Rocket Propulsion

Heat Transfer in an LRE TCA

Thrust Chamber Assembly (TCA)

- C.C. + nozzle
  - **exposed to high temperatures and high pressures**
- To minimize weight, TCA walls must be relatively light
  - thin but with sufficient strength at high temperatures to withstand structural loads
  - **generally requires cooling**

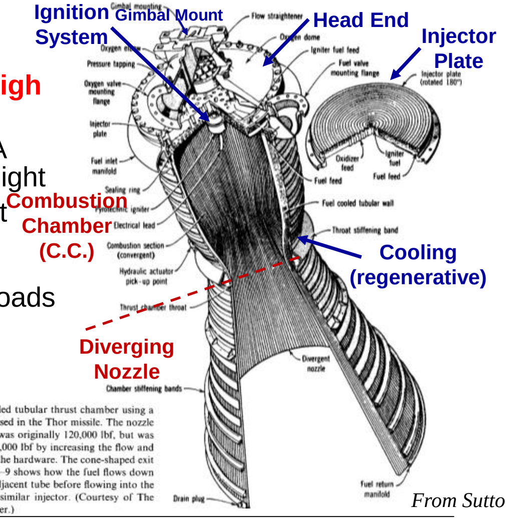


FIGURE 8–1. Construction of a regeneratively cooled tubular thrust chamber using a kerosene-type fuel and liquid oxygen, as originally used in the Thor missile. The nozzle inside diameter is about 15 in. The sea-level thrust was originally 120,000 lbf, but was uprated to 135,000, then 150,000, and finally to 165,000 lbf by increasing the flow and chamber pressure and strengthening and modifying the hardware. The cone-shaped exit cone was replaced by a bell-shaped nozzle. Figure 8–9 shows how the fuel flows down through every other tube and returns through the adjacent tube before flowing into the injector. Figure 8–4 shows the flow passages in a similar injector. (Courtesy of The Boeing Company, Rocketdyne Propulsion and Power.)

From Sutton

TCA Cooling Approaches

- Ways to keep TCA wall from getting too hot, lower strength
- **Regenerative Cooling**
  - flow cold fluid (propellant) along outside of wall
- **Ablative Cooling**
  - vaporizing thin layer of wall material on inner side absorbs lots of energy
- **Radiation Cooling**
  - hot outer wall radiates energy (to environment)
- **Film/B.L. Cooling**
  - inject cold fluid (propellant) along inner wall to shield it from hot gases

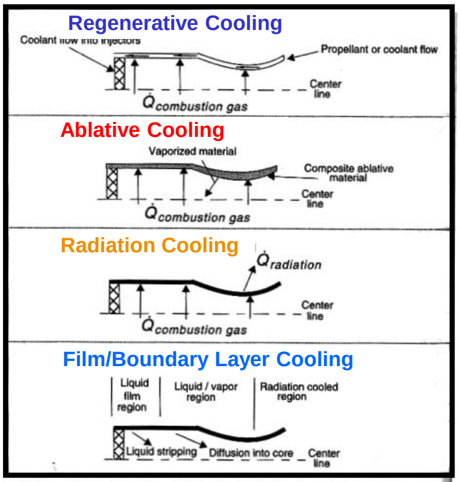
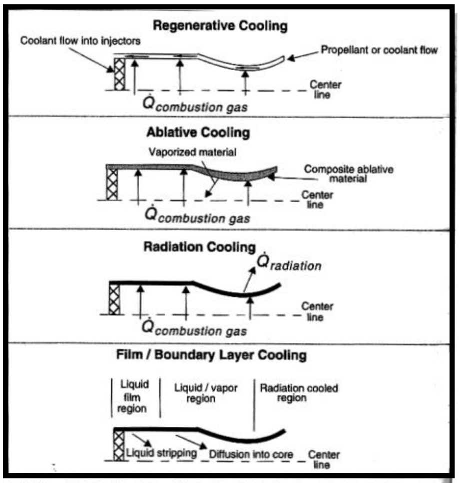


Fig. 5.28. **Sketch of Techniques for Cooling the Combustion Chamber.** This figure shows each of the cooling techniques work [$\dot{Q}$ = heat flow (W)]. *From Humble*

TCA Cooling Approaches

- What needs most cooling?
  - **C.C.**: hottest, highest p
  - **nozzle throat**: hot and highest heat flux ($\dot{Q}/A$)
- **LREs**
  - usually employ regen. cooling for most of TCA
  - film cooling often used in c.c. near injector plate
- **SRMs**
  - primarily use ablative cooling
  - propellant in C.C.; throat region, e.g., graphite
- Smaller **in-space** systems might rely on radiation cooling



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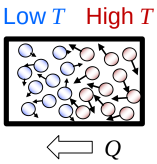
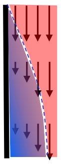
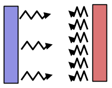
Heat Transfer Modes

- Heat transfer is transport of “thermal” energy between “systems”; 3 modes

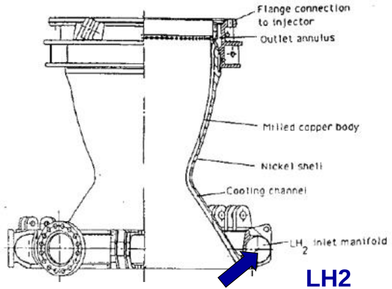
1. **Conduction** $\dot{q} = \dot{Q}/A = -k\,\nabla T$
   - molecules “collide” with each other; “fast”/hot molecules transfer energy to “slow”/cold ones
   - occurs in all substances
2. **Convection** $\dot{q} = h\,(T_f - T_s)$
   - conduction occurring alongside transport of mass due to flow
   - occurs in “fluids”, usually to or from solid
3. **Radiation**
   - energy transported as electromagnetic waves/photons
   - substances can **absorb, emit**, transmit and reflect radiation
   - hot objects emit more and at higher frequencies







LRE Regenerative Cooling

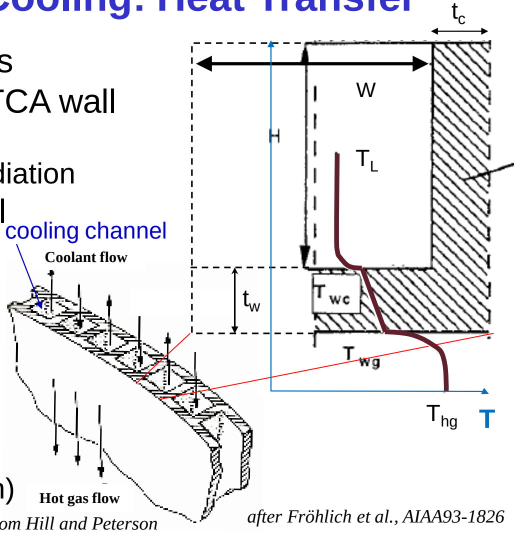


From Fröhlich et al., AIAA93-1826

- Vulcain (LH2/LOX) example
  - liquid H_2 used to cool walls
  - flowed through closely arranged small tubular cooling channels within combustion chamber wall

Regenerative Cooling: Heat Transfer

- Heat transfer occurs
  - from hot gas to TCA wall
    - $T_{hg} \rightarrow T_{wg}$
    - convection + radiation
  - through TCA wall
    - $T_{wg} \rightarrow T_{wc}$
    - conduction
  - from TCA wall to low T coolant
    - $T_{wc} \rightarrow T_L$
    - convection
    - (can usually neglect radiation)

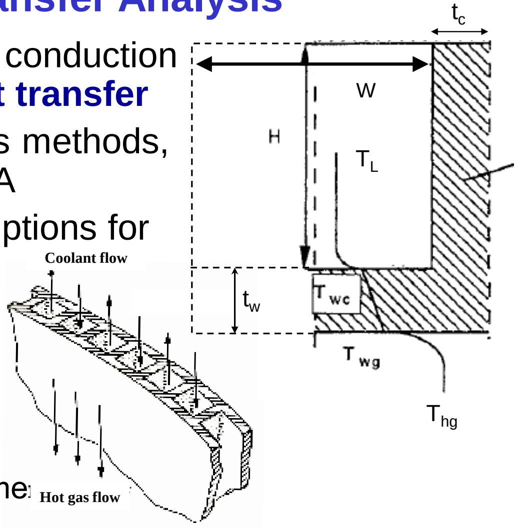


from Hill and Peterson

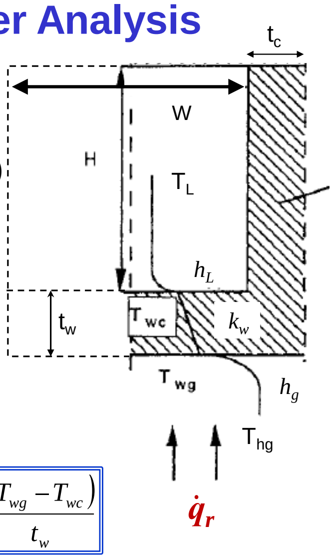
after Fröhlich et al., AIAA93-1826

Heat Transfer Analysis

- Convection + wall conduction
  ≡ **conjugate heat transfer**
- Advanced analysis methods, e.g., CFD and FEA
- Simplifying assumptions for 1st order analysis
  - 1-d
    - large H/t_w
    - $H/W > 1$
  - steady
    - “long” thrust time



Simplified Heat Transfer Analysis



- 1-d, **steady** analysis, no backside (rad.) cooling

$$\dot Q = A_{wg}\left[h_g\left(T_{hg}-T_{wg}\right)+\dot q_r\right] = -k_w A_{wg}\frac{dT_w}{dx} = h_L A_{wc}\left(T_{wc}-T_L\right)$$

  - $h \equiv$ convective heat transfer coeff.
    $k_w \equiv$ thermal conductivity of wall

- If side walls "thin", $t_c << W$

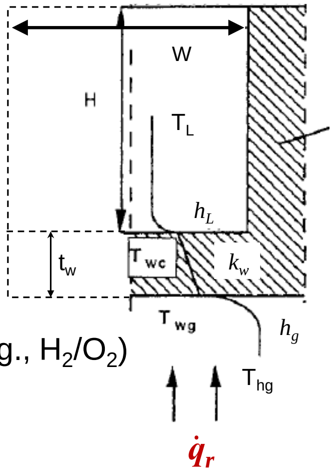
$$\dot q = h_g\left(T_{hg}-T_{wg}\right)+\dot q_r = -k_w\frac{dT_w}{dx} = h_L\left(T_{wc}-T_L\right)$$

  - $\dot q \equiv$ heat flux (per unit area)

- For uniform (composition) walls and 1-d

$$\boxed{\dot q = -k_w\frac{dT_w}{dx} \cong k_w\frac{\left(T_{wg}-T_{wc}\right)}{t_w}} \qquad \textbf{(IV.31)}$$

Simplified Heat Transfer Analysis



- Solution
  - heat flux from combustor

$$\boxed{\dot q = \frac{T_{hg}-T_L+\dot q_r/h_g}{1/h_g+t_w/k_w+1/h_L}} \qquad \textbf{(IV.32)}$$

  - hot-side wall temperature

$$T_{wg} = T_{hg}-\left(\dot q-\dot q_r\right)/h_g$$

  - if radiation to wall is small
    - no particles (non-sooting, e.g., H_2/O_2)

$$\boxed{T_{wg} = T_{hg}-\frac{T_{hg}-T_L}{1+t_w h_g/k_w+h_g/h_L}} \qquad \textbf{(IV.33)}$$

Want this term to be large ⇒ cooler wall

Reducing Hot Wall Temperature

$$\Uparrow \quad \frac{T_{hg} - T_L}{1 + t_w h_g / k_w + h_g / h_L}$$

- Low temp. coolant (T_L)
  - in combustion chamber, $T_{hg} >> T_L$ (e.g., 3000K vs 100-250K), so small changes in T_L have small effect
- High conductivity wall material (k_w)

Material	k (Wm^{-1}K^{-1}) @ 1000°C	σ_y (MPa)
Nickel Super Alloy	20-30	>500 @ 600°C
Copper	350	70 @ 20°C

- Thin walls (t_w)
  - structural limits

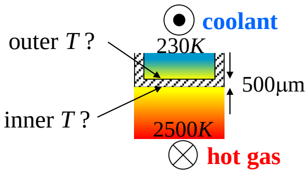
$$t_w \geq p_{o,cc} D_{cc} / 2\sigma_{\max}$$

$\sigma_{\max}$ = maximum allowed wall stress (< σ_y)

- Low ratio h_g/h_L
  - reduce rate to hot wall, increase from cold wall

Heat Transfer Example

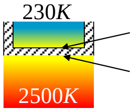
- **Given**:
  - location within TCA where hot propellant gas is at 2500 K; coolant flow at 230 K; TCA wall of thickness 500 μm and thermal conductivity 250 W/mK; hot-side heat transfer coefficient of 9.0 kW/m^2K; h_g/h_L = 0.17
- **Find**:
  - inner and outer wall temperatures
- **Assume**:
  - steady, 1-d analysis okay



Heat Transfer Example

- **Analysis**:
  - T_{wg} = 589 K
  - T_{wc} = 555 K

thin walls, high conductivity
⇒ small ΔT across wall



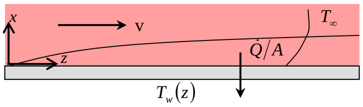
678K

710K

for h_L↓, T_w↑:
$h_g/h_L = 0.17 \rightarrow 0.25$

Convective Heat Transfer Coefficients

- So to solve heat transfer problem need information on the convective heat transfer coefficients
- Recall, convective heat transfer
  - due to fluid moving over surface
  - thermal boundary layer develops, similar to momentum boundary layer



$\tau_{shear} = \tau_{shear}(Re_z)$

Reynolds number

- Conv. heat transfer coefficient h=h(Re_z, Pr)
  - since $Re_z \propto z$
    T_w varies downstream

Prandtl number

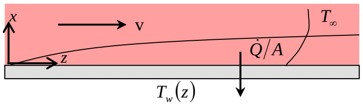
$Pr \equiv \nu/\alpha$

Thermal diffusivity

Kinematic Viscosity

$\alpha \equiv k/\rho c_p$

Convective Heat Transfer Correlations



- Heat transfer coefficients for specific geometries typically given in terms of correlations of related parameters
- **Stanton number** $$\boxed{St \equiv \frac{h}{\rho u c_p}}$$ **(IV.34)**
- **Nusselt number** $$\boxed{Nu_\ell \equiv \frac{h\ell}{k}}$$

Dimension, e.g., *z*

gas prop's. (ρ, u, …) often evaluated at freestream conditions

$$\Rightarrow Nu = St\frac{u\ell}{\alpha} = St\frac{u\ell}{\nu}\frac{\nu}{\alpha}$$

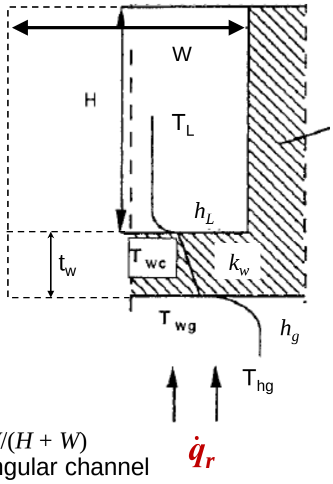
$$\boxed{Nu = StRe_\ell Pr}$$

(IV.35)

- Example correlation for flat plate, laminar (subsonic) flow

$$St = 0.332Re_z^{-1/2}Pr^{-2/3} \;\Rightarrow Nu_z = 0.332Re_z^{1/2}Pr^{1/3}$$

Correlations for LREs



- Correlations (semi-empirical) available for rocket (LRE) type geometries and conditions (e.g., compressible flow)
- Hot gas side, Bartz correlation*

$$Nu_D \propto Re^{0.8}Pr^{0.4}$$

diam of TCA at given axial location

- Coolant side, typical to use correlations for fully-developed turbulent flow in a channel

$$Nu_{D_H} \propto Re^{0.8}Pr^n \qquad n = 0.33\text{-}0.37$$

hydraulic diam of cooling channel

$D_H = 2HW/(H + W)$ for rectangular channel

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*D.R. Bartz in *Advances in Heat Transfer, Vol. 2*, Hartnett and Irvine Ed. (1965)

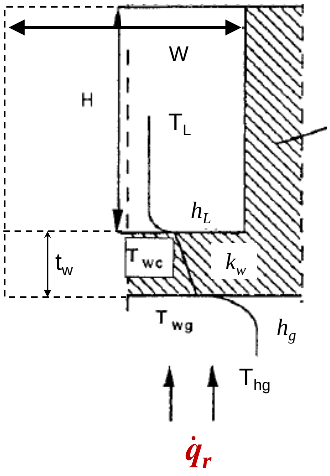
Summary of Heat Transfer Analysis

- From IV.31-33 (negl. rad.)

$$\dot{q} = \frac{T_{hg} - T_L}{1/h_g + t_w/k_w + 1/h_L} = k_w \frac{\left(T_{wg} - T_{wc}\right)}{t_w}$$

$$T_{wg} = T_{hg} - \frac{T_{hg} - T_L}{1 + t_w h_g/k_w + h_g/h_L}$$

- If fluid temperatures (T_{hg}, T_L) wall properties (t_w, k_w) and h values known
  - can get hot and cold side wall temperatures



General Trends

$$\dot{q} = \frac{T_{hg} - T_L + \dot{q}_r/h_g}{1/h_g + t_w/k_w + 1/h_L}$$

$$T_{wg} = T_{hg} - \frac{T_{hg} - T_L}{1 + t_w h_g/k_w + h_g/h_L}$$

- Combustor walls typically made of thin material with high thermal conductivity
  - $(T_{wg} - T_{wc}) << (T_{hg} - T_L)$
- Typical h_g/h_L ~ O(10^{-2}–10^{-1})
- High h_L will reduce wall T's
  - fins, roughness, small coolant tubes or more coolant flow $h_L \propto \dot{m}_L/D^{1.8}$
  - tends to lower T_w's without large change in $\dot{Q}$
- Low h_g will decrease $\dot{Q}$ to wall, so also reduce T_w's
  - smooth inner combustor, keep boundary layer thick
  - primary influence on $\dot{Q}$ (w/o rad.)