CT 5550 Pumping stations and transport pipelines

Guest lecture on waterhammer

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Learning goals

- Understand basic waterhammer phenomena
- Key notions for preliminary risk assessment
  - Pipe period – characteristic time
  - Wave speed
  - Joukowsky pressure
- Mitigating measures to reduce transient pressures

Waterhammer problems in practice

Pipe burst during commissioning tests of 150 km, 1.6 m Diam. Pipe.

Control valve closed too early

Waterhammer problems in practice

Check valve closure caused
severe pipe motion

Waterhammer problems in practice

Movie from Youtube –
waterhammer on the highway

TU Delft

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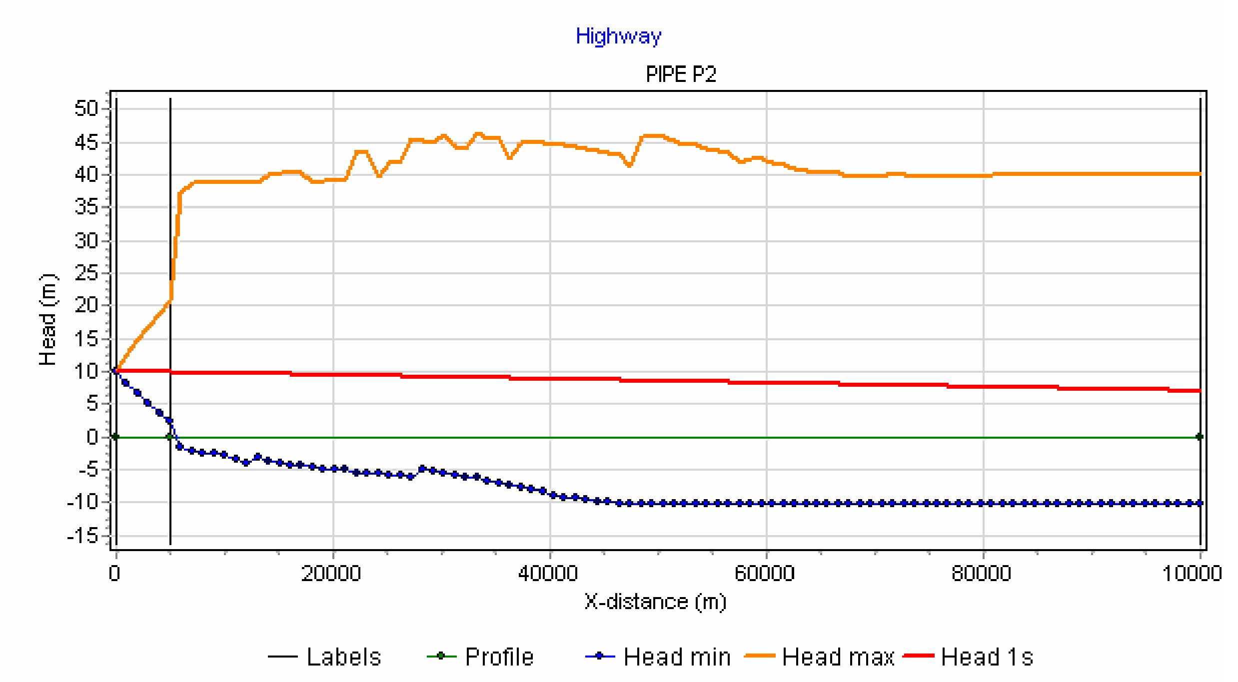
Waterhammer on the highway



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Water hammer

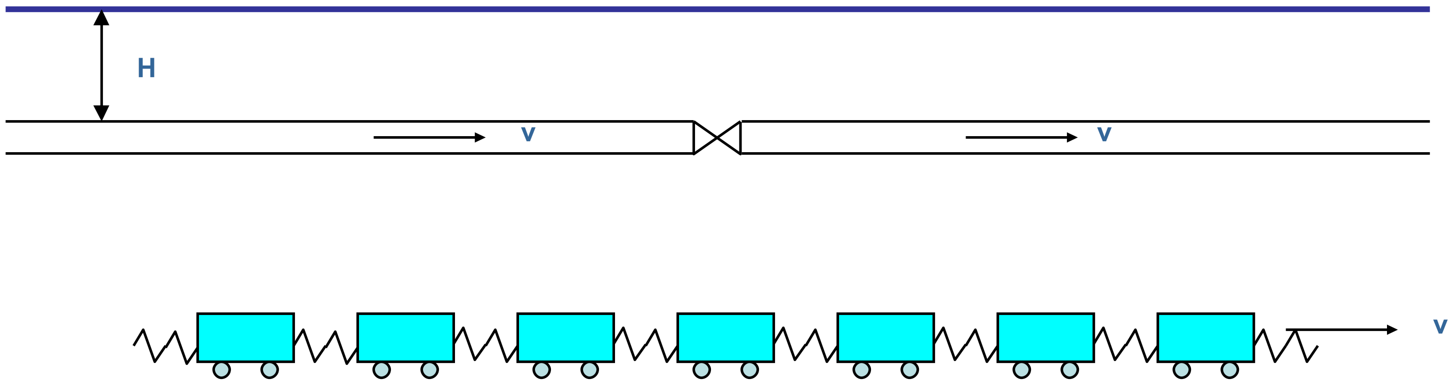
Pressurised systems

Exchange of kinetic and potential energy:

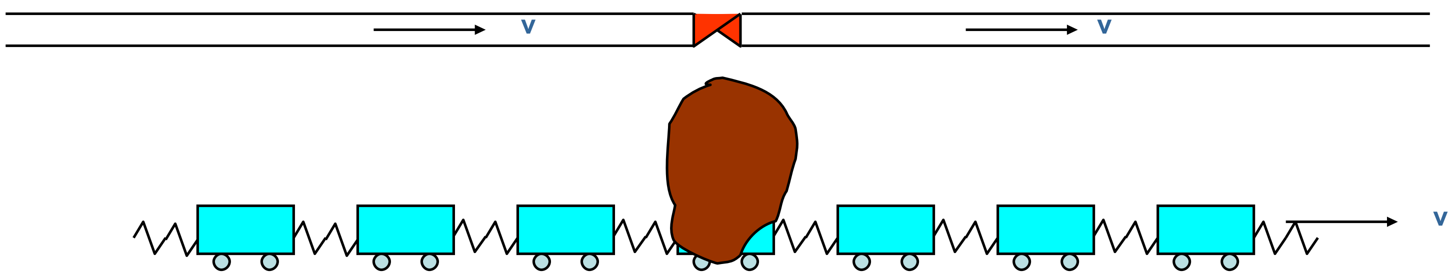
velocity changes ⇔ pressure changes

Changes are propagated through the pipeline system as high speed waves (pressure surges, water hammer)

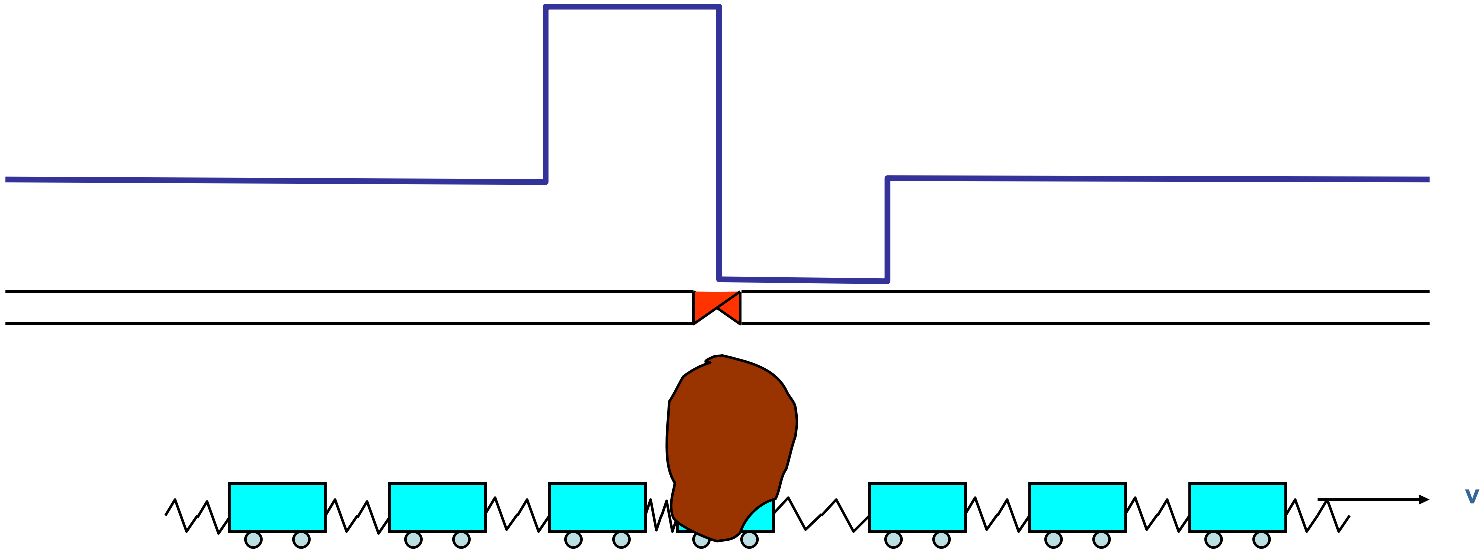
The water hammer phenomenon



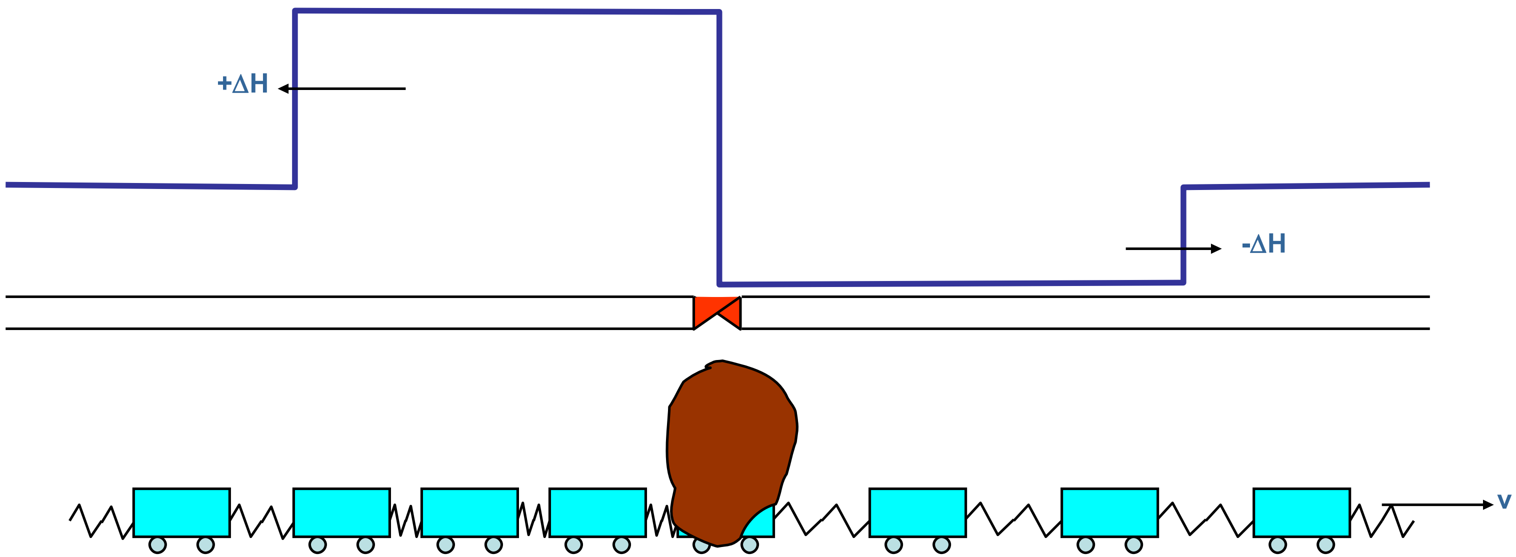
The water hammer phenomenon



The water hammer phenomenon



The water hammer phenomenon



Overpressure and negative pressure waves

Head and velocity are interrelated

Pressure waves travel trough system

Water hammer essentials

Equations

Assumptions

Wave propagation speed

characteristic time

Joukowsky pressure pulse

Water hammer equations

Momentum:

$$g \frac{\partial H}{\partial s} + \frac{\lambda}{8 \ A \ / \ P} v \left| v \right| + \frac{\partial v}{\partial t} = 0$$

Continuity:

$$\frac{\partial v}{\partial s} + \frac{g}{c^2} \frac{\partial H}{\partial t} = 0$$

with

$$c^2 = 1 \Big/ \rho \left(\frac{1}{K} + \frac{1}{A} \frac{dA}{dp} + \frac{1}{\Delta s} \frac{d \Delta s}{dp} \right)$$

in which $H(s,t)$ and $v(s,t)$

Assumptions

Momentum

- uniform velocity
- velocity head is negligible
- $v\frac{\partial v}{\partial x} << \frac{dv}{dt}$
- quasi-steady friction applies

Continuity

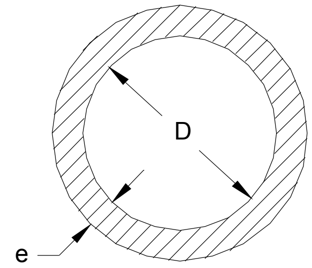
- $\frac{\partial \Delta s}{\partial s} v \quad << \quad \frac{\partial \Delta s}{\partial t}$
- $v\frac{\partial p}{\partial s} \quad << \quad \frac{\partial p}{\partial t}$

Wave speed

- axial stress in pipe is zero => $c_1 = 1$

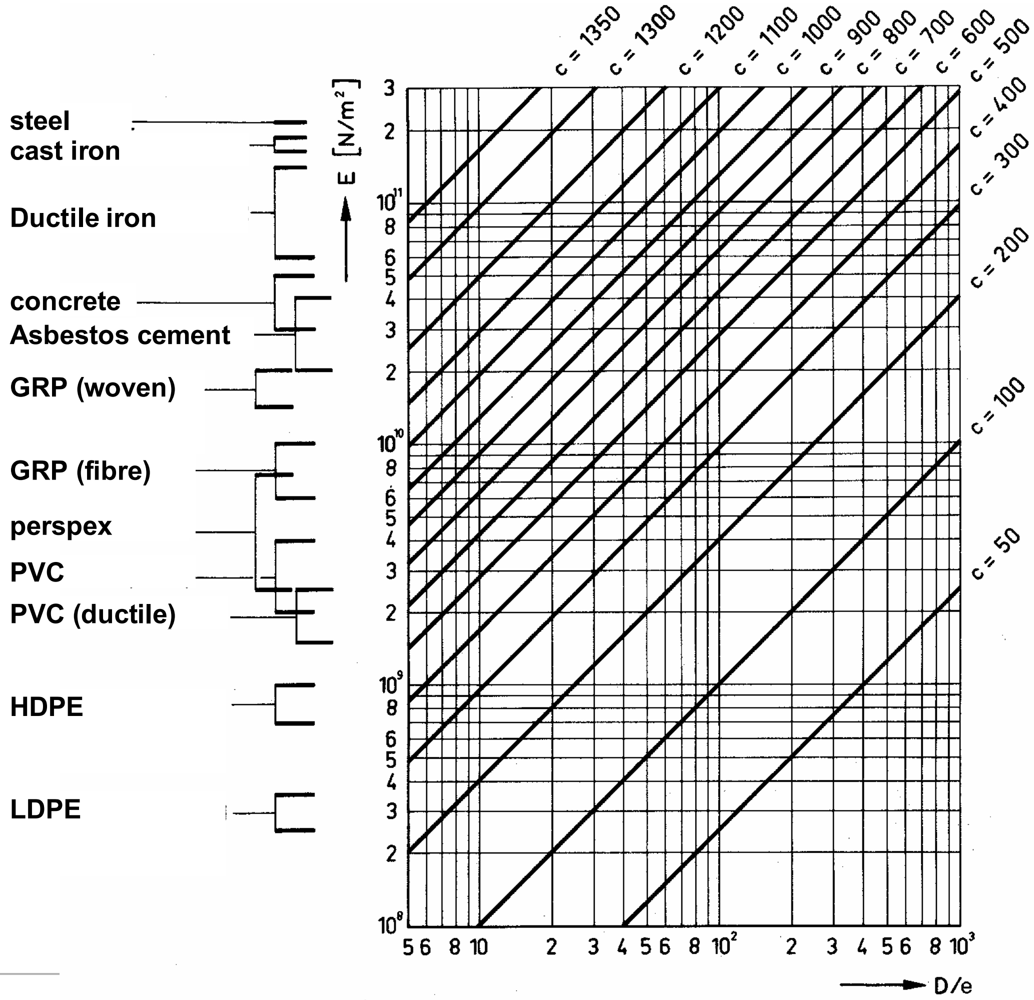
Wave propagation speed

Pipe elasticity, Young's modulus (E [Pa]), +
liquid bulk modulus (K [Pa]), +
density (ρ [kg/m^3], -
diameter - wall thickness ratio (D/e [-]), -



$$c = \frac{1}{\sqrt{\rho\left(\frac{C_1 D}{eE} + \frac{1}{K}\right)}}$$

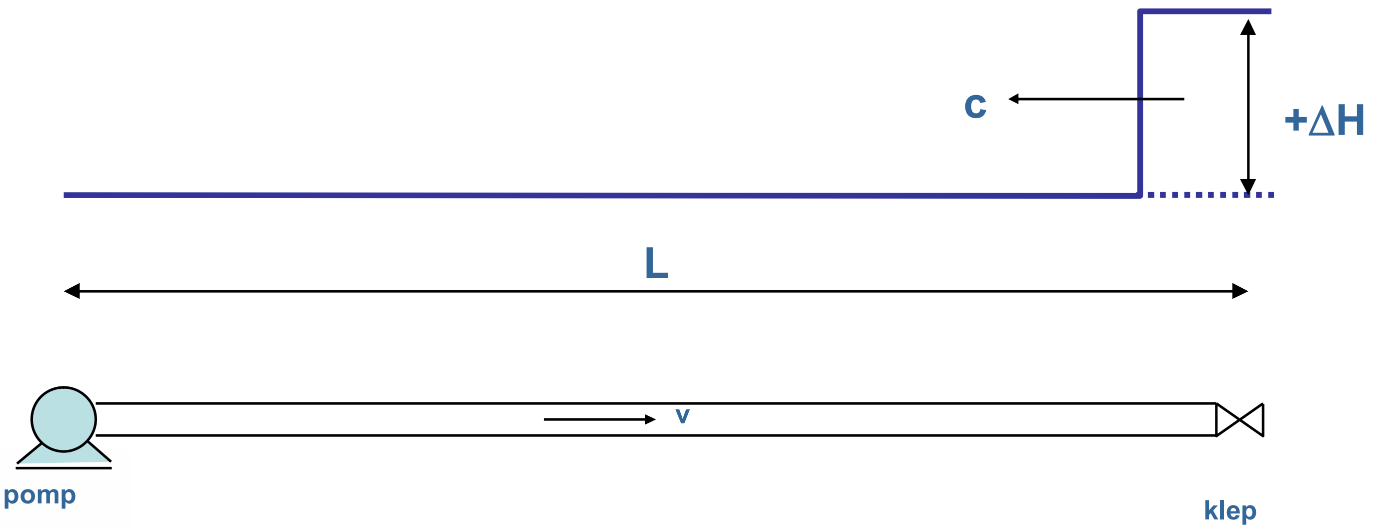
Wave propagation speed in water



Characteristic time

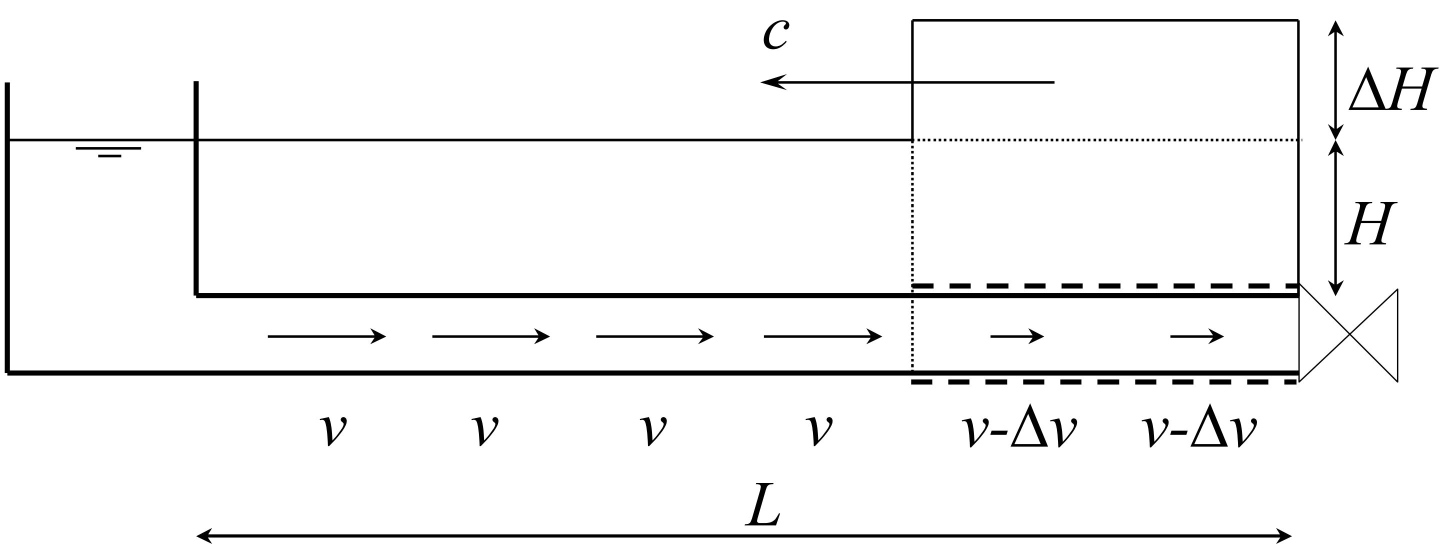
$$\mu = \frac{2L}{c}$$

Travel time of a pressure wave to return to the source of the wave



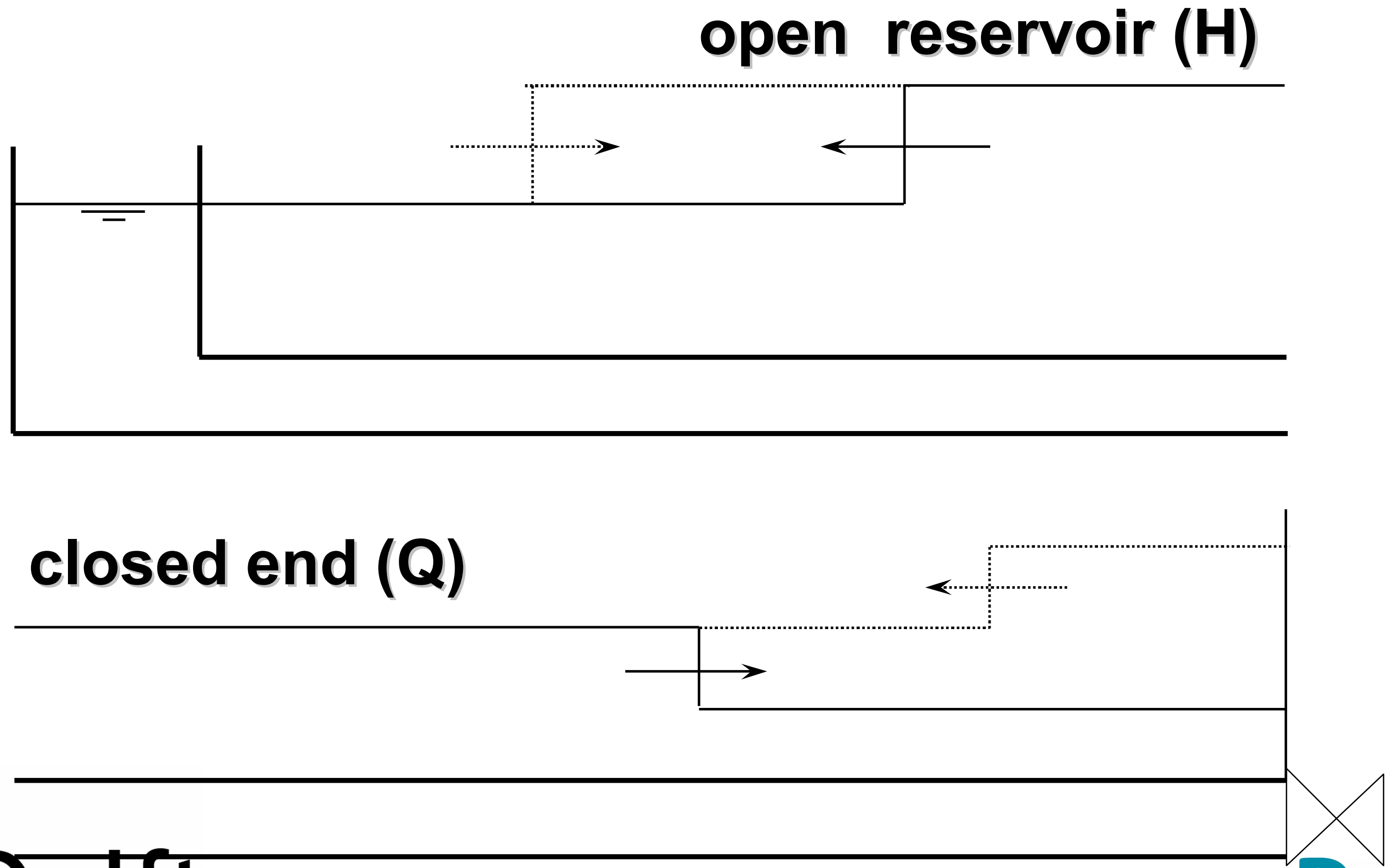
Water hammer first estimate

Joukowski: $\Delta H = \dfrac{c}{g}\Delta v$ **or:** $\Delta p = \rho\, c\, \Delta v$

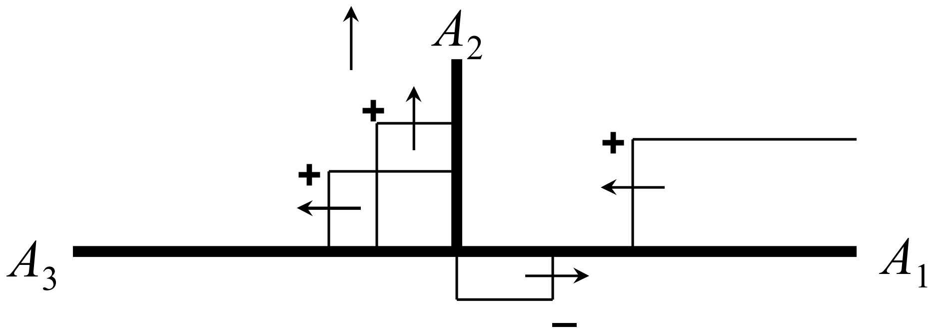


$$\mu = 2L/c$$

Reflections:



Reflections on branches or diameter changes:



reflection: $r = \dfrac{2A_1}{\sum_{i=1}^{n} A_i} - 1$

transmission: $s = r + 1$

If $A_1 = A_2 = A_3$:

$$r = \frac{2A}{3A} - 1 = -\frac{1}{3}$$

$$s = -\frac{1}{3} + 1 = \frac{2}{3}$$

Examples in WANDA

Valve closure (cases 1, 2)

Diameter change (cases 8, 9)

Mitigation of waterhammer

Prevention of unacceptable transient pressures

$$\Delta H = \frac{c \cdot \Delta v}{g}$$

Reduce “c”

Reduce rate of “Δv”

Limit local pressures

Geometrical modifications

Reduce "c"

$$c = \frac{1}{\sqrt{\rho\left(\frac{1}{K} + \frac{D}{eE}\right)}}$$

Other pipe material (E)

Increase "free gas" concentration (K) (tricky measure)

Thinner pipe wall (e), not realistic

Reduce rate of “Δv” - overview

Air vessel

Water tower

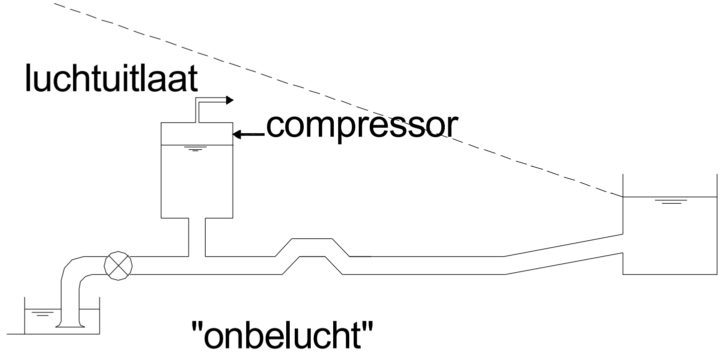
soft start/stop or frequency driven pumps

Slower valve manipulations

Flywheel on pumps

Air vessels

reduce rate of “Δv”



Pro’s

- Applicable at any pressure discharge combination

Cons (depends on installation)

- Air volume must be maintained (air dissolves) with compressor, which requires maintenance
- Air vessels in side branches are vulnerable for biological contamination

NOTE: check valve requirements

Fast closing check valve or damped check valve is required

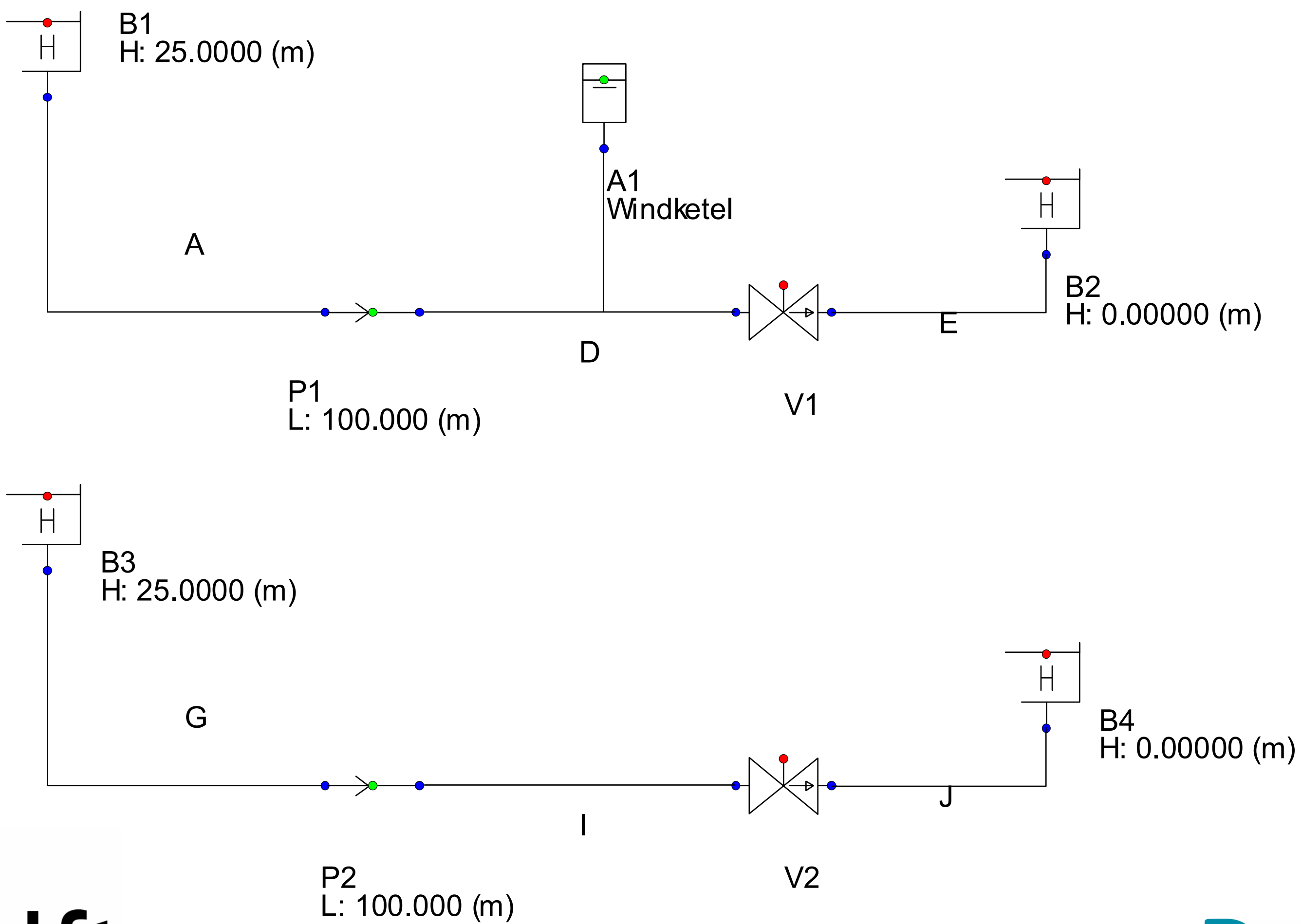
Sufficient distance between air vessel and suction level

Anchor forces

See also presentation on check valves

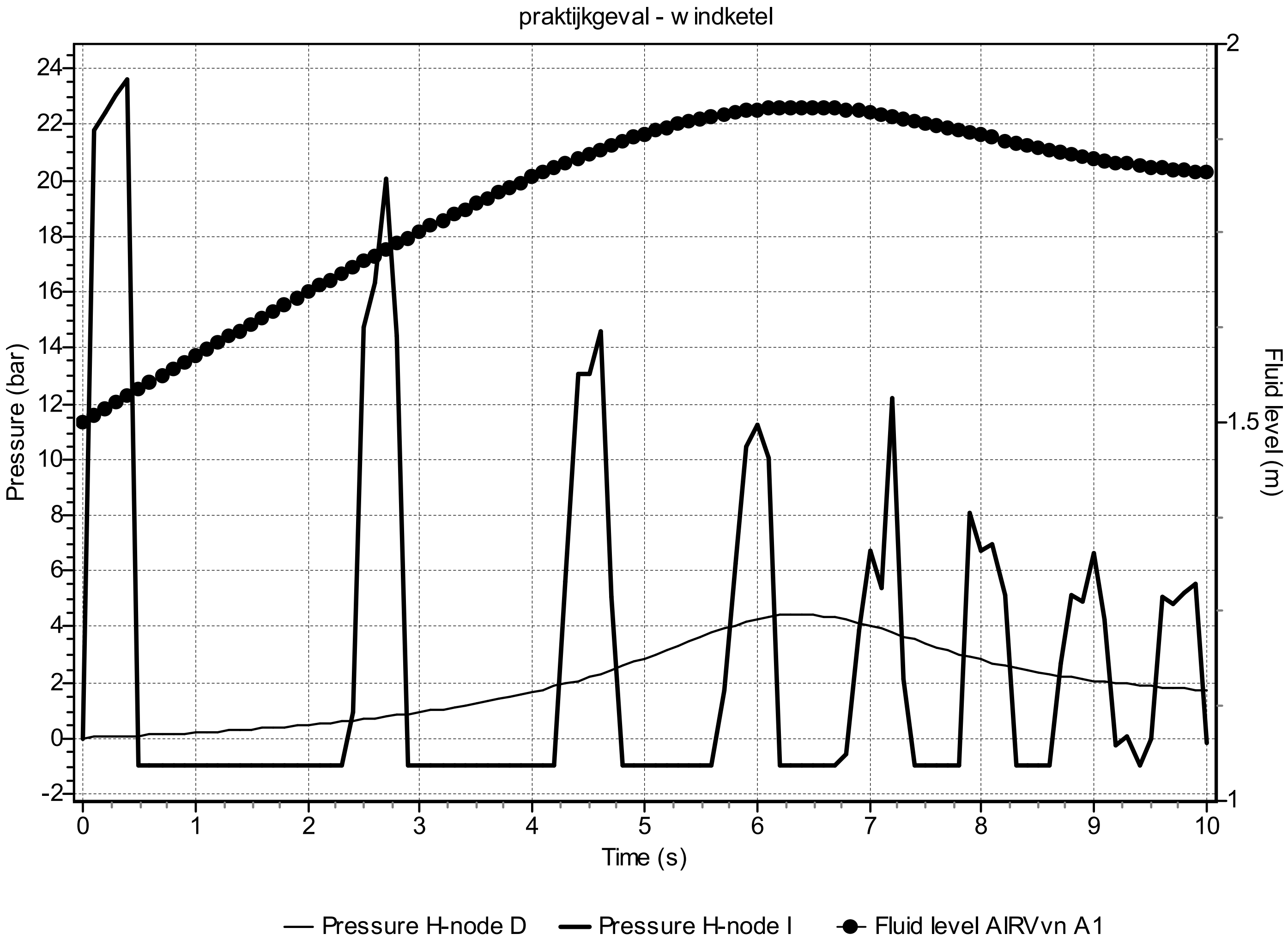
Effect air vessel (1)

reduce rate of "Δv"



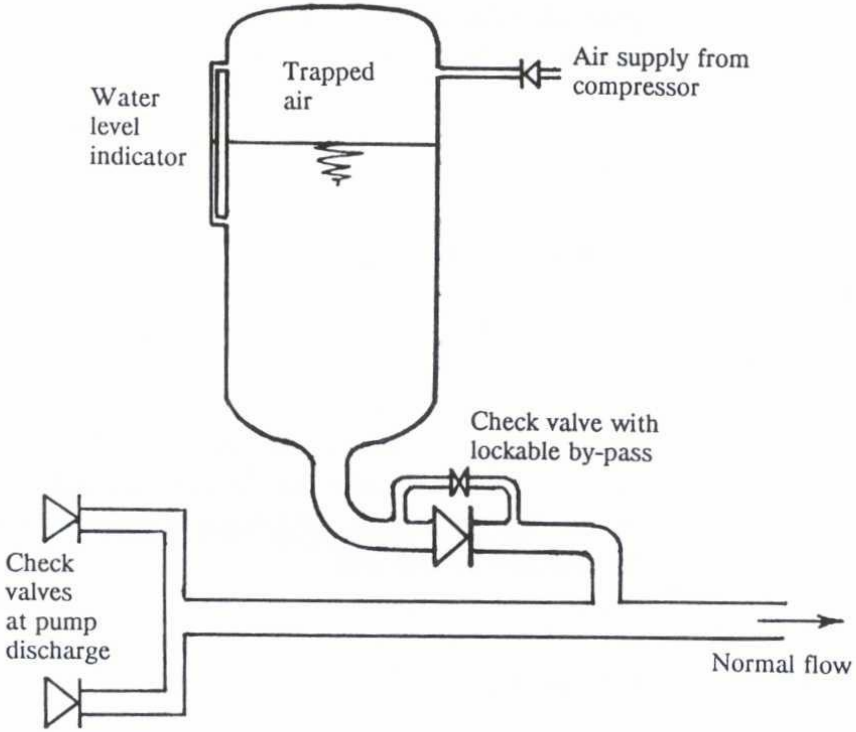
Effect air vessel (2)

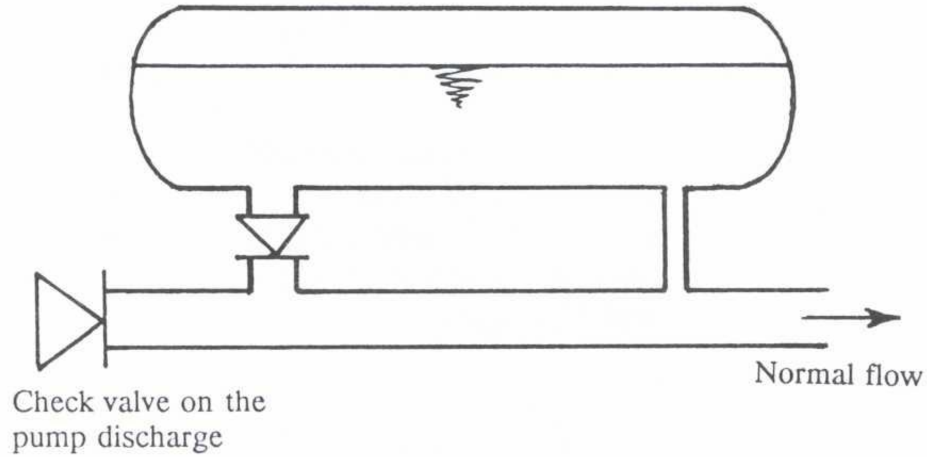
reduce rate of "Δv"

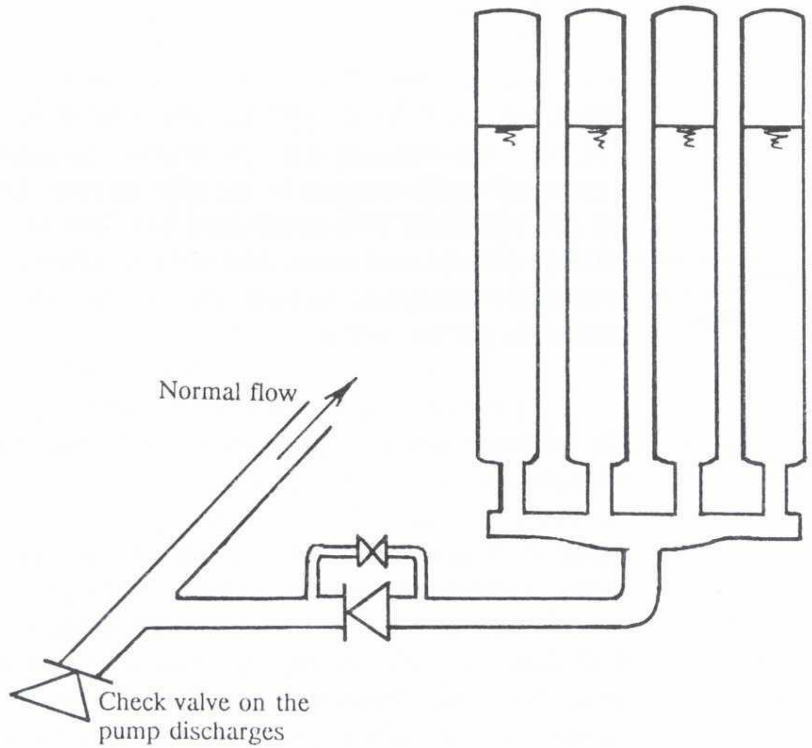


Air vessels

reduce rate of "Δv"

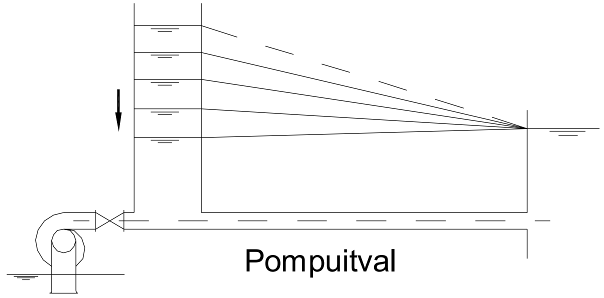


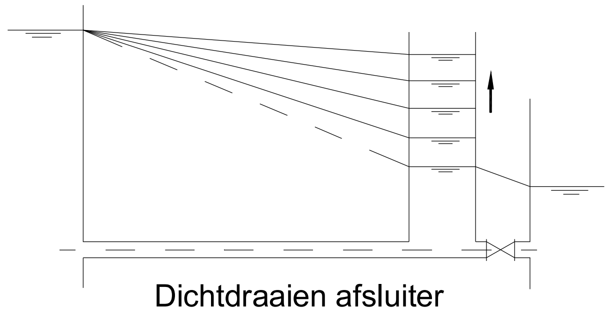




Water tower

reduce rate of "Δv"





Pro

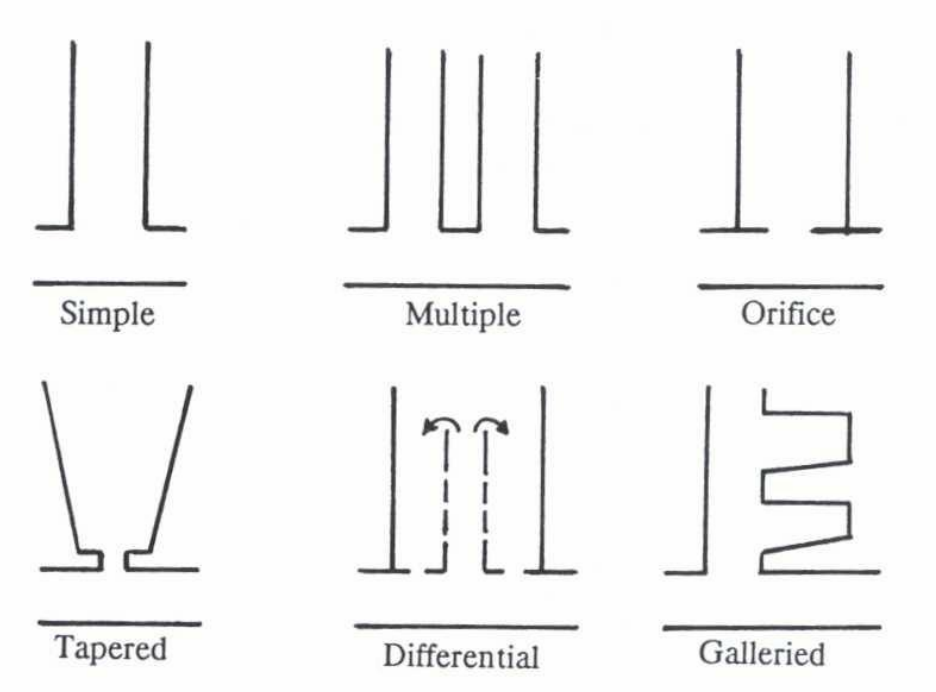
- simple and reliable (no mechanical components required)
- Relatively large storage capacity (e.g. filling up the water tower before the break of a world cup final soccer)

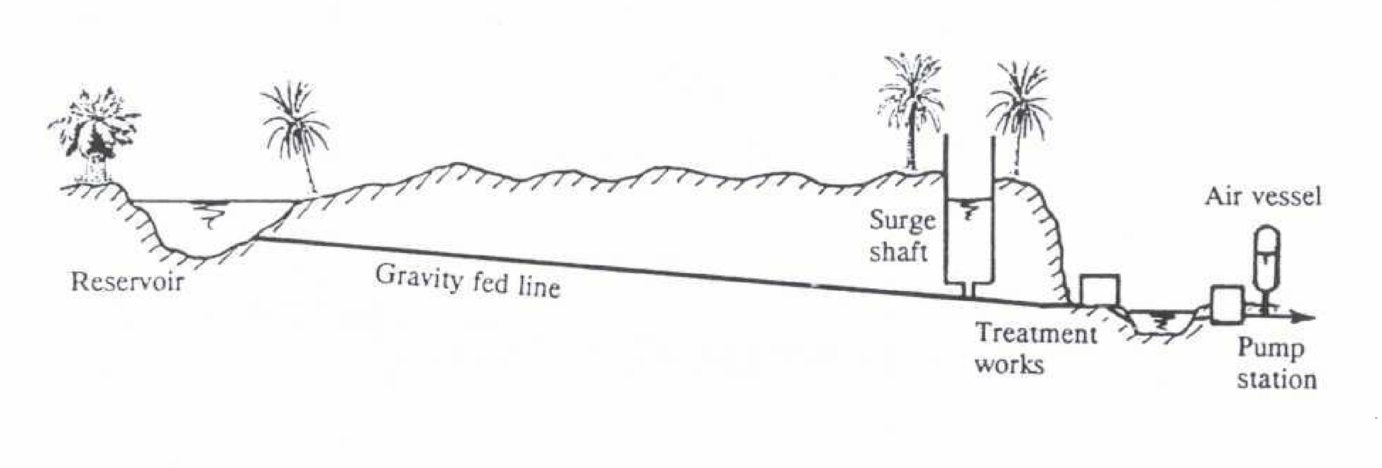
Cons

- Application is limited
  - height of tower must exceed pump shut off head
  - esthetic objections against high tower
- capacity of tower cannot be increased on an increase of the water demand
- odour problems (sewerage)
- risk for water quality deterioration
- maintenance is expensive

Water tower

reduce rate of "Δv"





Deltares

By-pass line

reduce rate of “Δv”

Pro

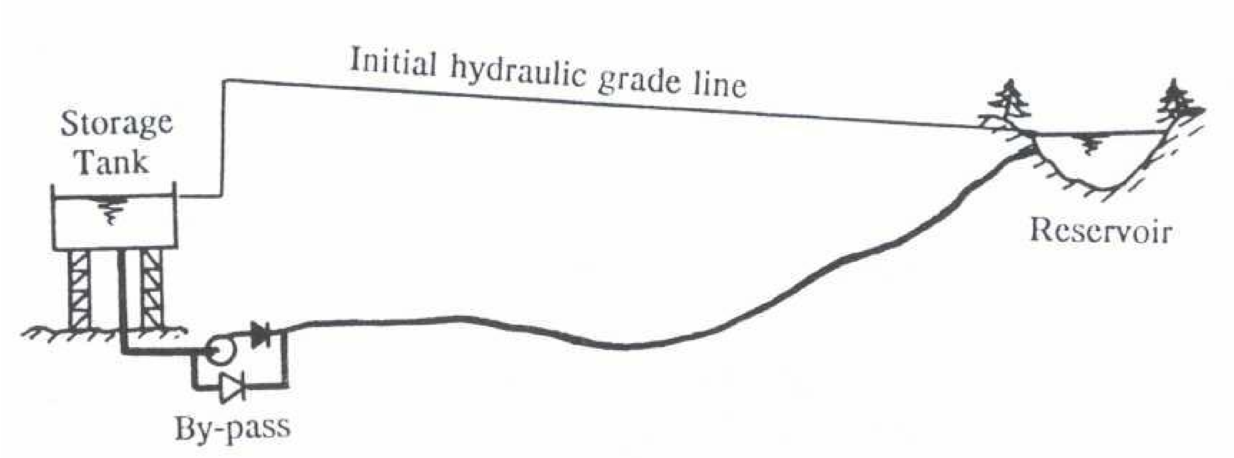
- No special requirements for pump check valves

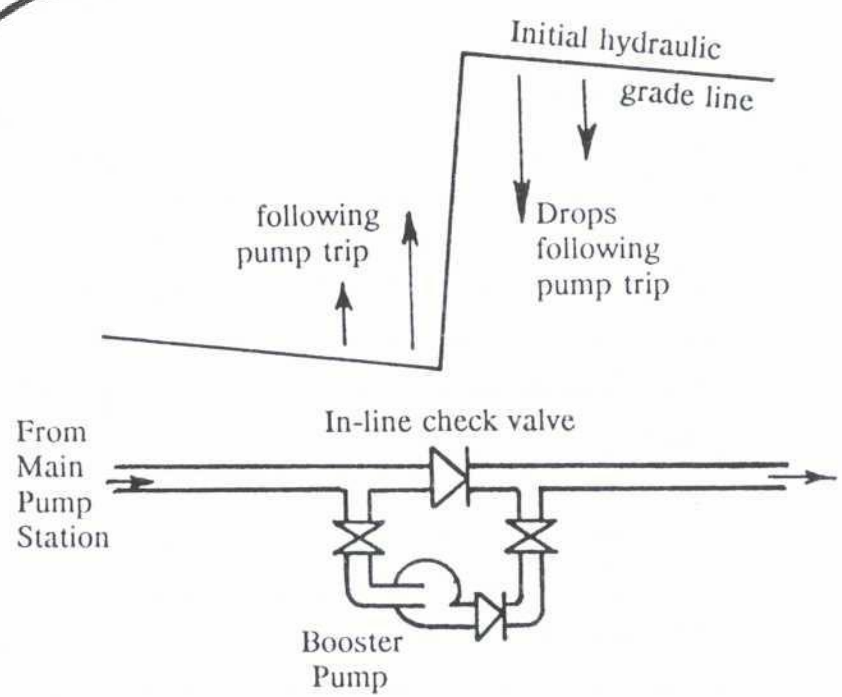
Cons

- ‘reservoir’ at sufficient level for effective by-pass
- by-pass delivery starts only after the system pressure has dropped to the suction level
- Application is limited to rel. short systems lengths

By-pass line

reduce rate of “Δv”





Soft-starters / FO pumps

reduce rate of "Δv"

Pro

- Beneficial during normal operation

Cons

- After power failure these measures provide no protection

Slower valve manipulation

reduce rate of "Δv"

Pro

- No expensive anti-surge devices required

Cons

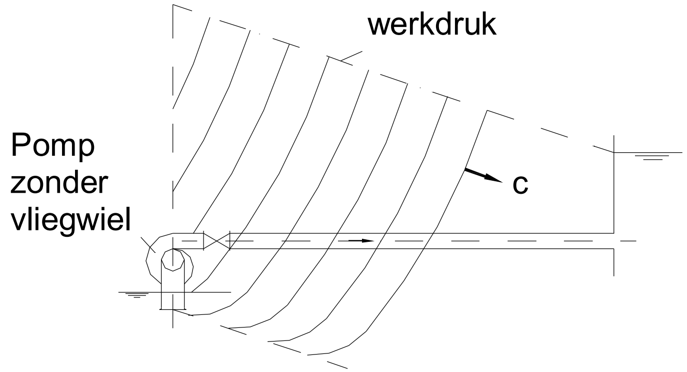
- Manipulations must be slower than several (> 5) pipe periods
- Pipeline cannot be blocked or opened very quickly

Flywheel

reduce rate of "Δv"

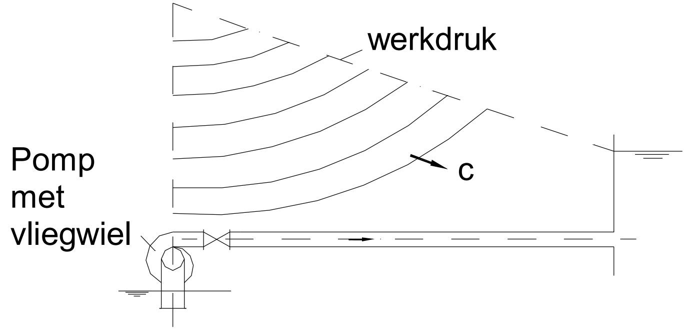
Pro

- Cheep construction
- Gradual check valve closure
- Limited maintenance



Cons

- effect is limited to several km
- Pump motor must be large enough to start the flywheel
- No effect if impeller blocks
- Pump start costs more energy. Only economically feasible for pumps that run continuously on fixed speed



Limit pressures - Overview

Local effect. Hence less effective than previous measures

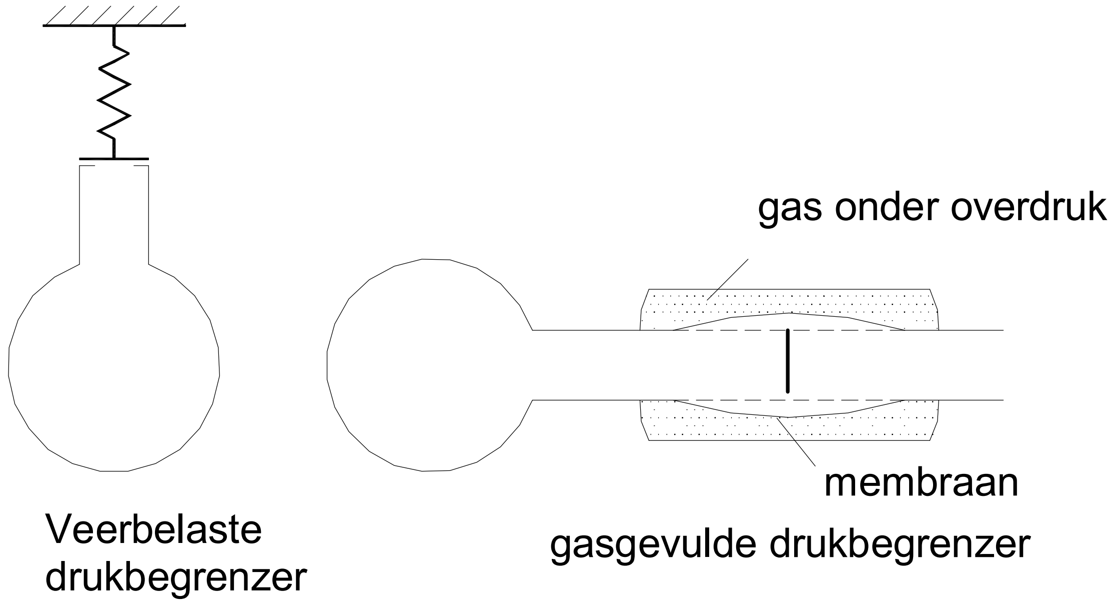
Suitable if inadmissible pressure are local as well (e.g. high points in cooling water system)

Safety valve / Pressure Relief Valve (PRV)

Air valve / vent / vacuum breaker

Pressure relief valve

Limit pressures



Pro

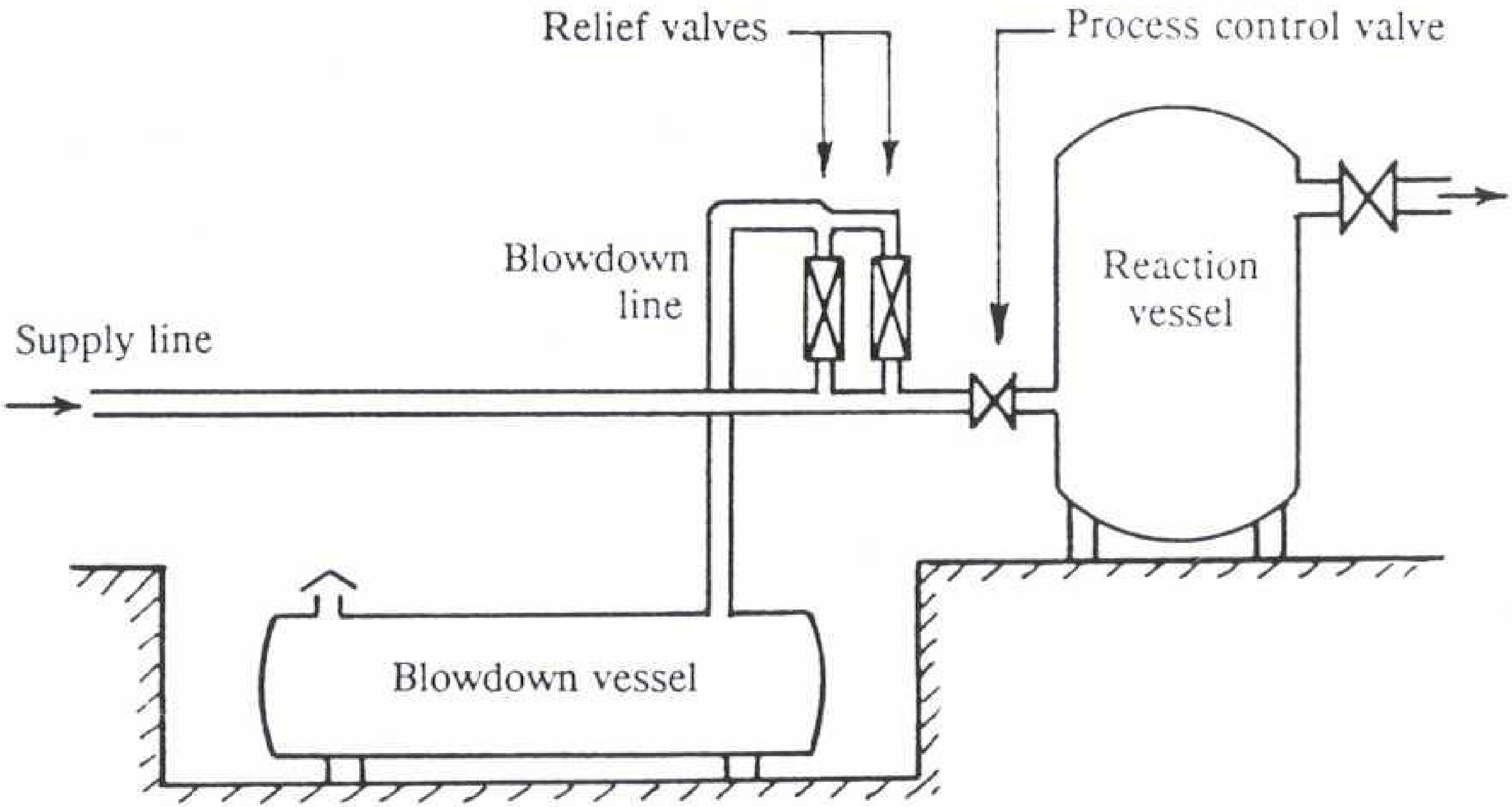
- Pressure is limited locally

Cons

- Periodic maintenance required
- Relief lines required to dump ejected liquids
- Risk of hammering PRV, if PRV capacity is not well sized

Pressure relief valve

Limit pressures



Damper/accumulator

Gas pocket separated by a membrane

Pro

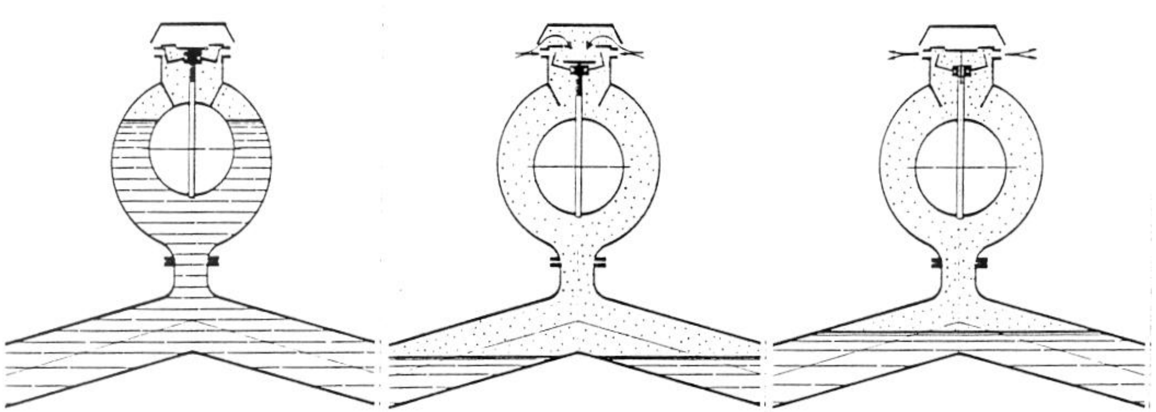
- No direct contact with liquid
- Gas pocket does not dissolve
- Set pressure provides flexibility

Cons

- Volume limited
- Activated only after set pressure is exceeded

Air valve

Limit pressures

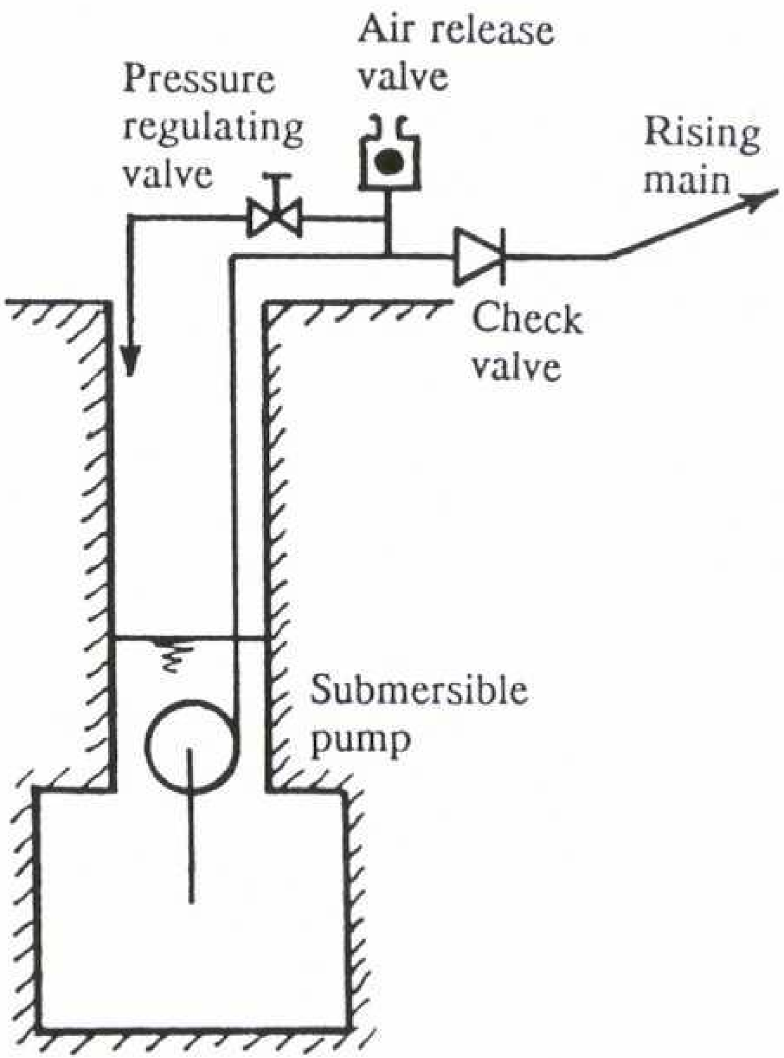


Pro

- Limit pressure locally

Cons

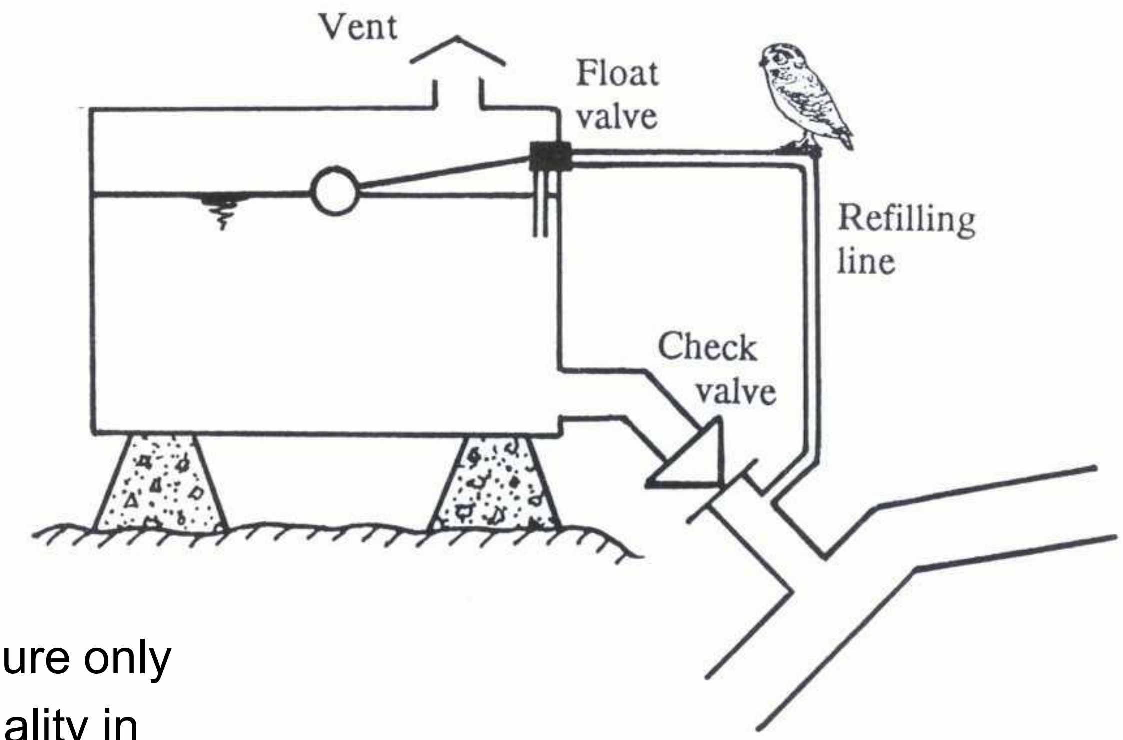
- All incoming air should be released afterwards
- Correct installation and location are paramount for correct operation
- Vulnerable for fouling, blocking. Hence periodic maintenance required


Air release
valve
Pressure
regulating
valve
Rising
main
Check
valve
Submersible
pump

Feed tank

Pro

- Simple construction
- Self refilling



Cons

- Limits negative pressure only
- Risk of poor water quality in feed tank

Geometrical modifications

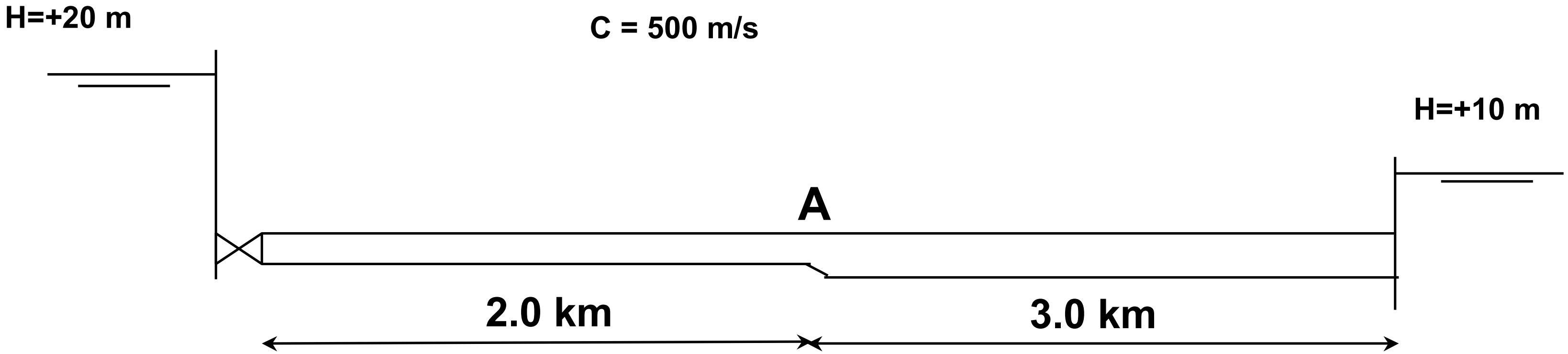
Increase pipe diameter

Reduce average system pressure

- Minimise number of bends, etc.
- Reduce downstream boundary head

Exercise 8

Fast valve opening



L = 1000 m

D_1 = 300 mm; D_2 = 424 mm

frictionless pipe, conveying water

Draw time graphs of head at 0 km, 2.5 km and 5 km (first 22 s)

Exercise 9

Derive Joukowsky's Law from Newton's second law of motion. You may assume the wave speed equals c.