Turbomachinery: Pumps, Fans, and Compressors
Introduction

• Turbomachines add or extract energy from a fluid stream.
• We are mainly concerned with performance and system modelling.
• We will examine those which add energy to a fluid stream:
  • Pumps
  • Fans
  • Compressors
Pumps and Pump Performance

• Pumps increase a fluid’s pressure and must overcome pipe friction, fittings losses, elevation changes, and component losses.

• Common pump designs include
  – Positive displacement
  – Centrifugal flow
  – Axial Flow
  – Special design/application
  – Mainly they fall into “Displacement” and “Kinetic” types of machines
Pumps and Pump Performance

See Fig. 4.1
Classification Chart
Pumps and Pump Performance

• For a simple centrifugal design, one can show that the theoretical pump head is:

\[ H_t = \frac{\omega^2 r_2^2}{g} - \frac{\omega \cot \beta_2}{2\pi l_2 g} Q \]

\[ H_t = A - BQ \]

• In reality, a pump’s performance is more readily modelled as:

\[ H_p = A - BQ^2 \]
Pumps and Pump Performance

• Pump Performance

Actual Head:

$H_p = H_t - h_L$

Actual Fluid Power:

$\dot{W}_f = \rho g H_p Q = \Delta p Q$

Brake (Impeller) Power:

$\dot{W}_p = \omega T$

Efficiency:

$\eta_p = \frac{\dot{W}_f}{\dot{W}_p} = \frac{\rho g H_p Q}{\omega T} < 1$
Pumps and Pump Performance

• Pump Selection
Pumps and Pump Performance

- Pump Curves
  - \( H \) vs \( Q \), \( \text{NPSH}_R \), Brake Horse Power, and Efficiency
Pumps and Pump Performance

• Matching System and Pump Curves
Pumps and Pump Performance

• If the system and pump curves are given by simple expressions:

\[ \Delta p_p = a_o + a_1 \dot{m} + a_2 \dot{m}^2 + \cdots + a_n \dot{m}^n \]

\[ \Delta p_s = b_o + b_1 \dot{m} + b_2 \dot{m}^2 + \cdots + b_n \dot{m}^n \]

• The operating point is found at the intersection of the two curves:

\[ \Delta p_p = \Delta p_s \]
Example 4.1 (Problem 4.1)

• A piping system requires a pump to be selected to deliver at least 75 gpm of flow at 400 ft of head. The pump is to operate on a 60 Hz fixed nominal speed of 3500 RPM. Select a pump using Fig. 4.2 and determine the nominal impeller size, operating efficiency, and NPSHR for the desired characteristics.
Example 4.2 (Problem 4.2)

• Given a pump curve of the form:

\[ H_p = 200 - 0.3m^2 \]

and system curve of the following form:

\[ H_f = 100 + 2.5m + 0.5m^2 \]

find the system operating point.
Example 4.3 (Problem 4.5)

- Consider the closed loop pumping system sketched in class. If the total length of piping is 60 [m], with a diameter of 5 [cm], and a roughness = 0.0001 [m], what is the resultant flow in the system if the pump has the following characteristic:

\[ H_p = 250 - 0.25m^2 \]

- and the filter has the following pressure loss:

\[ H_f = 50 + 0.5m^2 \]
Pumps and Pump Performance

• Pump Performance (Series Combinations)
  – Pumps are combined in series to increase pump head when discharge is satisfactory

At constant flow we add $H$:

$$H_s = H_1 + H_2 + \cdots + H_n$$
Pumps and Pump Performance

• Pump Performance (Parallel Combinations)
  – Pumps are combined in parallel when pump head is adequate but discharge is not

At constant head we add $Q$:

$$Q_p = Q_1(H) + Q_2(H) + \cdots + Q_n(H)$$
Example 4.4

• Consider a pump with the following performance characteristic:

\[ \Delta p = 100,000 - 25m^2 \]

• Find the equivalent pump curve for two pumps in series (2PS) and two pumps in parallel (2PP)
Example 4.5 (Problem 4.5 con’t)

• A continuation of problem 4.5. If the desired discharge were \( m^\prime = 25 \) [kg/s] and the pump was normally run at 1750 RPM, can the desired discharge be achieved with two pumps in series or two pumps in parallel.
Example 4.6 (Old Midterm-2007)

• Recently a local fellow with a cabin, contacted me about a problem he was having with a Honda W X15 CX1 pump he’d bought several months earlier. The pump is rated for a maximum flow of 240 [L/min] and maximum head of 40 [m] and contains 1.5 [inch] inlet/outlet fittings. It seems that the salesman who also sells snow blowers, lawn mowers, and generators, knew absolutely nothing about what he was selling this fellow. Now this fellow’s problem was that he wished to fill two large tanks atop a hill near his cabin to allow water to gravity feed a bathroom (or fancy outhouse) he was building for his cabin. His desired flow rate was approximately 35 [gpm] or 132 [L/min] and a friend had instilled him with doubts of success with this selected pump model. The water is to flow in [1.5] inch rubber hose from a nearby lake along a length of hose of approximately 120 [ft]. The top of the hill where the tanks are located is approximately 40 [ft] above the lake surface. Assuming that the density of water is 1000 [kg/m$^3$] and its viscosity is 0.001 [Pa s] determine the following:
  – Will the pump “as is” fill his two tanks if one can wait all day, i.e. although the salesman could not say with certainty, I am asking you if this model of pump will work, assuming YOU are the salesman. Please explain simply and clearly and use a sketch.
  – Next, obtain an approximate performance curve for the pump using the given data I provided from the pump data sheet which was given to me by the fellow when he came to see me.
  – Develop the necessary energy balance for this pump/system interaction.
  – Solve the equation obtained in part c for the flow in L/min. Is his desired flow rate met?

• If you are successful at validating my calculations for this fellow, then you have come one step closer to replacing the Honda salesman, who sold him the pump, on your final work term!!!!!!
Example 4.7 (Old Exam Question)

- We discussed the 2007 exam problem related to combining pumps in series, parallel, and series-parallel. The complete family of curves is below. The individual curves follow.
Example 4.7 (Continued)

Basic System

Series System
Example 4.7 (Continued)

Parallel System

Series-Parallel System
Pumps and Pump Performance

• Cavitation in Pumps
  • Cavitation is the formation and collapse of bubbles in the impeller housing of a pump.
  • It can lead to erosion pitting of the impeller leading to a loss of pump performance.
  • We ensure cavitation does not occur by ensuring that Net Positive Suction Head (NPSH) available (A) exceeds that required (R) by the pump.

\[ NPSH_A > NPSH_R \]

• NPSH(A) is a design parameter, while NPSH(R) is a characteristic of the pump.
Pumps and Pump Performance

• NPSH(A) is defined as follows:

\[
NPSH_A = \frac{p_i}{\rho g} + \frac{V_i^2}{2g} - \frac{p_v}{\rho g}
\]

\[
NPSH_A = \frac{p_a}{\rho g} - Z_i - h_{f,i} - \frac{p_v}{\rho g}
\]

• The head losses up to the inlet are what are included, nothing else!

• This leads to a number of analysis problems such as: finding vertical placement \((Z_i)\), horizontal placement \((L_i)\), intake diameter \((D_i)\) or minor loss factor \(K\).
Example 4.8 (Problem)

- A particular pump is required to pump 24000 gpm of water whose free surface is at atmospheric pressure. If the losses leading up to the inlet at this flow rate are 6 ft of head, where should the pump be placed with respect to the free surface to avoid cavitation if the NPSH(R) = 40ft. The vapour pressur eof water is 0.26 psi and the $\gamma=\rho g$ value is 62.4 lb/ft$^3$.
Pumps and Pump Performance

• Pump Performance: Scaling
  – In general pump performance varies according to:

  \[ \phi \left( \dot{W}, \omega, D, Q, H, \rho, \mu, \frac{l_1}{D}, \frac{l_2}{D}, \ldots \right) = 0 \]

  – For geometrically similar machines we only consider:

  \[ \phi(\dot{W}, \omega, D, Q, H, \rho, \mu) = 0 \]
Pumps and Pump Performance

- Pump Performance

\[
C_w = \frac{\dot{W}}{\rho(\omega D)^3 D^2}
\]

\[
C_Q = \frac{Q}{(\omega D)D^2}
\]

\[
C_p = \frac{\Delta p}{\rho(\omega D)^2}
\]

\[
C_H = \frac{Hg}{(\omega D)^2}
\]

\[
\eta = \frac{C_Q C_H}{C_W}
\]

Power
Flow
Pressure
Efficiency
Pumps and Pump Performance

- Pump Performance:
  - Geometrically Similar Machines

\[
\begin{align*}
\frac{\dot{W}_2}{\dot{W}_1} &= \left( \frac{\rho_2}{\rho_1} \right) \left( \frac{\omega_2}{\omega_1} \right)^3 \left( \frac{D_2}{D_1} \right)^5 \\
\frac{H_2}{H_1} &= \left( \frac{\omega_2}{\omega_1} \right)^2 \left( \frac{D_2}{D_1} \right)^2 \\
\frac{Q_2}{Q_1} &= \left( \frac{\omega_2}{\omega_1} \right) \left( \frac{D_2}{D_1} \right)^3
\end{align*}
\]
Pumps and Pump Performance

• Pump Performance
  – Partially Similar Machines

\[
\frac{\dot{W}_2}{\dot{W}_1} = \left( \frac{\rho_2}{\rho_1} \right) \left( \frac{\omega_2}{\omega_1} \right)^3 \left( \frac{D_2}{D_1} \right)_i^3 \left( \frac{D_2}{D_1} \right)_h^2 = \left( \frac{\rho_2}{\rho_1} \right) \left( \frac{\omega_2}{\omega_1} \right)^3 \left( \frac{D_2}{D_1} \right)^3
\]

\[
\frac{H_2}{H_1} = \left( \frac{\omega_2}{\omega_1} \right)^2 \left( \frac{D_2}{D_1} \right)^2
\]

\[
\frac{Q_2}{Q_1} = \left( \frac{\omega_2}{\omega_1} \right) \left( \frac{D_2}{D_1} \right)_i \left( \frac{D_2}{D_1} \right)_h^2 = \left( \frac{\omega_2}{\omega_1} \right) \left( \frac{D_2}{D_1} \right)
\]

– “I” = impeller and “h” = housing
Fans and Fan Performance

• Fan Performance
  – Fan performance and scaling is much the same as it is for pumps
  – Major difference is that for many fans, total pressure is used in the performance curve as the inlet and outlet areas are often not equal
  – Thus, we define:

\[ P_t = P_s + \frac{\rho V^2}{2} \]
Fans and Fan Performance

- Fan Performance
Fans and Fan Performance

• Fan Performance
Fans and Fan Performance

• Flow Control

a) Flow control device (system controlled), b) pump/fan controlled, c) both
Examples

• A few more examples from old exams and midterms.