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Hydraulic Design of WW Lift Stations

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1. Centrifugal Pumps

Submerged centrifugal pumps are the most common type of pumps used in wastewater conveyance systems. Centrifugal pump will pump fluid at the point where the system curve intersects the pump curve as shown in Fig. 1.

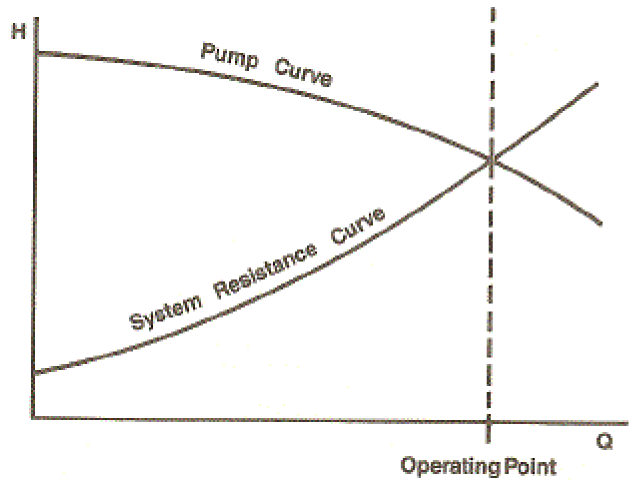

Fig.1. Pump Best Operating Point (BOP).

The BOP corresponds to a certain pump efficiency value. Pump efficiency charts and capacities are provided by pump manufacturers or vendors. Normally, for lead pumps the BOP is chosen based on the average dry daily flow (ADDF) rate since these pumps work more frequently than the lag pumps. The latter are normally sized to handle flows in excess of ADDF for peak wet weather flow (PWWF). There could be several lead and lag pumps arranged in various configurations. If a variable frequency drive (VFD) is used on the pumps, a single pump may be capable of serving the entire range of flows to the lift station. A second identical pump is required for redundancy and is a standby pump. Most if not all local municipalities require pump efficiencies at BOP above 50%. Choosing constant speed pumps that would operate at efficiencies above 50% at both ADDF and PWWF is a challenging task. For more flexibility, pumps are installed in either series or parallel with the first pump. The reader is directed to the following link for choice of pump speed vs capacity:

https://en.wikipedia.org/wiki/Affinity_laws.

2. Pumps in Series

When two or more pumps are arranged in series, their TDH (total dynamic head) doubles whilst the flow rate does not change as shown in Fig.2.

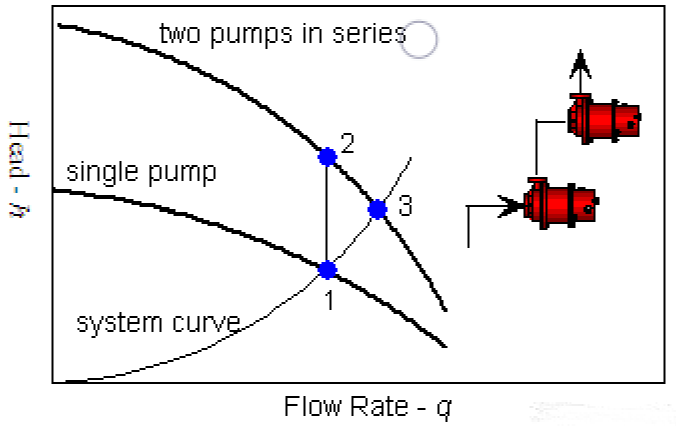

Fig. 1. Head for Two Pumps in Series.

Centrifugal pumps in series are used to overcome a larger system head loss than can be handed by a single pump. For a constant q, the combined head moves from point 1 to point 3 along the system curve rather than jumping to point 2. Points 1 and 3 represent a system with one and two pumps in operation, respectively.

Some things to consider when installing pumps in series:

- Both pumps must have the same impeller; otherwise the difference in capacities (gpm) may cause cavitation if the first pump cannot supply enough liquid to the second pump.
- Both pumps must run at the same speed (rpm).
- The casing of the second pump needs to be strong enough to resist the higher pressure. Higher strength material, ribbing, or extra bolting may be required.
- The stuffing box of the second pump needs to sustain the discharge pressure of the first pump which may require a high-pressure mechanical seal.
- Both pumps must be filled with liquid during start-up and operation.
- The second pump must be started after the first pump is running.

3. Pumps in Parallel

Two or more pumps in parallel result in a higher flow rate than a single pump depending on the slope of the system curve which, in turn, depends mostly on the friction factor and force main length. The combined flow will double, i.e. 2Q, with no friction but, in reality, will be in the range from to 1.4Q to 1.75Q.

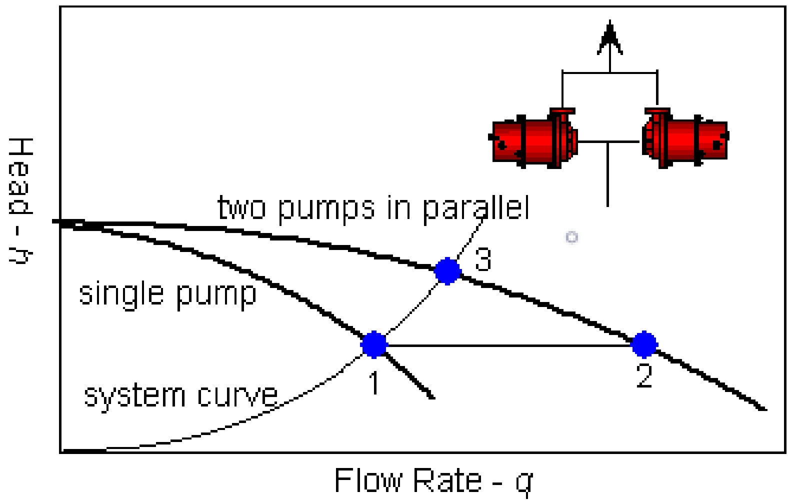

Fig. 3. Two Pumps in Parallel.

In Fig. 3, points 1 and 3 are where a system operates with a single and dual pump, respectively. Pumps are connected to a common discharge line (Fig. 4) and share the same suction conditions. Some things to consider when pumps are operated in parallel:

- Both pumps must produce the same head which means they must be running at the same speed, with the same diameter impeller.
- When pumps are run in parallel, the head shall rise at least 10% of the head at rated capacity.
- Two pumps in parallel will deliver less than twice the flow rate of a single pump in the system because of the increased friction in the piping.
- The shape of the system curve determines the actual increase in capacity. If there is additional friction in the system from throttling, two pumps in parallel may deliver only slightly more than a single pump operating by itself.

- A single pump will operate at a higher flow rate than if it were working in parallel with another pump because it will be operating further out on the curve requiring increased power. If a pump is selected to run in parallel, its driver needs to be rated for single operation.
- Most LSs read only total flow and cannot read the differences in individual pump performance.
- Parallel pumps are notorious for operating at different flows. Often a lead pump is operating close to its shut off point while the lag pump is operating to the far right of its curve and running out of $NPSH_{A.}$

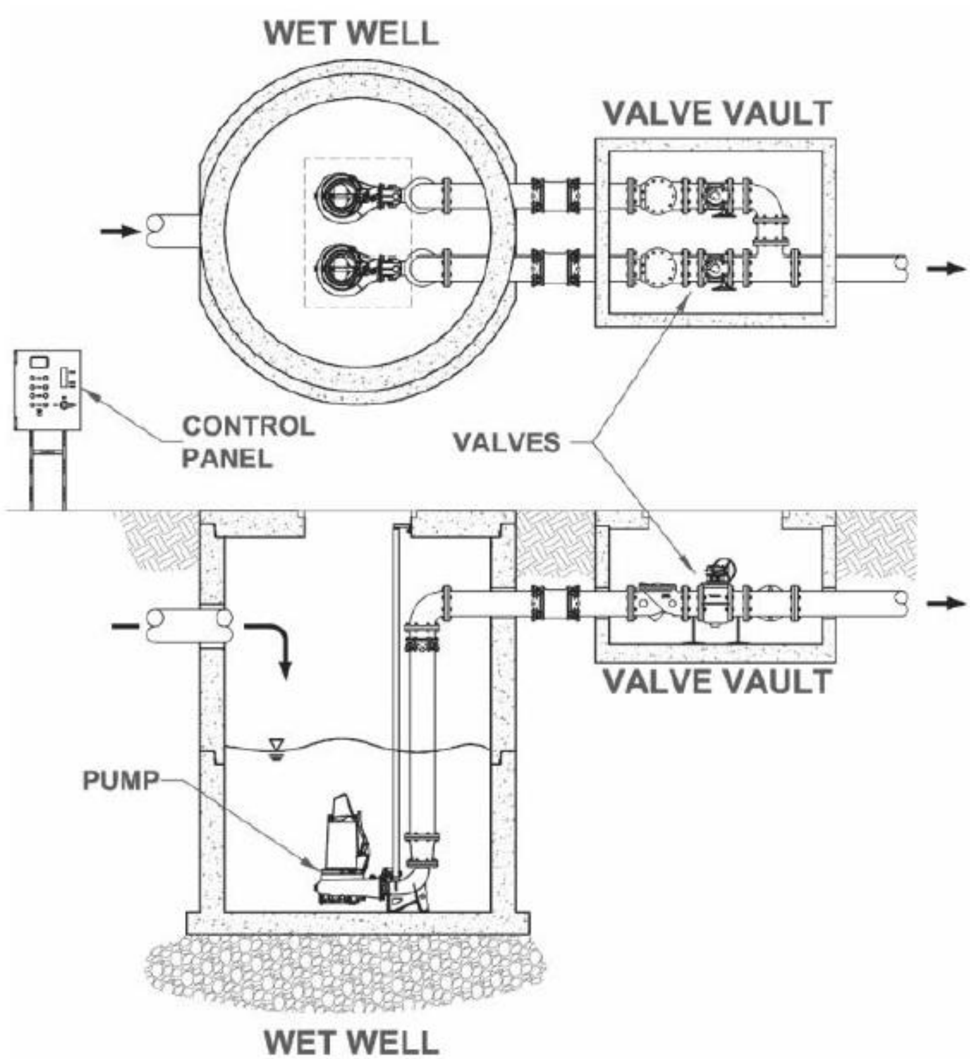

Fig. 4. Typical Duplex Submersible LS with Parallel Pumps.

4. Hydraulic Design Basics for Wastewater Lift Stations

The following definitions and values are provided as **guidelines only**. The design engineer is referred to the local, municipal, county, state and provincial design guidelines as they differ.

1. Wastewater Flow Rates

- Residential: 200 - 300 gals/day per Equivalent Dwelling Unit (EDU)
- Commercial: 0.05-0.1 gals/day (GPD) per SF
- Multi-family Units: 0.65-0.85 EDUs per Unit
- Peaking Factor: 2 – 4 times the Average Daily Flow (ADF)
- Inflow and Infiltration (I/I): 300 GPD/acre
- Inflow and Infiltration (I/I): 200 GPD/mile-inch of pipe diameter

2. Average Dry Weather Flow (ADF)

This is the base flow developed without the maximum flow peaking factor. This flow is used to determine the average detention time in the wet well.

- ADF (GPD) = Residential (single and multi-family) + Commercial GPDs
- ADF (GPM) = ADF (GPD) / 1440 (Min/Day)

3. Peak Dry Weather Flow (PDWF)

This flow is used to determine pipe size in the collection system.

- Peaking Factor (PF) = 1.4-2.5
- PDWF (GPD) = PF * ADF
- PDWF (GPM) = PF * ADF (GPM)

4. Peak Wet Weather Flow (PWF)

This flow is used to determine the LS design capacity. All lift stations are designed to handle the maximum wet weather flow for its service area.

- Inflow and Infiltration (I/I): Total Development Acreage * 300 GPD/acre
- PWF (GPD) = PDWF (GPD) + I/I (GPD)
- PWF (GPM) = PWF (GPD) / 1440 (Min/Day)

5. Minimum Dry Weather Flow (MDWF)

This is used to determine the maximum detention time in the wet well.

$$MDWF = (0.2 * (0.0144 * ADF)^{0.198}) * ADF \quad (1)$$

6. Minimum Pump Requirements (Peak Wet Weather Flow, PWF)

- For two-pump stations, size each pump to handle PWF.
- Calculate Total Dynamic Head (TDH):

  1) Static Head (Hs)
     Eh = Maximum force main elevation
     El = Wet well low water elevation
     Hs = Eh — El

  2) Loss (Lf) due to friction in force main

     Length = Total equivalent length of force main and piping on station
     Lf = Length * Friction Factor (Use Hazen-Williams C of 100 and 140)

  3) TDH = Hs + Lf

- Plot System Curve and Pump Curve and determine the best operating point (Fig. 1) to select proper pump sizes.

Velocity produced in Force Main with one pump in operation are normally required to be between 2 and 3.5 feet per second (fps), less than 5 fps with two pumps in operation, 6 fps or less for three pumps in operation, and less than 8 fps for more than 3 pumps in operation. Below 2 fps, solids deposition in FM may occur.

The expression for flow velocity in a circular pipe is:

$$V = Q/A = 0.4087099 * (Q / d^2) \quad (2)$$

where
Q = Discharge flow for selected pump(s), in gpm
d = FM pipe interior diameter, inches.

7. Net Positive Suction Head

For suction lift stations, compare the net positive suction head required ($NPSH_R$) by the pump with the net positive suction head available ($NPSH_A$) in the system, at the operating range. The NPSH available shall be greater than the NPSH required by at least 3 feet.

$$NPSH_A \text{ (suction lift)} = P_B + H_S - P_V - H_{fs} \quad (3)$$

where

P_B = barometric pressure in feet absolute (34 ft = 14.7 psia)
H_s = minimum static suction head, in feet
P_V = vapor pressure of liquid in feet absolute, use 1.4 feet
H_{fs} = friction loss in suction, ft, including entrance losses and minor losses.

8. Total Suction Lift

A total suction lift calculation is performed for self-priming pumps. The total suction lift is the addition of the static suction lift plus the friction losses along the suction pipe. The static suction lift is the distance between the wet well level elevation at All Pumps Off and the elevation of the impeller eye.

Total Suction Lift = Static Suction Lift + Friction Losses along Suction Pipe
Static Suction Lift = Impeller eye elevation-elevation of wetwell level at All Pumps Off

9. Storage Requirements

Wet Well Volume between "lead pump on" and "all pumps off' elevation:

Vr (Gals) = Pump GPM * T (Minimum Cycle Time)

Wet Well Dimensions:

Minimum wet well diameter: 72-inches
Wet Well Depth = $\frac{4V_S}{\pi D^2}$

where

Vs = wet well storage volume in cubic feet
D = wet well inner diameter in feet

10. Buoyancy Check

A buoyancy check is performed for the pump station wet well and the retention chamber. “Skin friction”, in lbf/sf, between the soil and external LS surface is added to the weight of LS excluding piping, pumps and support, and divided by the buoyancy force to obtain a safety factor (SF). Normally, a SF of more than 1.15 is required.

11. Water Hammer Calculations

Calculate surge pressures and compare to the pressure rating of the force main material to determine the need for a surge relief valve.

$$a = \frac{4460}{\sqrt{\frac{E_W \cdot D_i}{E_P \cdot T_P}}} \quad (4)$$

where

a = pressure wave velocity factor
E_W = water bulk modulus (300,000 psi)
D_i = FM pipe inner diameter (inches)
E_P = FM material modulus of elasticity (130,000 psi – HDPE, 400,000 psi – PVC)
T_P = FM pipe wall thickness, inches

Water hammer pressure in FM is:

$$P = \frac{a \cdot V}{2.31 \cdot g} + OP \quad (5)$$

where

P = water hammer (surge) pressure (psig)
a = pressure wave velocity factor
V = flow velocity in force main at firm pumping capacity (ft/s)
g = acceleration of gravity (32.2 ft/sec^2)
2.31 = conversion factor
OP = FM peak flow operating pressure (psig).

Surge protection is required for P above 85 psig. FM pipe material must be rated at least 20-25 psi above P.

5. Wet Well Clearance Parameters

For submersible pumps, minimum pump submergence, shown in Fig. 5, is provided by the pump manufacturer. The purpose of minimum submergence is to prevent air, always present in wastewater, from entering a pump. Air volumes of above 2.5-3 % of wastewater volumes may cause pumps to “choke”. Lack of minimum submergence will also cause what is known as a “pre-swirl” which can lead to a vortex.

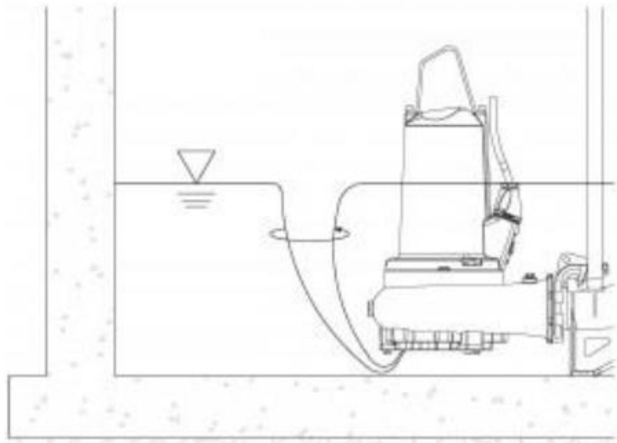

Fig. 5. Example of Pump Vortex.

To prevent a vortex, the following equation has been developed which is the minimum submergence (minimum distance between the inlet and the water surface elevation):

$$S_{min} = d(1+2.3F_D) \tag{6}$$

where F_D is the Froude number (unitless), given by:

$$F_D = \frac{v}{(gd)^{0.5}} \tag{7}$$

where

d = pump inlet (bell) diameter, ft
g = gravity acceleration (32.2 ft/s^2)
v = fluid velocity at the inlet (ft/s) = Q/A
Q = pump discharge (cfs)
A = inlet area (ft^2).

Eq. 7 for flows up to 20,000 gpm is shown in Fig. 6.

Surface vortices may be reduced with increasing S_{min}. There are situations where increasing depth has negative effect as vortices are highly dependent on approach flow patterns besides the inlet Froude number. The reader is referred to the Hydraulic Institute publication “HI Pump Intake Design – 1998” for additional details.

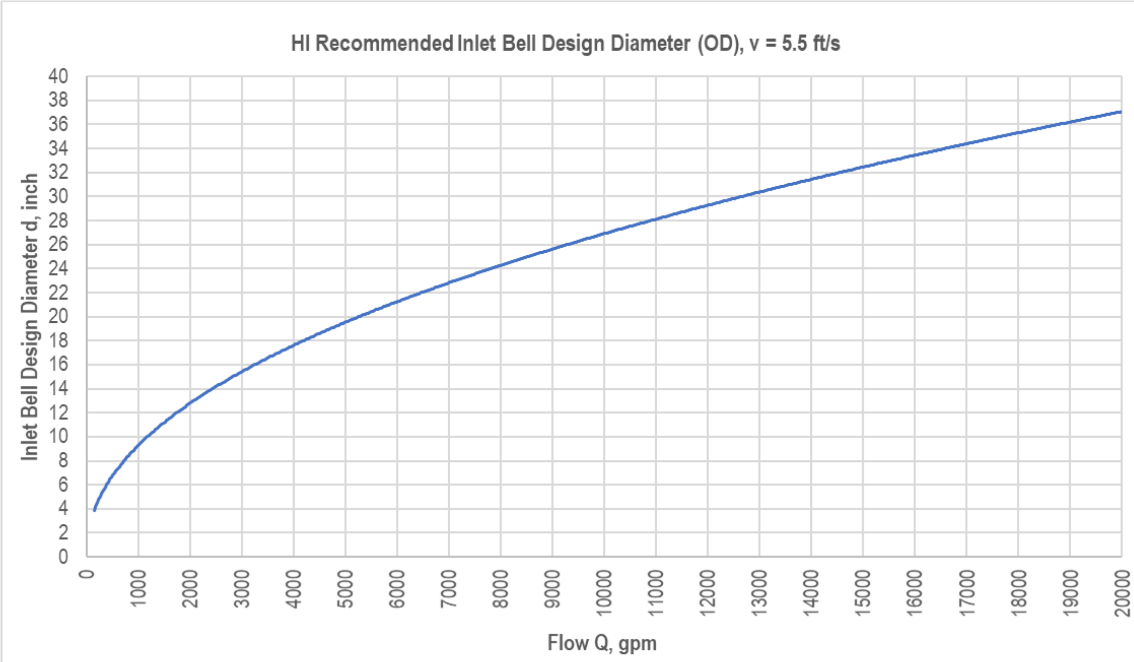

Fig. 6. HI Recommended Inlet Bell Outside Diameter (OD) vs Velocity of 5.5 fps.

The publication lists several methods to reduce sub-surface vortices:

- Wall splitter plate
- Floor splitter plate
- Floor cone
- Back wall
- Corner fillets
- Back wall fillets
- Side wall fillets
- Center splitter
- Strainer with guide vanes.

Fig. 7 shows an example of back wall and side wall fillets.

Submerged vortices are also sensitive to floor clearance which is the vertical distance C (Fig. 8) between the sump or wet well floor and the horizontal plane of the pump inlet bell. Recommended floor clearance is between 0.3D and 0.5D where D is the wet well inside diameter. The minimum clearance m between an inlet bell or a pump volute and a wet well wall is 0.25D or at least 4 inches. The minimum clearance b between adjacent inlet bells or volutes is also 0.25D or at least 4 inches. It is important to position the inflow pipe(s) radially normal to the pumps to minimize rotational flow patents as shown in Fig. 8.

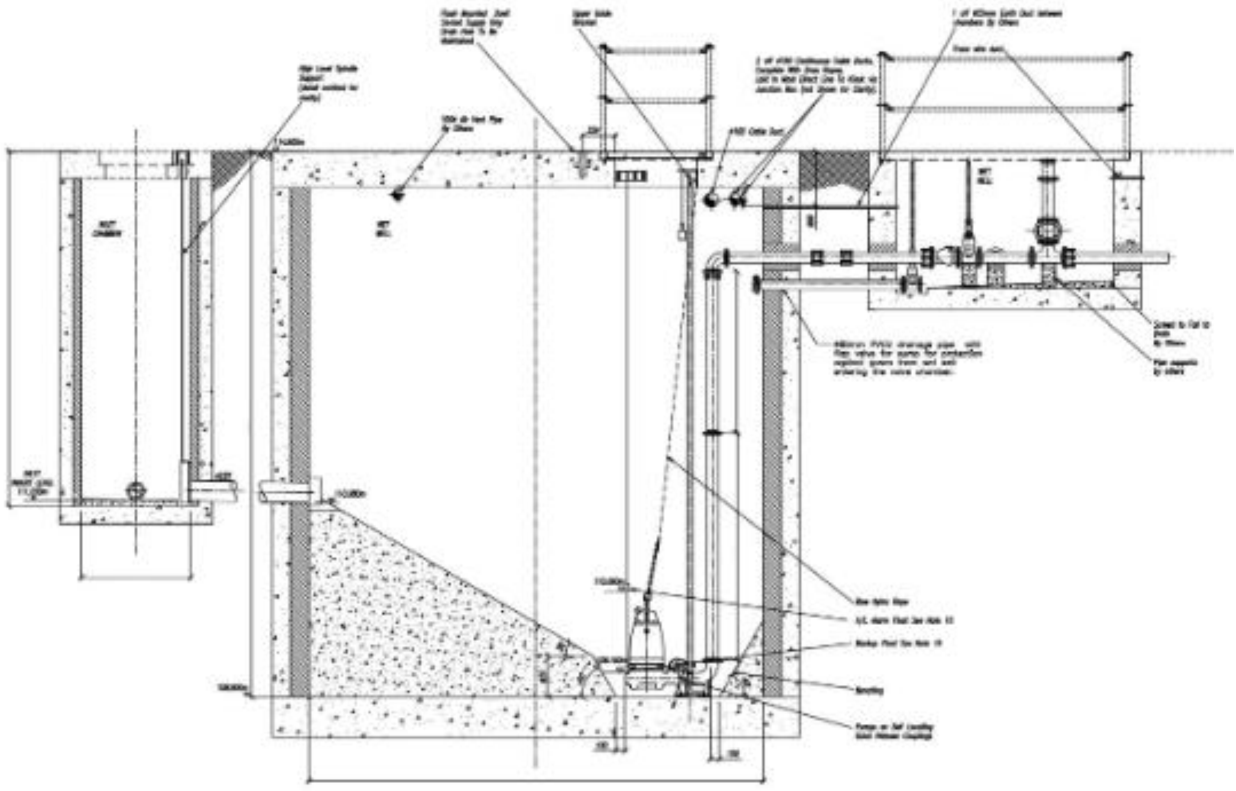

Fig. 7. Example of Back and Side Wall Fillets.

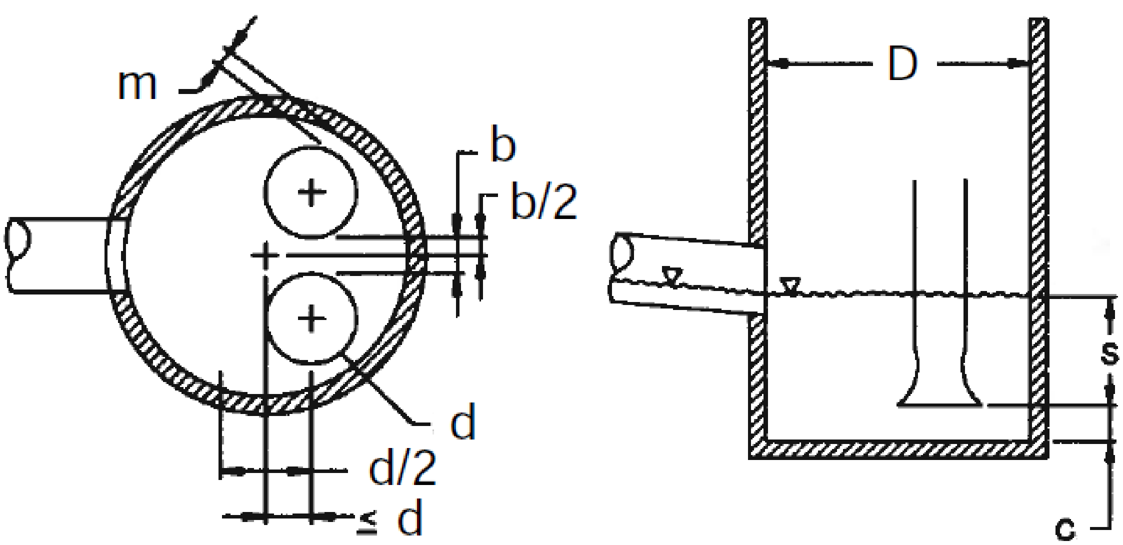

Fig. 8. Wet Well Clearance Parameters.

6. Pump Cycle Time and Detention Volume Calculation

The objective of this part is to present equations defining the minimum pump cycle time and the wet well volume required for constant speed pumps. These equations can be used for but don't necessary apply to pumps with variable frequency drives (VFD) as those allow more flexibility in terms of cycle time and storage volume.

Lift stations (LS) must be capable of discharging all anticipated peak wet weather flow. In a 2-pump type LS, the "lead" pump is turned on at the first "on control elevation" and the "lag" pump starts with a rising liquid level at the "second on control elevation." The "lead" and "lag" pumps continue to operate until the "pump off control elevation" is reached. The "lead" and "lag" automatically alternate between the two pumps at the completion of each pumping cycle. This applies to 3-Pump, 4-Pump and 5-Pump type LSs as well. Fig. 9 shows a 4 pump sequence.

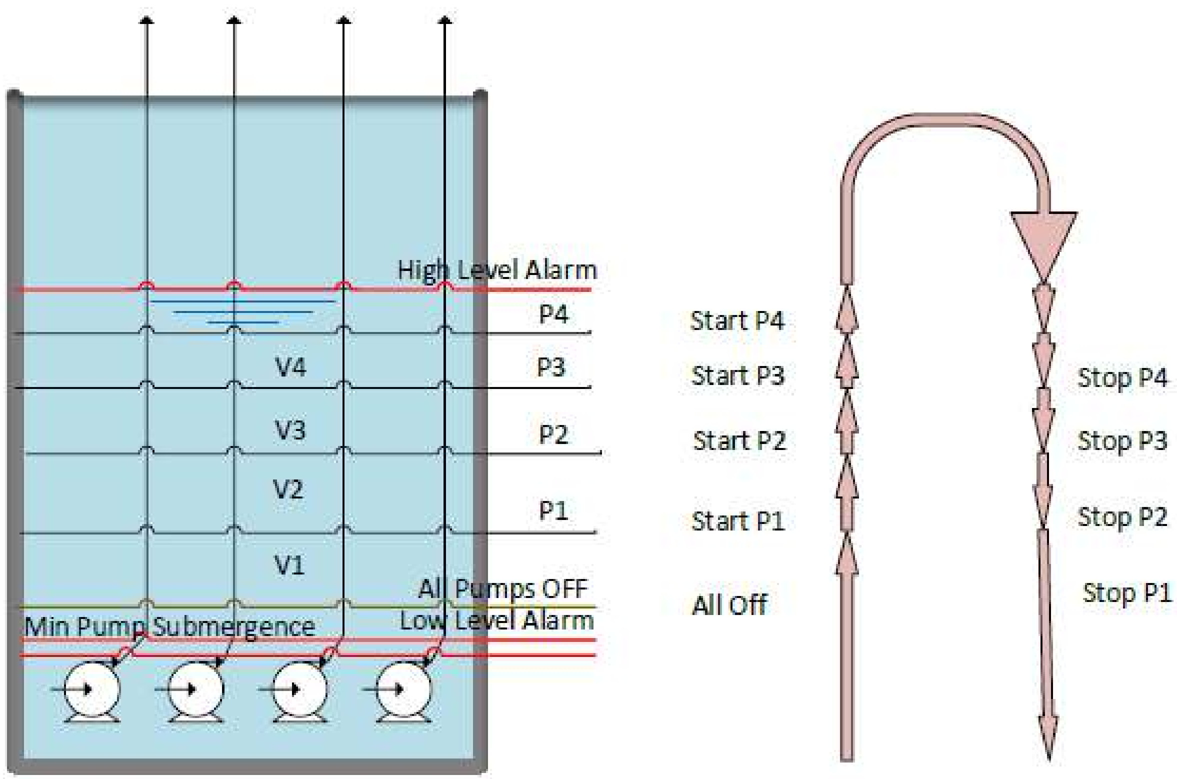

Fig. 9. Lift station with a 4-pump sequence.

Fig. 9 shows the most common pump operating scheme for multiple pumps in parallel or series. Pumps start when certain water levels in a wet well are reached and stop when water recedes to the previous level. In this sequence, the inflow rate increases such as $Q_{in1} < Q_{in2} < Q_{in3} < Q_{in4}$.

Let Pumps 1,2, 3 and 4 have capacities of A (Q_{in1}), B (Q_{in2}), C (Q_{in3}) and D (Q_{in4}), respectively. Only P1 is "on" when inflow to the wet well is less than A and the water level is between "All Pumps Off" and "P1". As soon as inflow exceeds A by say b, i.e. (A + b), P2 starts (A+B). When inflow exceeds A+B by c, i.e. A+B+c and the level is between "P2" and "P3", P3 starts (A+B+C), etc. When the water level is down to "P2", the outflow rate is down to A+B. When the inflow rate is less than A, all pumps are "off". The other pump operating schedule is similar to that shown in Fig. 9 except that P1, P2, P3 and P4 stop at the same time at "All Pumps Off". This would happen when inflow to a LS suddenly stops which is rarely a case in wastewater. The present paper shows calculations for the pump sequence shown in Fig. 9.

Whilst the P1, P2, P3 and P4 levels are calculated as shown in the following discussion, low and high level alarms are set arbitrarily by the design engineer. Normally, a high level alarm is set at least 12 inches below and less than 24 inches from the incoming gravity sewer line(s) invert elevation(s). A low level alarm is 6-12 inches above the minimum pump submergence level and 6-12 inches below "All Pumps Off". Larger LSs may have larger vertical distances. Small to medium size LSs (up to 5000 gpm) with constant speed pumping normally have an active depth of 4 to 8 ft.

The pump cycle time, T, equals the off-time plus on-time:

$$T = t_{off} + t_{on} \tag{8}$$

$$t_{off} = V/Q_{in} \tag{9}$$

where

V = volume of wet well between pump start and stop

Q_{in} = rate of wastewater inflow to wet well.

The time on is:

$$t_{on} = V/(O_{out} \ - \ Q_{in}) \tag{10}$$

in which Q_{out} = rate of pump discharge.

Eq. 9 and 10 substituted into Eq. 8 result in the following:

$$T = V(\frac{1}{Q_{in}} + \frac{1}{Q_{out} - Q_{in}}) \tag{11}$$

Differentiating Eq. 11 shows that the minimum pump cycle occurs at an inflow rate which is half of the pumping (i.e. outflow) rate for P1:

$$Q_{in} = \frac{Q_{out}}{2} \tag{12}$$

The minimum cycle time for the first pump is obtained by substituting Eq. 12 into Eq. 11:

$$T_{min}^{P1} = \frac{V_1}{Q_{in}} = \frac{4}{Q_{p1}} \tag{13}$$

where

V_1 = volume of wetwell drained by 1st pump P1
Q_{P1} = rate of 1st pump discharge.

Eq. 13 can be rearranged to obtain the minimum storage volume for P1:

$$V_{min}^{P1} = \frac{T_{min}^{P1} Q_{P1}}{4} \tag{14}$$

P2 is "off" whilst the water level rises from "P1" to "P2". The water level does not go below "P1" until A exceeds Q_{in} for a period beyond T_{min} (Eq. 13). P2 off-time is defined as follows:

$$t_{off}^{P2} = \frac{V_2}{(A+b)-A} = \frac{V_2}{b} \tag{15}$$

P2 time on is:

$$t_{on}^{P2} = \frac{V_2}{(A+B)-(A+b)} = \frac{V_2}{B-b} \tag{16}$$

P2 minimum cycle time is then equal to:

$$T_{min}^{P2} = \frac{V_2}{b} + \frac{V_2}{B-b} \tag{17}$$

Differentiating Eq. 17, one obtains:

$$b = \frac{B}{2} \tag{18}$$

The minimum cycle volume for P2 is:

$$V_{min}^{P2} = \frac{T_{min}^{P2}}{4} \tag{19}$$

The minimum cycle time for P3 is:

$$T_{min}^{P3} = \frac{V_1+V_2+V_3}{C-c} + \frac{V_1}{A+B+c} + \frac{V_2}{B+c} + \frac{V_3}{c} \tag{20}$$

The minimum cycle volume for P3 is:

$$V_{min}^{P3} = \frac{T_{min}^{P3}}{4} \tag{21}$$

The minimum cycle time for P4 is:

$$T_{min}^{P4} = \frac{V_1+V_2+V_3+V_4}{D-d} + \frac{V_1}{A+B+C+d} + \frac{V_2}{B+C+d} + \frac{V_3}{C+d} + \frac{V_4}{d} \tag{22}$$

The minimum cycle volume for P4 is:

$$V_{min}^{P4} = \frac{T_{min}^{P4}}{4} \tag{23}$$

In Eq. 20 and 22, c and d are inflow rates greater than A+B and A+B+C but less than A+B+C and A+B+C+D, respectively. The minimum cycle times for P3 and P4 can be determined by trial-and -error solution to try V_3 and V_4 for different values of c and d, as the rest of the variables have been determined. Another value of V_3 or V_4 is selected and the trial continues until the desired minimum cycle time is obtained.

The minimum cycle time for the lift station (LS) is the sum of P1, P2, P3 and P4 minimum cycle times:

$$T_{min}^{cycle} = T_{min}^{P1} + T_{min}^{P2} + T_{min}^{P3} + T_{min}^{P4} \tag{24}$$

Likewise, the minimum detention volume for the lift station is the sum of P1, P2, P3 and P4 minimum detention volumes:

$$V_{min}^{LS} = V_{min}^{P1} + V_{min}^{P2} + V_{min}^{P3} + V_{min}^{P4} \tag{25}$$

The minimum vertical distance from the "All Pumps Off" to the "P4" levels in Fig. 9 is the minimum volume between these levels divided by the lift station area:

$$D_{min} = \frac{V_{min}^{LS}}{A} \tag{26}$$

The minimum filling time during a minimum cycle is as follows:

$$T_{min}^{LSfill} = \frac{V_{min}^{P1}}{Q_{in1}} + \frac{V_{min}^{P2}}{b} + \frac{V_{min}^{P3}}{c} + \frac{V_{min}^{P4}}{d} \tag{27}$$

Then the minimum empty time is:

$$T_{min}^{LSempty} = T_{min}^{cycle} - T_{min}^{LSfill} \tag{28}$$

In Eq. 28, the values of b, c and d are defined as follows:

$$b = Q_{in2} - A \tag{29}$$

$$c = Q_{in3} - (A + B) \tag{30}$$

$$d = Q_{in4} - (A + B + C) \tag{31}$$

where A, B and C are P1, P2 and P3 capacities, i.e. Q_{P1}, Q_{P2} and Q_{P3}, respectively.

The following expression can be served as a very rough estimate of detention volumes for pumps starting from P2 (defined as Pn):

$$V_{Pn} = (6 + 0.1HP)\left(\frac{Q_{Pn} - Q_{Pn-1}}{2} - \frac{\sum_{i=2}^{n-1} Q_P}{n-1}\right)\left(\frac{Q_{Pn} - \frac{Q_{Pn} - Q_{Pn-1}}{2}}{Q_{Pn} - \frac{\sum_{i=2}^{n-1} Q_P}{n-1}}\right) \tag{32}$$

where HP is the pump Pn horse power (HP) capacity. The minimum detention volumes for P1 and LS are defined by Eq. 14 and Eq. 25, respectively. The term (6+0.1HP) represents the average pump cycle time T_{cycle} in minutes as a linear function of pump horse power. Some municipalities specify minimum T_{cycle} as a step function of pump HP. Usually, a 6 min cycle is the shortest cycle albeit 5 min is also possible. As such, Eq. 32 needs to be used with caution. The design engineer is referred to the local, county, state and provincial regulations before starting the design. For a minimum cycle of 6 min, the term (6+0.1HP) can be incorporated into Eq. 14 as follows:

$$V_{min}^{P1} = \frac{(6+0.1HP)Q_{P1}}{4} \tag{33}$$

where Q is in gallons per minute (gpm). Eq. 25 is not valid for HPs above 300 due to long (over 30 min) filling times. If the detention time given by Eq. 24 exceeds 2 - 3 hrs, the local municipality may require the design and installation of an odor mitigation system. The reader is referred to the author's odor control class for wastewater lift station for details. An odor control measure is normally required if wastewater detention time in the wet well and force main (FM) exceeds 4 hrs. The FM detention tine can be defined as follows:

$$T_{Dt}^{FM} = \frac{FM\ Length \cdot FM\ Inside\ Diameter^2 \cdot \frac{\pi}{4}}{\frac{\sum_{i=1}^{n} Q_{Pn}^{Base\ Flow}}{n}} \cdot \frac{Maximum\ Cycle\ Time}{Pumps\ \text{"On"}Time\ For\ Maximum\ Cycle} \tag{34}$$

For base flow and the corresponding maximum cycle time, use Minimum Dry Weather Flow (MDWF) defined by Eq. 1.

Wastewater wet well ventilation pipe is sized for an air rate equal to that of wastewater inflow and a maximum pipe air velocity not exceeding 500-600 fps. Air release valves on FMs are normally sized based on at least 2 % of wastewater volume.

A free fall from the inflow sewer pipe(s) into wet wells should be minimized as it is common but improper practice to allow a free fall or cascade into the pool below. Even a short free fall entrains air bubbles that may be drawn into the pumps resulting in efficiency reduction and even damage. The turbulence caused by air bubbles sweeps malodorous and corrosive gasses into the atmosphere.

References

- ANSI/HI Standard 9.8-1998. Pump Intake Design. 1998.
- Hecker, G.E. "Swirling Flow Problems at Intakes". IAHR Hydraulic Structures Design manual 1, Ch. 8. 1987.