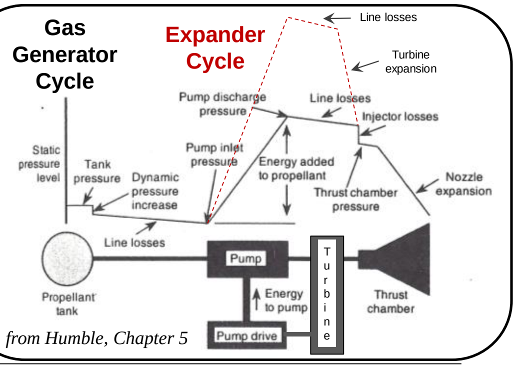
Pump-Fed LRE Cycles

Pressure Requirements and Pressure Drop Analysis

Pressure Requirements

- Significant difference between cycles is the pump pressure requirement
  - for example, an open vs. a closed cycle
  - higher pump pressure required if propellant stream passes through turbine before entering combustion chamber



from Humble, Chapter 5

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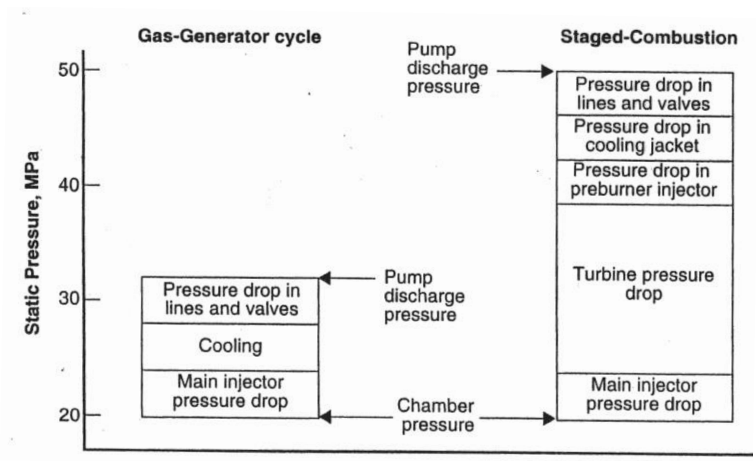
Example Pump Pressure Requirements



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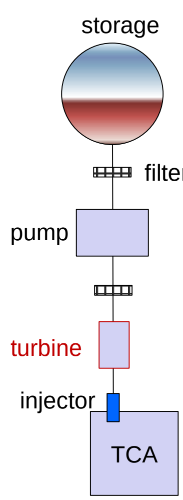
Pressure Losses in Propellant Path

1. Storage pressure
2. Dynamic pressure loss
   – static pressure drops as flow moves
3. Line losses between storage and pump
   – friction losses in piping
   – pressure drops in flow restrictions (orifices, filters, etc.)
4. Pump increase
5. Line losses
6. Injector presssure drop
7. Turbine pressure drop



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Pressure Modeling – "Rules of Thumb"

- **Dynamic pressure** $\Delta p = \frac{1}{2} \rho u^2$
- **Line losses: piping**
  - various modeling approaches, e.g., friction factor

Head Loss (height) — pipe length

$$\Delta p_f = \rho g_o H_f \qquad H_f = f \frac{L}{d} \frac{u^2}{2g_o}$$

(Darcy) friction factor — pipe diameter

  - f is function of Re_d, pipe material, surface finish
    - find values from Moody diagrams, empirical models

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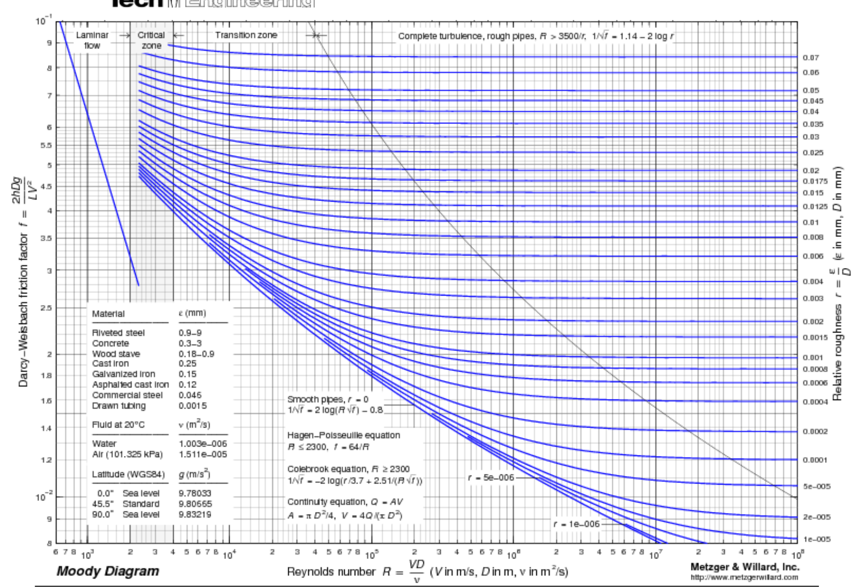
Moody Diagram



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Pressure Modeling – "Rules of Thumb"

- **Line losses: orifices**
  - flow restrictors, valves, etc.
  - typically use discharge coefficient

volumetric flowrate

$$C_d = \frac{Q}{A\sqrt{2\Delta p/\rho}} = \frac{\dot{m}/\rho}{A\sqrt{2\Delta p/\rho}}$$

orifice area

alternate definition

$$C_d = \frac{Q}{A\sqrt{\Delta p/\rho}}$$

  - essentially ratio of actual flow rate to flow rate through ideal "nozzle" that produces same expansion
  - so pressure drop given by $\Delta p = \frac{(\dot{m}/AC_d)^2}{2\rho}$

$$\Delta p = \frac{(\dot{m}/AC_d)^2}{\rho}$$

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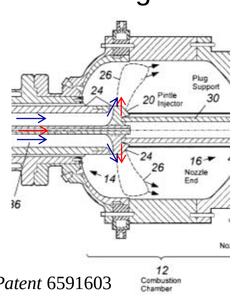
Pressure Modeling – "Rules of Thumb"

- **Typical line losses**
  - feed system: Δp_{loss}=10's kPa (4-8 psi)
  - regenerative cooling (of TCA): Δp_{loss}~10-20% of p_{cc}
- **Injector pressure drops**
  - required to produce required dispersion and mixing of propellant, isolation, etc.
  - depends on engine operational requirements and propellant type
    - Δp_{loss}~20% p_{cc} for unthrottled engines
    - Δp_{loss}~30% p_{cc} for throttled engines
    - as low as Δp_{loss}~5% p_{cc} for some pintle injectors



US Patent 6591603

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Pressure Modeling – "Rules of Thumb"

- **Turbine pressure drops**
  - based on required pressure ratio across turbine $Pr_t = \frac{P_{t_{inlet}}}{P_{t_{exit}}}$
  - gas generator cycle: Pr_t up to ~20
    - low flow rate so large expansion requirement
  - staged, expander cycles: Pr_t ~1.3-1.7
    - typically includes all of flow from one propellant stream
- **Pump requirements**
  - pump supply $p_{pump,exit} = p_{cc} + \Delta p_{inj} + \Delta p_{lines} + \Delta p_{cooling} + \Delta p_{turbine} + \ldots$
  - pump inlet $p_{pump,inlet} = p_{storage} - \Delta p_{dyn} - \Delta p_{lines}$

pump power requirement ⟸ $\Delta p_{pump} = p_{pump,exit} - p_{pump,inlet}$

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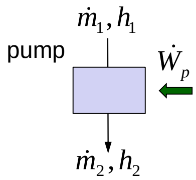
Pump Power Requirements



- **Conservation equations**
  - assume steady flow, adiabatic
  - mass: $\dot{m}_1 = \dot{m}_2 \equiv \dot{m}$
  - energy $\dot{m}h_1 + \dot{W}_p = \dot{m}h_2$

$$\dot{W}_p = \dot{m}(h_2 - h_1) \overset{?}{=} \dot{m}c_p(T_2 - T_1)$$

NO, not perfect gas

- **State equations**

$$h \equiv e + p/\rho \qquad dh = de + d(p/\rho)$$

$$\boxed{dh = cdT + \frac{dp}{\rho}}$$

assume incompressible liquid
ρ ~ constant → $dT = 0$

Gibbs' Eqn.

$$Tds = dh - \frac{dp}{\rho} \qquad \text{if isentropic} \Rightarrow dh = \frac{dp}{\rho}$$

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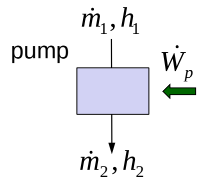
Pump Power Requirements



- **Ideal pump power**
  - so for incompressible liquid undergoing ideal (adiabatic, isentropic) pumping

$$\dot{W}_{p,ideal} = \dot{m}\Delta h_{ideal} = \dot{m}\frac{\Delta p_{pump}}{\rho_l}$$

- **Pump efficiency** *for same Δp across both*

$$\eta_p \equiv \frac{\dot{W}_{p,ideal}}{\dot{W}_{p,actual}} = \frac{\Delta h_{ideal}}{\Delta h_{actual}}$$

typical ~70-90%

- **Pump power**

in terms of pump head

$$\boxed{\dot{W}_p = \frac{\dot{m}\Delta p_{pump}}{\eta_p \rho}} = \frac{\dot{m} g_o H_{pump}}{\eta_p}$$

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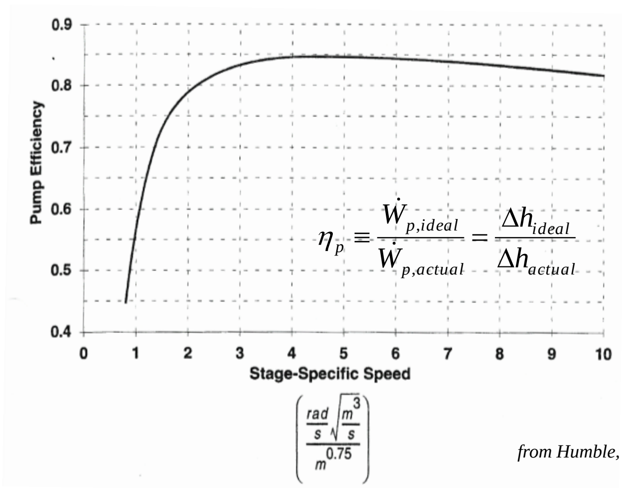
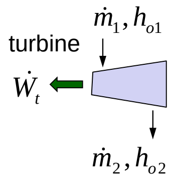
Example Pump Characteristics



from Humble, Chapter 5

Turbine Power Requirements



- **Power output needed**
  - depending on shaft/gear box efficiency

    $\dot W_t \geq \dot W_p$
- **Conservation equations** (steady, adiabatic)
  - mass: $\dot m_1 = \dot m_2 \equiv \dot m$
  - energy $\dot m h_{o1} = \dot m h_{o2} + \dot W_t \quad \Rightarrow \dot W_t = \dot m (h_{o1} - h_{o2})$
    - for cal. perfect gas $\dot W_t = \dot m c_p (T_{o1} - T_{o2})$
- **Turbine efficiency**
  - if also reversible (so isen.) $Pr_t = p_{o1}/p_{o2} = (T_{o1}/T_{o2s})^{\gamma/(\gamma-1)}$

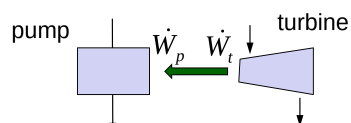
$$\eta_t \equiv \frac{\Delta h_{actual}}{\Delta h_{ideal}} \Rightarrow \boxed{\dot W_t = \dot m c_p T_{o1} \eta_t \left(1 - Pr_t^{(1-\gamma)/\gamma}\right)}$$

for same pressure ratio

$$\dot W_{t,ideal} = \dot m c_p (T_{o1} - T_{o2s})$$

$$\dot W_t = \dot m \eta_t (h_{o1} - h_{o2,s})$$

Power Summary



- **Power requirements**

$$\dot W_p = \frac{\dot m_l \Delta p_{pump}}{\eta_p \rho_l} \leq \dot W_t = \dot m_t c_p T_{o,t_{inlet}} \eta_t \left(1 - Pr_t^{(1-\gamma)/\gamma}\right)$$

e.g., shaft or gear transmission efficiency $\eta_{trans} = \dfrac{\dot W_p}{\dot W_t}$

  - so given
    - pump flow rate
    - pump pressure rise
    - pump and turbine efficiencies
  - have relation between
    - turbine inlet temperature *mat'l. or source limits*
    - turbine pressure ratio
    - turbine flow rate

can be linked in open and closed cycles

e.g., $p_{t,exit} > p_{amb}$ or p_{cc}+