A SunCam online continuing education course

Vertical Pump Selection

by

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Course Outline:

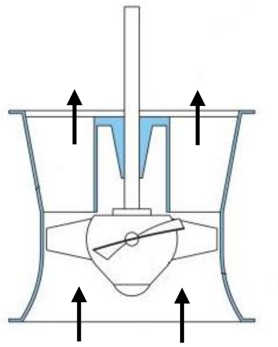
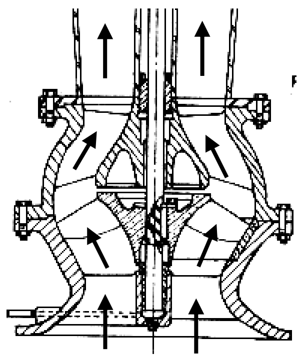
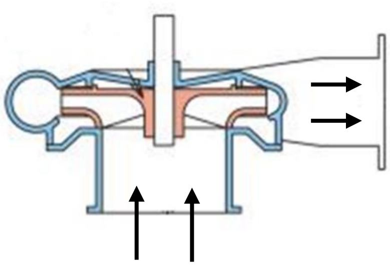
What is a Vertical Pump?

Pumps are mechanical devices that move fluids. Vertical pumps are a group of rotodynamic pumps. All rotodynamic pumps utilize a spinning impeller to add velocity and pressure to a liquid. Vertical pumps, also called vertical suspended pumps, are unique in that they have a vertical shaft with the motor above and impeller hanging below.

There are three main impellers: axial flow, mixed flow, and radial flow. The main difference is the angle the flow is changed by the impeller blades, as shown in Table 1.

- Horizontal pumps typically utilize a radial flow impeller spinning about a horizontal axis and are commonly termed centrifugal pumps. The impeller can be overhung with a bearing on one side only or between two bearings.
- Vertical pumps mostly utilize axial flow and mixed flow impellers that spin about a vertical axis. Some of the largest pump stations in the world utilize vertical pumps as they can efficiently move large volumes of water. See Figure 1a for examples.

Figure 1a: Left: Author next to the top of a large vertical pump for moving canal water. Right: The lower section of an 11’ dia. vertical pump for flood protection.
Source: Author, https://slfpaw.org/portfolio-items/8602/

Table 1: Comparison of Impeller Configurations			
Type	Section View	Flow Change	Best Performance
Axial Flow		0º	High Flow Rate Low Pressure
Mixed Flow		40º to 60º	Medium Flow Rate Medium Pressure
Radial Flow (Centrifugal)		90º	Low Flow Rate High Pressure

Sources: https://commons.wikimedia.org/wiki/File:Axial_flow_pump-diagram.jpg (modified) by Jonasz, CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:Centrifugal_pump-tech_diagram (modified) by Jonasz, CC BY-SA 3.0

See Figure 1b for an example of a vertical pump arrangement.

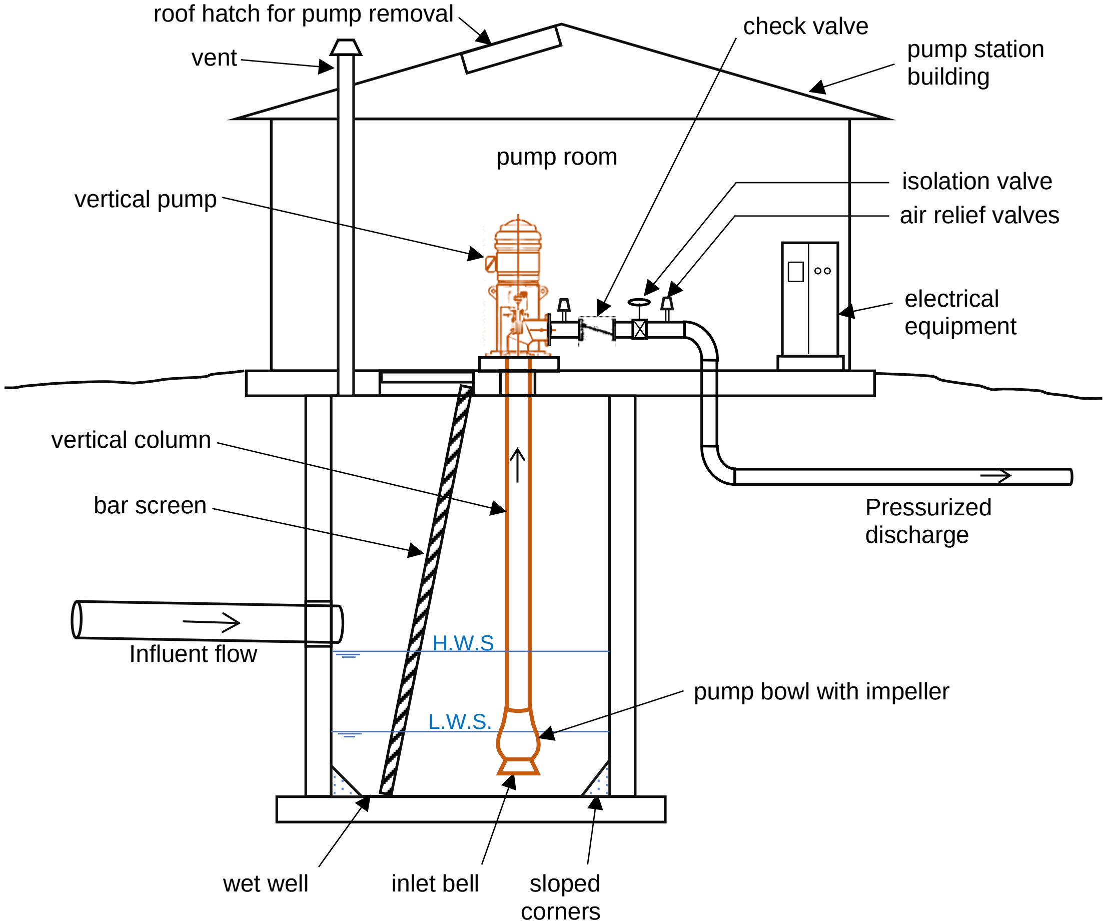


Figure 1b: Example pump station with the vertical pump in orange.
This arrangement is common for sewer lift stations.
Source: Author

<u>Benefits to Vertical Pumps</u>

There is no clear “winner” when comparing pump types. Pumps are selected based on the specifics of the application. However, some general advantages of vertical pumps compared to traditional horizontal centrifugal pumps are listed in Table 2.

Table 2: Advantages and Disadvantages of Vertical Pumps

Advantages	Disadvantages
Higher efficiency	Low flow can be a challenge
Multi-stage potential for high head	Backwards impeller rotation potential due to column of water
High flow, low head potential	Crane and roof openings often required for removal
Greater pressure control ability	Difficult to access the impeller for rag & debris removal
Steeper pump curve which provides greater flow stability	More bearings and bushings to maintain
Fewer cavitation and suction problems	Air valves are often needed
Less noise	Deep excavation or tall building often required
Smaller footprint	
Can drain a tank to the bottom	

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

- Agriculture
- Chemical
- Construction
- Food & Beverage
- Manufacturing
- Mining & Minerals
- Nuclear
- Oil & Gas
- Power Generation
- Pulp & Paper
- Stormwater
- Water & Wastewater

Many types of engineers regularly design vertical pumps, including:

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

Engineers are expected to select a vertical 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 accepted guidelines and specifications for the design of pumping systems. The HI Standards define three groups of rotodynamic pumps:

1. Overhung (OH) Pumps
2. Between Bearings (BB) Pumps
3. Vertically Suspended (VS) Pumps

Vertical pumps are covered by the relevant standards listed in Table 3.

Table 3: ANSI/HI Standards for Vertical Pumps

Standard No.	Standard Title
9.6.1	Rotodynamic Pumps Guideline for NPSH Margin
9.6.3	Rotodynamic Pumps – Guideline for Operating Region
9.6.5	Rotodynamic Pumps Guideline for Condition Monitoring
9.8	Rotodynamic Pumps for Pump Intake Design
14.1 & 2	Rotodynamic Pumps for Nomenclature and Definitions
14.3	Rotodynamic Pumps for Design and Application
14.4	Rotodynamic Pumps for Installation, Operation, and Maintenance
14.6	Rotodynamic Pumps for Hydraulic Performance and Acceptance Tests

Solids Handling
Pumps handling raw wastewater shall be capable of passing solid spheres of at least 3 inches (80 mm) in diameter, per the *Ten States Standards*. And pump suction and discharge openings shall be at least 4 inches (100 mm) in diameter. This also applies to stormwater and irrigation pumps. Vertical pumps are generally able to pass large solids and meet these requirements. Stringy material is more of a concern as it may wrap around the impeller and shaft.

Pump Types

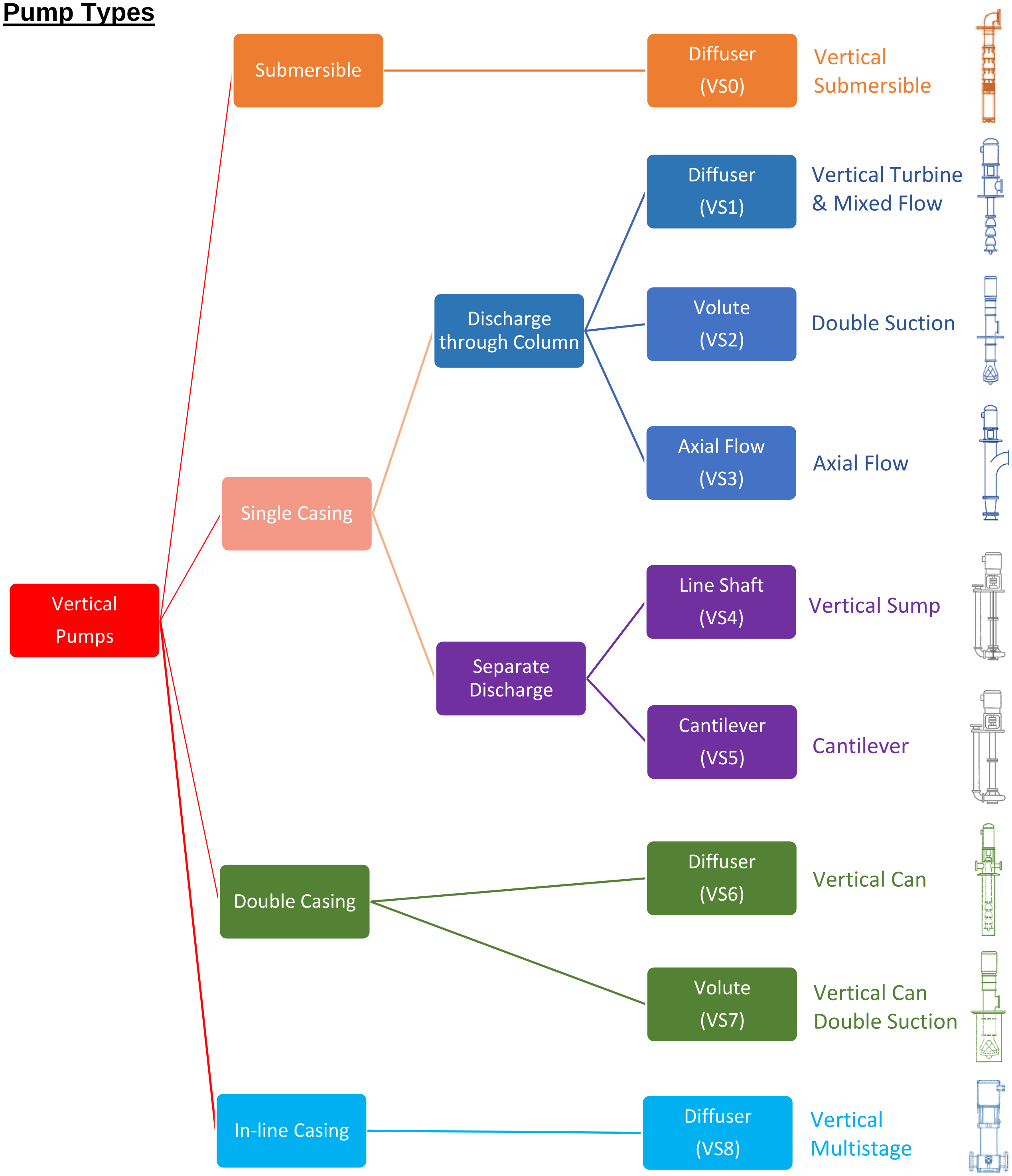


Figure 2: Chart of vertical pump types with VS numbers per API610.
Source: Author, API 610, HI Standard 14.1

The following tables provide details for each type of vertical pump, except double suction pumps (VS2 & VS7) as they are less common and for specialized applications.

(VS0) Vertical Submersible Pumps		
Function	**Configurations**	**Common Applications**
The motor is located below the intake. Flow enters through a screened column and is drawn up through a mixed flow impeller with diffusers. Additional stages increase the pressure and discharge the fluid upward through a pipe column.	• Submersible well pump • Downhole pump • Encased stages • Bowl stages	• Deep wells • Shallow wells • Irrigation wells or ponds • Raw water intake

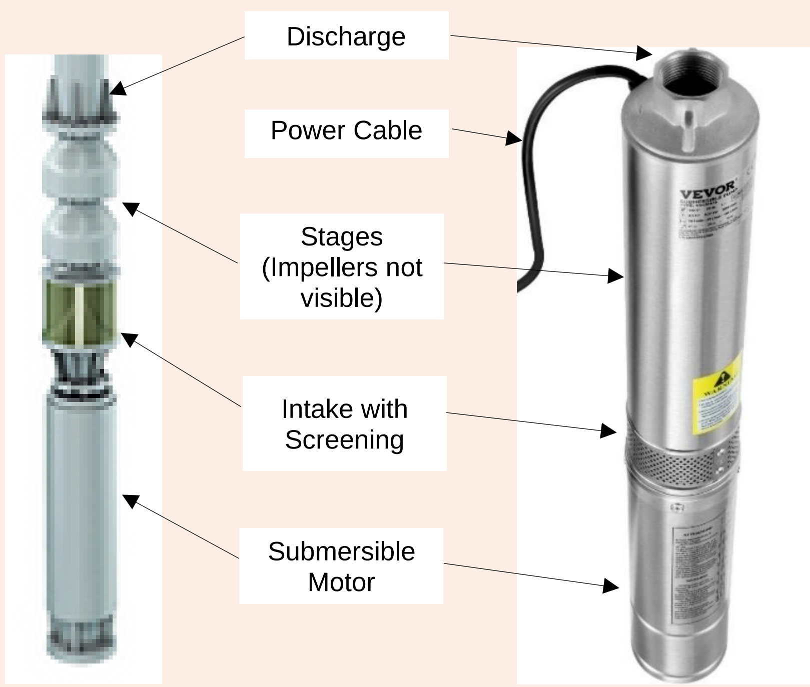


Figure 3: Example vertical submersible pumps.
Left: Large well pump with two bowls visible, one for each stage.
Right: Small well pump with (5) stages inside a stainless steel casing.
Source: www.bcu.id/Pumps/details/SJS?lang=id, www.ebay.com/itm/403946187179

(VS1) Vertical Turbine & Mixed Flow Pumps		
Function	**Configurations**	**Common Applications**
Flow enters through the bottom inlet and is drawn up through a mixed flow impeller with diffusers. Additional bowls/stages can be added. The fluid is discharged horizontally, typically above the mounting plate.	• Vertical turbine • Mixed flow • Single stage • Multistage • Enclosed shaft • Open shaft	• Oil & Gas • Mining • Stormwater & flood control • Groundwater • Water treatment and distribution • Wastewater

Figure 4: Left and Center: Example vertical turbine pumps.
Upper Right: View looking down inside a mixed flow pump. The shaft is typically enclosed in a vertical turbine style pump for protection from corrosion and stringy material.
Lower Right: Intake of a mixed flow pump with a bronze impeller.

Source: https://commons.wikimedia.org/wiki/File:Vertical_turbine_pumps.jpg, Mukund275, CC-BY-SA-3.0; author

(VS3) Axial Flow Pumps		
Function	**Configurations**	**Common Applications**
Flow enters through the bottom inlet and is drawn up through an axial flow impeller and column. The fluid is discharged horizontally, typically above the mounting plate.	• Enclosed shaft • Open shaft • Strainer on Inlet • Belt driven	• Irrigation • Mining • Stormwater & flood control • Groundwater • Petrochemical • Water treatment and distribution • Wastewater

Figure 5: Three axial flow pumps mounted on top of a wet well for transferring water to a storage tank. An axial flow pump is similar to a mixed flow pump, as shown in Figure 4, except it has an axial flow impeller as shown in Table 1.

Source: author

(VS4) Vertical Sump Pumps		
Function	**Configurations**	**Common Applications**
Flow enters through the bottom inlet and is drawn up through a radial flow (centrifugal) impeller and sent through a separate riser pipe. The fluid is discharged vertically above the mounting plate.	• Belt drive • All stainless steel • Extended suction	• Chemical transfer • Tank farms • Floor sump • Industrial wastewater • Hot fluids • Slurry handling

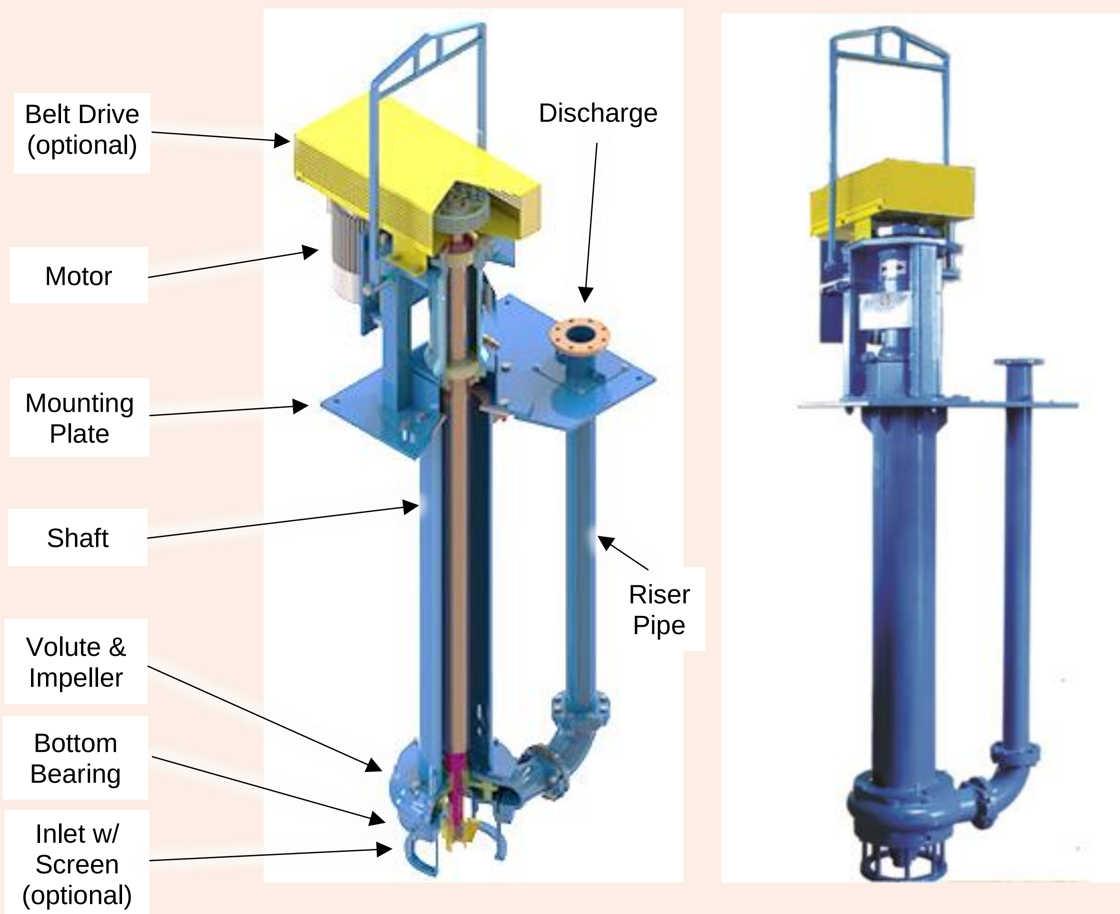


Figure 6: Vertical sump pump (a.k.a. vertical line shaft pump) with labels.

Source: commons.wikimedia.org/wiki/File:Vertical_Slurry_pump.png, Shayan ya 70, CC-BY-SA-3.0

(VS5) Cantilever Pumps		
Function	**Configurations**	**Common Applications**
Flow enters through the bottom inlet and is drawn up through a radial flow (centrifugal) impeller and sent through a separate riser pipe. The fluid is discharged vertically above the mounting plate.	• Belt drive • All stainless steel • Extended suction	• Chemical transfer • Tank farms • Floor sump • Industrial wastewater • Hot fluids • Slurry handling

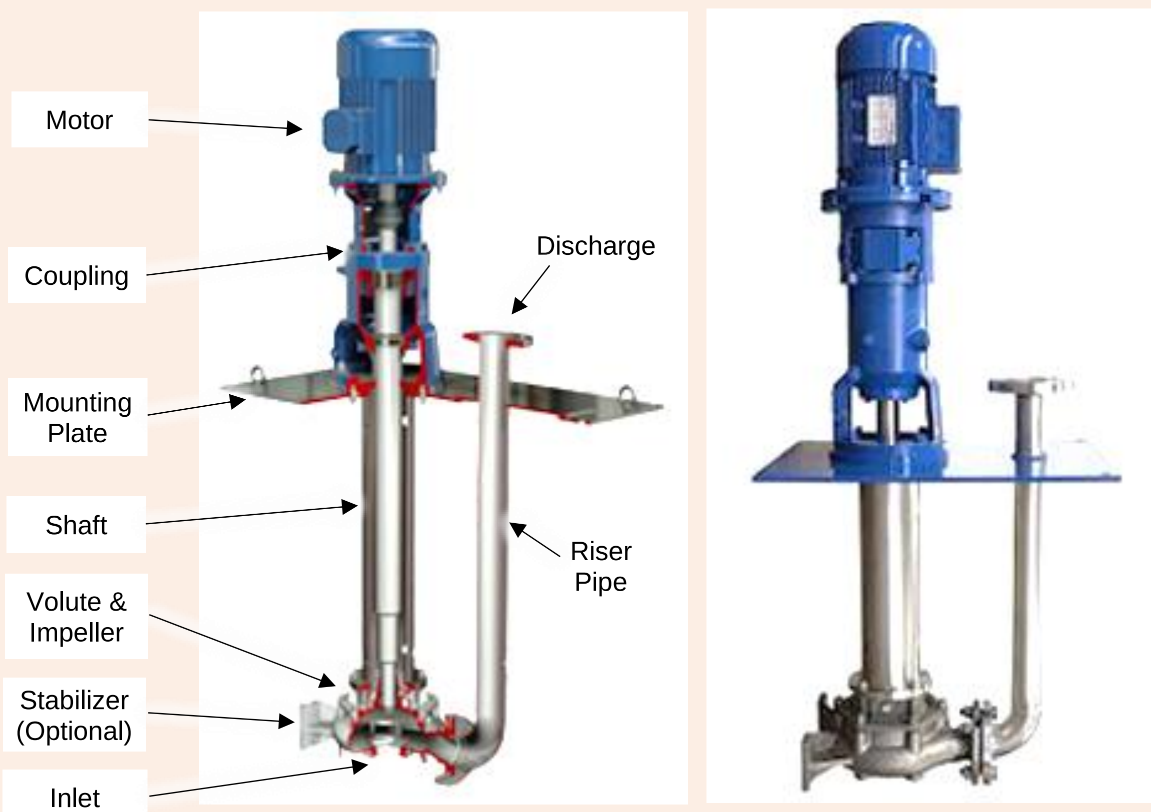


Figure 7: Cantilever pump with labels. The key difference from a vertical sump pump is the lack of bearings at the impeller. To avoid excessive deflections, the shaft is enlarged, height is limited, and a stabilizing bracket (optional) is secured to a wall.

Source: https://thaikhuongpump.com/en/product/vertical-cantilever-centrifugal-pumps-salvatore-robuschi/

(VS6) Vertical Can Pumps		
Function	**Configurations**	**Common Applications**
Flow enters an outer casing (a.k.a. can or barrel) through a side inlet and is drawn up through a mixed flow pump with one or more stages. The fluid is discharged horizontally above the mounting plate. No wet well is needed.	• Vertical turbine • Mixed flow • Single stage • Multistage • Enclosed shaft • Open shaft	• Oil & Gas • Mining • Nuclear and Energy • Stormwater • Water treatment and distribution • Wastewater

Figure 8: Four vertical can pumps (a.k.a. barrel pumps) prior to encasement in concrete.
Left: Cans installed without VS1 pumps. Inlet manifold piping also needs to be installed.
Right: After VS1 pumps set into the cans and bolted to the mounting plates.

Source: author

(VS8) Vertical Multistage Pumps

Function	Configurations	Common Applications
Flow enters through a side inlet and is drawn up through a series of impellers and redirected back down through an outer chamber. The fluid is discharged through a side outlet opposite of the inlet.	• All stainless steel • Horizontal mounting • High temperature	• Fire water • In-line booster • Industrial fluids • Hot fluids • Spray and irrigation • High pressure applications

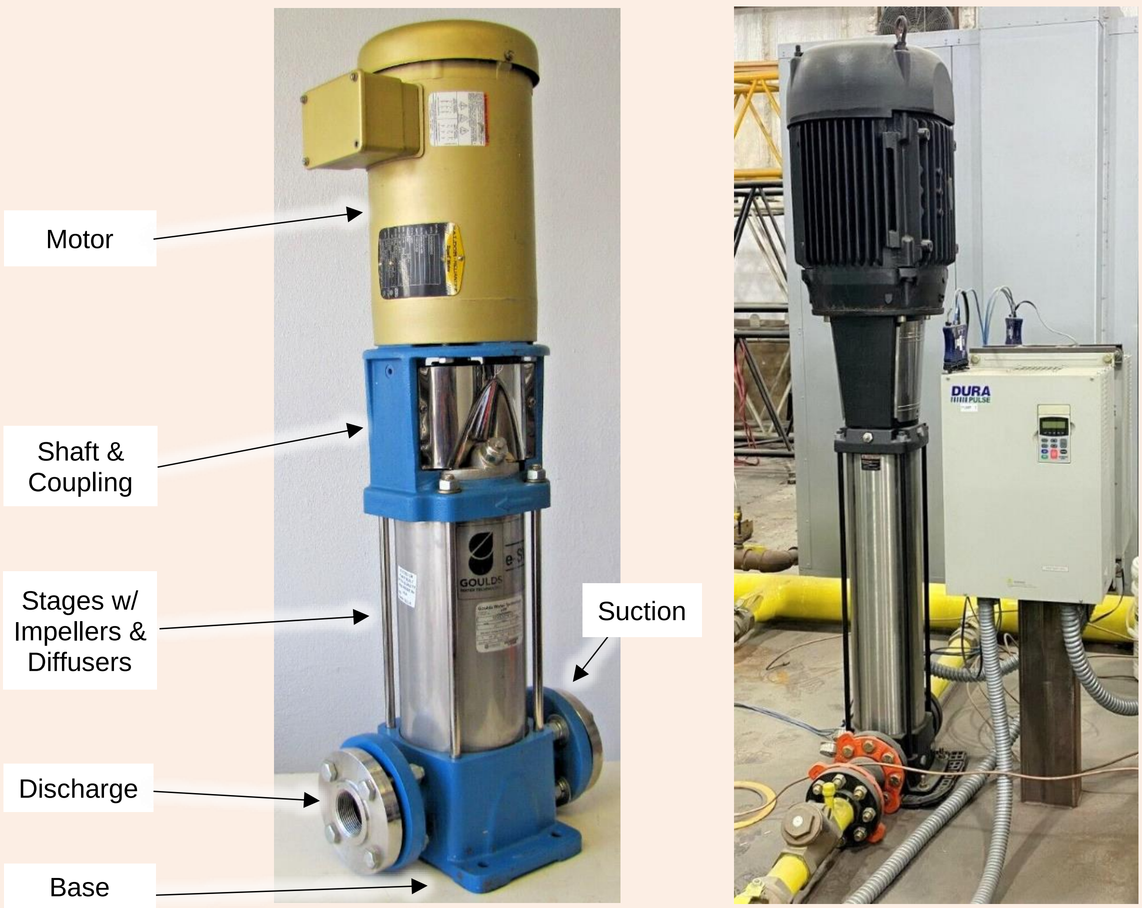


Figure 9: Examples of vertical multistage pumps with high discharge pressures.
Left: Pump rated for 26 gpm at 975 ft TDH with 10 stages
Right: Pump rated 160 gpm at 770 ft TDH with 11 stages

Source: https://www.ebay.com/itm/275925486881, https://www.ebay.com/itm/313810803043

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 TDH and plot system curves
7. Pump selection
8. Create a hydraulic profile
9. Quality review of calculations
10. 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:

- Flow and pressure capacity meets or exceeds demands.
- Pump type and materials suitable for fluid type.
- Pass solid sphere of specified diameter.
- Avoid clogging or ragging.
- Starts per hour not excessive.
- Speed control, stroke control, and minimum turndown allow for minimum flow.
- Avoid NPSH and cavitation problems.
- Allow future change to a larger or smaller pump or adding a pump.
- Minimize energy consumption (minimum efficiency).
- Minimize capital costs and lifecycle costs.
- Allow proper maintenance access and clearance for pump removal.
- Provide an installed redundant pump.
- Lead time is acceptable.
- 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

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.

Note that the pressure requirements are typically calculated later in the design process when developing the system curve. However, in some cases, pressure requirements are part of the initial design criteria. For example, a fire water pumping system is to maintain a minimum pressure of 100 psi in the standpipe across all potential sprinkler demands. In this example, the pump design criteria would be a discharge pressure of 100 psi at all flow rates.

Example Problem 1

Engineer Andrew is asked to list the design criteria for pumping stormwater from a canal into a basin. The pumping system must reliably pump a peak flow of 5000 gpm, an average flow of 4000 gpm, and a minimum flow of 2000 gpm, depending on the canal level. The discharge pressure ranges from 0 to 10 psi based on the water level in the basin. Two vertical mixed flow pumps with speed control are to be utilized.

Solution:

Andrew creates the following Table 4 to summarize the design criteria.

Table 4: Stormwater Pumping Design Criteria for Problem 1		
Fluid Type	Stormwater	
Pump Type	Vertical mixed flow	
Number of Pumps	3 (2 duty + 1 standby)	
Drive Type	Variable frequency	
Flow Conditions	Flow Rate (gpm)	Discharge Pressure at Basin (psi)
Peak	5000	0 to 10
Average	4000	0 to 10
Minimum	2000	0 to 10

Number of Pumps and Flow Control

Simplex Pump
A simplex pump (single pump) is seldom chosen as it can cease to operate and pumping stops. However, in some applications that is acceptable, especially if a spare pump is on the shelf and can be easily installed. For example, a single sump pump is often used for floor drainage. If the pump fails, the drainage will backup in the sump and an alarm will go off. Some temporary measures may be taken, and drainage may overflow into a designated area until a spare or replacement pump is installed.

Duplex Pumps
A duplex pump arrangement (two pumps in parallel) is the most popular. Typically, 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 over triplex:
- Simplicity in design, construction, and maintenance,
- Easier to calculate the flow/dosing rate and adjust the pump speed.
- Low construction cost, and
- Smallest footprint.

Triplex or more Pumps
Using three or more pumps is generally beneficial under the following conditions, although this is highly dependent on the type of pump:
- Peak factor great than 4,
- Large flow rates, such as a peak flow greater than 5,000 gpm, or
- Large pressure range, such as greater than 20 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 or well,
- If two pumps are out of service, a third can still pump at average flow, and
- Increase in pumping efficiency with associated energy savings.

Large pumping stations, and especially booster stations, may have a combination of small pumps and large pumps. The small pumps stay in the high-efficiency range during low flow events, while the larger pumps can efficiently handle flows during large events. This combination of small and large pumps requires a more complex control logic. Also, a redundant small and redundant large pump may be required.

Constant Speed
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. This is often acceptable for wet well, sump, or tank applications, for which the water level will fall when the pump is on and rise when the pump is off. The “pump on” and “pump off” levels need to be far enough apart to allow proper pump cycling. Often the storage volume needs to be larger than a variable speed control scenario.

Variable Speed
Variable speed controls can be used to control the flow, pressure, or for holding a fixed water level. This is achieved by adjusting the pump speed in small increments based on instrument readings and/or programming. The following are 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.
- Motor lasts longer since it has fewer starts and starts slowly.

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. Speed adjustment equipment adds a small amount of energy loss, typically 3% to 5%.

Example Problem 2

Engineer Kennedy is designing a pump station for transferring cooling water through a power plant. She needs to decide on the best combination of pumps to meet a peak flow of 1940 gpm and a minimum flow of 750 gpm, all while maximizing energy efficiency and minimizing cost. Pump representatives provided the information in the following table. Help Kennedy decide which alternative is best for the pump station.

Table 5: Pump Data for Problem 2

Alt. No.	Duty Pumps	Standby Pumps	Flow Range (gpm)	Efficiency at Avg Flow	Installation Cost
1	(1) 100 HP	(1) 100 HP	1100 to 2050	70%	$200k
2	(2) 50 HP	(1) 50 HP	800 to 2000	75%	$160k
3	(3) 30 HP	(1) 30 HP	700 to 1950	77%	$175k
4	(2) 40 HP + (1) 20 HP	(1) 40 HP	600 to 1980	77%	$190k

Solution:

Kennedy has the following observations:

- All alternatives meet the peak flow condition.
- Alternatives 1 and 2 do not meet the minimum flow requirement and thus are eliminated.
- Alternatives 3 and 4 have the same efficiency.
- Alternative 3 has a lower cost than Alternative 4.

Based on these observations, the best combination is Alternative 3 (total four 30 HP pumps).

Process Flow Diagram

It is helpful to make a schematic drawing of the overall pumping system early in the design process. This may start as a sketch with boxes and arrows, called a block flow diagram (BFD), as shown in Figure 10.

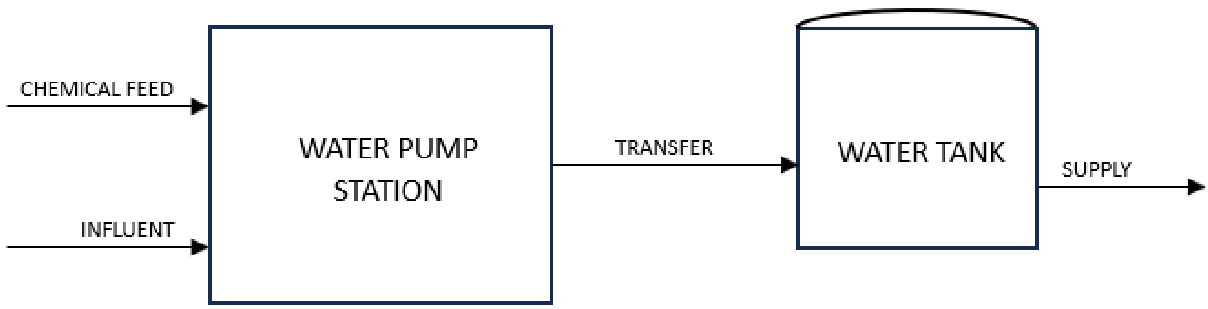


Figure 10: Example BFD for a Water Pump Station
Source: Author

As the design develops, a more detailed diagram should be developed known as a process flow diagram (PFD). A PFD is a simple schematic showing major components, such as pumps and tanks, with lines representing the piping and arrows for flow direction. This schematic helps to define the suction and discharge piping which impacts the headloss and pump selection. See Figure 11 for an example of a PFD with vertical pumps.

PFDs are often used as a starting point for controls or integration engineers to create piping and instrumentation diagrams (P&IDs). P&IDs include symbology for the controls features, such as instrumentation, control panels, and communications.

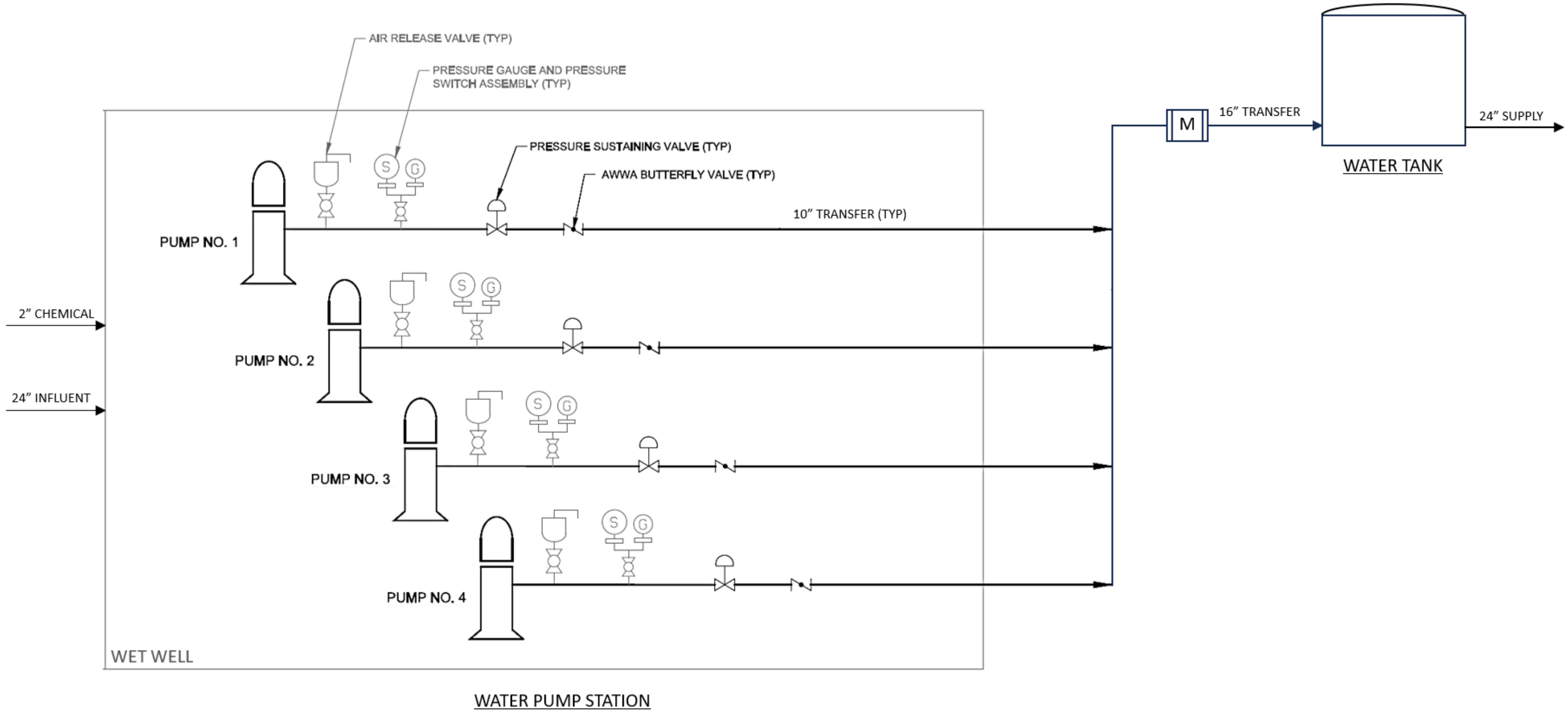


Figure 11: Example PFD for the BFD in Figure 10, with four vertical turbine pumps (VS1).

Source: Author

Intake Design

A proper intake design protects the pump from vortices, entrained air, and cavitation. The intake is the physical arrangement of walls, baffles, and/or piping that guides flow to the pump inlet.

- For vertical well pumps (VS0), the inlet is at the top of the pump and submergence requirements should be reviewed with the pump manufacturer.
- For most vertical pumps (VS1 to VS7), the inlet is the opening (or bell) at the bottom of the pump. See Figures 12, 13 and 14 for common vertical pump arrangements.
- For vertical multistage in-line pumps (VS8), the inlet is a pipe connection.

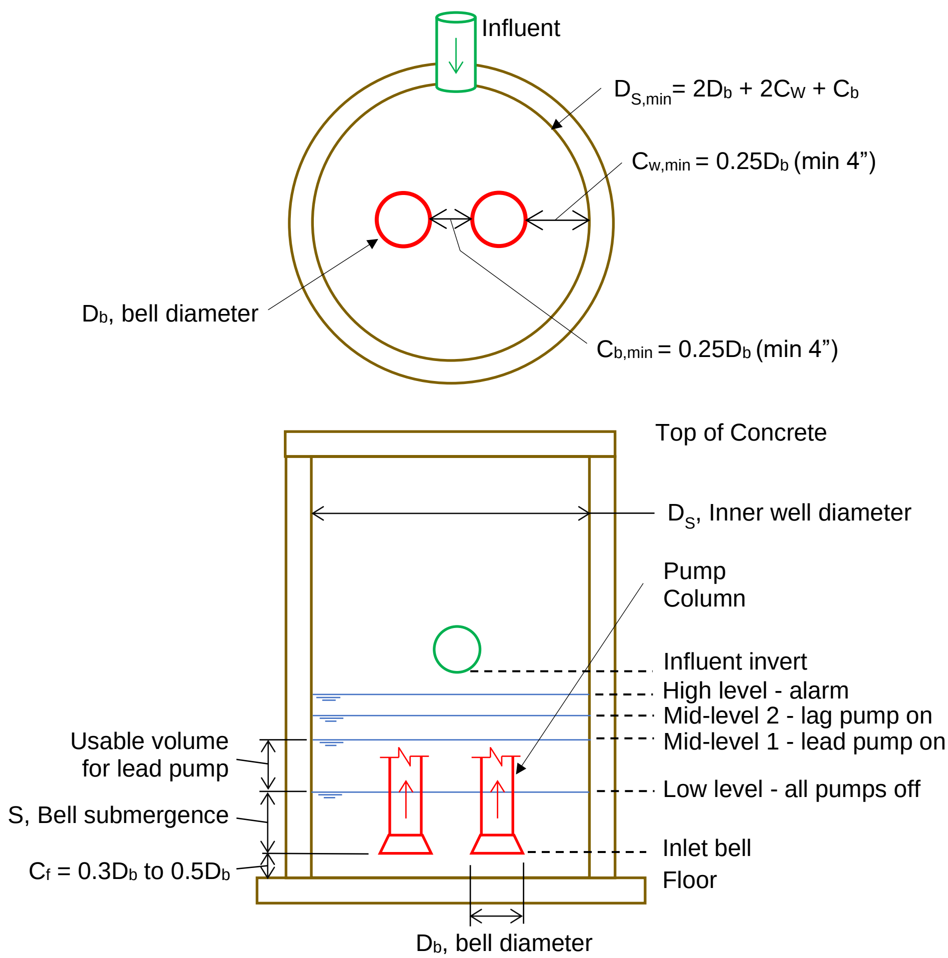


Figure 12: Circular wet well arrangement with two (duplex) vertical pumps.
Source: Author, HI Standard 9.8

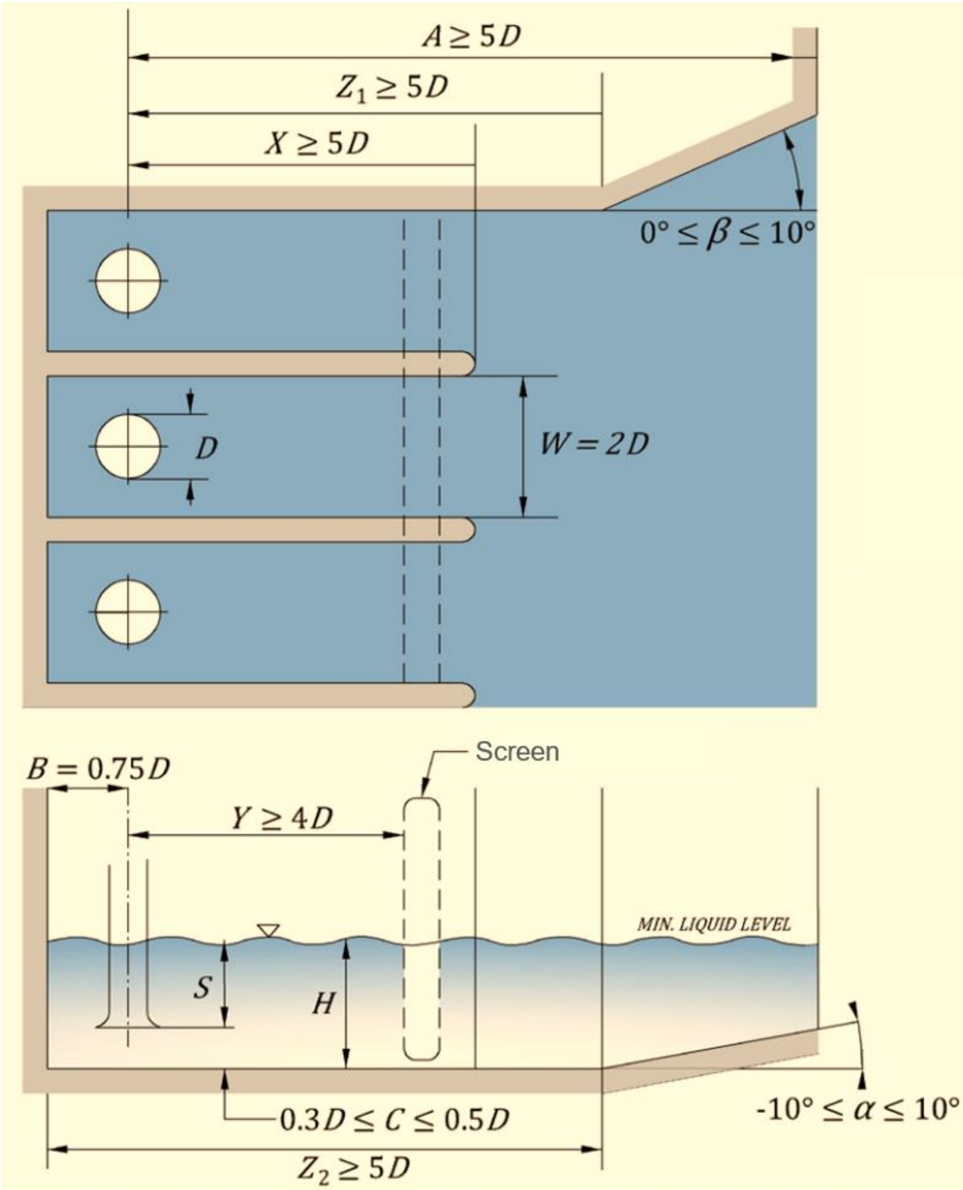


Figure 13: Rectangular intake arrangement with three (triplex) vertical pumps.
Dimensions are per HI Standard 9.8.
Source: Author, HI Standard 9.8

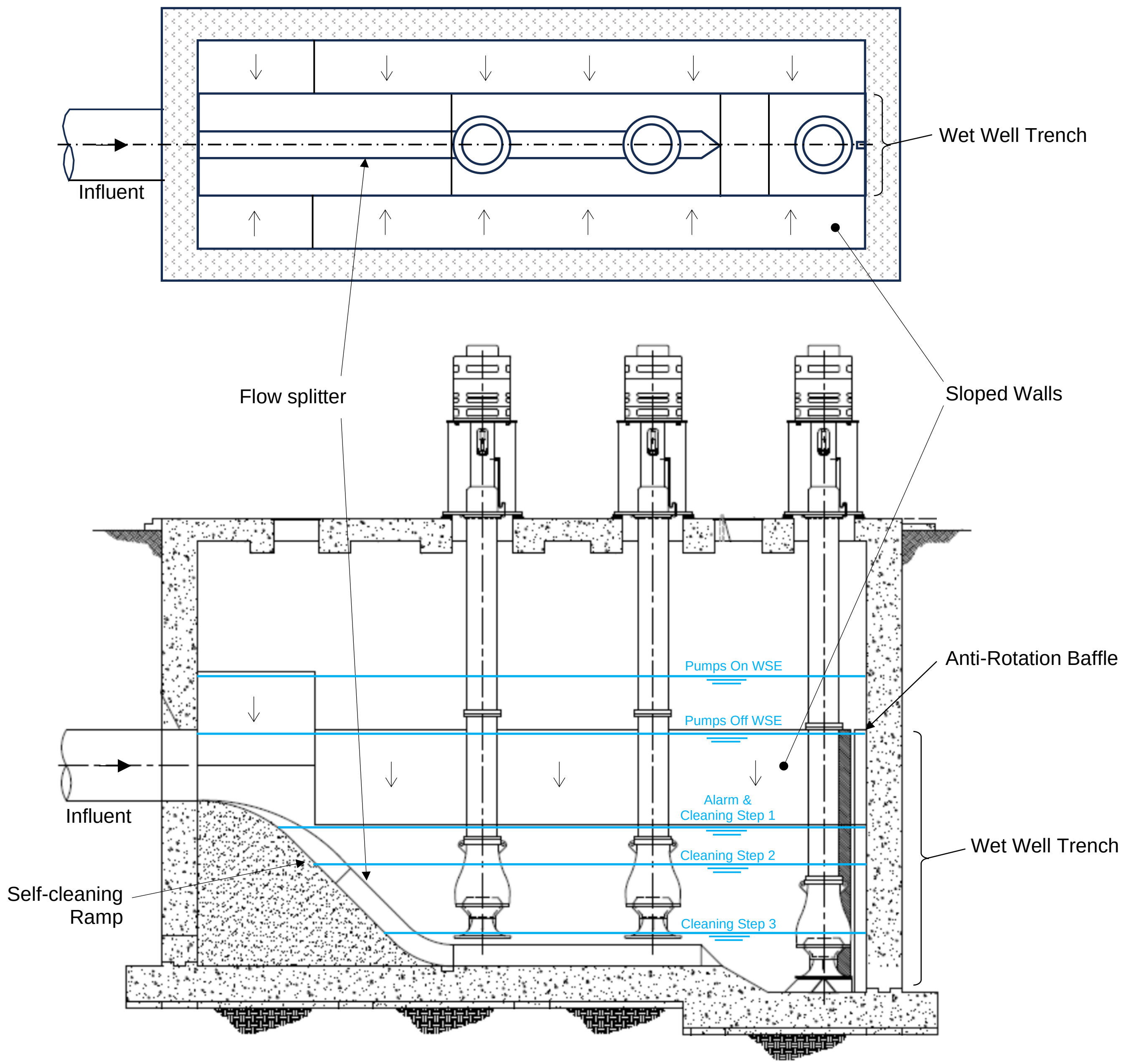


Figure 14: Tench (in-line) intake arrangement with three (triplex) vertical pumps.
The last pump is in a deeper channel to allow scouring/cleaning of the channel.
The flow splitter is triangular shaped grout that helps prevent vortices.
For cleaning step 3, only the last pump is on and for a short period.
Source: Author, HI Standard 9.8

Intake Dimensions

Once the intake arrangement has been decided, the wet well dimensions need to be determined. The pump manufacturer should provide recommendations for the pump inlet or bell diameter, distance from the floor, and minimum submergence to prevent air intake and to satisfy NPSH (see next section). The pump station design engineer should review this information, checking if any local codes or standards govern, and consider if hydraulic modeling is justified.

Important intake dimensions are as follows, per *HI Standard 9.8* on intake design:

- Bell diameter sized so velocity at maximum pump flow is approximately 5.5 ft/s (1.7 m/s).
- Clearance between multiple inlet bells (or pump volutes) to be a minimum of 0.25 times the bell diameter. For submersible pumps, confirm the minimum pump spacing and wall distance with the manufacturer.
- Distance from the center of the inlet bell to the nearest wall of the wet well should be a minimum of 0.75 times the bell diameter.
- Distance from the inlet bell to the flat floor should be from 0.3 to 0.5 times the bell diameter.
- Minimum inlet submergence (S), which is the depth in inches below the minimum water surface, based on bell diameter (D) in inches and maximum flow rate (Q_{max}) in gpm:

$$S = D + \frac{0.574 * Q_{max}}{D^{1.5}}$$

For wet well and dry well pumps, water levels should be defined by the engineer and stated on the drawings or a pump controls narrative, to help ensure pumps will be protected from entrained air during operation.

NPSH
To avoid cavitation, 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. Checking the NPSH is needed in addition to checking the minimum inlet submergence.

Often the pump curve will include an NPSHr curve. The engineer should confirm the NPSHr value at the maximum pump operating flow rate is less than the calculated NPSHa. If the NPSHr is greater than NPSHa, the following options are available to correct the issue:

- Increase inlet submergence,
- Increase suction pipe size,
- 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 6:

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

Table 6: NPSHa Definitions and Calculation		
Term	**Example (ft)**	**Definition**
H_{bar}	+33.5	Atmospheric pressure, which is 14.7 psi (33.96 ft) at sea level. Adjust based on elevation of the pump station.
h_s	+2.5	Minimum static head at pump. Height from pump inlet or impeller to low water level. Check with pump manufacturer if they measure NPSHr from the pump inlet/bell or the impeller.
H_{vap}	-1	Vapor pressure of water, at 75 deg F, expressed in feet.
h_{fs}	0	Suction pipe friction losses at the max pump operating flow rate. Zero for vertical pumps (VS1 to VS 7) in a well or tank.
Σh_m	-2	Suction pipe minor losses at max pump operating flow rate.
h_{vol}	-2	Partial pressure of dissolved gases, such as from air in water (customarily ignored as insignificant) and from organics in wastewater (estimated at 2 ft).
h_a	0	Acceleration head for positive displacement pumps only (N/A).
FS	-5	Factor of Safety, often from 2ft to 5ft, or 20% to 35% of NPSHr.
NPSHa	**26.0**	**Sum the above terms**

System Curves

A system curve is a plot of the total dynamic head (Y-axis) versus the flow rate (X-axis).

Ideally, the “system” starts with the static liquid elevation at the suction side to the static liquid elevation at the discharge side. However, the system can start or end at any point in the piping, provided that the flow and pressure are known at that points. For example, for a lift station, the system typically starts at the water level in the wet well and ends at the discharge pipe tie-in to the existing force main, with a known pressure at the tie-in.

The total dynamic head (TDH) represents the energy required to move the wastewater to the destination at a given flow rate. The pumps need to provide that energy. Another word for TDH is “loss” or “head”. Engineers use the unit of feet (or meters) for TDH for simplicity in calculations.

Steps to Create Curves

A system curve is created by calculating the system losses at several different flow rates and then plotting the points. The following are typical steps for creating a system curve:

1. Gather the following information:
   a) Design flow rates (i.e., minimum, average, and peak flow),
   b) Number and type of duty pumps,
   c) Suction and discharge pipe I.D., material, route, and tie-in elevations,
   d) Suction and discharge fittings and valves, and
   e) Water level elevations or tie-in pressures for suction and discharge.
2. Define the inputs and outputs (water levels or pressures) at the extreme low and high static operating conditions. For example, for pumping from a wet well into a tank:
   a) Lowest static head: high water level in well and low water level in tank.
   b) Highest static head: low water level in well and high water level in tank.
3. Tabulate and sum the following headloss values for the two static operating conditions in step two above, at each of the design flow rates, to get TDH values:
   a) minor losses,
   b) pipe friction losses, and
   c) static head change
4. Plot the TDH versus Flow points for the two static conditions. Create two system curves using 2nd order polynomial curve fitting. See Figure 15 for an example.

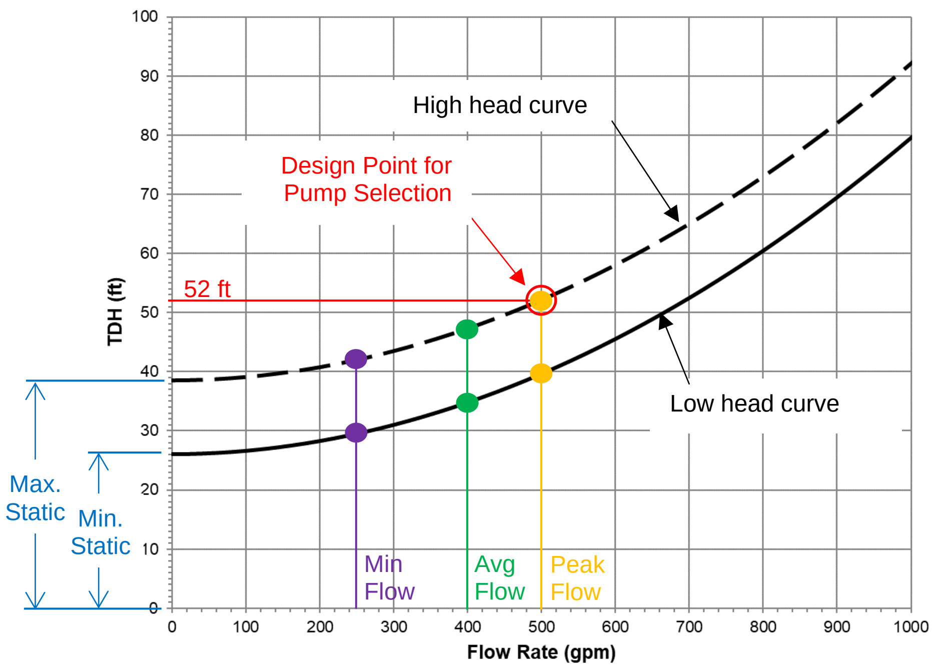


Figure 15: System curves in black drawn based on calculations for (6) TDH points shown as the solid circles (two at each design flow rate). The point circled in red (500 gpm @ 52' TDH) is used for initial pump selection.
Source: Author

Often only the "high head curve" (highest static head condition) is plotted for simple pump station designs or if the changes in static head are minor, since the high TDH controls for pump selection. However, it is good practice to plot both to check the high and low TDH pump operating conditions, as explained in the next section.

Hydraulic Calculations

There are excel templates or programs available for calculating headloss values. Please download the Free Software that comes with this course for a template for performing headloss calculations. The following are basic guidelines for hydraulic calculations.

For minor losses (H_{Lm}), the K-value method (shown below) is utilized, which requires finding the resistance coefficient (K) for each type of fitting or valve in the system.

$$\boldsymbol{H_{Lm}} = \sum K \frac{V^2}{2g}$$

where: K = resistance coefficient
V = velocity (typically in fps)
g = acceleration of gravity (32.2 ft/s^2 or 9.81 m/s^2)

For pipe friction losses (H_{Lf}), the Hazen Williams Equation (shown below) is by far the most used formula. Not only is it simple and easy to use, but its use is also accepted by many regulatory agencies.

$$\boldsymbol{H_{Lf}} = Le_{ft} / 100 * 0.2083\ (100 / c)^{1.852} * q_{(gpm)}^{1.852} / d_{(in)}^{4.8655}$$

where: Le = pipe length, feet
c = friction coefficient, 120 (cast iron), 140 (ductile iron), 150 (PVC)
q = flow rate, gpm
d = pipe diameter, inches

Coefficients for friction losses and K values for minor losses can be obtained from *Flow of Fluids Through Valves, Fittings & Pipe* by Crane, *Cameron Hydraulic Data* by Flowserve, or other documents listed under Helpful References. Also see Examples 3 and 4 in the course entitled "Centrifugal Pump Selection" for example TDH calculations.

Multiple Duty Pumps

When there is more than one duty pump, the calculations become a bit more complicated because the flow rate differs between the pump branches and manifold pipe.

The steps for creating system curves differ as follows:

- If the pumps are the same size and the piping at each branch is similar, then the flow rate through each branch will be the total flow divided by the number of pumps in operation.
- See the next subsection for branch headloss calculations for the following:
    - Pumps are different sizes,
    - Branches have different pipe diameters, or
    - Branches have very different fittings or valves.
- The minor losses and friction losses through each pipe branch are calculated with the branch flow rate instead of the total flow rate. For example, if there are two duty pumps, each branch flow rate is 50%.
- System curves can be plotted for each combination of pumps running (one pump running, two pumps running, etc.). However, the curve with all duty pumps running controls for pump selection (since pumps must meet the), so it is common practice to only plot the curve with all duty pumps running.

Different Size Pumps

If the pumps are different sizes, branch pipes are different sizes, or there is a significant difference in the fittings or valves in each branch, then the headloss calculations become more complicated.

The following options are available:

1. Iterative Calculations: Assume a flow balance between the branches, run the calculations, check the pressures at the discharge connection node, adjust flow rates, run the calculations again, check pressures again, and continue iterations until the pressures are near the same at the discharge connection node.
2. Hydraulic Modeling: The piping network is entered into a hydraulic model or similar software to solve TDH at various flow rates and to create a system curve for each branch.
3. Pump Curves with Branch Losses: With this approach, the pump curve is adjusted to include the branch losses. First, system curves are created without the unique parts of the branches at each pump. Next, the branch losses are calculated at various flow rates. Then, when choosing a pump size, the head losses at the branch are subtracted from the pump curve. This modified “pump+branch curve” is plotted with the system curves to confirm the operating point. See the next Section regarding plotting pump curves with system curves.

Example Problem 3
Mike is designing an irrigation water pump station with three axial flow pumps, VS3, two duty and one standby, as shown in Figure 16. The suction water level is to be maintained at a constant EL 4.0. The discharge is at the top of a tank at EL 12.0. The PHF is 2,000 gpm. Each branch has 30 feet of 10” DIP. The pipeline to the discharge tank has 4,000 feet of 12” DIP. Mike is to calculate the TDH at the PHF and plot the system curve with two pumps in operation.

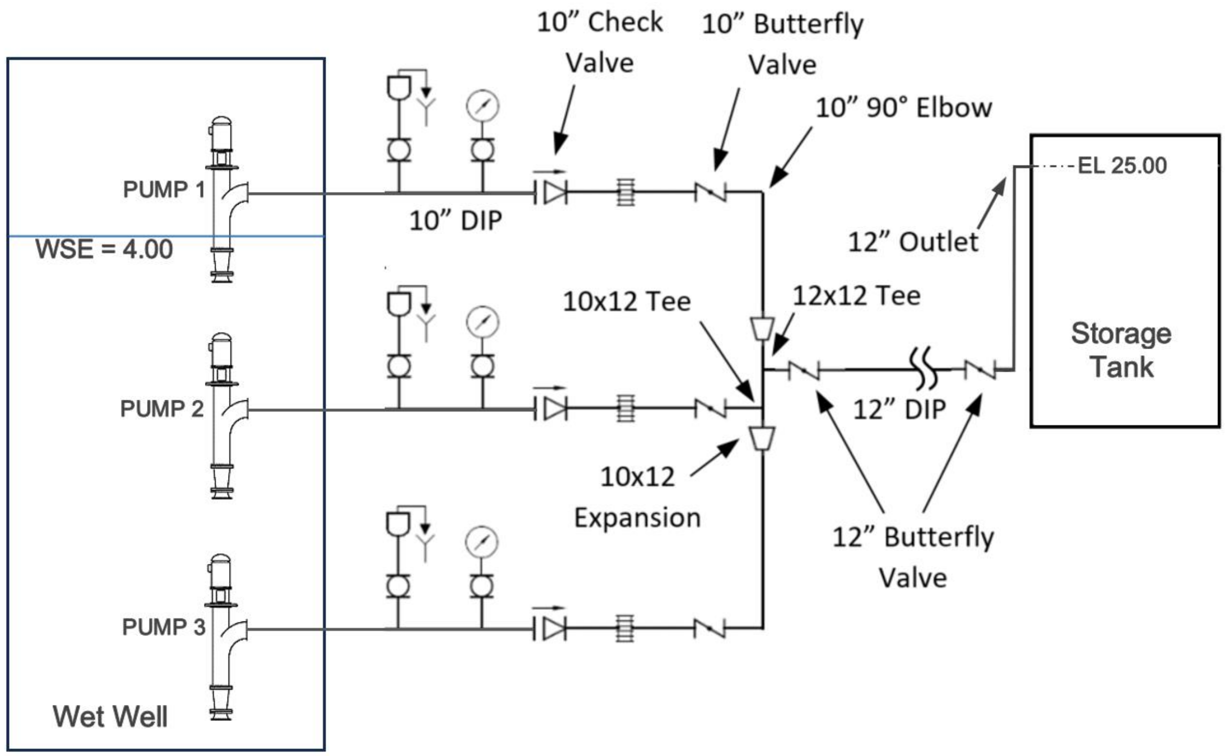


Figure 16: Process flow diagram for Problem 4.
Source: Author

Solution:
Mike determines that since the pipe branches are nearly identical, with two pumps running, the flow through each branch will be 1,000 gpm. Since the water levels in the wet well and storage tank are to remain constant, Mike decides that calculating a single system curve is acceptable. To be conservative, he chooses the bottom branch for the calculations since it has one more fitting than the other two branches.

To start, Mike calculates the static head:

H_{St} = 25.0' – 4.0' = **21.0 ft**

Mike calculates the minor losses at the PHF. Mike uses the K-value Method to calculate the minor losses at 1,000 gpm in the 10" branch and 2,000 gpm in the 12" pipeline. K-values are summarized separately in Tables 7 and 8. Note that joints, couplings, and small taps have insignificant loss contributions. Losses from the inlet and pump column 90 bend are not included as the pump manufacturer said that these are taken account in the pump curve.

Table 7: Branch Coefficients

Fitting	K-value
Check valve	3.00
Butterfly valve	0.50
90º elbow	0.30
10"x12" expansion	0.15
Sum K-values	**3.95**

Table 8: Pipeline Coefficients

Fitting	K-value
Tee – straight thru	0.60
Tee – out branch	1.80
Butterfly valve	0.50
Butterfly valve	0.50
90º elbow	0.30
90º elbow	0.30
Outlet, wall opening	1.00
Sum K-values	**5.00**

The minor losses are calculated for the branch and pipeline, and summed:

$$\boldsymbol{H_{Lm\_br}} = \sum K_{br} \frac{\left(\dfrac{\dfrac{1000_{gpm}}{448.8_{gpm/cfs}}}{\pi\left(\dfrac{5}{12}ft\right)^2}\right)^2}{64.4\dfrac{ft}{s^2}} = 3.95 * 0.26 = \mathbf{1.03ft}$$

$$\boldsymbol{H_{Lm\_pl}} = \sum K_{pl} \frac{\left(\dfrac{\dfrac{2000_{gpm}}{448.8_{gpm/cfs}}}{\pi\left(\dfrac{6}{12}ft\right)^2}\right)^2}{64.4\dfrac{ft}{s^2}} = 5.00 * 0.50 = \mathbf{2.50ft}$$

$$\boldsymbol{H_{Lm}} = \boldsymbol{H_{Lm\_br}} + \boldsymbol{H_{Lm\_pl}} = \mathbf{1.03 + 2.50 = 3.53ft}$$

The pipe friction losses are calculated with the Hazen Williams equation:

$$\boldsymbol{H_{Lf\_br}} = 30\text{ft}/100 * 0.2083\left(\frac{100}{140}\right)^{1.85}(1{,}000\text{gpm})^{1.85}/(10in)^{4.8655} = \mathbf{0.16ft}$$

$$\boldsymbol{H_{Lf\_pl}} = 4{,}000\text{ft}/100 * 0.2083\left(\frac{100}{140}\right)^{1.85}(2{,}000\text{gpm})^{1.85}/(12in)^{4.8655} = \mathbf{32.1ft}$$

$$\boldsymbol{H_{Lf}} = \boldsymbol{H_{Lf\_br}} + \boldsymbol{H_{Lf\_pl}} = \mathbf{0.16 + 32.1 = 32.3ft}$$

Mike sums the static head, minor losses, and friction losses for the total dynamic head, TDH, at 2,000 gpm.

$$\boldsymbol{TDH} = H_{St} + H_{Lm} + H_{Lf} = 21.0\text{ft} + 3.5\text{ft} + 32.3\text{ft} = \mathbf{56.8ft}$$

Mike plots the system curve shown in Figure 17. The calculations are provided in a tab called “Example 3” in the Free Software that comes with the course.

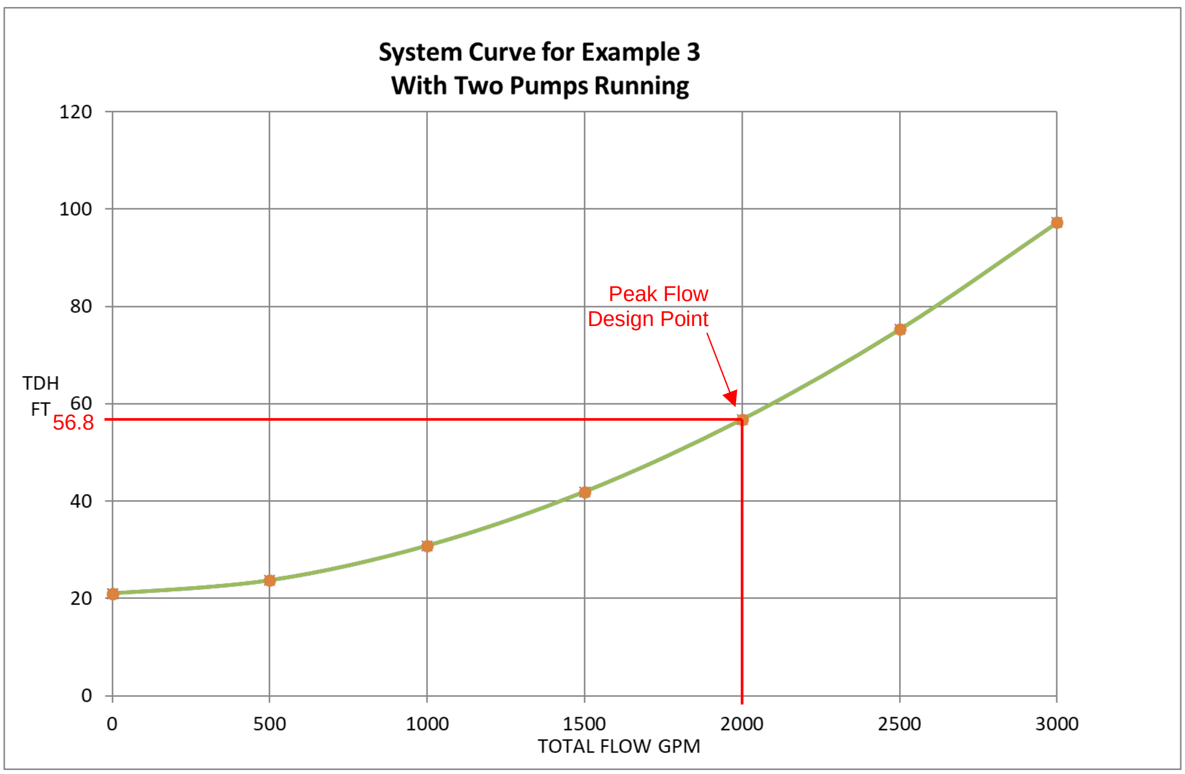


Figure 17: System curve for Problem 3 with the design point in red.
Source: Author

Example Problem 4

Continuing from Example Problem 3, Mike needs to create a table that summarizes the design criteria for the pumps. Mike checks flow data and determines the minimum flow would be around 500 gpm.

Solution:

Mike selects axial flow type pumps because they are commonly used for transferring irrigation water and are economical. He selects variable frequency drives for pump speed adjustments which will allow maintaining a constant water level in the wet well.

Mike recognizes that the minimum flow rate condition is with one pump running versus the peak flow rate condition with two pumps running. With one pump running, 100% of the flow goes through a single pump branch. Therefore, a new system curve is calculated for the one pump running condition, as shown in Figure 18. At 500 gpm, the TDH is 23.9 feet.

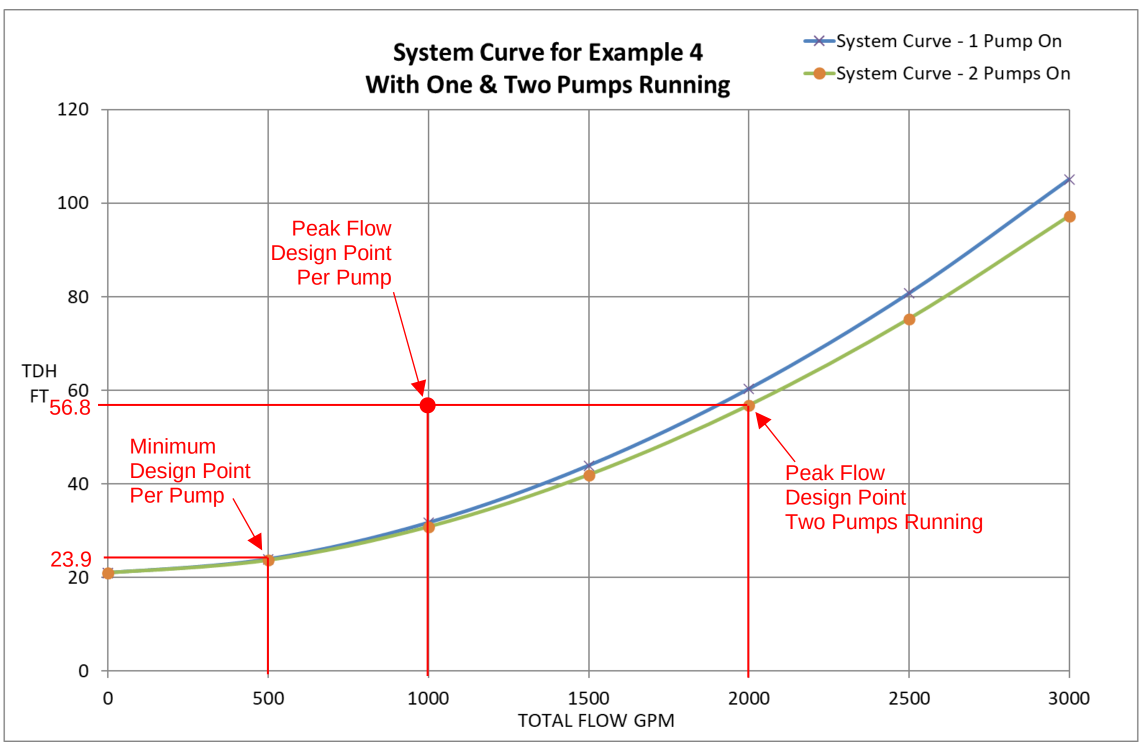


Figure 18: Example Problem 4 system curves with one pump running (blue), and two pumps running (green). Design points are in red.
Source: Author

Mike uses this information to summarize the pump design criteria:

Table 9: Irrigation Pump Station Design Criteria For Problem 4		
Fluid Type	Irrigation Water	
Pump Type	Axial flow vertical (VS3)	
Number of Pumps	3 (2 duty + 1 standby)	
Drive Type	Variable frequency	
Flow Conditions	Flow Rate (gpm)	TDH (ft)
PHF, Total	2,000	56.8
MDF, Total	500	23.9
Pump Design Point - Peak Flow	1,000	56.8
Pump Design Point - Minimum Flow	500	23.9

The hydraulic calculations are provided in a tab called “Example 4&5” in the Free Software that comes with the course.

Pump Selection

The main goal of pump selection is to choose a pump that meets the flow demands while staying within the operating range of the pump. The pump selection process is also called pump sizing. The design engineer is expected to use pump curves, also called performance curves, to choose a suitable pump for the application. This process is basically the same for any type of pump, not just vertical pumps.

Steps for Pump Selection

The following are typical steps for the pump selection process:

1. Review pump design criteria, PFD, and system curve(s)
2. Select the type of pump
3. Review pump manufacturer literature including pump curves
4. Make preliminary pump selections using design points
5. Compare preliminary selections and choose the best pump
6. Plot pump curve on system curves
7. Confirm pump capacity for full range of system conditions
8. Select motor HP
9. Review minimum submergence and net positive suction head (NPSH)
10. Design intake, pump connections, mounting, rails, hatches, etc.

Steps 3 through 8 are covered in this Section. The other steps have been covered in previous Sections.

Preliminary Selection (Steps 3 & 4)

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 review a chart of the capacity ranges of various pump models, as shown in Figure 19. This allows choosing one or more pump models that appear feasible. Although many pump curves are available in catalogs or websites, it is still a good practice to request the curves from the pump supplier while also confirming the pump is a good fit for the application.

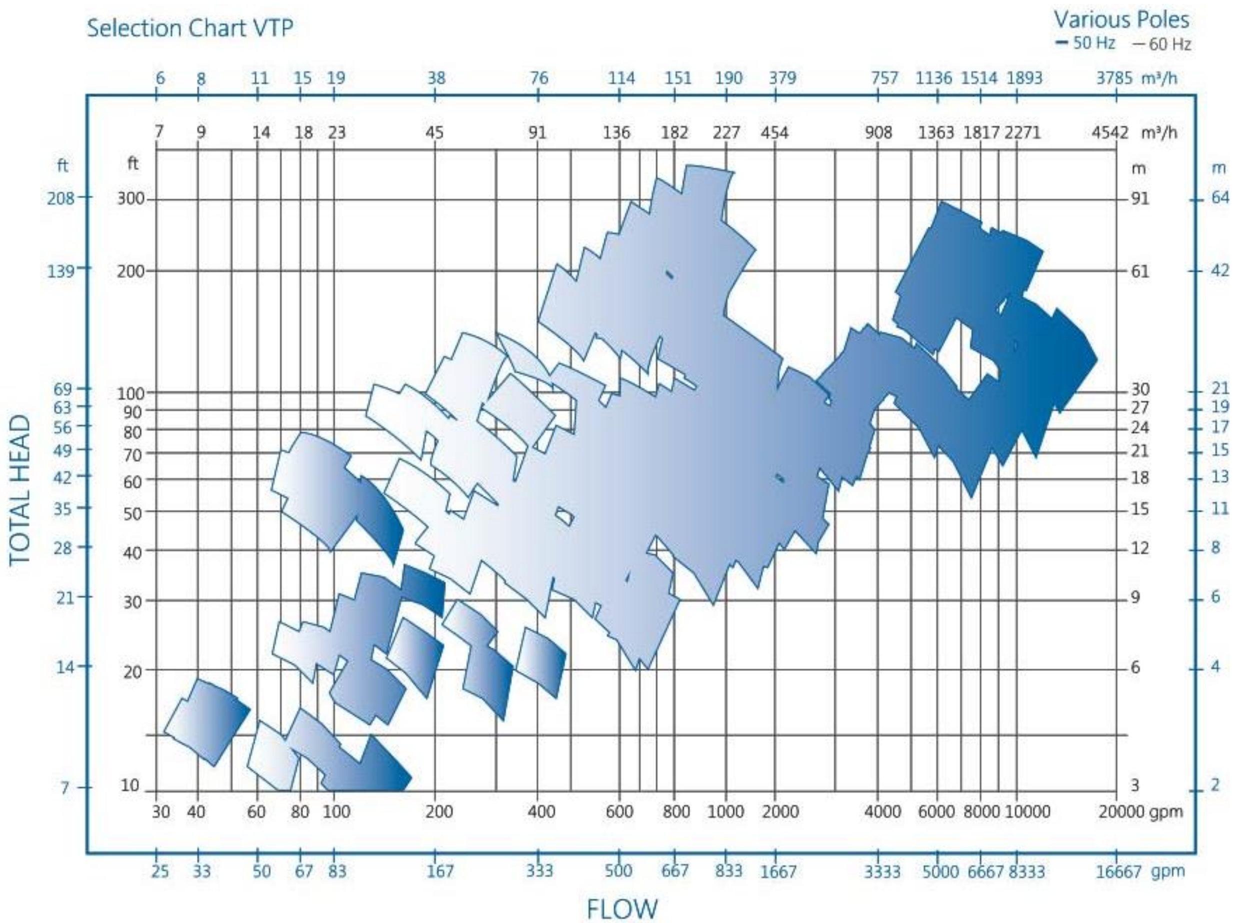


Figure 19: Example chart of capacity ranges for various vertical turbine (VS1) pump model numbers. Each box represents a different pump model.

Source: www.ruhrpumpen.com/en/products/vertical-pumps/vtp-vertical-turbine-pump

After the pump model is identified, detailed curves should be reviewed for different pump sizes. Note that catalogs typically show curves for full-size impellers or nominal size impellers. To get a pump selection that exactly hits the design point, the impeller often needs to the “trimmed” so the pump curve hits the precise design point. Some pump manufacturers provide software or online tools that allow the creation of trimmed impeller pump curves.

Compare Pump Curves (Steps 3 & 4)

In reviewing pump curves that meet the design point, consider which curve provides the following:

- The best efficiency point (BEP) near the average operating condition and between the high and low head conditions.
- All operating points are in the preferred operating range (POR), which is between 70% to 120% of the flow rate at the BEP.
- The curve is not excessively flat, excessively steep, and is smooth without hills or valleys.
- The flow rate at the intersection of the low head system curve and the pump curve is not excessive (typical of a flat pump curve).
- The lowest maximum shaft power across the full allowable operating range (AOR), which is the boldened part of the pump curve without dashes.

One strategy to visually compare pumps is to plot multiple pump curves on a single chart, as shown in Figure 20.

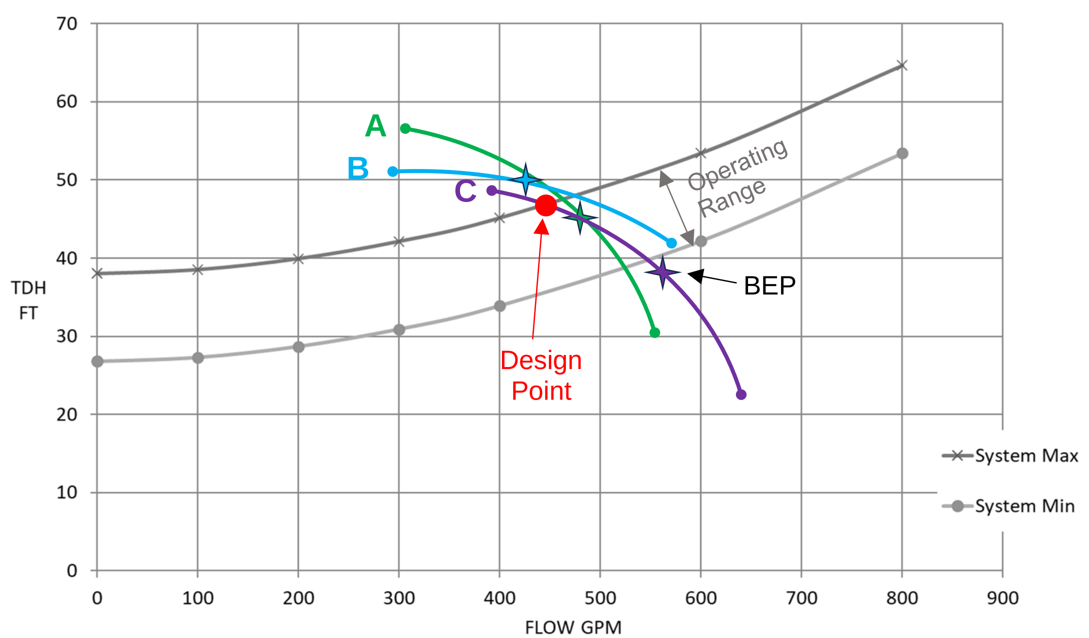


Figure 20: Three pump curves plotted on two system curves (grey) with the design point in red. All three pump meet the design point; however, the green curve, A, is best because it intersects both min and max system curves and has the best efficiency point (BEP) in the operating range.
Source: Author

Plot Pump Curve on System Curves (Step 6)

The pump curve is plotted with the system curves and the operating flow range defined, as shown in Figure 21. The actual maximum flow can be determined. If it is desired to limit the maximum flow to no more than the peak design flow, VFDs can be utilized to decrease the pump speed at low head conditions, or control valves can add headloss and thereby decrease the flow.

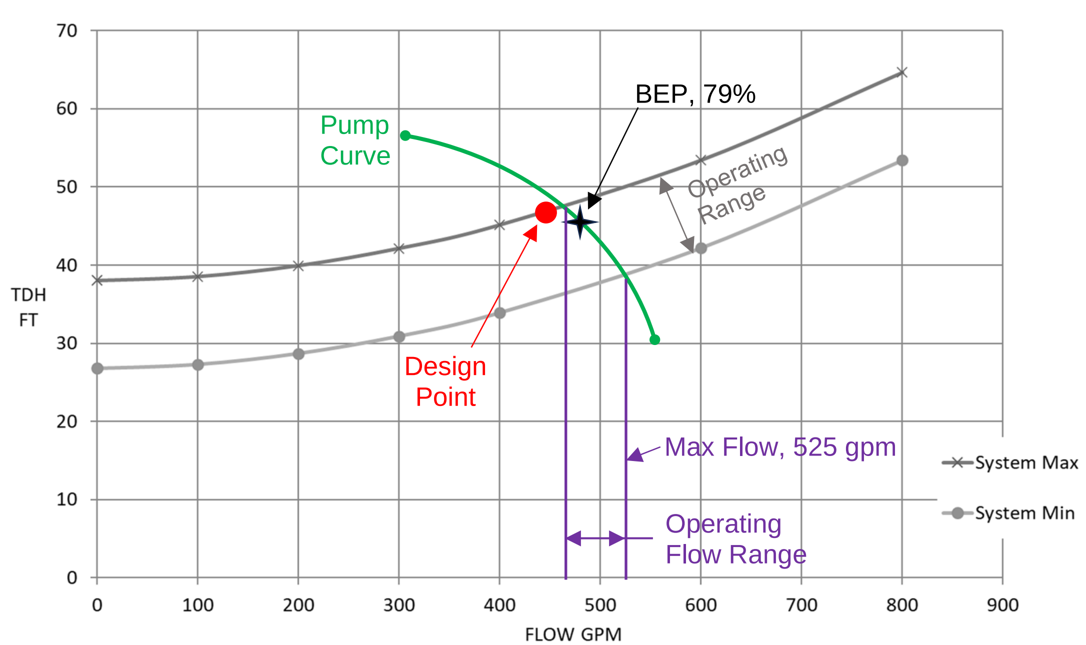


Figure 21: Selected pump curve (green) plotted on the system curves (grey) with the operating flow range in purple. Note that although the design point is 450 gpm, under minimum head curve conditions, the pump will operate at maximum flow of 525 gpm.
Source: Author

Check Full Range of Conditions (Step 7)

If there is only a single duty pump, then checking the full range of conditions can be as simple as reviewing the pump curve and system curves plot, as depicted in Figure 21. However, if the following situations require a more detailed review:

- Multiple duty pumps
- Different size pumps
- Variable speed pumps with need to pump at a minimum flow rate
- Future conditions such as ability to add a pump to meet future flows

<u>Multiple Pumps</u>

When there are two or more duty pumps in parallel, it is helpful to plot a combined pump curve showing the effect of multiple pumps running at once. The combined pump curve is obtained by adding the pump flow rates for each TDH value. See the dark red curve in Figure 23 for an example combined pump curve for two equal pumps in parallel.

<u>Variable Speed Curves</u>

Often variable speed drives are utilized instead of constant speed for the ability to fine adjust the flow in the future, to reduce the inrush current when a pump starts, or to reduce the frequency of starts and stops. In these cases, additional pump curves at slower speeds are likely not needed. However, if variable speed drives are specified for the ability to operate at a minimum flow, a pump curve is needed at the slowest speed (typically 50% for vertical pumps). Often the pump manufacturer will provide a plot of pump curves at different speeds.

If the pump manufacturer does not provide curves at varying speeds, the design engineer should calculate them using the following Affinity Laws:

- Flow rate: The flow rate varies proportionally with speed change. For example, half the speed results in half the flow: 1/2 speed = 1/2 flow
- TDH: Pump head/TDH varies by the square of speed change. For example, half the speed results in one-fourth the head: $(1/2 \text{ speed})^2 = 1/4$ head
- Power: Power consumption varies by the cube of speed change. For example, half the speed results in one-eighth the power: $(1/2 \text{ speed})^3 = 1/8$ power.

Table 10 provides an example of calculating the Flow and TDH at different speeds (last two columns), given the full speed pump curve data (first two columns). These points can be plotted to give pump curves at various speeds, as shown in Figure 22.

Table 10: Pump Curve Points using Affinity Laws

Full Speed Pump Curve (Given)		1/2 Speed Pump Curve (Calculated with Affinity Laws)	
Flow (gpm)	TDH (ft)	Flow (x1/2) (gpm)	TDH $(x(1/2)^2)$ (ft)
0	50	0	12.5
500	47.5	250	11.9
1000	45	500	11.25

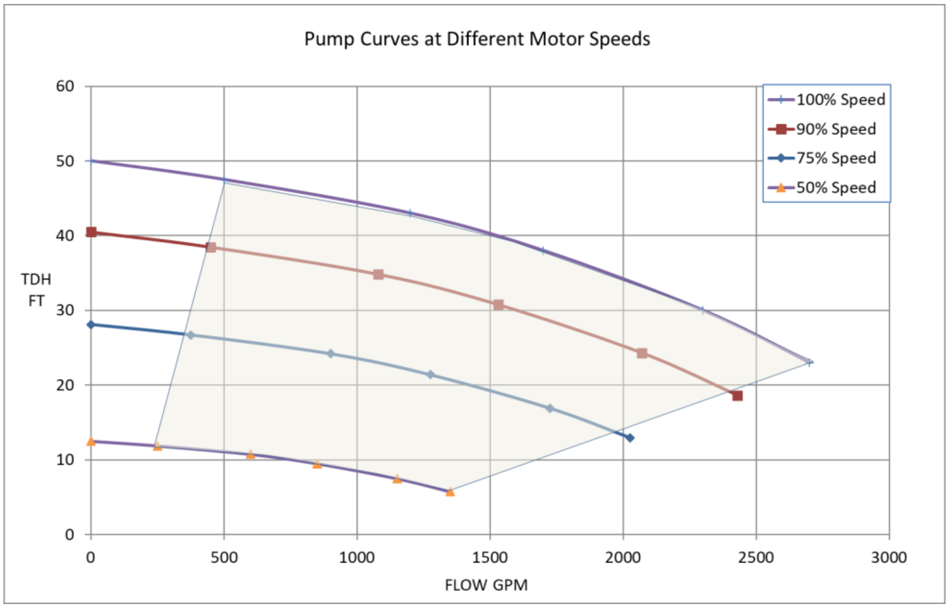


Figure 22: Plot of pump curves at (4) different motor speeds using affinity laws. The shaded region is the allowable operating range of the pump projected across the speed range.
Source: Author

Note that if the low flow point cannot be achieved, the following options are available:

- The number of duty pumps can be increased,
- Use a combination of large and small pumps,
- Add a modulating valve or pressure sustaining valve to increase headloss.

<u>Select Motor HP</u>

Manufacturer pump curves typically include a power curve that shows the shaft power (HP or kW) required at all operating points. See the center region of Figure 24 for an example. The greatest power value in the operating region is used for motor sizing.

This line shaft power from the pump curve is divided by the motor efficiency (90% to 95%), and multiplied by a service factor (1.0, 1.15, or 1.25), which gives the minimum motor HP:

$$Minimum\ Motor\ Size = \frac{Line\ Shaft\ Power * S.F.}{motor\ eff}$$

This is rounded up to the next nominal motor size in HP or kW.

Example Problem 5

Continuing Example Problem 4, Mike needs to plot pump curves with the system curves for the irrigation pump station design. Mike is to determine the speed at which a single pump meets the minimum flow condition and confirm it is within the AOR.

Solution:

Mike selects a pump curve that meets the design condition of 56.8 ft at 1,000 gpm. He plots the pump curve at 100% speed, from the manufacturer, and at the minimum recommended speed of 50%, using Affinity Laws. See Figure 23 for the result.

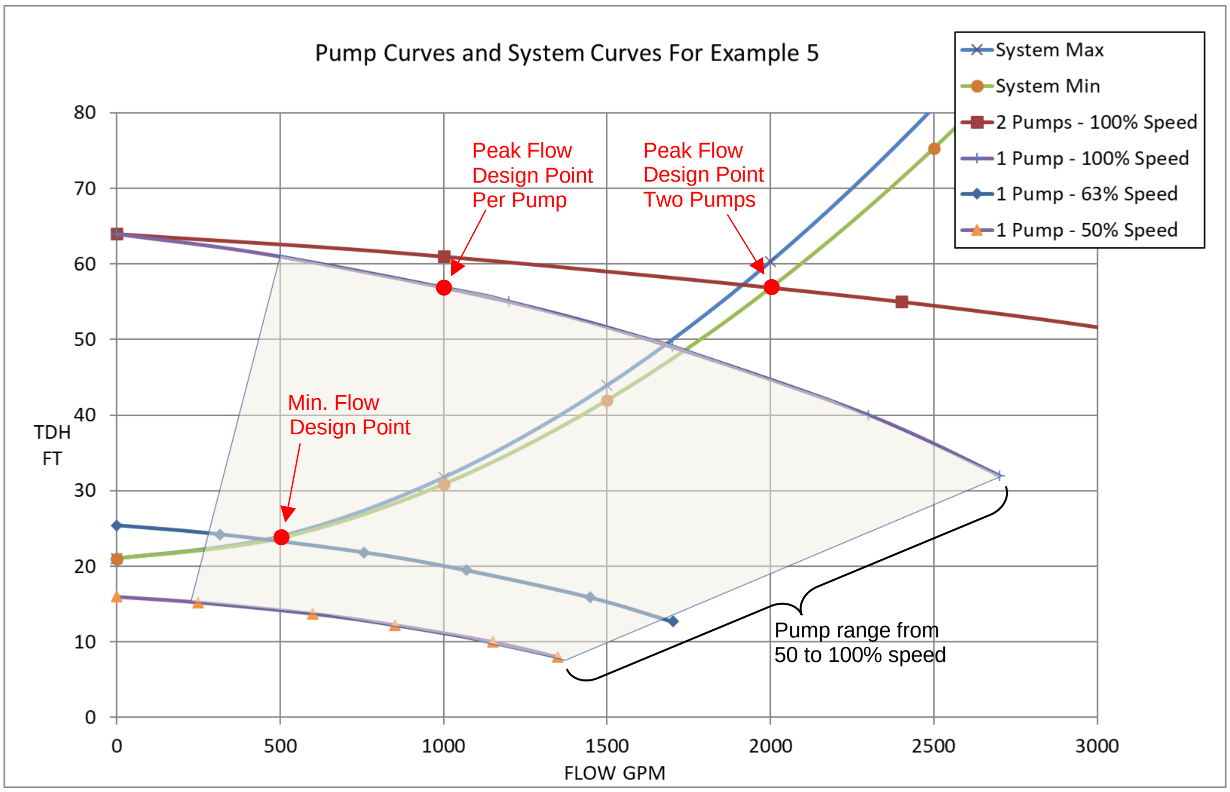


Figure 23: Plot of pump curves and system curves for Problem 5.
Source: Author

At 63% speed, the pump can meet the minimum flow condition and operate within the allowable pump range (AOR). At 50% speed, the pump curve does not intersection the system curve so the pump should not be operated at this speed. The VFD speed range can be set at 63% to 100%.

Example Problem 6

Engineer Ivy is designing a pump station with two vertical pumps, one duty and one standby. She performed hydraulic calculations and plotted the system curves. Each pump needs to meet the design condition of 500 gpm at 52 ft TDH. Now she needs to plot the pump curve with the system curves, identify the pump operating flow range, confirm the best efficiency point is within the range, and select the motor HP using a service factor of 1.15.

Answer:

Ivy obtained the manufacturer pump curve, shown in Figure 24. She plotted the pump curve and the system curves together in Figure 25. Based on the intersections of the curves, the normal operating range would be 500 to 615 gpm, with the best efficiency point (BEP) in that range at 570 gpm.

She added labels to the curves showing the range and BEP for clarity. The pump should not operate in the dashed area including the stall condition at zero flow and excessive TDH, such as from a closed valve.

Ivy reviewed the shaft power (HP) curve in the center chart of Figure 24. She identified the greatest power is 10.9 HP at the far right of the curve. To determine the motor HP, she multiplied this line shaft HP by the service factor, and divided by a typical motor efficiency of around 90%:

$$Minimum\ Motor\ HP = \frac{Line\ shaft\ HP * S.F.}{motor\ eff} = \frac{10.9\ HP * 1.15}{0.90} = 13.9\ HP$$

Ivy rounded up to the next nominal motor size, which is a **15 HP** motor.

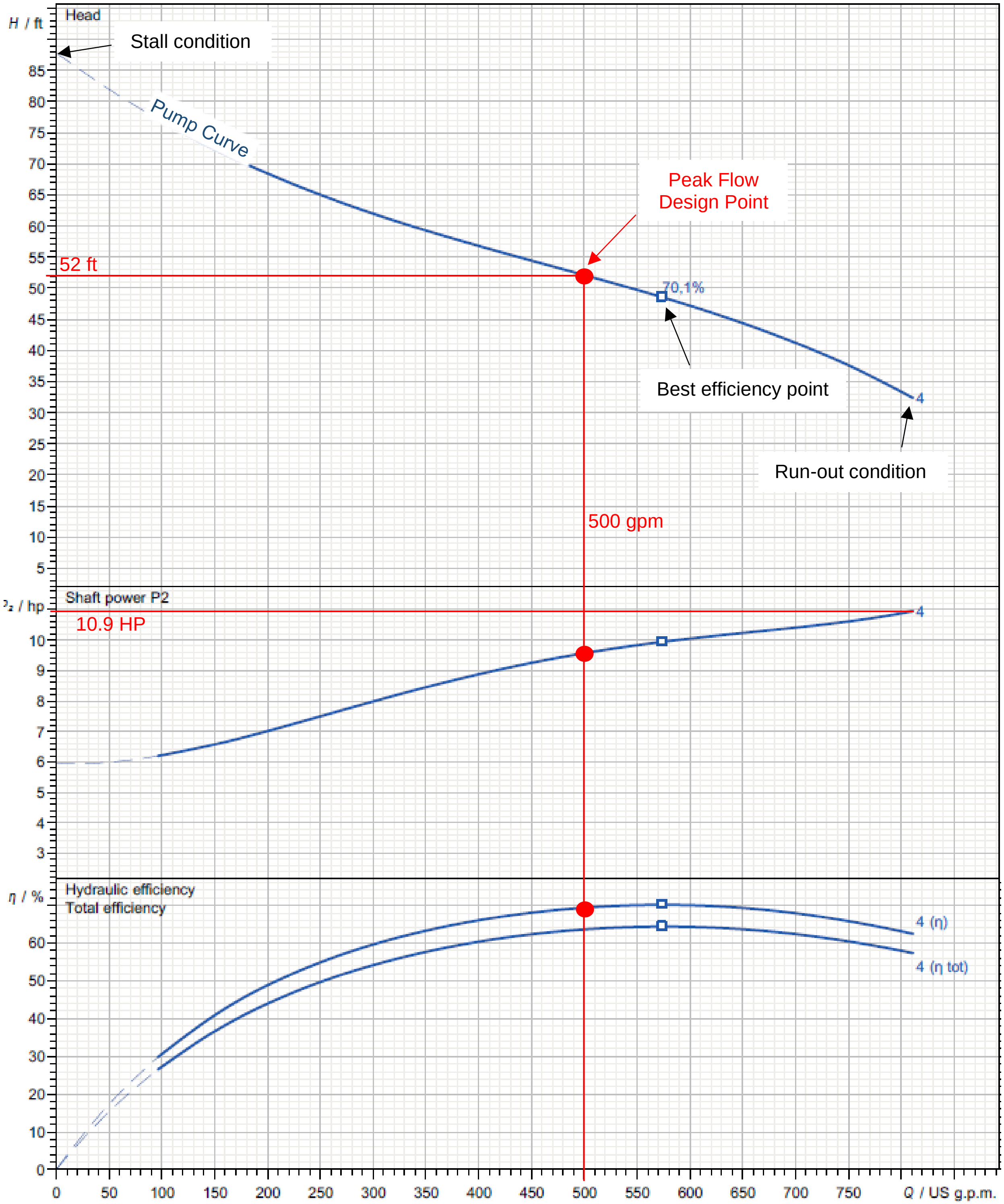


Figure 24: Manufacturer's pump curve for Problem 6, with design conditions in red.

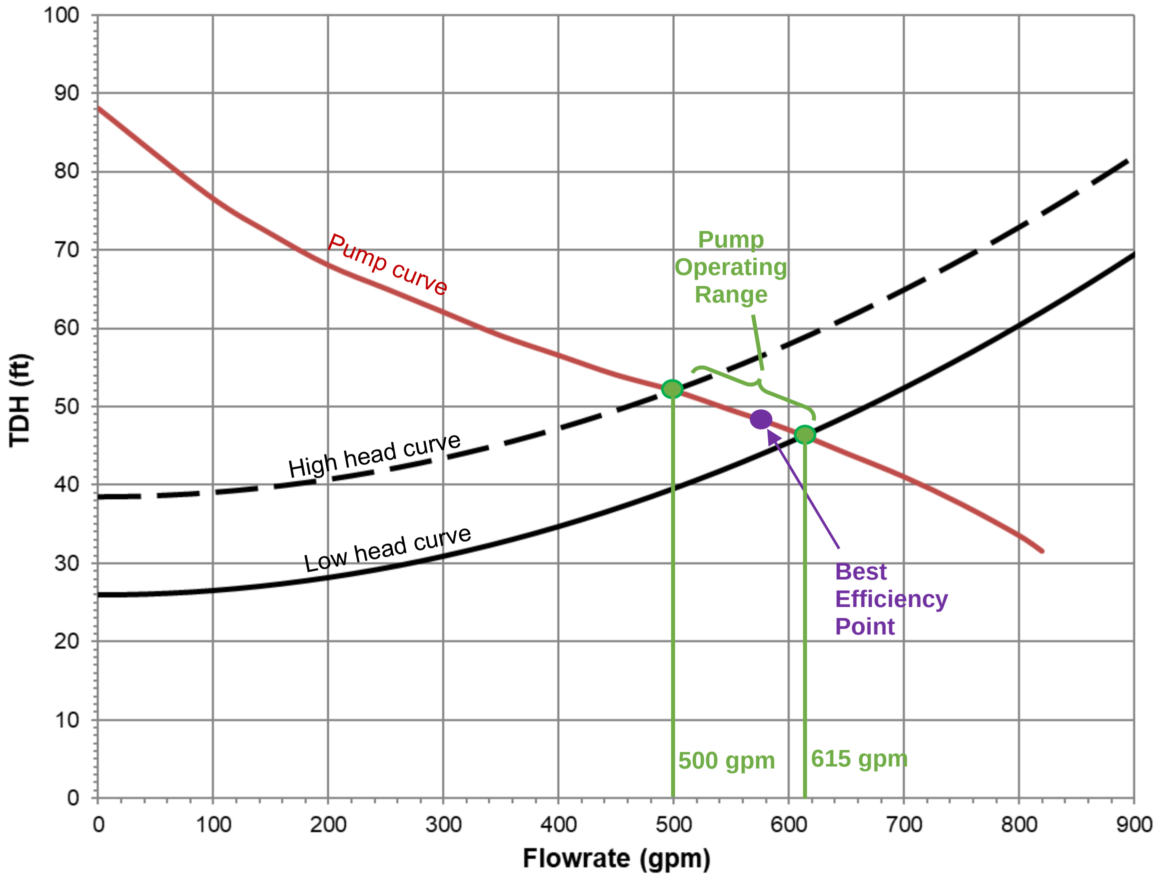


Figure 25: Plot of the pump curve and the system curves for Problem 6, showing the BEP within the pump design operating range of 500 to 615 gpm.
Source: Author

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