Pumping Stations Design
For Infrastructure Master Program
Engineering Faculty-IUG
Lecture 4: Pumping Hydraulics

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The main items that will be studied under the pumping hydraulics title are:

- Pumping pressure and head terminology
- Cavitation
- Pump characteristic curves
- Multiple pump operation
- Variable speed pumps
- Affinity laws
- Pump selection
3.6 Pumps selection (see Chapter 25)

- Use of specific speed in pump type selection:

Specific speed is a term used to describe the geometry (shape) of a pump impeller.

Specific speed is defined as:
“The speed of an ideal pump geometrically similar to the actual pump, which when running at this speed will raise a unit of volume, in a unit of time through a unit of head."

Specific speed is calculated from the following formula:

\[
N_s = \frac{nQ^2}{H_t^{3/4}}
\]

Where:
- \( N_s \) = specific speed (or type number)
- \( n \) = pump rotational speed, rpm
- \( H_t \) = total pump head, m
- \( Q \) = pump discharge, m\(^3\)/s
3.6 Pumps selection

Figure 10-8. Pump efficiency as related to specific speed and discharge. After Flowserve Corp.
3.6 Pumps selection

- Use of specific speed in pump type selection:

Example:
A flow of 0.01 m³/s against a head of 20 m. The pump is to be driven with an electric motor at a speed of 1750 rpm. What type of centrifugal pump should be selected and what is corresponding efficiency?

Solution:
Calculate the specific speed of the pump.

\[ N_s = \frac{nQ^{\frac{1}{2}}}{H_t^{\frac{3}{4}}} = \frac{175(0.01)^{\frac{1}{2}}}{(20)^{\frac{3}{4}}} = 18.5 \]

Using figure 10-8 the pump is radial flow with an expected efficiency of 62%
3.6 Pumps selection

- In the selection process the following important information is needed:

1. Type of the liquid to be pumped “water, wastewater, sludge”.
2. Type of installation preferred “submersible or dry”.
3. Pumps available in the market (KSB, FLYGT, ABS,...).

- Selection of the specific pump needed:

1. Draw the system curve envelope and decide the operating point.
2. Decide the number of pumps needed (see table 3.1).
3. Use the catalog of the manufacturers to select a suitable pump curve.
4. Draw the pump characteristics curve over the system curve.
5. Select a pump so that the Operating range of is within 60% to 115% of Q at BEP.
6. Compare pumps of different manufacturers for more economical choice.
Lecture 3: Pumping Hydraulics

3.6 Pumps selection

Flygt

KSB

ABS

KSB
3.6 Pumps selection

Table 3.1 Recommended number of pumps in operation and their stand by.

<table>
<thead>
<tr>
<th>Design flow m³/h</th>
<th>No. of pumps needed</th>
<th>Standby pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 160</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>160 - 450</td>
<td>2 or 3</td>
<td>1</td>
</tr>
<tr>
<td>More than 450</td>
<td>3 to 5</td>
<td>2</td>
</tr>
</tbody>
</table>
4.1 General Introduction (See chapters 6 & 7)

- **What is water hammer?**
  
  Water hammer is a phenomena that occurs in pressurized pipe systems when the flowing liquid is suddenly (instantaneously) obstructed by (for example) closing a valve or by pump stoppage (failure). A laud noise similar to hammer knocking noise occurs due to the collision of the liquid mass with the obstruction body (valve or pump) and the internal walls of the pipe.

- **What is water hammer scientifically?**
  
  Water hammer is a descriptive name of the phenomena but not scientific. The scientific name is hydraulic transient. Hydraulics Transient means temporary hydraulics since the phenomena last for a very short time. During this short time the flow in the pipe is disturbed and consecutive waves will be moving back and forth creating a very high pressure rise in the pipe.
4.1 General Introduction (See chapters 6 & 7)

- **What is the problem with water hammer?**

Hydraulic transient (water hammer) may cause disasters in pressurized liquid systems such as:

1. Rupture of pipes and pump casings.
2. Vibration and high noise.
3. Excessive pipe displacements.
4. Vapor cavity formation.
5. Environmental pollution.
6. Life and economical losses.

- **When water hammer occurs?**

The most common cases where water hammer occurs are:

1. Pump failure.
2. Pump start up.
3. Sudden closure a valve.
4. Failure of flow or pressure regulators.
4.2 Water hammer pressure surge

To illustrate the pressure waves resulting from the hydraulic transient we will discuss a tank, pipe, and valve system as an example. The figure below shows the normal operation of the system before the valve closure.
What happens when the valve is closed instantaneously?

- When a valve is closed instantaneously the liquid next to the valve comes to a halt.
- This liquid is then compressed by the liquid upstream which is still flowing.
- This compression causes a local increase in the pressure on the fluid.
- The walls of the pipe around the fluid are stretched by the resulting excess pressure.
- A chain reaction then takes place along the length of the pipe, with each stationary element of fluid being compressed by the flowing fluid upstream.
- This chain reaction results in a pressure wave which travels up the pipe with a velocity \( a \), which is called the celerity. (it may reach the speed of sound in water \( 1484 \text{ m/s} \)).
- The pressure wave creates a transient hydraulic grade line (HGL) which is parallel to the steady flow HGL, but at a height above it.
- The resulting increase in pressure is due to the water hammer surge.
- When the pressure wave reaches the reservoir the pressure cannot exceed the water depth in the reservoir.
What happens when the valve is closed instantaneously?

- A wave of pressure unloading travels back along the pipe in the opposite direction.
- As the unloading wave travels down the pipe the flow is reversed, toward the reservoir.
- When this unloading wave hits the closed valve the flow is stopped and a drop in pressure occurs.
- A negative pressure wave now travels up the pipe toward the reservoir.
- The process described above now repeats itself for a negative wave.
- A cycle of pressure waves (positive - unloading - negative - unloading) now travels up and down the length of the pipe.
- Friction has the effect of slowly damping out the effect of the pressure waves.
- When the negative pressure wave travels along the pipe very low pressures may cause cavitation.
What are the factors affecting the wave speed and How it can be calculated?

- The speed of pressure wave “a” depends on:
  - the pipe wall material.
  - the properties of the fluid.
  - the anchorage method of the pipe.
- For elastic pipes (steel, PVC,..) the wave speed is given by the following formula:

\[
a = \sqrt{\frac{K}{\rho} \frac{1}{1 + C\left(\frac{K}{E}\right)\left(\frac{D}{e}\right)}}
\]
What are the factors affecting the wave speed and How can it can be calculated wave? Continued …….

Where:

- $a$ = elastic wave speed in water contained in a pipe, m/s
- $K$ = Bulk modulus of elasticity of the liquid, N/m$^2$ ($K = 2.15 \times 10^9$ N/m$^2$ for water)
- $E$ = Modulus of elasticity of pipe material, N/m$^2$
- $D$ = Inside diameter of the pipe, m
- $e$ = Wall thickness of the pipe, m
- $\rho$ = Density of the fluid, kg/m$^3$
- $C$ = Correction factor depending on the type of pipe restrain
  - $(1.25 - \mu)$ for pipes anchored from one side only.
  - $(1.0 - \mu^2)$ for pipes anchored against axial movements.
  - $1.0$ for pipes with expansion joints throughout.
- $\mu$ = Poisson’s ratio of the pipe material
4.2 Water hammer pressure surge

What do we mean by instantaneous valve closure?

The time required for the pressure wave to travel from the valve to the reservoir and back to the valve is:

\[ t = \frac{2L}{a} \]

Where:

- \( L \) = length of the pipe (m)
- \( a \) = speed of pressure wave, celerity (m/sec)

- If the valve time of closure is \( t_c \), then
  - If \( t_c > \frac{2L}{a} \) the closure is considered gradual
  - If \( t_c \leq \frac{2L}{a} \) the closure is considered instantaneous
4.2 Water hammer pressure surge

What is the value of the pressure surge?

There are two cases for pressure surge:

1. Gradual closure of the valve:
   
   In this case \( t_c > \frac{2L}{a} \) and the pressure increase (\( \Delta H \)) is:
   
   \[
   \Delta H = \frac{LV_0}{gd}
   \]

   Where:
   
   \( V_0 = \) initial velocity of the fluid, m/s
   
   \( g = \) gravitational acceleration, m/s
   
   \( L = \) pipe length, m
   
   \( t = \) closure time, s
   
   \( a = \) Wave speed, m/s

2. Instantaneous closure of the valve:
   
   In this case \( t_c \leq \frac{2L}{a} \) and the pressure increase (\( \Delta H \)) is:
   
   \[
   \Delta H = \frac{aV_0}{g}
   \]

   Note: that (\( \Delta H \)) due to gradual closure is very small compared with the instantaneous (\( \Delta H \)).
Lecture 4: Water hammer phenomena

4.2 Water hammer pressure surge
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- **Reservoir**
  - Wave speed
  - HGL
  - a
  - b
  - HGL
  - c
  - d
  - H

- **Diagram**
  - **a**
    - $0 \leq t \leq L/a$
    - $v = 0$
  - **b**
    - $L/a \leq t \leq 2L/a$
    - $v = 0$
  - **c**
    - $2L/a \leq t \leq 3L/a$
    - $v = v_o$
  - **d**
    - $3L/a \leq t \leq 4L/a$
    - $v = v_o$
4.2 Water hammer pressure surge
4.2 Water hammer pressure surge
4.3 Time history of pressure wave due to water hammer:

The time history of the pressure wave for a specific point on the pipe is a graph that simply shows the relation between the pressure increase (ΔH, or ΔP) and Time during the propagation of the water hammer pressure waves. The following Figures illustrate the time history in the tank pipe system discussed previously.
4.3 Time history of pressure wave due to water hammer:

The figure below is the time history for a point “A” just to the left of the valve. The friction losses in the pipe are neglected.

Time history for pressure at point “A” (after valve closure)
4.3 Time history of pressure wave due to water hammer:

The time history for point "M" (at midpoint of the pipe). The friction losses in the pipe are neglected.
4.3 Time history of pressure wave due to water hammer:

The time history for point B (at a distance $x$ from the reservoir) The friction losses in the pipe are neglected.

Time history for pressure at point “B” (after valve closure)
4.3 Time history of pressure wave due to water hammer:

In real practice friction effects are considered and hence a damping effect occurs and the pressure wave dies out, i.e.; energy is dissipated.

Time history for pressure at point “A” (after valve closure) when friction losses are included.
Water hammer due to power failure:

As illustrated previously, one of the serious events that produce water hammer in delivery pipes of pumping stations is power failure.
4.4 water hammer in pumping mains

- **Column separation due to power failure:**

  - What do we mean by column separation?
  - After *power failure* a wave of negative pressure “down surge” occurs.
  - If the *hydraulic profile intersects the pressure pipe* and falls below it for a pressure less or equal to the vapor pressure, water vapor starts to accumulate. And large air pockets are formed.
  - The air pocket separates the water column in the pipe into two parts, upstream column and downstream column. This phenomena is called *column separation*.
  - Column separation is dangerous when the two water columns *join again with huge collision* when the reflected wave comes back. This collision produces an *upsurge pressure* that is much more than the first water hammer impulse calculated from the equation discussed previously $\Delta H = \frac{aV_0}{g}$. 

\[ \Delta H = \frac{aV_0}{g} \]
4.4 water hammer in pumping mains

- Column separation due to power failure:
  - How to predict column separation?

To predict the occurrence of negative pressure and column separation due to water hammer draw a mirror image of the normal hydraulic profile. If the mirror HGL falls below the pipe for a distance “d” = $h_{atmospheric} - h_{vapor}$, thin column separation will occur.
4.4 water hammer in pumping mains

- Graphical solution to calculate the water hammer surge after power failure:
  A. water hammer without column separation:

  The figure in the next slide illustrates the surge development in a pumping main after power failure. The following formulas are needed to understand the method:

  \[
  \tan \Lambda = \frac{a}{gA_p}
  \]
  \(\Lambda\) (Lambda) is the angle of inclination of the surge line PR, \(A_p\) is the cross section area of the pressure line.

  \(A_{0-1}\) : the subscripts 0-1 means the situation at point A between time 0 and time 1, the same notation is used for point B. Time 1 in this example is \(= L/a\).

  \[
  C_p = \frac{Q_0}{2H_0} \tan \Lambda
  \]
  \(C_p\) is the pipe constant, \((Q_0,H_0)\) is the operating point before pump failure.

  If \(C_p\) is <0.50 then the maximum pressure at the pump is positive as this case.
  If \(C_p\) is > 0.50 then the maximum pressure at the pump is negative and column separation will occur as the next case explained in B.
4.4 water hammer in pumping mains

Graphical solution to calculate the water hammer surge after power failure:

B. water hammer with column separation:

As indicated in Case A if $C_p$ is $> 0.50$ then column separation occurs. The following example illustrates this case.

Example

*Draw a surge diagram to obtain the maximum pressure head at the pump described below when the flow is suddenly stopped.*

The pump is placed in a dry well adjacent to the suction well and 4 ft below the water level in the suction well, which is considered as datum. Separation occurs at a negative head of 30 ft. The pipe normally discharges 8 cusecs along a 21 in. diameter main which rises uniformly to a reservoir in which the water level is 60 ft above datum. The length of the main is 16 600 ft and the friction head (assumed proportional to velocity squared) is 19 ft at normal flow. $a = 3320$ ft/sec.
4.4 Prevention of water hammer in pumping mains

Methods of preventing or minimizing the water hammer surge:

A. Control Tanks:
   - Open end surge tank or standpipe
   - one way surge tank
   - two way surge tank
   - Air champers (hydropneumatic tanks)

B. Control valves:
   - Vacuum relief valve
   - Air release valves
   - Air release and vacuum relief valves
   - surge relief valves
4.4 Prevention of water hammer in pumping mains

**Figure 7-4.** Open-end surge tank or standpipe.

**Figure 7-5.** One-way surge tank.

**Figure 7-6.** Two-way surge tank.
4.4 Prevention of water hammer in pumping mains

Figure 7-3. Horizontal hydropneumatic tank (air chamber) for clean water service. (a) End elevation; (b) side elevation.
4.4 Prevention of water hammer in pumping mains

Vertical Air chamber for water hammer prevention

Horizontal Air chamber for water hammer prevention
4.4 Prevention of water hammer in pumping mains
Lecture 4: Pumping Hydraulics

4.4 Prevention of water hammer in pumping mains

Air release valve
4.4 Prevention of water hammer in pumping mains

Vacuum relief valve

Air/Vacuum relief valve
4.4 Prevention of water hammer in pumping mains

- Using Air chambers to prevent water hammer surge:

![Diagram of Air chamber installation in pumping mains](image)

Fig 80
Example

Consider the pumping plant installation with an air chamber shown in Figure 80. It is desired to determine a chamber size such that the maximum upsurge in the discharge line adjacent to the pump will not exceed $0.43H_0^*$ and the maximum downsurge at the mid-length will not exceed $0.21H_0^*$. From the charts in Figure 83 it is found that these requirements are met by using the values $K = 0.3$ and $2C_0a/Q_0L = 21$ for which the maximum upsurge at the pump $= 0.27H_0^*$, the maximum downsurge at the mid-length $= 0.21H_0^*$, and the maximum downsurge adjacent to the pump $= 0.32H_0^*$. For this installation the pipe line friction loss for a flow $Q_0$ is about 3 feet. The differential orifice required at the chamber must then give a head loss for a flow of $Q_0$ into the chamber of $0.3 \times 234 - 3 = 67$ feet. With $2C_0a/Q_0L$ known, the initial volume of compressed air in the chamber $C_0$ is 709 cubic feet and the minimum volume for the whole air chamber $C''$ as determined from Equation (78) is 1040 cubic feet.
Charts to determine the size of the air champer

\[ \rho^* = \frac{aV_0}{2gH_0^*} \]

\[ K = \text{losses percent in the air champer orifice} \]

\[ C_0 = \text{The initial compressed air volume in the air champer} \]

\[ C' = \frac{C_0H_0^*}{H_{\min}^*} \]

\[ H_{\min}^* = H_0^* - \text{down surge adjacent to the pump} \]
4.4 Prevention of water hammer in pumping mains

- Using computer software for water hammer analysis:

  There are many computer software for water hammer analysis such as:

  - Hammer (Bently company)
  - HiTran
  - AFT
  - Pipe Expert

  These software are not free, they are very expensive. However, you can download DEMO versions and get good benefit out of it. You can also search for free software that I do not know.
5.1 General introduction

- Bar screen
- Grit removal
- Wet well or wet well + dry well
- Electricity distribution and control room (MDB + PLC)
- Transformer room
- Stand by generator and its fuel tank
- Guard room and its services (kitchen + showers and toilet)
- Pressure pipes and control valves
- Fence and landscaping