ENVE 301
Environmental Engineering Unit Operations

Lecture 15
Filtration - II

SPRING 2014

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Flow Control in Filtration

- Filter flow control is required to
  - make sure that all the filters share the total plant flow in an equal manner.
  - be able to deal with sudden changes in flow may occur
- Both of these reasons may change the filtrate quality drastically.

Rate Control Systems for Gravity Filters

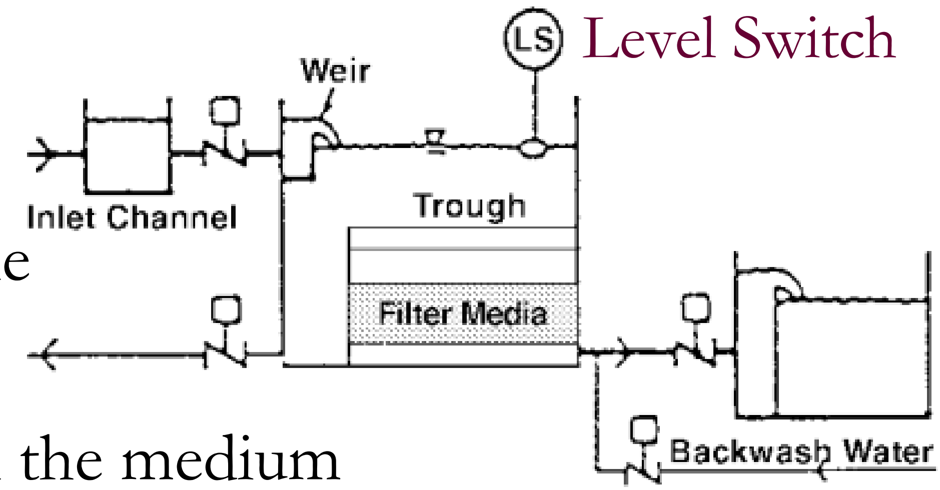
- Filter control systems can be dvided into two groups
  - Mechanical control systems
  - Nonmechanical control systems (hydraulics)
- Rate control systems can also be divided as
  - Constant rate filtration (Equal rate filtration)
    - True constant rate filtration can occur only if the total plant flow is constant-equal-rate filtration is a better way to describe these systems.
  - Declining rate filtration

Rate Control Systems for Gravity Filters

- Equal (Constant) rate filtration
  - Variable-level/head influent flow splitting
  - Proportional-level/head influent flow splitting
  - Proportional-level/head equal rate
- Declining-rate filtration
  - Variable-level/head declining rate
  - Proportional level/head declining rate

Constant Rate Filtration
Variable Level Influent Flow Splitting

- Equal-rate, non-mechanical system
- Each filter receives the equal portion of the flow
- Flow is splitted via inlet weir box or orifice on each filter inlet above the maximum water level of the filter
- Effluent is discharged to the clear well at a level above the surface of the filter medium
- As solids accumulate in the medium, the water level rises in the filter box to provide the head required to drive the flow through the medium



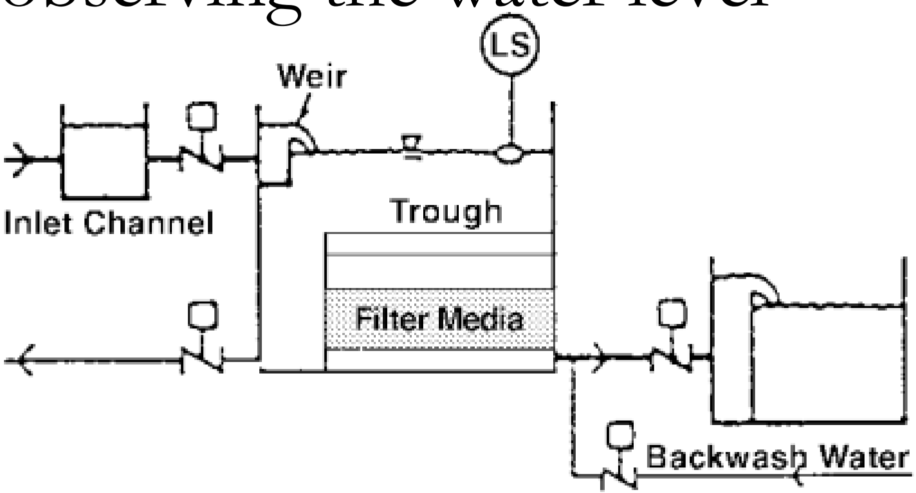
Variable Level Influent Flow Splitting

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Constant Rate Filtration
Variable Level Influent Flow Splitting

- The water level in each filter box is different and depends on the extent to which filter medium is clogged
- When water level in the filter box rises to certain level, filter should be backwashed
- Simplest system – instrumention is not required
- Head loss is evident by observing the water level

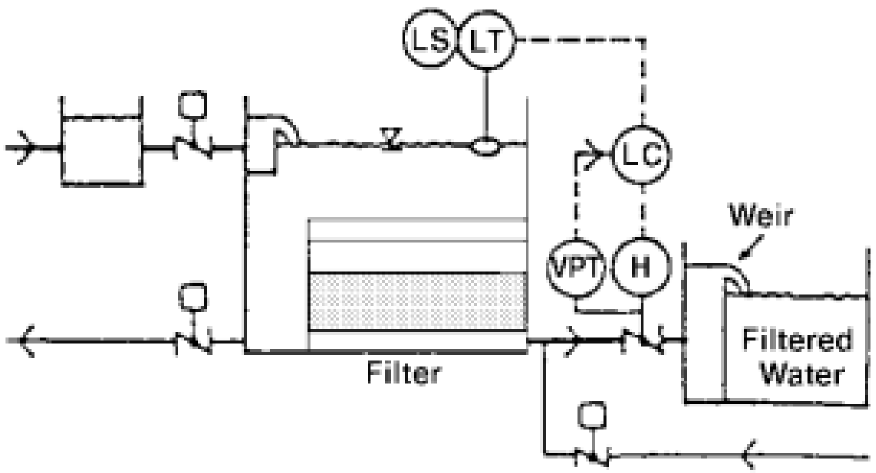
Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999



Variable Level Influent Flow Splitting

Constant Rate Filtration
Proportional Level Influent Flow Splitting

- It is an equal rate mechanical system
- Flow control occurs by inlet flow splitting as in the prior system
- Each filter requires a level transmitter, a level controller, a modulating valve, and head-loss instrument

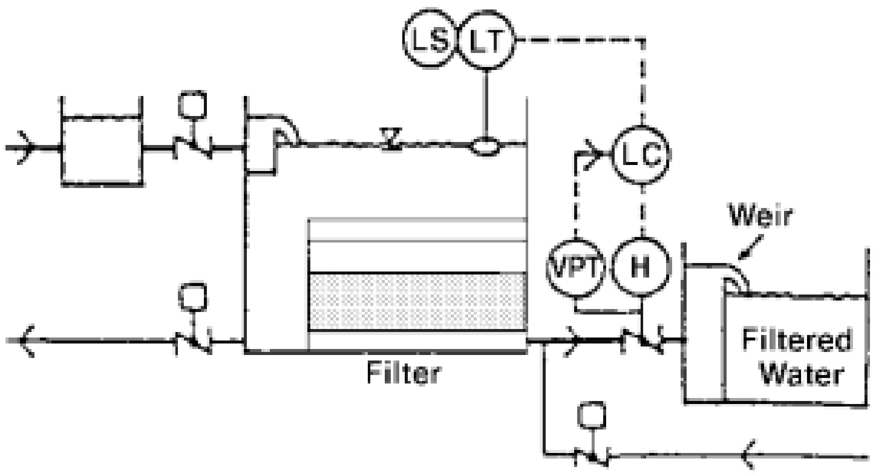


Proportional Level Influent Flow Splitting

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Constant Rate Filtration
Proportional Level Influent Flow Splitting

- Modulating valve controls the water level in each filter
- Effluent modulating valves open proportional to water level in the associate filter
- Head loss is monitored from back wash initiation
- Flow measurement in individual filters is not used.

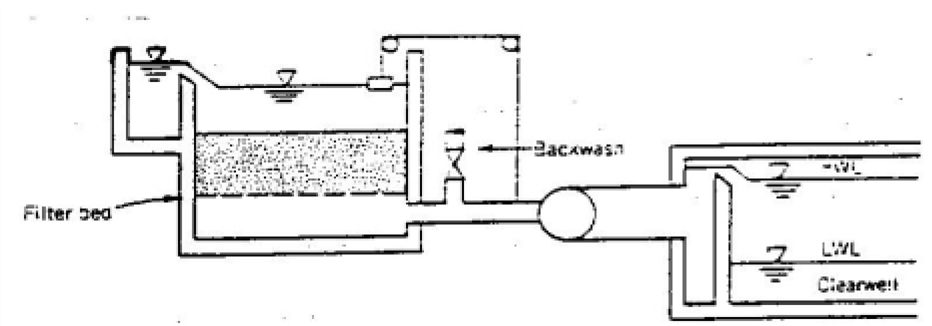


Proportional Level Influent Flow Splitting

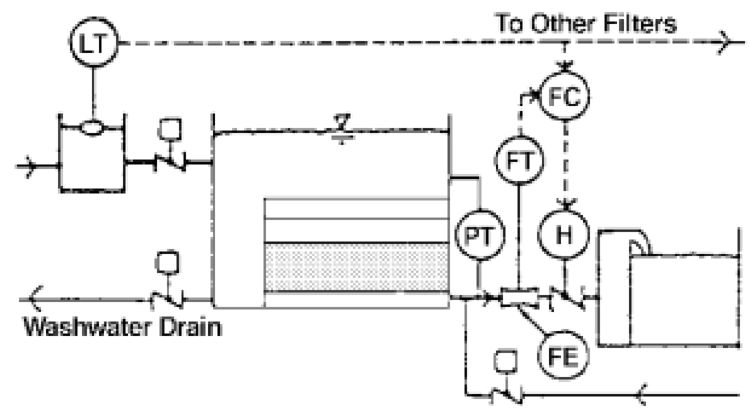
Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Constant Rate Filtration
Proportional Level, Equal Rate

- Most common equal rate mechanical control system
- It splits the total flow equally among the operating filters
- Each filter requires a flow meter, flow controller, a modulating control valve, and a head-loss instrument



Constant Level Filtration
(Influent control, level sensor & modulating valve)



Proportional Level Equal Rate

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Constant Rate Filtration
Proportional Level, Equal Rate

- Flow rate through each filter will be equal
- Flow controllers adjust the modulating valves to match the flowrates

Declining Rate Filtration
Variable-Level Declining Rate

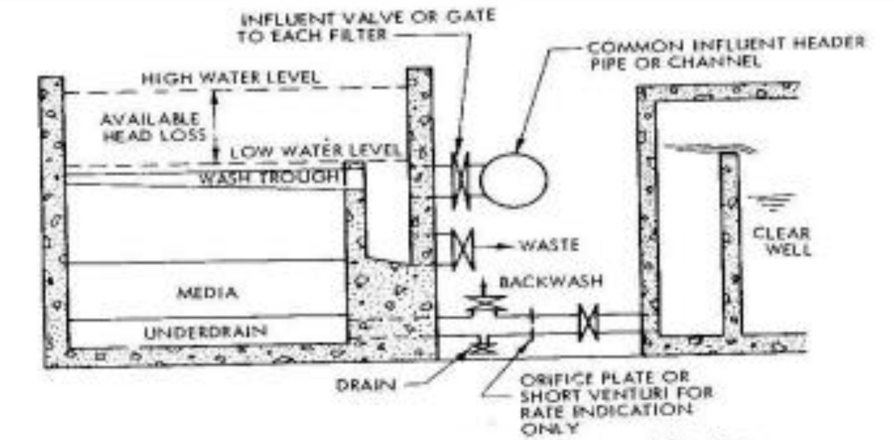
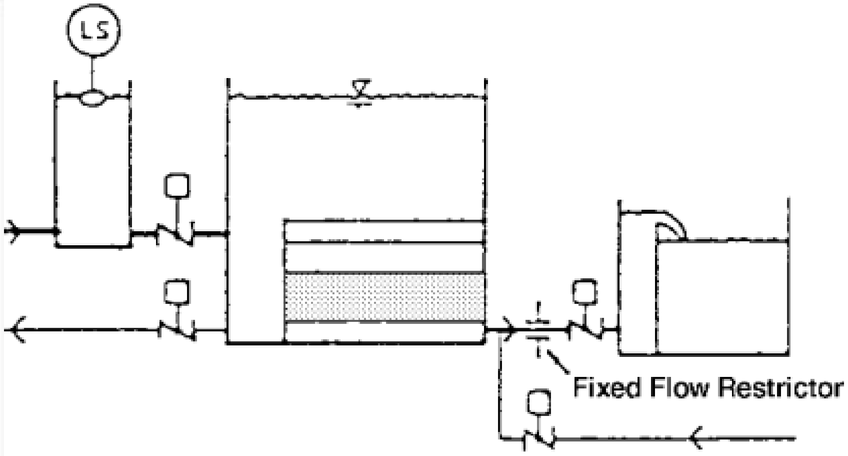


Figure 4-4 Gravity filter arranged for variable declining rate of filtration.



Variable Level Declining Rate

- Non-mechanical
- Flow enters the filter below normal water level
- Each filter discharges to the clearwell above the level of filter medium
- All filters are connected by a common inlet channel

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Declining Rate Filtration
Variable-Level Declining Rate

- Common inlet channel operate at approximately the same water level and thus have the same total headloss available to the effluent weir level at any instant
- Cleanest filter → Operate at the highest filtration rate
- Dirtiest filter → Operate at the lowest filtration rate

Declining Rate Filtration
Variable-Level Declining Rate

- As solids accumulate, water level rises in all connected filters
- A fixed flow restrictor (orifice plate or a fixed position valve) is provided for each filter to limit the starting rate on a clean filter

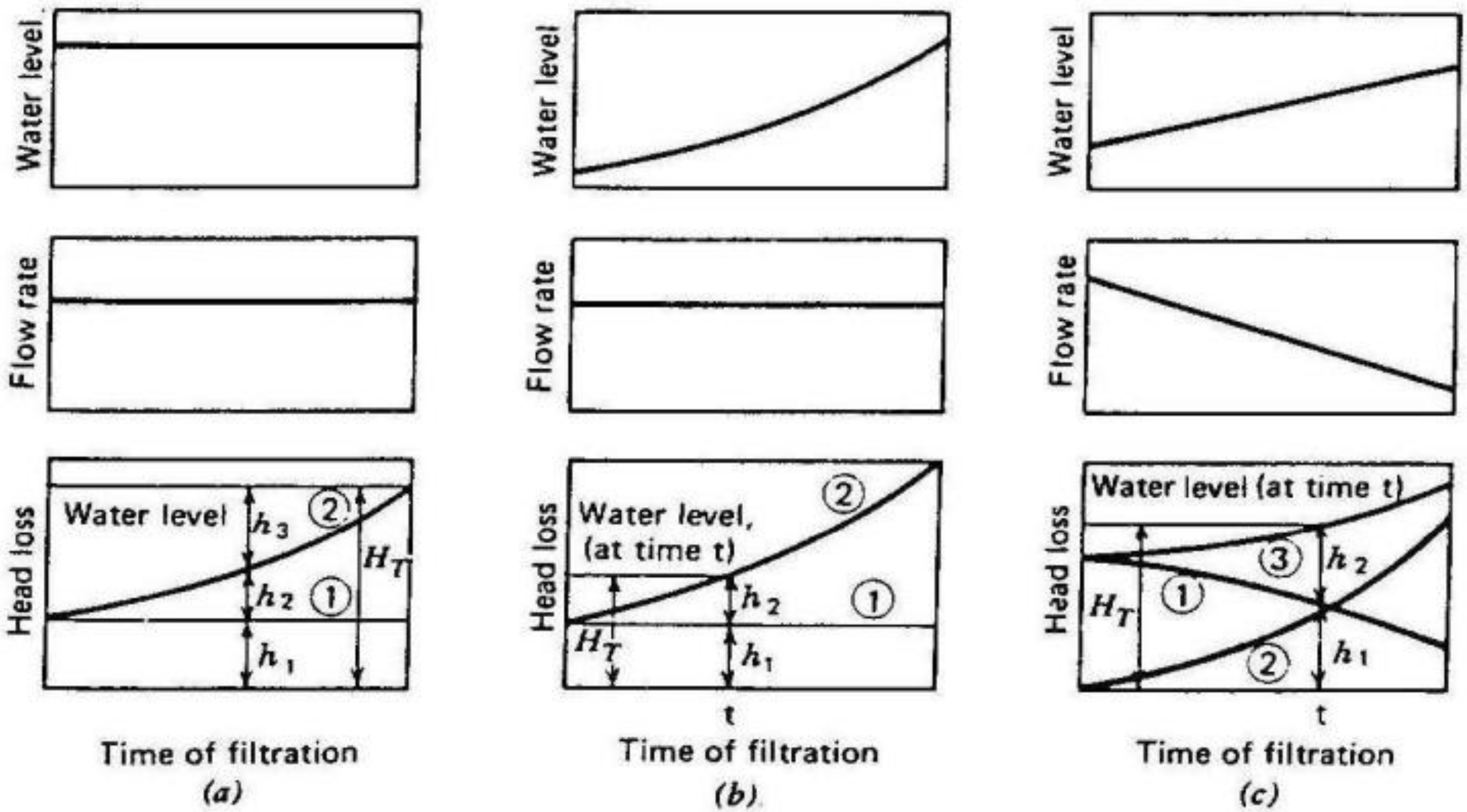
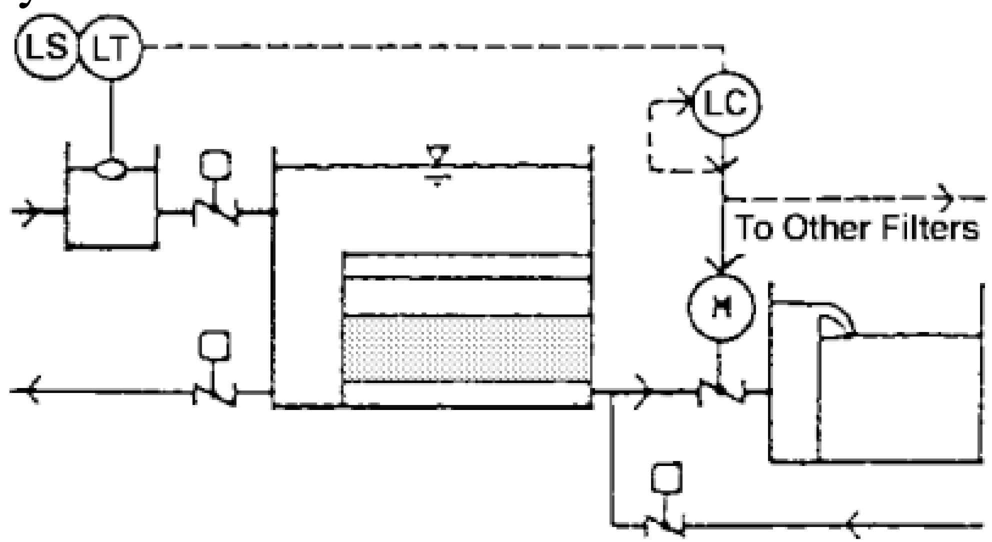


Figure 8.16. Head losses, flow rates, and water levels in filter control systems: (a) constant-rate filtration with rate controllers; (b) constant-rate filtration with increasing water level; (c) declining-rate filtration. One, h_1 = head loss due to clean bed, underdrains, valves, pipes and fittings; two, h_2 = head loss due to clogging of the filter bed; three, H_T = total head loss; h_3 = excess head (expended in rate controller or valve).

Declining Rate Filtration
Proportional-Level Declining Rate

- It is similar to variable-level declining rate filter
- However, modulating valve in the effluent of each filter is controlled by the water level in the inlet channel



Proportional Level Declining Rate

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Filtration Hydraulics

Hydralics in the desing of a filtration system should include

- Headloss through a clean filter bed
- Headloss resulting from the accumulation of particles in the bed
- The fluidization depth of the bed during backwashing
- Headloss in the expanding filter bed

Clean Filter Bed - Headloss

- Headloss occurs when clean water flows through a clean filter medium
- Flow in filter having
  - Grains size of 0.5 mm to 1.0 mm
  - Ordinary filtration rates of 4.9 m/h to 12.2 m/h
- Would be in a laminar range of flow
- Flow in laminar flow can be describe by Kozeny equation
- Equations calculating the headloss thhrough clean filter bed are derived from Darcy-Weisbach equation for flow in a close conduit.

Clean Filter Bed - Headloss

- If the flow is **laminar** (Re<6, based on superficial velocity)
  - Carmen and Kozeny
  - Fair-Hatch
  - Rose equatşıbs are used for sand filters
- **Transitional/turbulent** ranges for larger filter medias
  - Ergun equations is used

Clean Filter Bed - Headloss

$$Re = \frac{\phi . d . \rho . v}{\mu}$$

- ϕ: Shape factor
- μ: Dynamic viscosity
- ρ: density
- D: grain diameter
- v: Filtration velocity

TABLE 11-2
Formulas used to compute the clean-water headloss through a granular porous medium

Equation	Definition of terms
Carmen-Kozeny (Carmen, 1937)	d = grain size diameter, m
$h_L = \frac{f}{\phi}\frac{1-\varepsilon}{\varepsilon^3}\frac{L}{d}\frac{v_a^2}{g}$	f = friction factor
$h_L = \frac{1}{\phi}\frac{1-\varepsilon}{\varepsilon^3}\frac{L v_a^2}{g}\sum f \frac{p}{d_g}$	g = acceleration due to gravity, 9.81 m/s^2
$f = 150\frac{1-\varepsilon}{\mathbf{R}} + 1.75$	h_L = headloss, m
$\mathbf{R} = \frac{\phi d v_a \rho}{\mu}$	k = filtration constant, 5 based on sieve openings, 6 based on size of separation
Fair-Hatch (Fair and Hatch, 1933)	k_v = headloss coefficient due to viscous forces, dimensionless
$h_L = k v S^2 \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{L}{d^2}\frac{v_a}{g}$	k_i = headloss coefficient due to inertial forces, dimensionless
$h_L = k v \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{L v_a}{g}\left(\frac{6}{\phi}\right)^2 \sum \frac{p}{d_g^2}$	L = depth of filter bed or layer, m
Ergun (1952a)	$\mathbf{R}$ = Reynolds number
$h_L = k_v \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu L v_a}{\rho g d^2} + k_i \frac{1-\varepsilon}{\varepsilon^3}\frac{L v_a^2}{g d}$	p = fraction of particles (based on mass) within adjacent sieve sizes
	S = shape factor (varies between 6.0 for spherical particles and 8.5 for crushed materials)
	v_a = superficial (approach) filtration velocity, m/s
	ε = porosity
	μ = viscosity, Pa · s
	ν = kinematic viscosity, m^2/s
	ρ = density of water, kg/m^3
	ϕ = particle shape factor (1.0 for spheres, 0.82 for rounded sand, 0.75 for average sand, 0.73 for crushed coal and angular sand)

Ref: Davis M.L. *Water and Wastewater Treatment: Design Principles and Practice*. 2010. McGrawHill

Carmen-Kozeny Equation

Carmen-Kozeny (Carmen, 1937)

$$h_L = \frac{f}{\phi}\frac{1-\varepsilon}{\varepsilon^3}\frac{L}{d}\frac{v_a^2}{g}$$

$$f = 150\frac{1-\varepsilon}{\mathbf{R}} + 1.75$$

$$\mathbf{R} = \frac{\phi d v_a \rho}{\mu}$$

$$h_L = \frac{150\mu}{\phi^2 d^2 g}\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{V_a}{g}L$$

First term of the Ergun eqn

Ref: Davis M.L. *Water and Wastewater Treatment: Design Principles and Practice*. 2010. McGrawHill

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Uniform Media – Carmen-Kozeny Equation

$$\frac{h}{L} = \frac{k\mu}{\rho g}\frac{(1-\varepsilon)^2}{\varepsilon^3}\left(\frac{a}{v}\right)^2 V$$

h = head loss in depth of bed, L

g = acceleration of gravity

ε = porosity

a/v = grain surface area per unit of grain volume = specific surface (S_v) = $6/d$ for spheres and $6/\psi d_{eq}$ for irregular grains

d_{eq} = grain diameter of sphere of equal volume,

V = superficial velocity above the bed = flow rate/bed area (i.e., the filtration rate)

μ = absolute viscosity of fluid

ρ = mass density of fluid

k = the dimensionless Kozeny constant commonly found close to 5 under most filtration conditions (Fair, Geyer, and Okun, 1968)

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Uniform Media – Carmen-Kozeny Equation

$$\frac{h}{L} = \frac{k\mu}{\rho g}\frac{(1-\varepsilon)^2}{\varepsilon^3}\left(\frac{a}{v}\right)^2 V$$

$$h_L = \frac{5\mu}{\rho g}\frac{(1-\varepsilon)^2}{\varepsilon^3}\left(\frac{6}{\phi d}\right)^2 v_a L$$

$$h_L = \frac{180\mu}{\rho g}\frac{(1-\varepsilon)^2}{\varepsilon^3}\left(\frac{1}{\phi^2 d^2}\right) v_a L$$

Non-uniform Media – Carmen-Kozeny Equation

- Each sieve fraction is considered as a distinct layer

$$h_L = \frac{1}{\phi}\frac{1-\varepsilon}{\varepsilon^3}\frac{Lv_a^2}{g}\sum f\frac{p}{d_g}$$

L = depth of filter bed or layer, m
R = Reynolds number
p = fraction of particles (based on mass) within adjacent sieve sizes

$$f = 150\frac{1-\varepsilon}{\mathbf{R}} + 1.75$$

$$h_L = \frac{k\mu}{\rho g}\frac{(1-\varepsilon)^2}{\varepsilon^3}\left(\frac{6}{\phi}\right)^2 v_a \sum \frac{p}{d^2} L$$

$$\mathbf{R} = \frac{\phi d v_a \rho}{}$$

$$d_g = (d_1 d_2)^{0.5}$$

where d_g = geometric mean diameter of grain size distribution between sieves, mm
d_1, d_2 = diameter of upper and lower sieve openings, mm

Ergun Equation

- Larger media + higher velocities used → Kozeny equation cannot be used
- Ergun equation however is adequate for full range of laminar, transitional and turbulent flow (Re from 1 to 2000)

$$\frac{h}{L} = \frac{4.17\mu}{\rho g} \frac{(1-\varepsilon)^2}{\varepsilon^3} \left(\frac{a}{v}\right)^2 V + k_2 \frac{(1-\varepsilon)}{\varepsilon^3} \left(\frac{a}{v}\right) \frac{V^2}{g}$$

- First term is the viscous energy loss and the second term is the kinetic energy loss.

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Ergun Equation

$$\frac{h}{L} = \frac{4.17\mu}{\rho g} \frac{(1-\varepsilon)^2}{\varepsilon^3} \left(\frac{a}{v}\right)^2 V + k_2 \frac{(1-\varepsilon)}{\varepsilon^3} \left(\frac{a}{v}\right) \frac{V^2}{g}$$

- k_2 is originally reported to be 0.29 for solids of known specific surface
- Later k_2 is reported as 0.48 for crushed porous solids
- Second term of the equation becomes dominant at higher flow velocities

Rose Equation

$$h_L = \frac{1.067(v_a)^2(D)}{(\varphi)(g)(\varepsilon)^4}\sum\frac{(C_D)(f)}{d_g}$$

h_L = frictional headloss through the filter, m
v_a = approach velocity (also known as *face velocity, filtration rate,* or *loading rate*), m/s (or $m^3/s \cdot m^2$ of surface area)
D = depth of filter sand, m
C_D = drag coefficient
f = mass fraction of sand particles of diameter, d_g
d_g = geometric mean diameter of sand grains, m
φ = shape factor
g = acceleration due to gravity, m/s^2
ε = porosity

$$h_L = \frac{1.067}{\phi}\frac{C_D}{g}\frac{DV_a^2}{\varepsilon^4}\frac{1}{d}$$

$$d_g = (d_1 d_2)^{0.5}$$

where d_g = geometric mean diameter of grain size distribution between sieves, mm
d_1, d_2 = diameter of upper and lower sieve openings, mm

Backwash Hydraulics

- During backwashing, water flows from the bottom of the bed towards to top of the bed
- Filter grains will be lifted and bed will be expanded
- Filter backwashing is practiced to be above the minimum fluidization velocity
- Fluidization is the upward flow of fluid through a granular bed at sufficient velocity to suspend the grains of the fluid

Backwash Hydraulics

- During upward flow, headloss (pressure drop) will occur)
- Headloss should be at least equal to the buoyant weight of the particles in the fluid

Head loss required to initiate expansion:

$$h_L = \left(\frac{\rho_s - \rho}{\rho_s}\right)(1 - \varepsilon)D$$

hL: headloss required to initiate expansion, m
D: Uniform bed depth, m
ε: Porosity of fixed bed, m^3
ρs: Density of media, kg/m^3
ρ: Water density, kg/m^3

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Backwash Hydraulics

- Weight of packed bed = Weight of fluidized bed

$$\left(\frac{\rho_s - \rho}{\rho_s}\right)(1-\varepsilon)D = \left(\frac{\rho_s - \rho}{\rho_s}\right)(1-\varepsilon_e)D_e$$

$$h_{Le} = \left(\frac{\rho_s - \rho}{\rho_s}\right)(1-\varepsilon_e)D_e$$

$$\varepsilon_e = \left(\frac{V_b}{V_s}\right)^{0.22}$$

$$D_e = D\frac{1-\varepsilon}{1-\varepsilon_e}$$

h_{Le}: headloss, m
D_e: Expanded bed depth, m
ε_e: Porosity of expanded bed, m^3
ρs: Density of media, kg/m^3
ρ: Water density, kg/m^3
Vb: Backwash velocity (Qbackwash/A)
Vs: Settling velocity of the particles

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Backwash Hydraulics

- Fluidized bed depth in uniform media

$$D_e = D \frac{1-\varepsilon}{1-\left(\frac{V_b}{V_s}\right)^{0.22}}$$

- Fluidized bed depth in non-uniform/stratified media

$$D_e = D(1-\varepsilon)\sum \frac{f}{1-\varepsilon_e} = D(1-\varepsilon)\sum \frac{f}{1-\left(\frac{V_b}{V_s}\right)^{0.22}}$$

Minimum Fludization Velocity

- Minimum velocity required to initiate fluidization (V_{mf})

$$h_L = \frac{150\mu(1-\varepsilon)^2 D V_{mf}}{\phi^2 d^2 \rho \varepsilon^3 g} + 1.75\frac{1}{\phi}\frac{1-\varepsilon}{\varepsilon^3}\frac{D}{d}\frac{{V_{mf}}^2}{g} = D(1-\varepsilon)\frac{\rho_s - \rho}{\rho}$$

- Fixed bed headloss = Fluidized bed headloss

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Minimum Fluidization Velocity

- Wen and Yu (1966) eliminated both the shape factor and the porosity terms from the equation.

$$V_{mf} = \frac{\mu}{\rho d_{eq}} (33.7^2 + 0.0408\ \mathrm{Ga})^{0.5} - \frac{33.7\mu}{\rho d_{eq}}$$

Ga is the dimensionless Galileo number:

$$\mathrm{Ga} = d_{eq}^3 \frac{\rho(\rho_s - \rho)g}{\mu^2}$$

Minimum Fluidization Velocity

- Smaller grains will become fluidized at a lower velocity compared to larger grains
- Minimum fluidization velocity should be calculated for the largest particles to ensure the fluidizetion of most of the grains in the filter media
- d_{90} sieve size is used
- Backwash rate = 1.3 V_{mf}.

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Slow Sand Filtration

- Slow sand filters are operated at a very low filtration rate without the use of coagulation or pretreatment
- Grain size is smaller compared to that of slow sand filters
- Solids are mostly removed in a thin layer at the top of filter
- This thin layer is composed of dirt, microorganisms (schmutzdecke, dirty skin) – becomes the dominant filter medium

Slow Sand Filtration

- When the headloss becomes extensive, filter is clean by draining the water below the sand surface and then physically removing the dirt (13-50 cm of the sand) filter medium (scraping, manually or mechanically)
- Water level above the filter reaches to 1.25 to 2 m → indication of dirtiness
- When bed reaches to minimum thickness of 0.5 – 0.8 m, resanding is applied
- Accumulation of Schmutzdecke layer occurs in 6 h to 30 days.
- Optimum operation is reached when Schmutz [illegible] ver is formed

Slow Sand Filtration

Filtration rate	0.1 – 0.4 m/h
Effective size of sand	0.1 – 0.3 mm
Uniformity coefficient	2 – 3
Thickness of the bed	1 -1.5 m
Supporting gravel layer	0.3 – 0.5 m
Underdrain	Normally perforated pipes, lower portion of gravel
Flow control	Operated as constant (equal) rate

Slow Sand Filtration

- Sand filtration is used to remove pathogenic organisms such as Giardia Cysts and organic matter
- Used for raw waters with relatively low turbidity
- Biological treatment takes place in Schmutzdecke layer
- Bacteria is effectively removed (by a factor of 10^3 to 10^4 bacterial count)
- Cheap, simple and most efficient method for low turbidity surface waters (< 50 NTU)

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Pressure Filter

- The filter medium is contained in a steel pressure vessel
- Water enters the filter under pressure and leaves at slightly reduced pressure due to headloss
- Usually a cylindirical tank with vertical axis or horizontal axis
- Operating principles are identical to gravity filters
- Water leaves at positive pressure

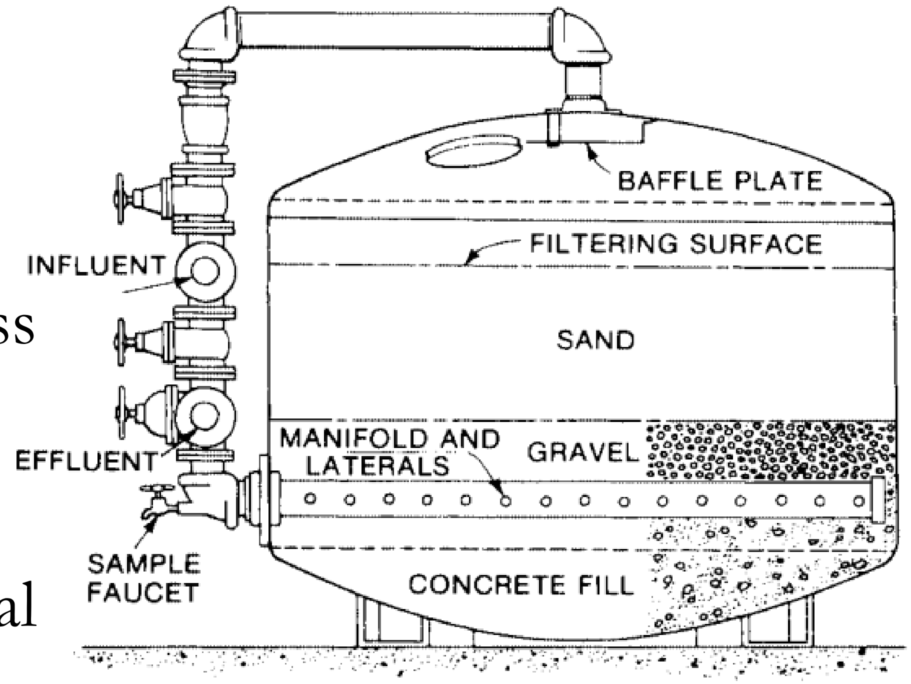


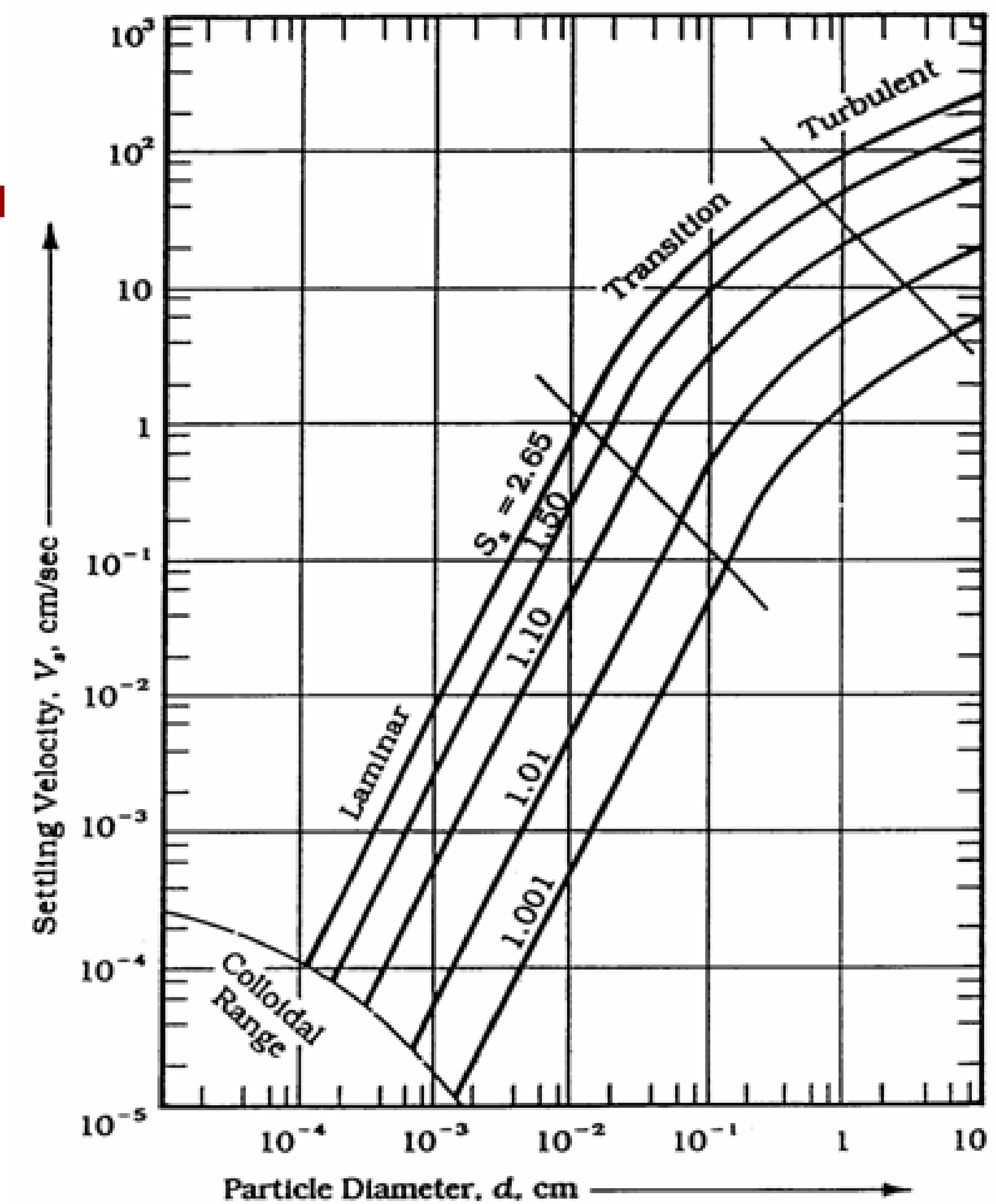
FIGURE 8.31 Cross section of typical pressure filter.

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Problem Session

U.S. sieve designation	Size of opening (mm)	U.S. sieve designation	Size of opening (mm)
3	6.35	35	0.500
4	4.76	40	0.420
5	4	45	0.350
6	3.36	50	0.297
7	2.8	60	0.250
8	2.38	70	0.210
10	2.00	80	0.177
12	1.68	100	0.149
14	1.41	120	0.125
16	1.19	140	0.105
18	1.00	170	0.09
20	0.841	200	0.074
25	0.710	230	0.063
30	0.590	270	0.053

Ref: Davis M.L. *Water and Wastewater Treatment: Design Principles and Practice*. 2010. McGrawHill



Ref: Reynolds, T. D., and P. A. Richards. Unit Operations and Processes in Environmental Engineering. 2nd ed. Boston, MA: PWS Publishing Company, 1996.