High Speed Propulsion

KTH Rocket Course 2008

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What velocities?

Isaac Newton:
Law of gravity 1687

\[ g = g_0 \frac{R_0^2}{R^2} \]

\[ V = \sqrt{2gR} \]

11200 m/s
to leave earth.
Hyperbolic velocity.

Perigee

Apogee

Circular velocity 7900 m/s.
Mach 26.

\[ V_0 = \sqrt{gR} \]
The spaceplane would give more flexible space access. (Eugen Sänger and Irene Bredt 1944).

Wings and atmospheric oxygene
The SR71— the highest speed aircraft ever (Mach 3.2)

The limits of the turbojet engine

\[ F = \dot{m}(V_j - V) \]
The turbine inlet temperature limits the thrust. \[ \frac{F}{m a_0} = \sqrt{\frac{2}{\gamma - 1}} \left( \sqrt{T_{t4}/T_0} - 1 \right) \]
Efficiency %

Turboramjet

Max
TIT,\(M_{\text{tip}}\)

Throttling down \(T_{t3} = T_{cm}\)

Design point

Main fuel=0, \(\pi_c=1\)

Ramjet mode
(afterburner)

\[
\eta = \frac{FV}{m_f(h+V^2/2)}
\]

Close down the turbomachine at high speed
Supersonic fan for less inlet losses

Precooling for extended turbojet operation

LH2
The principle of a Pulse Detonation Engine (PDE)
V1-German WW1 pulsejet
Humphrey (PDE) constant volume combustion

Brayton (ramjet and turbojet)
Constant pressure combustion
PDE more efficient than ramjet – less fuel

\[ \eta = \frac{FV}{m_f h} \]

- High efficiency
- Light weight
- Simple

Fig. 18.4
PDE has take-off thrust \[ \eta / M_0 = \frac{F a_0}{m_f h} = \frac{I_s a_0}{h} \]

Same max speed:

\[ M_{\text{max}} = \sqrt{\frac{2}{\gamma - 1} \left( \frac{T_{ia}}{T_0} - 1 \right)} \]

where stagnation temp = combustion temp

Fig. 18.4
The idea of the scramjet

Increase $M_3$ to keep $T_3$ low to prevent dissociation (1560 K)

$$T_t = T_0 \left(1 + \frac{\gamma - 1}{2} M_0^2 \right) = T_3 \left(1 + \frac{\gamma - 1}{2} M_3^2 \right)$$

Scramjet $M_3 > 1$ if

$$M_0 > \frac{2}{\gamma - 1} \left(\left(\frac{\gamma + 1}{2}\right) \frac{T_3}{T_0} - 1\right)$$

= 6
US scramjet test hardware
The jet speed of a scramjet

Constant Mach in combustor

Kinetic efficiencies

\[ V_3 = V_0 \sqrt{\eta_{ki}} \]

\[ \frac{V_4}{V_3} = \frac{M_4 a_4}{M_3 a_3} = \sqrt{\frac{T_4}{T_3}} = \sqrt{\frac{T_{t4}^{t4}}{T_{t3}^{t3}}} \]

\[ V_j = V_0 \sqrt{\frac{T_{t4}^{t4}}{T_{t3}^{t3}}} \eta_{ki} \eta_{kc} \eta_{kn} \]
The scramjet performance

Jet speed:

\[ V_j = V_0 \sqrt{\frac{T_{t4}}{T_{t3}}} \eta_{ki} \eta_{kc} \eta_{kn} \]

Heat release:

\[ (1 + f) C_p T_{t4} - C_p T_{t3} = \eta_b fh \]

Specific thrust:

\[ \frac{F}{\dot{m}} = (1 + f)V_j - V_0 \]

Note max stoich f = 0.0291 for hydrogen

There is a max flight speed of the scramjet at F = 0
The maximum Mach number of the scramjet

\[ M_{\text{max}} = \sqrt{\frac{2}{\gamma - 1} \left[ \frac{\eta_b h f_s}{C_p T_0} - \frac{\eta_{ke} (1 + f)}{1 - \eta_{ke} (1 + f)} - 1 \right]} \]

Kinetic efficiency 65-75% gives max Mach number 10-15.

Run fuel rich to reach a higher Mach number:
The scramjet functions between Mach 6 and Mach 15

\[ \eta = \frac{FV_0}{mf (h + V_0^2 / 2)} \]

- Kin effic 90%
- 80%
- Fuel rich \( f = 2f_{\text{stoich}} \)

The efficiency of a Scramjet
Problems with the scramjet

Fuel injection shock waves

Incomplete combustion

Note: \[ \frac{M_3}{M_0} \approx \sqrt{\frac{T_0}{T_3}} \]

High combustor Mach numbers

Very sensitive to kinetic efficiencies

\[ V_j = V_0 \sqrt{\frac{T_{t4}}{T_{t3}} \eta_{ki} \eta_{kc} \eta_{kn}} \]
Scramjet powered spaceplane

Large intake with variable geometry
Potentially catastrophic thrust loss at large drag

Small specific thrust surplus

\[
\frac{F}{mV_0} = (1 + f)\sqrt{\eta_{ke} T_{t4}/T_{t0}} - 1
\]

Potentially catastrophic thrust loss at large drag
The rocket has a higher specific impulse than the scramjet engine over about Mach 15.

What about low speed propulsion?
Specific impulse for spaceplanes

$$I_s = \frac{F}{\dot{m}_p}$$
Heat protection is a big problem

Stagnation temperature and materials

Ceramics
Superalloys
Al
Ti
Tsiolkovsky equation with gravity and atmosphere

Ordinary Tsiolkovsky:

\[ \frac{m_c}{m_0} = e^{-V/I_s} \]

Modified for aero and gravity losses:

\[ \frac{m_c}{m_0} = 1 - \frac{m_p}{m_0} = \exp\left(-\int_0^V \frac{dV}{\eta_f I_s}\right) \]

Flight efficiency

Konstantin Tsiolkovsky
Flight efficiency

\[ \eta_f = \frac{1}{1 + \frac{D}{L} \left( \cos \alpha - \frac{V^2}{gR} \right) \frac{g}{a} + \frac{g}{a} \sin \alpha} \]

The Lift-to-Drag ratio decreases with speed

Conventional L/D = \(\frac{4(M+3)}{M}\)

Waverider L/D = \(\frac{6(M+2)}{M}\)
Spaceplane trajectory

Atmospheric pressure: \( \frac{p}{p_{sl}} = e^{-h/h_0} \) \( h_0 = 6670 \text{ m} \)

\[
q = \frac{1}{2} \rho V^2 = \frac{1}{2} \frac{p}{RT} V^2 = \frac{\gamma p}{2} M^2
\]

\[
M = \sqrt{\frac{2q}{\gamma p_{sl} e^{-h/h_0}}}
\]

Flight at constant dynamic pressure q
Ozon layer

Stratosphere

50 km

20 km

q=50 kPa

Rocket

Spaceplane and rocket trajectories

50 km

20 km

Stratosphere

Ozon layer
Effective average specific impulses

\[
\frac{V_0}{I_{eff}} = \int_{0}^{V_0} \frac{dV}{\eta_f I_s}
\]

Propulsion cycles for spaceplanes

- PDE
- Precooled Turboram (5730)
- Ramrocket (5480)
- Scram
- Rocket (3409)
% take-off weight to satellite orbit \[ \frac{m_c}{m_0} = e^{\frac{-V_0}{I_{\text{eff}}}} \]

- Turbo/Scram/Rocket
- Ramrocket
- Structure winged single stage
- Liquid rocket
- Solid rocket
- Single stage
- Structure rocket
- Stages: 1, 2, 3
- Payload %
- Effective specific impulse m/s

\[ \text{Effective specific impulse } = 2000 \text{, } 4000 \]

\[ \text{Take-off weight to satellite orbit} = 20\%, 10\% \]
A jumbo to space? Yes, but how?

I_s / V_0

Ideal engine \( \eta_e = 1 \)

PDE

Turboram

Scramjet

\[
I_s = \frac{F}{m_p} = \eta_e \left( \frac{h}{V} + \frac{V}{2} \right)
\]

\[
m_{pl} / m_0 \approx 0.4 \quad (\eta_e = \eta_f = 1)
\]

Limits to airbreathing propulsion

Mach
Electricity; Magnetohydrodynamics
The Soviet AJAX system

Magnetohydrodynamic airbreathing vehicle

Virtual nose

Ionized boundary layer

Electrical energy
Most powerful of all engines

Humming bird 300 W/kg.

Insect 60 W/kg.

Gripen 2500 W/kg.

Ariane 20000 W/kg.

Man 3 W/kg.