Lecture 8: Engine Cooling

Types of Heat Transfer

Conduction: heat transfer inside a material

$$q = -\frac{k}{d}(T_2 - T_1) \cdot A = Q$$

Convection: heat transfer between a stationary and moving material

$$q = h(T_{adiab,wall} - T_s)$$

Radiation: heat transfer from electromagnetic emission of particles

$q_{rad} = \sigma \varepsilon$ [redacted] $F_{ij}(T_i^4 - T_j^4)$

C 1

Cooling Schemes for Rocket Engines

Can design for one or multiple cooling schemes. All present different design criteria for effective cooling

Heat Sink Cooling: Chunky engine with large wall thickness. Heat from chamber "sinks" into cooler material that is further out

Radiative Cooling: Thin-walled engine with higher temperature, allowing for large radiative heat flux into the atmosphere.

Regenerative Cooling: Feed the fuel/oxidizer into channels that line the chamber wall before entering the combustion chamber.

Film Cooling: Divert some amount of fuel or oxidizer to be injected along the inner chamber wall, providing film of coolant.

$$\alpha = \frac{k}{\rho c}$$

Heat Sink Cooling

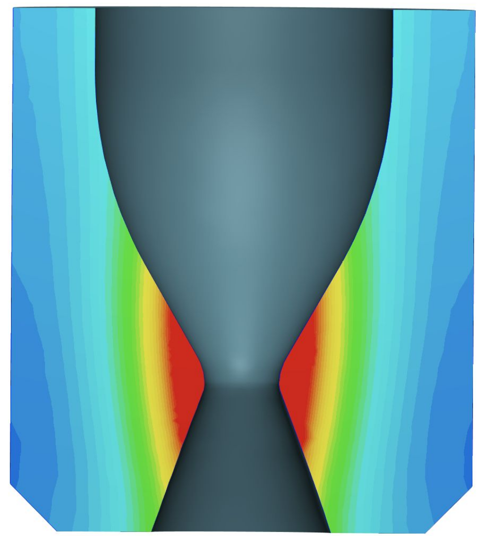
- Inherently an unsteady problem (unsteady conduction)

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

$$q_1(t) = \frac{k(T_1 - T_i)}{\sqrt{\pi \alpha t}} \quad W/m^2$$

time

- **Goal:** Maximize heat transferred out into the material
- **Favorable Design:**
  - Bulky engine (lots of material)
  - High conductivity material
  - High density material
  - High heat capacity material
  - Lower firing time
- **Example:** Helios Engine



Radiative Cooling

- Fundamentals seem a bit complicated (quantum), but heat transfer applications quite easy

$$q_{rad} = \sigma \varepsilon A_i F_{ij} (T_i^4 - T_j^4)$$

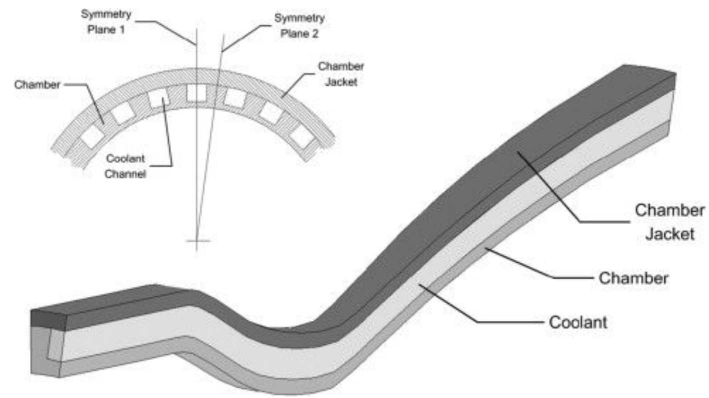
- **Goal:** Maximize heat transfer out to surroundings
- **Favorable Design:**
  - High emissivity on outside wall
  - High temperature difference
  - Convex body
- **Example:** SpaceX MVAC engines

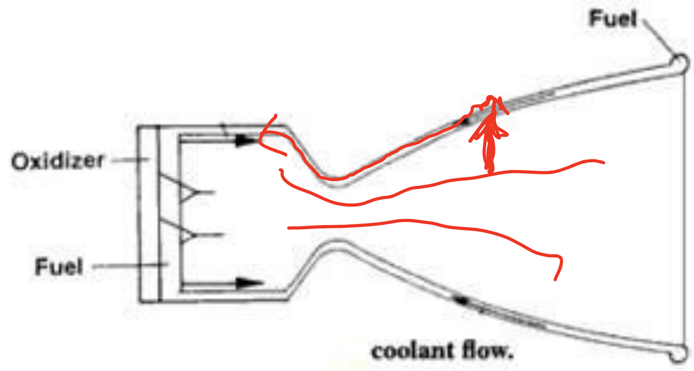
Material	Emissivity
Polished aluminium	0.04
Polished copper	0.025
Mild steel	0.2 – 0.3
Cast iron	0.3
Stainless steel	0.5 – 0.6
Black paint	0.9 – 0.95
Aluminium paint	0.5

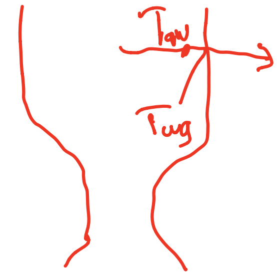
Regenerative Cooling

- Challenge is in designing the channels for cooling, and dealing with complex relations

- **Goal:** Maximize heat transfer into the coolant, which is carried out of the chamber wall
- **Favorable Design:**
  - High conductivity of wall material
  - Low wall thickness between chamber and channels
  - High coolant velocity
  - Pressure drop across channels can't be too high
  - Use all of the coolants heating capacity
- **Example:** Most stage 1 engines







Regenerative Cooling: Problem Specifics

- Multiple layers for heat transfer:
  - Across combustion gases (Tc->Taw)
    - Recovery factor (H&H pg. 85)
  - Across gas-side boundary layer (Taw->Twg)
    - Convection
  - Across chamber wall (Twg->Twc)
    - Conduction
  - Across cool-side boundary layer (Twc->Tco)
    - Convection
  - Across outer chamber wall (Tco->Tinf)
    - Conduction (ignore for now)

How can we model this seemingly complex problem?

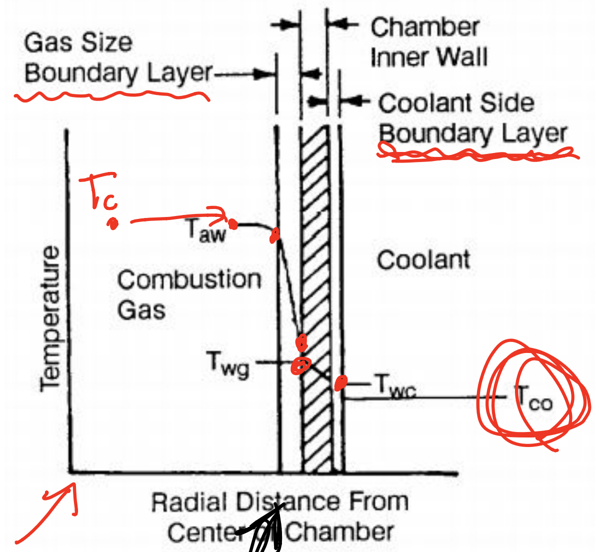


Fig. 4-30 Heat transfer schematic for regenerative cooling.

Regenerative Cooling: Thermal Resistance Network

- Circuit Analogy
  - Current = heat transferred Q
  - Voltage drop = temperature drop ΔT
  - Resistance = thermal resistance

$$I = \frac{V}{R}$$

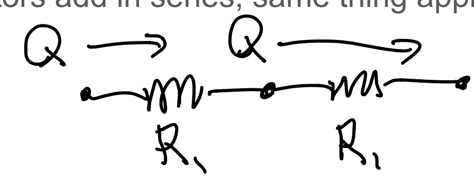
$$I = \frac{V}{R} \qquad Q = \frac{\Delta T}{R_{therm}}$$

- Thermal resistances for conduction and convection:

Conduction: $Q = A\frac{k}{t}(T_2 - T_1)$ $\qquad Q = \frac{(T_2 - T_1)}{R_{cond}}$ $\qquad R_{cond} = \frac{t}{kA}$

$Q = hA(T_2 - T_1)$ $\qquad R_{conv} = \frac{1}{hA}$

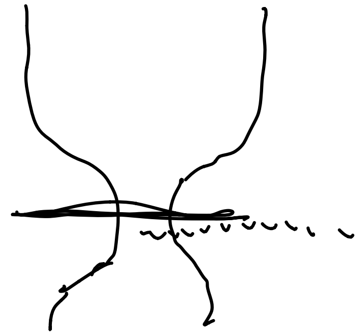
- Resistor network
  - Resistors add in series, same thing applies here



$$R_{eq} = R_1 + R_1$$

Regenerative Cooling: Illustrating the Problem

- Draw different sections of heat transfer
- Assume heat transfer in only 1 direction (radial)
- Draw nodes for temperatures, resistors between them



Regenerative Cooling: Simple Resistance Network

Knowns: T_{aw}, T_{wc}, h_c, t, k, A

Find: T_{wg}

Regenerative Cooling: More Complex Scenario

Knowns: Taw, Tco, hg, hc, t, k, A

Find: Twg, Twc

h_g

Regenerative Cooling: Gas side Heat Transfer Coefficients

Bartz correlation:

$$h_g = \left[\frac{0.026}{D_t^{0.2}} \left(\frac{\mu^{0.2} C_p}{Pr^{0.6}} \right)_{ns} \left(\frac{(p_c)_{ns} g}{c^*} \right)^{0.8} \left(\frac{Dt}{R} \right)^{0.1} \right] \times \left(\frac{A_t}{A} \right)^{0.9} \sigma \qquad (4\text{-}13)$$

$$\sigma = \frac{1}{\left[\frac{1}{2} \frac{T_{wg}}{(T_c)_{ns}} \left(1 + \frac{\gamma - 1}{2} M^2 \right) + \frac{1}{2} \right]^{0.68} \left[1 + \frac{\gamma - 1}{2} M^2 \right]^{0.12}} \qquad (4\text{-}14)$$

- Looks complicated, but most everything is known from fluid and geometry parameters
- Note the exponents of different groups. Larger exponent means more effect on hg
- Small throat diameter -> large heat flux
- Largest heat flux at the throat
- Higher chamber pressure -> more heat flux (almost linear relation)
- **Goal: make hg small**

h_c

Regenerative Cooling: Cool side Heat Transfer Coefficients

$\dot{m} = \rho V A$

Nusselt (Nu) number correlation:

$$Nu = C_1 Re^{0.8} Pr^{0.4} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

C_1 = Constant (different values for various coolants)

Nu = Nusselt number = $h_c d/k$ (diameter)

Re = Reynolds number = $\rho V_{co} d/\mu$

Pr = Prandtl number = $\mu C_p/k$

- Depends on flow through the channels and properties of the coolant
- Higher mass flow -> higher coolant velocity -> higher hc
- Smaller coolant channels -> higher coolant velocity -> higher hc
- **Goal: make hc large compared to hg**

$$\frac{h_c}{h_g} >> 1$$

$T_{aw} \rightarrow T_{wg}$

Regenerative Cooling: Thinking about design

- Thinking back to resistance network: $Q = hA(T_2 - T_1)$ $R_{conv} = \frac{1}{hA}$

$h_c \uparrow$ $h_g \uparrow$ ΔT $\downarrow$

- We want to lower Twg so material doesn't degrade, how do we do that?
  - Q is constant, so if hg is small, then (Taw-Twg) has to be large
- We want large thermal resistance through the hot side boundary layer, and small thermal resistance through the wall and cool side boundary layer
- Aim to **make hg/hc very small** by tweaking coolant scheme geometry

CFD → Star CCM+
ANSYS Fluent

Computational fluid dynamics

Regenerative Cooling: Parameters of Coolant Channels