Jet Aircraft Propulsion

Prof. Bhaskar Roy, Prof. A M Pradeep

Department of Aerospace Engineering,
IIT Bombay

Lecture 40

Performance of Ramjet Engines

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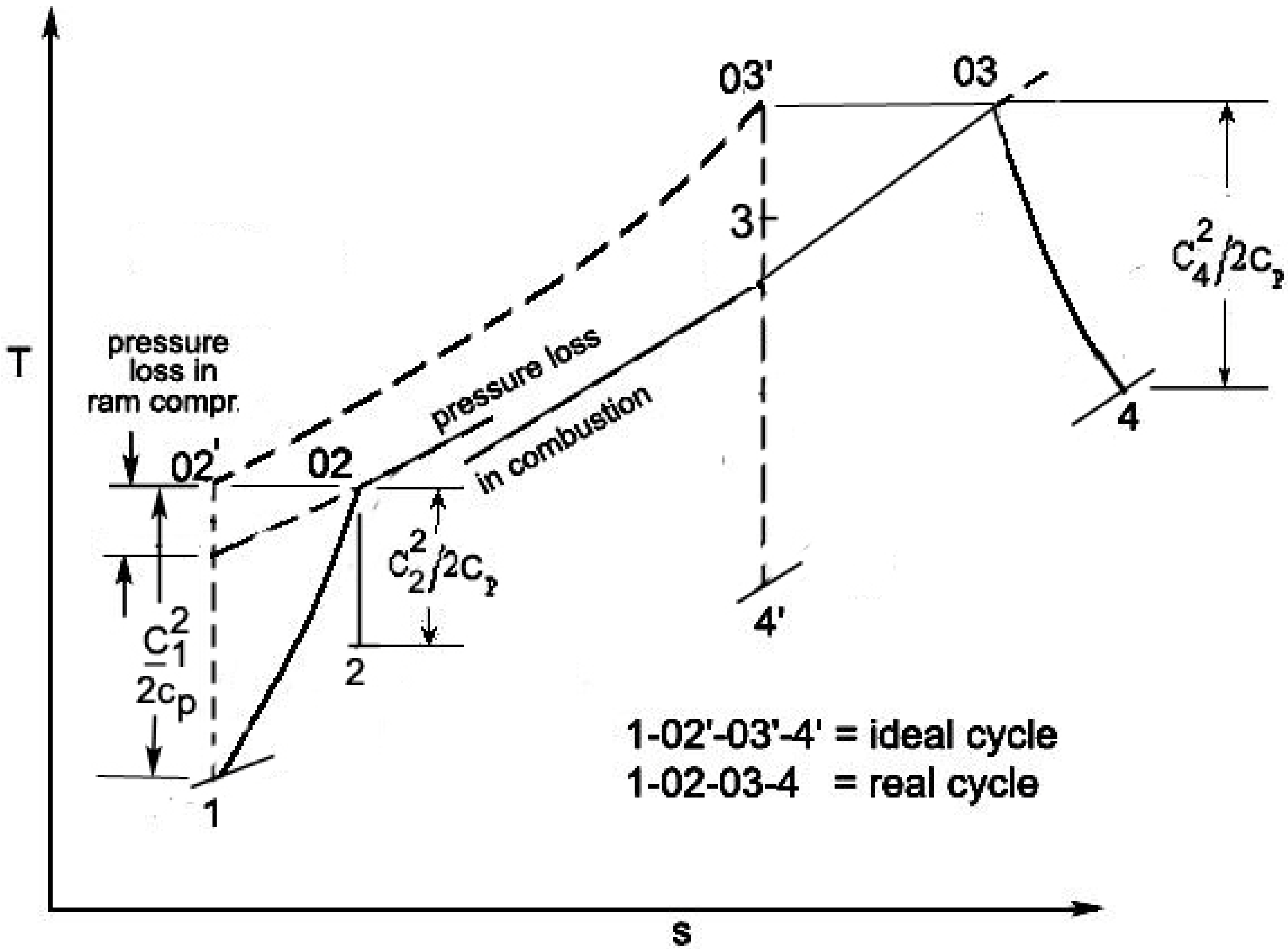
Ramjet Engine Thermodynamic cycle



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Performance Parameters

Thrust : Ramjet engine thrust is defined as the net change in total momentum as the working fluid passes through the engine.

The general expression for thrust,

$$F = \dot{m}(C_4 - C_1) + A_{e.}(P_e - P_a)$$

where P_e and P_a are the engine exit and ambient static pressures respectively

The general thrust equation may be modified to include fuel mass flow and then may be rearranged by substituting the mass flow term from the continuity condition,

$$F = \rho.V_a.A_1\left(\overline{m}.\frac{V_e}{V_a} - 1\right) + A_e p_a\left(\frac{p_e}{p_a} - 1\right)$$

Where, $\overline{m} = 1 + f$, f=fuel/air ratio, and A_1= Area of free stream air entering the engine

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Specific thrust may be written as :

$$\frac{F}{\dot{m}} = V_a \cdot \left(\overline{m} \frac{V_e}{V_a} - 1 \right) + \frac{A_e}{A_1} \cdot \frac{p_a}{\rho_a V_a} \cdot \left(\frac{p_e}{p_a} - 1 \right)$$

For a reasonable positive value of specific thrust to be achieved,

i) Either $V_e > V_a$ i.e. substantial acceleration through the engine needs to be accomplished,

ii) or $p_e > p_a$ i.e a substantial pressure (static) residual (at exit face) inside the engine

are required to be achieved.

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Specific fuel consumption :

The efficiency of an engine is expressed by its specific fuel consumption, which is defined generally under a specified operating condition, as :

$$sfc = \frac{\dot{m}_f}{F} = \frac{f}{F / \dot{m}_a}$$

Efficiency

The *thermal efficiency* of an engine represents the fraction of heat released in the combustion process that is converted to work (thrust work), and is a useful parameter for comparing various engine designs under standard operating conditions.

$$\eta_{th} = \frac{F.V_a}{f.\dot{m}_a.\dot{Q}_f}$$

where , $\dot{Q}_f$ = heating value of fuel, kJ/kg

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Design of a Ramjet

- Design of a ramjet engine and performance prediction involves estimation of pressures, temperatures, velocities and flow areas at the critical stations through the engine.
- Even though various analytical CFD techniques, including those incorporating reactive flow, have now come into use, it is still practical to start with an one-dimensional (constant flow properties across any passage area at any station) fluid flow theories.
- CFD techniques require a first cut geometry.
- Deviations from the one-dimensional flow may be corrected for with empirical correlations.

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In all the methods perfect gas law $p = \rho RT$, is valid as the equation of state --- for both fresh air and the combusted gas.

The energy equation may be expressed as :

$$h_a + \frac{V_a^2}{2} = h_b + \frac{V_b^2}{2} + Q$$

between any two points *a* and *b*.
And Q is the heat energy added
In between the two points.

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For a perfect gas undergoing an adiabatic process, this may, thus, be written as :

$$c_p T_a + \frac{V_a^2}{2} = c_p T_b + \frac{V_b^2}{2} = c_p T_0$$

where T_0 is the <u>total temperature</u> of the gas at that station.

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So that at any station ,

$$\frac{V^2}{2} = \int_{T}^{T_0} c_p \, dT$$

The exactness of the estimation of velocity depends on i) the method of estimation of c_p and on

(ii) the method of estimation or measurement of the average temperature at that station.

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(1) Varying specific heat method :

In the most exact method of computing energy content of a gas inside a ramjet engine, the energy equation is used by considering specific heat (at constant pressure) as :

$$c_p = k_0 + k_1 T + k_2 T^2 + k_3 T^3$$

and enthalpy change, $h = c_p dT$

which are then used with averaged temperature, T obtained either by analytical or empirical or experimental method.

(2) Average specific method :

As a first approximation, the specific heat is assumed to be an average value, which is constant across a process or a part of a process :

$$\frac{V^2}{2} = \int_T^{T_0} \bar{c}_p dT = \bar{c}_p (T_0 - T)$$

Where, $\bar{c}_p$ = average specific heat at a station

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(3) Arbitrary and/or constant specific heat method :

In these methods the specific heat values are considered to be constant, first arbitrarily held to be such that specific heat ratio $\gamma=1.4$ in air before the combustion and, $\gamma=1.3$ after the combustion process.
In a further simplification for quick first cut estimation $\gamma=1.4$, held constant across the entire engine, may be used for the engine performance prediction.

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Comparative discussion for design of an engine

- Comparison of these methods has shown that in a *subsonic* flow arbitrary specific heat method is useful for engineering approximations.
- But at *supersonic* flow conditions only the first two methods should be used for results within acceptable limits.
- Thus in a ramjet (or scramjet), where major portion of the flow is supersonic, last two methods can provide only approximate estimates.
- More accurate estimates shall require use of the first method in a scramjet.

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- Under 'design point' flow condition accurate analysis is desirable to arrive at or optimize the engine internal flow path geometry.
- On the other hand "off-design point" flow analysis is carried out with engine geometry already available.
- But a number of flow parameters may be unknown variables, requiring simpler approach at the initial stages of analysis, to be followed later on with more rigorous estimations (e.g. CFD).

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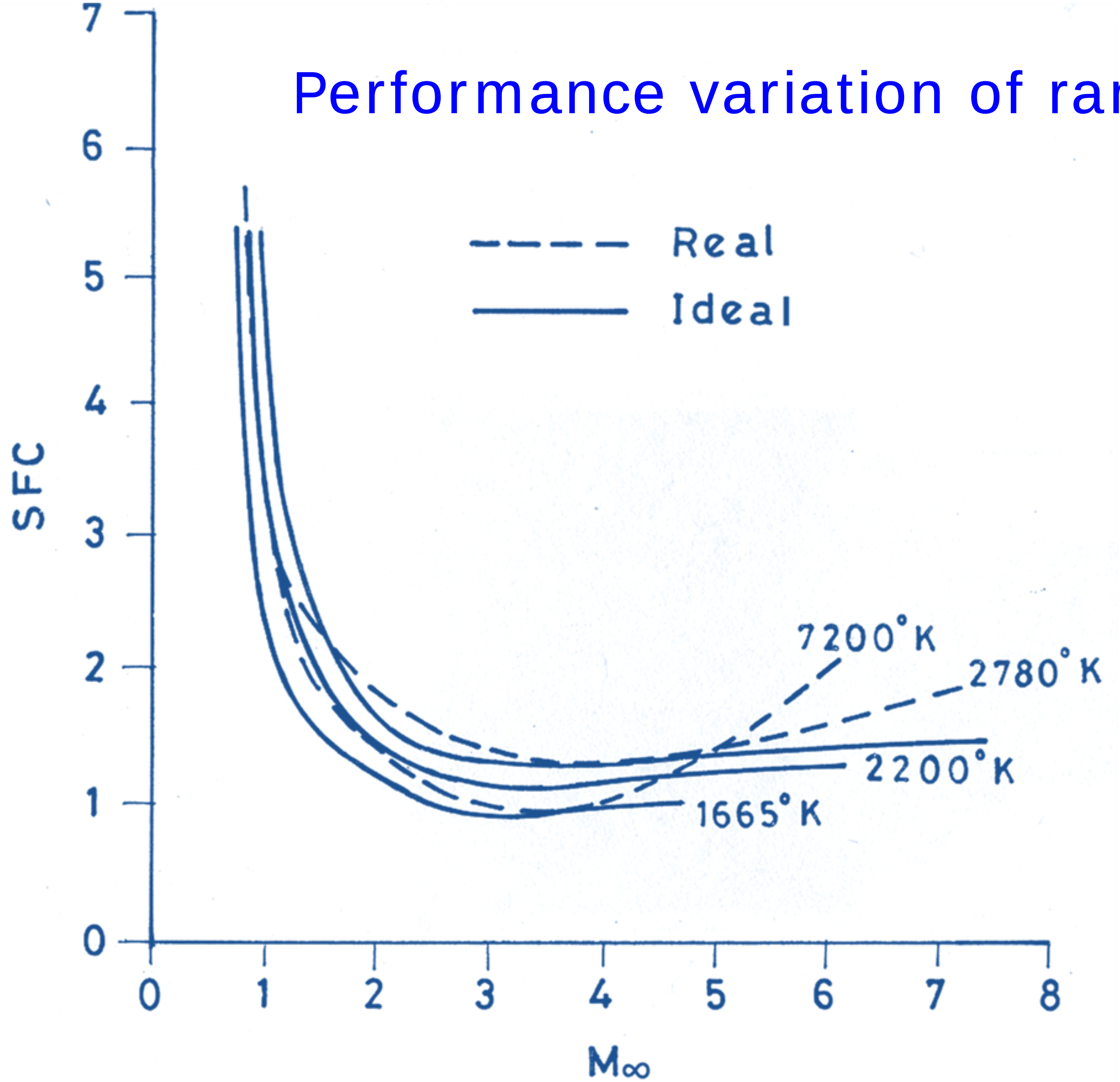
Performance variation of ramjet engine



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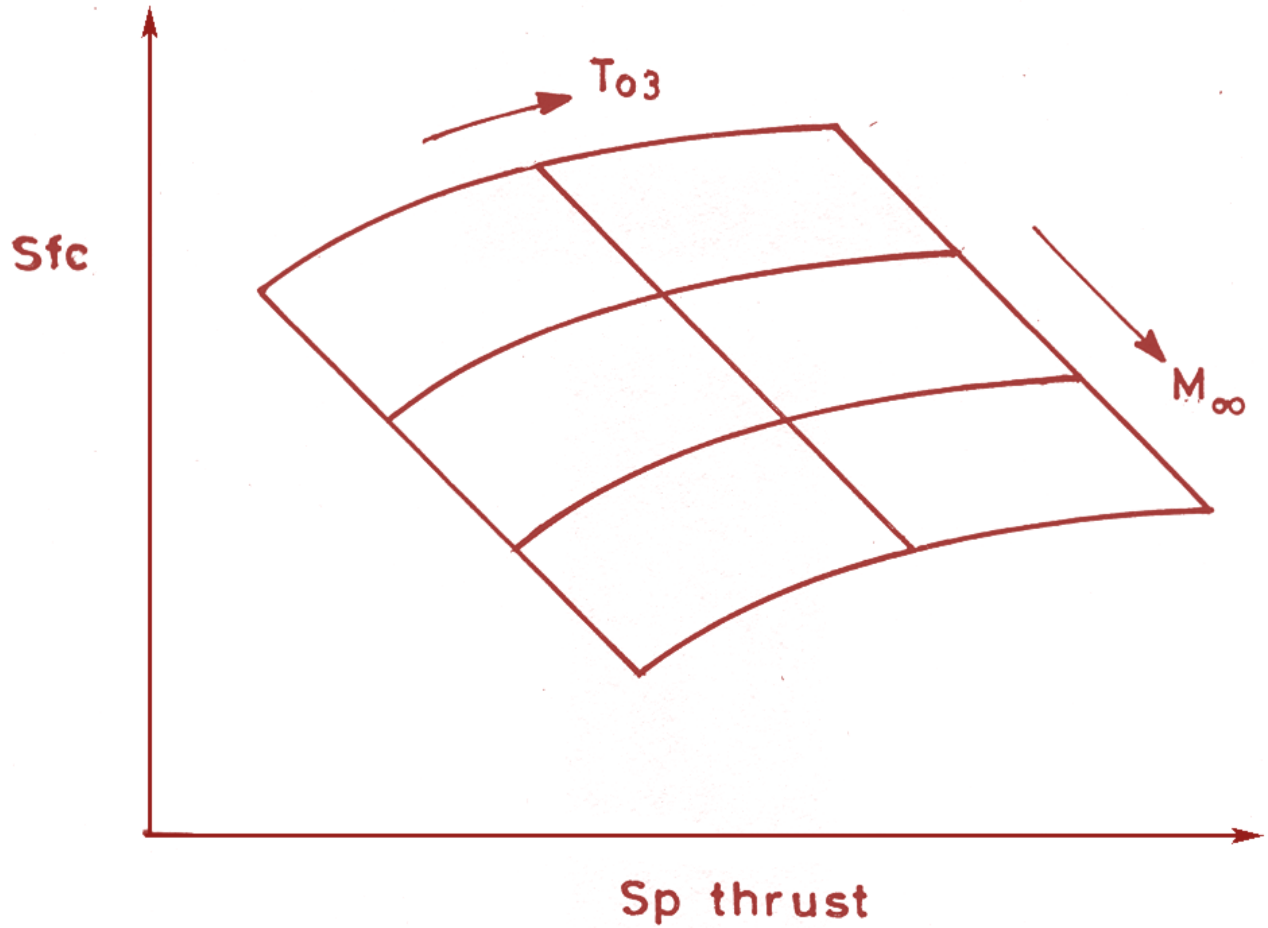

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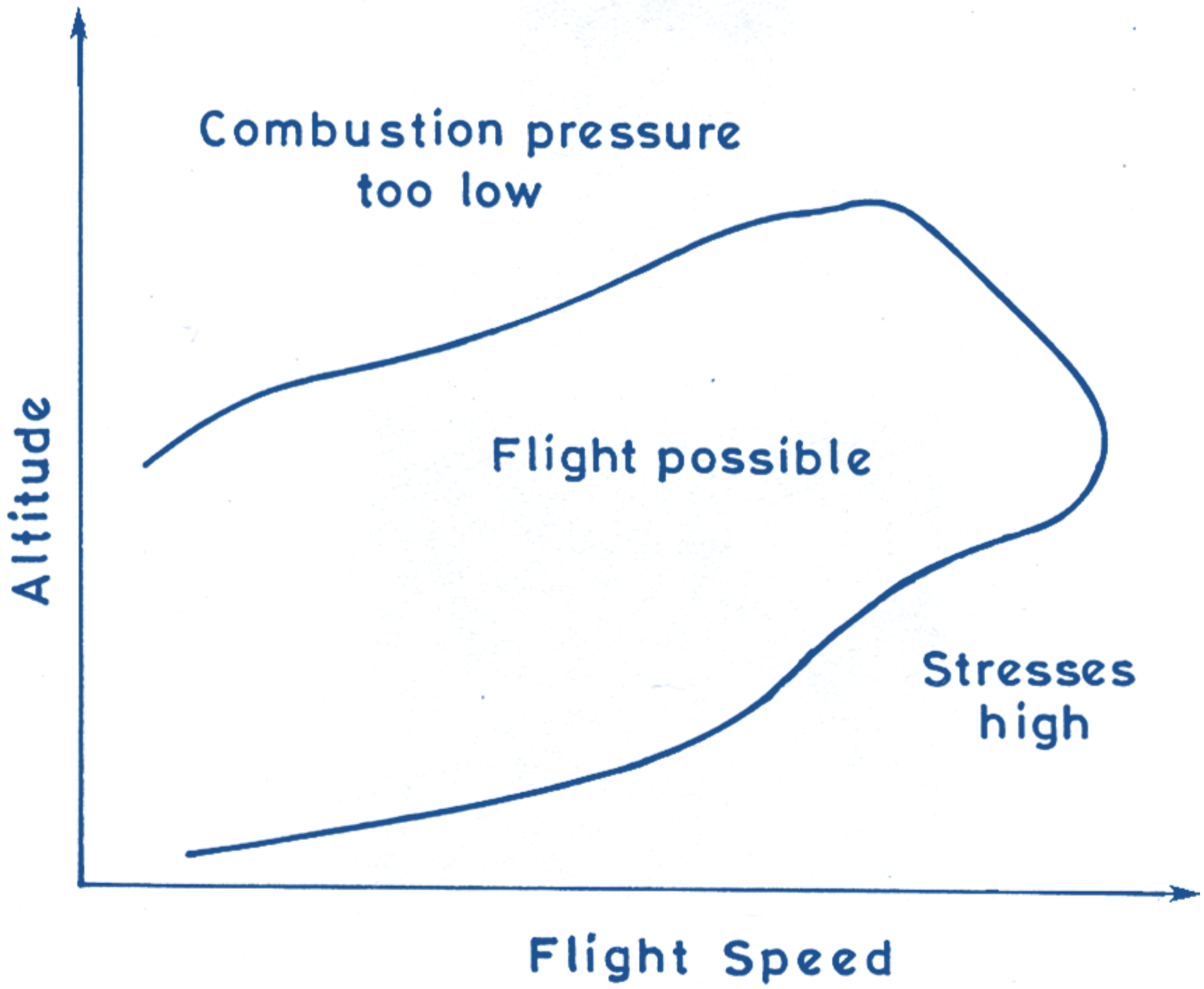
Performance variation of ramjet engine



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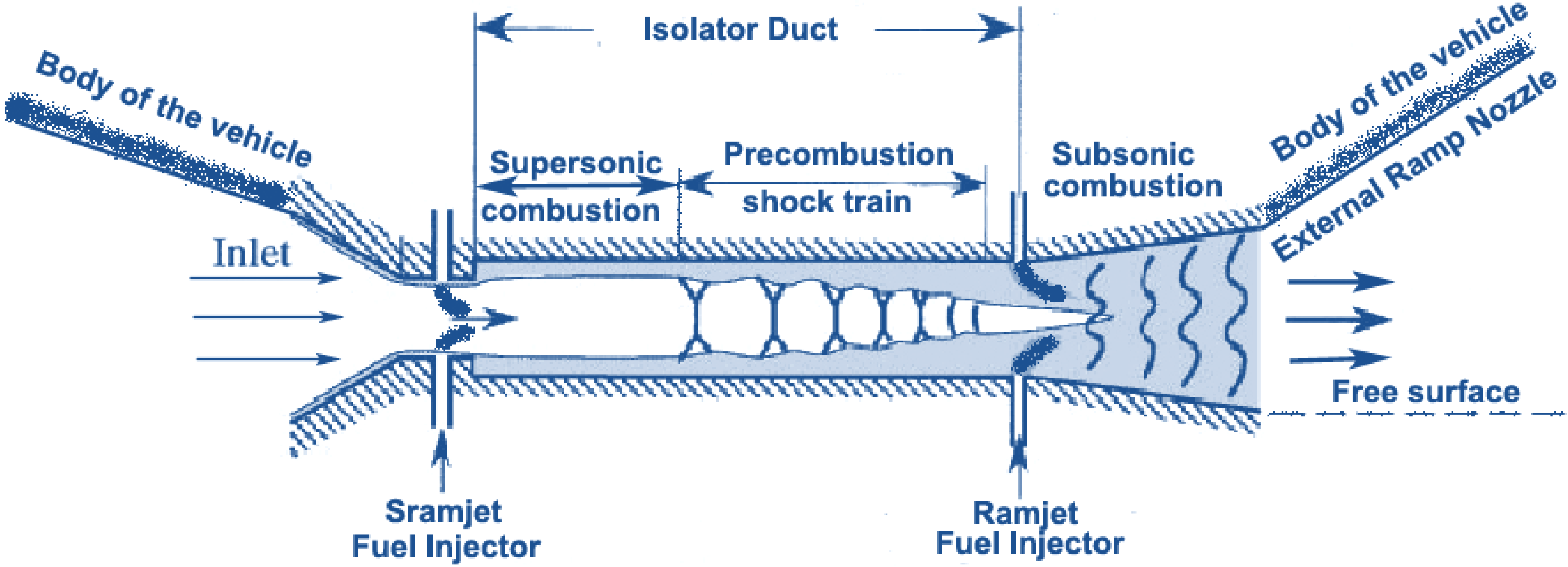
Typical Ramjet Engine (with Dual combustion – Sub and Supersonic Combustion)



Scramjet Powered Vehicle