Losses & Real Effects in Nozzles

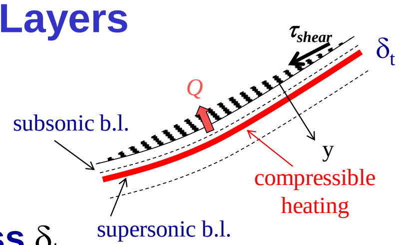
- Flow divergence ✓
- Nonuniformity ✓
- p_o loss due to heat addition
- Viscous effects
  - boundary layers-drag
  - boundary layer-shock interactions
- Heat losses
- Nozzle erosion (throat)
- Transients
- Multiphase flow
- Real gas properties
- Nonequilibrium flow

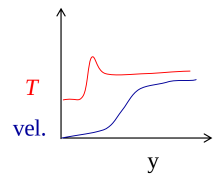
Small Combustion Chamber

- Combustion chamber area ratio
  - $\varepsilon_{cc} \equiv A_{cc}/A_t$
- If ε_{cc} < 3-4 then Mach number in combustion chamber too high and can result in significant p_o loss (Rayleigh flow)
  - ideal, constant area $$\underbrace{\frac{dp_o}{p_o}}_{<0} = \frac{-\gamma}{2} M^2 \underbrace{\frac{dT_o}{p_o}}_{>0}$$
  - e.g., for $\gamma=1.2$, $M=0.5$ pressure loss is ~15% of temperature increase
- Lower p_o means lower I_{sp} and less $\dot{m}$

Boundary Layers

- Flow near wall slower than freestream
  - also thermal b.l.
- **Displacement thickness δ_t**
  - one effect is less area available to freestream
  - e.g., $A_{effective} < A_{geom} \Rightarrow \dot{m}$ drop
  - can estimate from choked nozzle discharge coefficient





Displacement Thickness Estimate

- Choked nozzle discharge coefficient

$$C_D \equiv \frac{\dot{m}_{actual}}{\dot{m}_{ideal}} \cong \frac{A_{effect}}{A_t} = \left(\frac{R_t - \delta_t}{R_t}\right)^2$$

for $\delta_t / R_t << 1$

$$C_D \cong \left(\frac{R_t^{\,2} - 2R_t\delta_t}{R_t^{\,2}}\right)$$

$$\boxed{\frac{\delta_t}{R_t} \cong \frac{1 - C_D}{2}}$$

$$Re' = Re_t \sqrt{\frac{R_t}{R_1}}$$

Reynolds No. at throat

radius curvature at throat

Tang and Fenn, AIAA J **16,** 1978, p.41

$$C_D = 1 - \left(\frac{\gamma+1}{2}\right)^{3/4}\left[3.266 - \frac{2.128}{\gamma+1}\right]Re'^{-1/2} + 0.9428\frac{(\gamma-1)(\gamma+2)}{(\gamma+1)^{1/2}}Re'^{-1}$$

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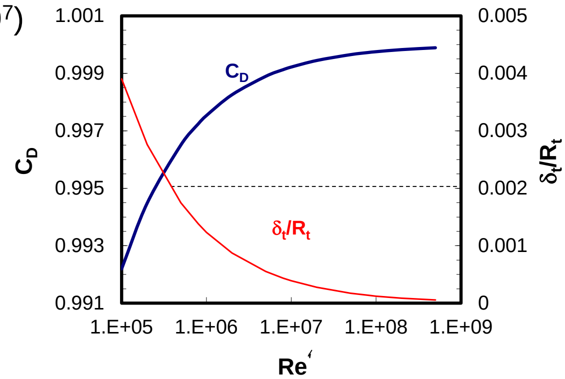
Displacement Thickness Example

- Typical values
  - H_2/O_2 products at 1000 psi, 2000 K (3140 F)
  - ν~6-7×10^{-6} m^2/s, γ~1.2, R_t/R_1~O(1), R_t~3"

    ⇒ Re'~O(10^7)
- C_D

  ⇒ small mass flowrate change
- δ_t<0.2%R_t even if Re'÷20 (p↑,R_t↓,…)

  ⇒ thin B.L. at throat



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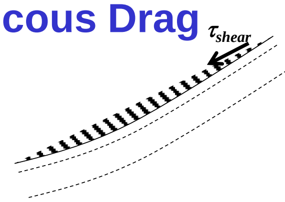
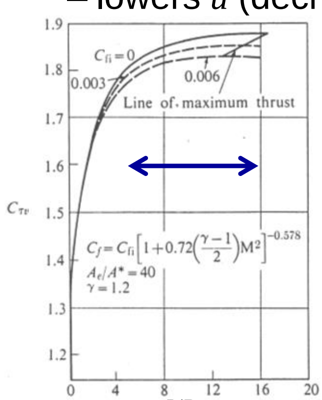
Boundary Layers – Viscous Drag



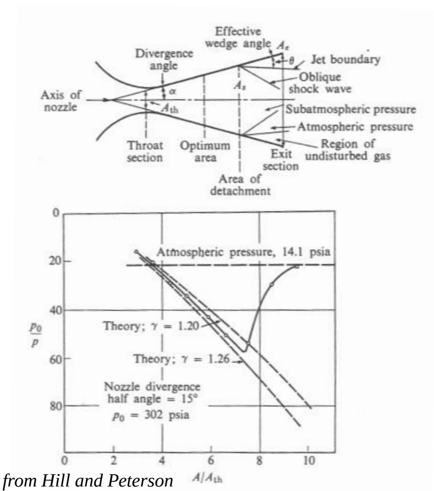
- Viscous drag at walls
  - lowers u (decreases p_o)



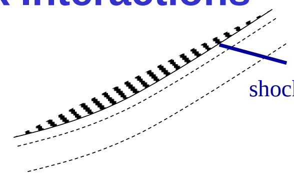
from Hill and Peterson L/D_t

  - usually small effect on axial thrust unless very long nozzle (usually τ << p)
  - result shown for truncated bell nozzle
    - < 1-1.5 % loss in τ, I_{sp}

Boundary Layers – Shock Interactions



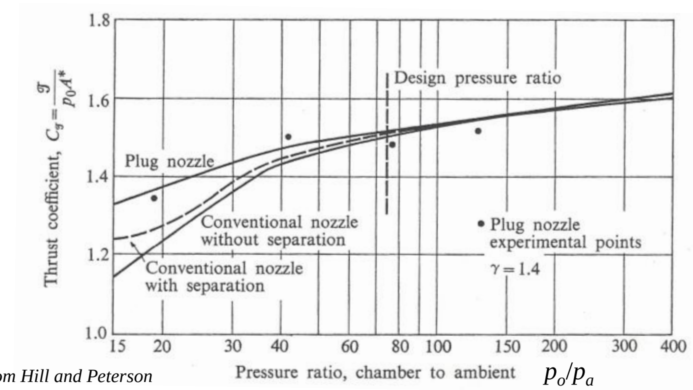
from Hill and Peterson



- Can lead to unsteadiness and flow separation
  - p_a information can propagate through subsonic b.l.
  - shock-induced b.l. separation

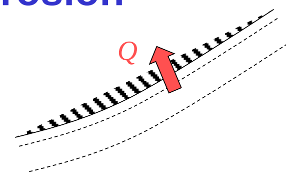
Boundary Layers – Shock Interactions

- Can improve c_τ for overexpanded bell nozzles by increasing pressure on nozzle walls



from Hill and Peterson

Heat Losses and Erosion



- Heat losses from nozzle will tend to lower u_e, I_{sp}
  - less enthalpy available for conversion to kinetic energy

$$u_e \propto \sqrt{h_o - h_e}$$

- Erosion (thermal and chemical) most significant near throat
  - highest temperature, harder to cool
  - will increase $\dot{m}$ with time, also reduces ε

Transient, Unsteady Flow

- Significant transients ($d/dt \neq 0$) tend to lower thrust of nozzle compared to steady value
  - unsteady pressure and mass flow rate
- Can occur during
  - start up, shut down
  - thruster pulsing
  - combustion instabilities in c.c.

Multiphase Flow

- Flow in nozzle includes condensed phases (liquid or solid) along with gas
  - Al_2O_3 in solid propellants, soot for HC fuels
  - condensation at low T for some propellants
- Condensed phases do not provide expansion (their density is ~constant)
  - lowers I_{sp} vs same mass of gas
- Larger loss if
  - volume fraction of particles ↑
  - size of particles ↑
    1. particles lag gas, drag on gas
    2. slower to give up their thermal energy
- But…can increase $\dot{m}$