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
  - $\varepsilon_{cc} \equiv \frac{A_{cc}}{A_t}$
- If $\varepsilon_{cc} < 3-4$ then Mach number in combustion chamber too high and can result in significant $p_o$ loss (Rayleigh flow)
  - ideal, constant area
  - 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 $m$
Boundary Layers

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

Displacement Thickness Estimate

- Choked nozzle discharge coefficient

\[
C_D = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{ideal}}} \approx \frac{A_{\text{effect}}}{A_t} = \left( \frac{R_t - \delta_t}{R_t} \right)^2
\]

for $\delta_t/R_t \ll 1$

\[
C_D \approx \frac{R_t^2 - 2 R_t \delta_t}{R_t^2}
\]

\[
\frac{\delta_t}{R_t} \approx 1 - C_D \frac{1}{2}
\]

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

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

- Typical values
  - $\text{H}_2/\text{O}_2$ products at 1000 psi, 2000 K (3140 F)
  - $\nu \approx 6-7 \times 10^{-6} \text{ m}^2/\text{s}$, $\gamma \approx 1.2$, $R_t/R_1 \approx \mathcal{O}(1)$, $R_t \approx 3''$
  - $Re' \approx \mathcal{O}(10^7)$

- $C_D$
  - small mass flowrate change

- $\delta < 0.2\% R_t$
  - even if $Re' \approx 20$
  - $\rho, R_t, \ldots$
  - $\Rightarrow$ thin B.L. at throat

Boundary Layers – Viscous Drag

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

- usually small effect on axial thrust unless very long nozzle
  - (usually $\tau \ll p$)

- result shown for truncated bell nozzle
  - $< 1-1.5\%$ loss in $\tau, I_{sp}$
• Can lead to unsteadiness and flow separation
  – $p_a$ information can propagate through subsonic b.l.
  – shock-induced b.l. separation

• Can improve $c_T$ for overexpanded bell nozzles by increasing pressure on nozzle walls
Heat Losses and Erosion

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

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

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

Transient, Unsteady Flow

- Significant transients ($dl/dt \neq 0$) 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
  - \( \text{Al}_2\text{O}_3 \) in solid propellants, soot for HC fuels
  - condensation at low \( T \) for some propellants
- Condensed phases do not provide expansion (their density is \( \sim \)constant)
  - lowers \( I_{sp} \) vs same mass of gas
- Larger loss if
  - volume fraction of particles \( \uparrow \)
  - size of particles \( \uparrow \)
- But...can increase \( m \)
  1. particles lag gas, drag on gas
  2. slower to give up their thermal energy