

Lecture 6

Rocket Engines

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Prepared by Colin Sledge

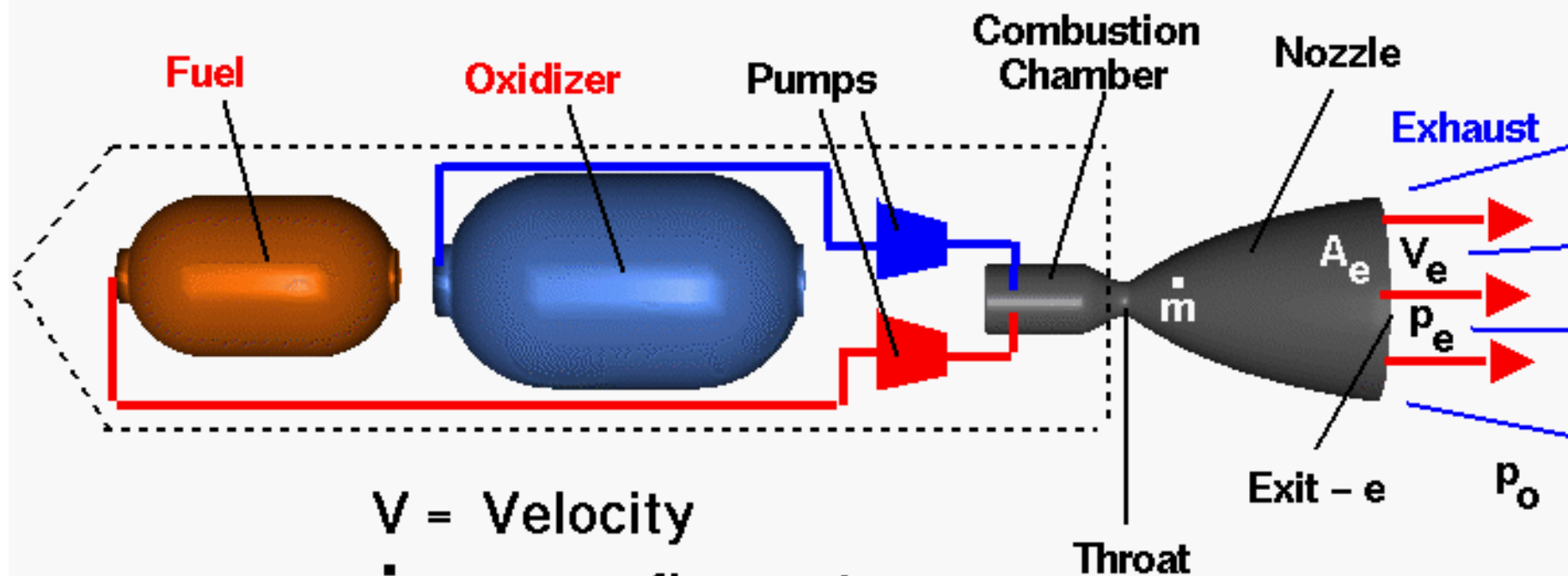
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Liquid Rocket Engine

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V = Velocity

\dot{m} = mass flow rate

p = pressure

$$\text{Thrust} = F = \dot{m} V_e + (p_e - p_o) A_e$$

Liquid Propellant Rocket Engine

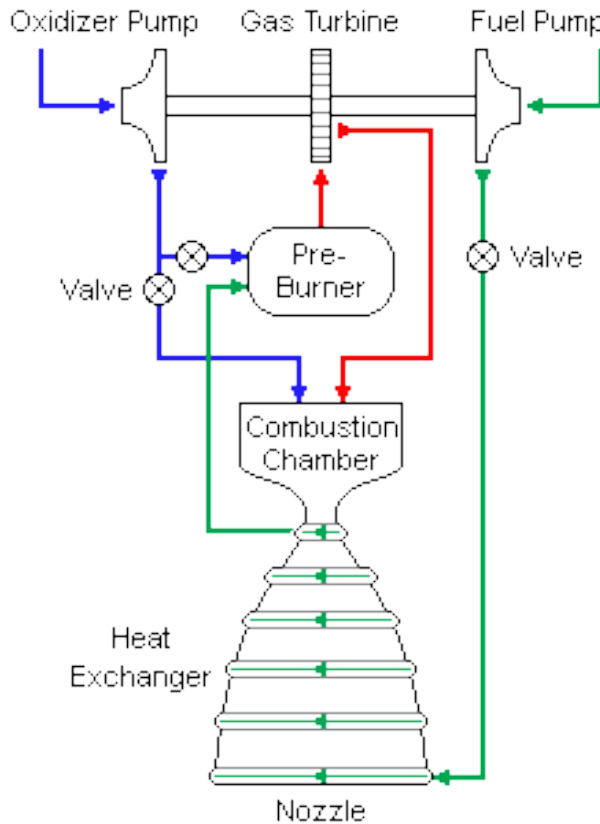
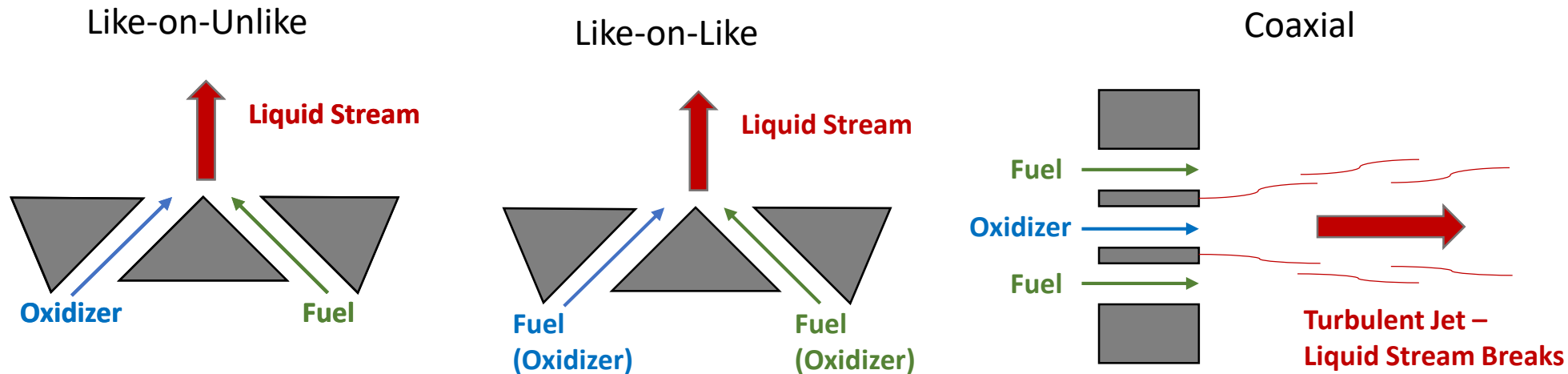


Fig. 1.9 - STAGED COMBUSTION

Liquid propellant rocket engine from Braeunig [1]

Liquid Propellant Rocket Engine

Different kinds of injectors



Formation of a spray maximizes surface area and thereby maximizes vaporization rate

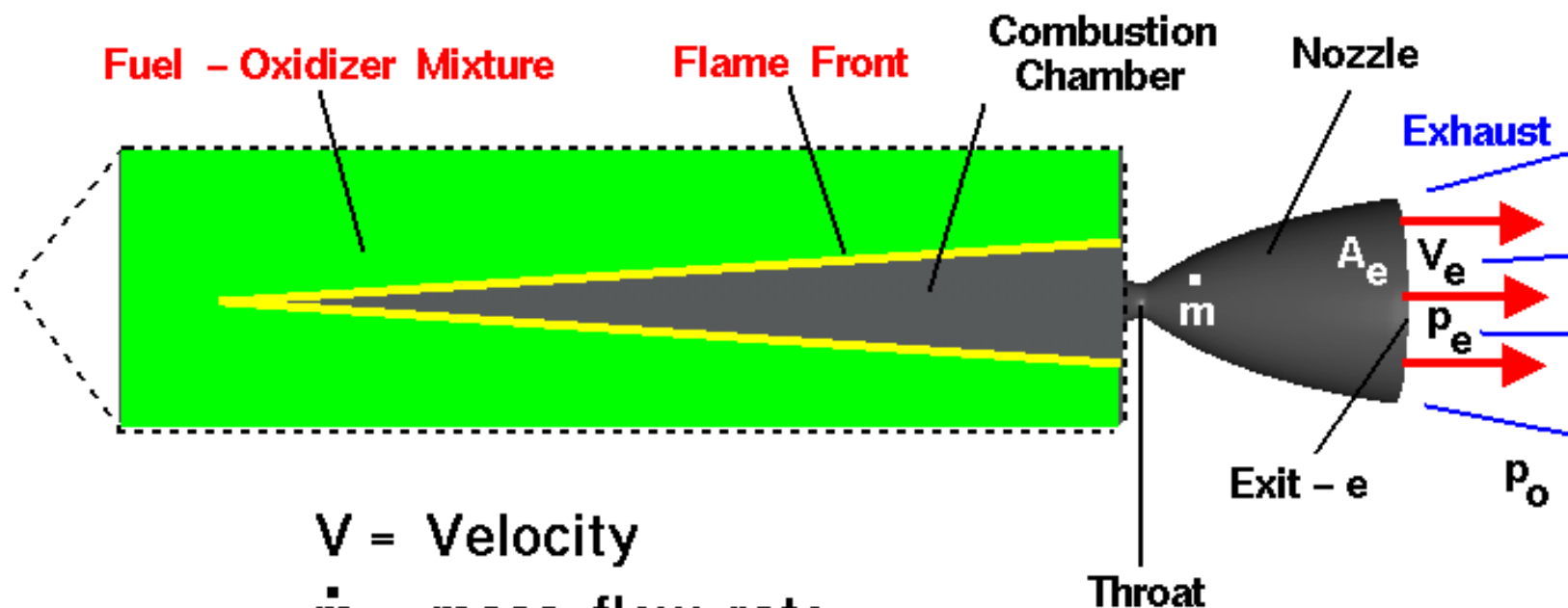
\dot{m}_d = the mass vaporization rate per droplet $\sim D \rightarrow D^{3/2}$ Droplet Diameter

$$N \sim \frac{1}{D^3} \quad \dot{m} = N\dot{m}_d \sim \frac{1}{D^2} \text{ to } \frac{1}{D^{3/2}}$$



Solid Rocket Engine

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V = Velocity

\dot{m} = mass flow rate

p = pressure

$$\text{Thrust} = F = \dot{m} V_e + (p_e - p_o) A_e$$

Solid Propellant Rocket Engine

Consider now a solid propellant rocket

Typically regression rate r of burning surface is given by: $r = aP^n$

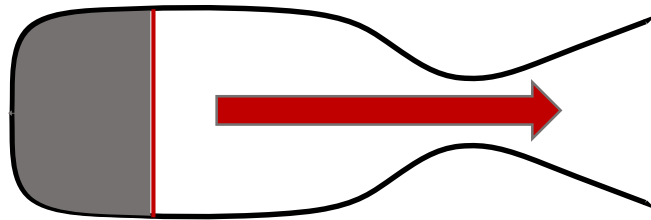
Mass burning rate: $\dot{m}_p = \rho_p r A_b$

A_b can depend upon time

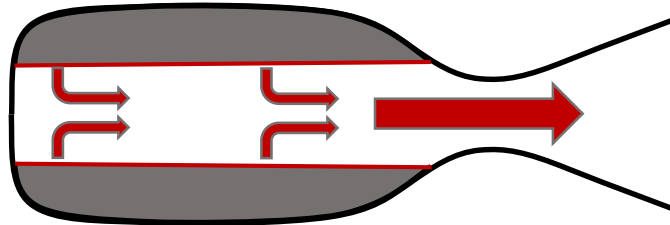
- ρ_p is propellant density (solid)
- A_b burn surface area

- P is pressure
- r is velocity
- a, n are constants

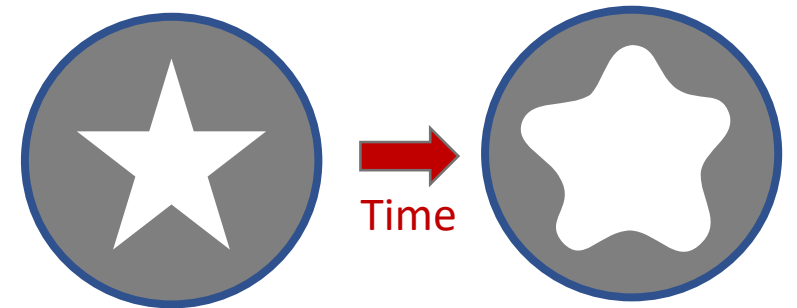
Mass burn rate = Mass flow thru the nozzle



End-Burning



Cylindrical Grain



Minuteman [ICBM missiles] had star-shaped channels for more uniform burning!
Many channels many nozzles

Attempt to keep A_b nearly constant with time!

Rocket Engine Example

Ammonium Perchlorate
 NH_4ClO_4

$$R = \frac{\Re}{mw} \quad \text{unit gas constant} \qquad \dot{m}_p = \dot{m} = P^\circ \frac{A^*}{c^*} \qquad \text{Where } c^* = \frac{\sqrt{RT^\circ}}{\Gamma(\gamma)} \approx \frac{\sqrt{RT}}{\Gamma(\gamma)}$$

$$\text{And } 1/mw = \sum_i (1/mw_i)(\rho_i/\rho) \quad ; \quad \Gamma = \sqrt{\gamma} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

Since the velocity in the combustion chamber is very low, in particular $M \ll 1$:

$$T^\circ \approx T \quad \text{and} \quad P^\circ \approx P$$

For a solid rocket:

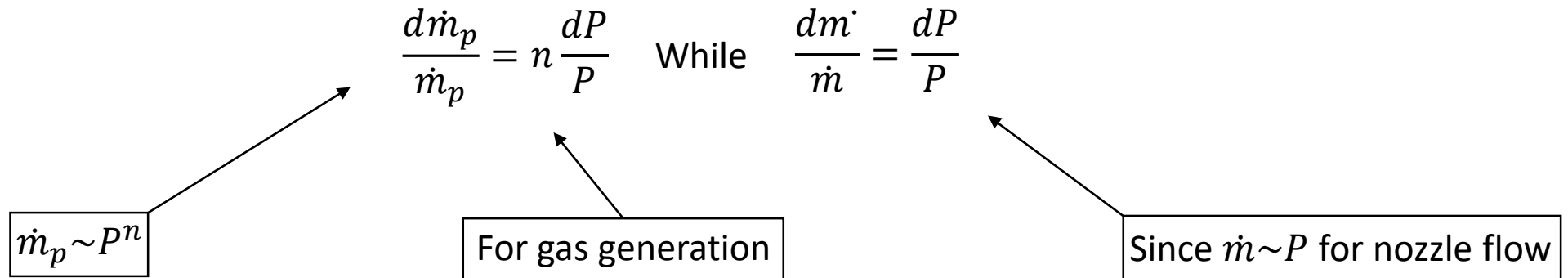
$$\rho_p A_b a P^n \approx P \frac{A^*}{c^*}$$

$$P^{1-n} = \left[a \rho_p c^* \frac{A_b}{A^*} \right]$$

$$P = \left[a \rho_p c^* \frac{A_b}{A^*} \right]^{\frac{1}{1-n}}$$

If $n > 1$, an unstable situation arises!

Rocket Engine Example



An increase in pressure causes \dot{m}_p to rise faster than \dot{m} , which cause accumulation of mass in the combustion chamber and further pressure rise. This eventually causes engine failure!

References

[1] Braeunig, R., 2020. *Basics Of Space Flight: Rocket Propulsion*. [online] Braeunig.us. Available at:
<<http://www.braeunig.us/space/propuls.htm?fbclid=IwAR2W5i0Ai7J7apvhk4WV0jysDbGte6hJC2nK4SH31mHlCnPbzatYiZYksp8>> [Accessed 20 July 2020].