A SunCam online continuing education course

Positive Displacement Pump Selection

by

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Course Outline:

What is a Positive Displacement Pump?

Pumps are mechanical devices that move fluids. A positive displacement pump has chambers that repeatedly fill (suction) and empty (discharge) to displace (move) fluid, as depicted in Figure 1. This results in the discharge of a known amount of fluid for each fill and empty cycle.

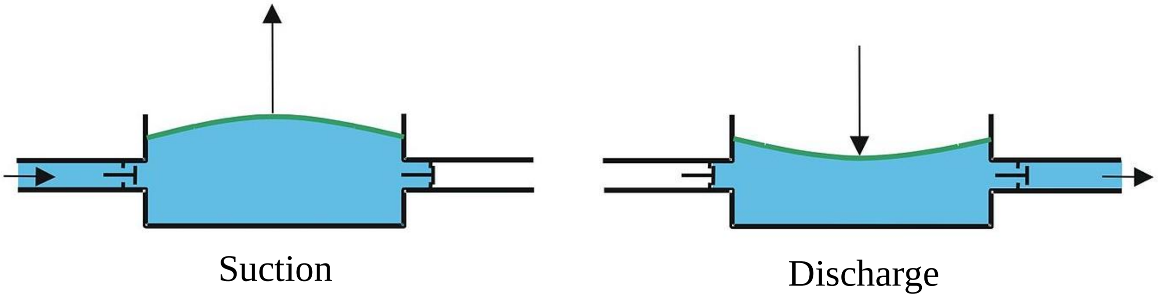


Figure 1: A positive displacement pump head during the fill cycle (left) and discharge cycle (right). In this case, a diaphragm moves up to pull in fluid from the left, then moves down to push out fluid to the right. There are check valves to ensure flow only moves to the right.

Source: https://commons.wikimedia.org/wiki/File:Membranpumpe_Pumpen.jpg, Schorschi2, CC BY-SA 3.0

Positive displacement (PD) pumps deliver a constant flow rate regardless of the suction and discharge pressures. This differs from centrifugal/rotodynamic pumps which use spinning impellers to move fluid. A centrifugal pump delivers different flow rates at different pressures.

PD pumps are grouped into two main categories:

- Reciprocating Pumps:
  - Uses back and forth (oscillating) motion to move fluid.
  - Accelerates the fluid with each cycle (a.k.a. pulsation).
  - Requires check valves on each end of the pump head.
  - The example in Figure 1 is a reciprocating pump.
- Rotary Pumps:
  - Uses rotating motion to move fluid.
  - Delivers a more consistent flow of fluid.

Benefits

There is no clear “winner” when comparing pump types. Pumps are selected based on the specifics of the application. However, some general advantages of PD pumps compared to centrifugal pumps are listed in Table 1.

Table 1: Advantages and Disadvantages of PD Pumps

Advantages	Disadvantages
Lower construction cost	Lower efficiency
Handles high viscosity fluids (slurries & pastes)	Pulsation/acceleration of fluid
Small pumps can handle high pressures	Maximum pressure less than large centrifugal pumps
Less priming issues	Maximum flow less than large centrifugal pumps
Can pull a high lift	More noise
Fewer cavitation and suction problems	More moving parts to maintain
Consistent flow during changing pressures	More complex internals
Speed adjustable to a very slow, giving greater flow range	Pressure relief valves are often needed
Separate flow meter not needed	Pulsation dampeners are often needed
Pneumatic, hydraulic, and electromagnetic drive options	Can’t maintain a constant discharge pressure

Flow Control

Virtually every type of pump can have the flow rate controlled by adjusting the pump speed. For reciprocating pumps, there are two ways to controlling the flow rate:

1. Stroke Length: By adjusting the distance the piston/plunger/diaphragm moves, the volume of liquid displaced per stroke of the pump is changed.
2. Stroke Speed: By adjusting the speed of the strokes. For example with a variable frequency drive (VFD).

PD pumps are often designed to accurately control the flow rate to a 10:1 turndown ratio, which is 10% of the design capacity. Many metering pumps (controlled-volume diaphragm pumps) are designed for a turndown of 100:1 (1%) to 1000:1 (0.1%). Note that for centrifugal pumps, the common turndown ratio is 2:1, or 50% speed.

Industries

PD pumps are commonly used in many industries around the world, including the following:

- Chemical
- Food & Beverage
- Manufacturing
- Marine
- Oil & Gas
- Power Generation
- Water & Wastewater

Many types of engineers regularly encounter PD pumps, including:

- Chemical Engineers
- Environmental Engineers
- Industrial Engineers
- Marine Engineers
- Mechanical Engineers
- Nuclear Engineers
- Petroleum Engineers

Engineers are expected to select a pump type that is appropriate for the application and of the correct size to handle the design conditions. This course will help prepare you for these tasks.

Standards

The Hydraulic Institute (HI) Standards are the most commonly accepted guidelines and specifications for the design of pumping systems. Positive displacement pumps are covered in the ANSI/HI standards listed in Table 2.

Table 2: ANSI/HI Standards for PD Pumps

Standard No.	Standard Title
3.1 - 3.5	Rotary Pumps for Nomenclature, Definitions, Application and Operation
3.6	Rotary Pump Tests
4.1 - 4.6	Sealless Magnetically Driven Rotary Pumps for Nomenclature, Definitions, Application, Operation, and Test
6.1 - 6.5	Reciprocating Pumps
6.6	Reciprocating Tests
8.1 - 8.5	Direct Acting Pumps
7.1 - 7.5	Controlled-Volume Metering Pumps
7.6	Controlled-Volume Metering Pumps for Tests
9.6.9	Rotary Pumps - Guidelines for Condition Monitoring
10.1 - 10.5	Air-Operated Pumps

Pressure Protection

PD pumps should be designed and operated to avoid flow restrictions in the discharge piping, which can cause excessive pressures or power demands. If the discharge pipe is blocked, the pump will continue to push fluid into the pipe which increases the pressure. To help protect the pumping system, a pressure relief valve is typically added to the discharge piping.

Pump Types

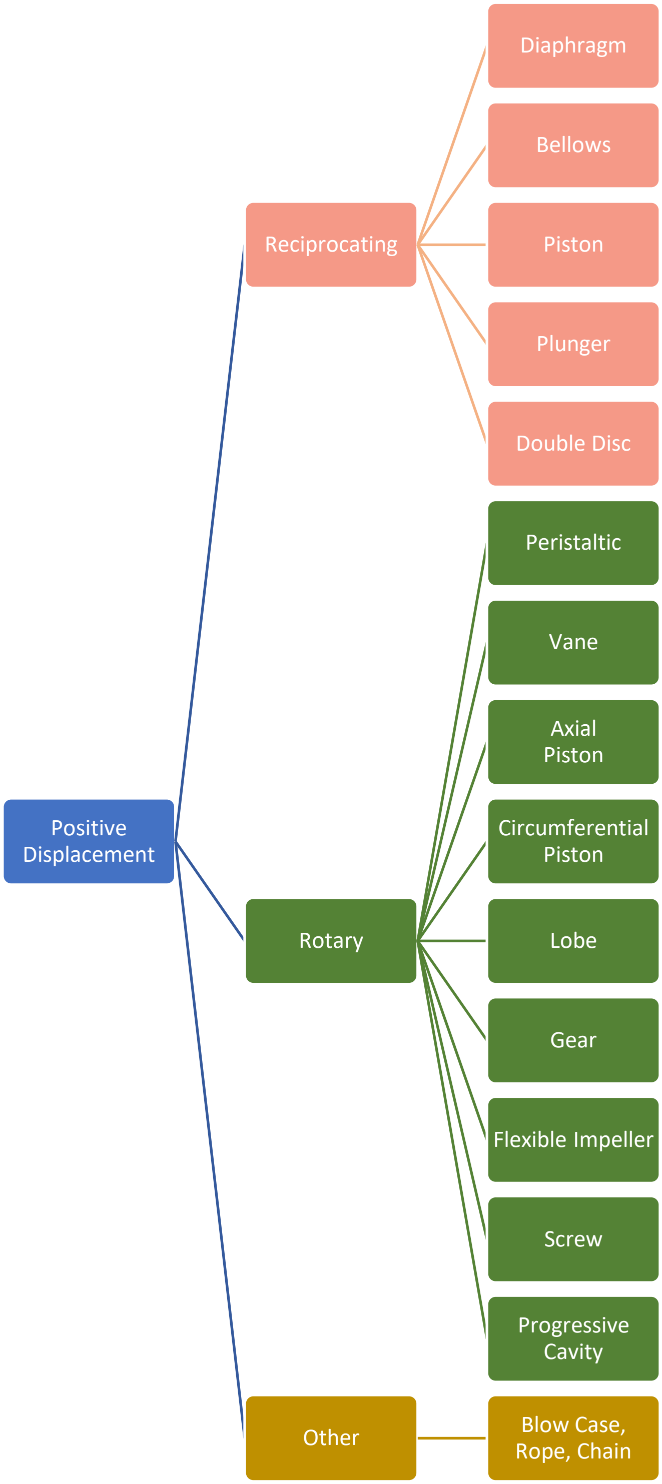


Figure 2: Chart of Positive Displacement Pump Types
Source: https://commons.wikimedia.org/wiki/File:Pump_Impellers-1.jpg CC BY-SA 3.0

Reciprocating Pumps

The following tables provide details for each main type of reciprocating pump. Diaphragms pumps are the most common type of PD pumps, so separate tables are presented for air diaphragm pumps and controlled-volume pumps.

Air Diaphragm Pumps		
Function	**Configurations**	**Common Applications**
Compressed air moves a diaphragm back and forth, drawing fluid in and pushing fluid out.	• Single diaphragm • Double diaphragm	• Low to medium viscosity • Food grade sanitary • Very common pump

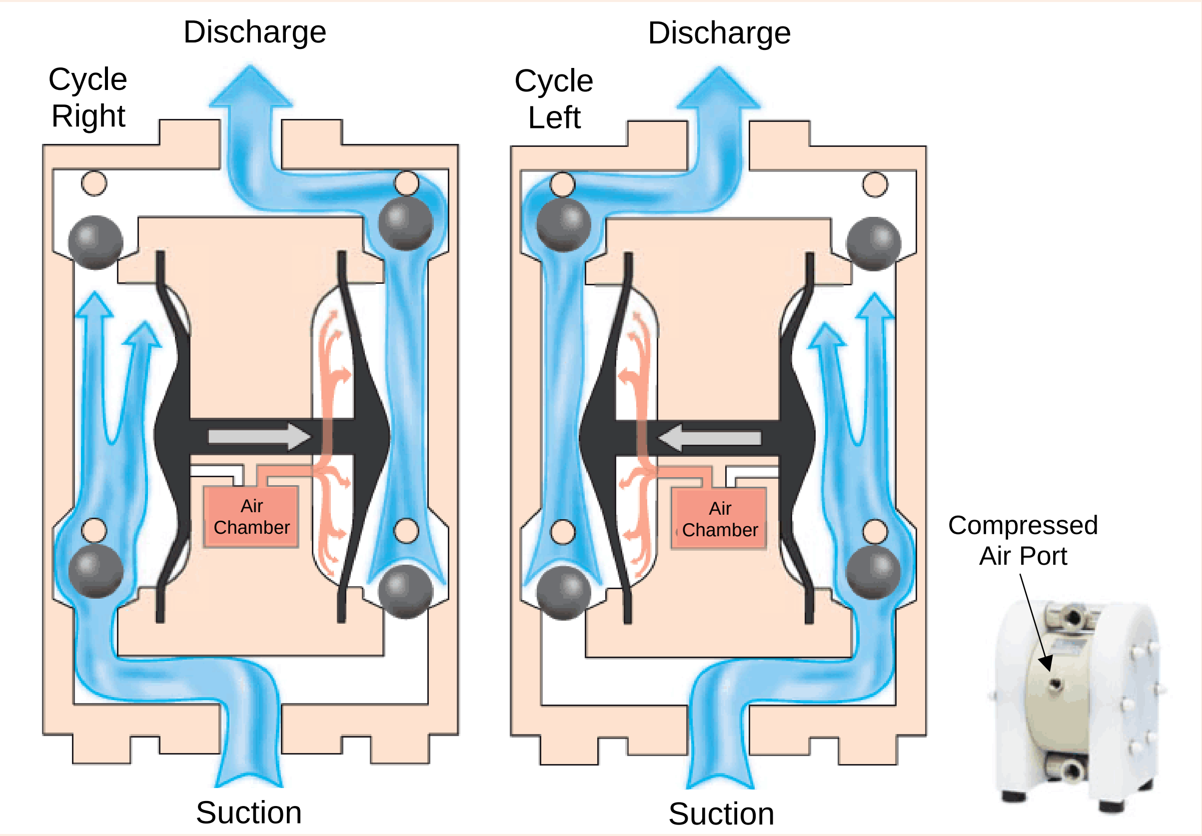


Figure 3: Pump head of an air-operated double diaphragm pump (AODD) showing the operation of the two chambers. The result is a relatively consistent discharge of fluid.

Source: commons.wikimedia.org/wiki/File:Pompe_pneumatique_membrane_tapflo.png, Delange.mobi, CC-BY-SA-3.0

Controlled-Volume Diaphragm Pumps

Function	Configurations	Common Applications
A motor moves a rod and diaphragm back and forth, drawing fluid in and pushing fluid out. The liquid chamber is designed to pass a precise volume of fluid with each stroke.	• Single diaphragm • Multiplex diaphragm • Mechanically coupled • Hydraulically coupled	• Low flow, high accuracy • Chemical feed • Very common pump • A.k.a.: metering pumps, proportioning pumps, or dosing pumps

Figure 4: Examples of mechanically actuated diaphragm pumps.
Left: Small metering pump with built-in speed control, control screen, and a standard outlet plug.
Right: Large metering pump with a vertical motor designed for pressures up to 15,000 psi. The wheel is for manual stroke adjustment.

Sources: commons.wikimedia.org/wiki/File:LMI%27s_EXCEL_XR,_Chemical_Metering_Pump.jpg, LaurelBloch, CC-BY-SA-4.0
commons.wikimedia.org/wiki/File:Milton_Roy%27s_Primeroyal_X_Chemical_Metering_Pump.jpg, LaurelBloch, CC-BY-SA-4.0

<table>
<tr><th colspan="3">Bellows Pumps</th></tr>
<tr><th>Function</th><th>Configurations</th><th>Common Applications</th></tr>
<tr><td>A bellows (accordion-shaped container) is pulled opened to draw fluid in and squeezed to push fluid out. The bellows pass a precise volume of fluid with each stroke.</td><td>• Single-acting
• Double-acting
• Air operated
• Electromagnetic</td><td>• Low flow, low pressure
• High accuracy flow
• Medical
• Washwater for electronics
• Fluid dispensers
• Air pumps</td></tr>
<tr><td colspan="3">

Figure 5: Example of a double-acting electromagnetic bellows pump. The two bellows are in white.

Source: http://sikopump.com/product-detail/bellows-dosing-pump</td></tr>
</table>

Piston Pumps

Function	Configurations	Common Applications
A piston is pulled to draw fluid in and pushed to force fluid out. The piston is sealed with a gasket.	• Single-acting (force pump) • Double-acting (lift pump) • Air operated • Electromagnetic • Steam • Controlled volume • Riding valve piston	• Pressurized water • Low viscosity fluids • Paint spraying • Pumpjack • Concrete pump

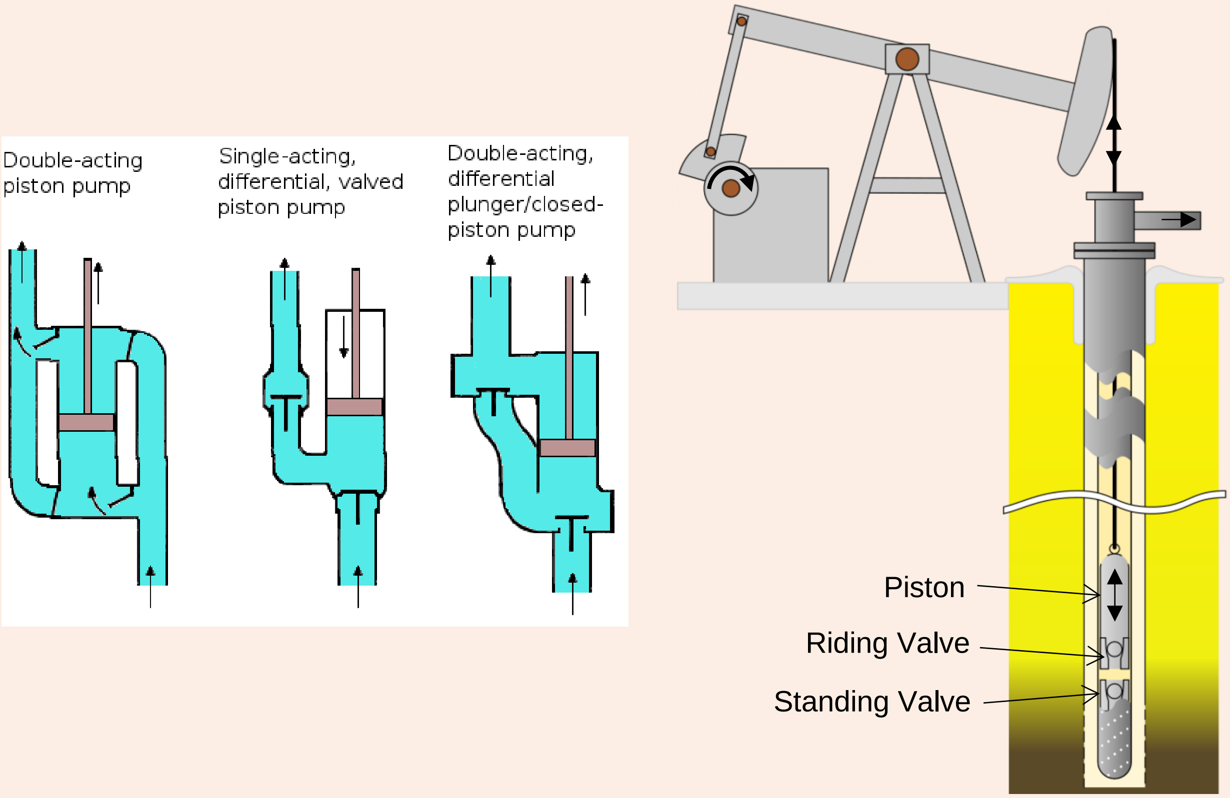


Figure 6: On the left, three common arrangements for piston pumps.
On the right, a pumpjack for an oil well, which is a unique piston pump arrangement.

Source: commons.wikimedia.org/wiki/File:Oil_well_scheme.svg, WarX, CC-BY-SA-2.5

Plunger Pumps

Function	Configurations	Common Applications
A plunger is pulled to draw fluid in and pushed to force fluid out. The plunger moves within the fluid-filled chamber.	• Single-acting • Double-acting • Air operated • Electromagnetic • Steam • Controlled volume	• High-pressure fluid, up to 30,000 psi • Oil production • Reverse osmosis • Pressure washing • Sludge handling

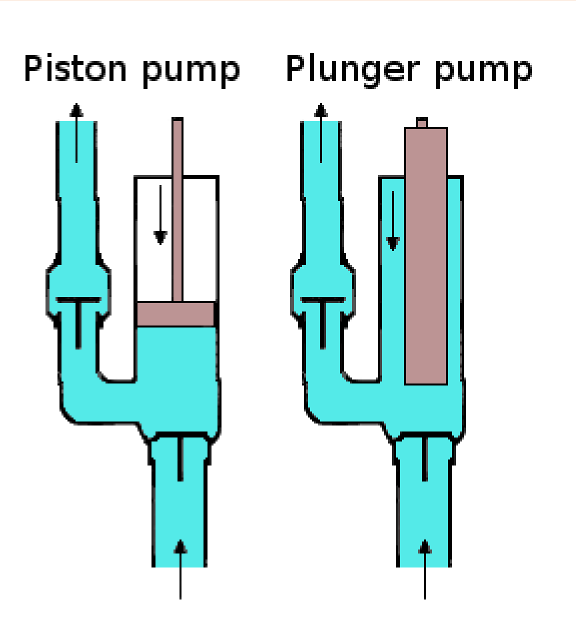


Figure 7: Difference between a single-acting piston pump (left) and plunger pump (right).

Source: https://commons.wikimedia.org/wiki/File:Piston_VS_Plunger_Pump.png (public domain)

Double Disc Pumps		
Function	**Configurations**	**Common Applications**
Two flexible discs are moved up and down at opposite times to draw in and push out fluid. A clack type valve is included at the suction end to allow for dry priming (pulling a lift while the suction pipe is empty).	• Electromagnetic drive • Belt and pulley or gearmotor • Air operated • Hydraulic operated • Portable with electric, gas, or diesel engine	• Raw sludge • Digested sludge • Thickened sludge • Scum, Septage • Food waste • Lime sludge/slurry • Polymer transfer

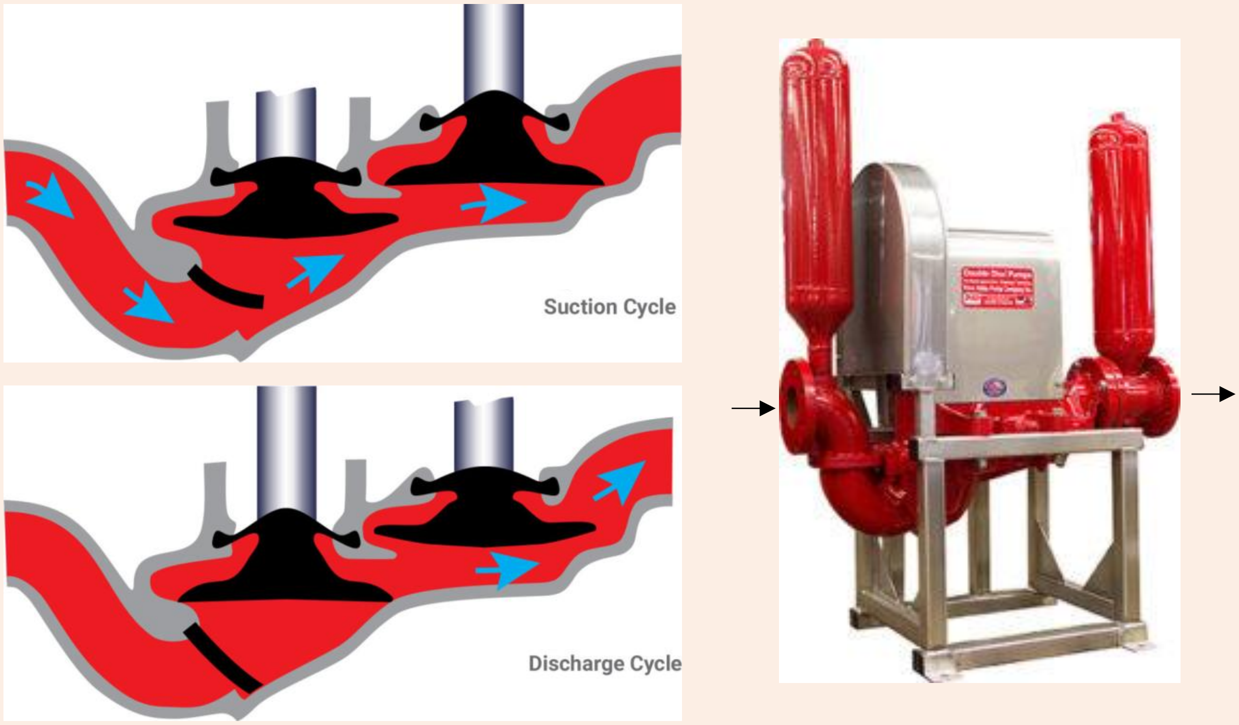


Figure 8: Left: Suction and discharge cycles of a double disc pump. During the suction cycle, the suction disc (on the left) rises and the clack valve opens to draw in fluid.
During the discharge cycle, the discharge disc (on the right) drops to force out the fluid.
Right: Example of double disc pump with vertical pulsation dampeners and 4-inch connections.

Source: www.pennvalleypump.com/double-disc-pump-technology/operating-principle, © 2021 Penn Valley Pump Company, Inc.

Rotary Pumps

The following tables provide details for the main types of rotary pumps. Peristaltic pumps are the most common type of rotary pumps.

Peristaltic Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by squeezing a flexible tube/hose while rotating in a circular or linear casing. The fluid does not touch the pump.	• Hose (with shoes) • Tube (with rollers) • Liner, Microfluidic • Linear (Infusion)	• Chemical metering/dosing • Food grade sanitary • Reactive fluids • Medical, such as IV fluids

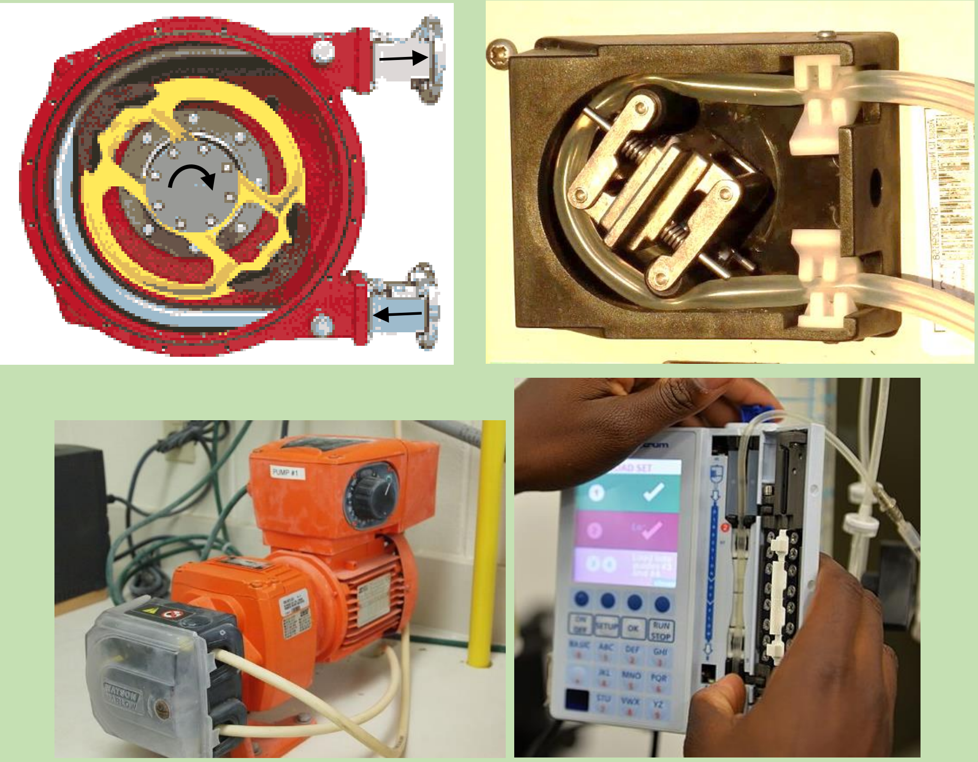


Figure 9: Top left: Hose pump internals with two shoes in black.
Top right: Tube pump internals with two rollers squeezing the clear tubing.
Bottom left: Example of a chemical metering tube pump with a speed control knob.
Bottom right: Linear IV infusion pump for injecting fluids into a patient.

Sources: commons.wikimedia.org/wiki/File:Bredel_Werkingsprincipe_animatie.gif (public domain)
commons.wikimedia.org/wiki/File:Peristaltic_pump_head.jpg, Andy Dingley, CC-BY-SA-3.0
commons.wikimedia.org/wiki/File:Watson-Marlow_Peristaltic_Pump.JPG, Z22, CC-BY-SA-3.0

Vane Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by vanes (plates) mounted to a rotating rotor. The vanes slide in and out of the rotor. The vanes create chambers that draw in fluid as they grow and discharge fluid as they shrink.	• Blade (a.k.a vane) • Bucket • Roller • Slipper • Single or multistage • Constant or variable displacement	• High-pressure hydraulic pumps • Automobile systems • Carbonators for soft-drink dispensers • Vacuum pump • Aircraft instruments • Braking booster

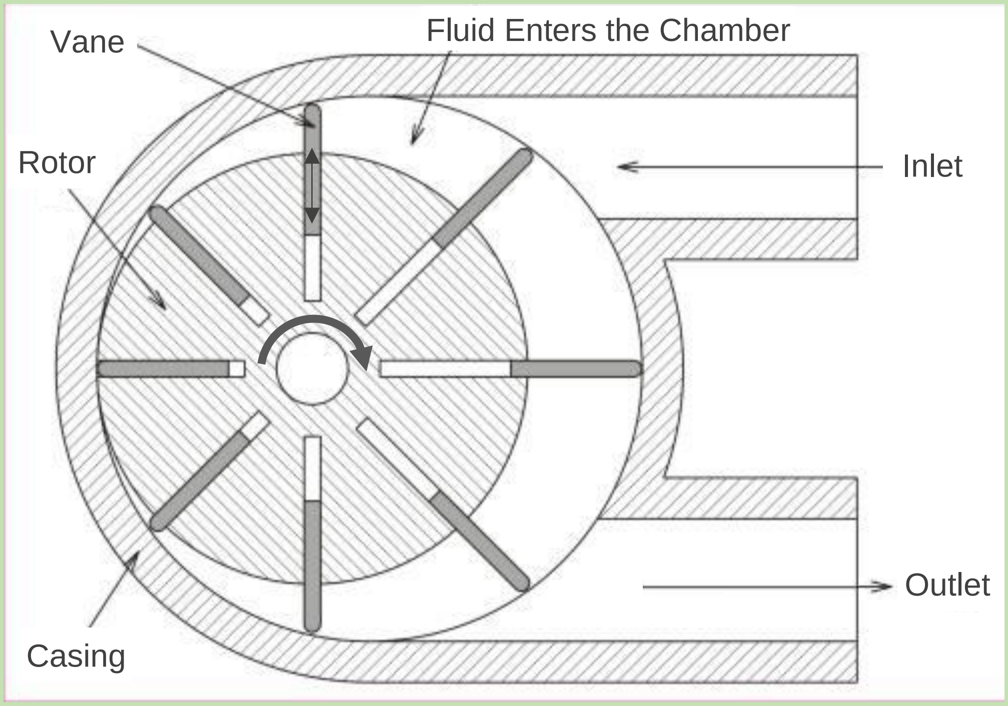


Figure 10: Section of a blade-type rotary vane pump. The vanes move in and out of vane slots.

Source: commons.wikimedia.org/wiki/File:Rotary_vane_pump-diagram.jpg, Jonasz, CC-BY-SA-1.0

Axial Piston Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by a circular arrangement of pistons that move back forth to drawn fluid in and out.	• Axial or radial arrangement	• High-pressure hydraulic systems • Automobile systems • Aircraft systems • Air conditioner compressor • Pressure washers

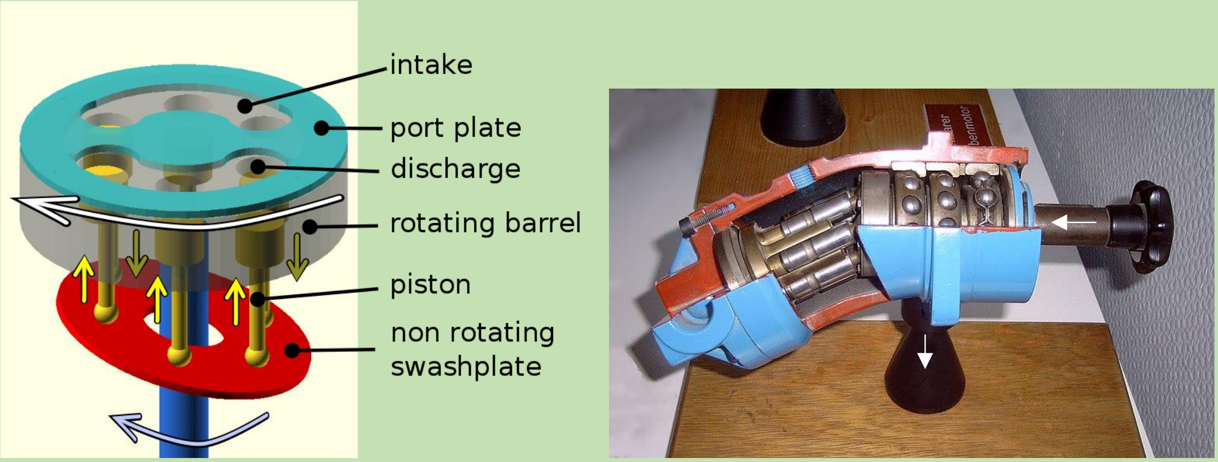


Figure 11: On the left, schematic of an axial pump.
Three pistons move up (discharge) and three pistons move down (intake cycle).
On the right, an example of an axial pump with the casing partially removed.

Source: commons.wikimedia.org/wiki/File:Axial_piston_pump_with_parts_label.svg, MichaelFrey, CC-BY-SA-4.0

Circumferential Piston Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by two piston-shaped rotors rotating in opposite directions. The rotors create growing chambers when passing the inlet and shrinking chambers when passing the outlet.	• Horizontal • Vertical	• High pressure • Low viscosity fluids • Food, dairy & beverage • Food grade sanitary • Clean-in-place (CIP)

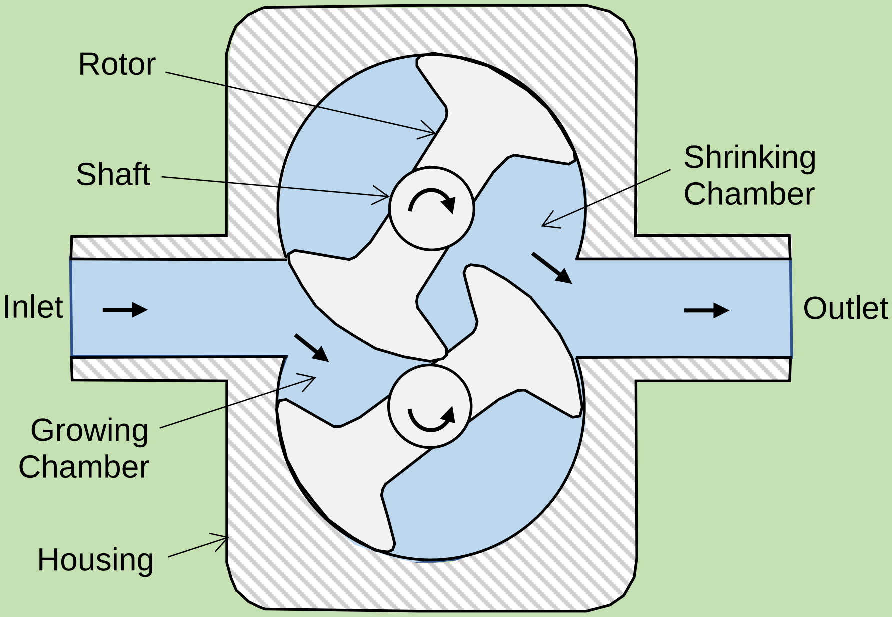


Figure 12: Section of a circumferential piston pump with labels and flow direction arrows.

Source: Author

Lobe Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by two tri-armed rotors rotating in opposite directions. The rotors create growing chambers when passing the inlet and shrinking chambers when passing the outlet.	• Horizontal • Vertical	• Solids, slurries, pastes • Food, dairy & beverage • Food grade sanitary • Pharmaceutical • Biotechnology • Wastewater sludge

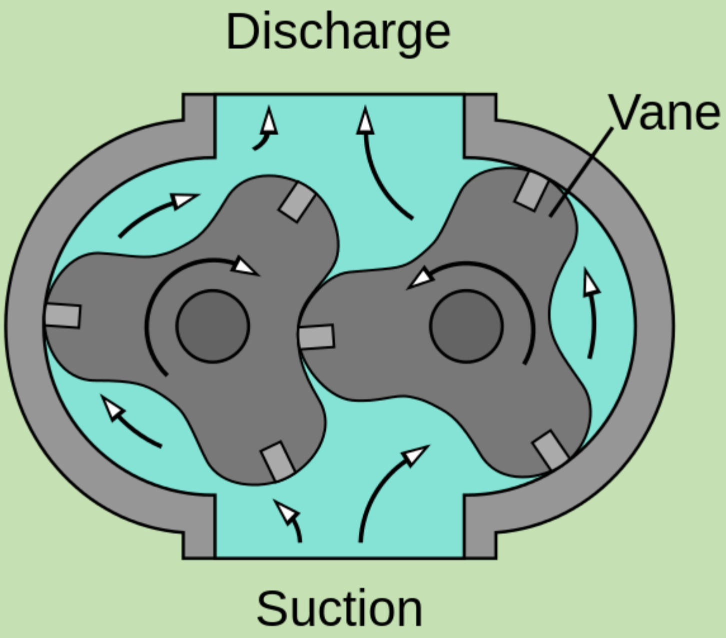


Figure 13: Section of a lobe pump with labels and flow direction arrows.

Source: https://commons.wikimedia.org/wiki/File:LobePump_en.svg, public domain

Gear Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by the meshing of two gears. The gears create growing chambers when passing the inlet and shrinking chambers when passing the outlet.	• External ○ Spur, helical, herringbone • Internal Gerotor • Internal Cresent	• Adhesives • Chemical feed • Food and Beverage • Paint and ink • Petrochemicals • Pulp and paper

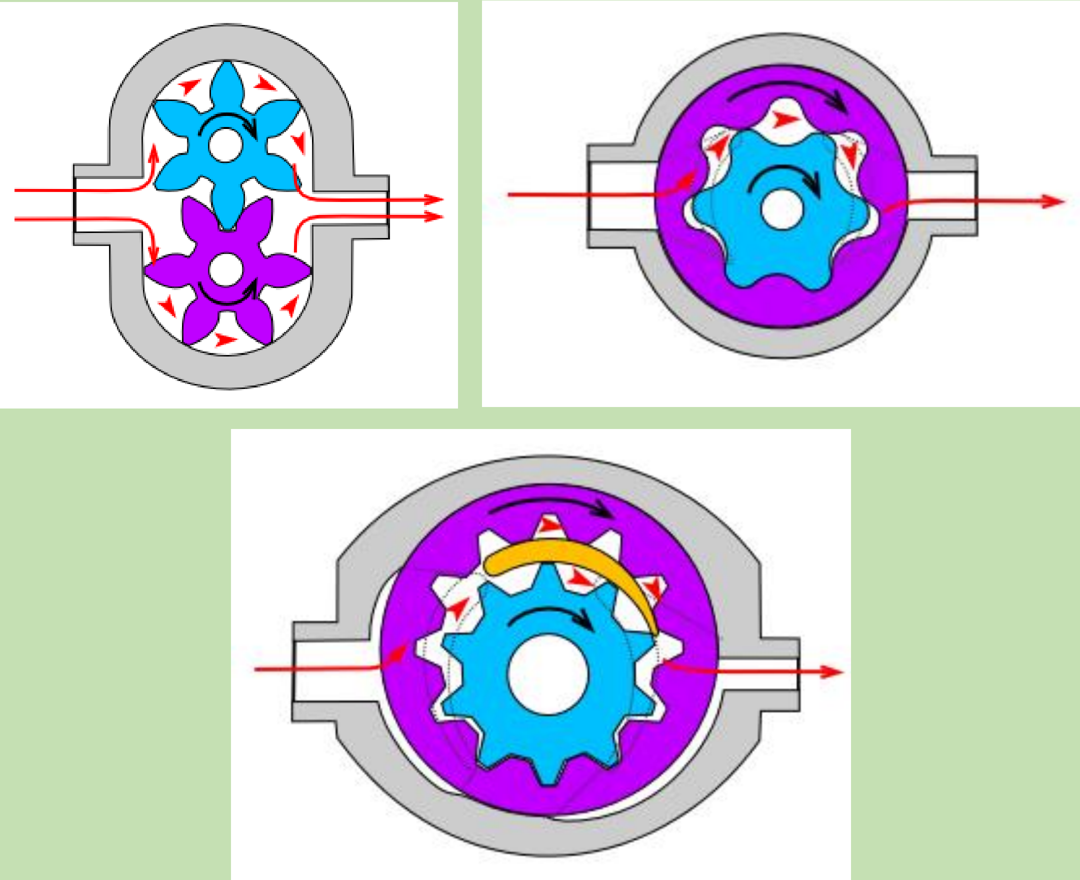


Figure 14: Sections of gear pumps with driver gear in cyan and driven gear in purple. Upper left: External gear. Upper right: Internal Gear Gerotor, Bottom: Internal Gear Crescent.

Source: commons.wikimedia.org/wiki/File:Gear_pump.png, Gear_pump_2.png, Gear_pump_3.png, me, CC-BY-SA-4.0

Flexible Impeller Pumps

Function	Configurations	Common Applications
Moves fluid by the rotation of an elastomer impeller with flexible vanes. The vanes extend to create growing chambers when passing the inlet and compress when passing the outlet.	• Bi-directional • Self-priming	• High viscosity and slurries • Delicate fluids and solids • Chemical feed • Cosmetics • Food processing • Marine • Oenological

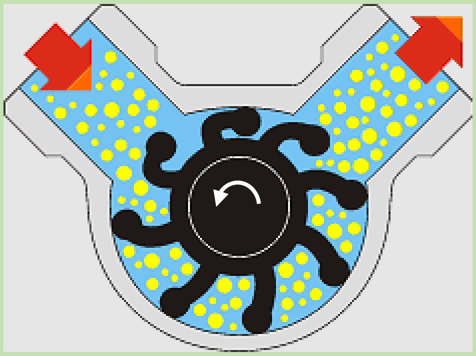


Figure 15: Section of a flexible impeller pump with the impeller in black. The vanes have thickened ends to seal against the housing and for longevity. The vanes can compress.

Source: commons.wikimedia.org/wiki/File:Flexible_impeller_pump.gif, Rac2665, CC-BY-SA-3.0

Screw Pumps

Function	Configurations	Common Applications
Moves fluid by the rotation of one or more screws. Inclined screws lift the fluid to a higher elevation. Enclosed screws can produce high discharge pressures.	• Singe spindle screw (Archimedes' screw) • Two or three spindle • Single or twin-screw • Horizontal, inclined, or vertical • Enclosed or open top	• Large flow, no pressure • Surface water & irrigation • Wastewater • Sludge and slurries • Oil & gas • Automotive

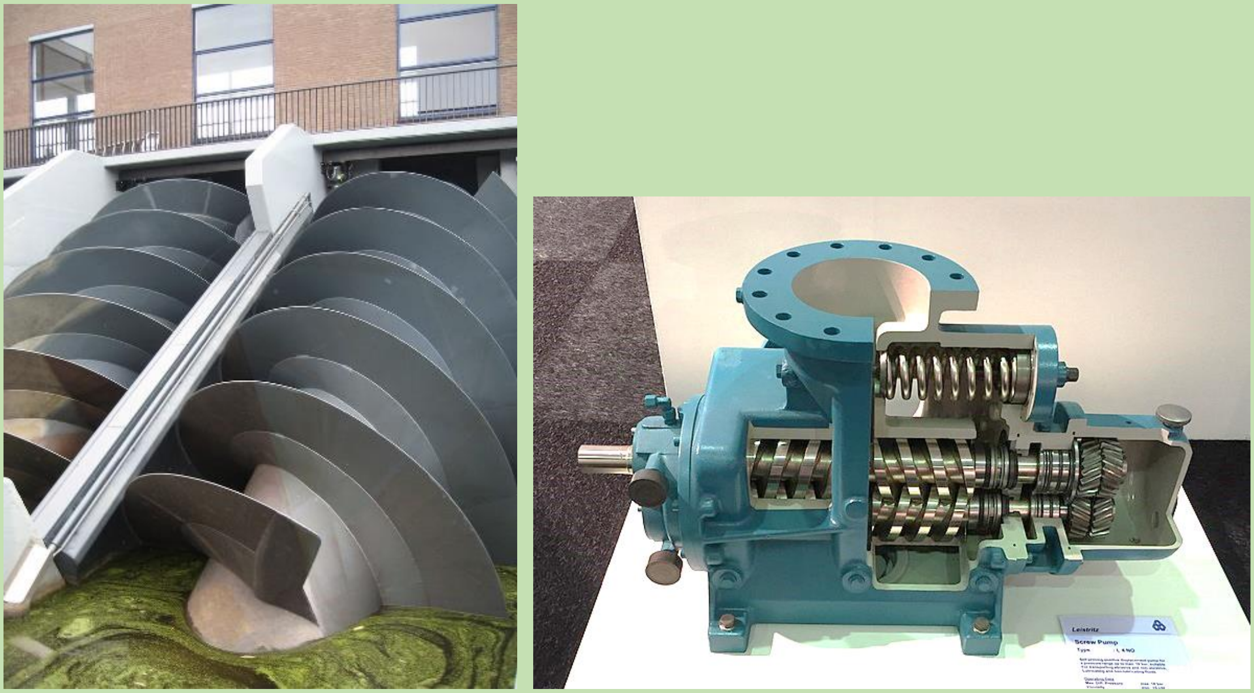


Figure 16: Left: Two single spindle screw pumps with open tops for lifting surface water. Right: Enclosed screw pump with twin screws for high-pressure pumping.

Sources: commons.wikimedia.org/wiki/File:Leistritz_Screw_Pump_type_L4NO_(01).JPG, S.J. de Waard, CC-BY-SA-3.0
commons.wikimedia.org/wiki/File:IMG_1729_Gemaal_met_schroef_van_Archimedes_bij_Kinderdijk.JPG, Ellywa, CC-BY-SA-2.5

Progressive Cavity Pumps		
Function	**Configurations**	**Common Applications**
Moves fluid by the rotation of a screw (called a rotor) rotating inside a double-threaded rubber stator. Can produce high discharge pressures.	• Bi-directional • Equal-walled • Un-equal-walled • A.k.a progressing cavity, eccentric screw, or cavity	• High viscosity and slurries • Fluids with solids • Wastewater sludge • Oil & hydraulic systems • Mud pumps for horizontal directional drilling

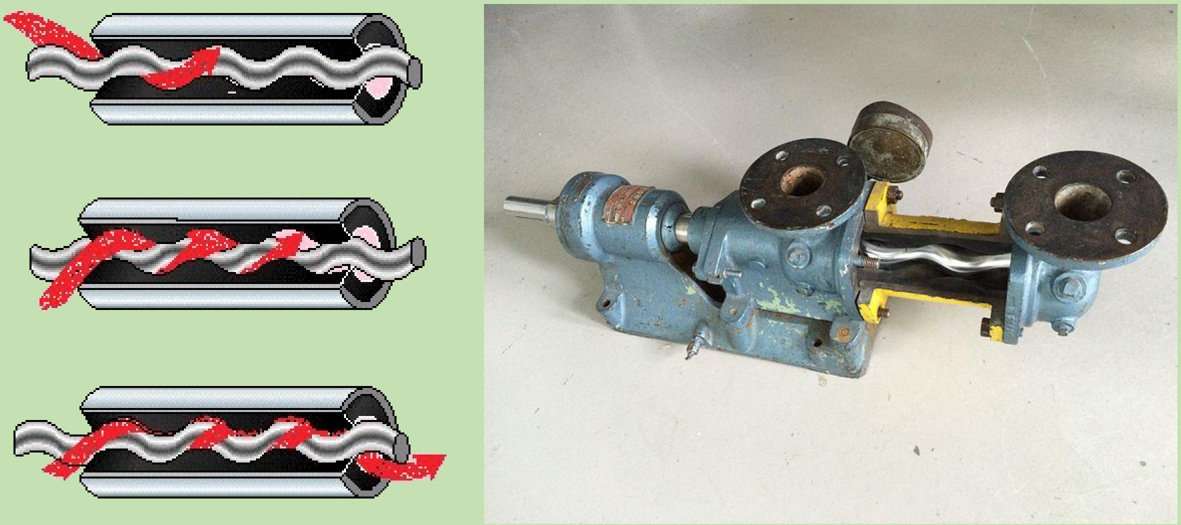


Figure 17: Left: Fluid flow shown in red as the rotor rotates inside the threaded stator. Right: Example of a small progressive cavity pump with the stator partially removed.

Sources: https://commons.wikimedia.org/wiki/File:PCM.tif, Gbmc2010, CC-BY-SA-3.0
https://commons.wikimedia.org/wiki/File:Cavity_pump.jpg, Bitjungle, CC-BY-SA-4.0

Pump Design Steps

The design of a pumping system can be accomplished in the following steps:

1. Define design criteria
2. Choose the number of pumps and speed control
3. Create a process flow diagram
4. Intake design
5. Discharge design
6. Calculate operating points
7. Review pump curves, as needed
8. Pump selection
9. Create a hydraulic profile, as needed
10. Quality review of calculations
11. Design of ancillary features

The order of these design steps can be modified. Pump design requires an iterative approach. For example, the number of pumps and pipe sizes are assumed and then checked and modified based on the final pump selection. Also, changes in pipe size, valves, or pump arrangement may affect the operating conditions, which impacts the final pump selection. These inter-dependencies increase the chance for oversights and mistakes and make the final quality review of high importance. Calculations and design decisions should be documented and kept organized for a quality review.

The following sections address the above design steps. Additional guidance can be found in the reference documents in the Helpful References section.

Design Criteria

Defining the design criteria is the first step in ensuring a successful pump selection. Design criteria are specific goals for the pumping system. The following are example design criteria to consider:

1. Flow and pressure capacity meets or exceeds demands;
2. Pump type and materials suitable for fluid type;
3. Pass solid sphere of specified diameter;
4. Avoid clogging or ragging;
5. Speed control, stroke control, and minimum turndown allow for minimum flow;
6. Avoid NPSH problems;
7. Allow future change to a larger or smaller pump or adding a pump;
8. Minimize energy consumption;
9. Minimize capital costs and lifecycle costs;
10. Allow proper maintenance access and clearance for pump removal;
11. Provide an installed redundant pump;
12. Choose a pump with readily available parts; and
13. Provide common spare parts and/or a spare pump on the shelf.

It is recommended to gain stakeholder input to ensure important goals are not missed. Stakeholders may include staff from management, operations, maintenance, and consultants. Although the design criteria should be defined at the start of the design process, it is important to review the criteria throughout the design process to confirm nothing is forgotten or neglected, and to avoid redesign.

Design Flow Rates and Pressures

It is critical to define the flow rates and pressures for pump selection. The required flow rates are often called the flow demands or the design flow rates. When combined with pressure requirements, these are called the system demands or design conditions.

Each pumping system has a unique combination of flow sources and discharge requirements that should be identified and reviewed when defining the design conditions. The design flow rates should be defined for the overall pumping system, regardless of the number of pumps. After deciding the number of pumps and the piping arrangement, the flow rates per pump can be specified.

Common flow rates to define are as follows:

- Minimum design flow, or minimum hourly flow (MHF): This is the smallest flow rate expected to be maintained by the pumping system.
- Average design flow (ADF), or average daily flow (ADF): This is the average flow calculated as the volume of fluid divided by the time period (such as the number of days or months).
- Maximum design flow (MDF), or maximum day design flow (MDDF): This is the largest of the various calculated or measured flow rates, typically measured over days or months.
- Peak design flow (PDF), peak hourly flow (PHF), or instantaneous peak flow (IPF): This is the highest flow rate (measured in a short interval) to be maintained by the pumping system. Often this value is estimated by multiplying the average design flow by a peak factor. For example, a peak factor of 1.5 to 4 is common.
- Ultimate design flow (UDF), ultimate average flow (UAF), or ultimate peak flow (UPF): This is the estimated flow rate to be experienced in the future, taking into account predicted changes or growth in the system or flow sources. Often the pumping system is designed with the flexibility to meet the ultimate design flows. For example, the piping is designed so that the pumps may be upgraded, or an additional pump may be installed in the future.

Pumping systems are typically designed so that the “firm capacity” meets or exceeds the PHF. The firm capacity is the discharge flow rate with all the pumps running except one of the largest pumps. This requires the pumping system to be designed with an installed spare large pump.

For PD pump applications, pressure is often treated differently than for centrifugal pumps. This is because changes in the suction or discharge pressure have minimal impact on the flow rate through a PD pump. Each PD pump model has a maximum/ rated pressure which should be greater than the actual delivery pressure at the outlet of the pump. Also, the anticipated suction pressure may be needed to check for Net Positive Suction Head (NPSH).

For these reasons and more, anticipated or required pressures should be listed with the design conditions. Hydraulic calculations can be done later in the design for the delivery pressure/head at the pump. For example, a chemical feed system is to inject a chemical into a pipe with a pressure range of 60 psi to 80 psi. The design criteria would be a pipe discharge pressure of 60 psi (minimum) to 80 psi (peak) at all flow rates. The delivery pressure at the pump would need to be calculated based on the piping details.

Example Problem 1

Engineer Amy is asked to list the design criteria for pumping syrup from a storage tank into a mixing tank. The pumping system must reliably pump a peak flow of 40 gpm, an average flow of 30 gpm, and a minimum flow of 20 gpm. The discharge pressure ranges from 15 to 25 psi, regardless of the syrup flow rate. Two rotary lobe pumps with speed control are to be utilized.

Solution:
Amy creates the following Table 3 to summarize the design criteria.

Table 3: Syrup Pumping Design Criteria

Fluid Type	Syrup	
Pump Type	Rotary lobe	
Number of Pumps	3 (2 duty + 1 standby)	
Drive Type	Variable frequency	
Flow Conditions	Flow Rate (gpm)	Discharge Pressure at Tank (psi)
Peak	40	15 to 25
Average	30	15 to 25
Minimum	20	15 to 25

Number of Pumps and Flow Control

Early in the design process, it is helpful to choose the number of pumps and the type of flow control. The assumed number of pumps can be used to performing an initial pump selection, which can be revisited and modified to confirm the ideal number.

A duplex pump arrangement is the simplest design. There is one duty (or lead) pump and one standby (or lag) pump. Each pump is the same and each pump can operate at the peak flow.

A duplex pump arrangement has the following advantages:
- Simplicity in design, construction, and maintenance,
- Easier to calculate the flow/dosing rate and adjust the pump speed.
- Lowest construction cost, and
- Smallest footprint.

Duplex arrangements are common for pumping fluid out of a single storage tank. If there are multiple tanks, either a common suction pipe feeds multiple pumps or each tank can have two pumps. See Figure 18 for alternative arrangements.

Using three or more pumps is generally beneficial under the following conditions, although this is highly dependent on the type of PD pump:
- Large flow rates, such as a peak flow greater than 5,000 gpm,
- Peak factor great than 4, and
- Large pressure range, such as greater than 40 psi.

Three or more pumps offers the following benefits:
- Ability to cover a greater range of flows and pressures,
- Better ability to maintain a fixed water level in a tank (suction or discharge),
- If two pumps are out of service, can still pump at average flow, and
- Increase in pumping efficiency with associated energy savings.

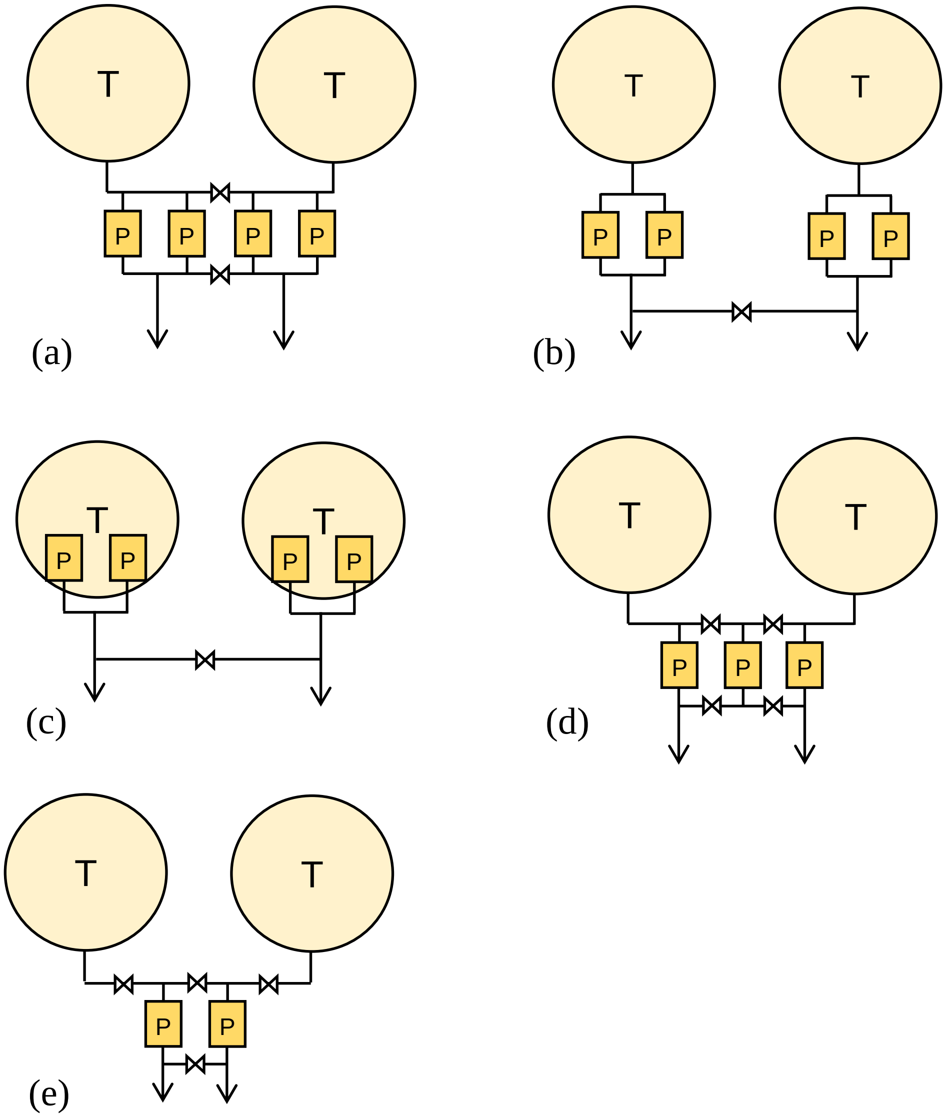


Figure 18: Alternative tank (T) and pump (P) arrangements to provide for redundancy of tanks, pumps, and piping. For (c), the pumps are mounted on top of the tanks. The level of redundancy decreases from (a) highest to (e) lowest. The capital cost also decreases from (a) highest to (e) lowest.

Source: Author

For PD pumps, it is uncommon to have a combination of small pumps and large pumps. Having different size pumps adds complexity and is not commonly required since PD pumps can provide a large flow range through speed and/or stroke control.

Flow Control

A decision needs to be made if the pumps will be constant speed or variable speed and, for reciprocating pumps, if stroke length will be adjustable. Constant speed pumps mean the pump will output a relatively constant flow. This is often acceptable for applications for which the pump can turn on and off to draw down a tank level, without the need to deliver a certain volume of fluid. The pump may cycle on and off to keep the tank within a water level range. In this case, the storage tank volume may need to be larger than a variable speed control scenario, where a precise water level can be maintained by adjusting the pump speed.

Variable speed controls can be used to control the flow, such as for chemical dosing, or for holding a fixed water level. This is achieved by adjusting the PD pump speed in small increments based on instrument readings and/or programming. The following are additional benefits to variable speed control:

- For large flow applications, variable speed pumping may allow a given flow range to be achieved with fewer pumps than a constant speed alternative.
- Variable speed pumping is often used to optimize pump performance and minimize power use.
- Variable speed pumping can reduce the storage volume.

Several types of variable speed pumping equipment are available, including variable frequency drives (VFDs), variable voltage drives, eddy current couplings, and mechanical variable speed drives. Many PD pumps come with integral speed adjustment features and a control screen or buttons. Speed adjustment equipment adds a small amount of energy loss, typically 3% to 5%. If unsure, it is wise to include speed control and stroke control features, in case they are needed or helpful.

PD pumps typically have a linear speed to flow relationship: if the speed is reduced in half, the flow is reduced in half. The same is true of the stroke length for reciprocating pumps. The formula is as follows:

$$\text{Pump Flow} = \text{Max Pump Flow} * \%\ \text{Speed} * \%\ \text{Stroke}$$

Example Problem 2

Engineer Pat is to determine the pump speed required to deliver 50 gpm with a diaphragm pump with a maximum flow of 100 gpm and the stroke length set at 80%.

Solution:
Pat rearranges the following formula and calculates the pump speed:

$$\text{Pump Flow} = \text{Max Pump Flow} * \frac{\%\,\text{Speed}}{100} * \frac{\%\,\text{Stroke}}{100}$$ rearranged:

$$\%\,\text{Speed} = \frac{\text{Pump Flow} * 100 * 100}{\text{Max Pump Flow} * \%\,\text{Stroke}} = \frac{50\text{ gpm} * 10000}{100\text{ gpm} * 80} = \mathbf{62.5}\%$$

Chemical Feed Rate

There are a variety of PD pump applications for delivery chemicals. One of the most common is to feed chemical into a flow of water in a pipe, channel, or well. Three different dosing/feed rate formulas can be used in this application, as follows. Select the formula based on how the chemical dose is expressed in parts per million (ppm). For example, ppm by volume, ppm by liquid weight, or ppm by dry weight.

1. Volumetric based:

$$\text{Feed rate (gpm)} = \frac{\text{Volumetric Dose (ppm)} * \text{Water Flow Rate (gpm)}}{10^6}$$

2. Liquid weight based:

$$\text{Feed rate (gpm)} = \frac{\text{Liquid Weight Dose (ppm)} * \text{Water Flow Rate (gpm)}}{\text{Specific Gravity} * 10^6}$$

3. Dry weight based:

$$\text{Feed rate (gpm)} = \frac{\text{Dry Weight Dose (ppm)} * \text{Water Flow Rate (gpm)}}{\text{Specific Gravity} * \text{Chemical Concentration} * 10^6}$$

Other dosing applications include:
- Feeding a specified volume into a mixing tank with various ingredients,
- Feeding into a storage tank to achieve a specified concentration,
- Feed rate adjusted based on instrument readings, such as pH, temperature, oxidation-reduction potential (ORP), residual concentration, etc.

Example Problem 3

Engineer Tom is designing a chemical feed system with controlled-volume diaphragm pumps. He performs jar testing of different amounts of a ferric chloride solution and determines the optimal dosage is 30 ppm by volume. The ferric chloride is to be injected into a water pipe flowing at 2,000 gpm. What is the required flow rate of the ferric chloride solution?

Solution:

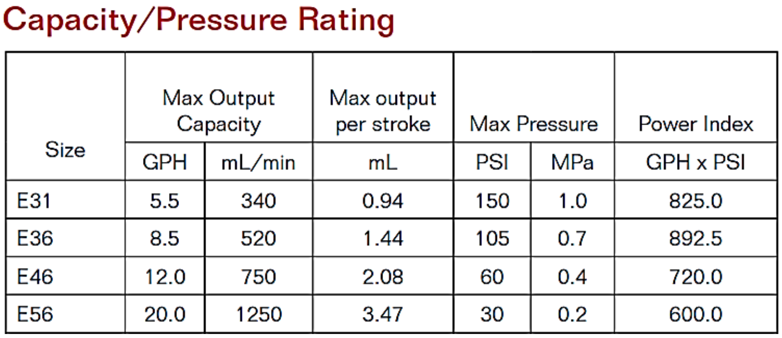
Tom uses the volumetric based feed rate formula to calculate the flow rate of the chemical solution:

$$\text{Feed rate (gpm)} = \frac{\text{Volumetric Dose (ppm)} * \text{Water Flow Rate (gpm)}}{10^6}$$
$$= \frac{30\text{ ppm} * 2{,}000\text{ gpm}}{10^6} = 0.06\text{ gpm} = \mathbf{3.6\ gph}$$

Tom expressed the flow rate in gallons per hour (gph), as this is conventional for chemical metering pumps.

Example Problem 4

Continuing with example problem 3, the plant manager informs Tom that he has two extra diaphragm pumps in the warehouse with nameplate model/size “E31”. Tom finds the below data sheets for this pump model. Can these pumps provide the required feed rate with redundancy? If so, at what speed?



Capacity/Pressure Rating

Size	Max Output Capacity		Max output per stroke	Max Pressure		Power Index
	GPH	mL/min	mL	PSI	MPa	GPH x PSI
E31	5.5	340	0.94	150	1.0	825.0
E36	8.5	520	1.44	105	0.7	892.5
E46	12.0	750	2.08	60	0.4	720.0
E56	20.0	1250	3.47	30	0.2	600.0

Solution:

Tom finds row E31 in the table and compares the max output capacity of 5.5 gph to the required feed rate of 3.6 gph. Since the pump capacity is larger, it will work for the application. Since there are two pumps available, there can be one standby pump, thereby providing redundancy. Tom calculates the required pump speed as follows, assuming the stroke length will be kept at 100 percent:

$$\%\ \text{Speed} = \frac{\text{Pump Flow} * 100 * 100}{\text{Max Pump Flow} * \%\ \text{Stroke}} = \frac{3.6\ \text{gph} * 10000}{5.5\ \text{gpm} * 100} = \mathbf{65.5}\%$$

Process Flow Diagram

Early in the design process, it is important to make a schematic drawing of the overall pumping system. This may start as a back-of-the-envelope sketch with boxes and lines, similar to the tank and pump configurations in Figure 18. As the design develops, a more formal diagram should be developed and drawn in CAD. A process flow diagram (PFD) is a simple schematic showing major components such as pumps and tanks, and lines representing the piping. This schematic helps to define the piping arrangement which often impacts the pump selection.

See Figure 19 for an example of a PFD. Note that these examples have valve and instrument details that would be developed later in the design.

PFDs are often used by electrical and controls engineers to create instrumentation and controls diagrams (P&IDs). P&IDs include symbology for the controls features, such as instrumentation, control panels, and communications. See Figure 20 for an example P&ID.

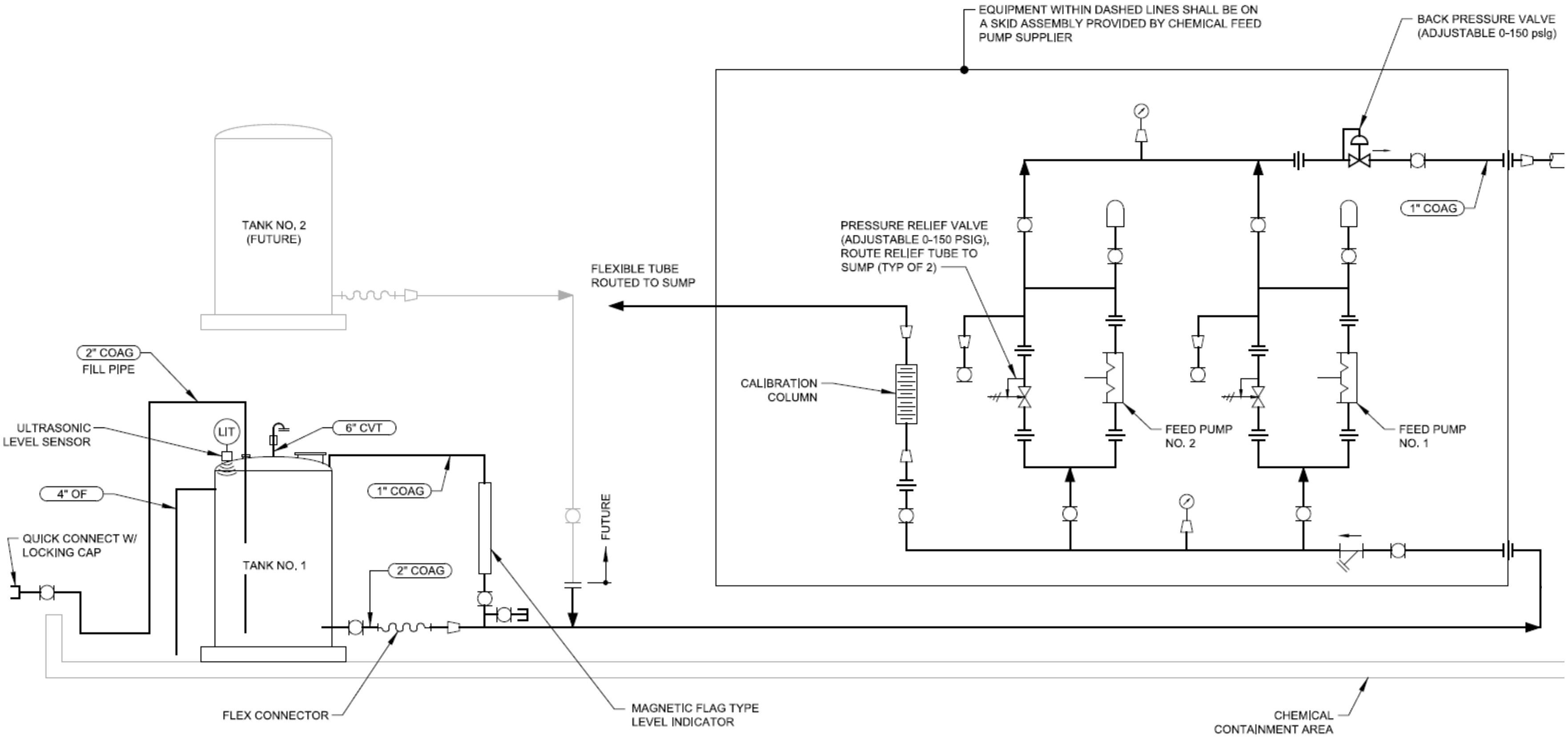


Figure 19: Example PFD for a chemical feed system with two diaphragm pumps, one storage tank, and a pipe connection for a future tank.

Source: Author

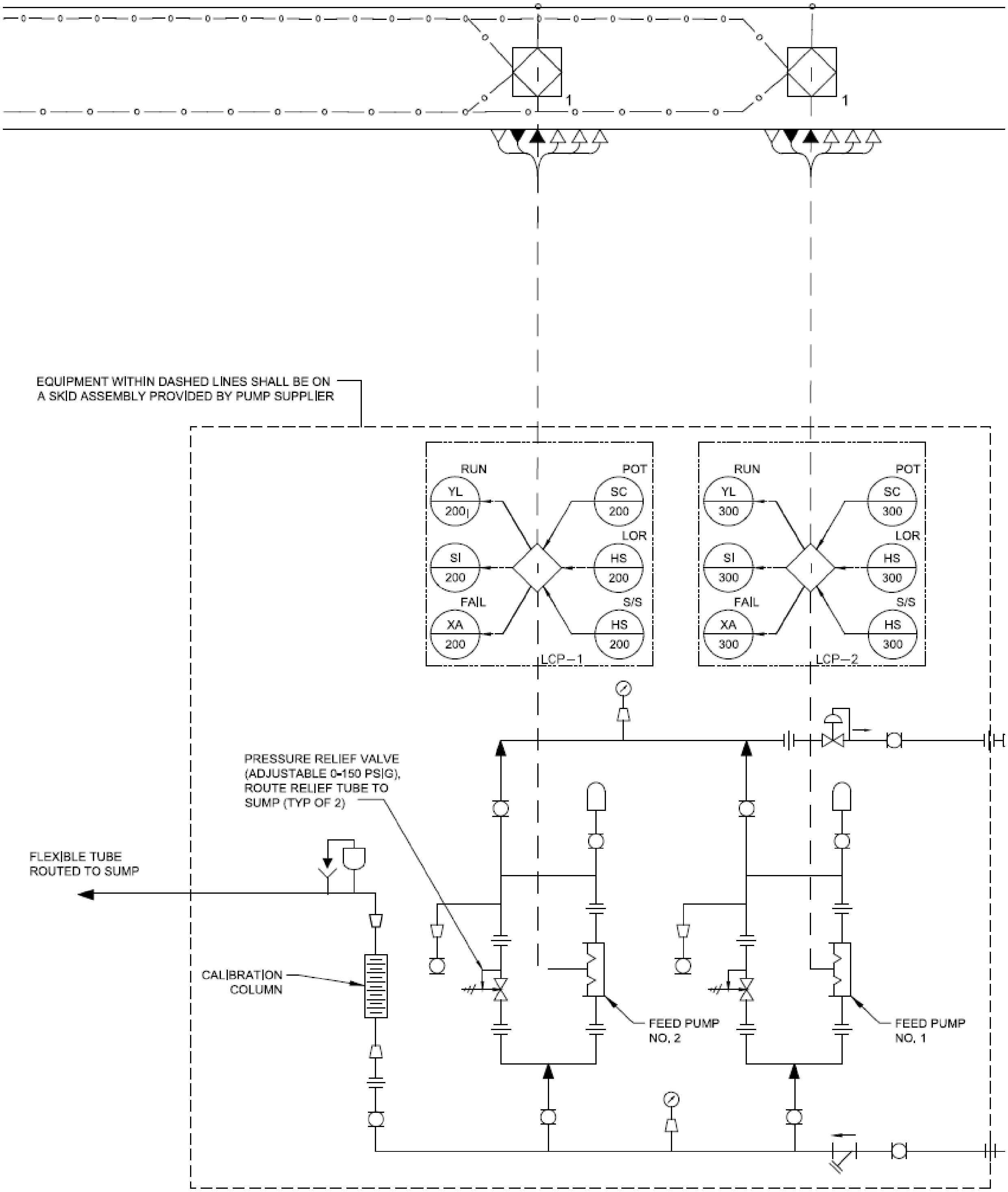


Figure 20: Example P&ID for two pumps, with symbols indicating the controls design.

Source: Author

Suction Design

The suction or intake design concerns the suction piping and any inlets that guide flow into each pump. A proper suction design prevents entrained air or cavitation problems. The pump manufacturer should be consulted for intake design recommendations. Important intake dimensions should be per *HI Standard 9.8* for intake design. The depth of the inlet below the water level should be checked by the engineer to ensure pumps are protected from entrained air.

Common suction sources for PD pumps are as follows:

1. From a channel, well, or basin
2. From the top of a tank
3. From the side of a tank
4. From a pressurized pipe/manifold

Items 1 and 2 may require pulling a lift and self-priming. A ***lift*** is when a pump is higher than the suction water level, so the pump must suck up the fluid. ***Self-priming*** is when the pump must pull a lift when the suction pipe is empty. Centrifugal pumps commonly struggle in these situations. Meanwhile, most types of progressive cavity pumps can pull a high lift and be self-priming.

Lift

Pump manufacturers will often provide a maximum lift height. Some PD pumps have achieved a lift of 22 feet (versus 15 feet for centrifugal pumps). However, the maximum lift height listed in pump literature makes certain ideal condition assumptions, such as pure water, the pump mounted directly over the tank, no pipe joints, ideal inlet, and ideal pipe diameter. Engineers can check the achievable lift for a particular application by calculating the net positive suction head available (NPSHa).

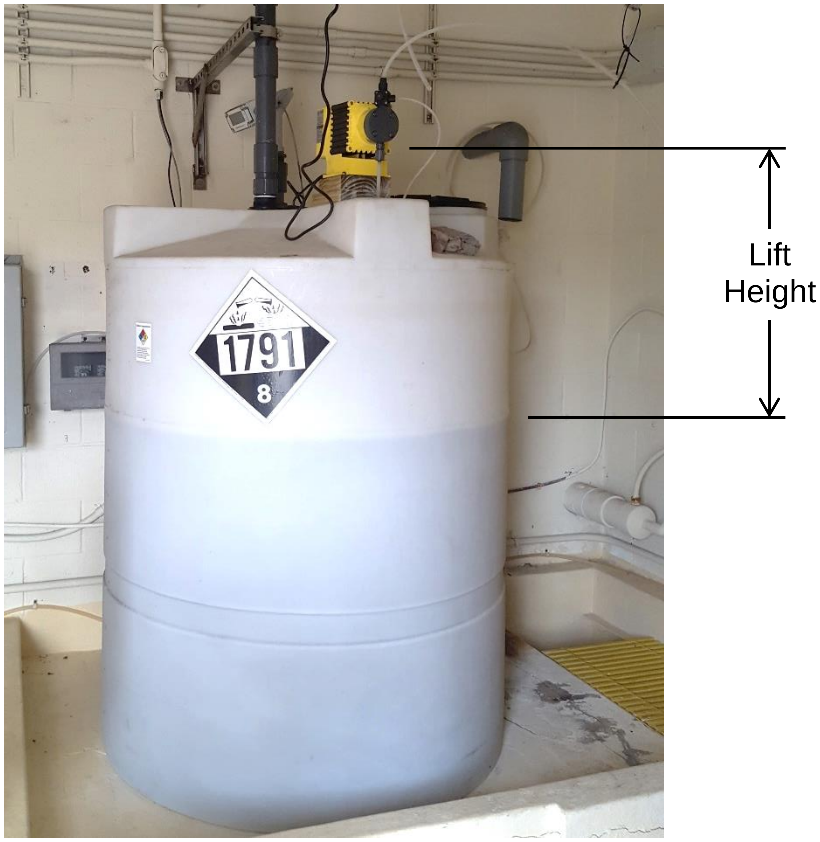


Figure 21: Chemical metering (diaphragm) pump mounted on a tank.
The suction pipe (clear tube) drops straight down into the tank to near the bottom, where there is a foot valve on the inlet (not shown) to keep the tube full of fluid and thereby avoid self-priming. This pump can pull a lift of 7 feet to empty the tank.

NPSH

To avoid cavitation and related pumping problems, the net positive suction head available (NPSHa) should be greater than the net positive suction head required (NPSHr). The NPSHa is based on the details of the intake design, while the NPSHr is from the pump manufacturer.

The design engineer should confirm that the NPSHr value at the maximum flow rate for the selected pump is less than the calculated NPSHa. If the NPSHr is greater than NPSHa, the following options are available to correct the issue:

- Lower the elevation of the pump,
- Increase water level,
- Increase suction pipe size,
- Add pulsation dampeners,
- Eliminate elbows or use long radius elbows on the suction piping, or
- Choose a different pump.

The NPSHa formula is as follows, with definitions and an example in Table 4:

$$NPSHa = H_{bar} + h_s - h_{vap} - h_{fs} - h_m - h_{vol} - h_a - FS$$

Table 4: NPSHa Definitions and Calculation

Term	**Example (ft)**	**Definition**
H_{bar}	+33.96	Atmospheric pressure, which is 14.7 psi (33.96 ft) at sea level.
h_s	+2.50	Minimum static head at the pump. Measure the height from pump intake to low water level.
H_{vap}	-1	Vapor pressure of water, at 75 deg F, expressed in feet.
h_{fs}	-0.50	Suction pipe friction losses at the max pump operating flow rate. Perform hydraulic calculations as needed.
Σh_m	-1.96	Suction pipe minor losses at max pump operating flow rate. Perform hydraulic calculations as needed.
h_{vol}	-2	Partial pressure of dissolved gases. For example, air in water (customarily ignored as insignificant) and organics in wastewater (estimated at 2 ft).
h_a	-0	Acceleration head for reciprocating pumps (zero for centrifugal pumps and most rotary pumps). See the formula below.
FS	-5	Factor of Safety, which can range from 2ft to 5ft, or 20% to 35% of NPSHr.
NPSHa	**26.0**	**Sum the above terms**

The acceleration head, h_a, is calculated as follows:

$$h_a = \frac{\mathrm{L}*v*\mathrm{n}*\mathrm{C}*\mathrm{SG}}{\mathrm{K}*g}$$

where:

h_a = Acceleration head (ft), to be subtracted in the NPSHa calculation
L = Length of suction line (ft)
v = Velocity in suction line (fps)
n = Pump speed in rpm
C = Cycle constant for reciprocating pump type (min/s):
  C = 0.4 for simplex, single-acting
  C = 0.3 for simplex, double-acting
  C = 0.1 for simplex double disc
  C = 0.2 for duplex, single-acting
  C = 0.115 for duplex, double-acting
  C = 0.06 for duplex double disc
  C = 0.066 for triplex (three pumps)
  C = 0.04 for quintuplex (four pumps)
SG = Specific gravity of liquid (1.0 for water)
K = Fluid factor:
  K = 2.5 for hot oil
  K = 2.0 for hydrocarbons
  K = 1.5 for amine, glycol, water
  K = 1.4 deareated water
  K = 1.2 wastewater sludge
  K = 1.0 urea and liquids with entrained gases
g = gravitational constant (32.2 ft/s^2)

Pulsation Dampening

Often pulsation dampeners are added to both the suction and discharge of reciprocating pumps. These contain bladders that expand and contract to absorb and reduce peak flows. Adding pulsation dampeners reduces pressure fluctuations and reduces fluid acceleration in the area of the dampener. Pulsation dampers have this effect over a distance of 5 to 15 pipe diameters when properly maintained. The pump and dampener manufacturer should be consulted to confirm the impact on the acceleration head calculation.

Example Problem 5

Engineer Amy is tasked with calculating the acceleration head for two double-acting piston pumps in parallel, for transferring water. The pumps run at 100 rpm. The suction pipe is 2” diameter and 10 feet in length. The design flow is 10 gpm. Calculate the acceleration head with one pump in operation and two pumps in operation.

Solution:

First, Amy calculates the velocity in the pipe, in fps:

$$v = \frac{flow}{area} = \frac{10\ gpm * \frac{1\ cfs}{448.8\ gpm}}{\pi\left(\frac{2}{12}\right)^2/4} = \frac{0.02\ \frac{ft^3}{s}}{0.02\ ft^2} = 1.0\ fps$$

Next, she calculates the acceleration head with one pump running (simplex):

$$h_a = \frac{\mathrm{L}*v*\mathrm{n}*\mathrm{C}*\mathrm{SG}}{\mathrm{K}*g} = \frac{10\ \mathrm{ft} * 1.0\frac{ft}{s} * 100\mathrm{rpm} * \mathbf{0.3} * 1.0}{1.5 * 32.2\frac{ft}{s^2}} = \mathbf{6.2}\ \boldsymbol{ft}$$

And, with two pumps running (duplex):

$$h_a = \frac{10\ \mathrm{ft} * 1.0\frac{ft}{s} * 100\mathrm{rpm} * \mathbf{0.115} * 1.0}{1.5 * 32.2\frac{ft}{s^2}} = \mathbf{2.4}\ \boldsymbol{ft}$$

Pump Selection

The importance of choosing a pump that is a good fit for the application cannot be understated. The main goal is to choose pumps that meet the design criteria, namely fluid type, flow, and pressure. This is known as pump selection or pump sizing. The design engineer is expected to confirm the proper pump selection.

The following are typical steps for the pump selection process:

1. Review pump design criteria
2. Select the type of pump
3. Define operating points with hydraulic calculations, if applicable
4. Review pump manufacturer literature including pump curves
5. Make a preliminary pump selection
6. Compare and choose a pump
7. Plot pump curve on the system curve, if applicable
8. Confirm pump capacity at different pump conditions
9. Review net positive suction head (NPSH)
10. Select motor HP, if applicable
11. Design pump connections, mounting, etc.
12. Quality review of the entire pumping system

Examples of pump selection techniques are provided in this section. For further details, consult the Helpful References Section.

Define Operating Points

Most PD pumps provide an essentially constant flow rate at all pressures up to a maximum/rated pressure. Hydraulic calculations may be required to define the head/pressure requirements for the pump. At each design flow rate, the pump needs to provide energy, expressed as total dynamic head (TDH), to overcome the energy losses in the piping system and to move the fluid to a higher elevation or pressure. For centrifugal pumps, TDH is expressed in feet or meters. For PD pumps, the TDH is often expressed as pressure in psi, bar, or MPa. The conversion is 1 ft TDH = 2.31 psi.

For reciprocating pumps and peristaltic pumps, it is not necessary to calculate the TDH at various flows nor to develop a system curve (as is done for centrifugal pumps). Instead, the *delivery pressure* at the pump outlet/discharge needs to be lower than the *rated pressure* of the pump. The delivery pressure is the sum of the pressure at the pipe discharge plus the head losses from the discharge piping at the peak flow rate.

For rotary pumps, it is common to plot the system curve on the pump curve. See Figure 22 for an example in which three TDH points have been calculated.

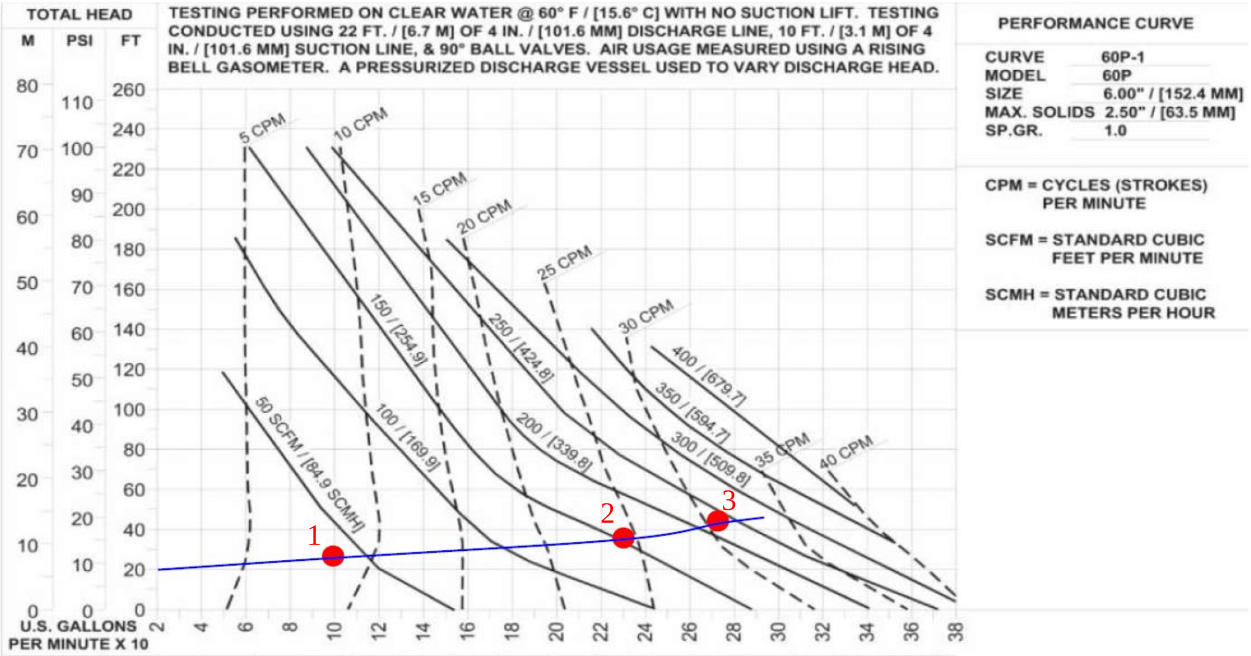


Figure 22: Pump curves for a large air-operated diaphragm pump, with system TDH points in red for three flow conditions, and the system curve in blue. The solid black curves represent the required compressed air demand in scfm or scmh. So, the approximate air demand would be 40 scfm at Point 1, 155 scfm at Point 2, and 230 scfm at Point 3. The dashed lines represent the pump speed up to a maximum of 40 cpm. So, the approximate speed would be 8 cpm (20%) at Point 1, 24 cpm (60%) at Point 2, and 31 cpm (78%) at Point 3.

The formula for TDH is as follows:

$$\mathbf{TDH} = \mathrm{H_{Static}} + \mathrm{H_{Lm}} + \mathrm{H_{Lf}}$$, where:

H_{Static} = Static head (elevation and/or pressure difference from inlet to outlet)
H_{Lm} = Minor losses from fittings, valves, etc.
H_{Lf} = Friction losses from the pipe walls

For further instructions on how to calculate TDH and develop a system curve, see the SunCam course entitled “Centrifugal Pump Selection”.

Pump Model and Size

Preliminary pump selection is the process of reviewing pump models and choosing one or more good fits for the design conditions. A good start is to confirm the type of pump based on reference applications, manufacturer recommendations, or pump design literature. Next, a list of potential pump manufacturers should be made.

For each manufacturer, review tables or charts of the capacity and pressure ranges of various pump models, as shown in Figure 23. This allows choosing the pump model. It is good practice to contact the pump supplier to request pump information and to confirm the pump is a good fit for the application.

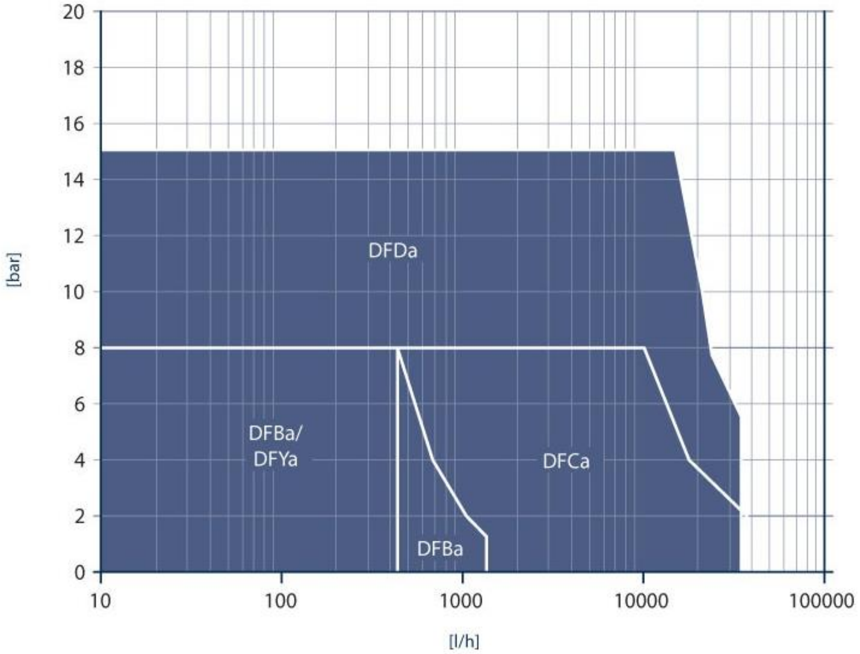


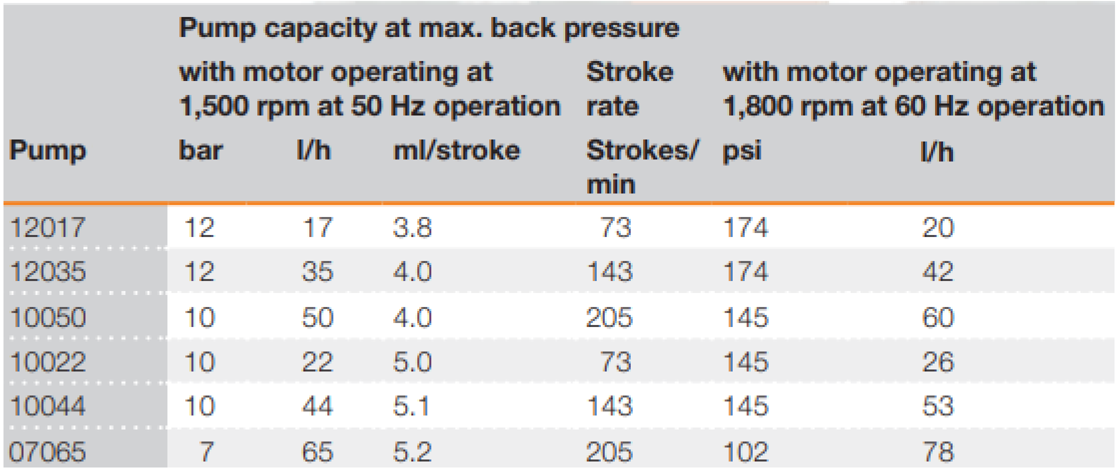
Figure 23: Example chart of capacity and pressure ranges for various diaphragm pump models. Note that 1 liter per hour (l/h) = 0.2642 gph and 1 bar = 14.5 psi.

Source: https://www.prominent.com/en/Products/Products/Peristaltic-Pumps/pg-peristaltic-pumps.html

After a pump model is identified, capacity tables or curves should be reviewed for different pump sizes. Some pump manufacturers provide software or online tools that allow for a pump model and size selection.

Example Problem 6

Engineer Randy is to select a pump size from the following capacity table. The pump draws from a tank and discharges into a nearby pipe with a maximum pressure of 150 psi. The pipe/tube length is short so friction & minor losses are negligible (less than 2 psi). The peak flow rate is 10 gph. The pump is to have a standard motor (60 hertz).



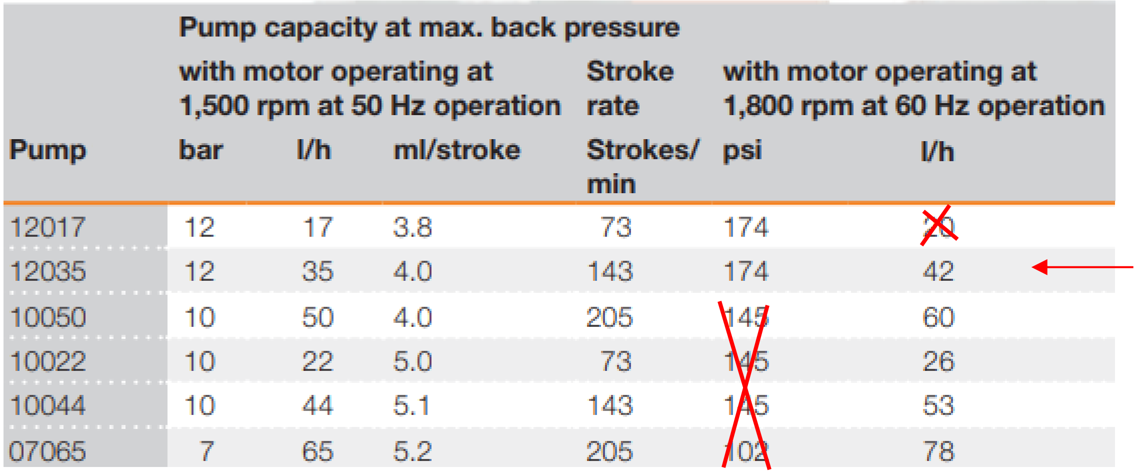
	Pump capacity at max. back pressure					
	with motor operating at 1,500 rpm at 50 Hz operation			Stroke rate	with motor operating at 1,800 rpm at 60 Hz operation	
Pump	**bar**	**l/h**	**ml/stroke**	**Strokes/ min**	**psi**	**l/h**
12017	12	17	3.8	73	174	20
12035	12	35	4.0	143	174	42
10050	10	50	4.0	205	145	60
10022	10	22	5.0	73	145	26
10044	10	44	5.1	143	145	53
07065	7	65	5.2	205	102	78

Solution:

Randy converts the flow to liters per hour (l/h) as follows:

Peak Flow = 10 gph * 1 l/h / 0.2642 gph = 37.8 l/h

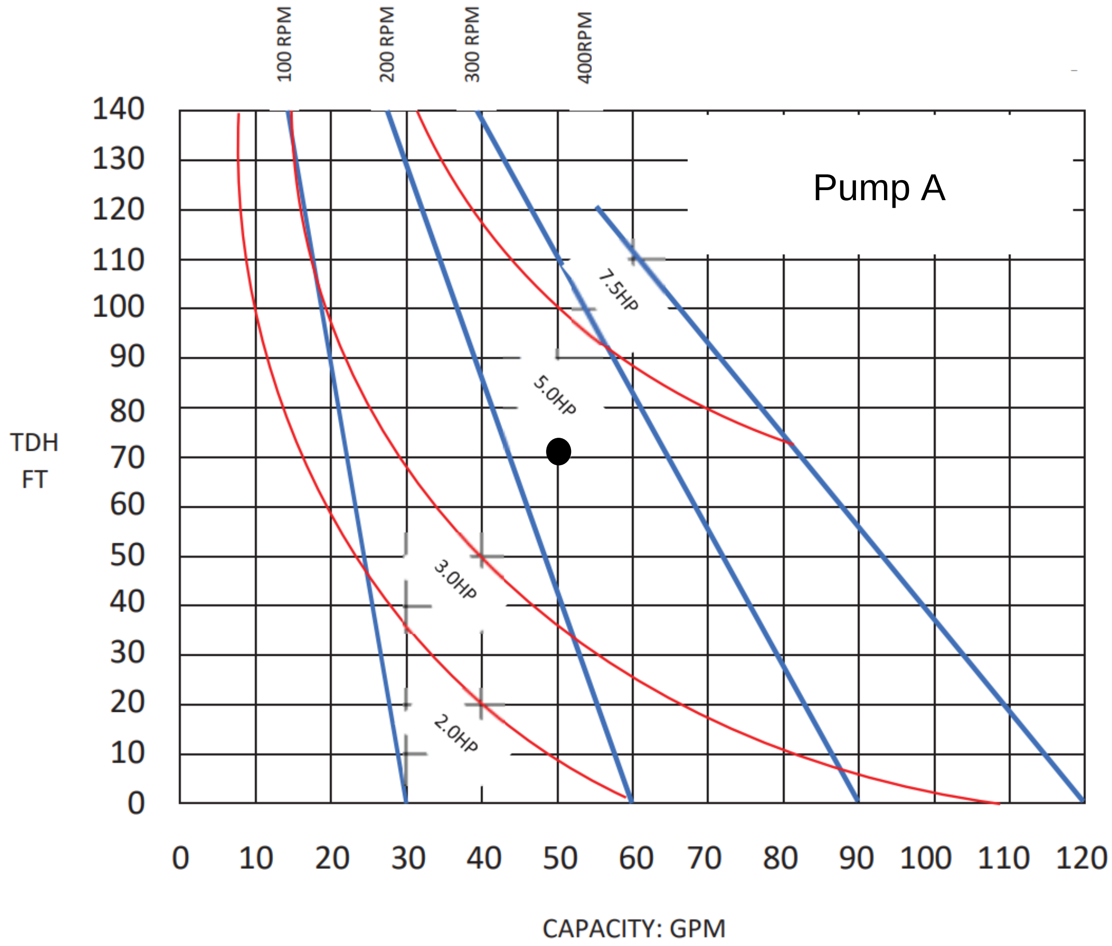
Randy crosses out pumps that do not meet the maximum pressure or peak flow, as seen below. He selected **Pump No. 12035** as the only pump that can meet the conditions.

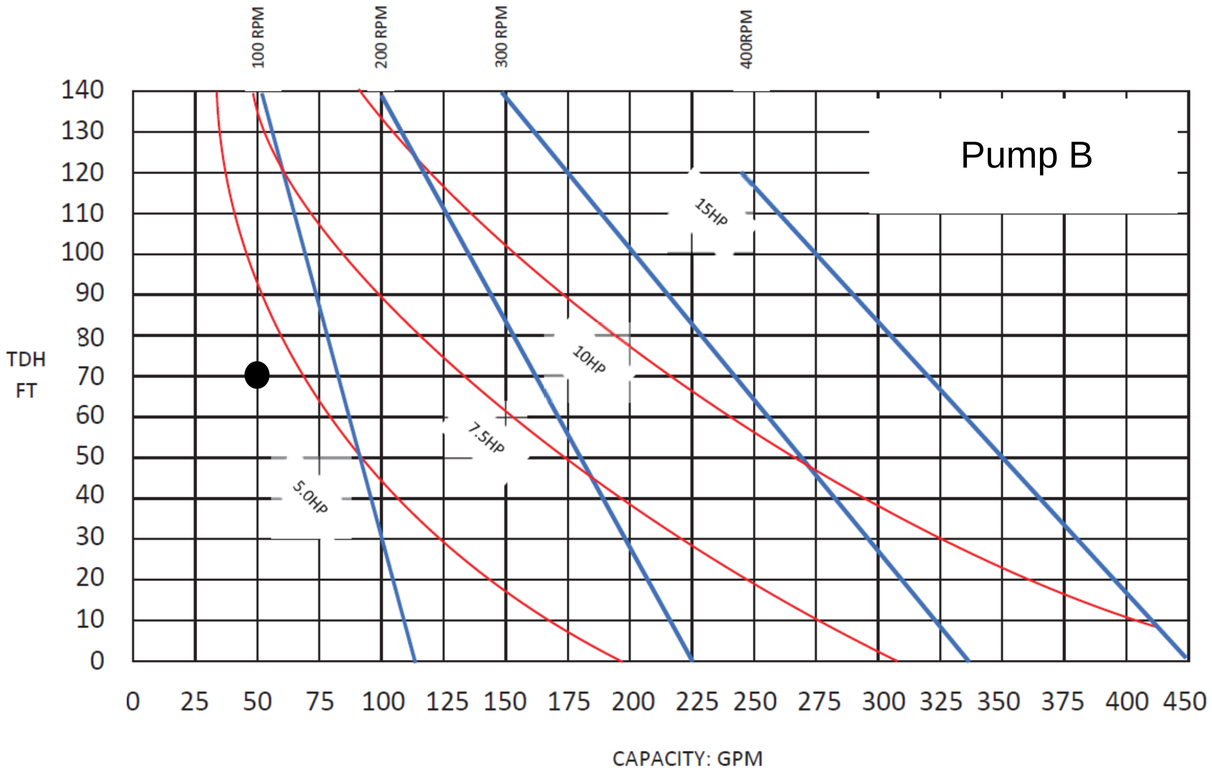


	Pump capacity at max. back pressure					
	with motor operating at 1,500 rpm at 50 Hz operation			Stroke rate	with motor operating at 1,800 rpm at 60 Hz operation	
Pump	**bar**	**l/h**	**ml/stroke**	**Strokes/ min**	**psi**	**l/h**
12017	12	17	3.8	73	174	~~20~~
12035	12	35	4.0	143	174	42
10050	10	50	4.0	205	~~145~~	60
10022	10	22	5.0	73	~~145~~	26
10044	10	44	5.1	143	~~145~~	53
07065	7	65	5.2	205	~~102~~	78

Example Problem 7

Engineer Susan is to size a double disc pump for pumping sludge. She calculates a TDH of 70 ft (30.3 psi) at a peak flow of 50 gpm. The pump manufacturer tells Susan that two pump sizes would work (A or B), and provides the following two pump curves. Each pump has a maximum speed of 400 rpm. Pump A costs $20,000 and pump B costs $40,000. Susan needs to choose between pumps A and B and identify the motor HP and speed at the peak flow.





Solution:
Susan draws circles at the operating points (70 ft @ 50 gpm), shown in black in the above pump curves. She clarifies with the manufacturer that the HP values in the charts represent the nominal motor HP after applying service factors. The red curves represent the transition to the next nominal HP value.

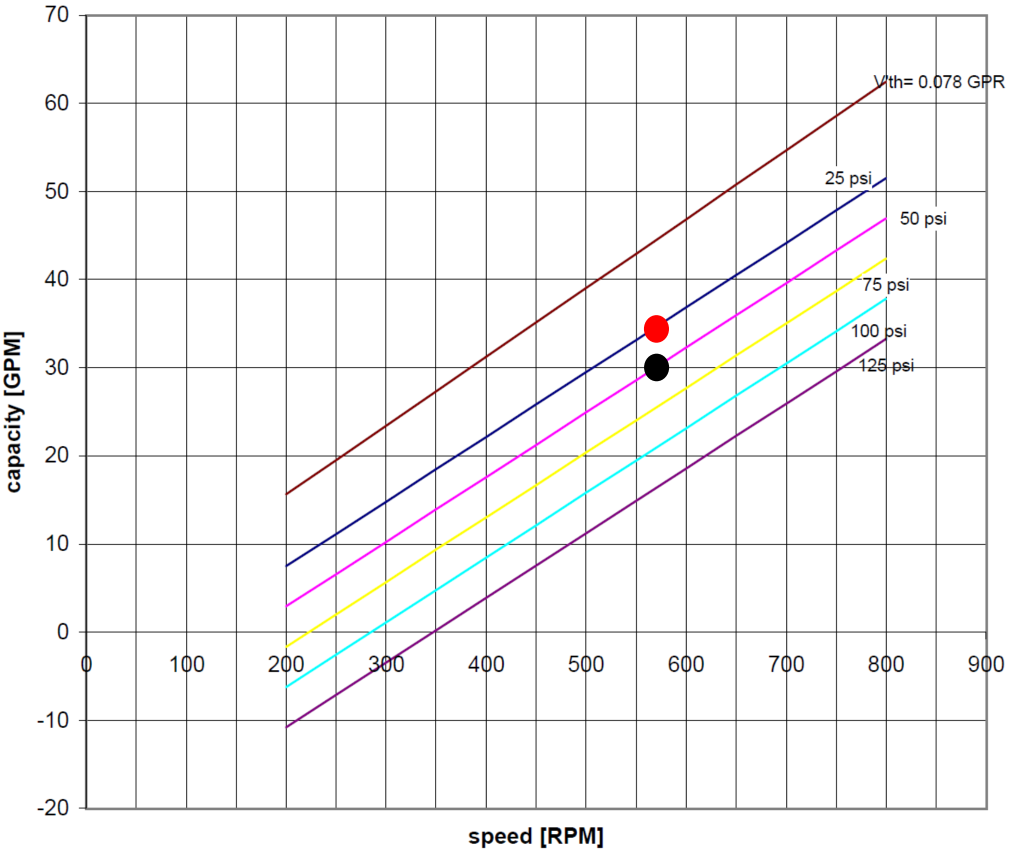
For Pump A, the operating point is at a speed of approximately 230 rpm (58%) with a 5 HP pump.

For Pump B, the operating point is at a speed of approximately 60 rpm (15%) with a 5 HP pump.

Susan chooses **Pump A,** with a speed of **230 rpm** and a **5 HP motor**, because the operating point is near the middle of the speed range, allowing more flexibility to increase or decrease the speed in the future.

Example Problem 8

Engineer Chris is to size a rotary lobe pump for pumping a slurry to a mixing tank. He calculates a delivery pressure of 50 psi (115 ft) at a peak flow of 30 gpm. Based on the below pump curve, Chris must identify the pump speed. Also, he must indicate how much the flow rate would change (percent change) if the discharge pressure drops by 25 psi.



Solution:

Chris draws a black circle in the above pump curve at the operating point: 30 gpm and the 50 psi line in pink. This point corresponds to a speed of approximately **570 rpm** (71%) on the x-axis.

For the case when the delivery pressure drops to 25 psi (50 - 25 = 25), the flow increases to approximately 34 gpm, as shown with the red circle on the chart. This is a 13% increase in flow ((34 – 30) / 30 = 0.13) for a 50% drop in pressure.

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