

Where h is the total vertical height of the ramjet duct, h_{ramp} is the vertical height of the ramp, and h_{open} is the vertical distance between the top of the ramp and the ceiling of the duct. β_1 is the wave angle of the first oblique shock, and β_2 is the wave angle of the second oblique shock. The horizontal ramp length is found by using the following trigonometric equation,

$$\text{—————} \quad (12)$$

Where x is the horizontal length of the ramp.

III. Design Results

Using the equations mentioned in the previous section with the desired requirements, an optimum ramp angle can be found. The airflow is desired to be decelerated from Mach 3.3019 to Mach 0.5438. This would raise the stagnation pressure to 4.67 ksi and be enough to ignite a controlled explosion for the combustor.

The geometry to achieve these values can be calculated by using recursive iterations for the ramp angle θ . The range is set to integer numbers between 1 and 20 degrees from the horizontal. The iteration finds that the greatest pressure recovery occurs when the ramp angle θ is set to 10 degrees. This results in an exit opening height of 2.004 in. for the oblique shock to land on the crest of the ramp.

IV. Fabrication and Assembly

After the dimensions of the inlet are found, the inlet design is created using Solidworks. The final design of the inlet is shown below in Fig. 3.

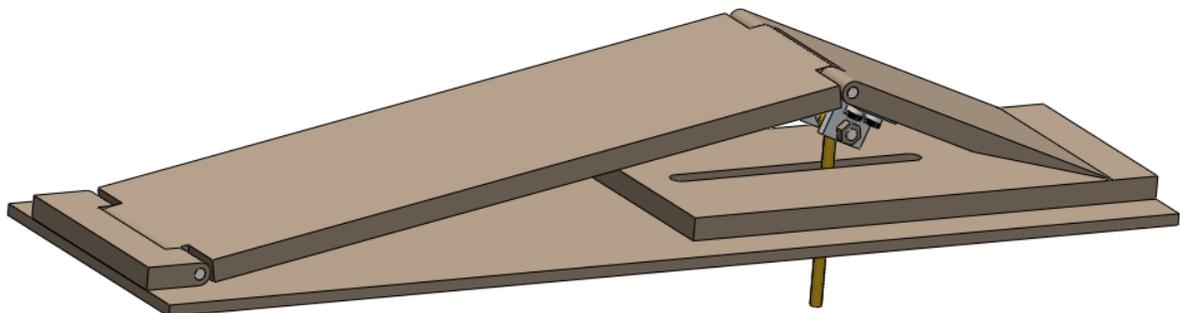


Figure 3. Inlet design. *The ramp height is hand adjustable. Flow goes left to right.*

Figure 3 does not show the ceiling, sidewalls, or surrounding pieces of the inlet assembly. The exit ramp of the inlet comes to a narrow edge to stay close to the bottom plate at all times. The inlet is designed to be movable in height. The adjustment is done by hand in between runs of the ramjet engine. The height of the ramp is adjusted by rotating the hex nuts about the vertical threaded rod. A closer diagram is shown in Fig. 4. A close up of the slot shows that the threaded rod has two hex nuts attached to it. The top hex nut is located in the wider slot of the upper base plate to prevent rotation. The bottom hex nut is located under the inlet and is used as a fastener to keep the vertical rod in place. When used in combination, the threaded rod is easily adjusted up or down to move the ramp to a desired height or angle.

The connections for the ramp are made of three male and female connections. The connections are held in place with $\frac{1}{4}$ in. diameter pins. The inlet walls keep the pin from moving out of the connection. The extra spacing on the faces of the connections are covered with aluminum tape to ensure laminar flow for the inlet.

The material used for the inlet was mostly mild steel. The one exception being the flanges for the vertical rod actuation were aluminum. Mild steel was chosen, because it has a tensile strength of 58 ksi and elastic modulus of 30,500,000 psi. These properties made the ramp strong enough to withstand the bending from the high pressure in the inlet.

The components were fabricated in the metal shop of the Cal Poly Bonderson Projects Center. The $\frac{1}{4}$ in. holes were drilled using a #7 drill bit with a drill press. They were then tapped using a $\frac{1}{4}$ -20 tapping kit. The slot in both the base plate and the upper base plate were cut using a milling machine. The interlocking ramp piece ends were also milled, and later drilled for the connection pin. The outer curves of the interlocking ramp pieces were created by grinding the ramp ends.

The assembly of the inlet is done by using a tight tolerance on each of the components. The tolerance is $\frac{1}{16}$ inch for the overall assembly. The width of the ramp and the length of the pins are toleranced to be no greater than

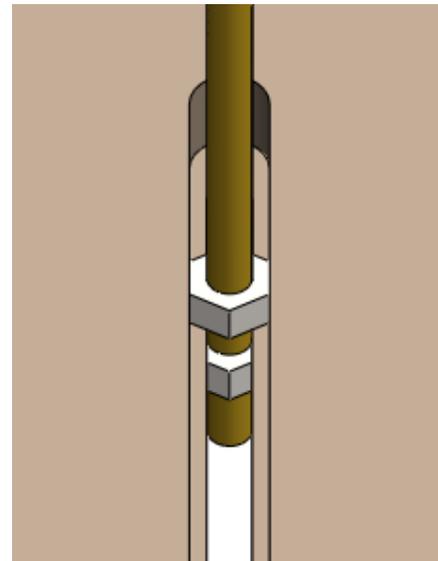


Figure 4. Close-up of threaded rod.
The nuts rotate about threads, the nut on top is snug in the upper slot to prevent rotation.

the width of the inlet which is 4.94 in. The male and female components have a tighter tolerance of 1/32 in to assist the aluminum tape with ensuring laminar flow.

V. Conclusion

As shown in this report, the inlet should work effectively for providing the desired pressure and airflow speed to the combustor portion of the ramjet engine. After the geometry was established in the design process, the inlet was fabricated and it was installed as an integral piece on the ramjet engine. A dry run test is to be conducted first on the entire ramjet engine with pressure transducers on the inlet ramp to corroborate the design values. Next, the ramjet is to be run with fuel and the inlet adjusted to ensure successful start to the engine. For future work, it would be beneficial to use a double ramp to slow the airflow instead of the single ramp currently used. This would result in a higher pressure recovery for the inlet and better property values for the combustor. The compression could still use a single sided three shock internal compression, but it would occur in two stages so as to decelerate the airflow at a more gradual rate.

References

- [1] Seddon, J. and Goldsmith E.L. *Intake Aerodynamics*, AIAA Education Series, Washington, DC, 1985, Chaps. 6-8
- [2] Coratekin, T., Keuk, J.V., and Ballmann Lehr, J. "Preliminary Investigations in 2D and 3D Ramjet Inlet Design", AIAA Database, VA, 1999
- [3] Benson, Tom, "Reflected Shock Wave," *Glenn Research Center Database* [online database], URL:
<http://www.grc.nasa.gov/WWW/BGH/reflects.html> [cited 14 May, 2013]
- [4] John, John E., Keith, Theo G., *Gas Dynamics*, 3rd ed., New Jersey, 2006, pp. 210-275.

Appendix

```
% Ramjet Physical Approximation code

clear ; close all; clc;

format compact
format short

%%% Old test section
width1 = 4.937/12; %ft
height1 = 4.785/12; %ft

width = width1;%2/12; %ft
height = height1;%2/12; %ft

%% Design values
% Mi = [6,5.5,5,4.5,4.0,3.5,3.0,2.5];%2.0,1.5]; % Mach at start of inlet
% Mfneed = 0.5; % Mach at exit on inlet
gamma = 1.4;
R = 1716.49; %ft lbf/(slug .R)
R_u = 1.986/453.59237*778.169262 ; % btu /(lb-mol .R)*lb-mol/mol * ft Lbf/BTu = ft lbf/(mol .R)
%8.314462 j/(mol k);
Kerosene_molM = 170.3400*6.85217659e-5; % g/mol * slug/g = slug/mol
R_K = R_u/Kerosene_molM;

T0i = 70+460; % R
p0i = 60*144; % psf
pexit = 14.7*144; % psf

A_CDthroat = 4.1896/144; % ft^2
A_CDdend = height1*width1; % ft^2

[~,~,~,~,~, M_CDdend] = IsentropicA(1, gamma, A_CDthroat, A_CDdend);
[T0_T, P0_P, Rho0_Rho_CD,~] = IsentropicPerfGas(M_CDdend, gamma);

pi = p0i/P0_P;
Ti = T0i/T0_T;
rhoi = pi/(R*Ti); % slug/ft^3
rho0i = rhoi*Rho0_Rho_CD;

a_i = (gamma*R.*Ti).^(.5); % ft/sec
V_i = M_CDdend*a_i;
mdotai = rhoi*A_CDdend*V_i; % slugs/sec

Mi = M_CDdend;
%% inlet design

% 1 ramp
theta = 10.0;%linspace(5,20,50); % degree

%%% oblique shock due to ramp

[Beta1,M2,rho2_rhoi,p2_pi,T2_Ti,p02_p0i] =...
    obliqueshockfunct(theta,Mi,gamma,R);

%%% Check isentropic relations
[T02_T2, P02_P2, Rho02_Rho2,~] = IsentropicPerfGas(M2, gamma);

p_2 = pi*p2_pi;
p0_2 = p0i*p02_p0i;

% test11=p_2/p0_2
% test12=1/P02_P2

if M2>1
    %%% oblique shock due to ceiling
    [Beta2,M3,rho3_rho2,p3_p2,T3_T2,p03_p02] =...
        obliqueshockfunct(theta,M2,gamma,R);
```

```

    %%% Check isentropic relations
    [T03_T3, P03_P3, Rho03_Rho3,~] = IsentropicPerfGas(M3, gamma);

    p_3 = p_2*p3_p2;
    p0_3 = p0_2*p03_p02;

%     test21=p_3/p0_3
%     test22=1/P03_P3

    % shock reflections relations matrix
    Amat = [ 1/tand(theta) -1/tand(Beta2-theta); 1 1];
    Bmat = [ height/tand(Beta1); height];
    Ymat = Amat\Bmat;          % 2x1 matrix with height of the ramp in row 1 and the opening in row
2

    y1 = Ymat(1);
    y2 = Ymat(2);

    if M3>1
        % Reflection Shock intersects ramp (location of normal shock)
        x_it = Ymat(1)/tand(theta);

        %%% Normal Shock on crest of ramp
        [Beta3,Mf,rhof_rho3,pf_p3,Tf_T3,p0f_p03] = ...
            obliqueshockfunct(0,M3,gamma,R);
        %%% Check isentropic relations
        [T0f_Tf, P0f_Pf, Rho0f_Rhof,~] = IsentropicPerfGas(Mf, gamma);

        p_f = p_3*pf_p3;
        p0_f = p0_3*p0f_p03;
%         Mf
%         M3
%         test31=p_f/p0_f
%         test32=1/P0f_Pf
    else
        Mf = M3;
        rhof_rho3 = 1;
        pf_p3 = 1;
        Tf_T3 = 1;
        p0f_p03 = 1;
    end
else
    Mf = M2;
    rho3_rho2 = 1;
    p3_p2 = 1;
    T3_T2 = 1;
    p03_p02 = 1;
    rhof_rho3 = 1;
    pf_p3 = 1;
    Tf_T3 = 1;
    p0f_p03 = 1;
    y1 = 0;
    y2 = height;
end

rhof_rhoi = rhof_rho3.*rho3_rho2.*rho2_rhoi;
pf_pi = pf_p3.*p3_p2.*p2_pi;
Tf_Ti = Tf_T3.*T3_T2.*T2_Ti;
p0f_p0i = pf_pi*P0f_Pf/P0_P; %p0f_p03.*p03_p02.*p02_p0i;

    %%% Inlet throat Properties
    T_it = Tf_Ti.*Ti;
    rho_it = rhof_rhoi.*rhoi;          % slug/ft^3
    p0_it = p0f_p0i.*p0i;
    p_it = pf_pi.*pi;
    [T0f_T_it, ~, rho0f_rho_it, ~] = IsentropicPerfGas(Mf, gamma);
    T0_it = T0f_T_it.*T_it;
    rho0_it = rho0f_rho_it.*rho_it;

    a_it = (gamma*R.*T_it).^(.5);

```

```

mdota = rho_it.*y2.*width.*Mf.*a_it; % slugs/sec
Voldot = mdota./rho_it;

%%% Intro to combustor

[T2_T_ic, T02_T0_ic, p2_p_ic, p02_p0_ic,...
 rho2_rho_ic, rho02_rho0_ic, M_ic] = ...
    IsentropicA(Mf, gamma, (y2*width), (height*width));

T_ic = T2_T_ic.*T_it;
rho_ic = rho2_rho_ic.*rho_it; % slug/ft^3
p0_ic = p02_p0_ic.*p0_it;
p_ic = p2_p_ic.*p_it;
T0_ic = T02_T0_ic.*T0_it;
rho0_ic = rho02_rho0_ic.*rho0_it;

```