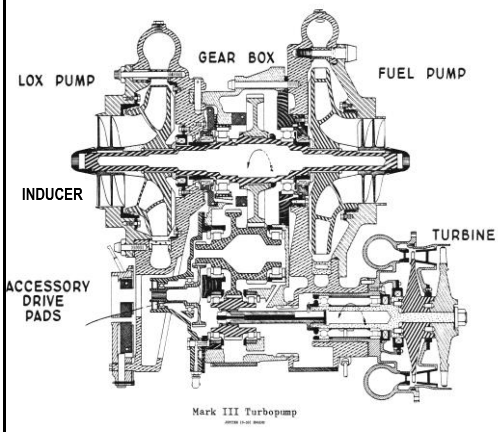
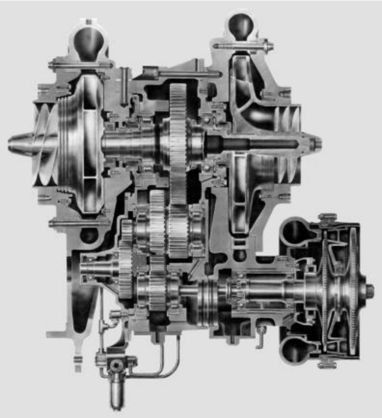
Turbomachinery for LRE

Configurations and
Euler Turbomachinery Equations

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

LRE Turbopump: Gear Connected



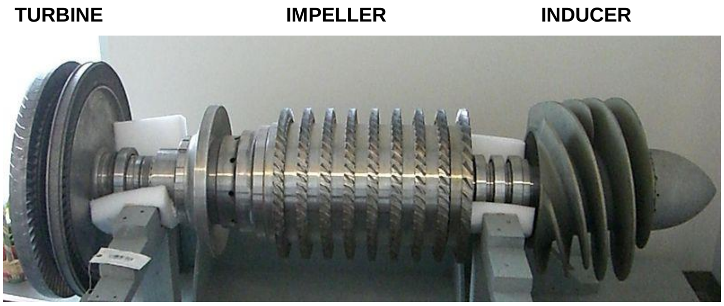


Rocketdyne Mark 3 Turbopump

Modified from Humble, and Hill and Peterson

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

LRE Turbopump: Direct Connect

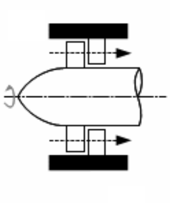


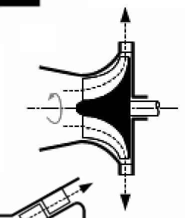
M-1 (LOX ?) Turbopump

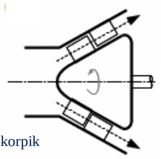
Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

Flow Configurations (Turbine or Pump)

- Typically characterized by flow direction versus axis of rotation
  - **axial**
    - flow primarily parallel to axis
  - **radial**
    - entering or exiting flow perpendicular to axis
  - mixed
    - in-between the two extremes



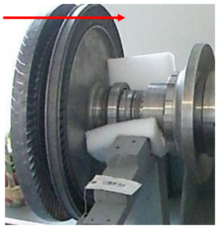




from J. Skorpik

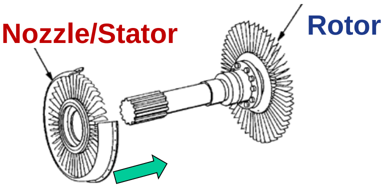
Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

LRE Turbines



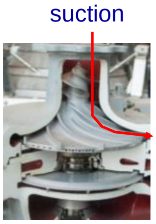
- **Configurations**
  - – axial flow turbines most common
  - – combination of stationary blades that tend to increase flow velocity, than flow over (push) rotating blades

    Stage=stator/rotor pair
  - – also radial (centrifugal) systems

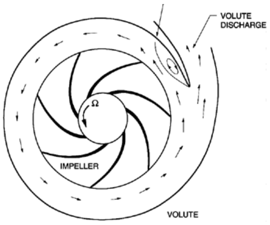


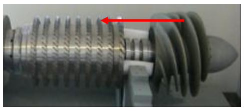
Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

LRE Pumps



- **Configurations**
  - – most common to find centrifugal (radial) pumps, lower specific mass
  - – impeller increases liquid velocity (and stagnation pressure)
  - – volute (and/or stationary diffuser blades) slows flow, static pressure rises
  - – some cases of axial systems (large flowrates?)





Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

Pump Caviation

- Minimum inlet pressure limit for pumps
  - to prevent cavitation in pump, need to ensure that pressure entering is sufficiently above pressure that would produce gas bubbles, e.g., $p_{inlet} >> p_{vap}$
  - limit typically given in terms of **N**et **P**ositive **S**uction **H**ead

$$NPSH \equiv \frac{p_{o,in} - p_{vap}}{\rho g_o}$$

i.e., minimum $NPSH$

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

Turbomachinery Analysis

- How to analyze the performance and design turbomachinery (rotating system)?
- Start by developing conservation eqns.
- First define appropriate control volume for rotating machinery

c_z = axial vel.
c_θ = azimuthal vel.
c_r = radial vel.
Ω = rotational speed

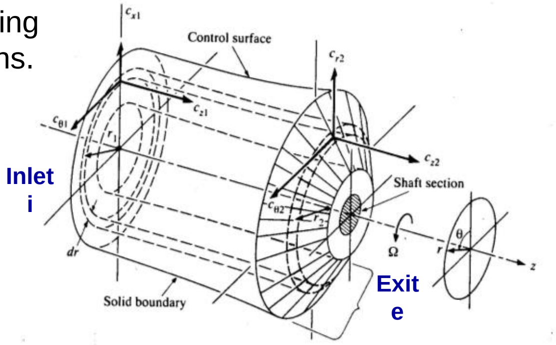


FIGURE 7.3 Special control volume for application to steady axisymmetric flow entering and leaving a rotor.

Mechanics and Thermodynamics of Propulsion, Hill and Peterson

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

Euler Turbomachinery Equations

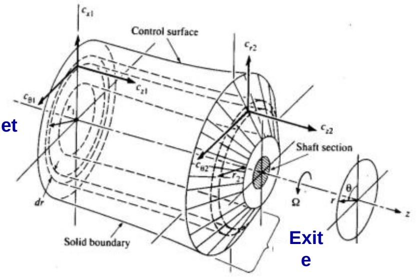
- **Mass**

0,steady

$$0 = \cancel{\frac{d}{dt}\int_{CV} \rho dV} + \int_{CS} \rho(\vec{c}\cdot\hat{n})dA$$

$$0 = 0 + \dot{m}_e - \dot{m}_i$$

$$\boxed{\dot{m}_e = \dot{m}_i = \dot{m}}$$



- **Angular Momentum**
  - Interested in torque

torque

$$\mathrm{T} = \cancel{\frac{d}{dt}\int_{CV} \rho r c_\theta dV} + \int_{CS} \rho r c_\theta (\vec{c}\cdot\hat{n})dA$$

0 for steady…okay if time avg. over high freq. fluctuations that result from blades going by

$$\mathrm{T} = \int_{CS} \rho r c_\theta (\vec{c}\cdot\hat{n})dA = \dot{m}\left[(rc_\theta)_e - (rc_\theta)_i\right]$$

rc_θ either some spatial avg. or rc_θ must be uniform ("vortex free")

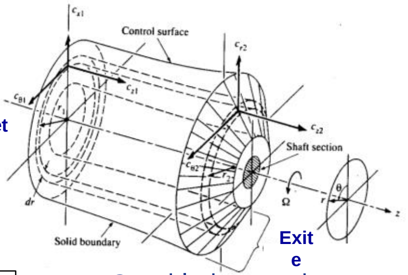
for prelim. design, typically use a mean radius location (between inner and outer radii)

based on area mean $r_m^2 \equiv \left(r_{tip}^2 + r_{root}^2\right)/2$

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

Euler Turbomachinery Equations

- So $\boxed{\mathrm{T} = \dot{m}\left[(rc_\theta)_e - (rc_\theta)_i\right]}$
  - what about power?
- **Power/Energy**
  - from mechanics



$$\dot{W} = \mathrm{T}\Omega = \dot{m}\Omega\left[(rc_\theta)_e - (rc_\theta)_i\right]$$

Ωr = blade speed $\equiv u$

$$\boxed{\dot{W} = \dot{m}\left[(uc_\theta)_e - (uc_\theta)_i\right] = \dot{m}\Delta(uc_\theta)}$$

  - from thermodynamics $\boxed{\dot{W} = \dot{m}\left[h_{oe} - h_{oi}\right] = \dot{m}\Delta h_o}$ *steady, adiabatic, uniform*

for equations as written

for compressor/pump $\mathrm{T},\dot{W} > 0$ $\quad \dot{W} = \dot{m}\,\Delta p/\rho\eta_p$ *incomp. liquid*

for turbine $\mathrm{T},\dot{W} < 0$ $\quad \dot{W} = \dot{m}c_p\Delta T_o = \dot{m}\,\eta_T c_p T_{oi}\left(\mathrm{Pr}_T^{1-\gamma/\gamma} - 1\right)$ *TPG, CPG*

  - combining $\Delta(uc_\theta) = \Delta h_o$ *enthalpy change due to change in tangential velocity*

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.

Important Definitions

- Combine mechanical and thermodynamic power expressions
  - for fixed radial position ($r_i = r_e$), $u_i = u_e \equiv U$ blade velocity

$$\Delta\left(u c_\theta\right) = \Delta h_o$$

$$U \Delta c_\theta = \Delta h_o$$

- **Stage Loading Coefficient**
  - normalized power per flow rate

$$\psi \equiv \frac{\Delta h_o}{U^2} = \frac{\Delta c_\theta}{U}$$

- **Reaction** (Degree of Reaction)

$$R \equiv \frac{\Delta h_{rotor}}{\Delta h_{stage}} \begin{matrix} \leftarrow \text{energy change across rotor} \\ \leftarrow \text{energy change across stage} \end{matrix} \sim \frac{\Delta p_{rotor}}{\Delta p_{stage}}$$

  - describes balance of torque, pressure gradients between rotating and stationary surfaces

Copyright © 2012 ,2017, 2019 by Jerry M. Seitzman. All rights reserved.