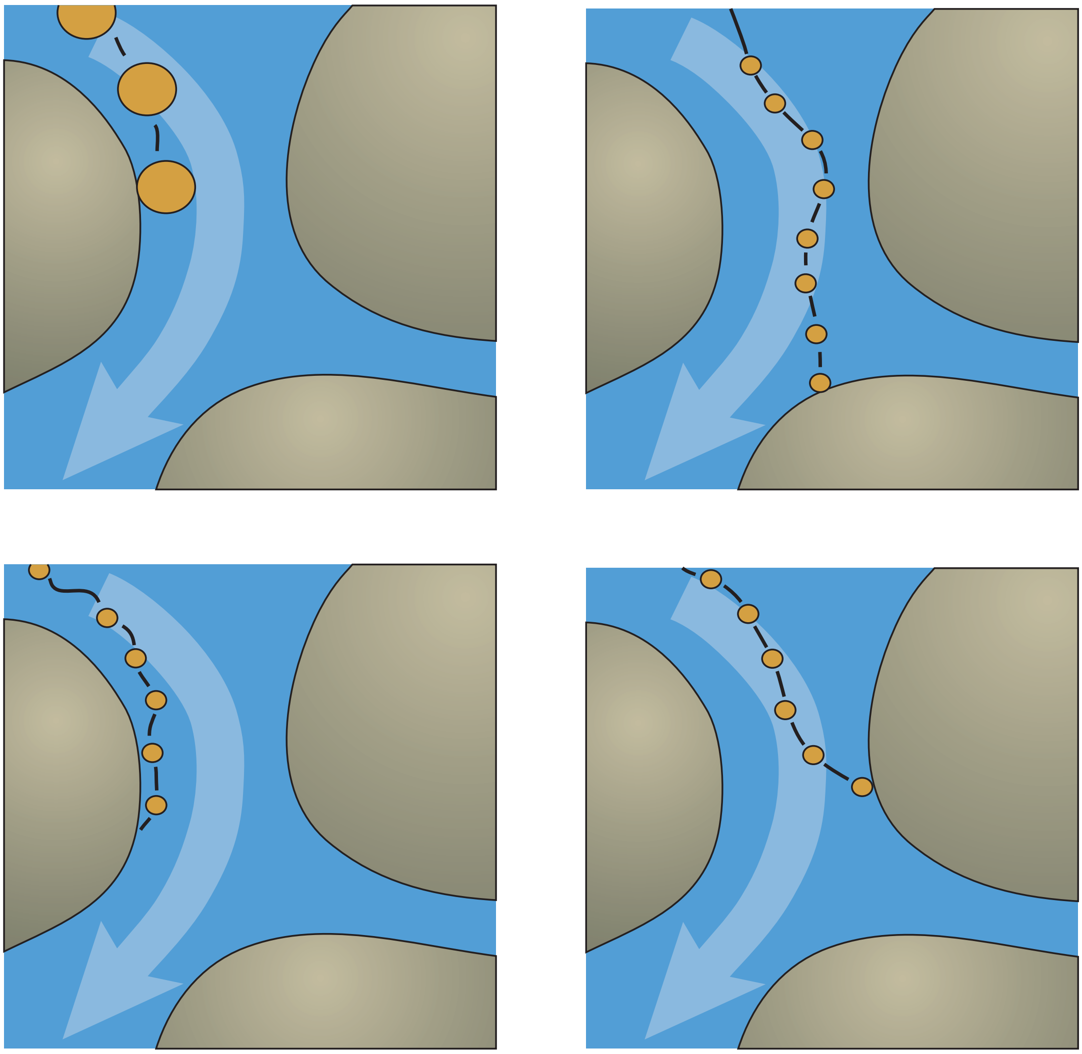
WATER TREATMENT

Granular filtration



Framework

This module explains filtration.

Contents

This module has the following contents:

1 Introduction

In general, filtration is a process where water flows through a permeable layer, either a membrane, filter paper, a sieve, a porous medium or such.
In water treatment, granular filtration is a process where water flows through granular material (often sand) while suspended solids (sand, clay, iron and aluminum flocs) are retained, substances are biochemically decomposed and pathogenic microorganisms (bacteria, viruses, protozoa) are removed.

The suspended solids slowly fill the pores, resulting in an increase in hydraulic resistance.
The suspended solids are removed by periodically cleaning the filter beds. This prevents the resistance from becoming too high or the break through of suspended solids.
Filters are also used for chemical and biological reactions. This is mainly of importance for the treatment of groundwater where the oxidation of iron, manganese, ammonium and, in case of poor gas stripping, methane takes place.
The removal of pathogenic microorganisms is of importance for surface water treatment, and the efficiency is approximately 90 to 99%. The removal of pathogenic microorganisms occurs by decay and retention on the (sand) grains.

The most common application of filtration is rapid sand filtration (Figure 1).
Rapid sand filtration consists of a bed with a coarse granular medium (0.8-1.2 mm) and supernatant water. The filtration velocities (between 5 and 20 m/h) are controlled by varying the supernatant water level (inlet-controlled) or by operating a valve at the outlet pipe (outlet-controlled).
Due to clogging, maximum resistance is reached, and the filter bed must be cleaned by backwashing. During backwashing the filter bed is expanded, and the accumulated suspended solids are removed. The backwash water is drained through a central trough to a waste receptacle. The backwash frequency is repeated every few days.

Rapid sand filters are present in nearly every water treatment plant.
Surface water treatment uses the filters after floc formation and removal to get rid of the remaining flocs and pathogens and to decompose ammonium.
In groundwater treatment, the filters are usually placed after aeration to remove iron flocs, manganese and ammonium. With softening, filters are often placed after pellet reactors to remove the 'carry-over'.

2 Principle

2.1 Filtration mechanisms

When water flows through the filter bed, suspended and colloidal particles are retained by the filter material.
Particles that are larger than the pores in the filter bed will remain on the bed (Figure 2). With rapid filtration this does not occur often, because the larger particles (iron or aluminum flocs) are already removed in the preceding floc removal process (sedimentation or flotation).
If smaller filter material is used, the pores are also smaller and the screening process results in the so-called cake filtration. The cake will also retain

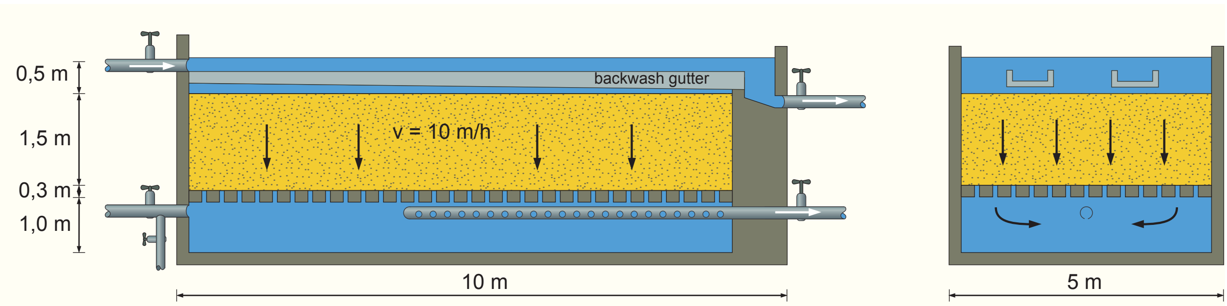


Figure 1 - Principle of rapid sand filtration(side and front view respectively)

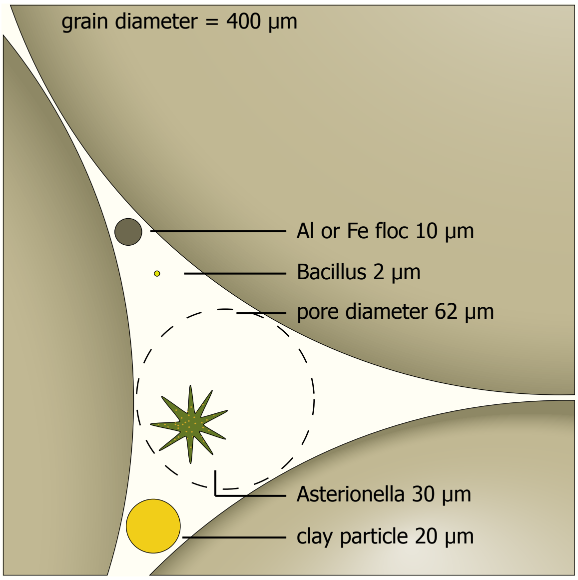


Figure 2 - Principle of screening

small particles, and treatment occurs mainly in the top layer of the filter.
The disadvantage of cake filtration is that with high concentrations of suspended and colloidal particles rapid clogging of the filter bed occurs.

During rapid filtration the removal of suspended and colloidal particles usually occurs inside the filter bed.
The clogging will thus be spread over the entire height of the filter bed.
The suspended and colloidal particles are transported to the filter material in different ways (Figure 3).
Generally, the particle follows the trajectory of the water that flows through the filter bed. This trajectory follows the complicated pore structure of the bed. When the trajectory curves, a heavy particle can be transported to the filter material due to inertia. If the trajectory approaches the filter grains, then particles can also be intercepted. Heavy particles are especially subject to sedimentation, lighter particles to diffusion. Due to these mechanisms, the particle can switch to other trajectories that flow nearer to a grain or can collide directly with a grain, and it remains at the surface or on the grain.

When the suspended and colloidal particles collide with the filter grains, attachment could take place.
There are two types of forces that result in attraction and repulsion of the particles.
The VanderWaals forces ensure that two bodies are attracted.
Electrostatic forces can have an attracting or repulsing effect, depending on the charge of the particles.
In general the filter material (sand) and the suspended and colloidal particles have a negative charge and repulsion takes place.

Attachment of the particles depends on the magnitude of both opposing forces. If the particles are destabilized by the addition of trivalent iron or aluminum salts, attachment will be easier than without destabilization.

In addition to physical processes to remove suspended and colloidal solids as described above, chemical and biological processes occur in the filter bed.
From groundwater, iron(II) and manganese must be removed by oxidation. By adding oxygen in the preceding aeration step, iron(II) will be transformed into iron(III) and iron flocs will be formed. The iron flocs are removed by the same mechanisms as described for the removal of suspended and colloidal particles.

Manganese is transformed to manganese oxide in

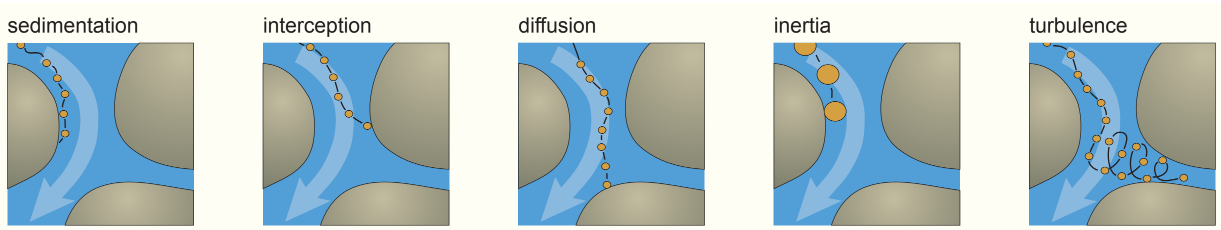


Figure 3 - Transport of impurities towards the grain

Chemical and biological decompositions in the filter bed

$$4\,Fe^{2+} + O_2 + 2\,H_20 + 8\,HCO_3^- \rightarrow 4\,Fe(OH)_3 + 8\,CO_2$$
$$2\,Mn^{2+} + O_2 + 6\,H_2O \rightarrow 2\,MnO_2 + 4\,H_3O^+$$
$$NH_4^+ + 2\,O_2 + 2\,H_3O^+ \rightarrow NO_3^- + 3\,H_2O$$

the presence of previously deposited manganese oxide (catalytic process).
Consequently, it can take several months before manganese removal in the filter bed is initialized. Therefore, measures have to be taken to avoid the total removal of manganese oxide during back-washing to keep the oxidation process alive.
There are also indications that manganese is oxidized in the presence of bacteria, suggesting a biological process.
Other biological processes in the filter bed are the decomposition of methane, ammonium, and (biodegradable) organic matter.
The decomposition of methane in the filter bed has to be avoided, because it results in an uninhibited growth of bacteria, which can lead to clogging and breakthrough. Methane, therefore, must be removed early in the process.

Ammonium is transformed into nitrate in two steps.
A group of nitrifiers (e.g., nitrosomonas) take care of the transformation of ammonium into nitrite; another group of nitrifiers (e.g., nitrobacteria) transform nitrite into nitrate.
The nitrifiers are situated on the surface of the filter material and for their growth they use energy that is produced during the transformation of ammonium or nitrite. The amount of ammonium that can be transformed depends on the growth rate of the bacteria, the size of the bacteria population, and the amount of ammonium that is transported to the bacteria (by diffusion).
In the beginning the growth rate of the bacteria is optimal and uninhibited. The population during this lag phase is small and little ammonium is transformed. After some time the population will grow and finally stabilize (growth is equal to decay). At that time the maximum ammonium removal occurs.

For iron and manganese removal, the oxygen consumption is limited.
Iron is normally present in concentrations lower than 10 mg/l and manganese concentrations are seldom above 1 mg/l. The oxygen concentrations that are needed for these reactions are, after aeration, dissolved in water (approximately 10 mg/l).
For biological processes the oxygen consumption is considerably higher. When low concentrations of ammonium and/or methane are present in the water (few mg/l), the amount of oxygen that can be dissolved in water under atmospheric conditions is insufficient to complete these reactions. A single filtration step is no longer sufficient. Furthermore, high bacteria concentrations in the filter can increase the risk for the growth of Aeromonas.

2.2 Filtration, column tests

It is important to learn from the experiences of other treatment plants that have had to deal with

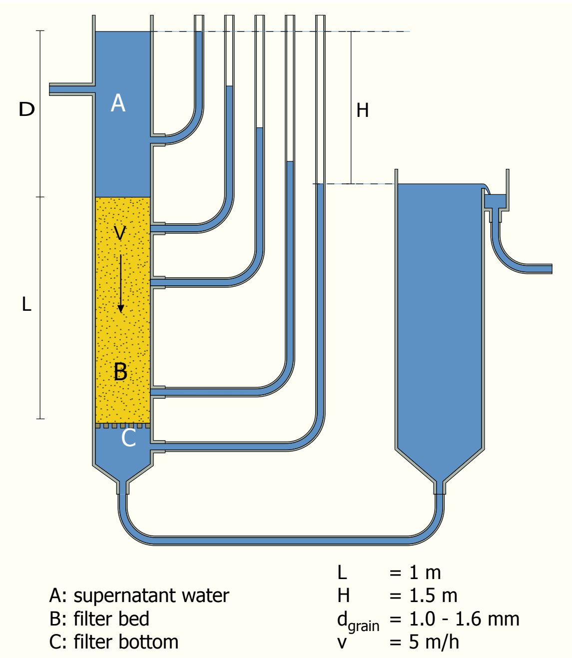


Figure 4 - Filtration, experimental setup

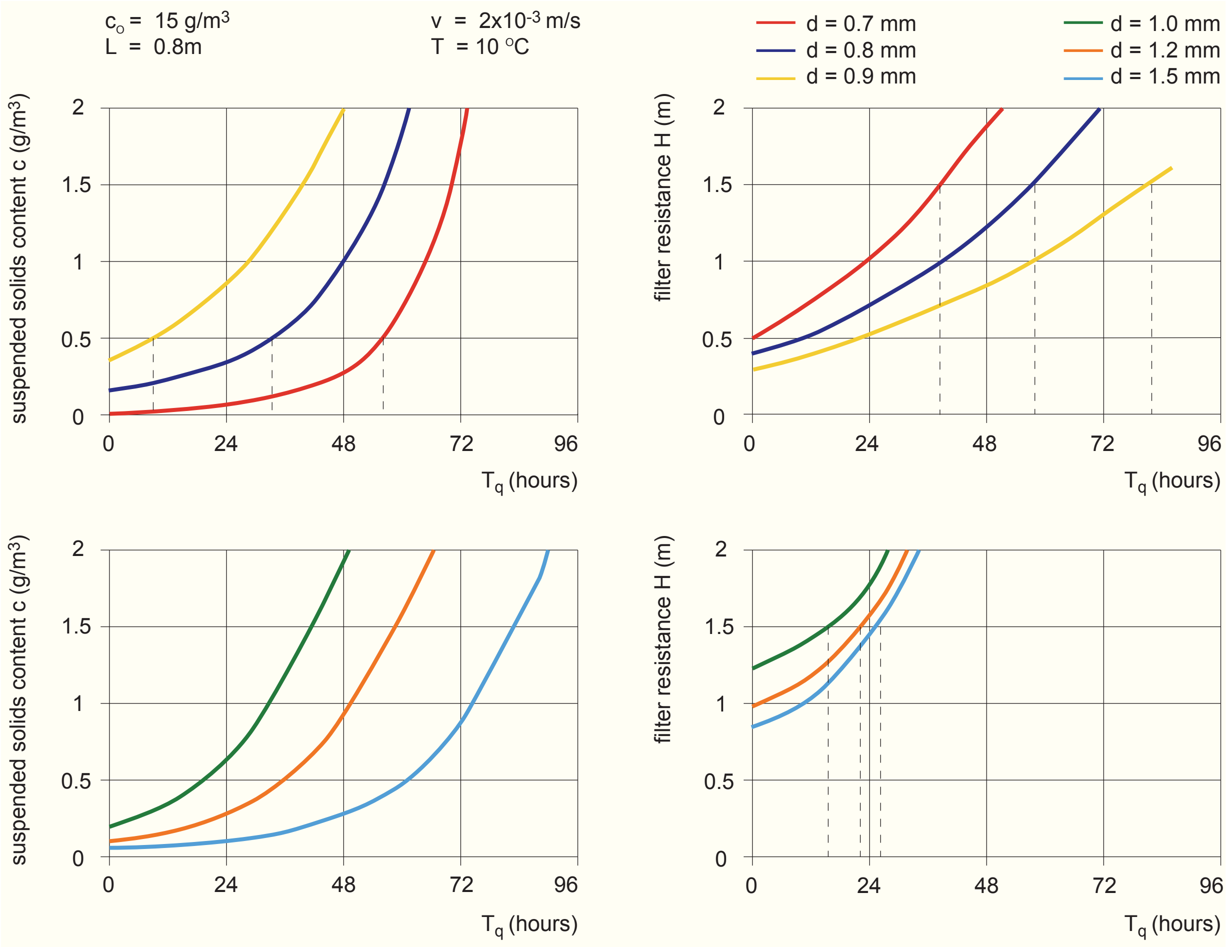


Figure 5 - Results of different filter runs to obtain an optimally functioning filter

similar water to determine the dimensions of a filter.

Further information can be obtained with a test filter (Figure 4).

In the test setup, the optimal combination of the following design parameters should be found:

- grain diameter of filter material
- filtration velocity
- height of the filter bed
- height of the supernatant water.

The optimal combination leads to a filter that is cheap, always satisfies the required effluent quality and has a reasonable filter run time. In addition, during the filter run, the suspended solids should be divided over the filter bed height to avoid cake filtration.

The filter surface area has to be as small as possible to reduce investment costs.

Consequently, the filtration velocity has to be high. The higher the filtration velocity, the sooner the effluent quality will deteriorate during the filter run. This can be compensated for by increasing the filter bed height or by choosing filter material with a smaller grain size.

A higher filter bed, however, means a higher filter construction and, thus, higher construction costs.

Filter material with a smaller grain size will clog faster, shorter filter runs will occur and operational costs will be increased.

In the graphs of Figure 5 the effluent quality and the filter resistance are represented for different filter materials and for different filter bed heights.

In general it is assumed that the effluent quality has to remain under a determined effluent guideline. The filter run time during which the effluent quality satisfies the guideline is called T_q.

Normally, filters are backwashed after run time T_r , when a predetermined maximum resistance is reached.
To prevent the water quality from deteriorating before the maximum resistance is reached, the filter design should fulfill the condition: $T_r<T_q$.
The aforementioned design parameters determine the values of both T_q and T_r (Figure 5).
In practice some restrictions are given to this optimization process.
Normally, safety margins are introduced to maintain the quality of drinking water above all suspicion and filter run times of 1 to 2 days are used.
In addition, a filter plant is always designed to take future developments into account. Consequently, most of the time a filter is operated below its capacity and far from the optimal situation.

3 Theory

3.1 Filtration

Without making use of the filtration theory, a long series of filtration experiments would be necessary to come to an optimal solution for an installation, in practice.
This is problematic, because the raw water quality varies during the year and experiments would take at least a year to complete.
The filtration theory makes it possible to quantitatively predict the effects of changes in design parameters, based on the results of a reduced number of filtration experiments.

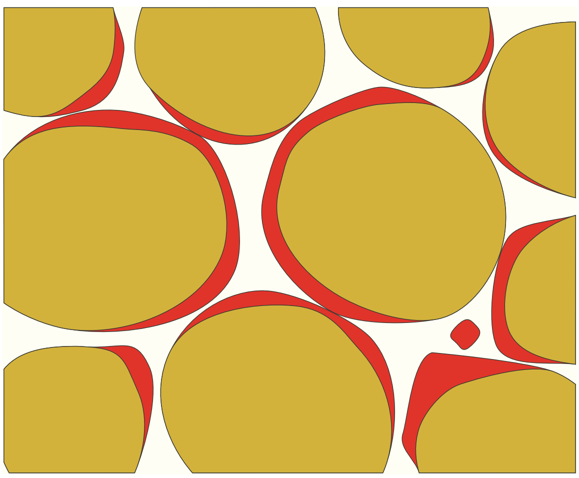


Figure 6 - Reduction of pore volume as a result of accumulated solids

Effluent quality

During the filtration process suspended and colloidal solids accumulate on the grains. Consequently, the concentration of suspended and colloidal solids decreases with the increasing filter bed depth.
In addition, the pore volume will be reduced in time due to the accumulation of suspended and colloidal solids, and the grain size of the filter material will be increased.
With a constant filtration rate (superficial velocity), the pore velocity will increase as filter clogging proceeds.

The equation that is formulated for filtration:

$$\frac{\partial c}{\partial t} = -u \cdot \frac{\partial c}{\partial y} - \lambda \cdot u \cdot c$$

together with the mass balance:

$$\frac{\partial \sigma}{\partial t} = -v \cdot \frac{\partial c}{\partial y}$$

in which:

c	=	concentration of suspended and colloidal solids	(g/m^3)
y	=	depth of the filter bed	(m)
v	=	filtration rate	(m/s)
p	=	porosity	(%)
u	=	pore velocity (=v/p)	(m/s)
λ	=	filtration coefficient	(m^{-1})
σ	=	accumulated solids	(g/m^3)

In the stationary situation the following is valid:

$$\frac{\partial c}{\partial t} = 0$$

therefore the kinetics equation is transformed into:

$$\frac{\partial c}{\partial y} = -\lambda \cdot c$$

To solve the system of equations the value of the

filtration coefficient λ must be known.
However, λ depends on different factors, such as the filtration velocity, viscosity, grain size, quality of the raw water, and the clogging of the bed.
After start-up of the filtration process, the filtration coefficient will initially increase because of better attachment characteristics on the preloaded material.
Due to pore clogging, the pore velocity increases and fewer solids will accumulate, expressed by a lower filtration coefficient λ.
When the solids are retained in the top layer of the filter bed, lower layers will take over until the filter is saturated and the filter breaks through.

The clean bed filtration coefficient λ_0 and the relationship between λ and σ have to be determined in practice (through column experiments).
Several researchers have found empirical relationships. Well-known relationships are those of Lerk and Maroudas.

Lerk:

$$\lambda_0 = \frac{k_1}{v \cdot \nu \cdot d^3}$$

Maroudas:

$$\lambda = \lambda_0 \cdot \left(1 - k_2 \cdot \frac{\sigma}{\rho_d \cdot p_0}\right)$$

in which:

d	= grain size	(m)
p_0	= initial porosity	(%)
k_1, k_2	= constants	
ν	= kinematic viscosity	(m^2/s)

The ratio between the accumulated solids σ and the density is the reduction in pore volume (σ_v)

$$\frac{\sigma}{\rho_d} = \sigma_v$$

in which:

ρ_d	= density of the flocs	(kg/m^3)
σ_v	= volume concentration in pores	(m^3/m^3)

The value of the constant k_1 is often assumed to be $9 \cdot 10^{-18}$ and the constant k_2 is the reciprocal value of the maximum pore filling n (0<n<1).

Notice that in the case of Madouras it is assumed that the filtration coefficient decreases linearly as clogging increases. Although this is a simplification, with this assumption the system of equations can be solved.
With the boundary conditions y = 0, $c = c_0$ and the initial condition t = 0, $\sigma_v = 0$ and:

$$\alpha = \frac{v \cdot c_0 \cdot \lambda_0}{n \cdot \rho_d \cdot p_0}$$

The solution becomes:

- general solution:

$$c = c_0 \cdot \frac{e^{\alpha \cdot t}}{e^{\lambda_0 \cdot t} + e^{\alpha \cdot t} - 1}$$

- effluent quality (y=L):

$$c_e = c_0 \cdot \frac{e^{\alpha \cdot t}}{e^{\lambda_0 \cdot t} + e^{\alpha \cdot t} - 1}$$

and:

$$\sigma_v = n \cdot p_0 \cdot \frac{e^{\alpha \cdot t} - 1}{e^{\lambda_0 \cdot y} + e^{\alpha \cdot t} - 1}$$

Filter resistance
During filtration, pore clogging increases and, therefore, so does resistance in the filter bed.
When the filter reaches the maximum available , the filter needs to be backwashed to avoid a decrease in the filtration velocity. The maximum available head loss is the difference between the supernatant water level and the head of the outflowing water, minus the clean bed resistance and head loss caused by filter bottoms, pipes and valves (Figure 7).

The clean bed resistance (H_0) can be derived from the equation of a flow through a pipe (pore)

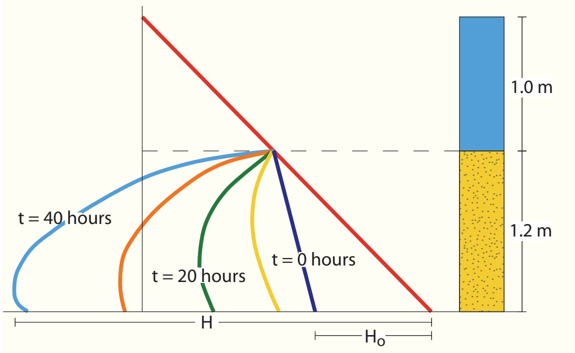


Figure 7 - Progress of the filter bed resistance in time, the so-called Lindquist diagram

and can be described with the Carman-Kozeney equation:

$$I_0 = \frac{H_0}{L} = 180 \cdot \frac{\nu}{g} \cdot \frac{(1-p_0)^2}{p_0^3} \cdot \frac{v}{d_0^2}$$

in which:

I_0 = initial resistance gradient (-)

This equation (the linear relationship between velocity and resistance) is only valid when:

$$Re = \frac{1}{p_0} \cdot \frac{v \cdot d_0}{\nu} < 5$$

When clogging occurs, the resistance formula changes to:

$$I = I_0 \cdot \left(\frac{p_0}{p_0 - \sigma_v} \right)^2$$

in which:

I = resistance gradient (-)

The solids accumulation in the pores σ_v is known along the height and thus the resistance gradient can be calculated over the height of the filter bed.

By integrating the gradient, the total resistance over the filter bed can be calculated.

As presented in Figure 7 the largest resistance is built up in the upper layers of the filter bed, where most of the solids accumulate.

In the lower layers the resistance gradient is almost equal to the clean bed gradient.

In time the resistance in the upper layers will increase.

A pressure drop in the filter bed below atmospheric (negative pressure) must be avoided. In such a case, dissolved gases will come out of solution and, then, released gas bubbles will disturb the filter bed.

Accumulated gas bubbles hinder downward water movement, increase filter resistance and end filter runs prematurely.

Negative pressure can be avoided by maintaining a high supernatant water level and shortening filter runs. This can be achieved by increasing the height of the outflow weir.

3.2 *Backwashing*

After a certain operation period the pores in a filter bed are filled with accumulated suspended solids. The porosity has decreased from p_0 to p, which results in a higher resistance and/or a poor effluent

Figure 8 - Filtration, backwashing with water and air

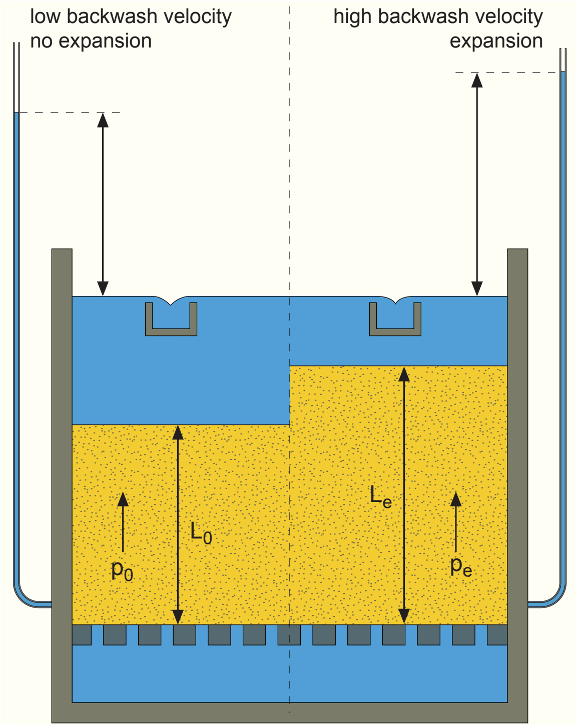


Figure 9 - A non-expanded and expanded filter bed

quality. Rapid filters are cleaned by backwashing with clean water (filtrate).

During backwashing, the water flows in an upward direction through the filter. The water scours the filter grains, erodes the accumulated solids from the filter material, expands the filter bed, and transports the solids towards the backwash troughs.

The shearing (scouring) force of the water is equal to the mass of grains under water:

$$\tau \cdot \pi \cdot d^2 = \frac{\pi}{6} \cdot d^3 \cdot (\rho_f - \rho_w) \Rightarrow \tau = \frac{d}{6} \cdot (\rho_f - \rho_w)$$

in which:

τ	=	shearing force	(kg/m²)
ρ_f	=	mass density of the filter material	(kg/m³)
ρ_w	=	mass density of the water	(kg/m³)

The larger the diameter of the grains, the larger the shearing forces.
From practice, it is known that with grain diameters smaller than 0.8 mm backwashing is difficult. Therefore, a combination of water and air is used. By using air a more turbulent situation is created which facilitates the removal of the solids from the pores.

Hydraulics of back washing
Bed expansion is an important parameter for the design of a backwash facility:

$$E = \frac{L_e - L_0}{L_0}$$

in which:

E	=	bed expansion	(-)
L_0	=	initial height of the filter bed	(m)
L_e	=	height of the expanded filter bed	(m)

The applied bed expansion depends on the diameter of the filter material.
When the filter material has a diameter of 0.8 mm an expansion of 15 to 20% is used, while a diameter of 1.2 mm requires an expansion of 10%.
During backwashing, the amount of filter material remains constant (with a well-designed filter no loss of filter material occurs). When the initial porosity (p_0), the height of the filter bed during filtration, and the height during backwashing are known, the porosity during expansion can be calculated:

$$(1-p_0) \cdot L_0 = (1-p_e) \cdot L_e \Rightarrow p_e = \frac{p_0 + E}{1+E}$$

in which:
p_e = porosity of expanded bed

A backwash rate of 40 m/h through a filter bed with a porosity of 40%, a grain diameter of 1 mm and a temperature of 10 °C gives a Reynolds number of 14.1. Thus, the water flow during backwashing is no longer laminar, but situated in the transition zone between laminar and turbulent, and the Karman-Kozeney equation is not valid.
From experiments, an empirical equation for the resistance during backwashing has been derived:

$$H = 130 \cdot \frac{\nu^{0,8}}{g} \cdot \frac{(1-p_e)^{1,8}}{p_e^{\,3}} \cdot \frac{v^{1,2}}{d^{1,8}} \cdot L_e$$

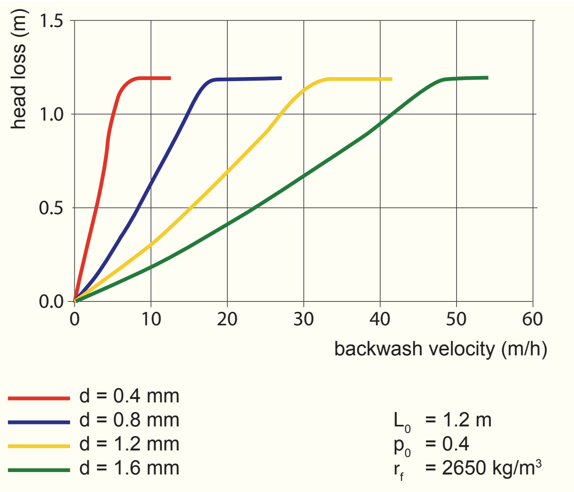


Figure 10 - Resistance during backwashing a sand filter bed with a height of 1.2 m as a function of the backwash velocity and grain diameter

This empirical equation is valid until the upward flow rate becomes so high that the bed fluidizes, the grains do not support each other and float. Fluidization occurs when the resistance is equal to the mass of the filter bed under water:

$$\rho_w \cdot g \cdot H_{max} = (1-p)\cdot L \cdot (\rho_f - \rho_w)\cdot g$$

$$H_{max} = (1-p)\cdot L \cdot \left(\frac{\rho_f - \rho_w}{\rho_w}\right)$$

When sand is used as filter material (ρ_f = 2600 kg/m³ and p=0.4), the maximum resistance is almost equal to the bed height, since after substituting the values in the equation follows that H»L.

Figure 10 represents the resistance as a function of the backwash velocity. From the graphs it can be concluded that the maximum resistance is independent of the grain diameter.

Table 1 - Backwash rates for obtaining a specific bed expansion at different temperatures for sand (r_f= 2600 kg/m³, d = 1.0 mm, p = 0.38)

Temperature	Expansion			
	0%	10%	20%	30%
0	16.2	24.5	33.5	42.8
10	20.2	30.2	41.4	52.9
20	23.8	36.0	49.0	63.0
30	27.7	41.8	56.9	73.1

The backwash velocity needed to achieve a certain expansion E and a resulting porosity p_e can be calculated with a combination of equations given earlier:

$$(1-p)\cdot L \cdot \left(\frac{\rho_f - \rho_w}{\rho_w}\right) = 130 \cdot \frac{\nu^{0,8}}{g} \cdot \frac{(1-p_e)^{1,8}}{{p_e}^3} \cdot \frac{v^{1,2}}{d^{1,8}} \cdot L_e$$

From this equation it follows that:

$$v^{1,2} = \frac{g}{130 \cdot \nu^{0,8}} \cdot \left(\frac{\rho_f - \rho_w}{\rho_w}\right) \cdot \frac{{p_e}^3}{(1-p_e)^{0,8}} \cdot d^{1,8}$$

In Table 1 the backwash rate for sand is given under variable bed expansions and water temperatures. To achieve a bed expansion of 20% a backwash rate of 30 m/h is necessary. This backwash rate is considerably higher than the filtration rate that varies from 1 to 20 m/h (for rapid filtration).

4 Practice

4.1 Backwashing

When a rapid filter is backwashed, the water supply (valve A in Figure 11) is stopped. The supernatant water still filtrates through the bed.

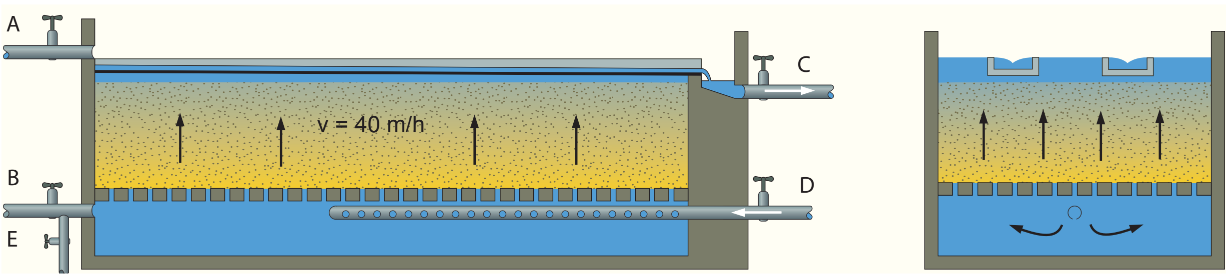


Figure 11 - Schematic representation of the backwash process

After the filtrate drainage is blocked (valve B), the backwash process is started. That is when valves C and D are opened. The filter is backwashed for a certain period of time with water and air. When the bed is sufficiently clean, the supply of water needed for backwashing is stopped and the wash water drain is closed by valve D.
By opening valve E the supernatant water filtrates through the bed. Then valve A is opened. Since the water that leaves the filter during the ripening period is generally of poor quality, this water is drained into a waste receptacle.
After the ripening period, valve E is closed and B is opened.
The total time that a filter is not in operation due to the backwash procedure varies from 30 to 60 minutes. The backwashing process itself will last approximately 20 minutes.
When the filter run time and the backwash time are known, the net production through the filter can be calculated.

Over a short period of time a high wash water flow is needed. There are two possibilities to supply these flows:
- backwash pumps
- elevated water reservoir.

When using backwash pumps, water is obtained directly from the filtrate reservoirs.
During a short period, high energy consumption takes place. This is expensive. The pipes that transport the wash water from the filtrate reser-

A filter with a surface area of 80 m^2, a filter run time of 72 hours, and a filtration rate of 5 m/h is backwashed for 20 minutes with a backwash rate of 50 m/h. In addition, the filter is not operating for 20 minutes due to drainage of the supernatant water, and also due to filter the waste.
The filtrate production is:
$(72-40/60)*5*80=28.533\ m^3$.
The quantity of filtrate used for backwashing is $0.333*50*80=1.333\ m^3$, that is a water loss of 5%.

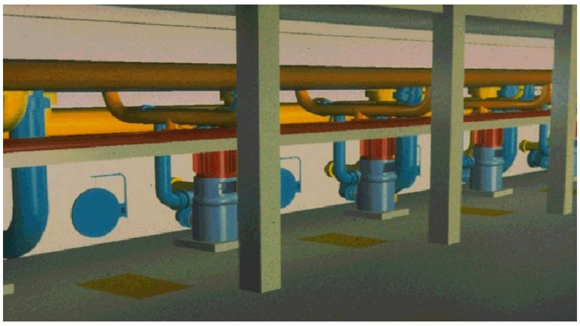


Figure 12 - Discharge pipes for backwash water are the largest pipes in a filter installation

voirs to the filters are the largest pipes in a water treatment plant.
Assuming that the maximum permitted velocity in a pipe is 1 m/s, it can be calculated that the diameter of the backwash supply pipe to a filter with a surface area of 80 m^2 and a backwash rate of 50 m/h is almost 1.2 meters.
The diameter of the supply pipe for raw water is much smaller. When the filtration rate is 5 m/h, this diameter is 0.35 meter.

When an elevated water reservoir is used, backwash pumps with a lower capacity (10 to 20% of the backwash capacity) can be applied. These backwash pumps continuously fill the reservoir.
A disadvantage, however, is that a separate el-

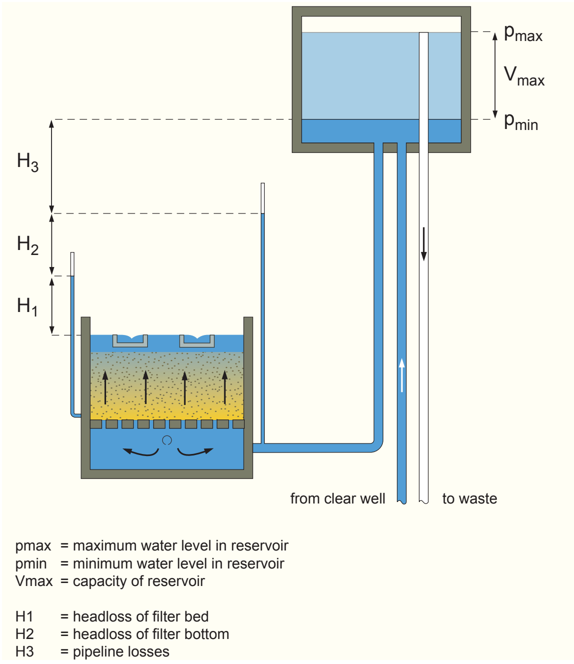


Figure 13 - Elevated water reservoir as backwash system

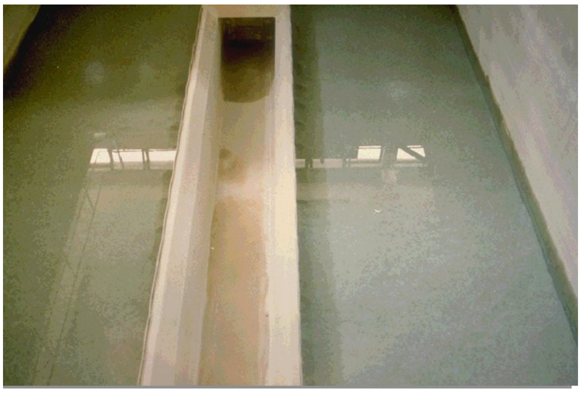


Figure 14 - A central backwash trough

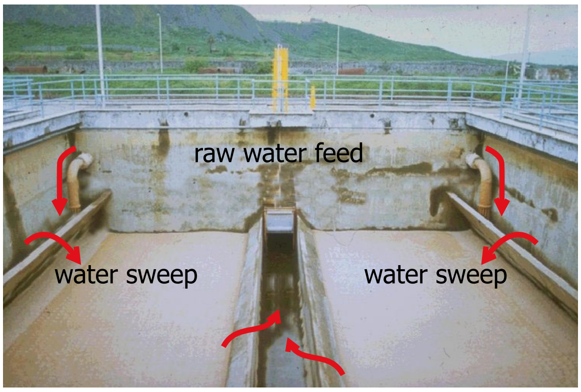


Figure 16 - Water sweep

evated water reservoir needs to be built, thereby increasing the investment costs.

The required pressure for backwash water is around 2-5 mWc. In addition to the static elevation height, most of the pressure losses are due to the resistance resulting from the flow of water through the filter bottom, the filter bed, and the piping system.

After passing the filter bed, the wash water is drained through a system of troughs.
The troughs are designed to limit the (horizontal) distance the water must travel after leaving the filter bed.
The moment the water leaves the filter bed, the wash water velocity decreases by a factor of 2.5 and settling in the supernatant water can occur.

The right configuration of backwash water troughs is found by optimization. The more troughs, the higher the investment costs, but the lower the wash water loss is.
In practice, it turns out that troughs on the sides and troughs at the front side are satisfactory and cheap.

In large filters, a "water sweep" is applied to reduce the volume of backwash water. Raw water is supplied from the sides onto the filter bed. Thus, the water flows from the sides to a central trough, resulting in a stable flow without short-circuits and eddies.
In the past wash water was drained to waste water ponds, the solids would settle and the supernatant water was drained to the surface water or sewerage system.
Because of stricter regulations concerning discharge to surface waters, soil protection and groundwater protection measures, backwash water ponds are not used anymore. These days, backwash water is transported to backwash water treatment installations.
In such installations, a coagulant is added to the backwash water, resulting in floc formation incorporating the solids. The flocs are removed afterwards by tilted-plate separators and rapid sand filters. After UV-disinfection the treated water can be recycled into the main treatment process.
An alternative backwash water treatment plant consists of micro-/ultrafiltration.

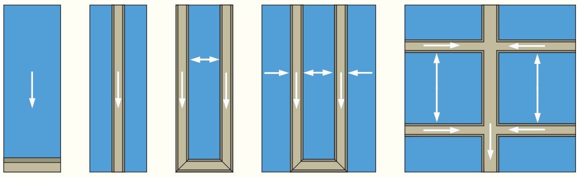


Figure 15 - A central backwash water trough

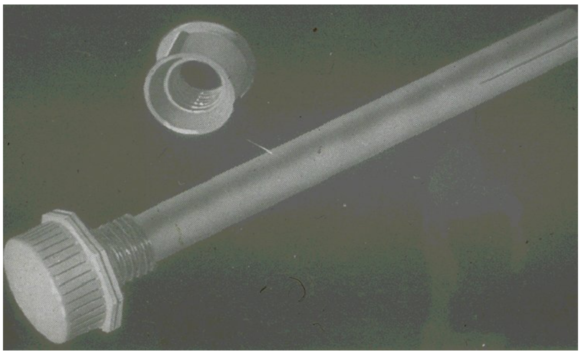


Figure 17 - Nozzle

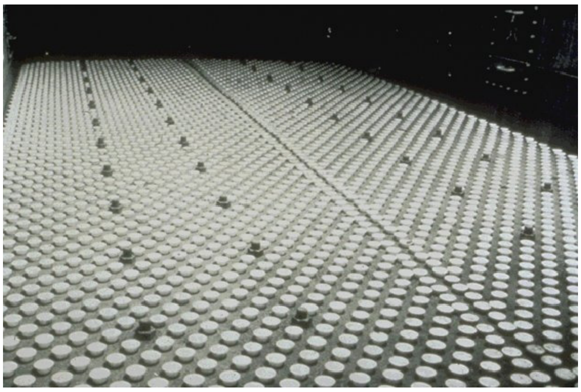


Figure 18 - Nozzle bottom

4.2 Filter bottom

Water that passes the filter bed is drained through nozzles to the filtrate reservoir.
Nozzles are synthetic tubes that are incorporated into the construction of the filter bottom.
To avoid loss of filter sand, perforated heads are placed onto the tubes (Figure 17 and 18).
Frequently, a number of support layers of coarse filter material are placed between the filter bottom and the filter bed to enable larger slot sizes in the nozzle, to avoid clogging the nozzles.

In addition to draining the filtered water, nozzles also have a function in the supply of backwash water and air.
The most important aspect is a uniform distribution of water and air over the filter bed, which can be achieved by introducing a considerable filter bottom resistance (0.5-2 m).

4.3 Filter material

Not all granular material can be used as filter material.
The material should have certain characteristics, such as:

- resistant to abrasion (wear)
- free of impurities
- uniform grain-size distribution.

Typically, river sand is applied as filter material. River sand has a great variety of grain sizes and must therefore be sieved before application. The uniformity of the filter material can be expressed in the uniformity coefficient, defined as:

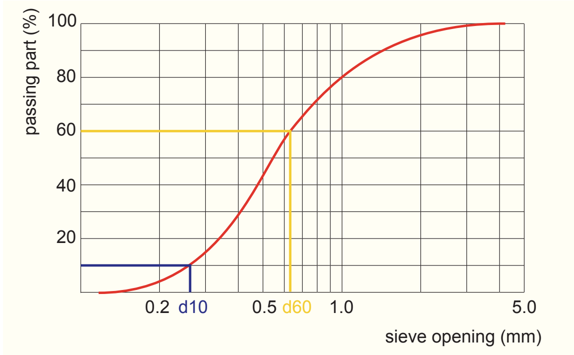


Figure 19 - Sieve curve of filter sand

$$U = \frac{d_{60}}{d_{10}}$$

in which:

U = uniformity coefficient (-)

d_{10} = size of sieves that let pass 10% of the sand mixture (mm)

d_{60} = size of sieves that let pass 60% of the sand mixture (mm)

If the uniformity coefficient equals 1, the material is uniform. A higher coefficient indicates a larger variety in the grain sizes (Figure 19).
For rapid filtration the value of the uniformity coefficient should be between 1.3 and 1.5 to avoid stratification of the filter bed during backwashing. A lower value of the coefficient is possible, but this results in higher sieving costs and provides little additional advantage.

Other filter materials are given in Table 2.
Filter material with a low density is used when the diameter of the filter material should be large and the backwash rate is limited.
The heavier filter materials are used during upflow filtration to avoid premature expansion of the filter bed.

Table 2 - Density of different filter materials

Filter material	Specific density
Plastic grains	1,050-1,300
Pumice	1,200
Anthracite	1,400-1,600
Sand	2,600
Garnet	3,500-4,300
Magnetite	4,900-5,200

4.4 Filter troubles

In spite of rapid filtration being a simple process, many problems can occur.
The choice of the filter material and the design of the filter bottom are crucial.

When the filter material is badly sieved and thus not uniform, stratification will occur during the backwash process. Hence, the lighter, smaller grains will collect at the top of the filter bed, and the heavier, larger grains will settle on the bottom of it.
During filtration all suspended solids will accumulate in the fine upper layer. This phenomenon is called surface or cake filtration. The cake is difficult to remove during regular backwash procedures. Cracks will be formed in the cake, and preferential flows will occur. In addition, mud balls will form and settle on the filter bottom, clogging the nozzles.

When a stratified bed is backwashed at low velocities, only the upper layer will be expanded (with the small grain sizes). The lower layers will not or will hardly be expanded and accumulated solids will not be removed. A faster backwash rate will result in a washing out of the upper layers.

Figure 20 - Result of a poorly designed filter bottom

A non-uniform flow during backwashing (by a poor design or clogging) can lead to preferential flows in and disturbance of the filter bed.
This can result in total mixing of the filter material, and support layers that must be situated at the bottom can be found at the surface. This phenomenon is called sand boil.

The filtrate and the wash water must be able to pass through the filter bottom, but filter material must be retained.
Because the grain size of the filter material is about 1 mm, a small crack in the bottom is large enough for the grains to pass through it and for the filter to become a huge sandglass (Figure 20)
These cracks can be caused by damage in the nozzle or inaccurate sealing of the bottom plates.

5 Alternative applications of filtration

5.1 Multi-layer filtration

Multiple layer filtration consists of a filter bed with

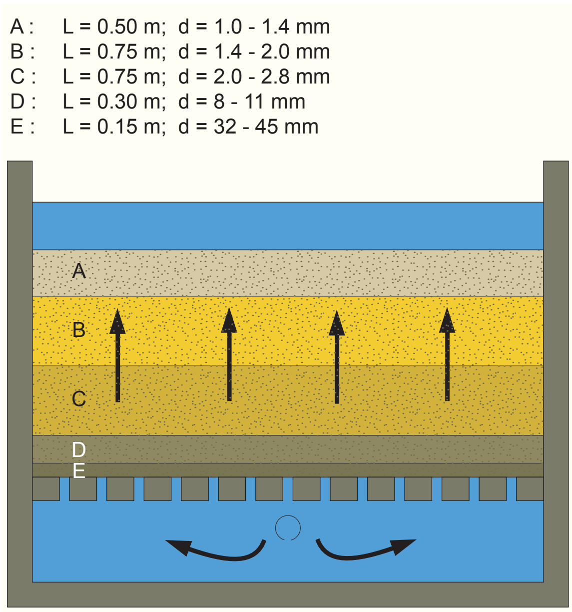


Figure 21 - Multiple layer filtration (upflow filter)

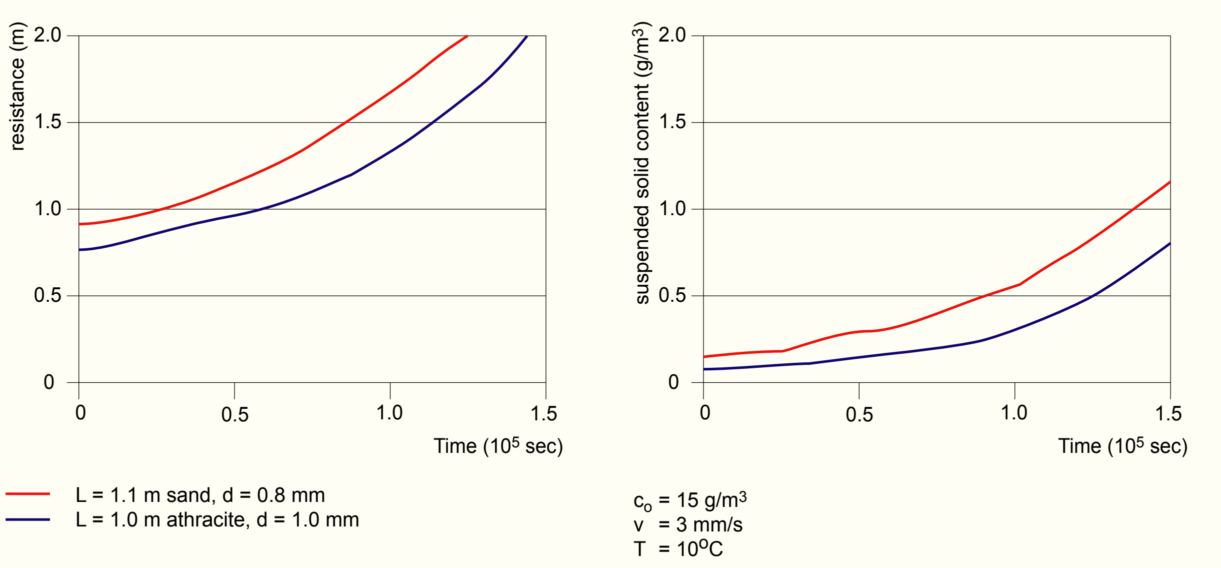


Figure 22 - Difference between single and multiple layer filtration for equal bed heights

various layers of different grain sizes. The water passes the coarser grains first, resulting is a tapered filtering.

In upflow filters, the coarse grains are at the bottom (Figure 21).

In downflow filters, the grain size decreases in a downward direction.

The size and the density are chosen so that the settling velocity of the material in the bed increases in a downward direction and mixing between the two layers during backwashing does not occur.

Usually sand is used as filter material in combination with either:

- a filter layer with a large grain size and a low density on top of the sand (anthracite)
- a filter layer with a small grain size and a high density below the sand layer (garnet).

Multiple layer filtration has an advantage that the larger solids are retained in the top layer of the bed and the smaller ones in the lower parts of the bed.

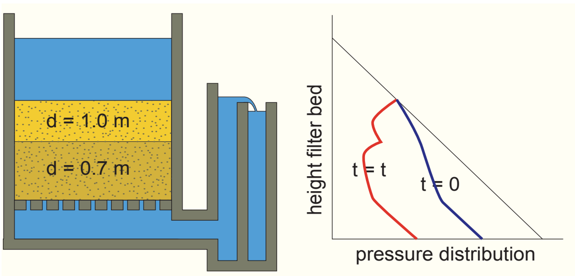


Figure 23 - Resistance build-up for a multiple layer filter

Consequently, the increase in filter resistance is spread over the entire height of the bed, resulting in an extended filter run time.

In Figure 22 the progress of the water quality and the resistance are represented for a single layer and a double layer filter bed.

Using the same filtration velocity the resistance of a double layer bed is lower than of a single layer bed and the effluent water quality is better.

5.2 Pressure filtration

Pressure filters are based on the same principles as gravity rapid filters. The only difference is that the filter bed with the supporting filter bottom and the supernatant raw water are encased in a water-tight steel cylinder. This gives a closed system in which the water to be treated can be forced through the filter bed under pressure.

On one hand, this high pressure allows a large filter resistance without the danger of negative heads; while on the other hand, filtered water pumps are no longer required and the filter can be placed at any random level. Hence, the hydraulic head does not have to be considered.

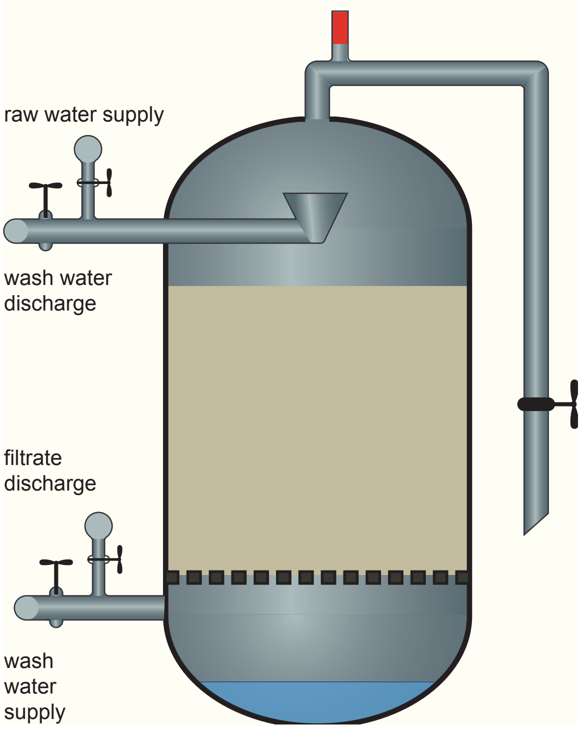


Figure 24 - Principle of pressure filtration

In addition, the application of a large filter resistance permits the use of high filtration rates through filter beds with long filter run times (T_r). The filtration rates normally vary from 7 to 20 m/h, while values of 55 m/h are no exception. The surface area of a pressure filter can thus be small.

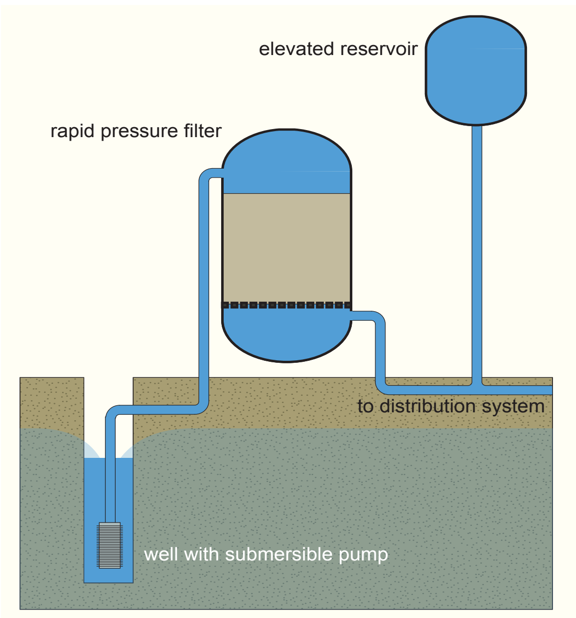


Figure 25 - The filtered water flows without a pumping phase towards the next treatment step

Figure 26 - Cylindrical steel pressure filters

The contact time between the water to be treated and the filtering material becomes a limiting factor, requiring a higher filter bed (3 m).

In practice, pressure filters are hardly used in drinking water treatment because regular inspections are difficult and the systems are rather sensitive. Pressure filters are widely used in industrial water supply.

The diameter of the steel cylinders are at the most 5 m. Hence, the capacity of the filter is 1000 m^3/h at its maximum.
When larger capacities are required, a horizontal pressure filter can be applied. This is a pressure filter with a width of 4 to 5 meters and an unlimited length and, therefore, large filter surface areas can be obtained. In practice this length has a maximum of 15 meters.

The height above the filter is determined by the distance between the drainage troughs and the filter bed. This distance varies between 0.4 and 0.6 meters.

5.3 Upflow filtration

The longest filter runs and the best water quality are obtained when water passes a coarse fraction first and then a finer fraction of the filter material. In upflow filtration the coarse material is situated at the bottom and the fine material at the top.
During backwashing and filtration, the filter bed is conserved as a result of (natural) stratification.
The elevation height of the water is equal to the

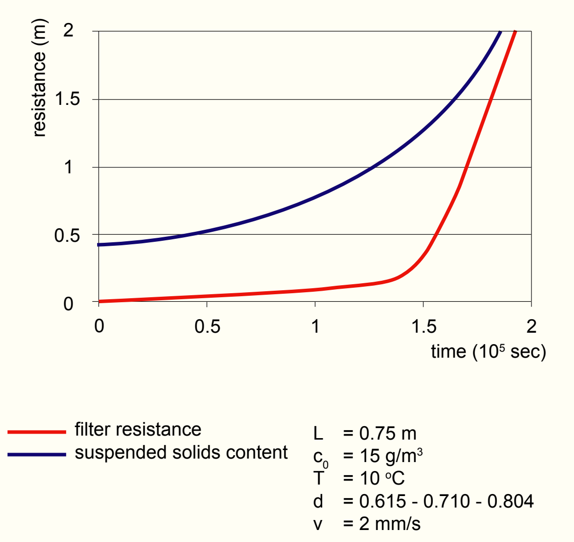


Figure 27 - Changes in quality and resistance of an upflow filter

hydrostatic water pressure plus the resistance due to flow and clogging. This resistance is the largest in the bottom of the bed (y=L).

Fluidization of sand with a density of 2600 kg/m^3 and a porosity of 40% will occur when the resistance is approximately equal to the height of the filter bed.

If fluidization occurs too quickly, a higher filter bed or filter material with a higher density can be applied.

In addition to the aforementioned advantage of good effluent quality, upflow filtration has several disadvantages:

- wash water and filtrate are drained with the same trough. This increases the risk of contamination of the filtrate

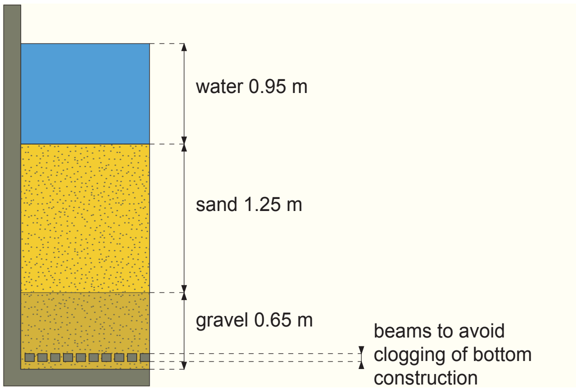


Figure 28 - Principle of uplow filtration

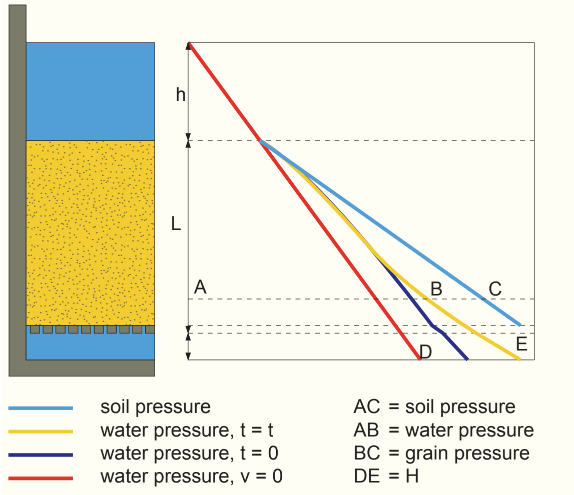


Figure 29 - Pressure distribution in an upflow filter

- fluidization of the top layer of the filter bed can occur, resulting in a washing out of filter material, diminishing the filter bed height and lowering the removal efficiency
- raw water is uniformly distributed by nozzles in the bottom of the filter. The nozzles can become clogged by impurities in the raw water,resulting in extra resistance and a non-uniform distribution of water over the filter bed.

5.4 Limestone filtration

Limestone filters are filled with grains of calcium carbonate or half-burned dolomite. When aggressive water (with high levels of carbonic acid) passes these filters, the concentration of carbonic acid will decrease and the levels of hydrogen carbonate and pH will increase.

Water that is not in (calcium-carbonic acid) equilibrium dissolves limestone grains (calcium carbonate) according to the reaction:

$$CaCO_3 + CO_2 + H_2O \longleftrightarrow Ca^{2+} + 2{\cdot}HCO_3^-$$

Because the limestone grains are dissolved, they need to be replenished regularly.

Normally, replenishing is executed when 10% of the limestone is used. If limestone filtration is used in groundwater treatment after aeration, ferric and manganese removal and nitrification can occur in the filter.

5.5 Continuous filtration

In a continuous filter, sand is re-circulated and purified by a pump centrally placed in the filter. Hence, the backwash process can be continuous.
In a continuous filter, the water flows in an upward direction, and the transport of sand occurs in a downward direction (Figure 30). The inlet of raw water (with impurities) is at the bottom of the filter. At the top of the filter the water flows over a weir and is transported to other treatment processes.

The sand retains the impurities. By means of a sand pump (mammoth pump), the lowest layers of sand are removed from the filter and brought to a sand washer that is situated above the filter. The sand washer removes the impurities from the sand and the clean sand is supplied on top of the continuous filter.

Due to the continuous removal of impurities, the quality of the filtrate, the bed resistance and the pressure distribution in the filter are constant and time independent. The filtration rates of a continuous filter vary from 14 to 18 m/h.

The advantages of a continuous filter compared to a rapid sand filter are:

- continuous filtration process
- continuous wash water flow
- less accumulation of sludge.

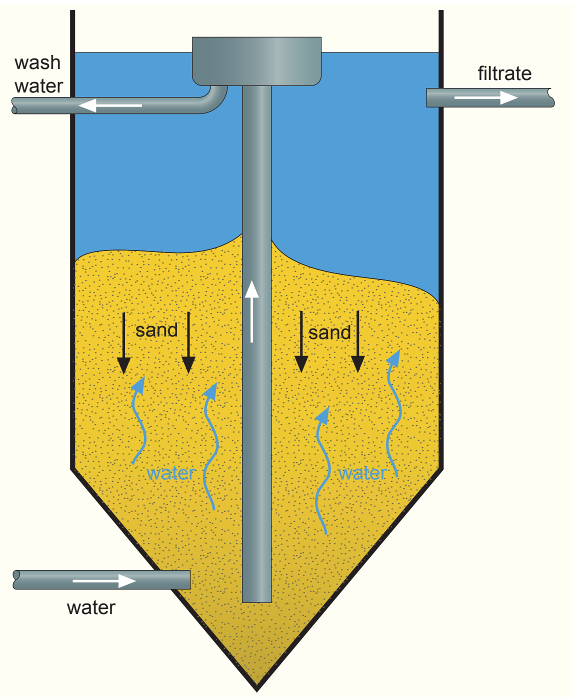


Figure 30 - Schematic representation of a continuous filter

The disadvantages of a continuous filter compared to a rapid sand filter are:

- large wash water flows
- sand wash installation is in direct contact with filtrate, resulting in contamination risks.

5.6 Dry filtration

Dry filtration is used when the water contains a high ammonia concentration. Therefore, dry filtration is only applied in river bank and groundwater treatment.
The oxidation of ammonia into nitrate requires large amounts of oxygen: 3.55 mg/l O_2 per mg/l NH_4^+. The oxygen concentration of water is approximately 10 mg/l. Hence, in water with ammonia concentrations larger than 2.5 mg/l, nitrification will be incomplete.
Dry filtration has no supernatant water level. The water to be treated flows in a downward direction through a bed of granular material, accompanied by a downward or upward flow of air of about the same magnitude. A continuous gas transfer between air and water will take place. The oxygen consumed during the treatment can be replenished directly by the accompanying air. The formed carbon dioxide is removed from the water. The pores are only partially filled with water and, thus, the velocity of the water through the pores is greater than in rapid sand (wet) filtration. The flow conditions through the pores are turbulent ,thereby promoting the hydrodynamic transport of impurities from the flowing interstitial water to the filter grain surfaces where they attach.

The filtered water collects below the filter bottom and flows via gravity to the next treatment process. From the filtrate chamber, air is continuously pumped by a ventilator maintaining a (forced) simultaneous flow of air through the filter bed (Figure 31). When, in addition to oxygen transfer, the dry filter is also used for gas stripping, a counter-cur-

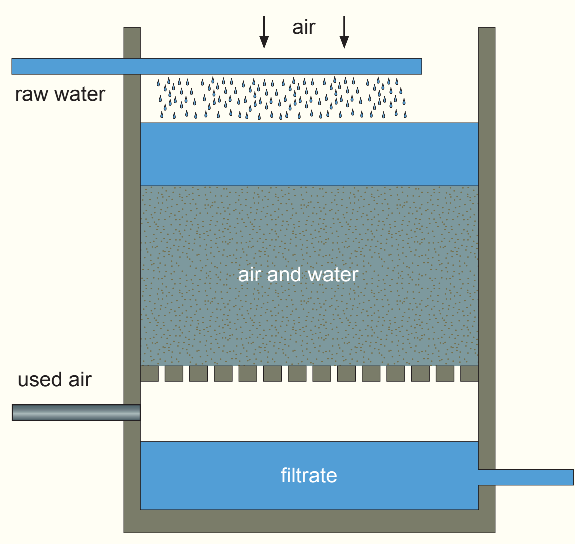


Figure 31 - Schematic representation of a co-current filter

rent flow of water and air can be used in the filter (Figure 32).

The water to be treated is distributed over the full area of the dry filter bed as evenly as possible with the help of spray nozzles.
Spraying has two objectives:
- gas transfer (addition of oxygen and removal of methane and carbonic acid)
- uniform distribution of the water over the filter.

A dry filter does not only remove ammonia, but also iron and manganese. In the top layer of the filter bed (depth of 0.5 to 1.5 m) iron removal takes place. After completion of this process, manganese and ammonia removal occurs more or less simultaneously. Dry filters are often followed by rapid filters. The reason is that in a dry filter bacteria form. The rapid sand (wet filter) forms a barrier against the breakthrough of these bacteria.

5.7 Slow sand filtration

When the most important objective of a filter is to remove bacteria and viruses and the filter is an alternative for chemical disinfection, slow sand filters are suitable.
The filter material has a small grain size (e.g., 0.2 to 0.6 mm) and the filtration rate is below 1 m/h.

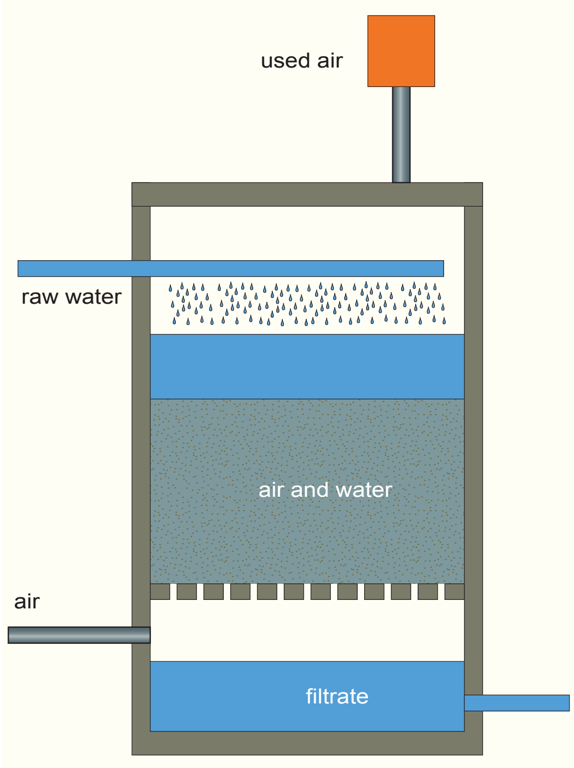


Figure 32 - Schematic representation of a counter-current dry filter

For treatment of the same water flow, a larger filtration surface area is needed than that used for rapid filters. This is illustrated in the aerial picture of the treatment plant at Leiduin (Figure 33).

Filtration occurs mainly in the top layer of a slow sand filtration, where a biologically active "Schmutzdecke" is formed.

Figure 33 - Difference in surface area between rapid filtration(orange) and slow sand filtration red)

To clean the filter, backwashing cannot be applied. Instead, the upper sand layer (usually 1 cm) is scraped.

Because slow filters are normally placed after rapid filters, slow filters are barely loaded with impurities and the filter run time can have an order of magnitude of several years.

Further reading

- Rapid filtration,TU-Delft (2004)
- Water treatment: Principles and design, MWH (2005), (ISBN 0 471 11018 3) (1948 pgs)
- Filter troubleshooting and design handbook, Richard P. Beverly, AWWA (2005), (ISBN 1 58321 349 X) (337 pgs)
- Filter evaluation procedures for granular media, Daniel K. Nix, John Scott Taylor, AWWA (2003), (ISBN 1 58321 235 3) (185 pgs)