Matching Pumps and Systems

ME 322 Lecture Slides, Winter 2007

Gerald Recktenwald*

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*Associate Professor, Mechanical and Materials Engineering Department Portland State University, Portland, Oregon, gerry@me.pdx.edu

Overview

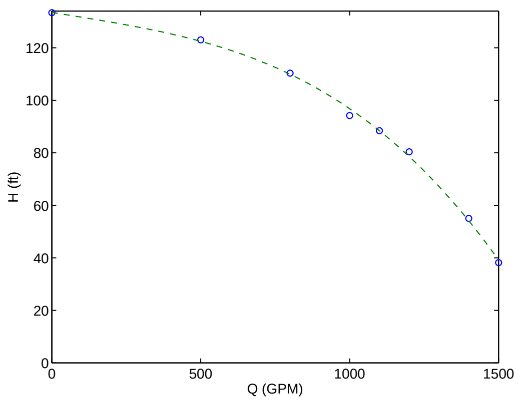
Learning Objectives

- Be able to sketch a basic system curve.
- Be able to modify a sketch of a system curve to take into account changes in elevation and changes in valve settings.
- Be able to define NPSH, $\mathrm{NPSH_A}$, and $\mathrm{NPSH_R}$
- Be able to define the vapor pressure of a liquid
- Be able to explain why maintaining adequate NPSH is necessary for pump operation.
- Be able to sketch the balance point of a system and a pump.
- Be able to show how the balance point changes when a valve in the system changes.
- Be able to identify the role of pump efficiency and motor efficiency in overall system performance.

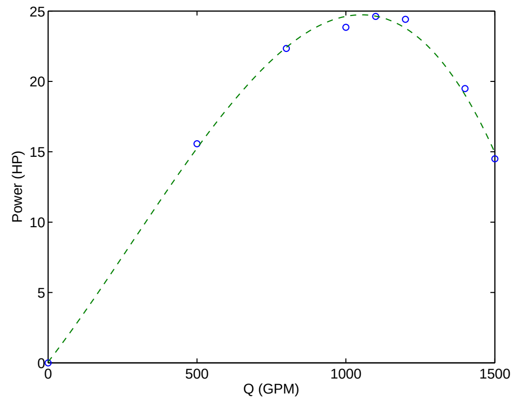
Pump Performance Data

Data from Problem 11.13 in Fox and McDonald

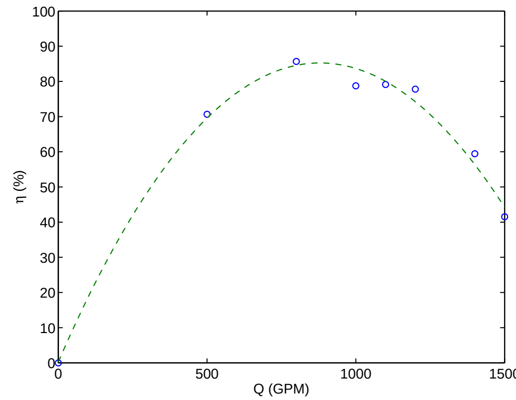
$$h = f_1(Q)$$



$$\dot{W}_f = f_2(Q)$$

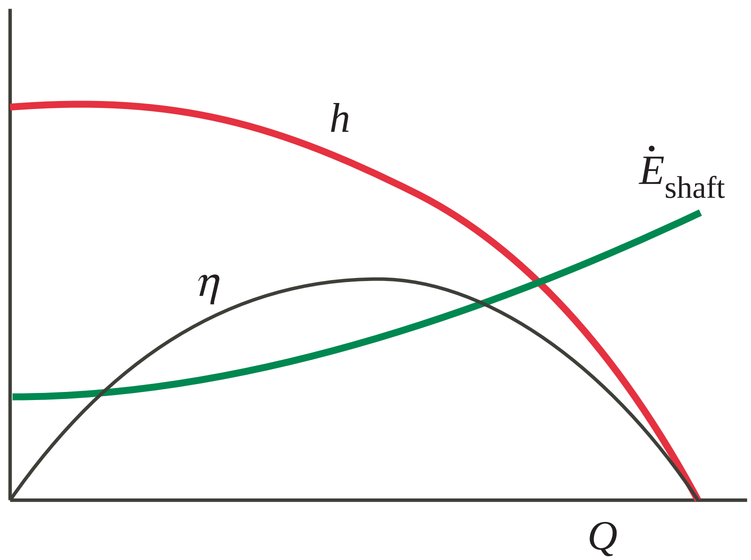


$$\eta = f_3(Q)$$

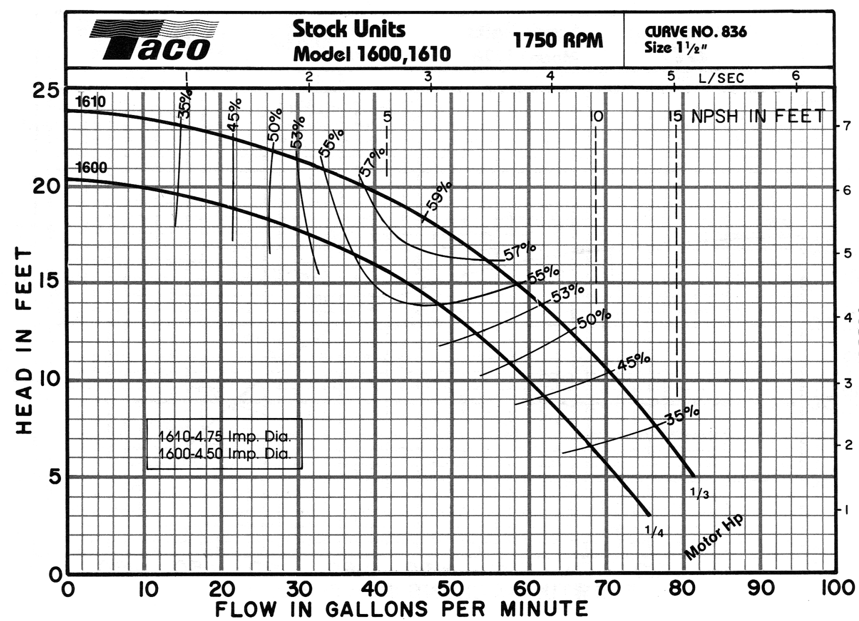


Pump Performance Data

Simplified



One Manufacturer's version



Net Positive Suction Head (1)

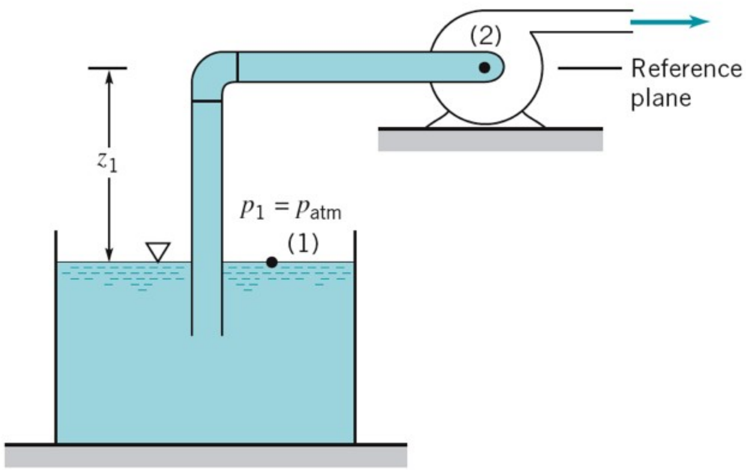
Goal: Avoid cavitation in the pump

Cavitation: Spontaneous generation of vapor caused by lowering the pressure in a liquid.

Vapor is generated when $p < p_{\rm sat}$, where $p_{\rm sat}$ is the vapor pressure of the liquid.

Review vapor pressure in §1.8 in the textbook.

Net Positive Suction Head (1)



Source: Munson, Young and Okiishi, Figure 12.13

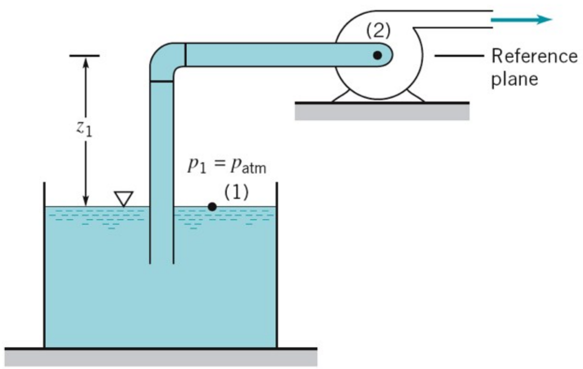
Apply energy equation with *absolute pressures*

$$\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 = \frac{p_{\rm atm}}{\gamma} + z_1 - h_L$$

Solve for p_2

$$p_2 = p_{\rm atm} - \frac{\rho V^2}{2} - \gamma(z_2 - z_1) - h_L$$

Net Positive Suction Head (2)



Source: Munson, Young and Okiishi, Figure 12.13

$$p_2 = p_{\text{atm}} - \frac{\rho Q^2}{2A^2} - \gamma(z_2 - z_1) - h_L$$

If $p_2 < p_{\text{sat}}$ the liquid cavitates at station 2
The pressure *inside* the pump is less than p_2, so cavitation can still occur.

Manufacturers provide *Net Positive Suction Head* data to specify a safe margin for the pressure immediately upstream of the pump inlet (suction).

Net Positive Suction Head (3)

Define Net Positive Suction Head (NPSH)

$$\mathrm{NPSH} = \frac{p_i}{\rho g} + \frac{V_i^2}{2g} - \frac{p_v}{\rho g}$$

where p_i and V_i are the pressure and average velocity at the pump inlet, and p_v is the vapor pressure of the liquid at the design temperature

If $\mathrm{NPSH} < 0$ the pump will *cavitate*

Net Positive Suction Head (4)

Design procedure

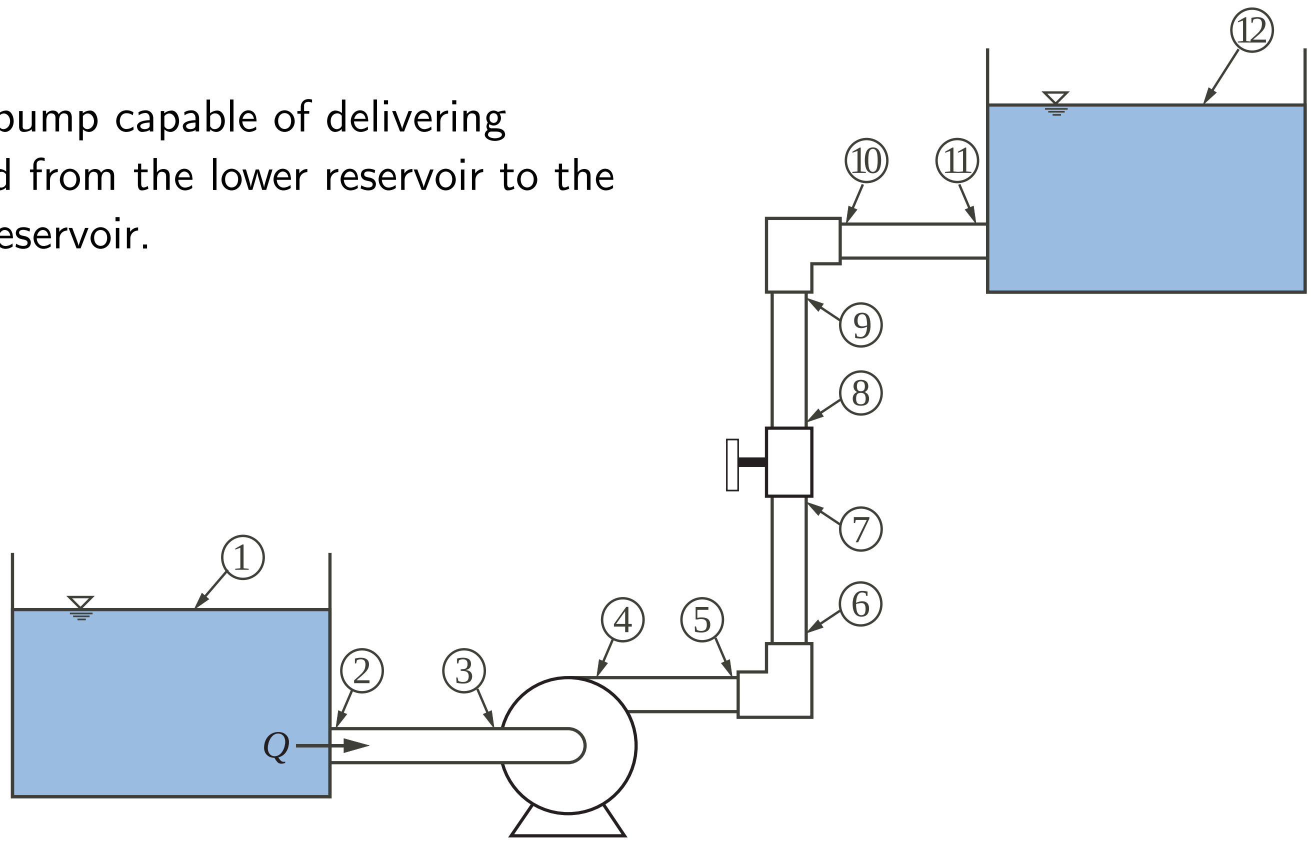
- Compute NPSH_A, the *actual* NPSH, at the *maximum flow rate*. Write the energy equation between a known datum and the pump inlet. Use *absolute pressure* units.
- Look up NPSH_R, the *required* NPSH, on the pump performance map

make sure that $\mathrm{NPSH}_A > \mathrm{NPSH}_R$

- Adjust system design as necessary to allow for proper NPSH
  - ▷ Place pump in lowest spot in loop to maximize NPSH_A You may need to place the pump lower than any other system components. This might *increase* the pumping requirements by increasing the length of pipe.
  - ▷ Choose another pump

A Typical Pump Application (1)

Goal: Find a pump capable of delivering the fluid from the lower reservoir to the upper reservoir.



A Typical Pump Application (2)

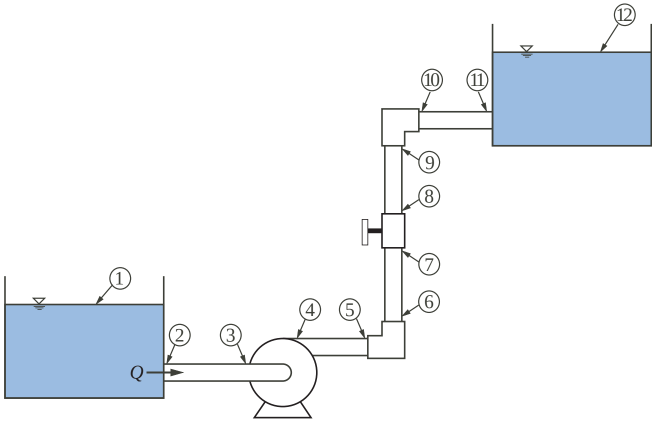
Energy Equation:

$$z_{12} - z_1 = h_s - h_L$$

$$h_s = \mathcal{H}(Q) \qquad \text{pump head curve}$$

$$h_L = \sum f_{i,j} \frac{L_{i,j}}{D_{i,j}} \frac{V_{i,j}^2}{2g} + \sum K_{L,i} \frac{V_i^2}{2g}$$

$$= \sum f_{i,j} \frac{L_{i,j}}{D_{i,j}} \frac{Q^2}{2gA_{i,j}^2} + \sum K_{L,i} \frac{Q^2}{2gA_i^2}$$



Solution is a root-finding problem: Find Q such that

$$z_{12} - z_1 - \mathcal{H}(Q) + \sum f_{i,j} \frac{L_{i,j}}{D_{i,j}} \frac{Q^2}{2gA_{i,j}^2} + \sum K_{L,i} \frac{Q_i^2}{2gA_i^2} = 0$$

A Typical Pump Application (3)

The energy equation (from preceding slide) is

$$z_{12} - z_1 = \mathcal{H}(Q) - \sum f_{i,j} \frac{L_{i,j}}{D_{i,j}} \frac{Q^2}{2gA_{i,j}^2} - \sum K_{L,i} \frac{Q^2}{2gA_i^2}$$

Factor out Q from summations on the right hand

$$z_{12} - z_1 = \mathcal{H}(Q) - Q^2 \left[\sum f_{i,j} \frac{L_{i,j}}{D_{i,j}} \frac{1}{2gA_{i,j}^2} - \sum \frac{K_{L,i}}{2gA_i^2} \right]$$

Define C as the big term in brackets

$$z_{12} - z_1 = \mathcal{H}(Q) - CQ^2$$

or

$$\mathcal{H}(Q) - CQ^2 - \Delta z = 0$$

where Δz is the elevation difference between the outlet and the inlet

Matching a Pump to a System (1)

The simplified view of the energy equation is

$$\mathcal{H}(Q) - CQ^2 - \Delta z = 0 \qquad \text{or} \qquad \mathcal{H}(Q) = CQ^2 + \Delta z$$

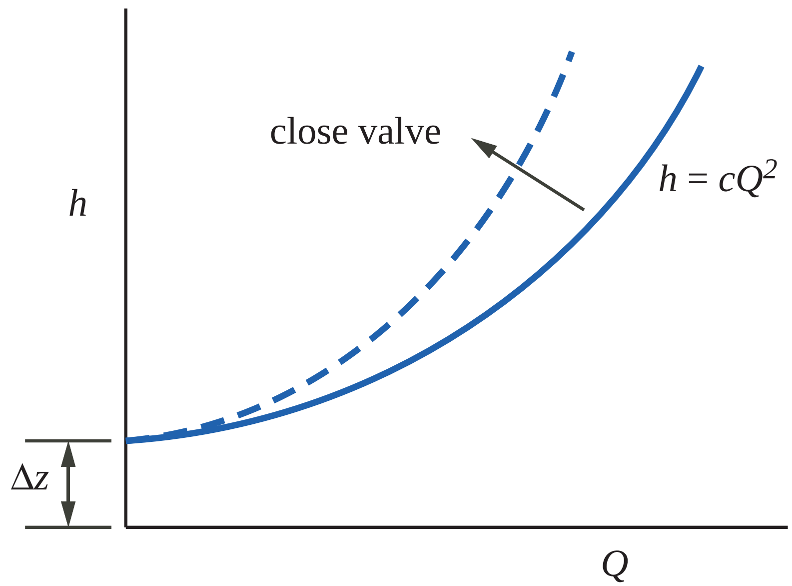
where complexity of head loss calculation is hidden in C.

Although a pump can operate over a range of h and Q values, *there is only one operating point where the pump output matches the system*. This operating point is the *balance point for the pump and system*.

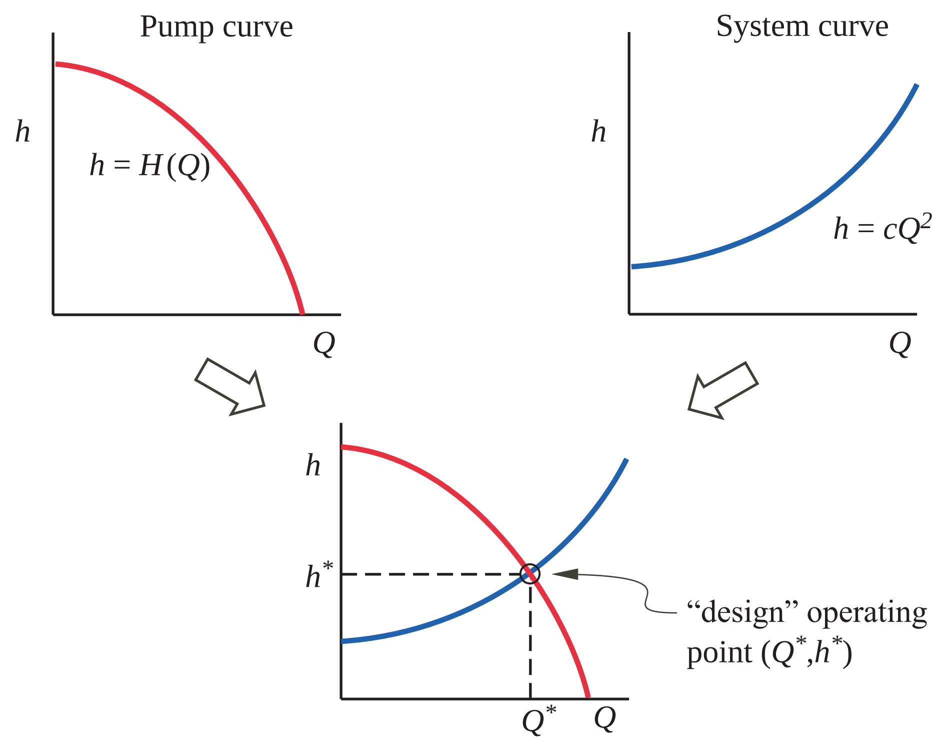
Matching a Pump to a System (2)

System curve:

$$h_L = \sum f_{i,j} \frac{L_{i,j}}{D_{i,j}} \frac{Q^2}{2gA_{i,j}^2} + \sum K_{L,i} \frac{Q^2}{2gA_i^2} = CQ^2$$



Matching a Pump to a System (3)



The energy equation contains the matching condition

$$\mathcal{H}(Q) - CQ^2 - \Delta z = 0 \qquad \text{or} \qquad \mathcal{H}(Q) = CQ^2 + \Delta z$$

Matching a Pump to a System (4)

Minimal objectives

- Pump needs sufficient "capacity" (h and Q)
  $\Longrightarrow$ pump and system curves should intersect
- Pump operates with $\mathrm{NPSH}_A > \mathrm{NPSH}_R$

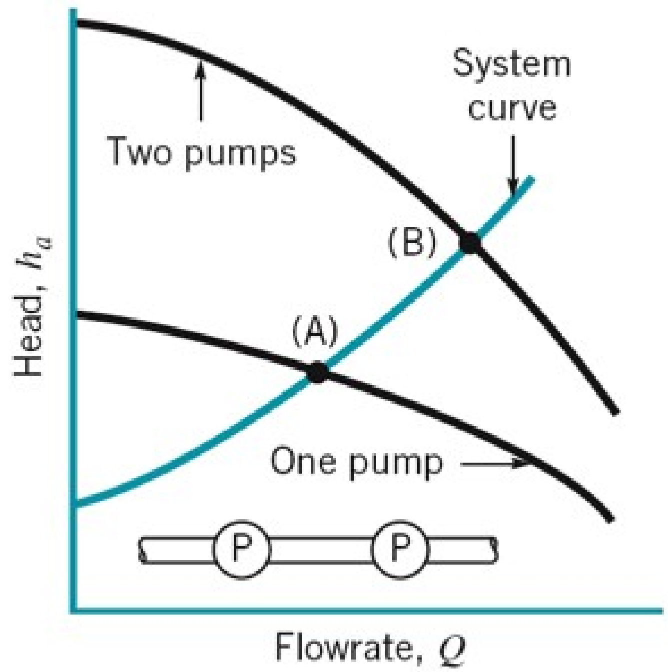
Optimization

- Select pump so that the design operating point is near BEP
- Pumps will likely operate at "off-design" conditions
- Economic analysis should weigh first-cost versus life-cycle cost

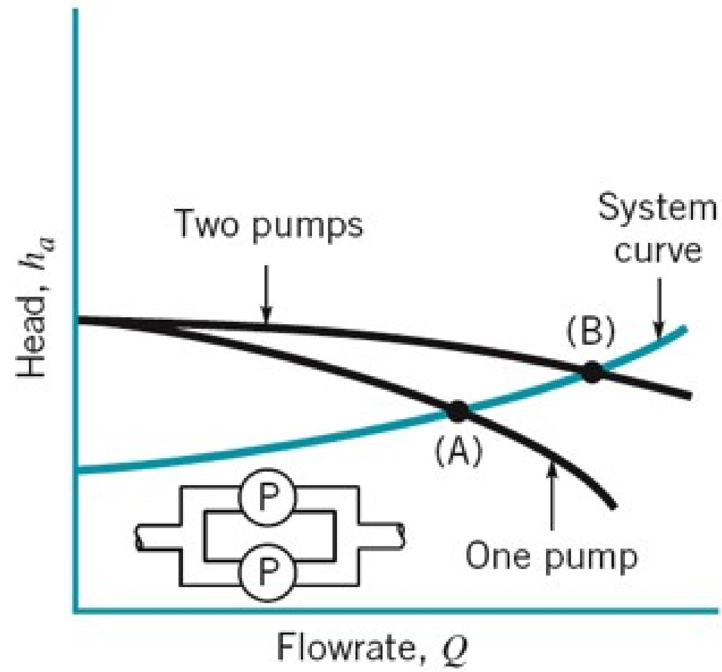
Other considerations

- Aging of pipes: scale build-up reduces flow area
- Critical installations will require redundant pumps to allow for maintenance

Pumps in Series and Parallel



(*a*)

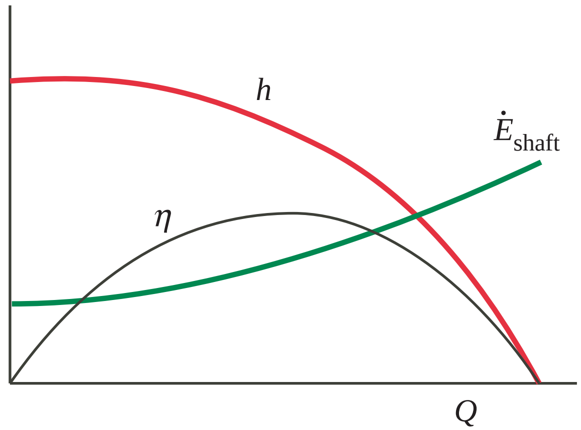


(*b*)

Pump Performance

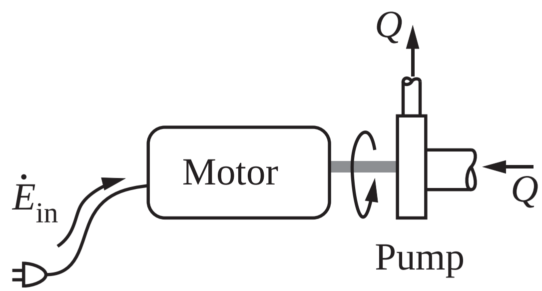
Other pump performance parameters:

$$\eta = \text{efficiency} \qquad \dot{E}_{\text{shaft}} = \text{shaft power, a.k.a. BHP}$$



Note: The $\dot{E}_{\text{shaft}}$ curve is *not* a system curve. The $\dot{E}_{\text{shaft}}$ curve shows the shaft power required to deliver flow rate Q.

Power Input to the Pump

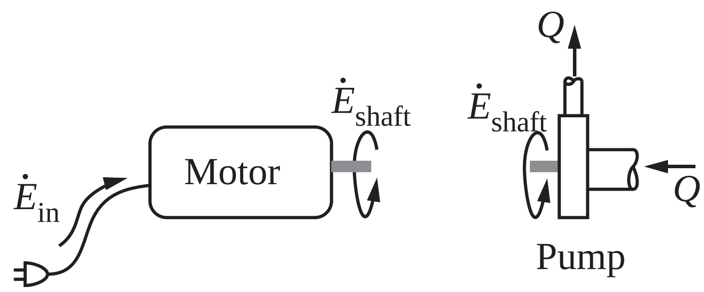


The motor supplies the shaft power to the pump.

Overall efficiency of the motor/pump combination relates the power delivered to the fluid to the electrical power supplied to the motor.

$$\eta = \frac{\dot{E}_f}{\dot{E}_{\rm in}} = \frac{\text{power supplied to the fluid}}{\text{electrical power supplied to the motor}}$$

Shaft Power from the Motor



Motor inefficiencies

$$\dot{E}_{\text{shaft}} < \dot{E}_{\text{in}}$$

Pump inefficiencies

$$\dot{E}_f < \dot{E}_{\text{shaft}} < \dot{E}_{\text{in}}$$

Overall and Mechanical Efficiency

Overall efficiency

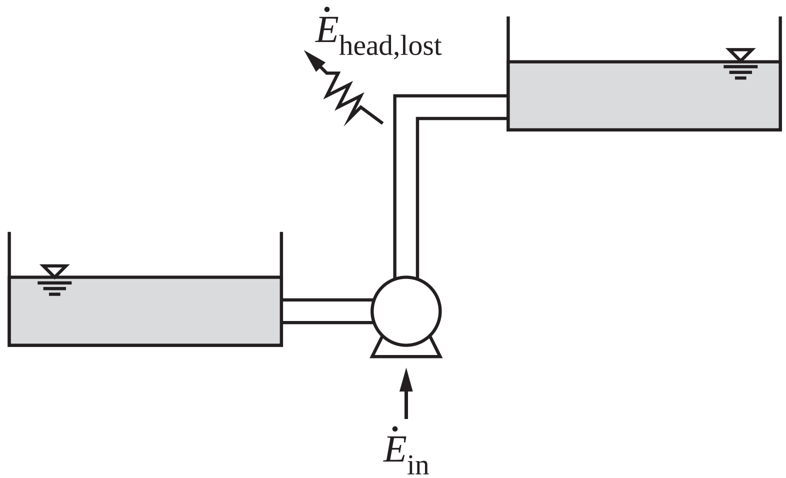
$$\eta = \frac{\dot{E}_f}{\dot{E}_{\mathrm{in}}} = \frac{\text{power supplied to the fluid}}{\text{electrical power supplied to the motor}}$$

Mechanical efficiency of the pump alone

$$\eta_{\mathrm{mech}} = \frac{\dot{E}_f}{\dot{E}_{\mathrm{shaft}}} = \frac{\text{power supplied to the fluid}}{\text{shaft power supplied to the pump}}$$

Power Loss in System

Power loss in the piping system does not directly affect the efficiency of the pump.



Power lost in the fluid system is

$$\dot{E}_{\text{head,loss}} = \gamma Q h_L$$

where h_L is the head loss for the fluid system.