An overview of the Hydraulics of Water Distribution Networks

June 21, 2017

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Outline

- Pressurized vs. open-channel flow in closed conduits
- Uniform vs. nonuniform flow & steady vs. unsteady flow
- Conservation of mass principle
- Conservation of energy principle: Friction and minor headlosses
- What about HGL and EGL?
- Water distribution network analysis
- Software for steady-state analysis and extended-period simulations
- Pumps and turbines
- Hydraulic transients (surge analysis)
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- References
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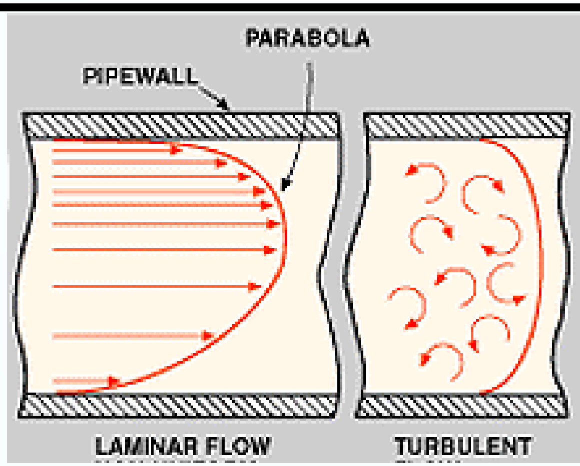
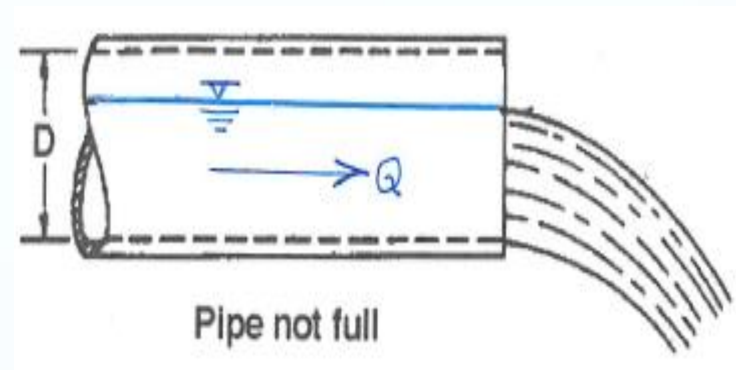
- Q&A session

Pressurized vs. open-channel flow in closed conduits

Pressurized flow	Open-channel flow
	
Driven by head differential and/or pump(s)	Gravity driven
Reynolds number *(Re):* Laminar, transition zone or wholly turbulent	Froude Number *(Fr):* Subcritical, critical or supercritical flow
Friction loss: Darcy-Weisbach’s, Hazen-Williams’ or Chezy’s equation	Friction loss: Manning’s equation

Reynolds Number

- Reynolds Number (ratio of inertia force to viscous force)

- V = velocity (m/s or ft/sec)
  D = pipe diameter (m or ft)
  ρ = density of fluid (Kg/m^3 or lbm/ft^3)
  μ = dynamic viscosity of fluid (N.s/m^2 or lbf.s/ft^2)
  ν = kinematic viscosity (m^2/s or ft^2/s)

$$\mathrm{Re} = \frac{VD\rho}{\mu} = \frac{VD}{\nu}$$

Laminar vs. turbulent flow

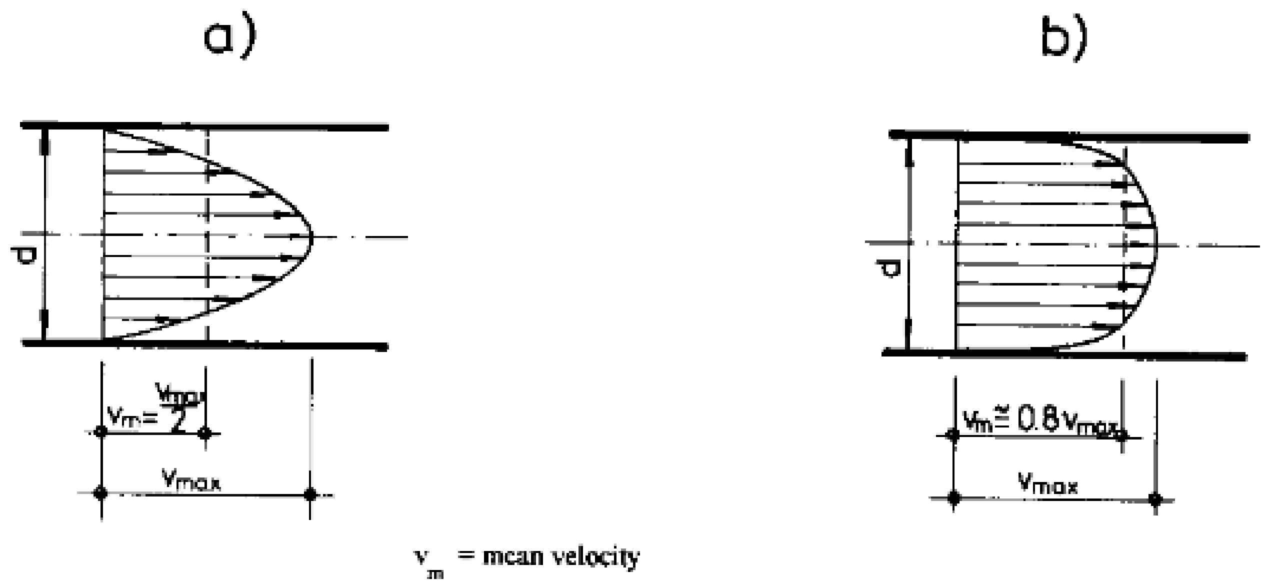


FIGURE A 4:
Velocity distribution in pipe flow for a) laminar flow and b) turbulent flow

- Re < 2,000: laminar flow
- Re from 4,000 to 800,000,000 (or more): turbulent flow (transition zone and wholly turbulent zone)

Moody Diagram

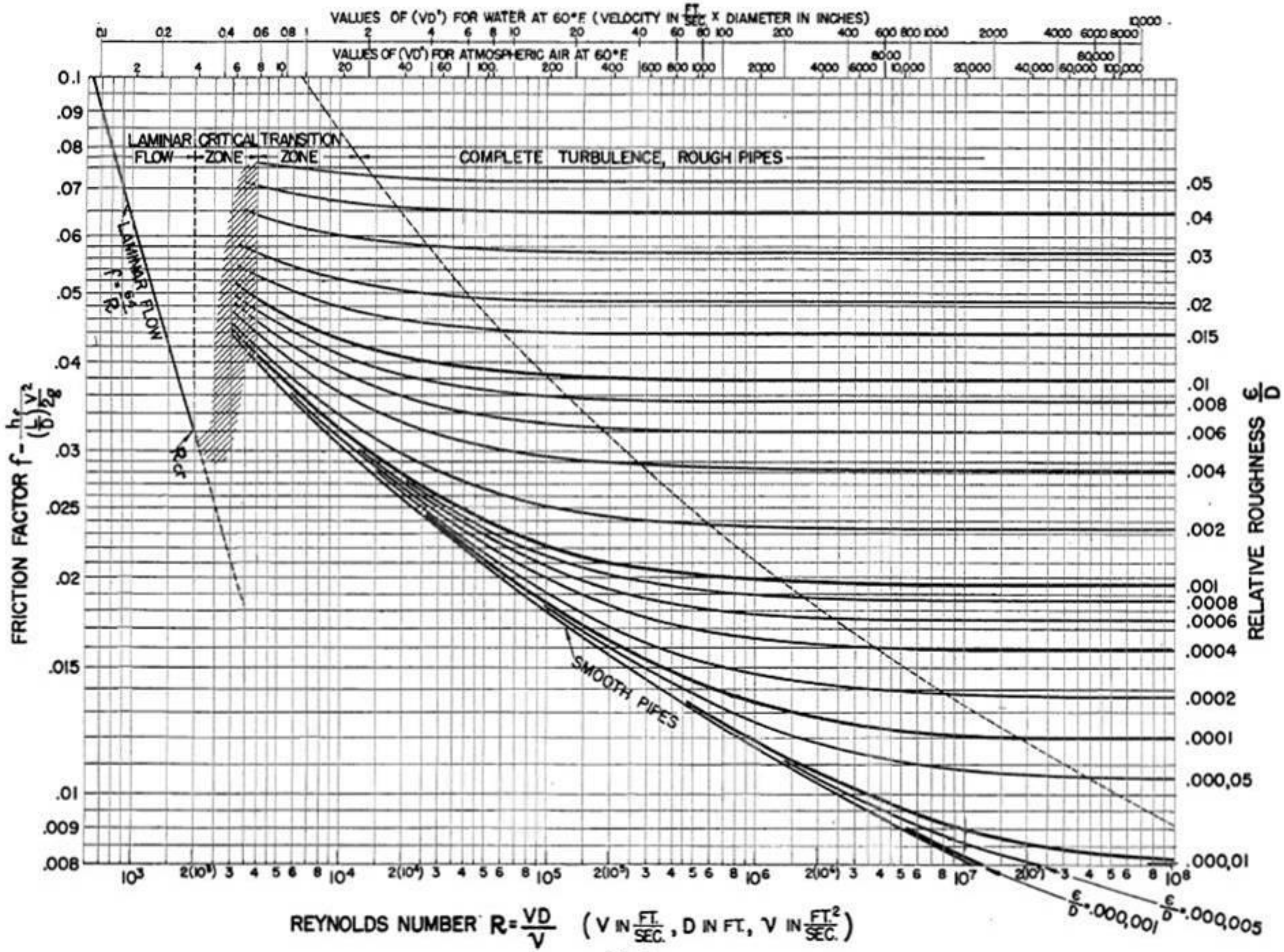
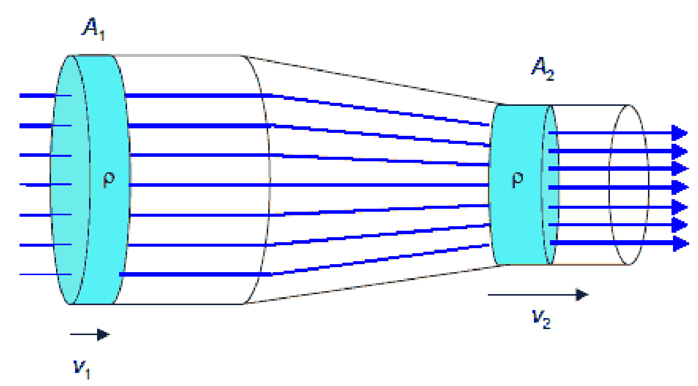


Fig. 1

Uniform vs. Nonuniform Flow & Steady vs. Unsteady Flow

- **Uniform** flow: Constant flow characteristics (like velocity) with respect to ***space***
- **Nonuniform** flow, like in the case of changing pipe size



- **Steady** flow: Constant flow characteristics with respect to ***time***. Steady flow is considered when designing a pipe network (looking for pressures at certain locations and velocities in the pipes)
- Consider **unsteady** (transient) phenomena to refine the design (pipe pressure class and thickness)

Conservation of Mass Principle

- In a control volume:

$$\frac{dS}{dt} = In - Out$$

(change in storage over time = inflow – outflow)

- For **steady** & incompressible flow: $dS/dt = 0$,

continuity equation becomes:

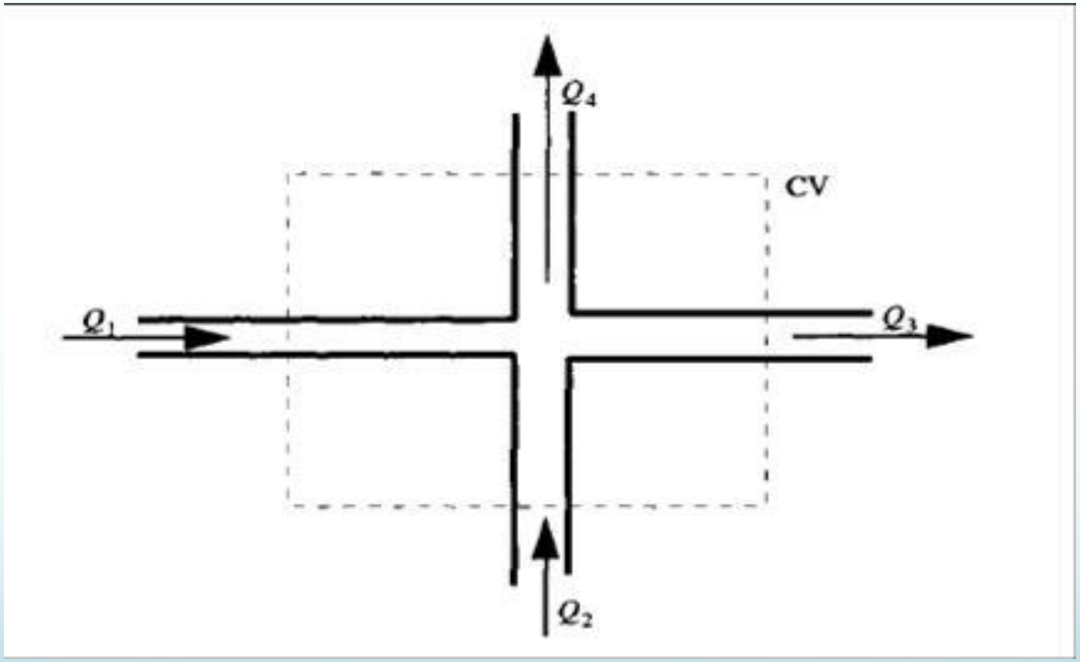
In = Out (inflow = outflow)

i.e., $\Sigma Q_{in} = \Sigma Q_{out}$

Conservation of Mass Principle

- Continuity equation applied to a pipe junction:

$$Q_1 + Q_2 = Q_3 + Q_4$$



Conservation of Energy Principle

- In pipeline design, most often consider steady-state flow (does not vary with time). **Energy equation** is written as:

$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1+h_{pump}=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+h_{turbine}+h_{losses}$$

- Steady-state **Bernoulli's Equation** (no head loss nor gain) along a streamline:

$$\frac{p_1}{g}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{g}+\frac{V_2^2}{2g}+z_2$$

Conservation of Energy Principle

- Pressure head: p/γ
  (where γ is the specific weight of water: $\gamma = \rho\ g$)
- Elevation head: z
- Velocity head: $V^2/2g$
- Piezometric head: $p/\gamma + z$
  (a.k.a. **Hydraulic Grade Line or HGL**)
- Total head: $p/\gamma + z + V^2/2g$
  (a.k.a. **Energy Grade Line or EGL**)
- Headlosses: h_{losses} = friction headloss (h_{Lf}) + minor headloss (h_{Lm})
- *Turbine head:* $h_{turbine}$ = *pressure head dissipated in a turbine to produce electric energy*
- *Pump head:* h_{pump} = *pressure head gained from a pump*

Friction Headloss

- Friction loss results from friction between the fluid and pipe wall

- The most useful headloss equation for pressurized pipe flow is the **Darcy-Weisbach equation:**

Friction headloss

Pipe length

Pipe velocity

$$h_{Lf} = f \frac{L}{D} \frac{V^2}{2g}$$

Dimensionless friction coefficient

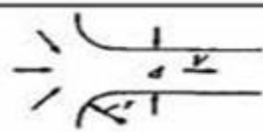
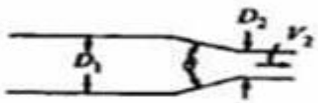
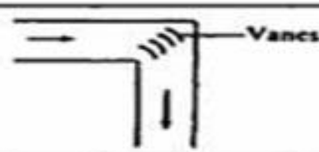
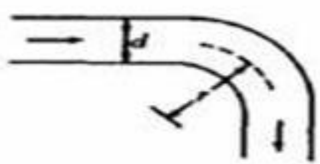
Pipe diameter

Gravitational acceleration

Minor Headloss

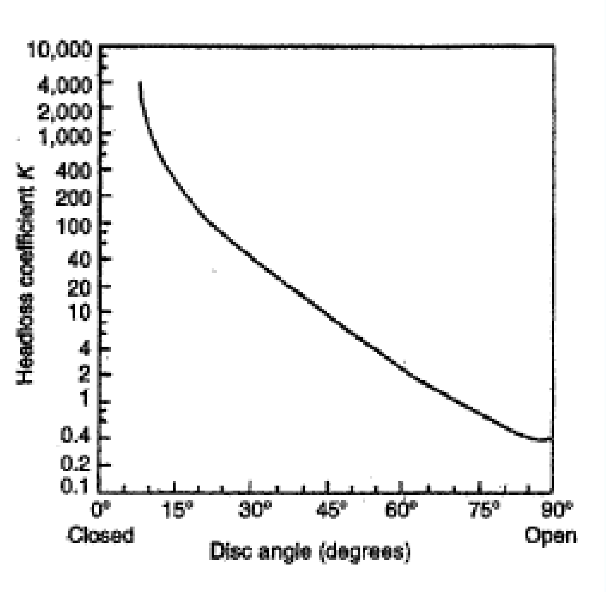
- Minor headloss can be caused by the presence of a valve in the network, entrance to a pipe from a reservoir, exit to a tank, bend in the pipe, elbow, pipe expansion, pipe contraction (reducer), or other fittings
- Use a minor headloss coefficient *(K)* in the following minor headloss expression:

$$h_{Lm} = K\frac{V^2}{2g}$$

Description	*Sketch*	*Additional Data*	*K*	
Pipe entrance		r/d	K_e	
		0.0	0.50	
		0.1	0.12	
$h_L = K_eV^2/2g$		> 0.2	0.03	
Contraction			K_c	K_c
		D_2/D_1	$\theta = 60°$	$\theta = 180°$
		0.0	0.08	0.50
		0.20	0.08	0.49
		0.40	0.07	0.42
		0.60	0.06	0.32
		0.80	0.05	0.18
$h_L = K_cV_2^2/2g$		0.90	0.04	0.10
Expansion			K_E	K_E
		D_1/D_2	$\theta = 10°$	$\theta = 180°$
		0.0		1.00
		0.20	0.13	0.92
		0.40	0.11	0.72
		0.60	0.06	0.42
$h_L = K_EV_1^2/2g$		0.80	0.03	0.16
90° miter bend		Without vanes	$K_b = 1.1$	
		With vanes	$K_b = 0.2$	
90° miter bend		r/d		
		1	$K_b = 0.35$	
		2	0.19	
		4	0.16	
		6	0.21	
		8	0.28	
		10	0.32	
Threaded pipe fittings	Globe valve—wide open		$K_v = 10.0$	
	Angle valve—wide open		$K_v = 5.0$	
	Gate valve—wide open		$K_v = 0.2$	
	Gatevalve—half open		$K_v = 5.6$	
	Return bend		$K_b = 2.2$	
	Tee		$K_t = 1.8$	
	90° elbow		$K_b = 0.9$	
	45° elbow		$K_b = 0.4$	

Valves

A large butterfly valve shown as partially open



Headloss coefficient *(K)* for a butterfly valve

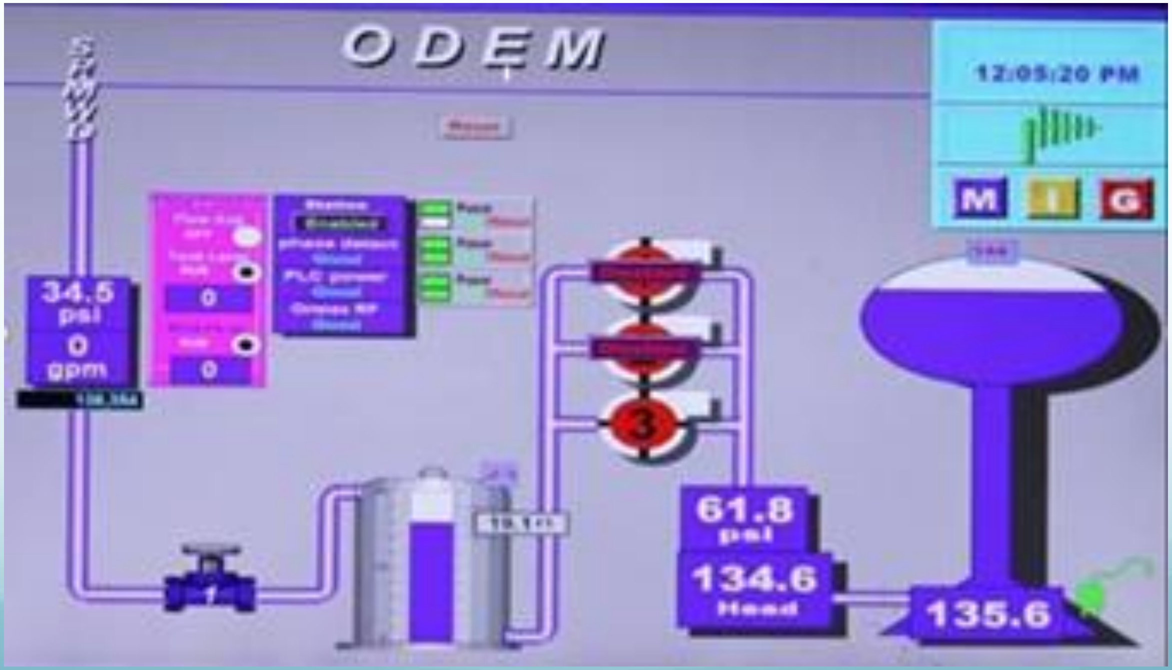
(Bosserman and Hunt, 1998)

$$h_{Lm} = K\frac{V^2}{2g}$$

When K is very large, minor headloss could become larger than the major (friction) headloss. So the word "minor" is a misnomer

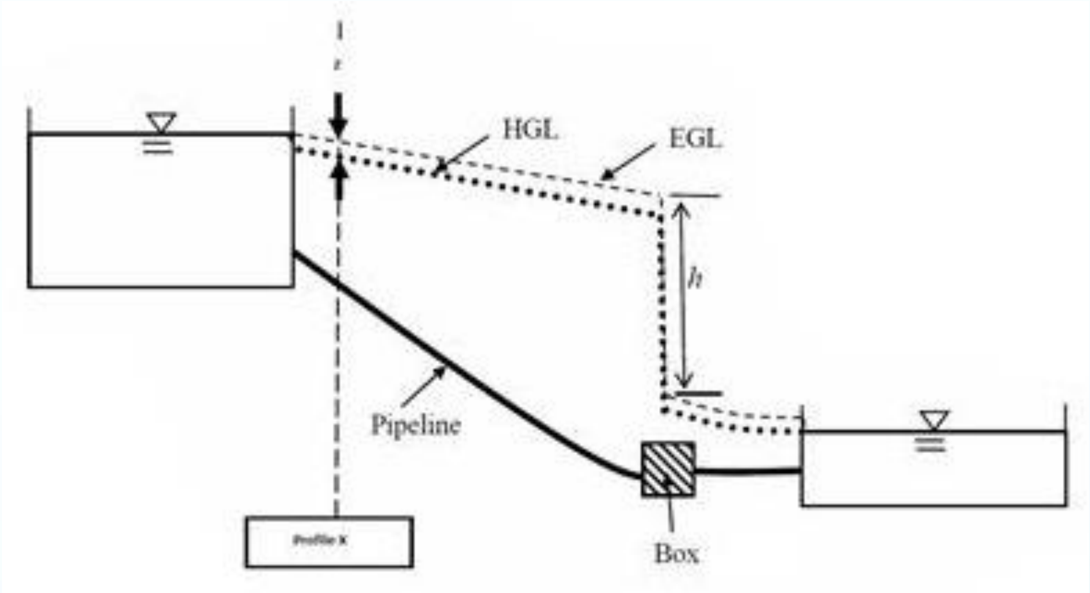
What about HGL and EGL?

The Supervisory Control And Data Acquisition (**SCADA**) system records and reports on a screen various parameters data for a pipe network, a treatment plant, etc. Parameters such as: flow, pressure and hydraulic grade line (HGL)



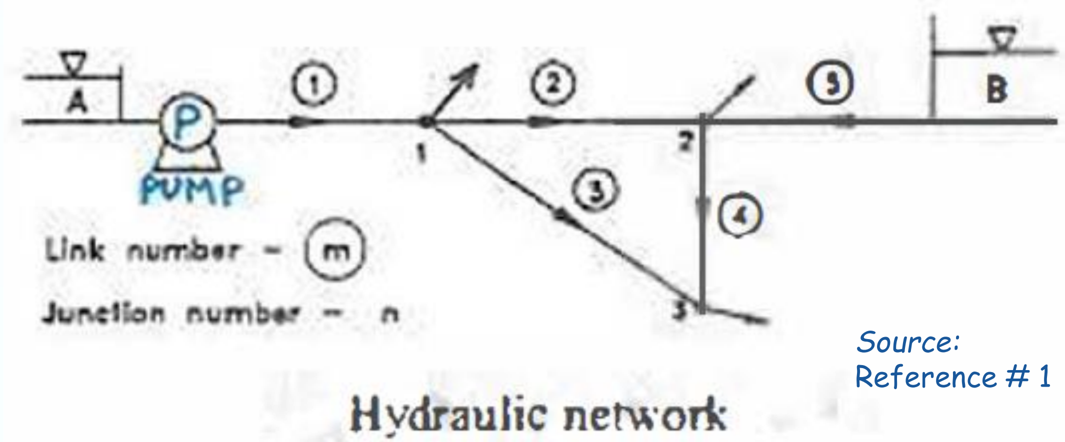
What about HGL and EGL?

- **EGL =** $p/\gamma + z + V^2/2g$
- **HGL =** $p/\gamma + z$



- *<u>Test your knowledge:</u>* What does the distance between the two arrows at "Profile X" represent? What does "h" refer to? Does the "Box" represent a pump or a turbine? Is the flow (discharge) in the pipeline going from left to right or vice versa? Explain your answer.

Water Distribution Network Analysis



Source: Reference # 1

- For the simple network shown above with 5 unknown flow values in the 5 pipes, we need to solve 5 equations. These are:
  - 3 linear continuity equations at 3 junctions, and
  - 2 nonlinear energy equations along 2 paths.
- Solution of a nonlinear system of 5 equations is not straightforward

Water Distribution Network Analysis

- Hardy-Cross Method, 1936 (manual technique only suitable for small networks)
- Numerical Methods (like Newton-Raphson technique) use iterations but are prone to problems of diverging solutions
- Linearization Method (approximation)
- Perturbation Method (Basha & Kassab, 1996), a direct, mathematical solution:

Zeroth order:

$$[A_c][h_0] = +[C_1]$$
$$[A_e][h_0] = +[\Delta H] \tag{19}$$

First order:

$$[A_c][h_1] = -[\alpha h_0 \ln h_0]$$
$$[A_e][h_1] = +[0] \tag{20}$$

Second order:

$$[A_c][h_2] = -\left[\alpha\left(h_1 + h_1 \ln h_0 + 0.5 h_0 \ln^2 h_0\right)\right]$$
$$[A_e][h_2] = +[0] \tag{21}$$

Third order:

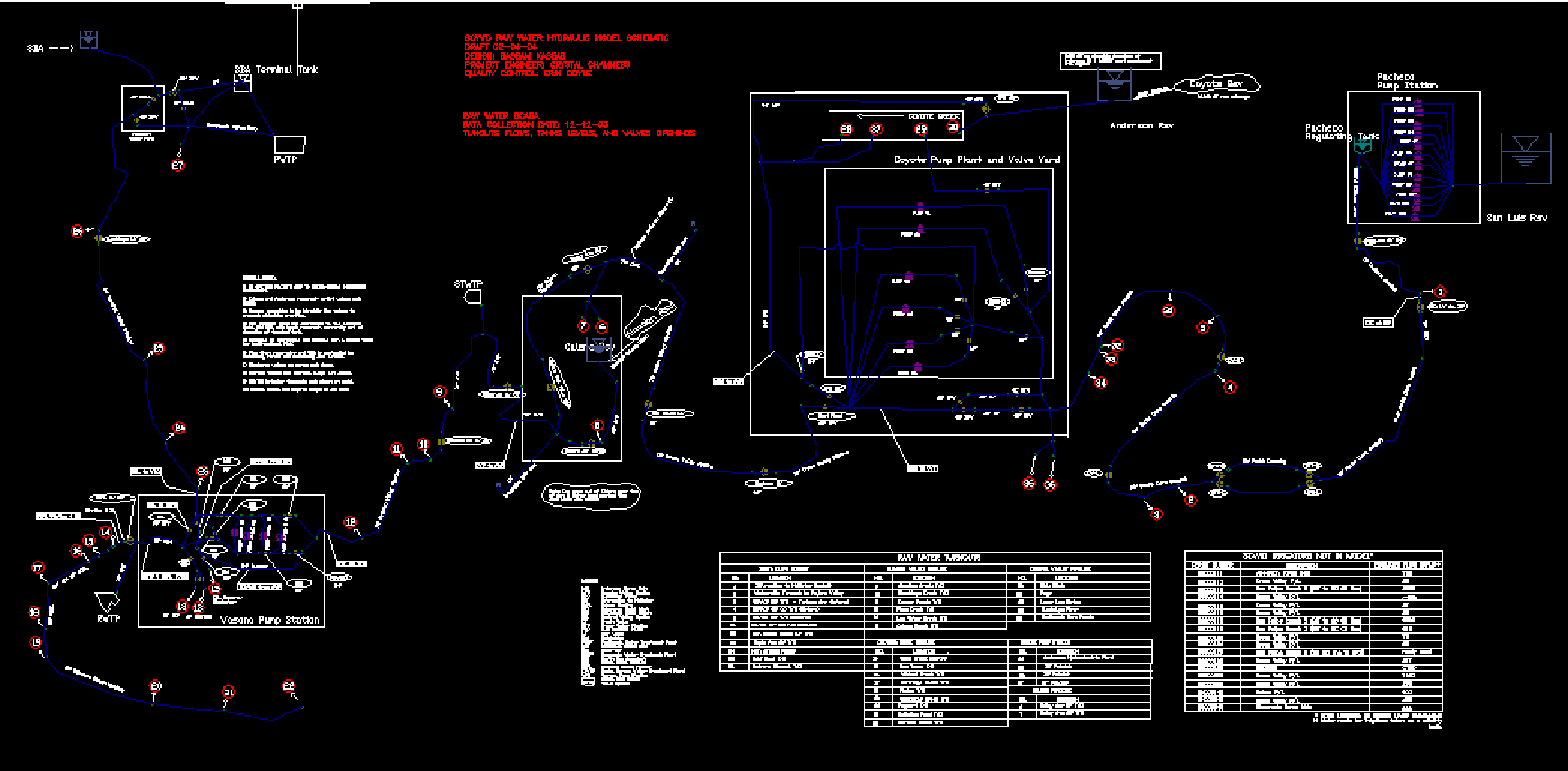
$$[A_c][h_3] = -\left[\alpha\left(h_2 + \frac{h_1^2}{2h_0} + h_1 p_n h_0 + h_2 \ln h_0 + \frac{h_1}{2}\ln^2 h_0 + \frac{h_0}{6}\ln^3 h_0\right)\right]$$
$$[A_e][h_3] = +[0] \tag{22}$$

Source: Reference # 1

Software for steady-state analysis & extended-period simulations (EPS)

- Hydraulic modeling software use numerical algorithms to obtain the steady-state solution for a water distribution network
- EPS: used for water quality analysis (water age, contaminant tracing). EPS is simply a series of steady-solutions over time
- Free software: EPANET
- Commercial software (H2ONET, InfoMAP, WaterCAD, WaterGEMS, *etc.)* give same results as EPANET but have additional bells and whistles. Some have better graphic user interface (GUI), others work in a GIS environment or can have an add-on surge software.

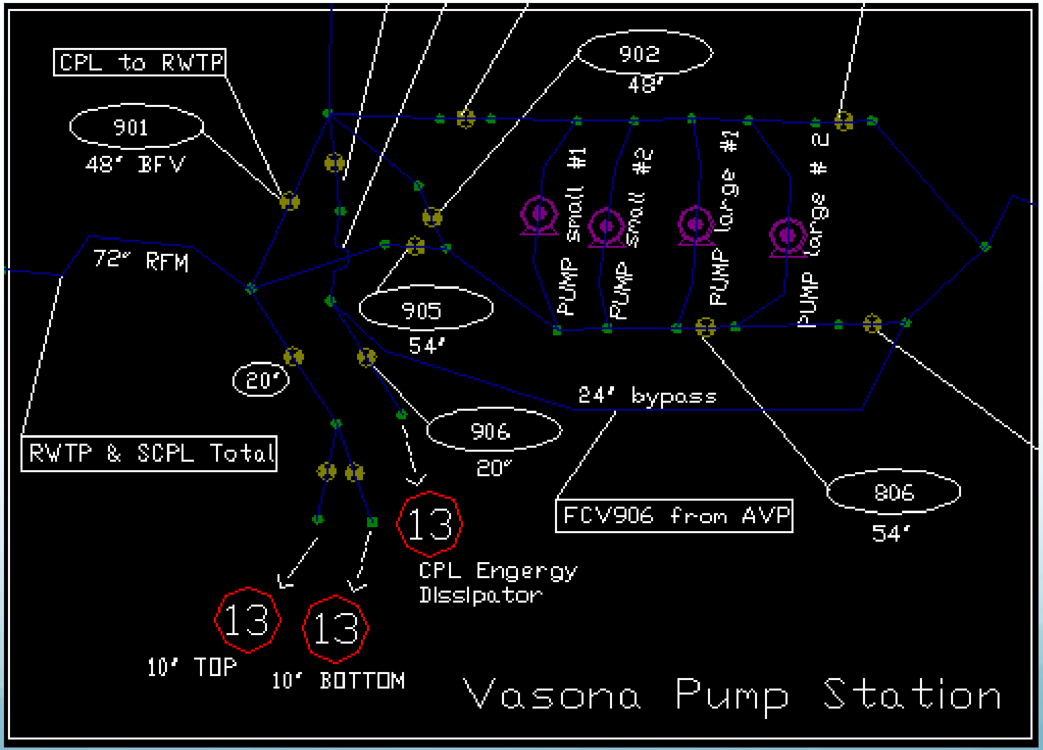
Skeletonizing a Water Distribution Network



The raw water distribution system of Santa Clara Valley Water District was modeled using H2ONET

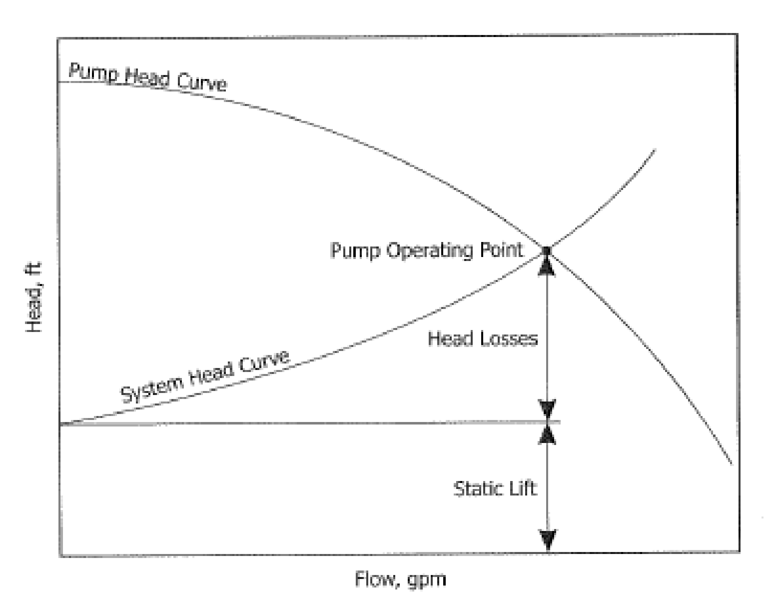
Pumps and Turbines

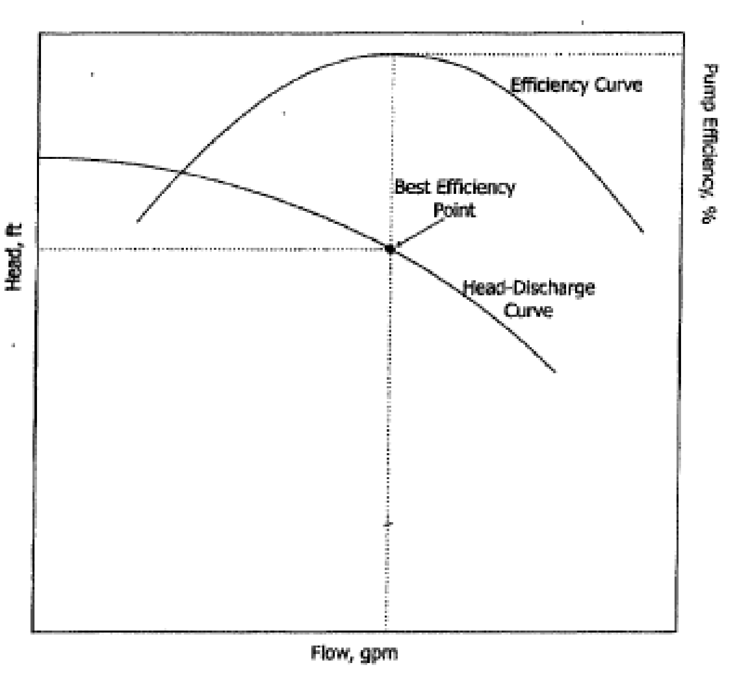
- Pumps and valves are easily modeled using commercial software
- But it is important to have a solid understanding of pump curves, operating point concept, and pump efficiency



Pumps

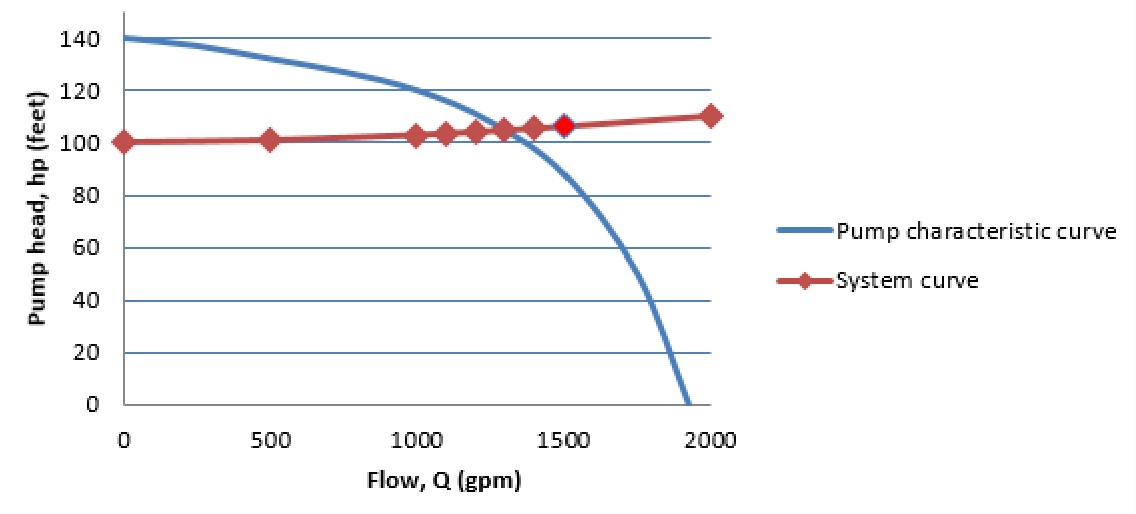
- Pump characteristic curve (pump head *hp* vs. flow *Q*): originally provided by manufacturer, then updated by technicians/engineers who calibrate the pump regularly
- System curve: *hp* vs. *Q* as obtained from energy equation. Note that system curve changes every time conditions change (like tank level fluctuates)
- Operating point: where the 2 curves meet
- Operating point is not always point of best (maximum) efficiency





Source: Reference # 2

Finding the Pump Operating Point



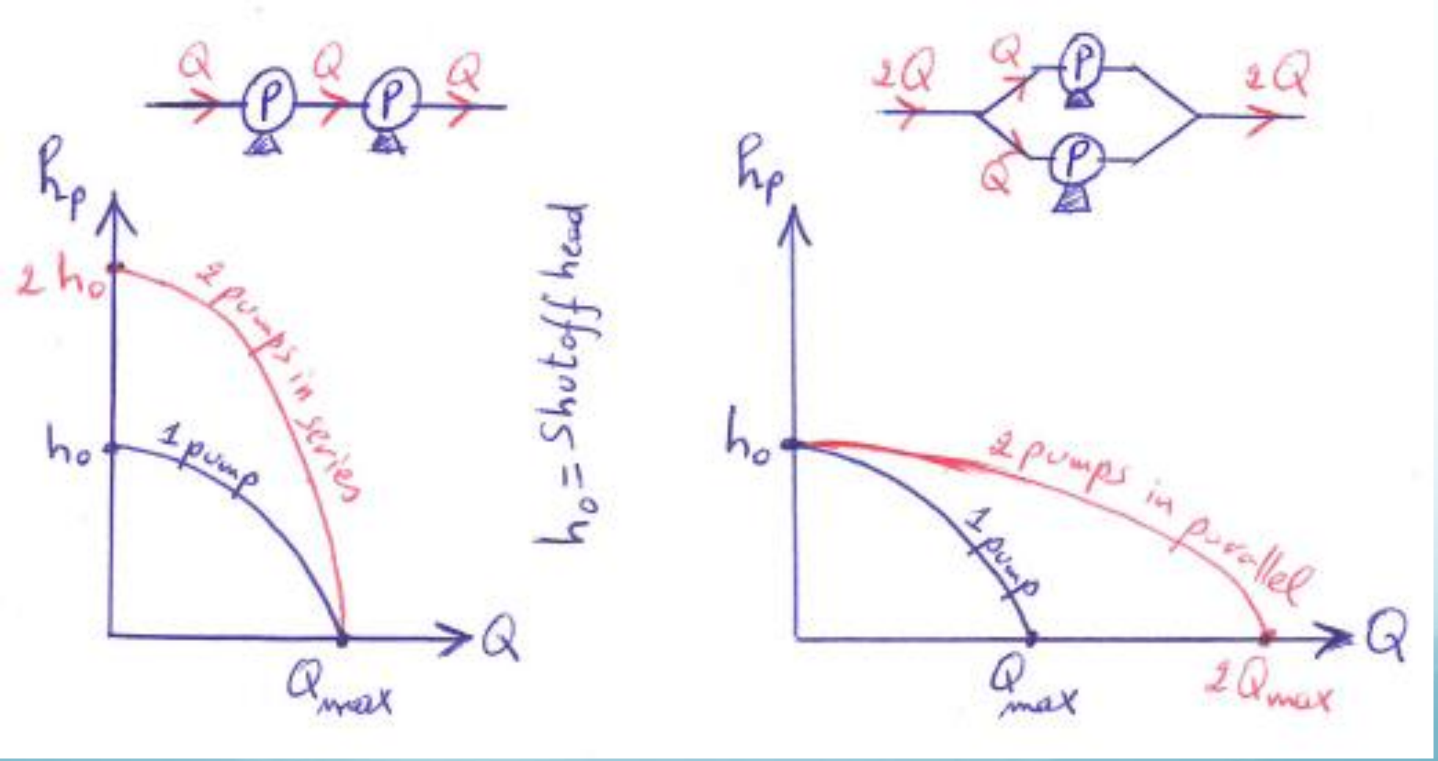
System curve *(a parabolic equation) for the case of a pump on a pipe connecting two reservoirs/tanks:*

$$h_{pump} = (z_2 - z_1) + h_{Lf} + h_{Lm}$$

Pumps in Series & Pumps in Parallel

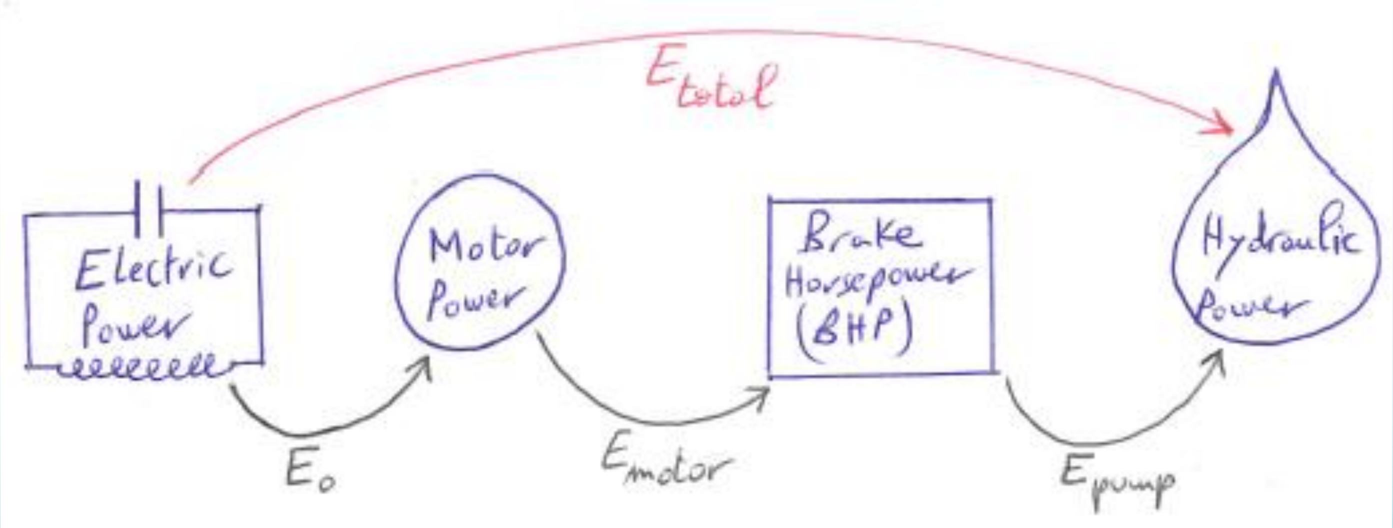
- *For pumps in series:* Pump head *(h_p)* adds up but the flow *Q* remains constant

- *For pumps in parallel:* Flow *(Q)* adds up but pump head h_p remains the *same*



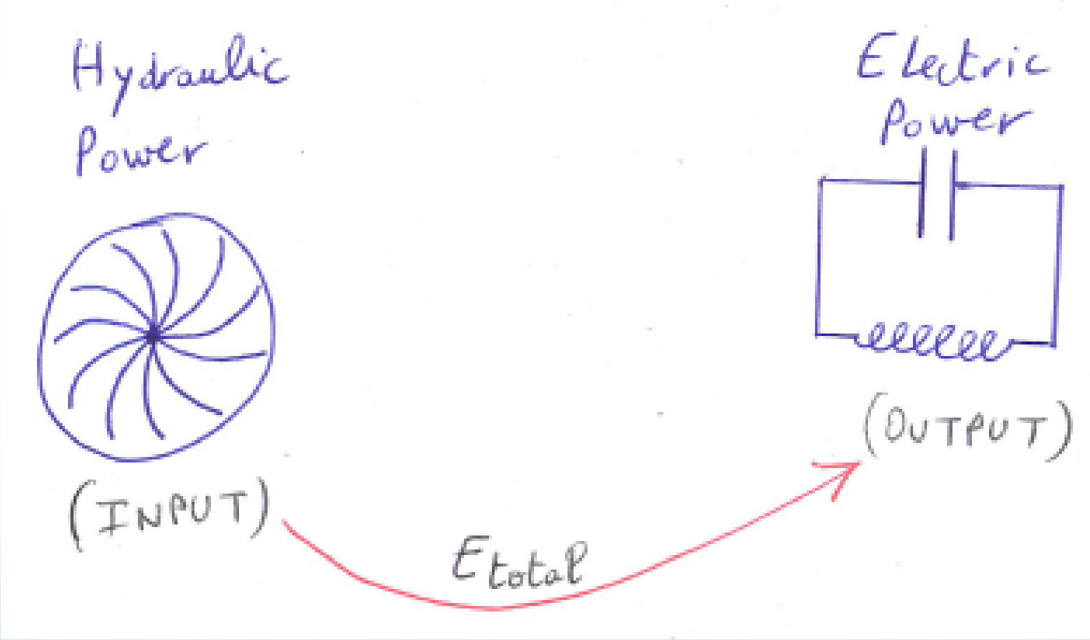
Pump Power and Efficiency

- Hydraulic power of a pump = $\gamma\ Q\ h_p$
- E_{total} = overall (total) pump efficiency = output power / input power = Hydraulic power / electric power
- $E_{total} = E_o\ .\ E_{motor}\ .\ E_{pump}$



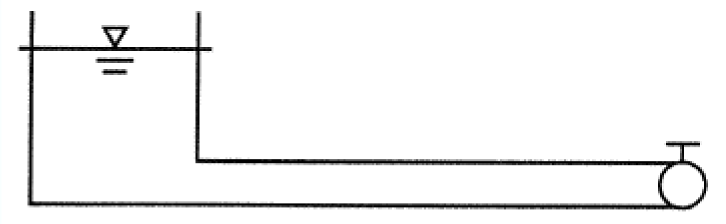
Turbines

- Hydraulic power of a turbine = $\gamma\ Q\ h_T$
- E_T = Overall turbine efficiency = ouput power / input power = electric power / hydraulic power



Hydraulic Transients (Surge Analysis)

- Hydraulic transients (aka waterhammers) are caused by a sudden opening or closure of a valve, starting or stopping a pump or a turbine, or accidental events, like power outage.



The analysis of transient flow in pipes requires the simultaneous solution of the linear continuity equation:

$$\frac{\partial h}{\partial t} + \frac{a^2}{g}\frac{\partial v}{\partial x} = 0 \qquad (1)$$

and the nonlinear momentum equation:

$$\frac{\partial v}{\partial t} + g\frac{\partial h}{\partial x} + \frac{f}{2D}v^2 = 0 \qquad (2)$$

where h is the piezometric head, v is the fluid velocity, g is the gravitational acceleration, and a is the waterhammer wave celerity. The source of the nonlinearity in the above set of partial differential equations is in the friction term $fv^2/(2D)$ where f is the Darcy-Weisbach's friction factor, and D is the diameter of the pipe.

Source: Reference # 3

Hydraulic Transients (Surge Analysis)

Solution by:

- Arithmetic Method (Joukowski, 1904), approximation
- Method of Characteristics (MOC), most popular
- Wave-Plan Analysis Method (Wood et al., 1966)
- Linear methods (approximation)
- Perturbation Method (Basha & Kassab, 1996), direct, mathematical solution (Reference 3)

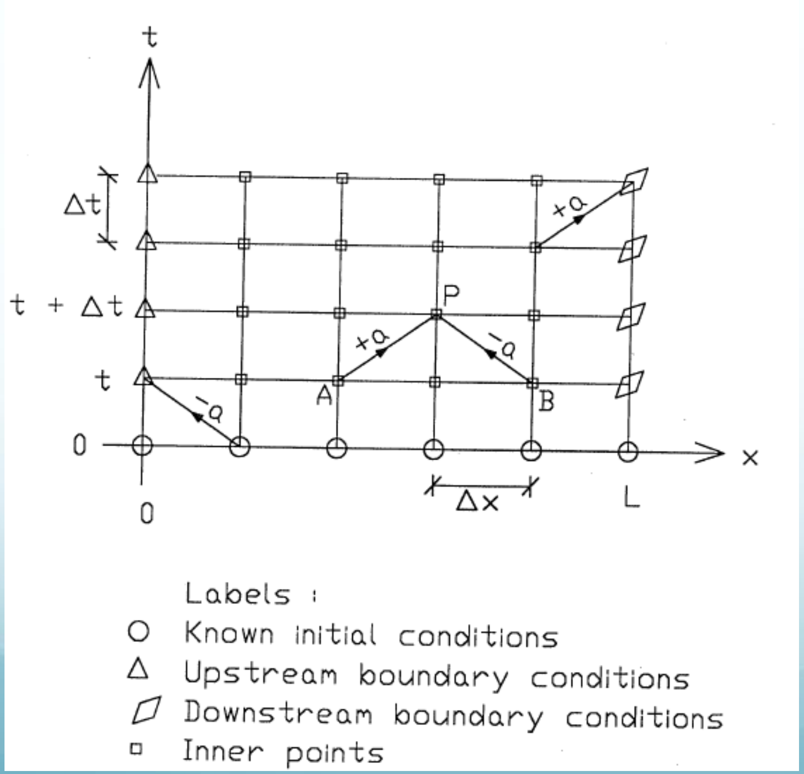
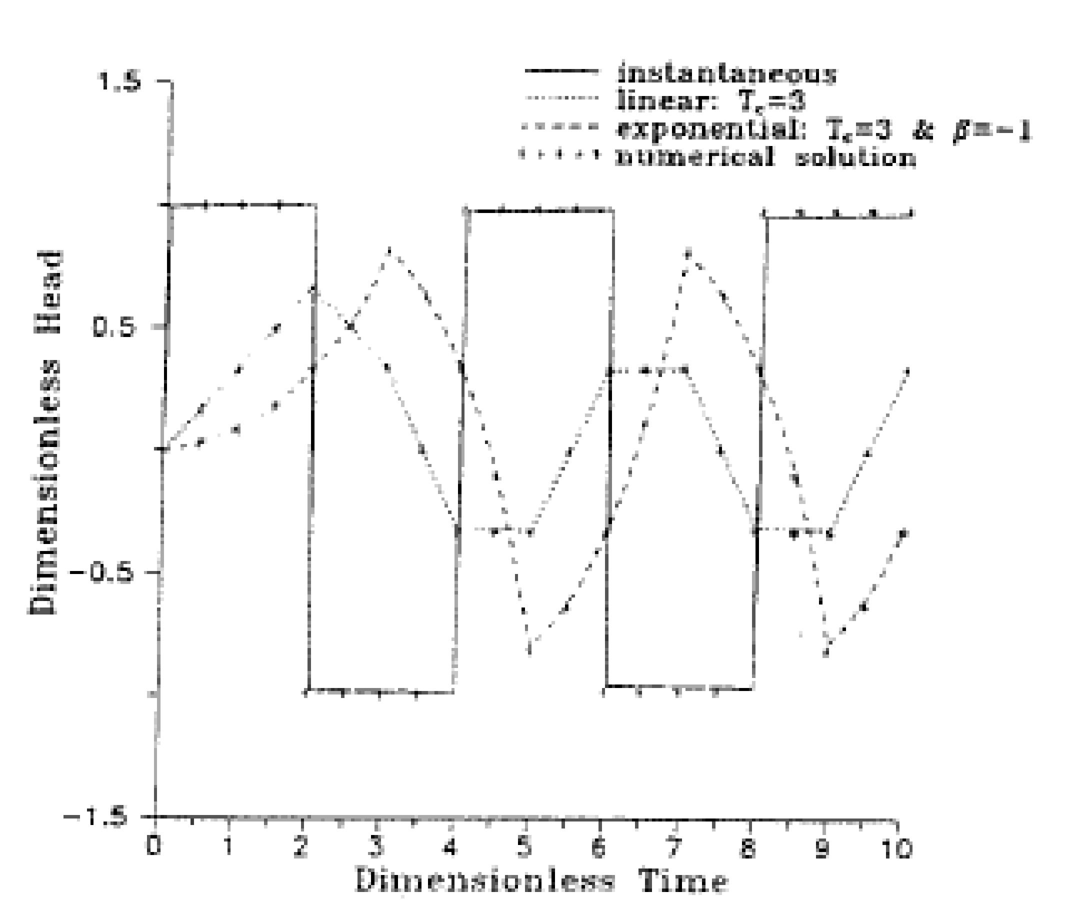


Diagram representing the solution of a waterhammer problem by the MOC

Hydraulic Transients (Surge Analysis)

The solution by the Perturbation Method (a direct, mathematical approach) matches very well with the numerical MOC

Pressure head at the valve, as obtained by the Perturbation Method, for the cases of instantaneous, linear and exponential valve closure scenarios and their comparison to the numerical solution by the MOC



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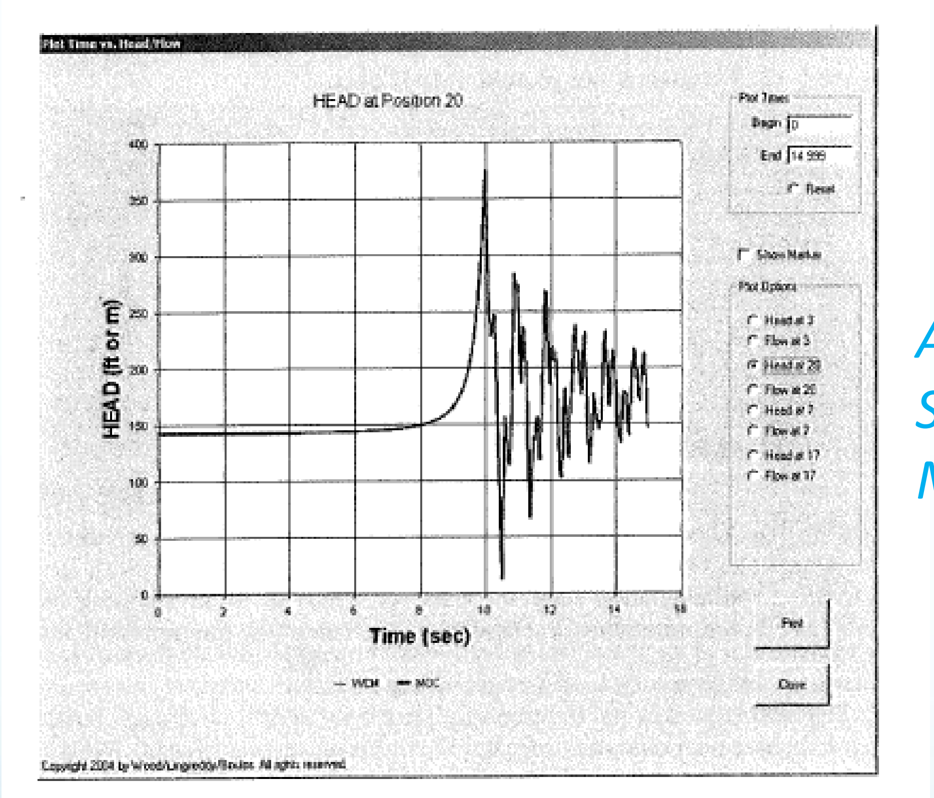
Reference # 3

Hydraulic Transients (Surge Analysis)



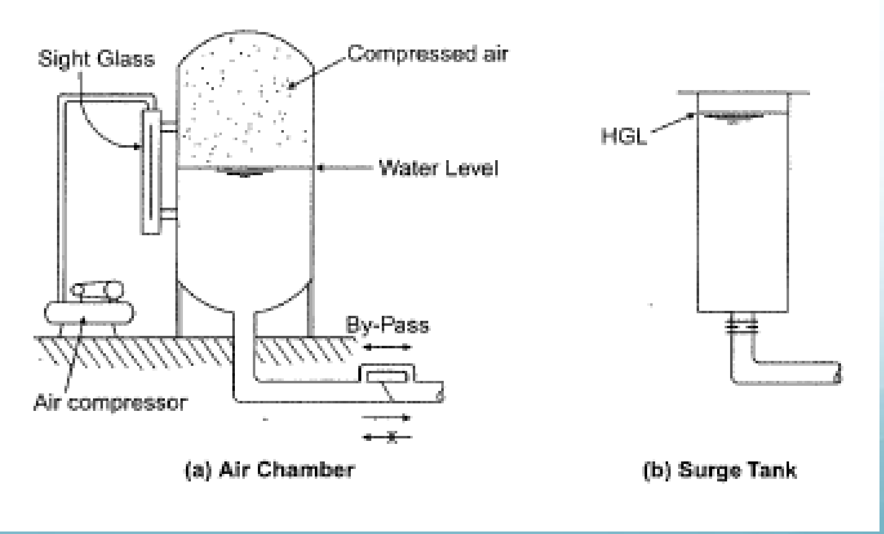
Another valve closure case: Solution by Wave Characteristic Method matches with MOC

Source:
Reference # 4

Hydraulic Transients (Surge Analysis)

- To prevent transients:
  - Slowly open and close of valves
  - Properly close of fire hydrants
  - Use pump controls to ramp pump speed up and down
  - Lower pipeline velocities
- To control maximum and/or minimum pressures: Use surge tanks; air chambers; one-way tanks; pump bypass valves; relief valves; air inlet valves

Source: Reference # 4



Hydraulic Transients Software

- Many software programs on the market. They rely on numerical methods to solve the waterhammer equations
- Innovyze (previosuly MWH Soft) has:
  - H2OSurge program (an add-on to H2ONET), and
  - InfoSurge (add-on to InfoWater, in GIS environment)

References

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2. "Advanced Water Distribution Modeling and Management." Haestad Methods, Waterbury, Connecticut, 2002.
3. H. A. Basha and B. G. Kassab, A perturbation solution to the transient pipe flow problem. Journal of Hydraulic Research, 1996, 34 (5), 633-649.
4. "Pressure Wave Analysis of Transient Flow in Pipe Distribution Systems." D. Wood, S. Lingireddy and P. Boulos, MWH Soft, Pasadena, California, 2005.

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Q&A session