Pumping Machinery

2001 ASME Fluids Engineering Division Summer Meeting

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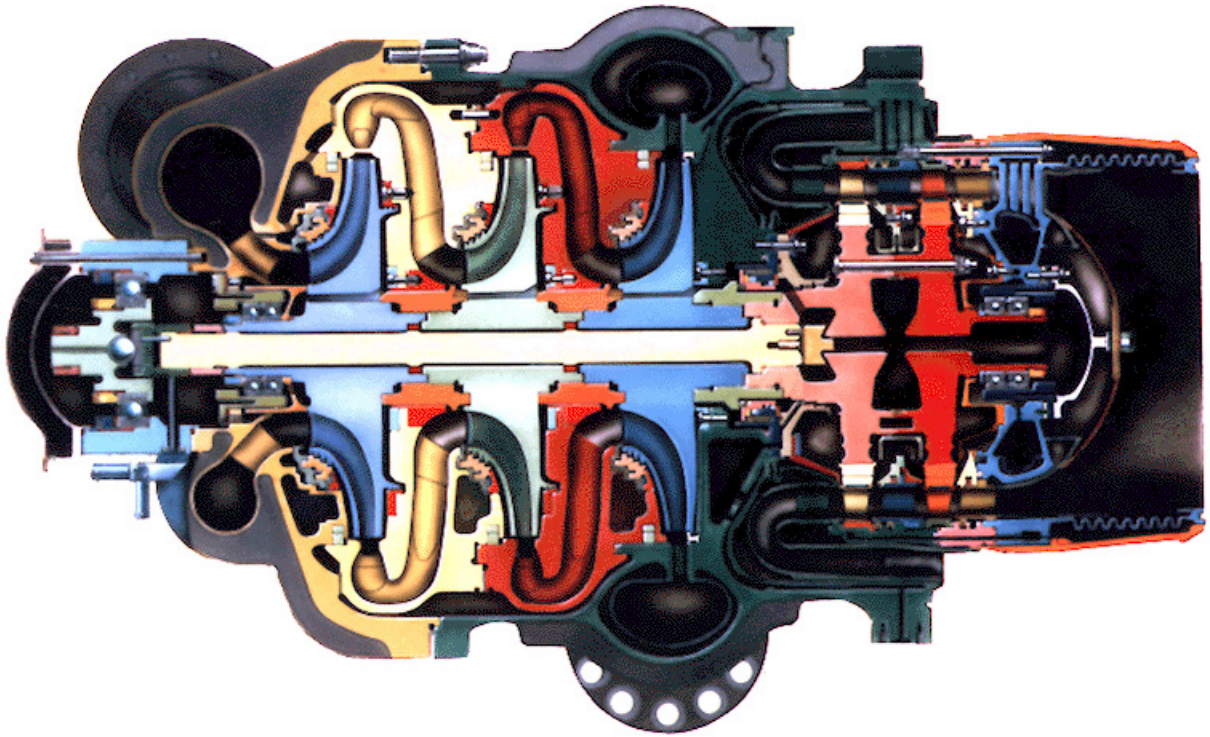
What is Turbomachinery?

Using working fluids to ***Boost*** *output,*

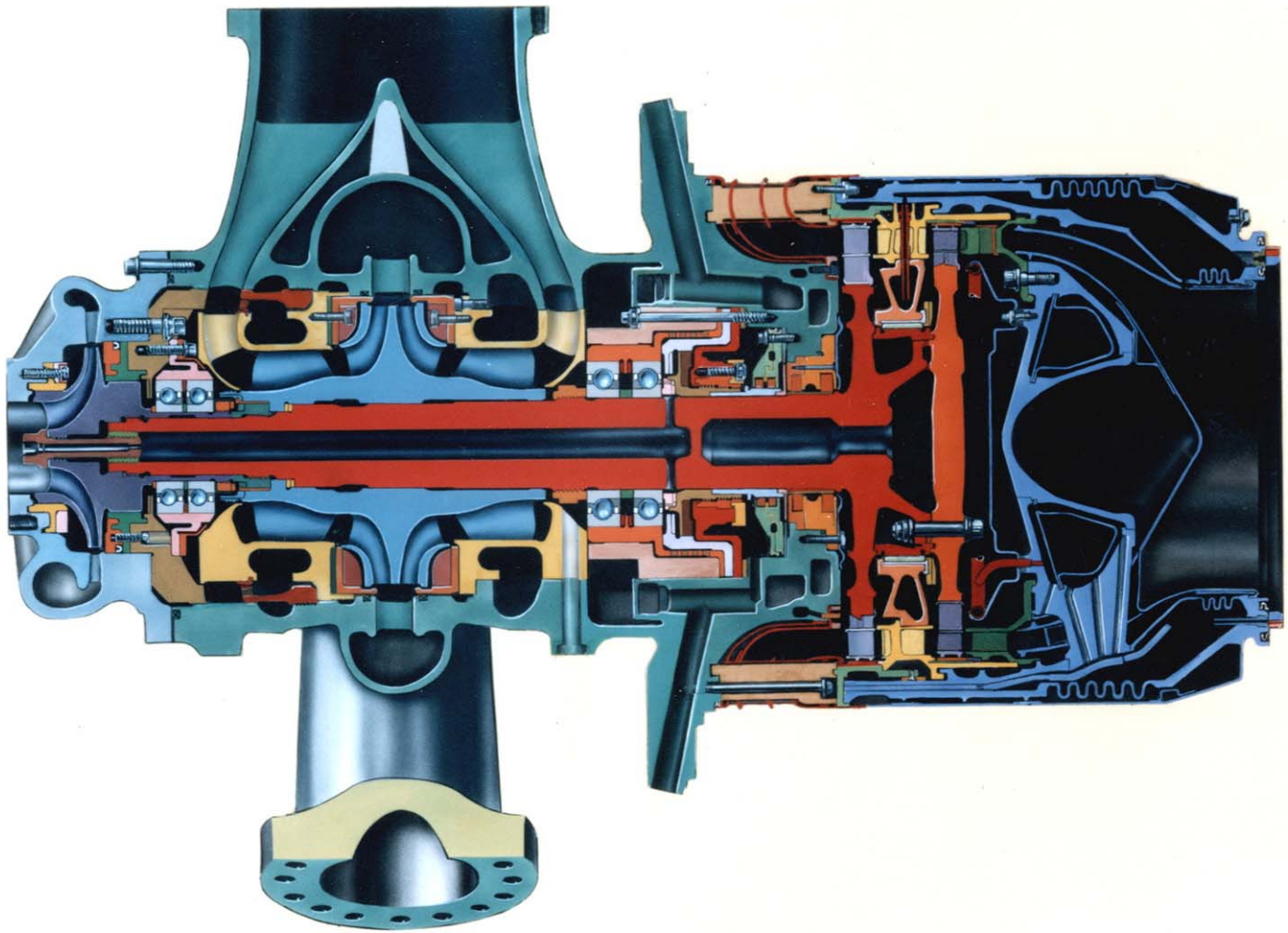
either ***increase*** *or* ***decrease*** *pressure*

by using *Machinery*

High Pressure Fuel Turbopump



High Pressure Oxygen Turbopump



Turbomachine Classification

- Turbines. Pumps and Compressors
- Incompressible. Compressible
- Axial-flow, Mixed-flow, Radial-flow geometry
- Single stage. Multi-stage
- Turbo-pump. Turbo-compressor. Torque-converter
- Impulse. Reaction

From Customer Requirements to Final Product

- Specification
- Preliminary Design, Conceptual design, ...
- Component Design
- Component Test, Analysis
- Acceptance Test
- .....

Design Trade-offs

- Performance
- Weight
- Cost
- Life
- Reliability
- Structural Strength
- Maintainability
- Envelope

Design Process

- In-house design database - scale
- Detail design
  - **(2D, Quasi 3D, CFD <=> stress analysis**
- Test Data Evaluation

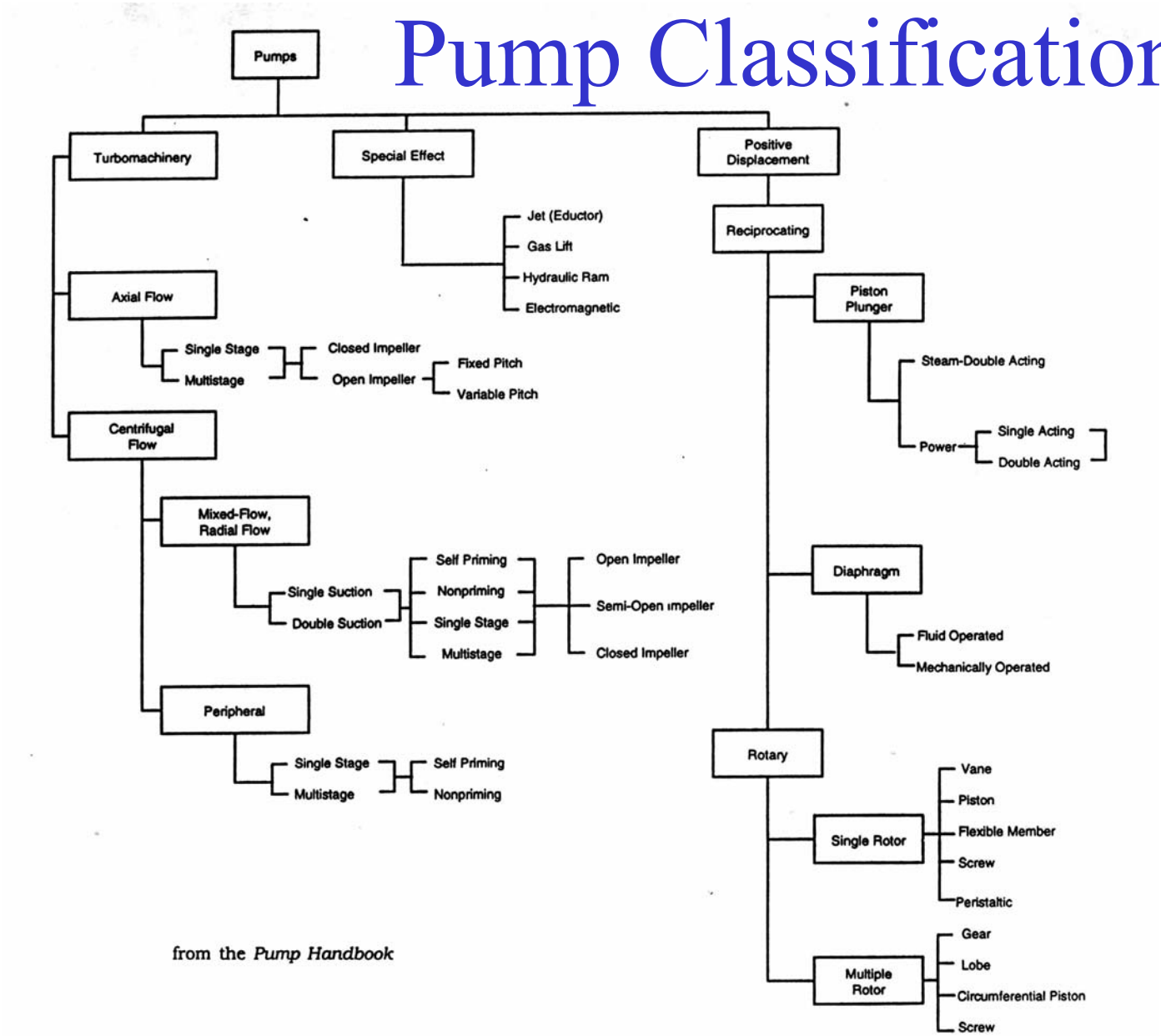
Turbomachine

$$Ps = \dot{m}[(h + \frac{v^2}{2} + gz)_{out} - (h + \frac{v^2}{2} + gz)_{in}]$$

Turbines

- Impart Kinetic Energy to rotor as Mechanical Energy of rotation
- Impulse
  - high Pressure, low Flow
- Reaction
  - low Pressure, high Flow

Pump Classification



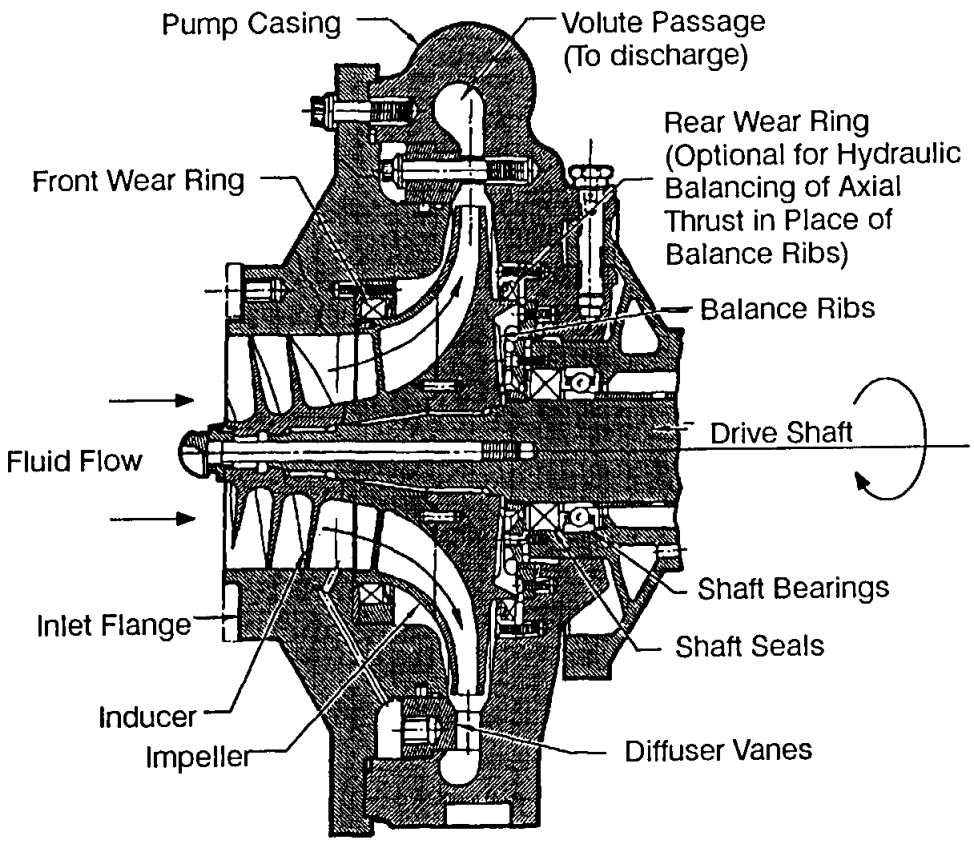
from the *Pump Handbook*

Centrifugal Pump

- rotor, stator
  - accelerate flow by imparting kinetic energy
  - decelerate (diffuse) in stator
  - results in increase in fluid pressure

Elements of a Centrifugal Flow Pump

- From Huzel, D. K. and Huang, D. H.



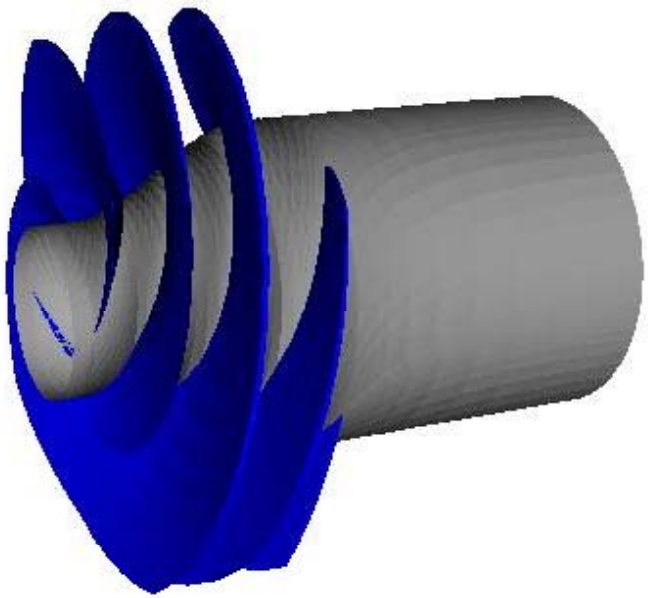
Rotor

- Inducer
- Impeller
- Bearings
- Shaft

Inducer

- Axial flow
- Increase total pressure
- permits non cavitating operation in impeller
- used as boost pump, permits main pump to operate at higher speeds
- e.g. LPOTP is only inducer

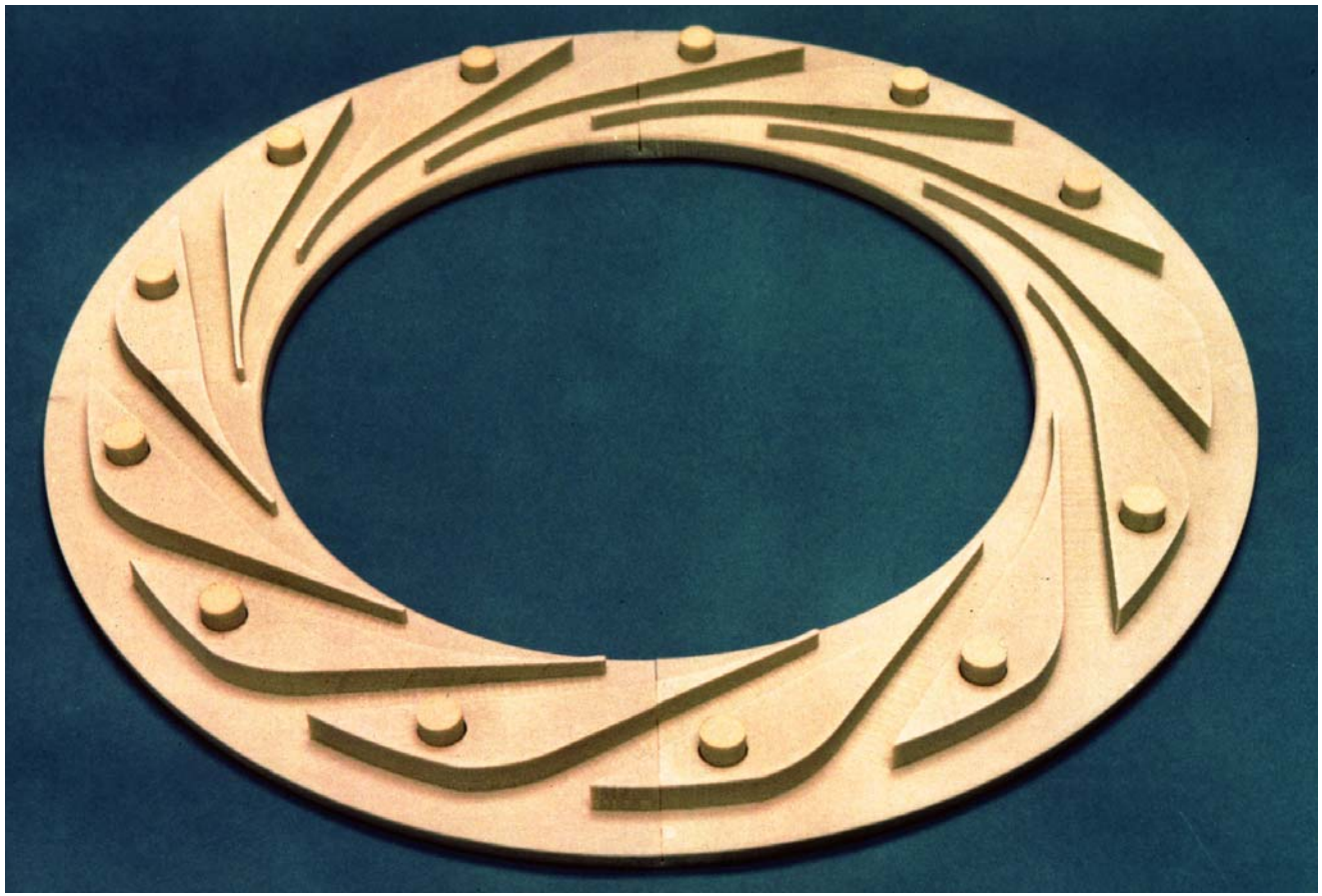
Inducer



Stator

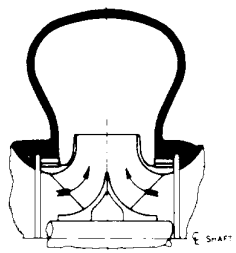
- Casing
- Diffuser vanes
- Volute
- Seals

Vane Island Diffuser (shown without shroud)

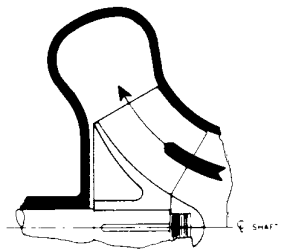


Impeller Profiles

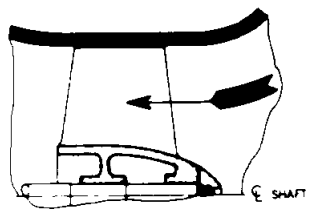
From BWIP pump pocket book



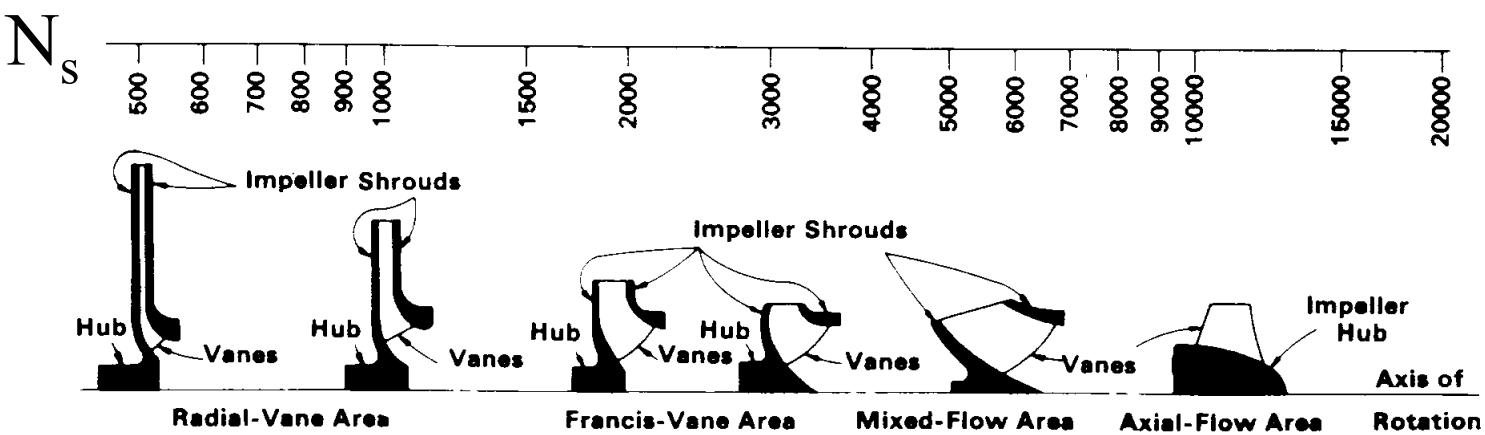
Radial Flow



Mixed Flow

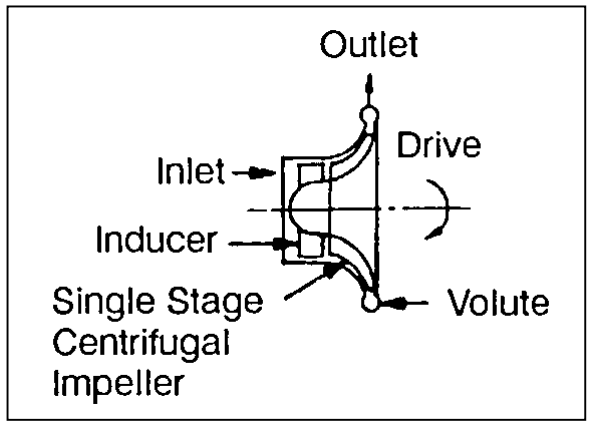


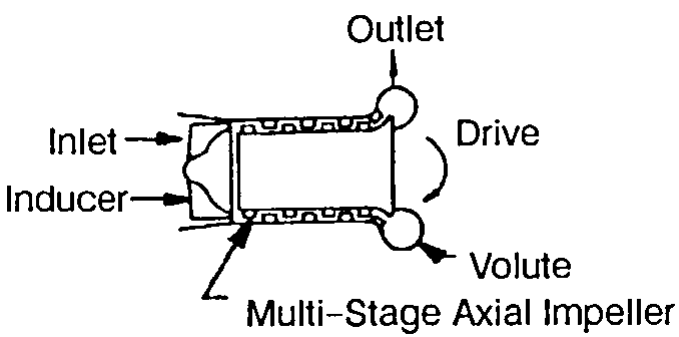
Axial Flow

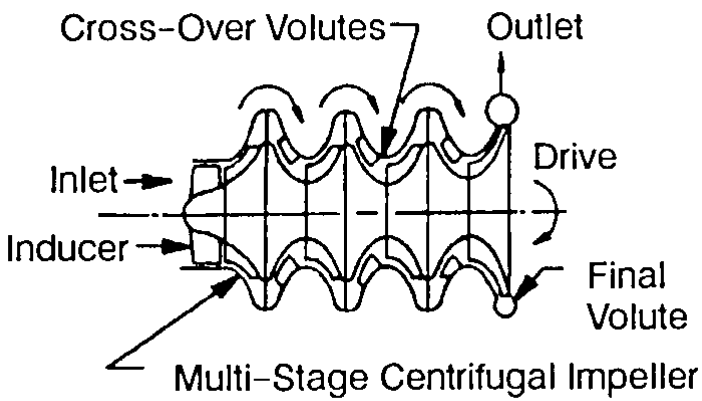


Pump Configurations

- From Huzel, D. K. and Huang, D. H.

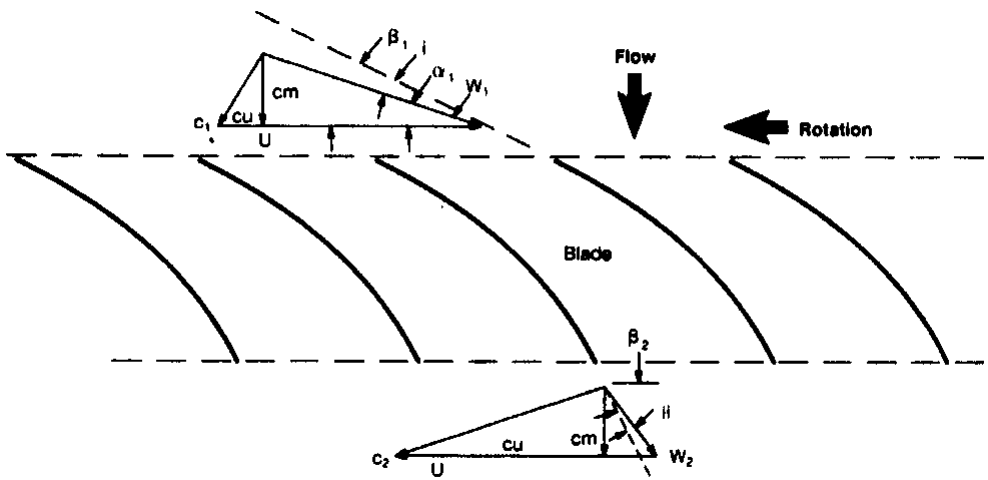






Velocity Triangle

- From Huzel, D. K. and Huang, D. H.



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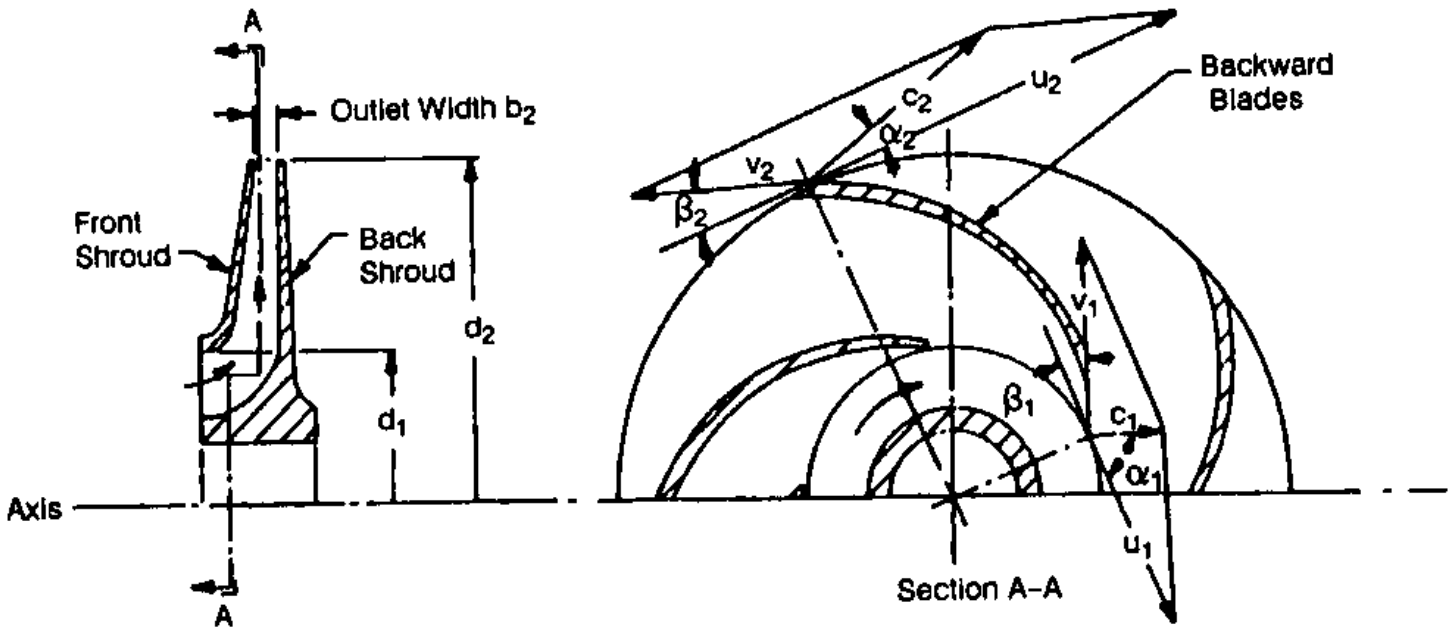


Impeller Loss Components

- Skin Friction
- Blade Loading
- Incidence
- Wake Mixing
- Impeller-shroud Clearance Leakage
- Disk Friction
- Recirculation

Flow Variables

$$P_T = P + \frac{1}{2}\rho v^2$$

$$P_T = P + \frac{1}{2}\rho\,(v_\theta{}^2 + v_m{}^2)$$

$$h_T = h + \frac{1}{2}\rho v^2 + gz$$

Dimensionless Quantities

- Head coefficient

$$\Psi = \frac{gH}{\Omega^2 R^2}$$

- Flow Coefficient

$$\Phi = \frac{Q}{A\Omega R}$$

Head rise

$$H = \frac{u}{g}\left(v_{\theta 2} - v_{\theta 1}\right)$$

Isentropic Enthalpy Rise

$\Delta H = 144.\Delta p/\rho$

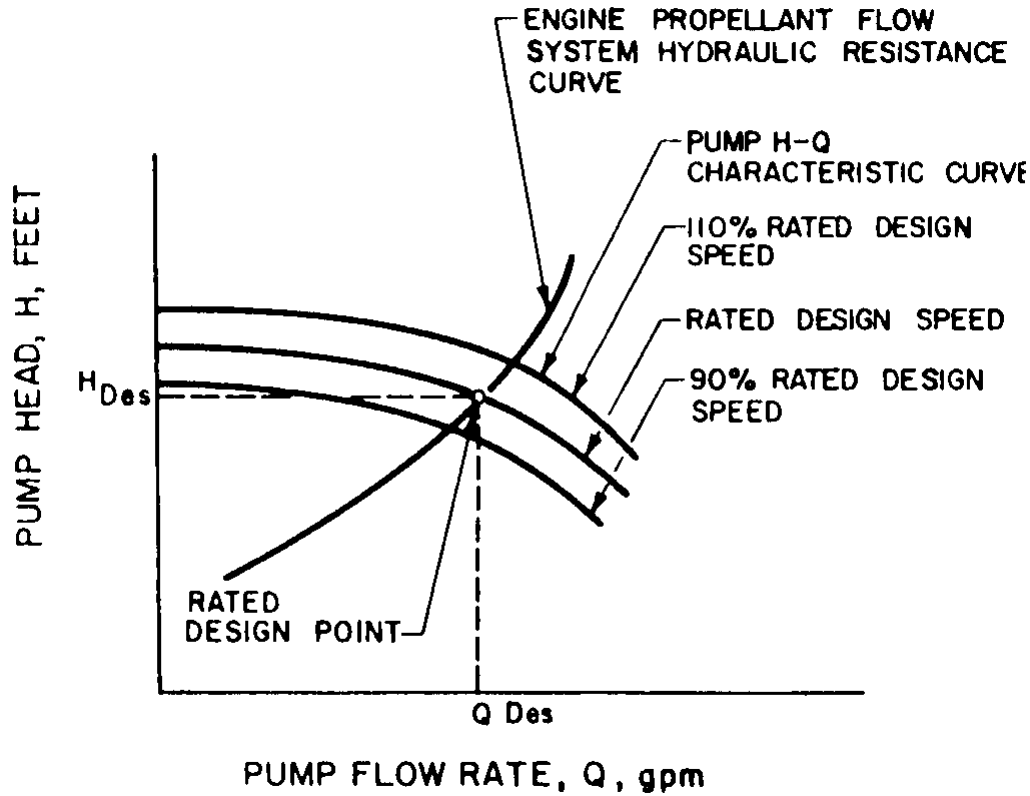
- ΔP (psi)
- ΔH (ft)
- ρ(lb/ft^3)

Affinity Laws

- $Q \sim \Omega D^3$
- $H \sim \Omega^2 D^2$
- $T \sim \rho \Omega^2 D^5$
- $P \sim \rho \Omega^3 D^5$

Engine System Resistance and Pump Characteristics

- From Huzel, D. K. and Huang, D. H.

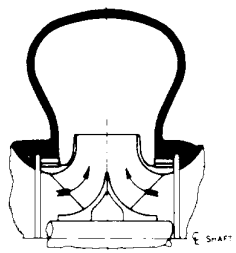


Specific speed

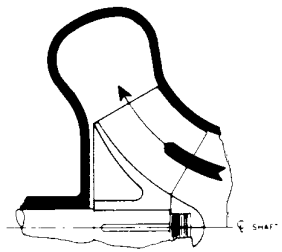
- Consistent units $\Omega s = \frac{\Omega Q^{\frac{1}{2}}}{(gH)^{\frac{3}{4}}}$
  - Ω (rad/s)
  - Q (m^3/s)
  - H (m)
- US $Ns = \frac{RPM.(GPM)^{\frac{1}{2}}}{(ft.)^{\frac{3}{4}}}$ $\Omega s = \frac{Ns}{2734.6}$

Impeller Profiles

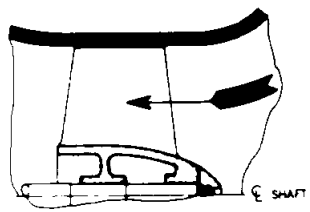
From BWIP pump pocket book



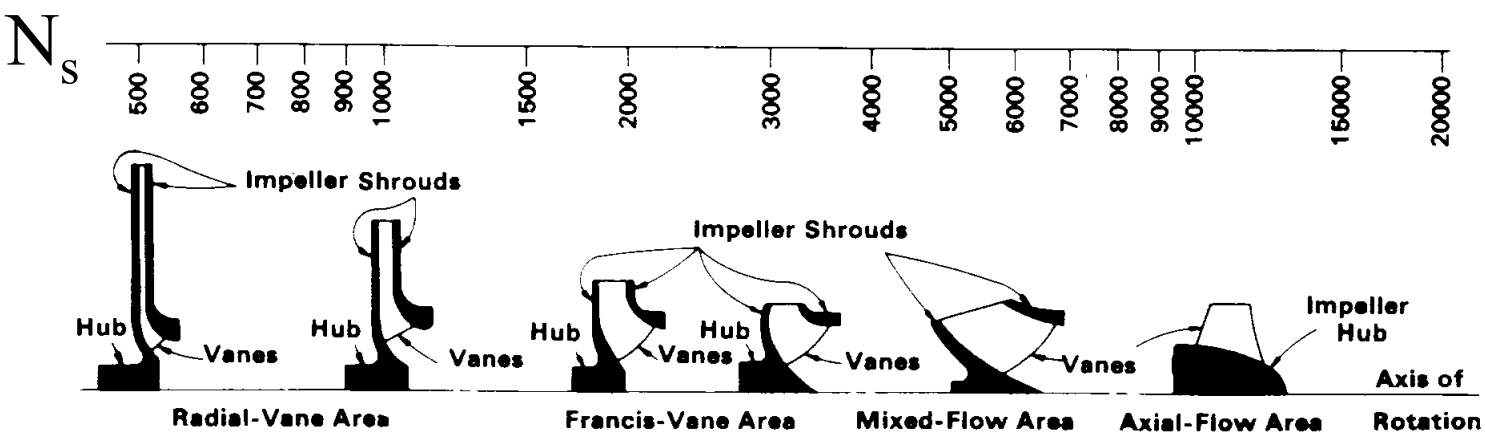
Radial Flow



Mixed Flow

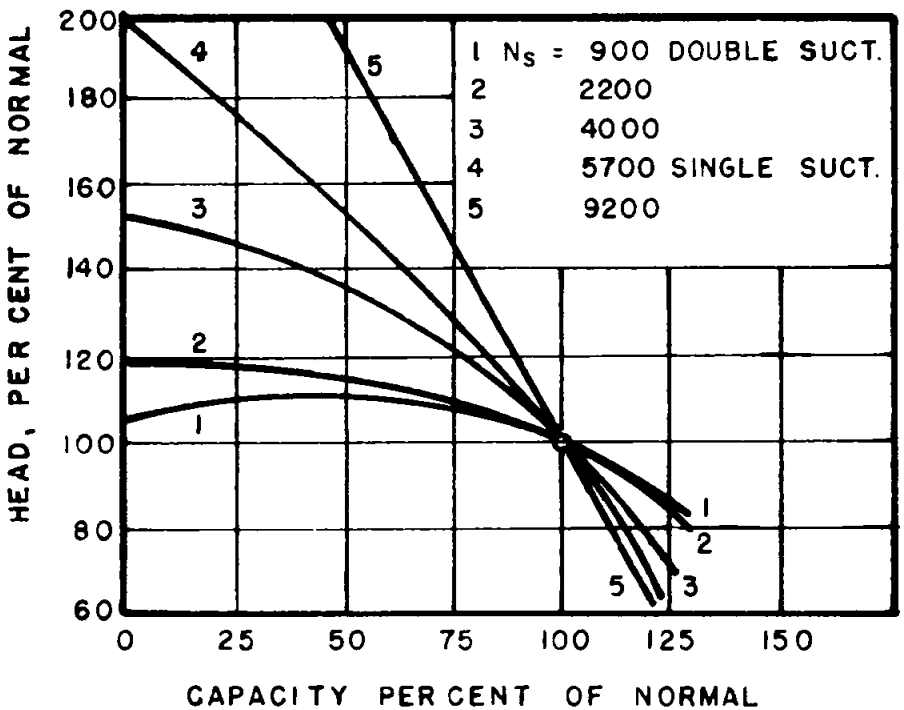


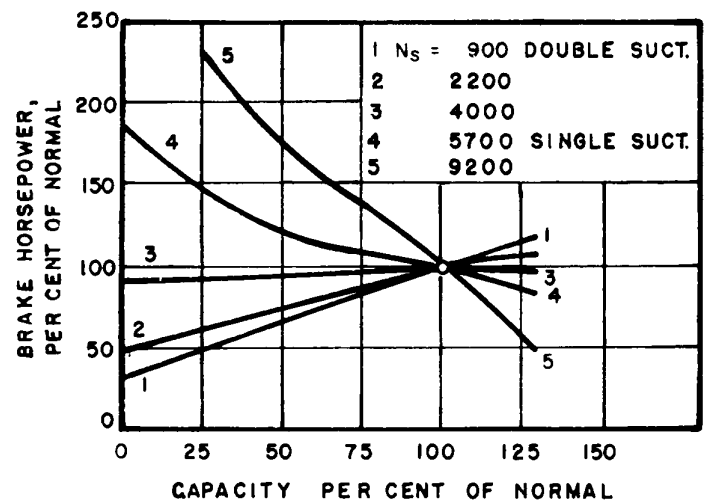
Axial Flow



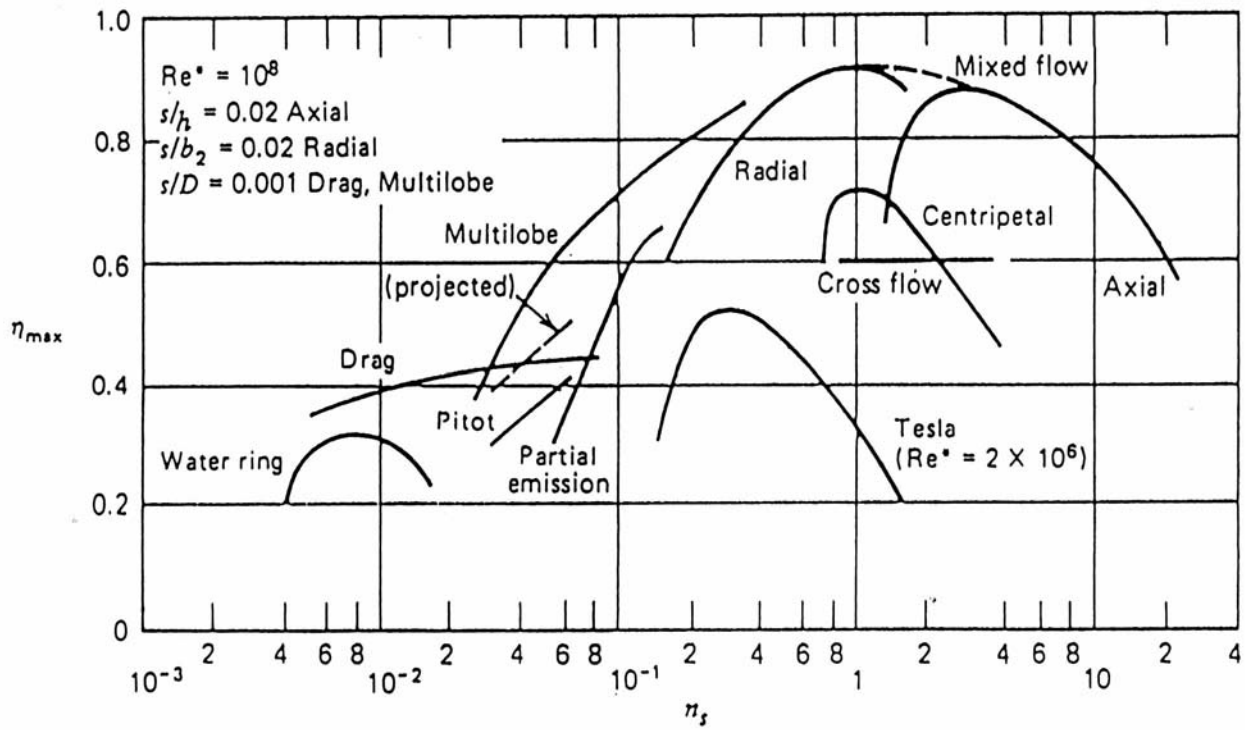
Effect of Ns on H-Q curve

- From Cameron Hydraulic Data





Profiles and Efficiencies Based on Specific Speed



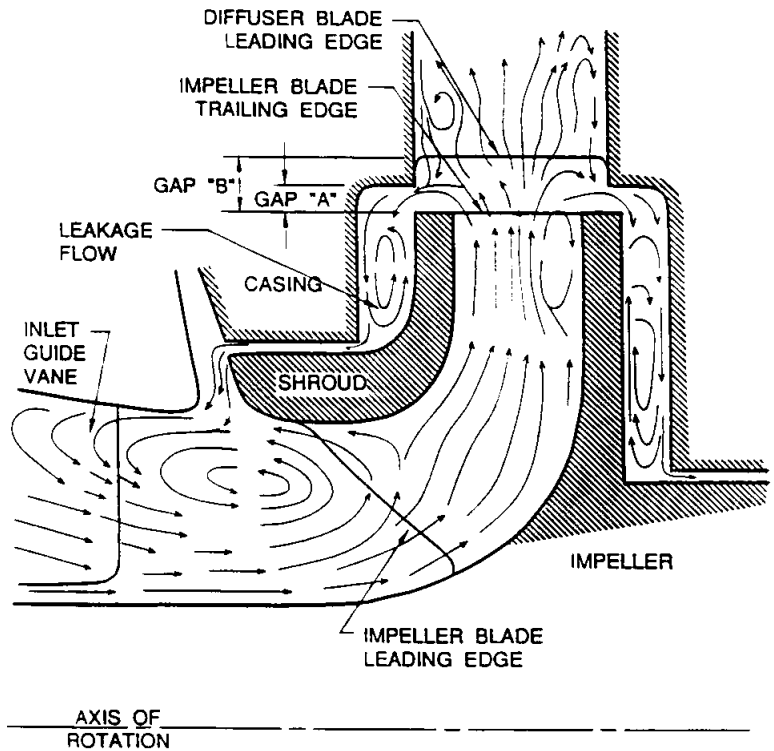
Issues

- H-Q instability
- Stall
- Cavitation induced dynamic pressure
- Radial loads
- Discharge and suction recirculation

Separation and Stall

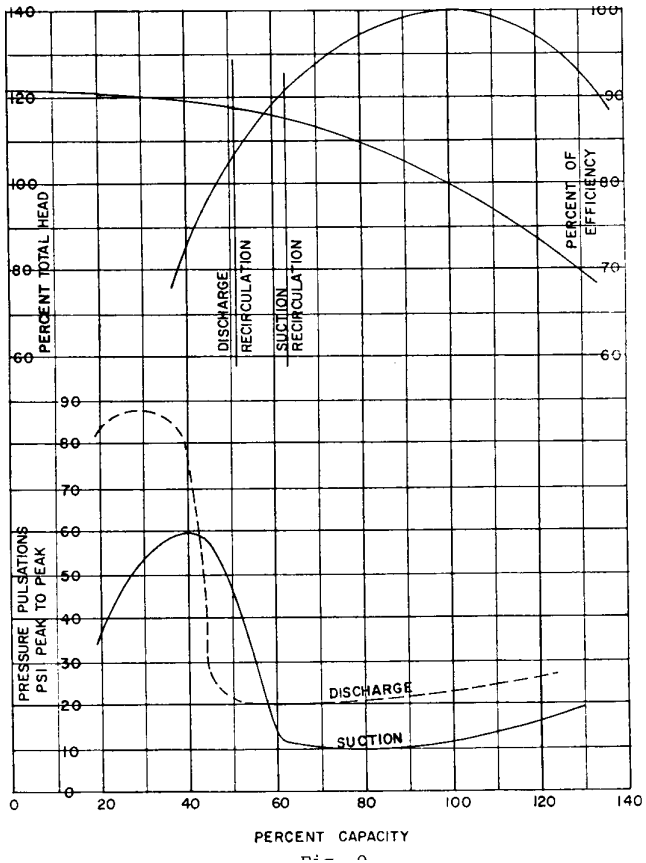
Jet and wake observed in each impeller passage. The eddying wake is seen on the suction side of the channel from Fischer and Thoma, 1932

Recirculation



Secondary flows in a centrifugal pump from Brennen (1994)

Recirculation



Sudden increase in pressure pulsation from Fraser (1981)

Stator Effect on Head Characteristics
(steepens H-Q curve)

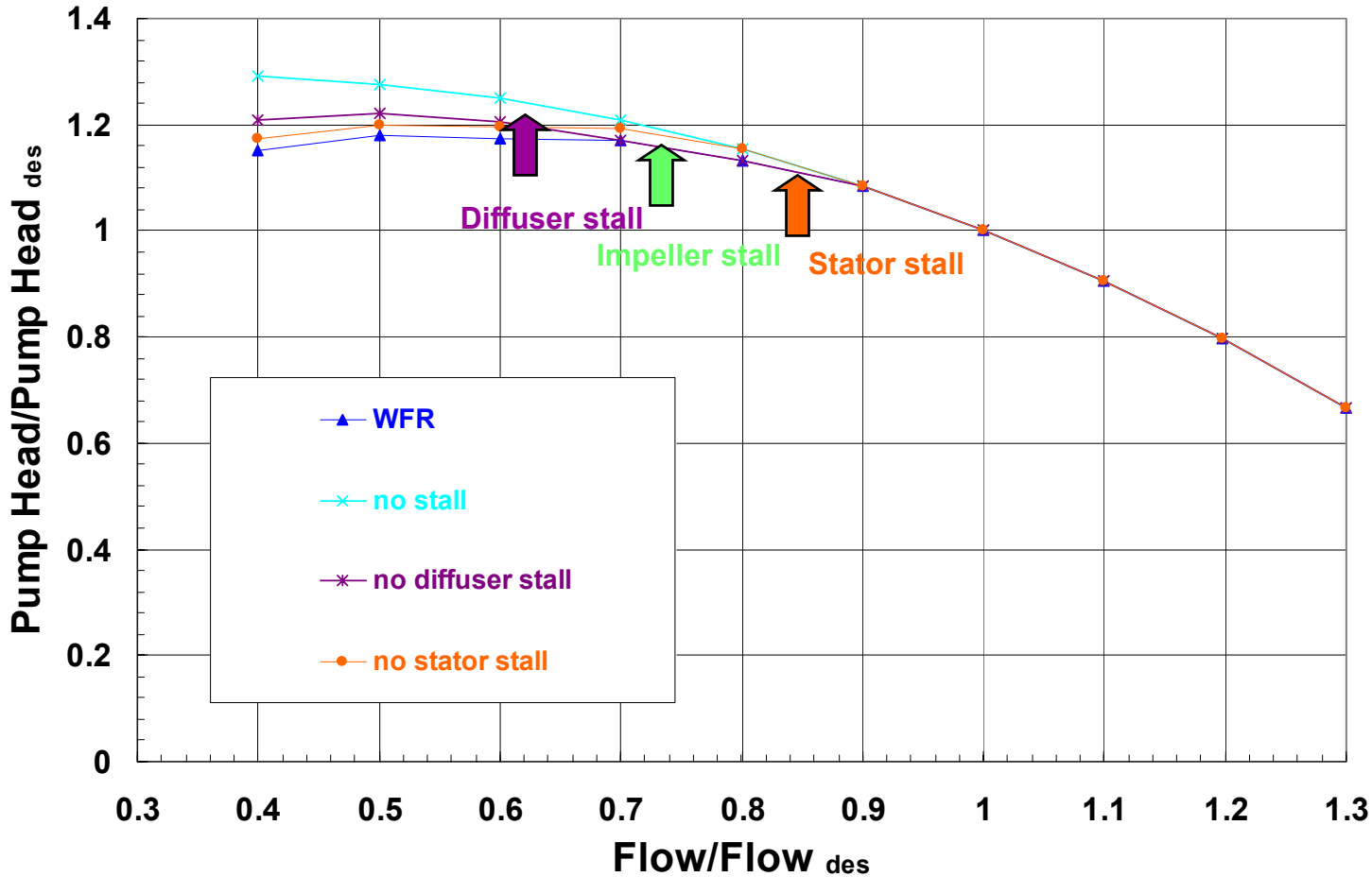
- reduce impeller inlet Cu at low flow
- increase impeller inlet Cu at high flow
- provide stability over wide operating range
- increase stator and impeller incidence angle at off design
- reduces inception of stall with negative incidence

Vaned Diffuser Effect on Head Characteristics

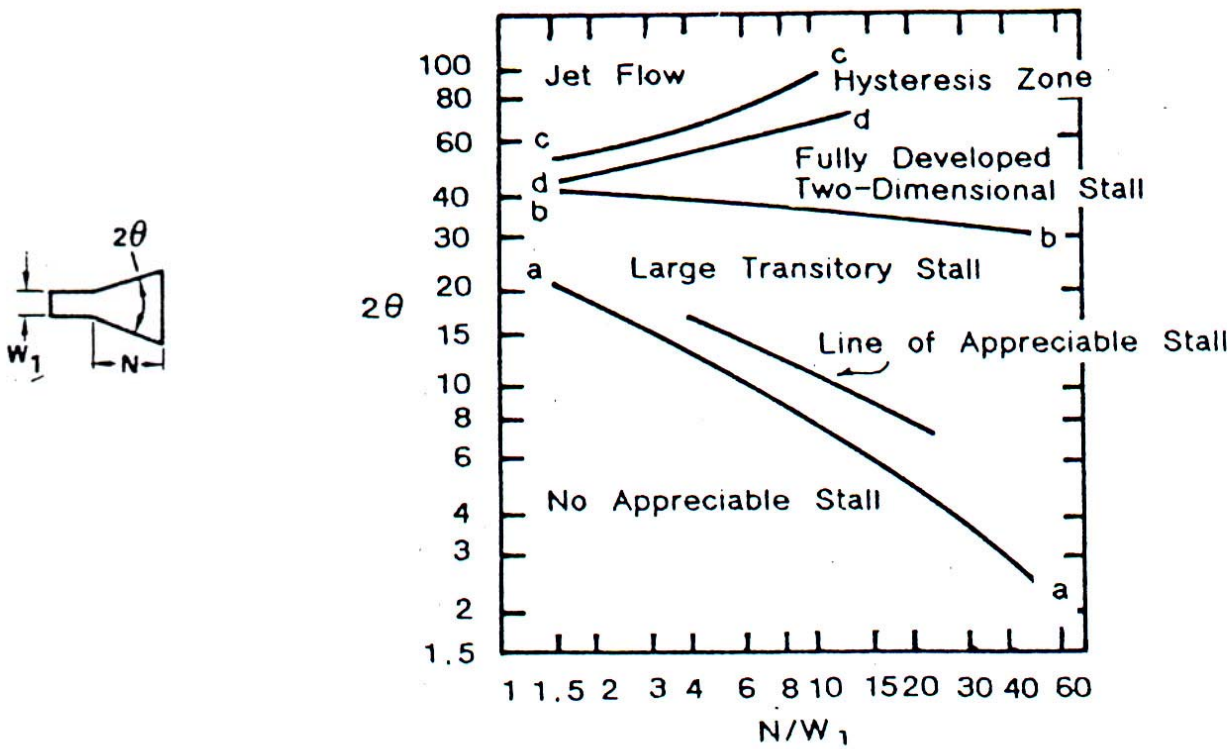
(flattens H-Q curve)

- convert kinetic energy of fluid leaving the impeller into static pressure rise
- flow incidence sensitive
- leading edge stall phenomenon believed to be cause of loss of diffuser performance
- rapid head falloff at low flow

Stall Characteristics

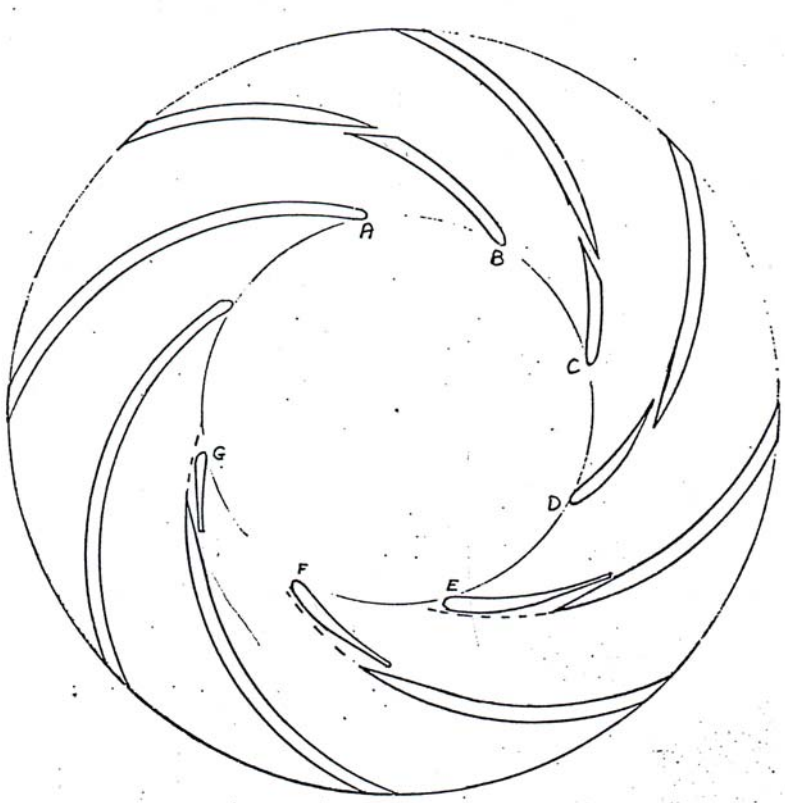


Two-Dimensional Diffuser Map



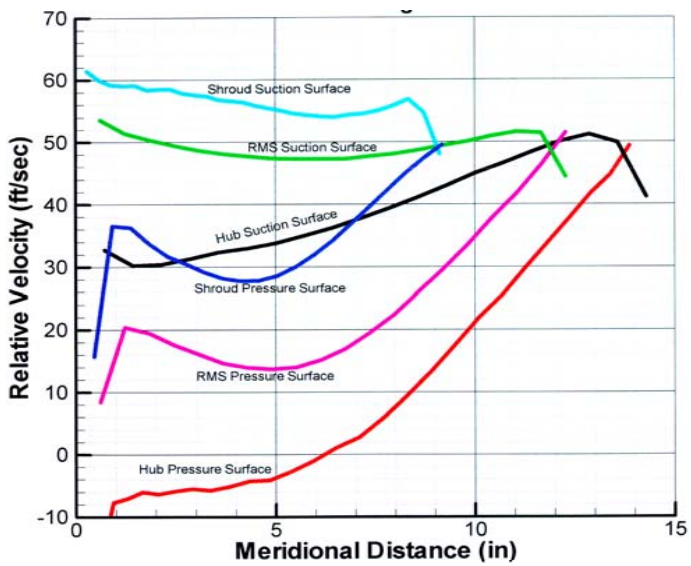
Flow Regimes in Straight Wall, Two-Dimensional Diffusers from Moore and Kline, 1955.

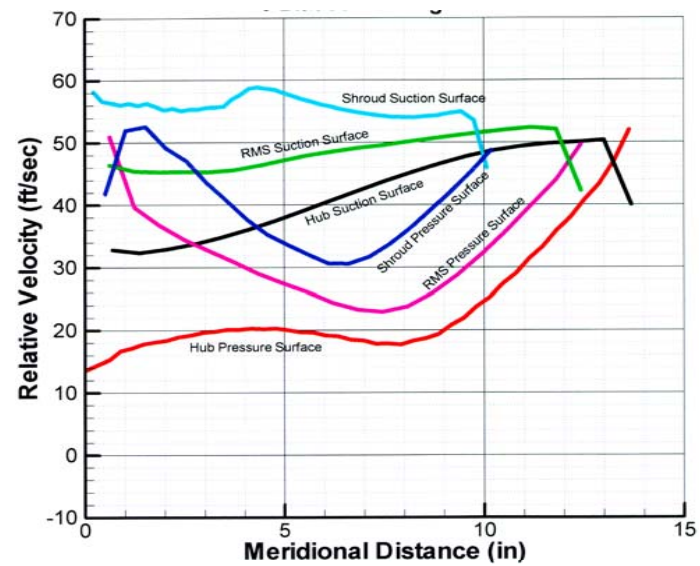
Slot Optimization



Slot geometry configuration optimization from Gostelow and Watson, 1972.

Blade Loading





From Guinzburg et al. (1997)

CFD as a Tool

- Before using a particular CFD code in a rotating machinery component design process, it is important to bracket the accuracy of the code results for that particular type of component.

Interpretation of CFD

- Another important issue is how accurately the component *inlet flow boundary conditions* have to be known (pre-computation) to get results that are consistent with test data.

CFD Process

- Validate a computational fluid dynamic code for integration into the impeller design process.
- The validation process consists of computing the impeller flow for a range of inlet conditions.

Accuracy of the CFD Results

- number of nodes used to discretize the flow domain
- accuracy of the numerical discretization scheme
- type of turbulence model used.

CFD Capabilities

- Transient Analysis
- Two Phase Flow
- Heat Transfer
- Temperature Dependent Properties
- Moving Mesh
- Non-inertial Reference Frames
- Selection of Turbulence Models
- Wall Function Models

Diffusion

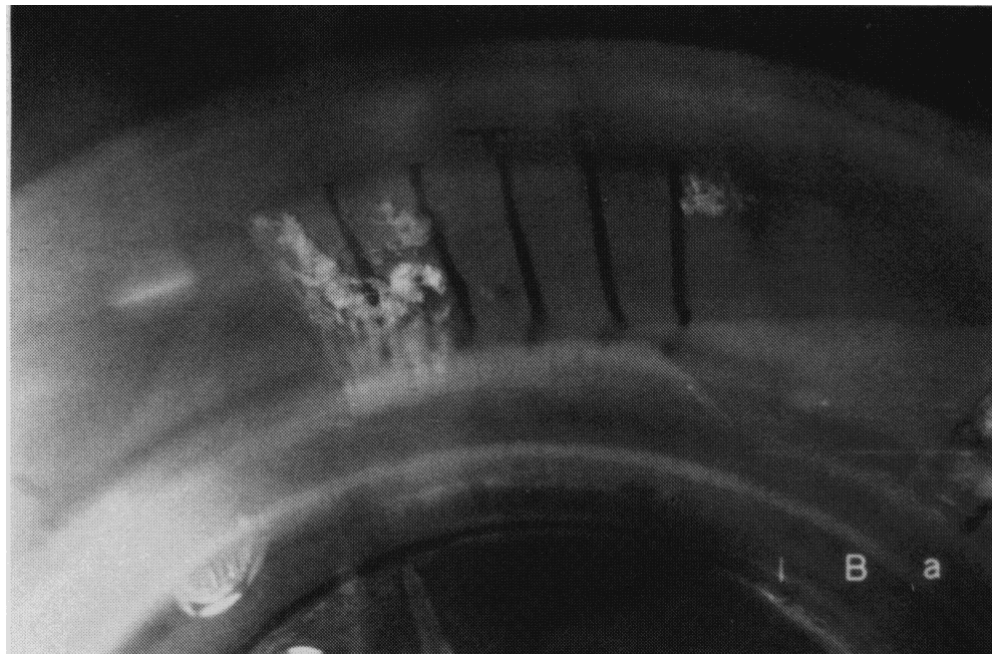
The diffusion factor D, can be adapted for pumps from Lieblein (1965) as follows:

$$D = \left(1 - \frac{W_2}{W_1}\right) + \frac{\left[V_{\theta 2} - \frac{r_1}{r_2} V_{\theta 1}\right]}{2\sigma W_1}$$

Duncombe (1964) explicitly examined the diffusion on both the suction (s) and pressure (p) sides of the blade and expressed the result as follows:

$$D = \left(1 - \frac{W_2}{W_{s,max}}\right) + \left(1 - \frac{W_{p,min}}{W_1}\right)$$

Cavitation



Typical cavity configuration within an impeller. Flowrate is half that of BEP; so, the cavity is broken up by recirculating flow. From Sloteman et al (1995).

Cavitation

- Thoma number, cavitation number

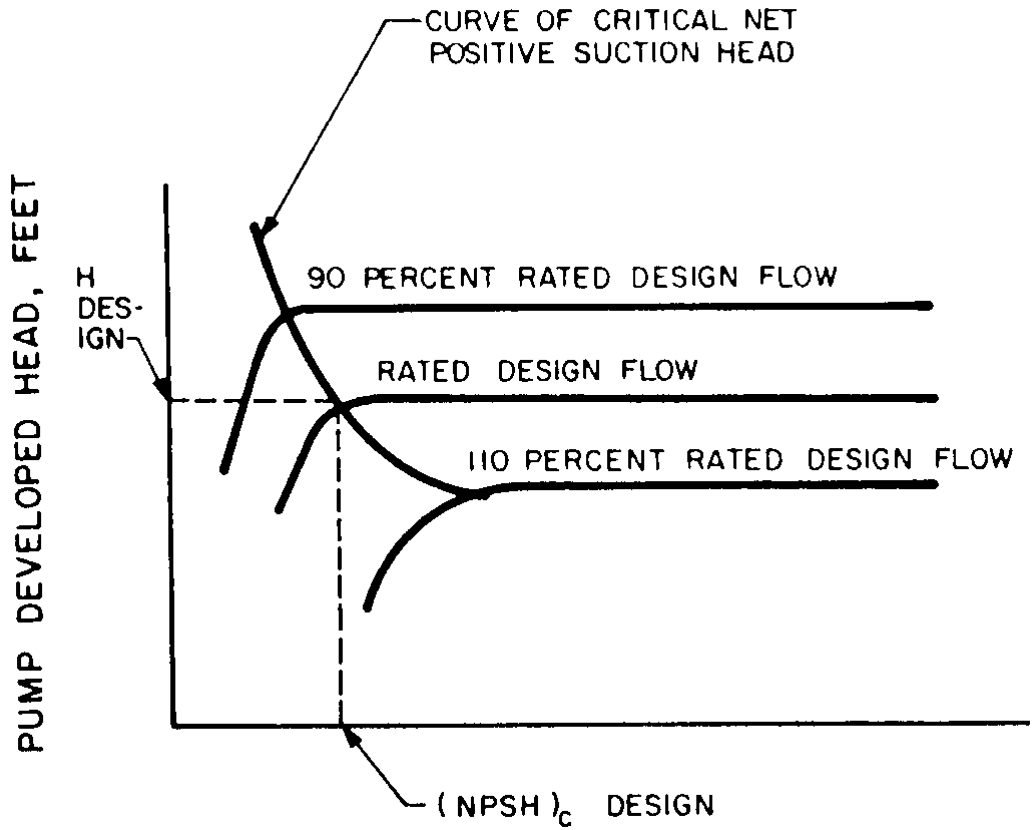
$$\sigma = \frac{p - p_v}{\frac{1}{2}\rho v^2}$$

Suction Specific speed

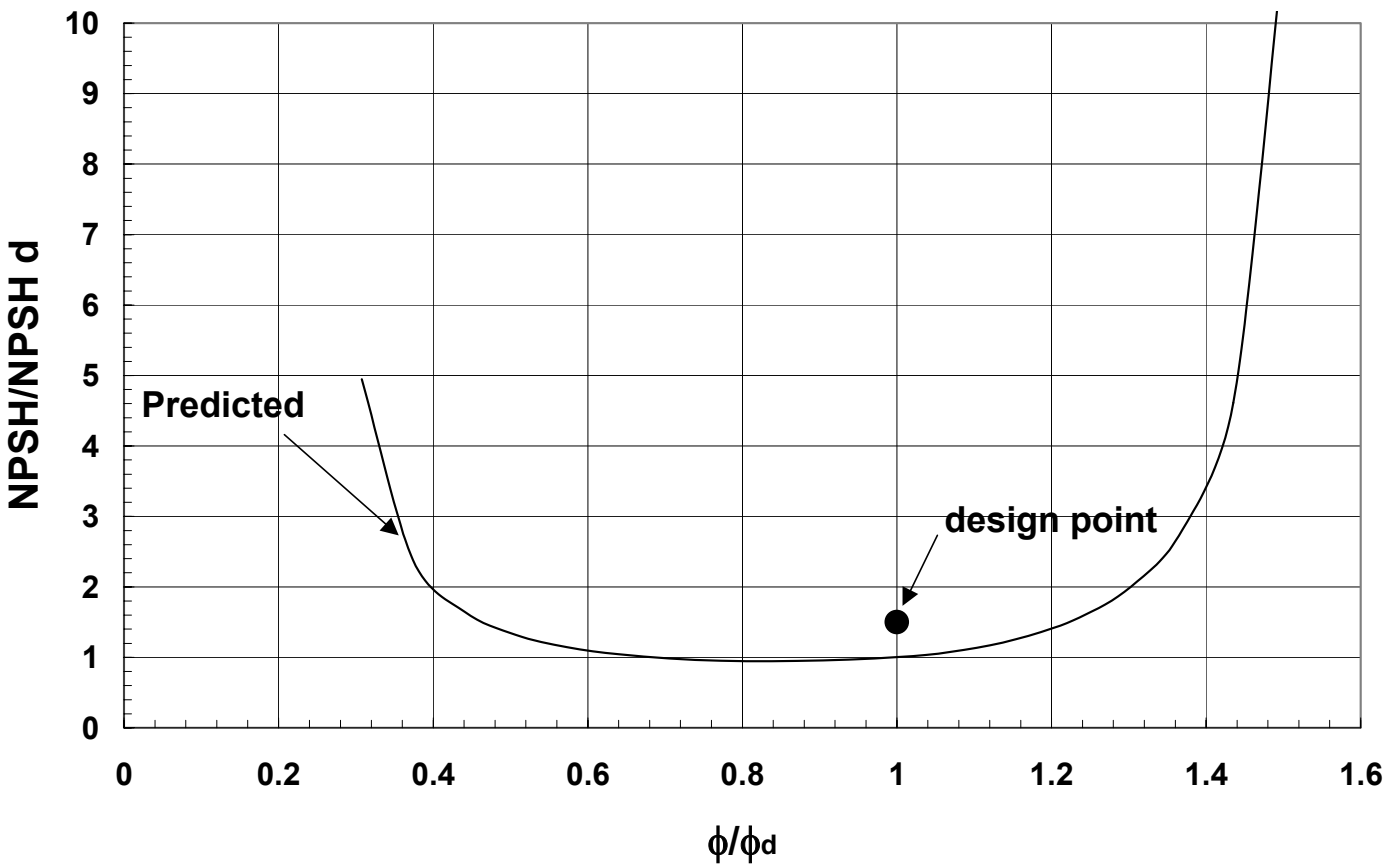
- Consistent units $\Omega ss = \dfrac{\Omega Q^{\frac{1}{2}}}{(gNPSH)^{\frac{3}{4}}}$
  - Ω (rad/s)
  - Q (m^3/s)
  - NPSH (m)
- US $Nss = \dfrac{RPM.(GPM)^{\frac{1}{2}}}{(ft.)^{\frac{3}{4}}}$ $\Omega ss = \dfrac{Nss}{2734.6}$

Pump Suction Performance

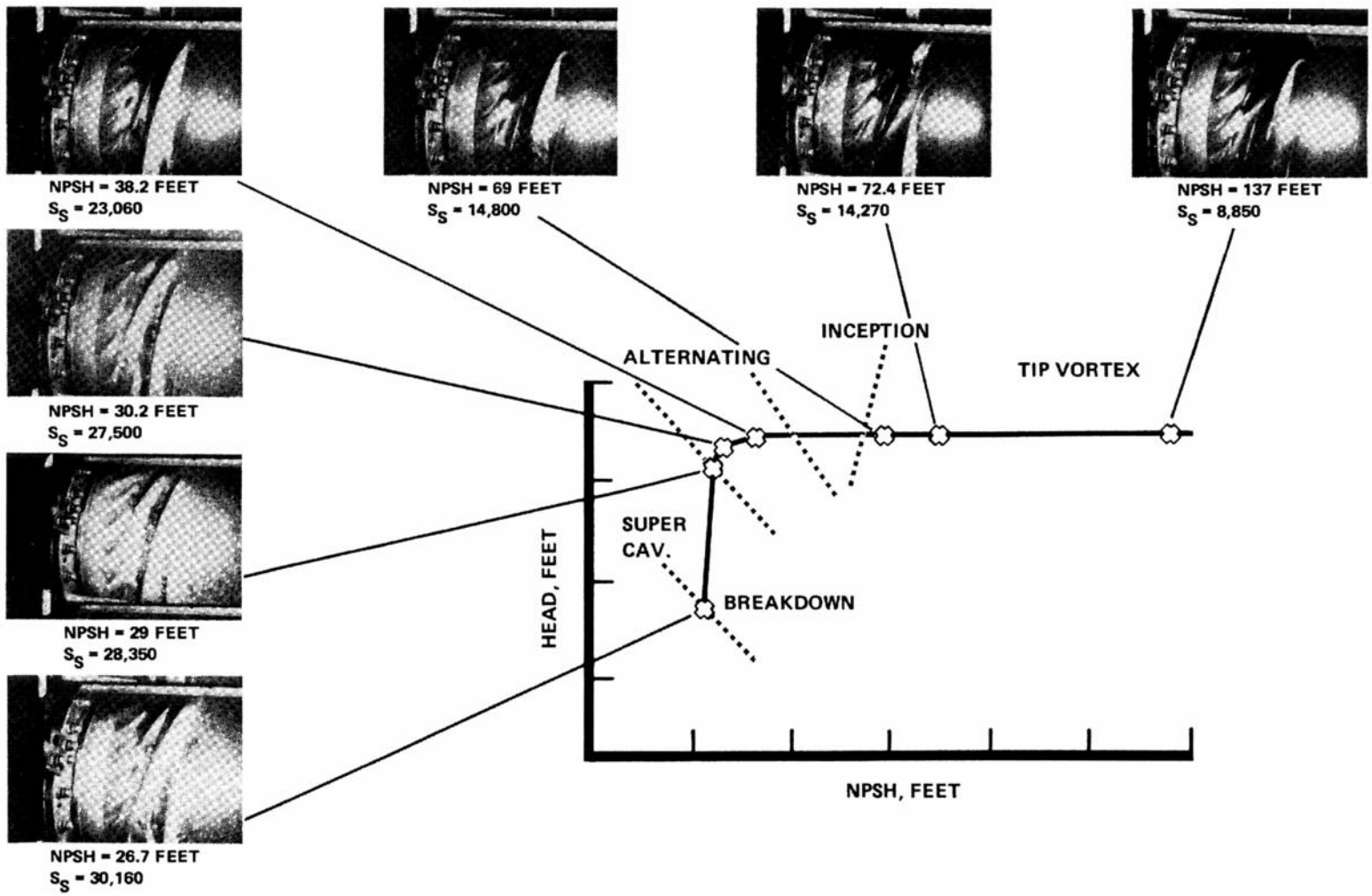
- From Huzel, D. K. and Huang, D. H.



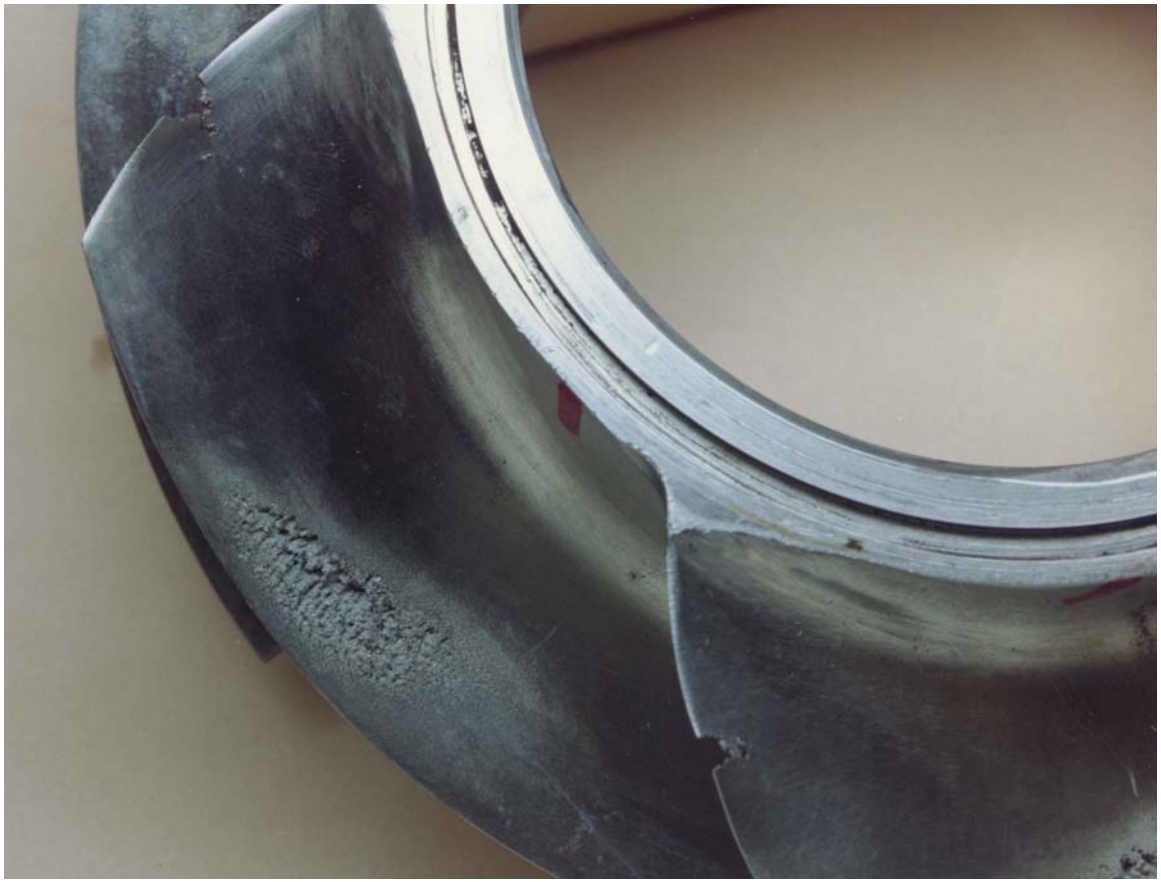
Bucket Curve



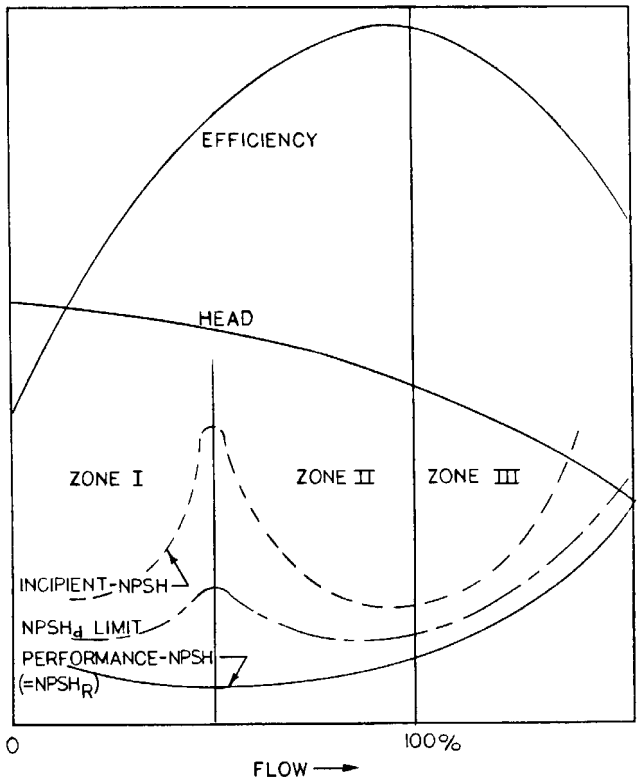
Experimental Inducer Cavitation



Leading Edge Cavitation Damage



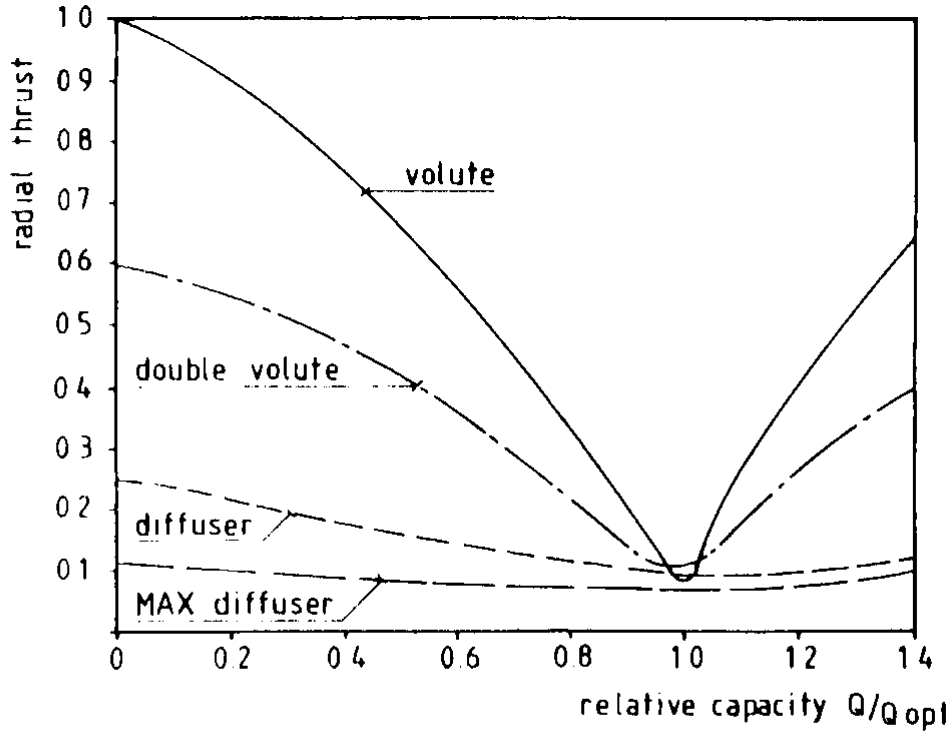
Typical Pump performance curve, showing NPSH required a) to maintain hydraulic performance or pump head ($NPSH_R$), b) to limit cavitation damage and therefore maintain pump life ($NPSH_d$), c) to prevent bubble formation entirely ($NPSH_i$) from Cooper and Antunes(1983)



Pump Losses

- mechanical
- hydraulic
- disk friction
- leakage

Radial Load



Comparison of radial forces

Figure 12. Radial Thrust Vs *Flow for Single Volute, Double Volute, and Diffuser Designs (Courtesy of Stork Pumps).*

Radial Load Profiles for Volutes of Different Specific Speed

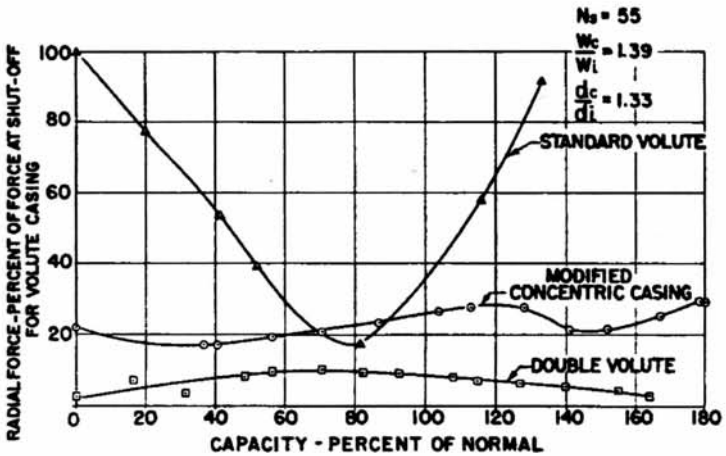


Fig. 8 Comparison of the effect of three casing designs on radial force for $N_s = 55$

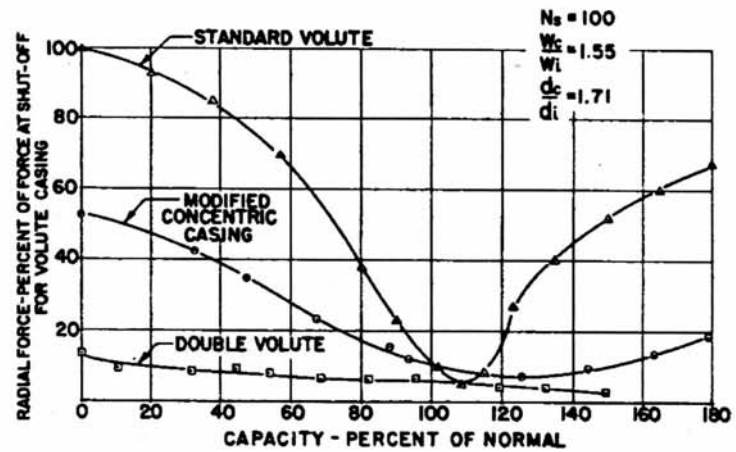


Fig. 9 Comparison of the effect of three casing designs on radial force for $N_s = 100$

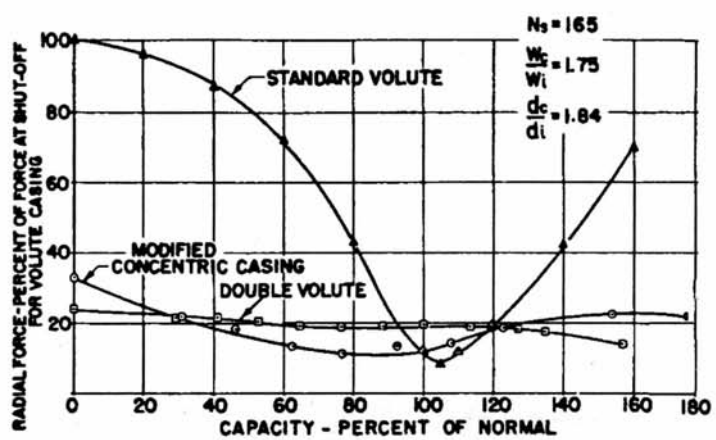
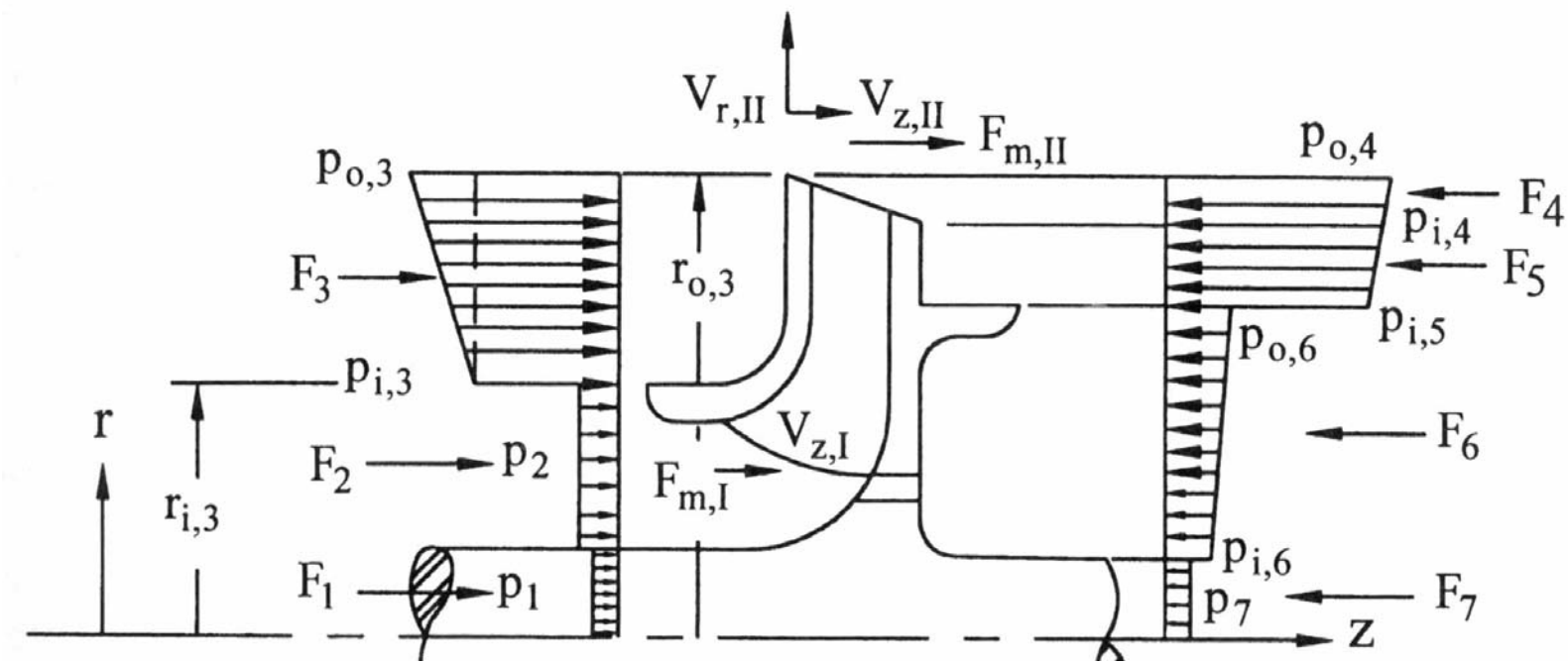


Fig. 10 Comparison of the effect of three casing designs on radial force for $N_s = 165$

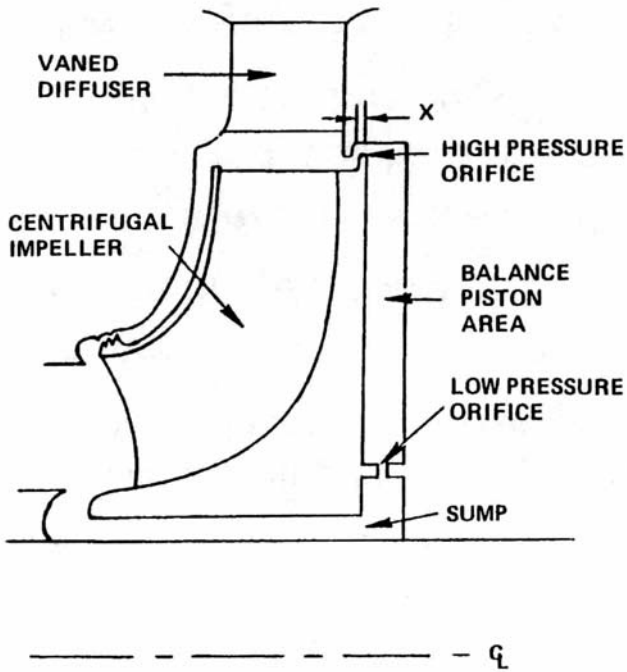
Axial Calculation

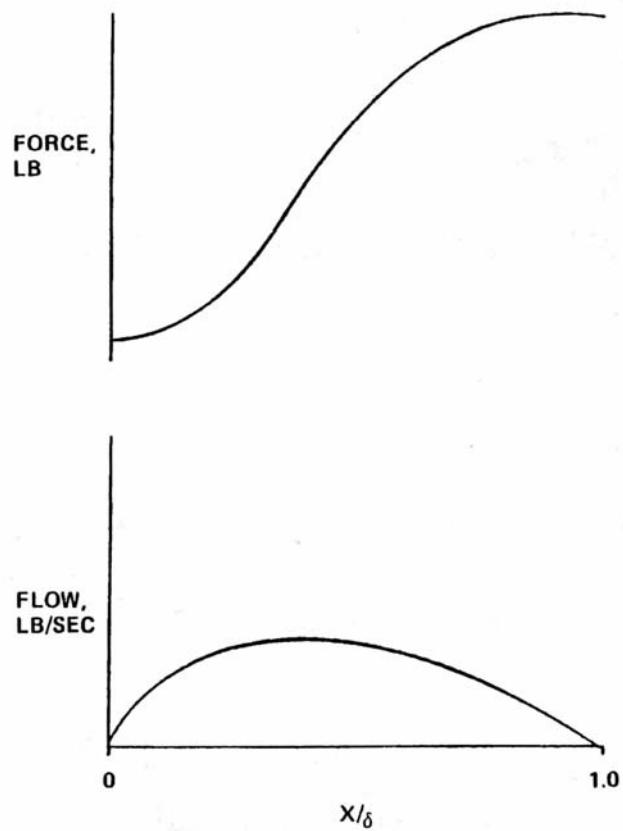


Axial Load Balancing Schemes

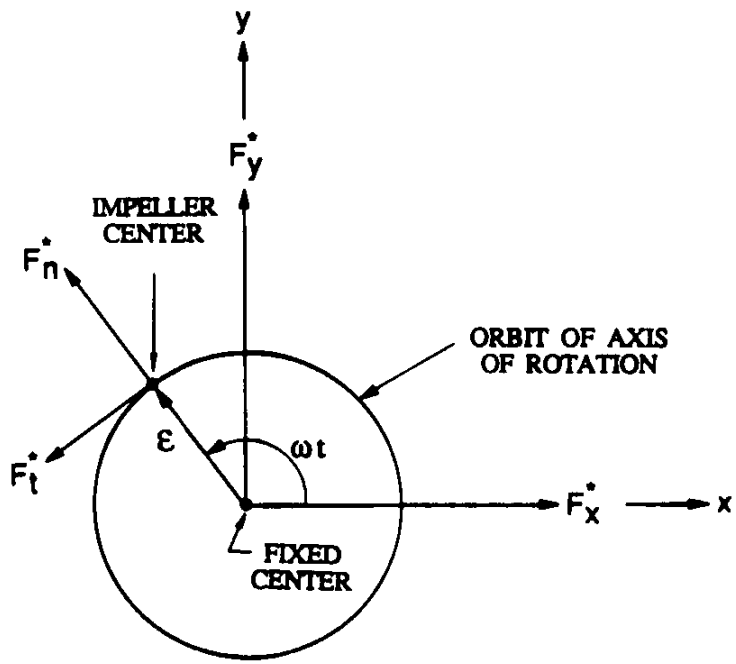
- Seal Leakage Return Path
- Pump out ribs or vanes
- Balance Drum
- Balance Disk

Pump Balance Piston



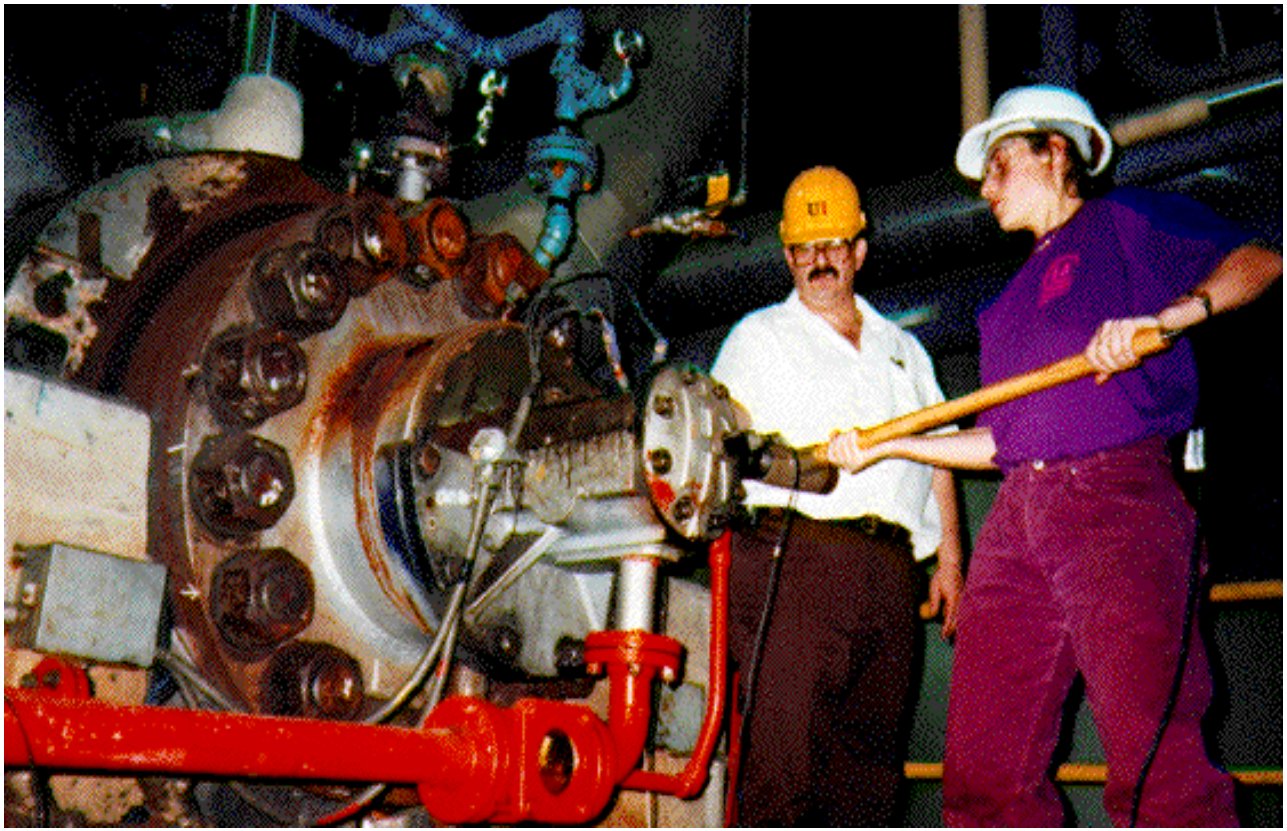


Rotordynamics



Relationship between the forces in the pump frame and the rotordynamic forces from Brennen (1994)

Impact Testing



References

- Anderson, H. H. *Centrifugal pumps*. The Trade and Technical Press Ltd., England
- Balje, O. E. (1981). Turbomachines. *A guide to selection and theory*. John Wiley and Sons, New York.
- BWIP Pump Pocket Book.
- Brennen, C. E. 1994. *Hydrodynamics of Pumps*. Concepts ETI, Inc. and Oxford University Press. New York.
- Brennen, C. E. 1995. *Cavitation and Bubble Dynamics*. Oxford University Press. New York.
- Cameron Hydraulic Data. (1988) Ingersoll-Rand Company.
- Cooper, P. and Antunes, F. F. 1983. "Cavitation damage in boiler feed pumps." Symposium Proceedings on: Power Plant Feed Pumps - The State of the Art, EPRI CS-3158, Cherry Hill, New Jersey, pp. 2.24-2.29.
- Csanady, G. T. (1964) Theory of turbomachines. McGraw-Hill, New York.
- Duncombe, E., 1964, "Aerodynamic Design of Axial Flow Turbines," in *Aerodynamics of Turbines and Compressors*, W. R. Hawthorne, Ed., Princeton University Press, p. 512.
- Fraser, W. H. 1981. "Recirculation in Centrifugal Pumps," *Materials of Construction of Fluid Machinery and Their Relationship to Design and Performance*, ASME Nov. 15-20. Pp. 65-86.
- Fischer, K. and Thoma, D. 1932. "Investigation of flow conditions in a centrifugal pump," Transactions of the ASME, Vol. 54, pp. 141-155.
- Furst, R B. (1973) *Liquid Rocket Engine Centrifugal Flow Turbopumps*. NASA SP-8109.
- Karassik, I. J. And Carter, R. (1960) *Centrifugal pumps*. F. W. Dodge Corporation, New York
- Huzel, D. K. and Huang, D. H. *Modern Engineering for Design of Liquid-Propellant Rocket Engines.* AIAA, Washington D. C.
- Katsanis, T., and McNally, W. D., 1969, "Revised Fortran Program for Calculating Velocities and Streamlines on a Blade-to-Blade Stream Surface of a Turbomachine," NASA TM X-1764.
- Katsanis, T., and McNally, W. D., 1977, "Revised Fortran Program for Calculating Velocities and Streamlines on the Hub-Shroud Stream Surface of an Axial-, Radial-, or Mixed-Flow Turbomachine or Annular Duct," NASA TN D-8430.
- Lazarkiewicz, S. And Troskolanski, A. T. (1965) *Impeller pumps*. Pergamon Press, New York
- Leiblein, S., "Experimental Flow in Two-Dimensional Cascades," in Aerodynamic Design of Axial-Flow Compressors, NASA SP-36, p. 203.
- Macaluso, S B. (1974) *Liquid Rocket Engine Centrifugal Flow Turbopumps*. NASA SP-8110.
- Sloteman, D. P., Wotring, T. L., March, P., McBee, D, and Moody, L. 1995. "Experimental evaluation of high energy pump improvements including effects of upstream piping," *Proceedings of the 12th International Pump Users Symposium*, Houston, Texas.
- Stepanoff, A. J. (1973) *Centrifugal and axial flow pumps*. John Wiley and Sons, New York.