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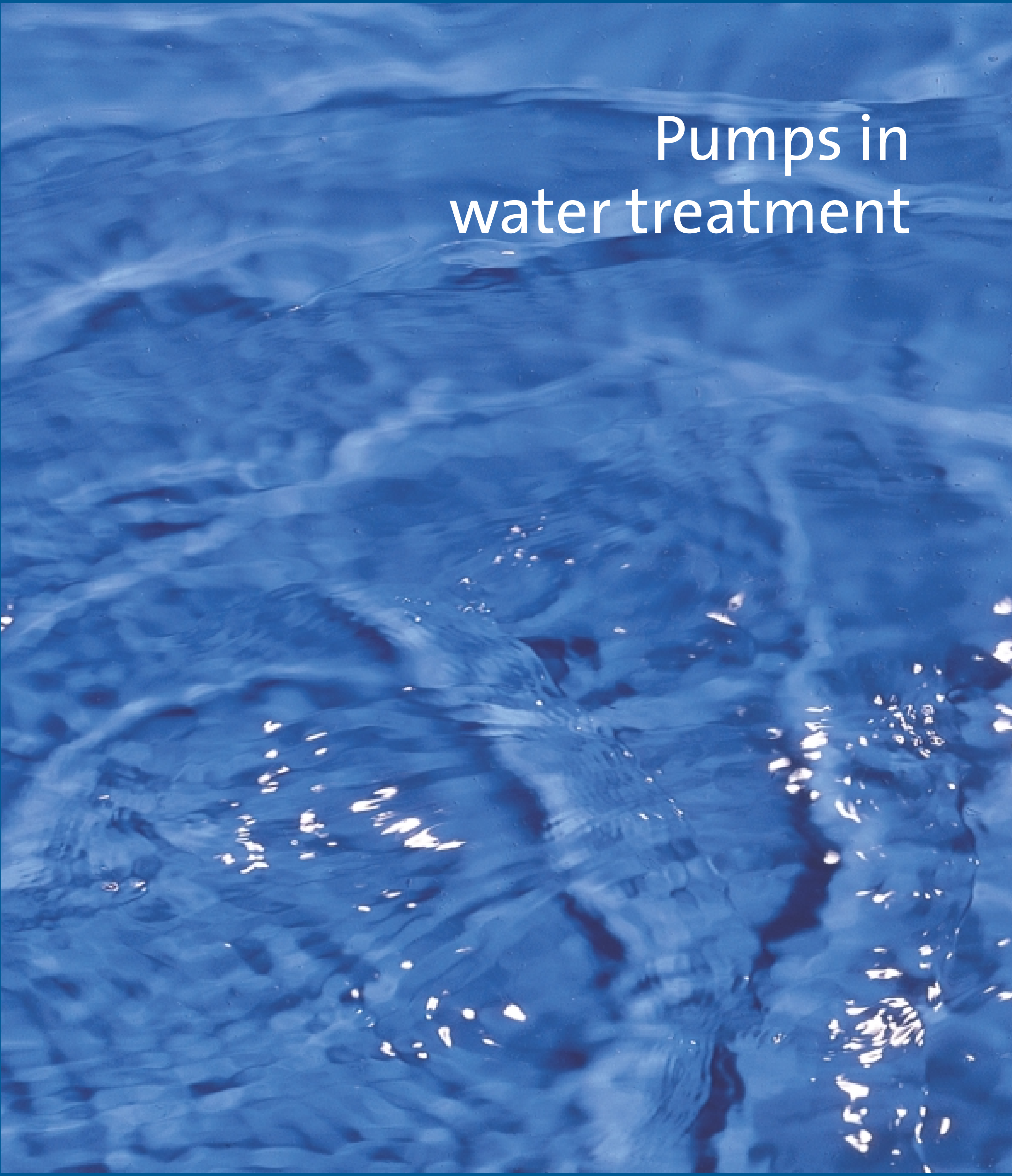

Pumps in water treatment

BE > THINK > INNOVATE >

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Foreword

Water treatment is an almost inexhaustible topic, and progress within this field has been explosive in recent years. There are numerous books available describing water treatment processes, filter technology and so on. This book, “Pumps in water treatment”, is intended to supplement these. It focuses on water purification systems where the pump forms an essential part of the system. Therefore, rather than providing a complete picture of the field of water treatment, it covers water treatment with the pump as a central element.

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1. Introduction

1.1 Why water treatment?

Pure water [H_2O] is a colourless, odourless and tasteless liquid. It plays a huge part in everyday life: 70% of the earth's surface is covered by water in the form of oceans, and the rest of the planet has large quantities of water in the form of lakes, rivers and watercourses, ice and snow, and humidity, as well as the principal element of animal life (>50%) and plants (approx. 80%).

When we talk about water in general, we usually mean water for some specific purpose, e.g. drinking water or process water for industry. This is where the term water treatment comes into the picture, as the available water resources or that provided by nature is not always of a suitable quality for immediate use for the specific purpose.

Drinking water must be pure, and should preferably taste good too, and it must not contain substances that could cause problems with daily use. Process water, which is water that forms a direct and important part of a process or product in industry, must have a chemical composition and temperature that is precisely suited to the specific requirements.

1.1.1 Treatment of drinking water

When we look at drinking water, the presence of fairly small undissolved (suspended) particles will often give it a cloudy appearance, making it look unappealing to drink. This problem is almost always seen with surface water intake (e.g. rivers). The colour, smell and taste of the water are also crucial for its suitability. The water may also have too high a content of dissolved salts, e.g. sea water, which is suitable neither for drinking nor for use as process water.

As the water is in contact with various types of metal in the form of pipes, fittings, tanks etc. on its way from intake location to end-user, one requirement will be that the water should not deteriorate these components, i.e. it should not be corrosive.

As mentioned above, pure water is colourless, odourless and tasteless. Totally pure water is not particularly enjoyable to drink, but it is safe and quenches thirst, just as water should. For drinking water to be good, it must contain certain substances, not only for its appearance, taste and smell, but also for health reasons. WHO has drawn up a list of a number of these substances that it recommends should be present in "good water". The list indicates recommended and/or upper limits for the concentration of these substances in drinking water. The water's microorganism content is also considered.

WHO's list, as a matter of routine, also takes into consideration non-health factors by including recommended quantities for substances that improve water and make it suitable for ordinary practical purposes in other respects. Recommended and maximum permissible concentrations for some of the most important substances in drinking water are listed in table 1 below. This list is by and large identical to WHO's recommendations.

Element or property	Unit	Recommended value	Maximum permissible value
Colour	mg Pt/l	5	15
Turbidity	FTU	0.3	0.5
pH		7.0 – 8.0	8.5
Conductivity	µS/cm	> 300	
Permanganate number	mg $KMnO_4$/l	6	12
TDS	mg/l		1500
Calcium	mg/l	See total hardness	
Magnesium	mg/l	30	50
Total hardness	°dH	5 to 30	
Sodium	mg/l	20	175
Potassium	mg/l		10
Ammonium	mg/l	0.05	0.5
Iron	mg/l	0.05	0.2
Manganese	mg/l	0.02	0.05
Bicarbonate (hydrogen carbonate)	mg/l	>100	
Chloride	mg/l	50	300
Sulphate	mg/l	50	250
Nitrate	mg/l	25	50
Fluoride	mg/l		1.5
Oxygen	mg/l	> 5	
Hydrogen sulphide	mg/l	Should not be quantifiable	
Methane	mg/l	Should not be quantifiable	
Chlorine, free and total	mg/l	approx. 1	
Bacteria	Number/100 ml	Should not be quantifiable	
Bacterial count (at 21°C)	Number/100 ml		10

Table 1: *Recommended and maximum permissible values for some of the most important substances in drinking water*

If water treatment sometimes removes too many of these important substances, it is fairly common for the treatment to be supplemented by re-addition (dosing) of some of these substances. This is particularly important in areas where the daily diet lacks some of the vital substances, such as fluorine and iodine.

Not all water for drinking purposes must undergo major water treatment before it can be drunk. A large proportion of the world's drinking-water resources is still drinkable direct from the source. There are many springs, rainwater pools and glacial watercourses that are excellent drinking-water resources. Even water from wells is also frequently designated as "good water".

1.1.2 Treatment of process water

In the case of process water, it seems, on the face of it, to be slightly simpler. There are generally no requirements for health, taste, smell and appearance; however, there are often very specific requirements regarding chemical composition and physical state, i.e. temperature and pressure. It covers a very wide range - at one end, for example, might be pure, clear water for the brewing of beer, in which it would be desirable that the water contain most normal substances, while at the other end might be ultrapure water for use in medical products in the pharmaceutical industry, from which any dissolved substances and microbes should be completely removed.

Another form of process water is the water used as an auxiliary resource in various processes, such as cooling, heating, flush-ing and rinsing. The requirements for this type of water are generally not particularly strict, and ordinary water (water from wells and surface water) is often used without much in the way of preliminary treatment. Water for washing and cleaning purposes is one of the most common in this category, and it is generally only the hardness of the water that is adjusted.

Substance	Chemical symbol	Substance	Chemical symbol
Ammonium	NH_4^+	Bicarbonate	HCO_3^-
Calcium	Ca^{++}	Carbonate	CO_3^{--}
Iron	$Fe^{++(+)}$	Chloride	Cl^-
Magnesium	Mg^{++}	Fluoride	F^-
Manganese	Mn^{++}	Hydroxide	OH^-
Potassium	K^+	Nitrate	NO_3^-
Sodium	Na^+	Phosphate	PO_4^{---}
		Silicate	SiO_3^{--}
		Sulphate	SO_4^{--}

Note:
The measuring units for ions are usually given in mg/l or mval/l. 1 mval contains naturally as many mg of the ion as its equivalent weight states. The equivalent weight is the ion's atomic weight (molecular weight) divided by the number of charges (see below). E.g.: Calcium has an atomic weight of 40. 1 mval Calcium/l is therefore: 40/2 = 20 mg/l.

***Table 2:** Chemical symbols for various soluble substances*

1.1.3 Requirements for water treatment pumps

In all water treatment processes it is necessary to move the water around and/or raise the water pressure significantly. Some forms of water treatment only require the water to be forced through a simple filter with a few metres' head, while others, such as reverse osmosis, for example, require up to 70 bar (10.15 p.s.i.) This factor, together with the varied chemical compositions and temperatures of water, means that there is a huge range of pumps for water treatment. In addition to the pressure requirement, aggressive (i.e. corrosive) water will make certain demands on material selection.
Therefore it is important to be well informed about the chemistry of the water and the parameters causing corrosion when choosing a pump.

1.2 The chemistry of water

Water, which has the chemical formula H_2O, has a fantastic ability to dissolve diverse substances, which can necessitate purification in order to achieve the desired quality for each application.

There is always a limit to how much of a given substance can be dissolved in water. Once this limit is reached, the solution is saturated. If a substance dissolves to a high degree, it is said to be readily soluble (e.g. common salt). Then there are slightly soluble substances (e.g. gypsum), and totally insoluble substances (e.g. sand). Those we are most interested in in connection with water treatment are typically the substances, or ions, as they are most usually designated, show in table 2 above.

The total content of dissolved substances in water, other than dissolved gases, is called TDS (Total Dissolved Solids).
The acidity of the water (pH value) and temperature are also stated.

1.2.1 Gases dissolved in water

In water, there are also dissolved gases such as oxygen [O_2], carbon dioxide [CO_2], and in some cases methane [CH_4] and hydrogen sulphide [H_2S].
The presence of oxygen and carbon dioxide makes the water fresh. Hydrogen sulphide [H_2S] makes water smell like rotten eggs.

1.2.2 The conductivity of water

The term ion is easiest to explain with an example: If we look at common cooking salt (sodium chloride), which has the chemical symbol NaCl, in an aqueous solution it will consist of two charged "particles", Na^+ and Cl^- ions, which can move freely in the solution. The solid form of the salt [NaCl] can be formed when the solution becomes supersaturated, e.g. by evaporation. The salt precipitates, the ions combine into a solid compound, and have now outwardly become electrically neutral. Ions with a positive charge are called cations and those with a negative charge are called anions.

Another measure of the ion content of water is the water's electrical conductivity. Conductivity is measured in S/m, Siemens per meter (Siemens = mho = ohm^{-1}). The most commonly used are mS/cm (milliSiemens per cm) or µS/cm (micro-Siemens per cm). There is, on the whole, direct proportionality between the concentration of ions in water and the water's conductivity. Therefore we often see a simplified water analysis given with only the water's conductivity, degree of hardness, pH and temperature. If you have some information or an impression of which ions are involved, an estimate of the concentration can be done using tables and graphs of the ions' conductivity in an aqueous solution.

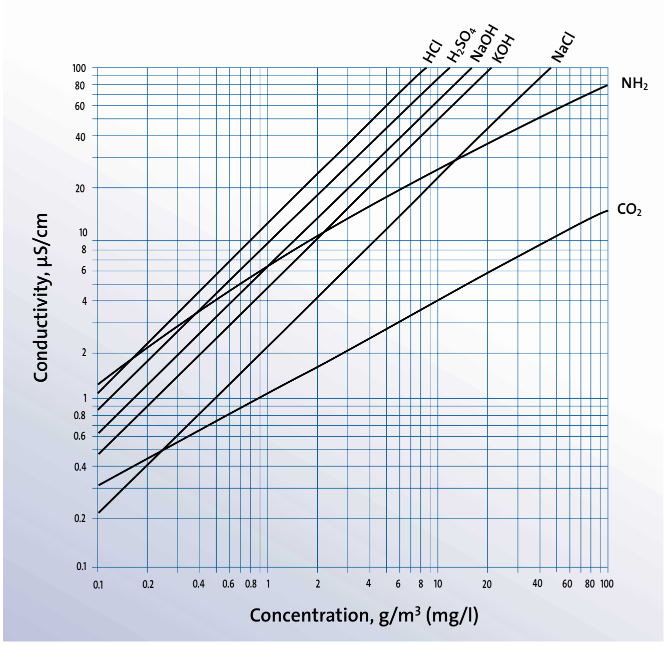


***Fig. 1:** The conductivity of various ions in water at different concentrations*

Fig. 1 shows an example of various ions' conductivity in water.

1.2.3 The hardness of water

As ions are electrically charged, they influence one another, and they enter into a state of chemical equilibrium in an aqueous solution. A fundamental state of equilibrium in water chemistry is one involving calcium [Ca^{++}] and bicarbonate [HCO_3^-]:

$$Ca^{++} + 2HCO_3^- \leftrightarrow CaCO_3\,(solid) + CO_2\,(gas) + H_2O$$

The equilibrium could also be written with Mg^{++} in place of Ca^{++}. The interesting thing about the equilibrium is that it expresses something about the hardness of the water (the quantity of Ca^{++} ions) and its CO_2 aggressiveness, i.e. the ability to dissolve lime scale [$CaCO_3$] and corrode metal surfaces. Depending which direction the equilibrium is shifted to, the water will be hard (a shift to the left) or aggressive/soft (a shift to the right). By removing CO_2 (e.g. by heating or degassing) the equilibrium will be shifted towards the right, Ca^{++} and HCO_3^- will form $CaCO_3$, which is deposited (limestone), and the hardness in the water is thus reduced.

This hardness is called carbonate hardness or temporary hardness, as it can be removed in this simple way.

What is most commonly understood by "hardness" is the water's total content of Ca^{++} and Mg^{++} ions. This is designated total hardness. A high calcium and magnesium content produces hard water, while a low content gives soft water.

Permanent hardness is defined as the difference between total and temporary hardness and can be loosely explained as the quantity of calcium and magnesium that corresponds to sulphate [SO_4^{2-}] and chloride [Cl^-]. Permanent hardness is characterised by the fact that it cannot be removed by boiling etc.

The correlation between the different specifications of hardness is that total hardness is equal to temporary hardness plus permanent hardness.

Hardness can be specified in several ways:

The German hardness degree, °dH, is defined as the hardness that corresponds to the equivalent quantity of CaO/l. 1°dH is equal to 10 mg CaO/l.

The French hardness degree, °F, is defined as the hardness that corresponds to the equivalent quantity of $CaCO_3$/l. 1°F is equal to 10 mg $CaCO_3$/l.

A commonly used unit for hardness, which is used by experts in water treatment technology, is the hardness that corresponds to the equivalent quantity of $CaCO_3$ and is measured directly in mg/l.

The relationship between these three methods of measuring hardness is:

$$1°dH = 1.8°F = 18\ mg\ CaCO_3/l$$

Water of varying hardness can be divided into the following groups:

Hardness	°dH	°F	$CaCO_3$ mg/l
Very soft water	0 - 4	0 - 7	0 - 70
Soft water	4 - 8	7 - 14	70 - 140
Moderately hard water	8 - 12	14 - 22	140 - 220
Fairly hard water	12 - 18	22 - 32	220 - 320
Hard water	18 - 30	32 - 54	320 - 540
Very hard water	Over 30	Over 54	Over 540

***Table 3:** Hardness of various types of water specified in three different units*

The hardness of the water has no effect on the taste, smell and appearance of the water or on health, but it can be a major nuisance, as it causes scaling (calcarous deposits) in pipes, boilers and sanitary appliances.

1.2.4 The pH value of water (degree of acidity)

The pH value of water expresses its degree of acidity, and for ground water is normally determined by the temporary hardness and the carbon dioxide content.

pH = 7 is equivalent to a neutral reaction, above pH 7 the water is alkaline (basic), and below pH 7 it is acidic.

CO_2-aggressive water (see the section on the hardness of water) will have a pH value below 7, and has the adverse property of corroding ordinary carbon steel, cast iron, hot-dip galvanised steel and copper.

1.2.5 Other ions in water

Too much iron causes rust-coloured water and discolouration of sanitary appliances. Too much potassium and the presence of ammonium, nitrate and phosphate is usually a sign of organically-polluted water. Too little fluorine causes caries and too much results in brown teeth. Too much chloride and partly also sulphate gives a salty taste, and so on. If the composition of the water fulfils the “WHO list” above, these inconveniences do not occur.

1.2.6 Content of organic and inorganic substances in water

Definition, organic substance: Substances that contain carbon chemically bound to hydrogen. They often contain other elements (particularly O, N, halogens such as chlorine, or S). Organic substances were once thought to be produced only by living things. We now know that any organic substance can be synthesised in the laboratory (although this can be extremely difficult in practice).

Definition, inorganic substance: A substance that does not contain carbon chemically bound to hydrogen. Carbonates, bicarbonates, carbides, and carbon oxides are considered inorganic substance, even though they contain carbon.

Measuring organic substances: For water containing organic substances, e.g. surface water, there are special methods for measuring these.

One of the methods of measurement is called BOD (“Biological Oxygen Demand”), which like the potassium permanganate number [$KMnO_4$] expresses the content of oxidable organic substances in the water.

The COD (“Chemical Oxygen Demand”) method of measurement slightly resembles BOD, but differs in that it includes all oxidable substances in the calculation.

Measuring inorganic substances: Water, surface water in particular, also contains varying quantities of suspended particles, such as clay which can harbour plant residues and microorganisms. The weight unit is as for organic substances mg/l and is designated SS (Suspended Solids).

There are various ways of indicating organic and inorganic substances. One of these is SDI (Silt Density Index), which can resemble turbidity, which expresses the cloudiness of the water caused by suspended, undissolved substances. The units of measurement are called FTU (Formazin Turbidity Units) or NTU (Nephelometric Turbidity Units).

If the water is discoloured, this can also be measured. The unit is called mg Pt/l, and water discolouration is measured by comparing a water sample with some known solutions of a platinum compound (Pt is the chemical symbol for platinum).

Finally, in connection with polluted water, we have microorganisms such as bacteria. A common measurement here is the number (germs) per 100 ml of water. WHO also specifies limits for the number of different microorganisms in drinking water. See Table 1.

The chemical composition of the water is not of particularly crucial significance for the pump, except where it causes corrosion or deposits, affecting a pump’s ability to function at a consistent level of performance over a long period.

1.3 Corrosion

1.3.1 Introduction

Definition: Corrosion is usually defined as the deterioration of a metal or its properties caused by a reaction with its environment. Most metals occur naturally in the form of oxides and are usually chemically stable. When exposed to oxygen and other oxidising agents, the refined metal will try to revert to its natural oxide state. In the case of iron, the oxides will be in the form of ferrous or ferric oxide, commonly known as rust.

Metallic corrosion generally involves the loss of metal at a particular location on an exposed surface. Corrosion occurs in various forms ranging from a generalised attack over the entire surface to a severe concentrated attack. In most cases, it is impossible or economically impractical to completely arrest the corrosion process; however, it is usually possible to control the process to acceptable levels.

1.3.2 The corrosion cell

Metallic corrosion is caused by the flow of direct current from one part of the metal surface to another. This flow of direct current causes the loss of metal at the point where current discharges into the environment (oxidation or anodic reaction). Protection occurs at the point where current returns to the metal surface (reduction or cathodic reaction). The rate of corrosion is proportional to the magnitude of the corrosion current. One ampere of direct current removes approximately ten kilograms of steel in one year. Where corrosion occurs and to

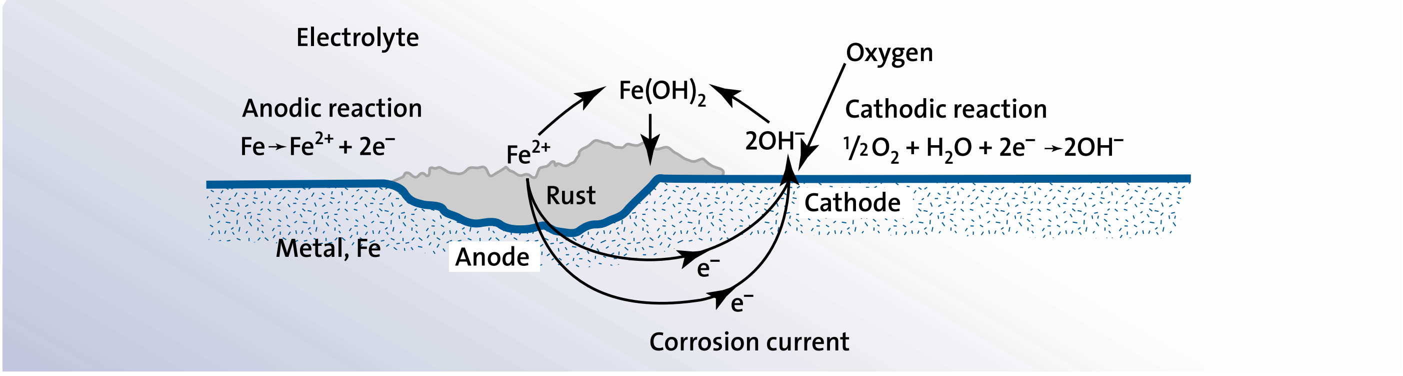


Fig. 2: The corrosion cell

what extent depends upon the environment to which the metal is exposed.

Four conditions must be met for corrosion to occur.

- **Anode** - the oxidation reaction occurs here. Electron release and metal loss (corrosion) are associated with this reaction.
- **Cathode** - the reduction reaction occurs here. Electron consumption and metal protection are associated with this reaction.
- **Electrolyte** - the environment to which both the cathode and the anode are exposed. The electrolyte must have the capacity to conduct electrical current through the flow of ions (e.g. salt water).
- **Metallic path** - the anode and the cathode must be connected via a metallic connection that conducts electrical current flow through the flow of electrons.

1.3.3 Causes of Corrosion

Corrosion is a natural process. The primary driving force of corrosion is based upon the transformation of iron from its natural state to steel. The refining of iron ore into steel requires the addition of energy. Steel is essentially an unstable state of iron and corrosion is the process of iron returning to its natural state. The energy used in the refining process is the driving force of corrosion.
Corrosion cells are established on structures for a variety of causes. One cause of corrosion is due to an effect known as galvanic corrosion.

All metals have different electrical potentials, and where two metals with different potentials are connected to each other in a common environment, current will flow, causing corrosion to occur. The coupling of steel to a different metal, such as copper, will cause a corrosion circuit to be established. Direct coupling of copper to steel will cause the steel to corrode much faster than normal. Another form of this is the coupling of rusty pipe to new, clean steel. The natural difference in potential causes the new steel to corrode more rapidly than the old steel. Other causes of corrosion cells include the effect of contact with different soil types, oxygen availability, salt content and microbiological growth.

In a mechanical construction like a pump, joining materials that are too different is avoided as far as possible in order to prevent galvanic corrosion of individual components.
This involves the galvanic electrochemical series where the metals are arranged according to corrosion tendency. This is how the most commonly used metals are arranged:

Less noble (most susceptible to corrosion)

↓
Magnesium
Zinc
Aluminium
Cast Iron
Bronze
Stainless Steel (passive)
Titanium (passive)
Graphite
Gold
Platinum

More noble (least susceptible to corrosion)

Fig. 3: Metals arranged according to corrosion tendency

1.3.4 Corrosion of pump materials

The section on corrosion only deals with the types of corrosion that are of relevance to the construction materials that Grundfos uses for pumps. For ordinary water, pumps produced from composites will generally be suitable. In instances where process water, for example, may contain chemical solvents etc., however, composite components could also be attacked.

Corrosion of the following materials is described below:

- Cast iron
- Bronze
- Stainless steel, types AISI 304, AISI 316 and 904 L.
- Titanium

Note: Several types of stainless steel are used, but in terms of corrosion they can be grouped with the types above.

The following parameters may influence corrosion of pumps in ordinary water:

- Aggressive carbon dioxide [CO_2]
- Aggressive ions (particularly chloride, [Cl^-])
- Free chlorine [Cl_2]
- Oxygen [O_2]
- Acidity [pH]
- Hydrogen sulphide [H_2S]
- Temperature

Cast iron: With cast iron, which is the most vulnerable of the above-mentioned materials, the pH value of the water will affect its corrosion resistance. It is normally recommended not to use cast iron with pH values below 6.5. The presence of aggressive carbon dioxide will cause problems for cast iron, while other pump materials will not be affected. Nevertheless cast-iron pumps are used, giving satisfactory results, in ground water and rainwater with a pH value as low as 5.
In these cases resistance will be determined by temperature, water composition and operating conditions for the specific application. The risk of discolouration, caused by iron contamination, will be greater, however.
Cast iron is very widespread for applications in ground water, and it is suitable in most instances. Even though corrosion will occur in a cast-iron pump, it is generally acceptable, provided the rate of corrosion remains at a suitably low level.
Usually corrosion of less than 0.5 mm/year will be acceptable provided a corrosion allowance of several millimetres of material thickness is taken into account. In brackish water and sea water, however, the corrosion resistance of cast iron will be limited.

Surface coating is also applied to cast iron, but this sets high requirements with regard to both the quality of the coating, which must be free of porosity, and the handling of the pumps, to avoid damage to the coating.

Bronze: Bronze is generally a better material than cast iron and can be used for ground water, brackish water and salt water. However, with bronze, as with cast iron, one must be aware of the water treatment processes that involve cleaning with various chemicals.
Cleaning with acids in particular is the most critical. With bronze specifically there is also a risk of corrosion attack if it comes into contact with ammonia compounds.
For the aforementioned reasons, the use of cast iron or bronze pumps for membrane filtration is prohibited, so the choice will usually come down to stainless steel or titanium.
For water treatment, therefore, most pumps supplied by Grundfos will be different grades of stainless steel and titanium.

Stainless steel: The term stainless steel covers a wide range of iron-based alloys with a variable content of chromium, nickel and molybdenum primarily, but also nitrogen and copper etc. This yields materials very diverse in mechanical properties and in corrosion resistance.
One common feature of stainless steel, however, is that the corrosion resistance depends on the formation of an invisible oxide film (passive film) on the surface. To achieve this the chromium content must be at least 12%.

If this passive film breaks down locally and is not re-formed immediately, localised corrosion (pitting) may occur. See Fig. 4a. Similarly localised corrosion (crevice corrosion) may occur in crevices and under deposits where there is insufficient oxygen to maintain the passive film. See Fig. 4b.
The propagation of localised corrosion is fairly unpredictable, and it cannot be calculated using a corrosion allowance in the same way as uniform corrosion.

Fig. 4a: *Picture showing pitting on a stainless steel component*

Table 4 shows a range of the stainless steel grades that Grundfos uses for manufacturing pumps. The table shows the content of

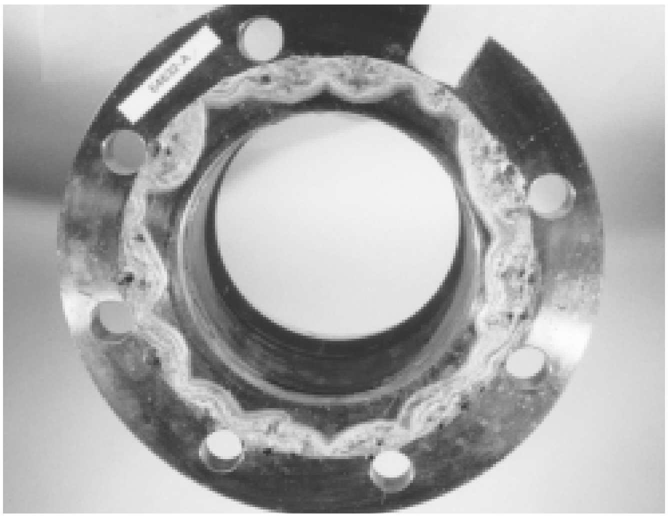


Fig. 4b: *Picture showing crevice corrosion on a stainless steel flange used in fish farming in Norway. Pumped liquid: sea water.*

AISI	W.-Nr.	Cr.	Ni	Mo	N	PRE
431	1.4057	17	2	-	-	17
304	1.4301	18	9	-	-	18
316	1.4401	17	12	2.3	-	24.6
316 L	1.4435	17	14	2.8	-	26.2
329	1.4460	26	5	1.4	-	30.6
*)SAF2205	1.4462	22	5.5	3.0	0.1	34.2
904 L	1.4539	20	25	4.5	-	34.9
*)254 SMO	1.4547	20	18	6.1	0.2	43.3

*) Has no AISI specification, but is known by the stated designation.

Table 4: *Stainless steel grades with alloy elements [w%] and PRE values*

principal alloying elements (chromium [Cr.], nickel [Ni] and molybdenum [Mo]) and the nitrogen [N] content.
The right-hand column gives the PRE value (Pitting Resistance Equivalent), which is used to rank the resistance of various stainless steels to "pitting" (localised corrosion).

The PRE value is calculated according to the formula: Weight % Cr + 3.3 x weight % Mo +16 x weight % N.

Stainless steel with a PRE value above 40 is considered to be resistant to sea water up to 30°C.
However, Grundfos produces pumps from AISI 904 L for use in sea water despite the fact that the PRE value - which also appears in the table above - is below 40. This is due to the fact that operating conditions have a great influence on the corrosion resistance of stainless steel in sea water. If certain procedures are observed, including avoiding long shutdown periods and performing regular flushing with fresh water, AISI 904 L can also be used in salt water at moderate temperatures.

Grundfos uses diagrams like Fig. 5 as an aid for material selection. The diagrams are based on experience with the various stainless steels in ground water, brackish water and sea water respectively.

The following are rules of thumb:
- 500 mg/l chloride is designated the maximum limit for ground water
- 500 – 5000 mg/l chloride is designated brackish water, and
- over 5000 mg/l chloride is designated sea water.

However, sea water typically has a content of around 20,000 – 30,000 mg/l chloride (approx. 3.3 – 5% NaCl).

The relation between chloride content and % sodium chloride [NaCl] is as follows:

NaCl % x 6100 = mg/l chloride [Cl^-]

The diagram Fig. 5 shows maximum application temperatures for various types of stainless steel and titanium in relation to specific chloride content.

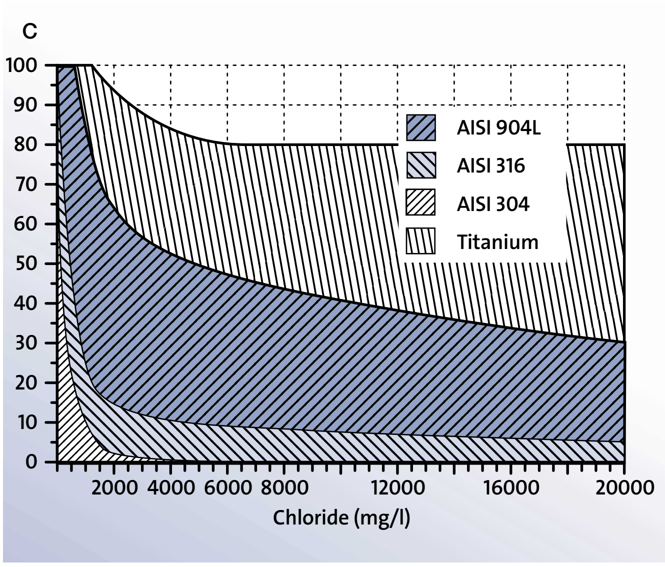


Fig. 5: *Corrosion diagrams for AISI 304, AISI 316, AISI 904 L and titanium*

Titanium: Unlike stainless steel, titanium is very corrosion resistant in chloride-containing environments.
The oxide film (passive film) on titanium is not attacked by chlorides in the same way as the oxide film on stainless steel, and titanium can be used in sea water up to 80°C with no risk of pitting and crevice corrosion.

This pump material is therefore expected to be widely used in water treatment in the future.
For the present, however, there is only a limited range of pumps (CRT) made of this material.

1.3.5 Service-induced corrosion

Wear (erosion, turbulence), cavitation and fatigue are examples of service-induced damage that can occur in pumps in unsuitable operating conditions. If the pumped liquid is also aggressive to the material, corrosion can be a strong accelerating parameter.

Stress corrosion cracking belongs to this group of corrosion types in instances where the mechanical stress is service-induced, but stress corrosion cracking (e.g. deriving from welding) may also occur due to residual stress in the material.

Stress Corrosion Cracking: (SCC) Stress corrosion cracking is characterised by cracking caused by the simultaneous effects of mechanical tensile stresses and corrosion. This type of corrosion only occurs with certain metals in fairly specific environments: for example, AISI 304 and AISI 316 are susceptible to stress corrosion cracking in chloride-containing environments, typically at higher temperatures.

Erosion: Erosion occurs primarily with cast iron and bronze at high flow rates, and is typically seen on impellers in centrifugal pumps. Stainless steel and titanium, due to the abrasion-resistant oxide film on their surfaces, can withstand very high flow rates, and erosion is rarely seen when these materials are used.

Fig. 6: *Cavitation in bronze impeller*

Cavitation: Cavitation occurs if the pressure in a liquid locally drops below the liquid's vapour pressure. Unstable steam bubbles will then be formed (local boiling), which will collapse again on pressure increase.
The impact effect from the collapse of the steam bubbles is so violent that the material can be destroyed. See Fig. 6.
Insufficient inlet pressure to the pump is a typical cause of cavitation.
Once again, cast iron and bronze are more susceptible to cavitation than stainless steel and titanium.

Fatigue: The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material. Corrosion can accelerate fatigue by increasing the crack rate.

1.3.6 Cathodic protection

If a pump experiences corrosion problems, you can often solve them by selecting a variant in a more corrosion-resistant material.

Another possibility is the application of cathodic protection. This method involves mounting of sacrificial anodes on the structure where corrosion is undesirable. Sacrificial anodes are metals that corrode more easily (i.e. are less noble) than the material the structure is made of. The sacrificial anode is positioned on or close to the structure to be protected and in metallic contact with it. A galvanic current will pass between the two materials, causing the reactive metal to corrode, and corrosion on the protected structure will be reduced or stopped completely.
Grundfos also supplies such cathodic protection for certain types of pump, using zinc as sacrificial anodes.
With cathodic protection, consumption of the sacrificial anodes takes place and they must be replaced regularly to maintain the corrosion protection.

1.3.7 Summary

For modern high-performance pumps that must work with sea water and other liquids with a high content of chloride and/or other corrosive substances, the correct choice of materials will often be complex, and the choice of pump will be based on a water analysis. Grundfos has detailed information on the corrosion-based problems, and in most instances can carry out an evaluation of the specific problem. Grundfos has also developed software to help select the most suitable pump for a given application.

1. Introduction

2. Aeration and sand filtration

2.1 Introduction

This section primarily deals with drinking-water purification, as aeration and sand filtration are the most common methods for purification of drinking water.

Drinking water comes from two sources:
- ground water, and
- surface water.

Table 5 below shows the proportion of ground water in the drinking-water supply of various countries in Europe. Ground water is clearly the primary drinking-water source.

Country	Proportion of groundwater
Belgium	67%
West Germany	64%
France	64%
Holland	59%
Sweden	25%
Switzerland	32%
Denmark	99%

***Table 5:** The proportion of ground water in the drinking-water supply*

A major explanation for this is the very widespread pollution of many of the earth's lakes and watercourses, that if of surface water. At a ground water well, however, you bring up ground water, which over many years has been filtered and purified in a natural way by passage down through the soil layers. As ground water is "prepurified" in this way the treatment is much less complicated than treatment of surface water.

In certain desert regions, where for good reasons no new ground water is formed, you can nevertheless fetch up water from underground. Submersible pumps bring up 1000-year-old water (fossil water).

2.2 Ground water

2.2.1 Introduction

To obtain ground water a borehole is drilled through the soil layers until the layer is reached from which the ground water can be extracted. A casing is inserted into the borehole to ensure that it does not collapse. A well screen, consisting of a slotted plastic tube surrounded by coarse sand and gravel (gravelling/packing), is positioned in the water-bearing zone. The water is normally pumped using a submersible pump. Piston pumps have also been used in the past. The water is conveyed from the borehole to the waterworks. Most waterworks have several boreholes. A collection of boreholes is called a well site. Very large waterworks have several well sites.

2.2.2 Treatment of ground water

In normal water treatment, first of all the iron, manganese and any gases such as methane, hydrogen sulphide and aggressive carbon dioxide are removed. In addition, oxygen is added to the water. The process is called aeration.

2.2.2.1 Aeration

Once the water reaches the waterworks, aeration is the first stage of the water treatment.
Ground water normally has a low oxygen content, or may be oxygen-free. To achieve a good taste it must have a minimum of 5 mg oxygen/l. Aeration may proceed by allowing the water to run freely from a sprinkler or down a cascade aerator. In this way it absorbs oxygen from the air. Another option is injection of air (by compressor) into the water. At newer waterworks pure oxygen is sometimes injected.

During aeration (degasification) it is possible to remove any hydrogen sulphide [H_2S], methane [CH_4], ammonium [NH_4^+] and aggressive carbon dioxide [CO_2], if the concentrations are not too high. High concentrations require special methods. For instance, the water would be treated with lime for high content of aggressive carbon dioxide.

Aeration also assists in removal of iron and manganese. Dissolved iron and manganese compounds in the water react with the oxygen to produce slightly soluble compounds that form "flakes" in the reaction vessel positioned under the aeration system. The iron compound is red (ferric oxide) and the manganese compound is black (manganese dioxide). Both compounds are subsequently "trapped" in the sand filter. With a high content of iron and/or manganese two sand filters are used, one after the other: A primary filter and a secondary filter.

2.2.2.2 Sand filtration

Sand filters, by far the simplest filter, are often constructed as open concrete tanks or open basins, with the filter layer set up in the bottom. A bar screen of reinforced concrete is covered by lay-

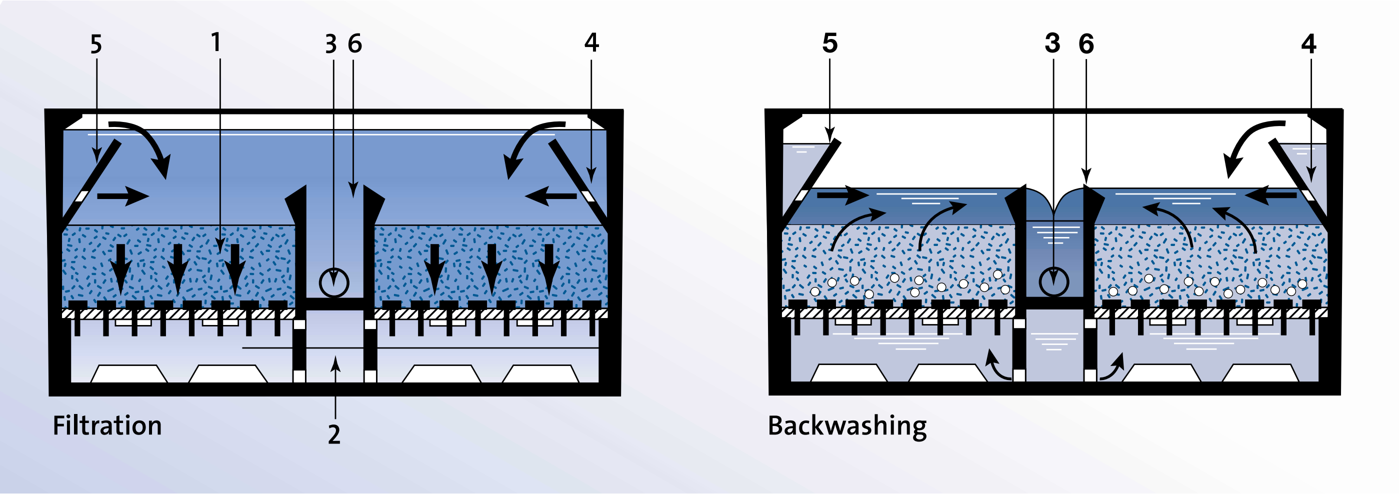


***Fig. 7:** Sand filter during filtration (left) and during backwashing (right)*

Pos.	Description	Pos.	Description
1	Filter sand	4	Jets for surface flushing during backwashing
2	Channel for filtered water (out) and rinsing water and possibly air (in)	5	V-shaped inlet for untreated water (raw water)
3	Draining valve for rinsing water	6	Overflow for rinsing water

ers of stones of decreasing grain size, ending with a top layer of sand, which provides the actual filtration, as the water, from its own weight (gravitation), sinks from above down through the filter layer. See Fig. 7.
Although the sand filter is designated as a mechanical filter, deliberate biological activity also takes place, as microorganisms develop in the top layer of the filter (the filter skin).

Cleaning of the sand filter: During operation the sand gradually becomes choked with sludge, and the filtration rate decreases sharply. At an appropriate time the filter should be cleaned, once the differential pressure is ~ 0.1 bar (1.45 p.s.i.), see section “3.4 Theory: Filter flow”. Water is directed through the filter from the bottom up, often at such a high speed that the sand is set in lively motion (the sand is fluidised), and the sludge that has stuck to the grains of sand is stripped off and washed away. This process can be accelerated by using compressed air together with the rinsing water. The process is called backwashing.

During the cleaning process the dirty rinsing water is directed to a number of basins where the sludge can settle. When, after repeated use, the settling basin has been filled up with sludge, the sludge is dug up and taken away.

Pump choice for sand filters: The filtration rate is between 7 and 20 m/h. The sand depth is around 1 m. Sand grain size is 0.7 – 2 mm. Filter area is up to 100 m^2 per basin.
A 100 m^2 basin will have a capacity from 700 to 2,000 m^3/h. A well site consisting of 4 to 10 large Grundfos pumps of the SP type would be able to supply a filter basin like this.

Pumps for backwashing are quite different. The flow here is from 7 to 15 $m^3/h \times m^2$ (+ air: 50 – 60 $m^3/h \times m^2$), so the flow for backwashing must be from 700 to 1,500 m^3/h, using only one pump. The head is just a few metres. A Grundfos pump of the NK type would be suitable.

2.2.3 Ground-water-based waterworks

Fig. 8 shows a schematic sketch for a complete waterworks based on ground water. Lime or leaching solution (sodium hydroxide) is added to the raw water to raise the pH value due to excessive carbon dioxide content. This also increases the precipitation rate of iron in the subsequent sand filter. To safeguard the water with regard to hygiene a dosing pump is used for dosing chlorine, and finally the pH value is adjusted with acid or leaching solution.

The treated water is stored in a clean-water reservoir, from where it is pumped to either a water tower, a pressure storage

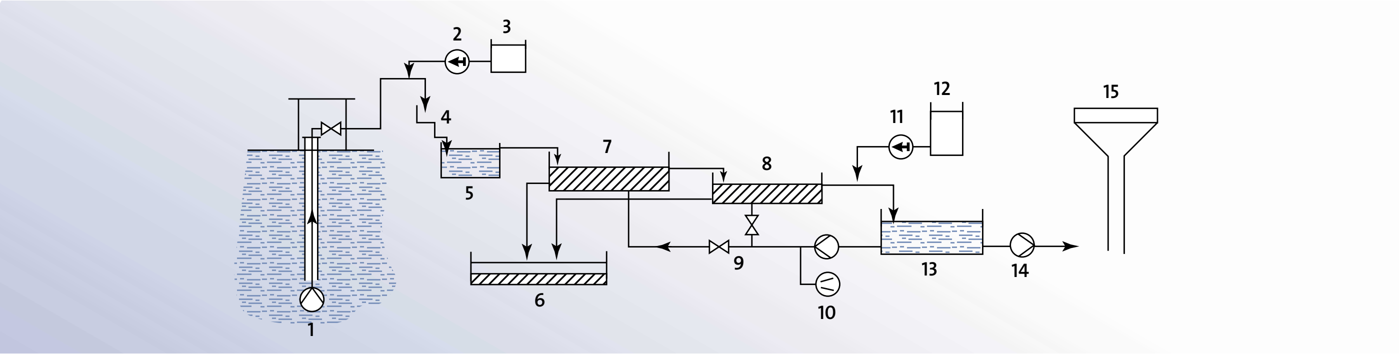


Fig. 8: Ground-water-based waterworks

Pos.	Description	Pos.	Description
1	Borehole	9	Backwashing
2	Dosing pump	10	Compressor
3	Lime tank	11	Dosing pump
4	Cascade aerator	12	Chlorine tank
5	Reaction vessel	13	Clean-water reservoir
6	Settling basin	14	Clean-water pump
7	Sand filter, primary filtration	15	Water tower
8	Sand filter, secondary filtration		

tank or direct out to the consumer using special pumping facilities, such as a booster system.

Disinfection of waterworks' water: Not all countries permit the use of chlorine in drinking water. It often gives a noticeable taste and smell. Chlorine is used in cities in particular, as the drinking water is often extracted from surface water and/or comes from far away. An alternative to disinfection of the water with chlorine that is in use today is ozone treatment and irradiating the water with UV light. See chapter "7. UV and Ozone".

Pump choice for treated water: CR or NK type pumps, often several in parallel with cascade operation. With water towers the pumps are level-controlled, and with hydrophores they are pressure-operated. In both cases one or more of the pumps may be frequency-controlled.

Corrosion in ground-water-based waterworks: The content of aggressive carbon dioxide in raw water means that it has a low calcium [Ca^{++}], magnesium [Mg^{++}] and bicarbonate [HCO_3^-] content. In other words, the water is also soft. This type of water can result in corrosion and the consequences are...

- solution of heavy metals in the drinking water.
- deterioration of the grid network and fittings.

At small waterworks the water is generally directed through basic filters that are closed tanks filled with granulated lime (e.g. calcined dolomite). The aggressive water reacts with the lime and forms bicarbonate in solution, and the pH value increases slightly. The lime gets used up and the tank must be replenished occasionally.
At large waterworks the lime is dosed as calcium hydroxide [$Ca(OH)_2$], either in dry form (powder) or in suspension (lime milk), directly into the raw water.

2.2.4 Sand filter in closed tank

Private and small public waterworks use sand filters in closed tanks instead of large, open concrete filters. Sand filters like this are also called rapid filters or pressure filters. The principle is the same: The tank has a sieve bottom covered with layers of gravel and sand, following the same concept as for the open filters. See Fig. 9. The raw water is directed in at the top and the filtered water is taken out at the bottom of the tank. During backwashing purified water (and possibly air) is directed in at the bottom of the tank, and the dirty rinsing water conveyed out at the top. As with the open filters, the first water after completion of the purification process is directed to the sewer. After a few minutes' operation the water is ready for delivery to the clean-water reservoir.

As the tank is closed it is possible to carry out the filtration under normal mains pressure, and it is also possible to utilise filter capacity better by continuing filtration up to a greater pressure drop across the sand.

The closed sand filter starts with a differential pressure (Δp), after cleaning, of 0.1 – 0.2 bar (1.45 – 2.9 p.s.i.) and finishes with a differential pressure, before cleaning, of ~1.5 bar (21.75 p.s.i.). The filtration rate goes up to 20 m/h, and backwashing is 1.5 to 2 times higher. The diameter ranges from approx. 0.5 m up to approx. 3 m. The material selection is usually glass-fibre reinforced plastic, coated or hot-galvanised sheet steel or stainless steel.

Fig. 9 shows a sand filter in a closed tank with accompanying piping and valve battery for routing water flow during operation and cleaning.

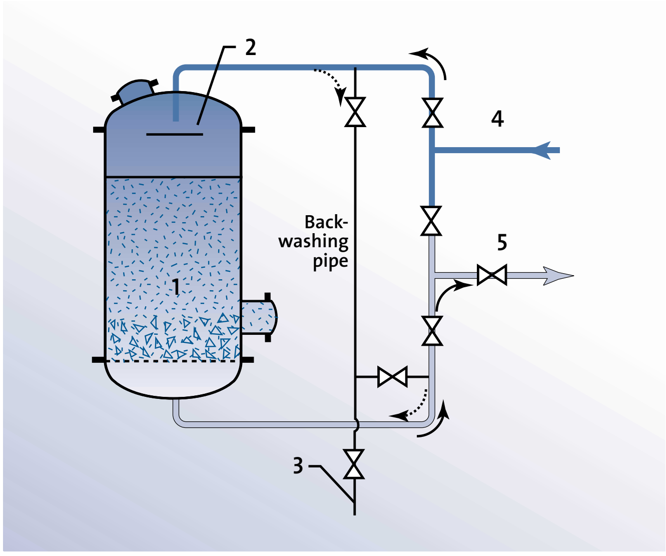


Fig. 9: *Sand filter in closed tank, pressure filter type*

Pos.	Description	Pos.	Description
1	Sand	5	Filtered water outlet
2	Distribution point	⟶	Direction of filtration
3	To sewer	- - -⟶	Direction of backwashing
4	Raw water inlet		

Cleaning of sand filter in closed tank: Sand filter tanks are often arranged with several in parallel operation. This makes it possible to backwash or clean one tank, while the others are in operation. If the number of tanks in parallel operation is sufficient, the purified water can be taken from the common collecting pipe and used for the backwashing. If the clean-water reservoir is too small, and the number of sand filters is also too small, i.e. less than 3 – 4, it is often necessary to have a separate pump for backwashing, and possibly a compressor.

Pump choice for sand filter in closed tank: Pump choice for a small waterworks is SP in the boreholes, CR or CRN in clean-water systems and CLM as backwash pump. As with large waterworks, in certain cases it may be necessary to use dosing pumps, DM.
For the clean-water pumps in a small waterworks a cascade set-up with frequency control on one or all of the pumps will often be best, particularly if the accompanying pressure storage tank is too small or it does not have one.

2.2.5 Organic substances in ground water

In rare cases organic substances may appear in ground water. Organic substances often alter the colour, taste and smell of the water and, moreover, can have serious health implications. The usual method for dealing with this problem is treatment in an active carbon filter. Many organic substances can be bound to the surface (adhesion) of carbon, and as active carbon has a very large surface area (1.2 km^2 per kg) it is well suited for this purpose.
The active carbon filter is constructed like a sand filter and operates in the same way. However, it is only an emergency solution when used for treatment of drinking water based on ground water. Active carbon filters are more common in the production of drinking water from surface water.

2.2.6 Corrosion connected with ground water

In the case of drinking water from ground water, only the water's content of aggressive carbon dioxide will cause corrosion of the pumps. If other corrosion-boosting ions, such as chloride, are present the water will no longer be described as fit for drinking water unless treatment methods other than those mentioned above (e.g. reverse osmosis) are introduced. If the water is aggressive, cast-iron pumps will be problematic. A stainless steel pump, on the other hand, will have great resistance to aggressive carbon dioxide.

If a well is near the sea or established in a saline soil layer, the water will be described as either brackish water or sea water. Drinking water production will then transfer to reverse osmosis or distillation. For more information on this, see chapter "6. Distillation".

2.3 Surface water

2.3.1 Introduction

A proportion of rainfall is absorbed by plants on the earth's surface, evaporates or percolates into underlying soil layers and forms ground water. The remaining proportion of rainfall flows from the upper layer of the earth's crust along watercourses into lakes and the sea. This is normally designated surface water.

Natural surface water almost always contains a mixture of dissolved suspended organic and inorganic substances in various quantities. These include salts, plant residues, clay, fertiliser residue, microorganisms, animalcules, humus and all possible decomposition agents from organic material. In addition, modern society contributes to this with various chemicals, sewage, artificial fertilisers and pesticides of all kinds.

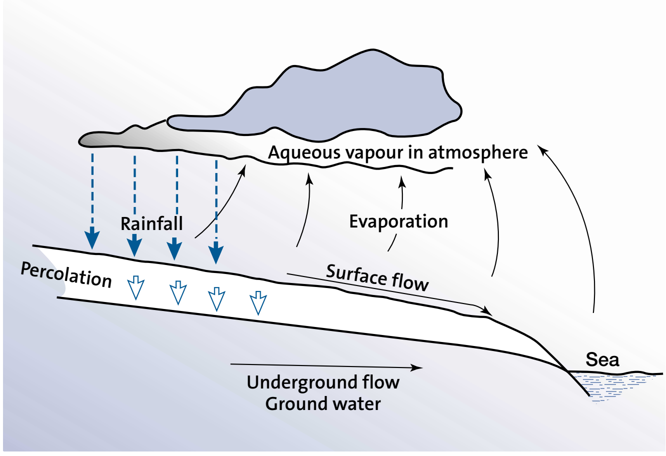


Fig. 10: *The natural cycle of water*

The pollution in major rivers around the world, which are widely used for water supply, is for the most part caused by effluent from both households and industry. In the last few decades agriculture has also contributed substantially to this. In some places the pollution in rivers is so severe that all forms of water treatment have been abandoned. It is simply too expensive to clean.

Production of drinking water from surface water is, all things being equal, significantly more complicated than production based on ground water. However, surface water can be clean and clear and ready to drink, e.g. in the form of a babbling brook or a clear forest or mountain lake.

2.3.2 Types of water treatment for surface water

Depending on the types of “pollution” the surface water contains, almost all imaginable forms of water treatment may be involved: Sedimentation, flocculation, sand filtration, standard filtration, ion exchange (softening), membrane filtration, distillation, active carbon, ozone, UV etc.

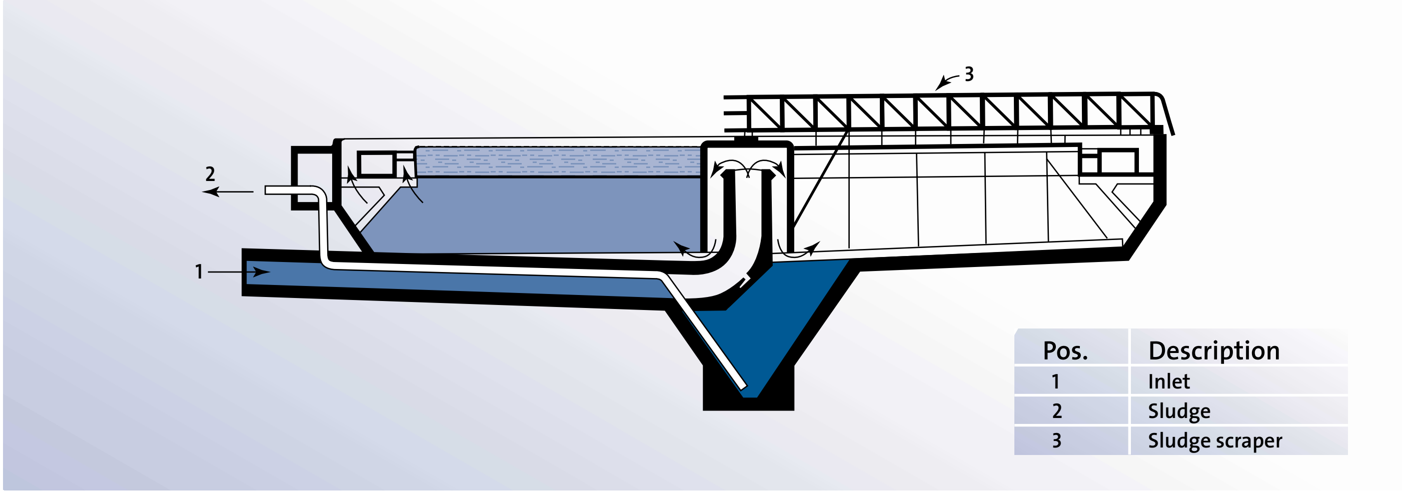
Surface water differs from ground water in the following ways:

1) Lower salt content.
2) Lower total hardness (typically below 10°dH).
3) Lower content of iron and manganese.
4) Higher $KMnO_4$ figure (COD and BOD).
5) Higher pH value, generally.
6) Discoloured, bad smell and cloudy.

2.3.3 Drinking water based on surface water

Production of drinking water based on surface water proceeds broadly as follows:

1) Pumping in of raw water from a river or lake. At the intake for raw water, which is located at or slightly above the bottom, is a coarse filtration system (bar screen with aperture size above 5 mm).
2) On land the raw water is directed to a sedimentation tank equipped with sludge scraper, where particles between 0.1 and 5 mm in size are deposited. See Fig. 11. Retention time 1 – 2 hours. An alternative to the sedimentation tank is filtration in a rotating drum filter (see “3.3.4 Drum filters”) with an aperture size of 100 – 200 µm, possibly followed by another drum filter of 25 – 40 µm.
3) After this, possible pre-chlorination can be carried out.



Pos.	Description
1	Inlet
2	Sludge
3	Sludge scraper

Fig. 11: *Sedimentation tank with sludge scraper*

4) Addition of flocculation chemicals (coagulants) for coagulation of colloidal particles in the raw water. The most widely-used flocculation chemicals are aluminium sulphate [$Al_2(SO_4)$], ferric chloride [$FeCl_3$] and various polymers of organic origin. Without the addition of flocculation chemicals, sedimentation of the colloidal particles would be practically impossible. The table below shows the settling time in water for some of the materials that are found in water.

Material	Size in mm	Settling time per m
Gravel	10	1 sec.
Coarse sand	1	10 sec.
Fine sand	0.1	125 sec.
Clay	0.01	108 min.
Bacteria	0.001	189 hours
Colloids	0.0001	755 days

***Table 6:** Settling time in water for selected materials*

The addition of the flocculating agents results in an increase in the electrical cohesive attraction between the colloids, after which they form flocks, which in turn by means of mass cohesive attraction agglomerate in even larger particles. An explanation for the behaviour of the flocculating agents is that, like the colloids, they are charged ions, but with opposite charge, and therefore form a kind of cement between the colloids (e.g. + – +), see section "8.5 Theory: Chemical treatment". The particles enlarged in this way subsequently have an acceptable settling time (3 – 4 hours). This can also be seen in Stoke's Law. A modified version of this is shown below:

Settling rate $$V = \frac{2}{9} \times \frac{g \times a^2 (d_1 - d_2)}{\eta} \text{ [cm/s]}$$

Where
g is acceleration due to gravity [cm/s^2]
a is the particle's size (radius) [cm]
d_1 is the particle's density [g/cm^3]
d_2 is the water's density [g/cm^3]
η is the water's viscosity [$dyne \times s/cm^2$]

The formula shows that the particle's settling rate is proportional to the square of the particle's radius, which of course is a great advantage seen in the light of the aforementioned formation of flocs and lumps during flocculation.The flocculation takes place during pH adjustment with the accompanying dosing equipment.

5) After vigorous stirring the water is directed to a settling basin, possibly equipped with sludge scraper. Retention time is 4 – 5 hours. These settling basins are also used within other variants of surface-water purification that combine chemical mixing, flocculation and sedimentation in one assembly. See Fig. 12.

6) Following precipitation further pH adjustment is performed before the water is clarified in a sand filter system like the type used for ground water treatment. See section "2.2 Ground water".

7) Unlike ground water treatment, surface water always has a disinfection process added in the final phase before the finished drinking water is pumped to the hydrophore or water tower. It is also fairly common for the treatment to conclude with flavour enhancement. This may involve dosing with potassium permanganate [$KMnO_4$], ozone [O_3] or chlorine dioxide [ClO_2].

An overall schematic sketch of a system for purification of surface water is shown in Fig. 13 The plant has a capacity of 3,800 m^3/h and is located near Paris, obtaining its raw water from the Seine. This is only one example. There are a large number of variants for purification systems for surface water.

Pump choice is as follows:

Raw water inlet:	SP in the river or NK on land (possibly with vacuum system for self-priming). Only small lift to overcome any friction loss, geometric difference of level and pressure loss in the filter before the first basin.
Dosing:	Unlike ground water systems, these have several dosing points, and several of these offer the option of dosing in liquid form (using dosing pumps).
Clean-water system:	Small plants - CR or CRN; large plants - NK. Pumps in cascade layout, possibly with frequency control on one or more of the pumps. Pressure or level control.

2.4 Environmental pollutants

Over the last half century pollution of many of the world's drinking-water resources has increased so much that in numerous places we have gradually become uneasy about drinking from them.
In adition to pollution of the surface water by the chemical industry in many places in the industrialised world, the intensive cultivation of the land is also causing growing pollution of the ground water. This is a question of pesticides and nitrate.

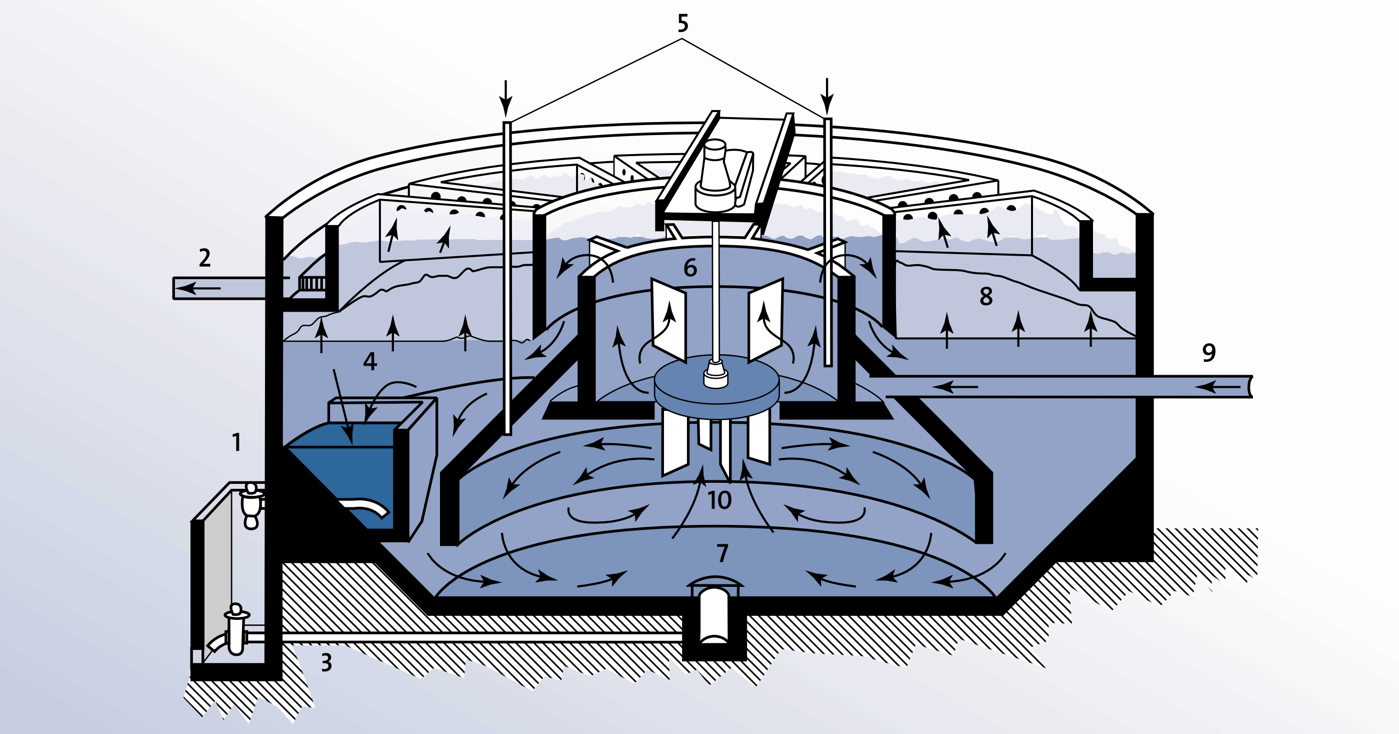


Fig. 12: Accelerator in which chemical mixing, flocculation and sedimentation take place.

Pos.	Description	Pos.	Description	Pos.	Description
1	Sludge drainage	5	Addition of chemicals	9	Inlet
2	Outlet	6	Secondary zone	10	Stirrer
3	Drainage	7	Primary mixing and reaction zone		
4	Concentrator	8	Clear water		

2.4.1 Pesticides and nitrate

Pesticides are crop sprays that are particularly used to combat weeds, fungus and insects. There is a huge number of these preparations, which are all chemical substances of widely different types.
Nitrate [NO_3^-] comes from fertiliser and is spread over the fields in the form of various nitrogenous artificial fertilisers, livestock manure and liquid manure.

A common feature of pesticides and nitrate is that they seep with the rainwater down to the ground water. Some of the substances are broken down completely or partially on the journey through the soil layers. Measurements have shown that rainwater seeps down through the earth at approx. 1 m/year in clay soil and approx. 3 m/year in sandy soil. Very deep wells are therefore barely affected yet. Slightly shallower wells in agricultural areas on light soils and small private wells in particular are affected. Some private wells have been abandoned for several years, and in recent years some medium-depth wells have suffered the same fate.

2.4.2 Phosphate

When talking about nitrate, phosphate [PO_4^{---}] should also be mentioned, as it often occurs together with nitrate, in artificial fertilisers, for instance. In addition, domestic detergents also have a high phosphate content. However, phosphate is transformed more quickly/easily than nitrate on the journey down through the soil layers, and is therefore hardly ever present in ground water. This is not the case with surface water. Here you will find phosphate, which together with all the other substances finds its way via small watercourses and rivers out to the sea, where they cause other kinds of pollution problems.

2.4.3 Localised pollution

Another source of water pollution is rubbish dumps, industrial properties and petrol stations. This is called localised pollution and can cause major problems in the delimited areas they occur in. Here the range of “toxic substances” is even greater than is the case with pesticides. On a worldwide scale it is estimated that around 80,000 different chemicals are in common use, and that the figure increases by 500 - 1000 new

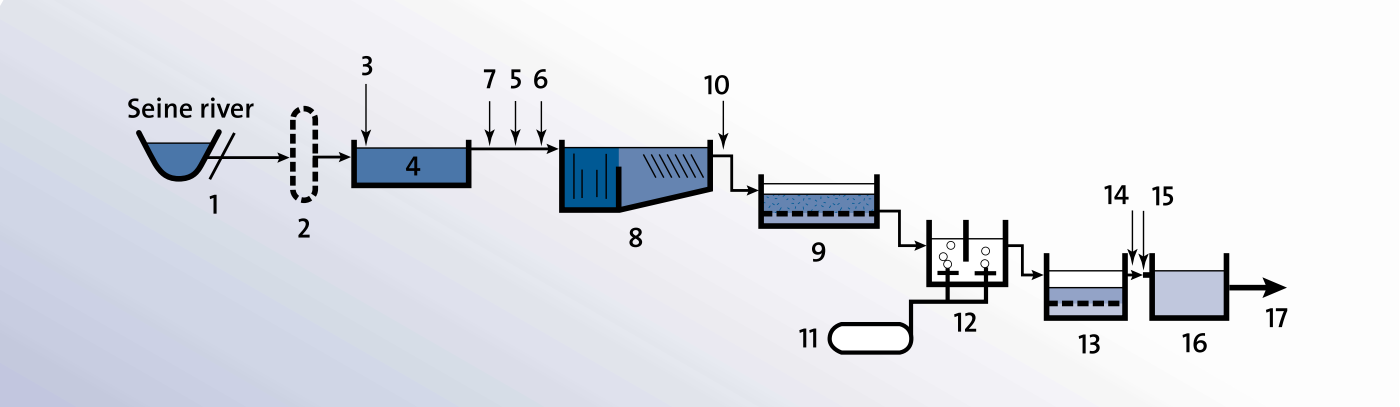


Fig. 13: *Purification of river water near Paris*

Pos.	Description	Pos.	Description
1	Coarse filtration	10	Dosing of flocculating agent
2	Macro-filtration (1.5 mm)	11	Ozoniser
3	Preliminary oxidation (chlorine)	12	Ozon dosing
4	Reaction vessel	13	Sand filter
5	Dosing of flocculating agent	14	pH regulation (dosing)
6	Auxiliary dosing	15	Disinfection (dosing)
7	Addition of active carbon (only in emergencies)	16	Clean-water reservoir
8	Settling tank (with lamella separator)	17	Pumping out of drinking water
9	Sand filter		

substances every year. It is obviously impossible to keep track of such a large number of chemicals and even more difficult to assign purification methods for just a small portion of them.

2.4.4 Can water treatment do anything about environmental pollutants?

Yes. But it is generally too expensive, and in some countries the authorities do not have a positive attitude towards water treatment due to the risk of infecting the water with pathogenic bacteria etc. They would rather abandon a resource, close a polluted borehole or dilute the water with water from a clean borehole nearby, in order to get below a specific threshold value.

At present we only know a little about how pesticides and many chemicals can be removed from drinking water, as the problem is still in the making, and therefore problem solving is postponed. Tests have shown that some types of pesticide can be removed using active carbon filters.
Nitrate is a different matter; it can be removed simply by means of reverse osmosis, ion exchange and denitrification.

Reverse osmosis and ion exchange are described later in the book. Both are characterised by the fact that they more or less remove all ions from the water being purified, which is not ideal. It means that the water lacks salts, which are important for good water quality. The water has an empty taste (flat taste). In addition, the ion-exchange process may risk adding microorganisms to the water, as ion-exchange material (like active carbon) is an excellent breeding ground for microorganisms.

In the case of ion exchange it is currently possible to produce ion-specific ion-exchange materials, i.e. the ion exchanger can only remove certain substances, e.g. nitrate. Great things are expected from this process in the future.

Reverse osmosis does not remove the nitrate. It ends up together with all the water's other natural salts in a partial current, the concentrate, and is transported to the sewer, for example. The other partial current (permeate/drinking water), which forms the greater part, has become nitrate-free.

In denitrification special bacteria are used that can convert nitrate into nitrogen. The nitrogen disappears up into the air, avoiding the problem of effluent. The process requires input of energy in the form of ethanol, methanol or acetic acid. This causes the problem of introducing bacteria into the waterworks operation. The presence of the microorganisms means that the water must be disinfected before distribution to consumers.

2.5 Process water

The aforementioned water purification methods can of course be used for water other than drinking water, namely for process water in industry.

The quality requirements for process water in industry vary greatly. Process water ranges from ultra-pure water in the electronics industry through slightly softened ground water for use in breweries to dirty water for rinsing or cooling purposes in large-scale industry.

The quantity of process water also varies greatly. Production of artificial fertilisers, paper and chemical products often uses huge quantities of water. The water can be taken from a river, used, cleaned and returned to the river. For the same reasons the type of water treatment will also be wide-ranging:

- Ultra-pure water for electronics manufacturing can be ground water that has been simultaneously treated by both reverse osmosis and ion exchange.
- Injection water in the pharmaceuticals industry, which can be ground water treated twice with reverse osmosis, before subsequently being sterilised by heat and irradiated with UV light.
- Surface water that has only been once through some drum filters, see section “3.3.4 Drum filters”, for application in the paper industry.

Within process water there are great capabilities with regard to pumps. There are far too many to list all of them here, but you can refer to the various types of water treatment described in this book, where you will find the accompanying pumps mentioned.

3. Standard filtration

3.1 Introduction

Standard filtration is a process in which solid particles are separated from either a gas or a liquid. As the topic of this book is water treatment, it only deals with particle separation in liquids.

Standard filtration is dead end filtration. See section "5.2 Membrane filtration is "cross-flow" filtration".

3.1.1 Filtration elements

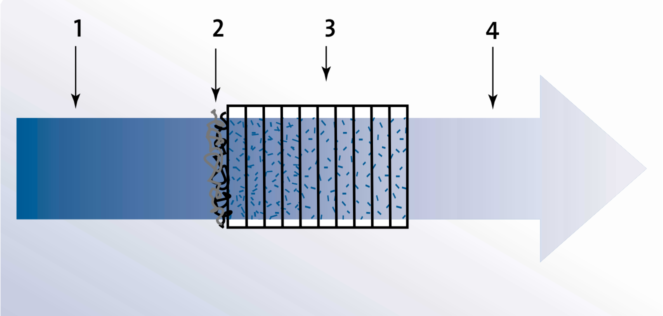


Fig. 14: *Filtration elements*

Pos.	Description
1	Liquid with suspension
2	Filter deposits (filter cake)
3	Filter (filtering medium)
4	Purified liquid (filtrate)

Separation in filtration is of a mechanical nature, as solid particles are retained by a porous filtering medium that the liquid is forced through. Driving pressure is required to "force" the liquid through the filtering medium, i.e. the system needs a pump of a certain size. In a few cases, where there is natural pressure in the system, e.g. from gravitational force, a pump will not be needed. For instance, if the supply is from a higher reservoir.

There are other methods for separating solid particles from a liquid, e.g. sedimentation or distillation of the liquid. See chapter "2. Aeration and sand filtration" and "6. Distillation".

Washing off the filter cake and cleaning the filter: The advantage of standard filtration is that the solid material (on the filter) can be washed. After completion of filtration, flushing out of the solid material is often required to either remove the original liquid and/or flush out any "impurities", using another liquid. Many mechanical filters can be reused after having filled up with solid material: The filter can be removed and washed, or backwashing can be carried out with the filtering medium still in place. The latter is called "Cleaning In Place" (CIP). Smaller types of filter, cartridge filters, are often disposable, i.e. they are replaced with a new one once blocked.

3.1.2 Types of filter

Filters can be divided into pressure filters (enclosed filters), where the liquid is forced through the filtering medium by means of pump pressure, and open filters, where the liquid passes down through the filter mass using gravity or a vacuum. In open filters the pump requirement will typically be reduced to simple transport of the liquid. The table below includes examples of both types of filter.

Pressure filters	Open filters
Bag filters Cartridge filters Centrifugal filters Filter presses Leaf filters Sand filters Slot filters	Band filters Drum filters Nutsche filters Sand filters

Table 7: *Examples of pressure filters and open filters*

3.2 Choice of pump for standard filtration

When choosing a pump for a filtration system, start with the filter supplier's requirements regarding initial differential pressure and terminal differential pressure, i.e. pressure before and after the filter (Δp) with new and used filters respectively.

Filter suppliers emphasise that the user should not burden the filter too heavily right from the start (See section "3.4 Theory: Filter flow"), and consequently often give a max. initial value for Δp. This value is typically 0.1 to 0.3 bar (1.45 – 4.35 p.s.i.).

Fig. 15 shows a simplified diagram of a specific filter and a pump. The pump in the example will produce a head that can be expressed by the formula: $H = (p_2 - p_0 + \Delta p) \times 10.2$ [m].

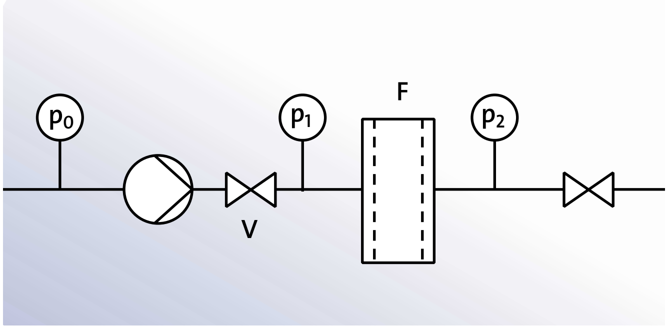


***Fig. 15:** Simplified diagram of filter and pump*

Pos.	Description	Pos.	Description
p_0	Feed pressure	V	Valve
p_1	Pump pressure	F	Filter
p_2	System pressure		

In Fig.16 we see a Q-Δp curve for a random selection of filters, all having the same physical dimensions (10”), but with different pore sizes, see section “3.4 Theory: Filter flow”. It also shows a single Q-H curve (top right) for a CR pump. In this instance it is a CRN 2-20.

From the graph we can see that even the smallest CRN 2 is too big, unless p_0 is relatively small and p_2 is relatively large, or the excessive head can be restricted over the valve (V) after the pump. The best solution would naturally be a frequency-controlled pump that makes the valve unnecessary and thus ensures optimal operation without a regulating valve.

Example of calculation for choice of pump, small filters:

Ex.: p_0 = 3 bar (43.5 p.s.i.), p_2 = 3.5 bar (50.75 p.s.i.), Δp = 0.2 bar (2.9 p.s.i.) and Q = 40 l/min. (= 2.4 m^3/h).

The necessary head for the pump is: H = (3.5 – 3 + 0.2) x 10.2 = 7.1 m.

CRN 2 – 20 at 2.4 m^3/h produces approx. 12 m, i.e. the difference of 4.9 m (= 12 – 7.1) can subsequently be suitably restricted by the valve V.

Fig. 30 shows that it is desirable to follow the differential pressure, Δp curve, over time. With the valve you can regulate the differential pressure to 0.68 bar (9.86 p.s.i.) (= 0.2 + 4.9/10.2), which will be quite suitable for the filter’s final state.

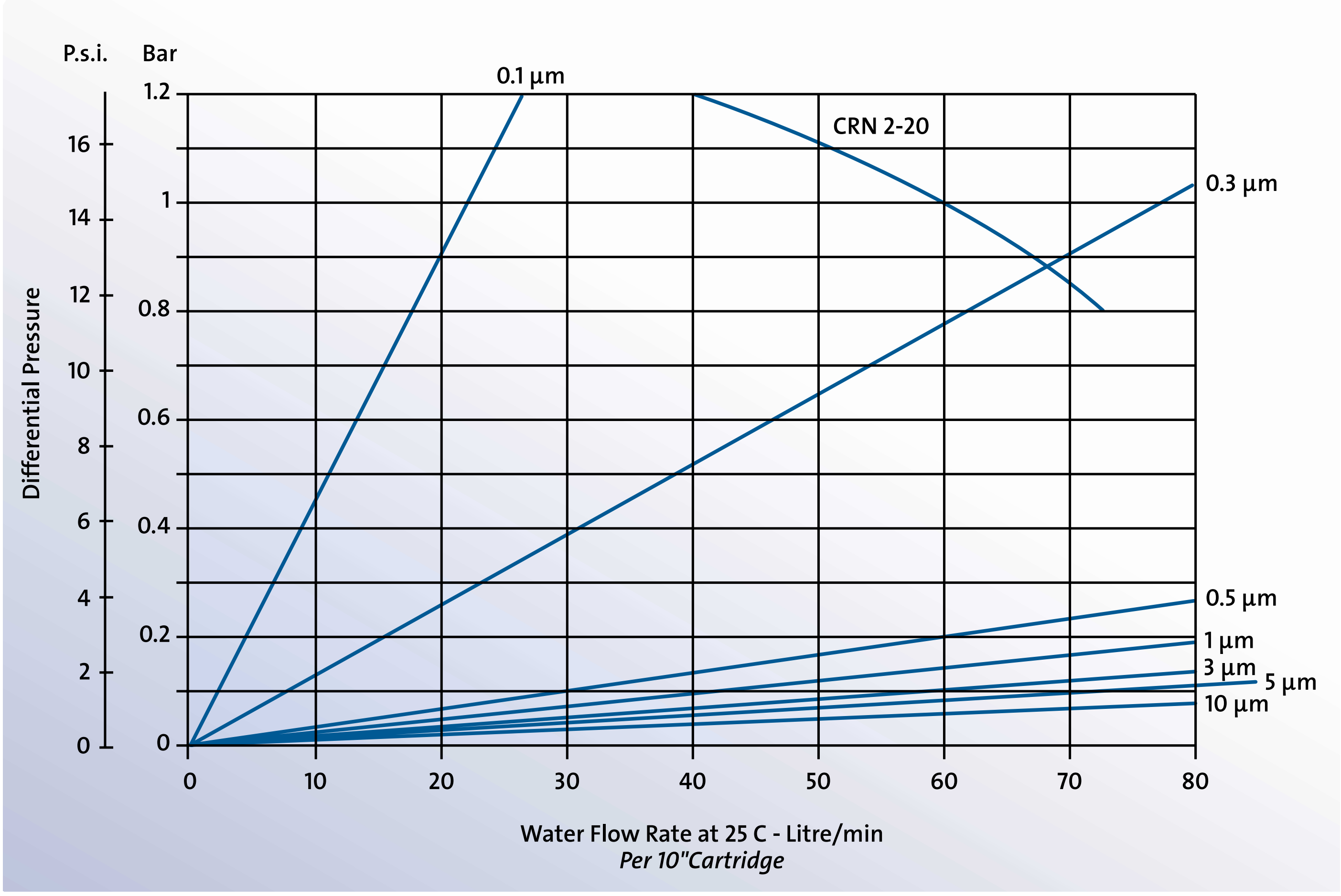


***Fig. 16:** Example of filter and pump curves*

This regulation will be economically disadvantageous for the customer. As the customer will hardly want to devote equipment to monitoring the Δp's progress over time in order to interrupt filtration if the curve shoots up, the supplier recommends an initial differential pressure and a terminal differential pressure. It is often around 1 bar (14.5 p.s.i.), so the slightly larger pump, CRN 2-30, will be more suitable, and the valve V would restrict the pressure even more throughout the entire process. Therefore a decision is often made to install a pump that is slightly too large and accept the fact that the filter will not be running at optimum for the entire processing time.

Large filters: For larger filters the frequency-controlled pump solution will naturally be best, as it will be a more economic solution in the long term.

Filters for relatively high Δp values: Many of the standard filters are also available designed for relatively high Δp values (higher than stated above). For instance, they are available equipped with strong support/stiffening material and can withstand drops in pressure of several bars without breaking down. A special type of filter in this context is the tubular slot filter, see section "3.3.3 Slot-filters". In this type of filter the filter cloth and stiffening material are the same, and the filter's degree of fineness is therefore never under 25 µm.

3.3 Types of filter for standard filtration

This section analyses the following types of filter: Cartridge filter, bag filter, slot filter, drum filter and band filter.

3.3.1 Cartridge filters

Application of cartridge filters: Cartridge filters are often used as a preliminary filter and/or safety filter prior to further, more advanced, water treatment such as membrane filtration.

Structure of cartridge filters: Cartridge filters are the most common filters. They occur in many different versions, with filter housings of cast iron, steel, stainless steel and various synthetic materials. External connections are generally via pipe thread. Specific types may have flanges, clamps and sanitary connections, primarily with filter housings of stainless steel. One feature common to all of them is that the actual filter element is mounted inside the filter housing, like a cartridge, and can easily be replaced by dismantling the housing.
The filter element is shaped like a cylinder with a fixed diameter and various lengths. These are typically 10", 20", 30" and 40". The external diameter of the cartridge is around 64 mm. There is usually only one filter element in each filter housing, but there are also filters with a larger number of elements installed in parallel in a large filter housing. See Fig. 17 and 18.

***Fig. 17:** Cartridge filter: The cartridges are produced either as a compact unit of felt or spun to look like a reel of yarn.*

***Fig. 18:** Several cartridge filters mounted in a filter housing*

Types of cartridge filter: Cartridge filters can be surface filters like a filter cloth, but are usually depth filters, i.e. the suspension penetrates the filter element, going in deep, and in this way contributes to a greater extent to the actual filtration. This can be an advantage in itself, but is also a drawback, as it makes the cartridges unsuitable for backwashing or washing. Only in particular instances of shortages of new cartridges, or if economising is necessary, will the cartridges be washed.

Cartridge filter materials: The material selection for cartridges covers a huge range. The most common materials are polypropylene, cotton, polyester, nylon and glass-fibre yarn. The wide range of materials for cartridges combined with the fact that the filter housing is also available in a variety of materials means that with regard to corrosion a cartridge filter can almost always be obtained for any kind of medium. In this context there will often be other components in a specific installation, such as a pump, that will be the limiting factor.

Fig. 19: Selection of cartridge filters

Filtration grade of cartridge filters: The filtration grade ranges from a bacteria size of around 0.5 µm to around 100 µm. From here on it is a matter of sieves, and the filter holes are visible to the naked eye.

The curves in Fig. 16 show typical performance curves for a randomly-selected cartridge filter, and the picture in Fig. 19 shows a selection of cartridge filters.

3.3.2 Bag filters

3.3.2.1 Bag filters, general description

When the load is too great for a cartridge filter, i.e. when the medium contains many particles to be filtered, a bag filter is often selected. As well as having a large filter surface, a bag filter also has the capacity to hold a large quantity of dirt in the bottom of the bag. In addition, a bag filter solution is less costly than a cartridge filter solution.

Application of bag filters: The spheres of application are the same as for cartridge filters.

Fig. 20: A row of bag filters mounted in a filter housing

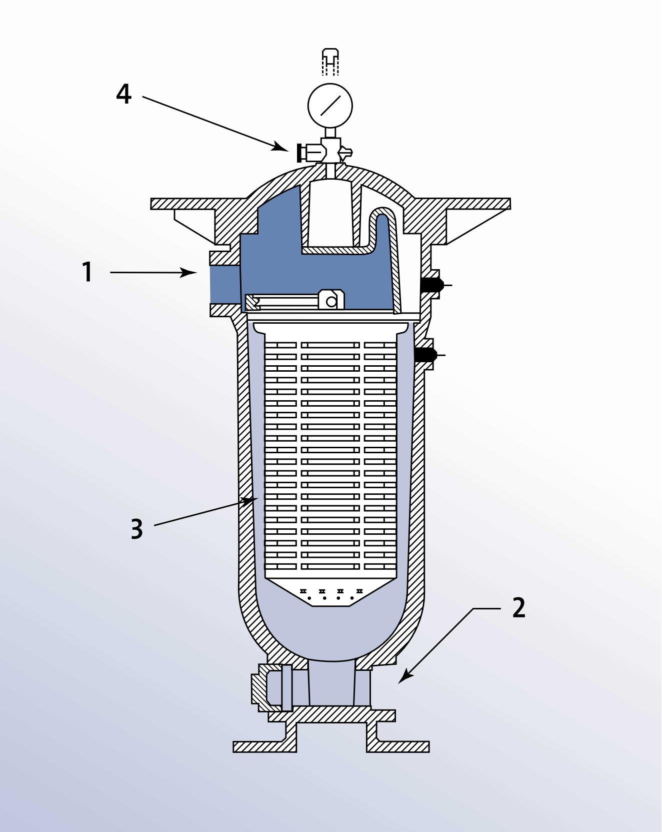


Fig. 21: Sectional drawing of bag filter

Pos.	Description
1	Inlet for untreated water
2	Outlet for purified water
3	Basket with filter bag
4	Valve for venting

Structure of bag filters: The bag is a filter cloth (surface filter) shaped like a bag and mounted inside a sturdy filter basket that functions as a support.
Fig. 21 shows a sectional drawing of a bag filter: The liquid enters at the top via (1), and is conveyed down into the bag, which is fitted inside the basket (3). After passing through the bag and basket the filtrate leaves the filter at the bottom via (2). At the top is a valve (4) for ventilation of the filter housing prior to commissioning.
The largest of the filters is 1.2 m in height and has a filter capacity of approx. 25 m^3/h.
Bag filters are also supplied in rows, with several bags in a large filter housing. These can easily achieve a capacity of several hundred m^3/h. See Fig. 20.

Bag filter materials: As with cartridge filters, the filter housings and bags are available in a wide range of materials.

Filtration grade of bag filters: The degree of fineness ranges from approx. 0.5 µm to 100 µm.

Re-using the filter bag: An interesting feature of a bag filter is that the bag is easy to clean for re-use (5-10 times). Some filter bags can be cleaned in a washing machine. Others cannot, as the fibres break down, affecting the bag's filtration properties.

Choice of pump for bag filters: The calculation for choice of pump is as for cartridge filters, and as described in section "3.2 Choice of pump for standard filtration".

3.3.2.2 Bag filters for off-line purification in district heating mains

Structure of off-line purification systems: A special kind of application of bag filters is off-line purification in district heating mains. Off-line filters are installed parallel to the main return pipe, and 5 to 10% of the medium is directed through this filter and back into the main pipe. In this way the water in the system is continuously purified of small and medium-sized impurities. To drive the filter process a circulator pump is installed ahead of the filter.

Fig. 22 shows a system of this kind.

Note: The connections to the district heating main are at the bottom, so that as much dirt as possible comes down into the filter.

Installing a permanent magnet (e.g. Neodymium) in the off-line filter clearly increases its efficiency by retaining magnetic and erosive particles generated within the system, i.e. magnetite and small iron particles detached from the pipe system or that come from machining in manufacture or maintenance of the district heating system.

Fig. 22 also shows a dosing system for pH regulation of the district-heating water: A dosing pump adds leaching solution or acid controlled by a pH meter with a pH electrode installed in a bypass pipe above the actual filter.

Instead of - or, even better - together with a bag filter, it can be advantageous to employ reverse osmosis in off-line filtration of district-heating water. The purpose of this is to reduce the content of dissolved salts.

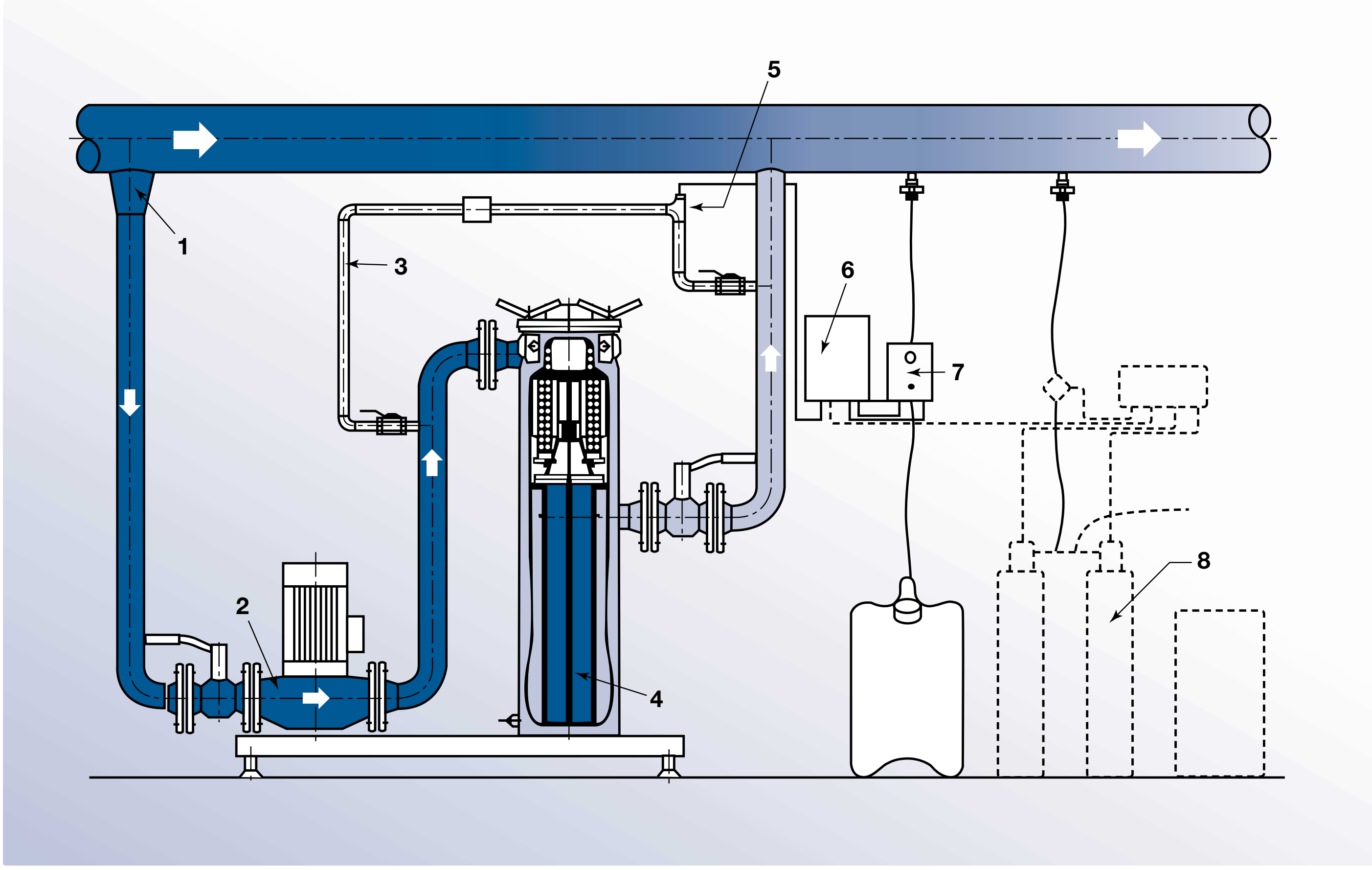


Fig. 22: *System for off-line purification in district heating main*

Pos.	Description	Pos.	Description
1	Connection at bottom of district heating main	6	pH-value gauge
2	Circulator pump	7	Dosing pump for addition of leaching solution or acid for regulating pH value for district-heating water
3	Bypass pipe	8	Other type of dosing
4	Bag filter		
5	Electrode for pH regulation		

Advantages of off-line purification systems:
An off-line filter offers the following advantages:
- Removes particles from the system.
- Extends the life of most installed instruments.
- Ensures correct readings from instruments and energy gauges.
- Counteracts erosion in the system.
- Minimises under-deposit corrosion in the system.
- Minimises galvanic corrosion in the system.
- Increases the time between servicing of pumps, thermostats and other components with moving parts.

Choice of pump for off-line purification system: A cast-iron pump will be adequate for an off-line filter (the district heating main is steel piping). The initial differential pressure will typically be 0.1 – 0.2 bar (1.45 – 2.9 p.s.i) and the terminal differential pressure, before the bag filter is cleaned or replaced, will be around 1 bar (14.5 p.s.i.). This will mean a diminish-ing flow over time. Users of these systems would like to see a constant flow over time, and frequency-controlled pumps have opened up this possibility.

3.3.3 Slot filters

3.3.3.1 Tubular slot filters

Application of tubular slot filters: A tubular slot filter, as shown in Fig. 23, is often used as a safety filter, and as such is built into a string of piping.

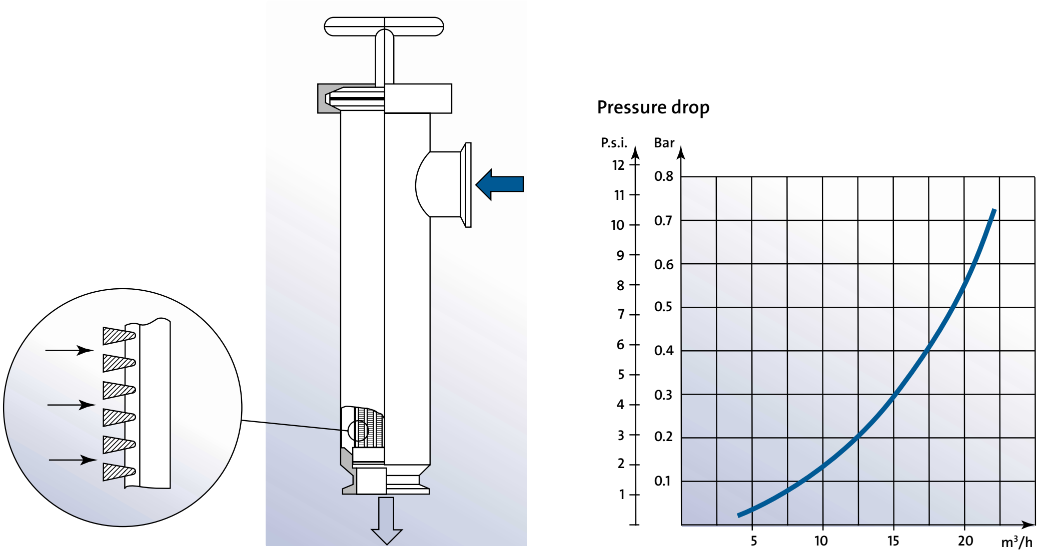


Fig. 23: Tubular slot filter with accompanying Q-Δp curve

Structure of tubular slot filter: Slot filters are usually called tubular slot filters, since for strength reasons they are tube-shaped. The direction of flow in the slotted tube can be either from the outside in or from the inside out. The slots in the tube are wedge-shaped, with the narrower end of the wedge turned towards the liquid stream, see Fig. 23. This minimises the risk of blockage of the slot.

Thanks to a very robust construction tubular slot filters can withstand high system pressure. The filter shown in Fig. 23, with stainless-steel housing, can withstand up to 80 bar (1160 p.s.i.). The direction of flow is from the outside in.

Filtration grade of tubular slot filters: Tubular slot filters are more of a sieve-type filter, as their degree of fineness ranges from 25 µm upwards.

Tubular slot-filter materials: The filter housings are often cast iron, steel or stainless steel and the slotted tube is stainless steel.

Tubular slot filter curve: The fact that tubular slot filters are open like a sieve means that their Q-Δp curve does not follow Darcy's law, see "3.4 Theory: Filter flow", and have a straight course, but on the contrary follows the law of flow resistance in general, with a parabolic course ($\Delta p = k \times Q^2$). Fig. 23 shows a tubular slot filter with accompanying Q-Δp curve, which is distinctly parabolic.

Choice of pump for tubular slot filters: Pump calculations do not apply for tubular slot filters, and the pressure drop across the filter is less important than with other types of filter, as they are easy to dismantle and quick and easy to clean.

3.3.3.2 Self-purifying tubular slot filters

Self-purifying tubular slot filters have certain requirements with regard to the accompanying pump's pressure (and flow). Inlet pressure of min. 4 bar (58 p.s.i.) is very common. This requirement is due to the fact that the self-purifying process (back-flushing) requires a certain pressure. To establish this pressure it may be necessary to install a separate pump that only handles the back-flushing. In the latter case the pump-pressure requirement will be slightly higher (min. 5 bar (72.5 p.s.i.)).

Applications of self-purifying tubular slot filters: The spheres of application include coolant for engines and generators, and process and wastewater in the chemical and petrochemical industries.

A special application is preliminary filtration of bog water for the production of drinking water, prior to further treatment, in which humus is removed, e.g. membrane filtration (nano-filtration). Installations of this kind are widely used in Norway, and in this case centrifugal pumps (CRN) are the obvious choice. As the filter can withstand fairly high operating pressure, it will be possible to use one and the same pump for input to both the preliminary filter and the membrane system (the pressure after the preliminary filter will be sufficient for the membrane system). Fig. 24 shows a self-purifying tubular slotfilter.

Mode of operation of self-purifying tubular slot filters: See Fig. 24. During operation the liquid is supplied to the filter via a common inlet (1) to the internal sides of a large number of concentrically-positioned slotted tubes (2). The filtrate collects in a large shared chamber (3) and leaves the filter via a common outlet (4). When the pressure drop across the slotted tubes reaches a certain value, or when indicated by a timer, a gear motor located on top of the filter will start the back-flushing: In one tube at a time the filtrate (flushing liquid) is now forced through from the outside in, and takes the dirt with it down through the interior of the tube to a rotating unpressurised port (5) linked to atmospheric pressure. The entire cleaning process takes only 13 sec. (standard setting), during which all the tubes, except the one being back-flushed, will be in normal filtration mode. So the filter can continue normal filtration during the entire back-flushing process.

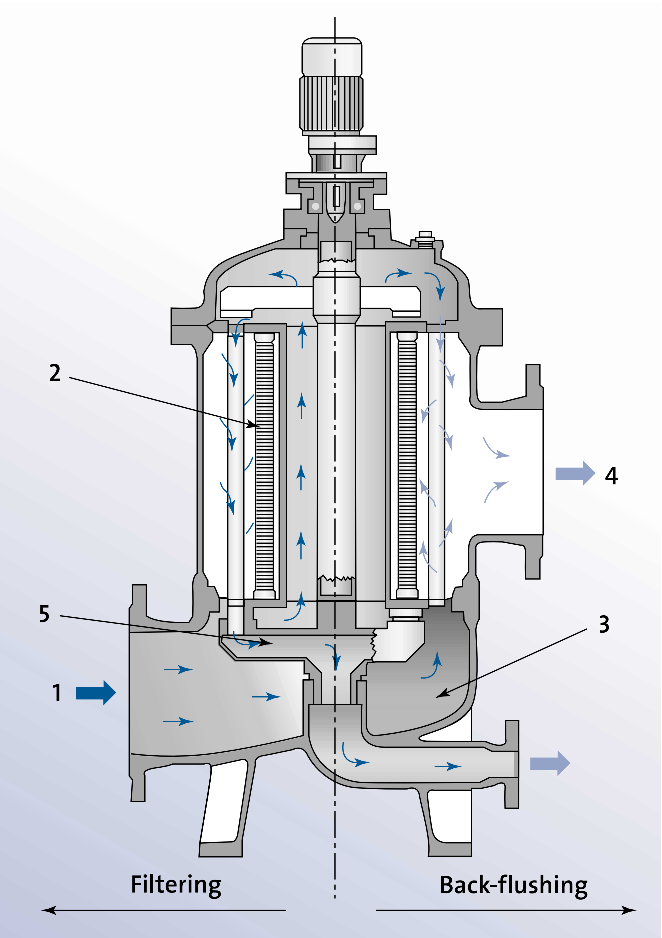


Fig. 24: Self-purifying tubular slot filter

Pos.	Description	Pos.	Description
1	Inlet for untreated water	4	Outlet for purified water (filtrate)
2	Slotted tube	5	Rotating unpressurised port
3	Shared chamber		

Filtration grade of self-purifying tubular slot filters: Self-purifying tubular slot filters have a degree of fineness down to approx. 50 µm and capacities up to several thousand cubic metres per hour.

Pressure drop across the filter: The pressure drop across the filter during operation is between 0.1 bar (1.45 p.s.i.) and 0.5 bar (7.25 p.s.i.). Max. operating pressure: 25 bar (362.5 p.s.i.).

Self-purifying tubular slot filter materials: The material selection is stainless steel for the slotted tubes, and welded sheet steel and cast iron for the housing.

3.3.4 Drum filters

Drum filters are often designated continuous rotating filters and, in contrast to older types of filter such as filter presses and leaf filters, which are chargeable working filters, require much less effort. However, they are very costly and are therefore primarily used for large-scale production requiring good utilisation.

Application of drum filters: A typical application is filtration of large volumes of surface water and process water in industry, where the water in question is not particularly polluted, as a drum filter is not suitable for slow-filtering liquids. A major reason for this is that the pressure drop across the cloth/sieve can only be measured in a few cm of water column.

Structure of drum filters: Fig. 25 shows a simplified diagram of a drum filter. The water is directed into the interior of the drum (1) and filters through the sieve (2) to the external side of the drum, from where it runs away freely. The sieve is kept clean by the sprinklers (3) that continuously backwash it. The dirty backwash water runs away down the channel (4).

Choice of pump for drum filters: Pumpwise it is a question of possibly transporting the water to and from the filter drum. Pump requirements will often concern material selection and shaft seal. The latter can be problematic, when the water, as is often the case, contains vegetable fibre. A typical example of this is the paper industry, where large volumes of process and rinsing water are pumped round in connection with production.

The Oliver filter: Another type of rotating drum filter is the Oliver filter. In an Oliver filter the drum has a partial vacuum inside, and the cake builds up on the outside of the drum as it rotates, submerged in the liquid to be filtered. The filter is equipped with a scraping device for continuous abrasion of the cake. Sprinklers for continuous washing of the cake can also be fitted.

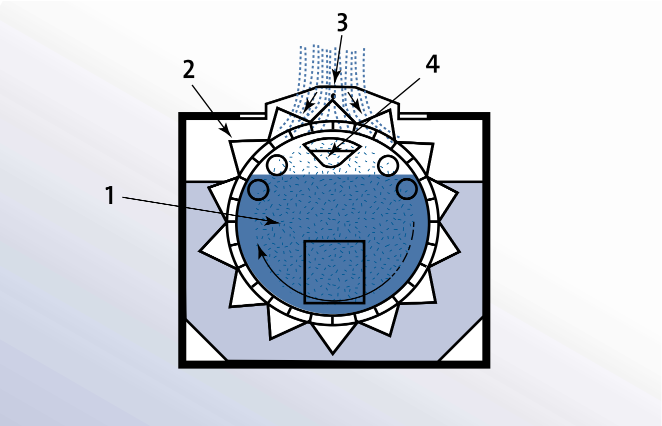


Fig. 25: *Schematic sketch of drum filter*

Pos.	Description	Pos.	Description
1	Inside of drum	4	Channel for dirty backwash water
2	Sieve		
3	Sprinklers		

3.3.5 Band filters

Band filters of the nutsche type are often used as pre-filtration for other types of water treatment, e.g. reverse osmosis and nano-filtration. Band filters only filter by gravitation, as the liquid level above the filter cloth is sufficient to maintain the necessary pressure drop across the cloth. When the liquid level above the cloth gets too high the filter cloth rolls forward slightly, new cloth comes into operation and the liquid level falls. This automatic forward movement of the cloth is controlled by a simple float function via a microswitch for the propelling motor.

The filter cloth is made from synthetic fibres in many variants and is suitable for almost all possible forms of liquid. It is shaped like a roll of paper and is positioned in one end of the filter device. During operation it rolls across a strainer to the other end of the device, where the dirt is scraped off, and finally the cloth is rolled up like used “paper” on another roll.

The material selection in band filters is AISI 304.

Capacities range from ~0 to 500 l/min per unit. The filtration grade goes down to 10 µm.

In addition to the aforementioned application in membrane filtration, band filters are also used for treatment of cleaning water in the food processing industry, chemical industry, car washing plants, spray booths, tanning industry, plastics industry and filtration/recycling of cutting coolant at plants carrying out machining/cutting.

Choice of pump for band filters: The pumps are usually immersible pumps of the SPK or CRK type designed to operate in applications with abrasive particles.

Fig. 26: *Central system with two bands, holding tank, cooling system and pumps*

3.4 Theory: Filter flow

This section explains the following:

- filter permeability
- the significance of the filter area in filtration
- the significance of the liquid temperature in filtration
- the significance of the filter scaling and fouling
- pulsating filter operation.

During a filtration process the liquid will flow through the filter cake and filter cloth, through more or less fine pores, and you can therefore assume that the liquid flow is laminar and follows the general equation (Poiseuille’s) for laminar flow. The formula is a general one and can be used for many other types of filtration.

$$\frac{\Delta p}{L} = k \times \frac{V \times \eta}{D^2}$$

Where:

Δp = pressure drop across the filter [N/m^2]
L = the porous channel lengths through the filter [m]
k = a proportionality factor
V = the liquid’s linear speed in the channels [m/s]
η = the liquid’s dynamic viscosity [kg/ms]
D = pore diameter (hydraulic diameter) [m]

3.4.1 Filter permeability

Some of these parameters are obviously difficult to measure. Therefore a more practical and common way of describing the phenomenon is by using the term "filter permeability", which expresses the filter's ability to transport the liquid through it. High permeability means easy passage for the liquid and low permeability means difficult passage for the liquid (great resistance).

According to Darcy's law this interrelationship can be expressed as follows:

$$\Delta p = \frac{1}{\alpha} \times \frac{Q \times \eta \times t}{A}$$

Where:

Δp = pressure drop across the filter [N/m^2]

α = the permeability coefficient
(1/α is the filter's resistance figure, often designated R)

Q = flow through the filter [m^3/s]

η = the liquid's dynamic viscosity [kg/ms]

t = the filter thickness [m]

A = the filter area [m^2].

If you look through brochure material for standard filters, you will find this formula in an even more simplified version or merely depicted as simple curves corresponding to installation characteristics in Q-H curves. The curves are related to individual types of filter with curve variants as a result of:

1. Filter size (area).
2. Liquid temperature.
3. Time for or degree of contamination.
   Note: Contamination depends on the composition of the feed (suspension) to the filter and the resulting build-up of the filter cake and/or blockage of the actual filtering medium.

3.4.2 The significance of the filter area in filtration

Fig. 27 shows a typical course for a filter curve. One curve for each area size (A). Note that the curves consist of straight lines, unlike pipe characteristics, for example, which are arc-shaped curves (parabola). The reason for this is that the transport of liquid, as mentioned, is through fairly narrow channels, resulting in laminar flow. The Poiseuille equation, and therefore also Darcy's law, indicate precisely the equation for a straight line when α, A, η and t remain constant. R (1/α) will thus be the line's slope. The straight lines in Fig. 27 actually only indicate the filter's initial state, i.e. the filter's Q-Δp curve when starting with a "fresh" filter. In other words, before deposits begin to build up. The curves will be true over time, if, for example, the water to the filter is pure and at a constant temperature the entire time.

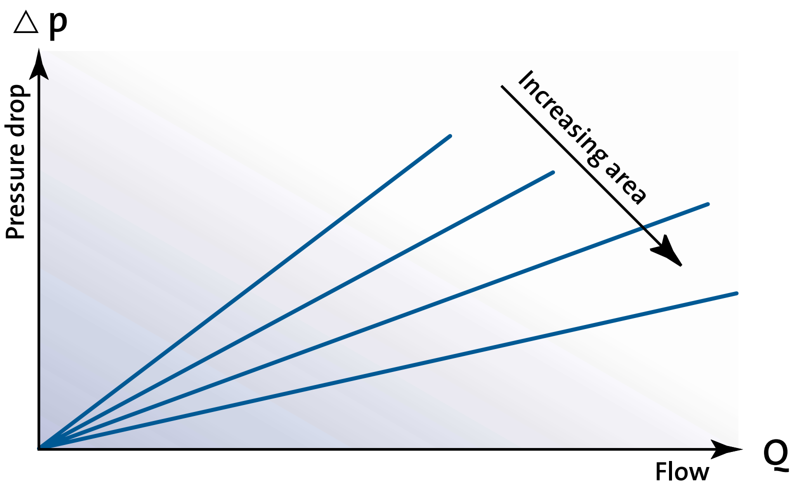
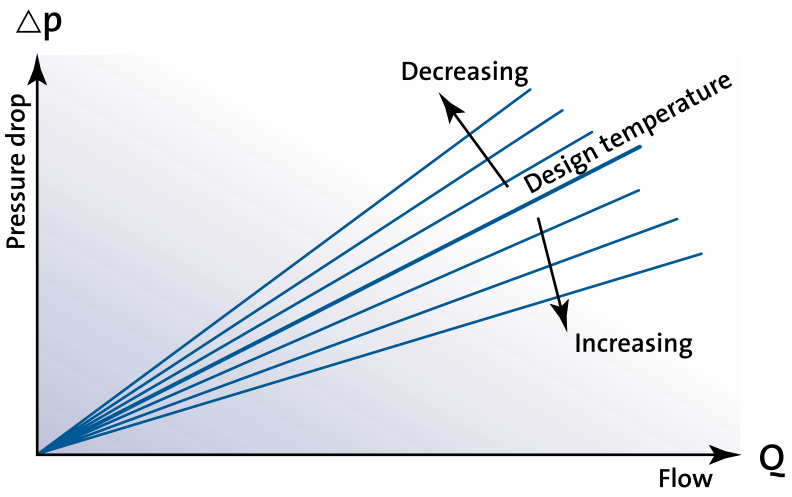


Fig. 27:
Pressure drop for various filter areas

Note: The pore diameter is constant

Fig. 28:
Pressure drop for various liquid temperatures



3.4.3 The significance of the liquid temperature in filtration

Fig. 28 shows Q-Δp curves dependent on temperature for one filter size (fixed A): Higher temperatures mean lower pressure drop across the filter and lower temperatures higher pressure drop above the filter. The explanation is quite simple: The viscosity of a liquid is inversely proportional to the temperature, and if you look at Darcy's equation above, it shows that the differential pressure will increase with increasing viscosity, and accordingly with falling temperatures.

3.4.4 The significance of the filter scaling and fouling

Fig. 29 shows changes in pressure drop as a result of time under the effect of scaling and/or blockage of the filter medium. In Darcy's equation the increase in differential pressure can be interpreted as an increase in the filter thickness (t) and/or deterioration in the permeability i.e. a greater resistance figure (R).
What happens is build-up of the filter cake (t increases) and compression of the cake, whereby the pores become smaller (R increases).

Fig. 29:
Influence of the filter cake on pressure drop over time

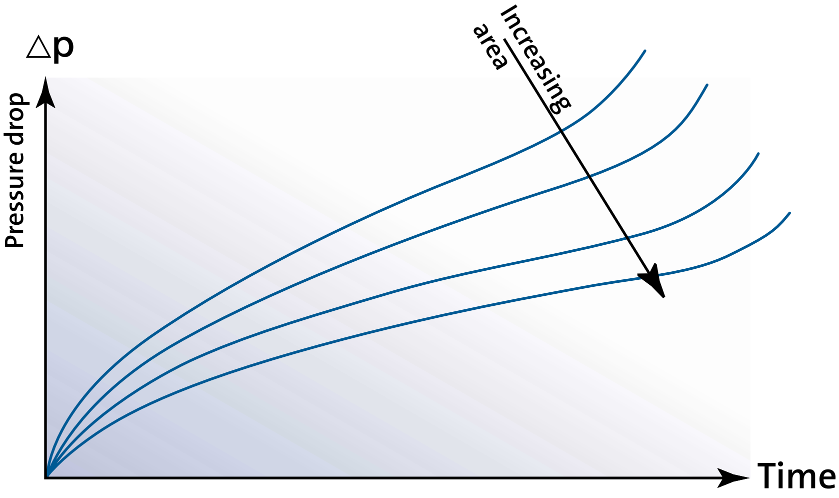
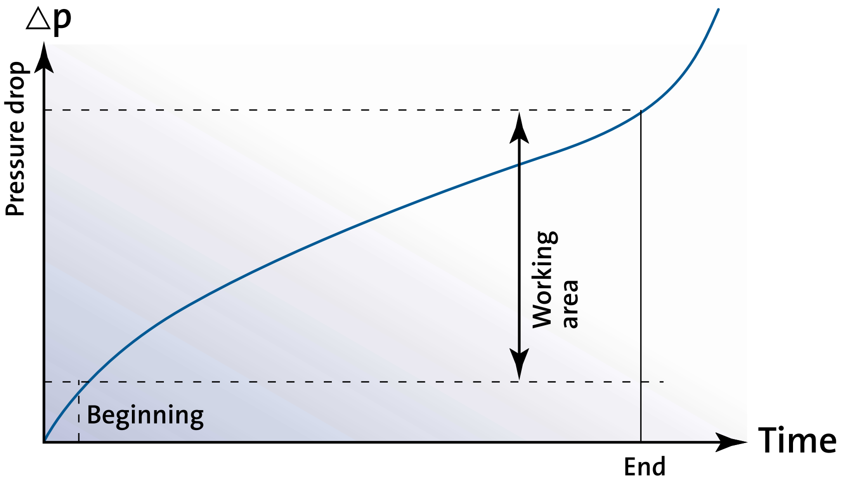


Fig. 30:
Working area for filter with cumulative filter cake



To begin with, the curve rises relatively quickly as the "fresh" filter rapidly builds up a cake or a slight blockage of the filter medium before subsequently increasing its filtering resistance at a slower rate. When we reach the point where the curve begins to rise sharply, the filter must be replaced, backwashed or washed. Fig. 29 also indicates several filter areas (various A values) to show that a larger filter, for the same capacity, has a longer life: With constant feedwater composition and temperature a specific flow will result in lower filter strain, and consequently slower formation of cake and naturally also slower head-loss increase across the filter.

The next curve in this series, Fig. 30, shows the same as Fig. 29, but here an adequate working area for the filter is marked: The actual filtration starts once the filter has built up its "initial cake" and ends when the pressure drop rises relatively steeply. The corresponding Δp limits can be appropriately monitored by specially designed pressure alarms.

A good pump solution for this kind of filter is a constant-pressure-controlled pump. This could be a frequency-controlled pump with a stop/alarm for the upper Δp limit. The new frequency-controlled pumps open up the possibility of this type of control. The flow of the filtered liquid will usually be controlled by the requirements of the subsequent apparatus and by the inlet pressure to the filter. And it will naturally result in a very variable flow through the filter, and consequently variable strain on the filter. This in itself is undesirable. However, it must be remembered that the quantity of "dirt" the filter collects in total is unchanged, and only the operating time changes.

The previously mentioned phenomenon can be understood by looking at Fig. 31, which is constructed in the same way as Fig. 30: Greater flow through the filter can only be generated by an increased Δp. This means that the curve will also be higher on the diagram, and the time (T_2) that elapses before the upper limit (blockage of filter) is reached is visibly shorter than previously (T_1).

Fig. 31:
Increased differential pressure results in comparatively quicker blockage of the filter

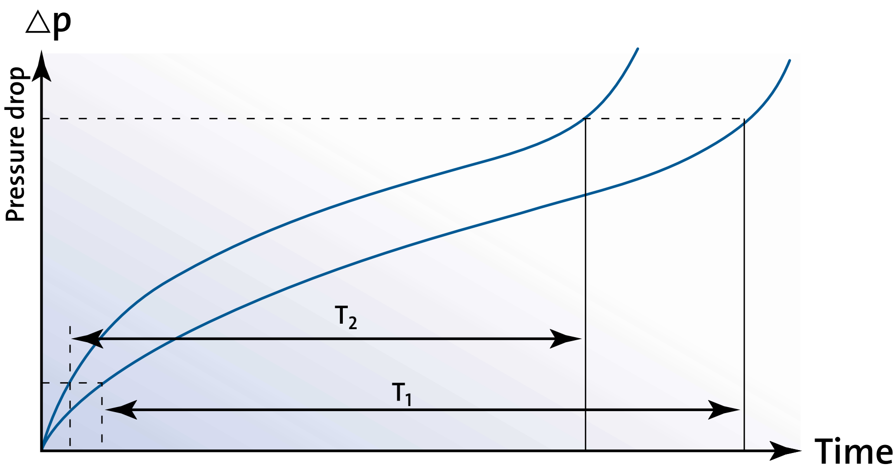
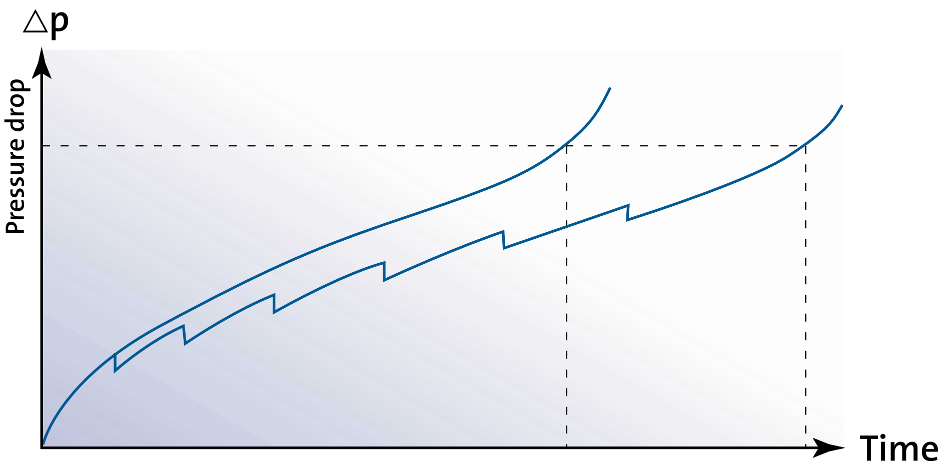


Fig. 32:
Pulsating filter operation extends the filter's process time



3.4.5 Pulsating filter operation

Standard filtration is often called "Dead End Filtration", because the suspended particles end up in the filter, unlike membrane filtration (Cross-Flow Filtration), for example. With membrane filtration the flow-off is divided into two streams, whereby the suspended particles are continuously washed away.

Nevertheless a little of this rinsing process can be achieved by introducing pulsating filter operation. In this way it is possible to constantly loosen a little of the cake on the filter, which subsequently falls to the bottom of the filter, where it collects in a reservoir. In this way the process is extended, as shown in Fig. 31. The filter's process time (before replacement or cleaning) is significantly extended, as shown in Fig. 32.
Note: This result can only be achieved with filters where the impurities rest on the surface of the filter, i.e. not with depth filters.

A frequency-controlled pump can provide pulsating operation. In the case of operation with several filters in parallel, pulsating operation can be achieved by alternating operation.

4. Ion exchange

4.1 Definition

Ion exchange is a reversible process in which ions are released from an insoluble permanent material (resin) in exchange for other ions in a surrounding solution; the direction of the exchange depends upon the affinities of the ion exchanger for the ions present, and the concentrations of the ions in the solution.

4.2 Introduction

Even though the principles of ion exchange were discovered and investigated more than 125 years ago and were first used commercially for conditioning of water around 95 years ago (1905), proper application only really got going within the last half of the century. Many natural materials display the ability to exchange ions. These include green sand, clay, sulphonated carbon and peat.

Natural soils contain solids with charged sites that exchange ions, and certain minerals called zeolites are quite good exchangers.
Ion exchange also takes place in living materials because cell walls, cell membranes, and other structures have charges. In natural water and in wastewater, there are often undesirable ions and some of them may be worth recovering. For example, cadmium ion is dangerous to health but is not usually present in concentrations that would justify recovery. On the other hand, silver ions in photographic waste are not a serious hazard, but their value is quite high. In either case, it makes sense to substitute an ion such as sodium for the ion in the wastewater.
However, it was only in 1944, when D'Alelio developed the first synthetic ion exchange materials (resins), that modern use of ion exchange really picked up.

4.2.1 Resins

Resin beads are formed by suspension polymerisation of styrene and divinyl benzene as a cross-linking reagent with an organic peroxide catalyst. Beads 0.5 to 2 mm diameter are formed in this manner. The ion exchange sites are introduced into the beads by a further chemical reaction stage.
The resin is contained in a tank or vessel, see Fig. 34, equipped with valves, piping and other components necessary for proper operation. These vessels are commonly referred to as columns.
Depending on the type, the raw water is directed through the vessel either from above and down, from the bottom and up or from the middle up and down. Once the resin's capacity has been exhausted (saturated), the activity of the resin has to be restored (regenerated) before reuse. See section “4.2.3 Regeneration”.

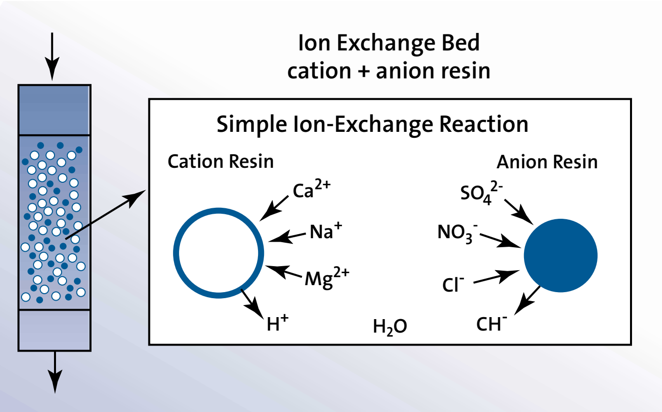


Fig. 33: *The principle for demineralization in a double ion-exchange system*

4.2.2 The ion exchange process

In water treatment this process adds and removes ions from water. In general the resin is used as the exchange site. The resin is permanently charged and attracts ions of the opposite charge. Each ion in the water has a different affinity for the resin. Those with greater affinity will replace those with less affinity.

Resins are basically classified as either cationic or anionic. See Fig. 33. The choice of resin for a particular application will depend on the ion or ions to be removed and recovered, and the chemistry of the process.

The anion resin exchanges anions in solution for other anions from the resin in the ion exchanger. In **demineralisation**, for example, bicarbonate [HCO_3^-], chloride [Cl^-] and sulphate [SO_4^{--}] anions are removed from the solution in exchange for a chemically equivalent number of hydroxide anions [OH^-] from the anion exchange resin. See Fig. 33.

Further in demineralisation, for example, calcium [Ca^{++}], magnesium [Mg^{++}], sodium [Na^+] and potassium [K^+] anions are removed and exchanged for a chemically equivalent number of hydrogen cations [H^+] from the cation exchange resin.

The cation resin exchanges cations in solution for other cations from the resin. See Fig. 33.

In **softening**, calcium [Ca^{++}] and magnesium [Mg^{++}] are removed from a solution in exchange for a chemically equivalent number of sodium anions [Na^{+}] from the anion exchange resin.

4.2.3 Regeneration

Before reuse the resin must be regenerated using a solution containing the ion initially present in the resin. The basic operating cycle consists of:

- **Service cycle:** The solution to be treated is passed through the column until the resin is saturated.
- **Backwash cycle:** Water is flushed through the column in reverse direction to the service cycle to redistribute the resin.
- **Regeneration cycle:** A solution rich in hydrogen ions [H^{+}] (or [Na^{+}] in case of softening) such as 10% hydrochloric acid [HCl] or 4% sulphuric acid [H_2SO_4] is passed through the cation resin. The concentration of hydrogen ions in the acid solution is high enough to force any other cations off the resin in preference for the hydrogen ions. The anion resin is treated with 5% sodium hydroxide [NaOH] so that its exchange sites are loaded with hydroxyl ions [OH^{-}]. The direction of flow is generally in reverse of the service cycle.
- **Rinse cycle:** Water is passed through the exchanger to remove excess regenerant.

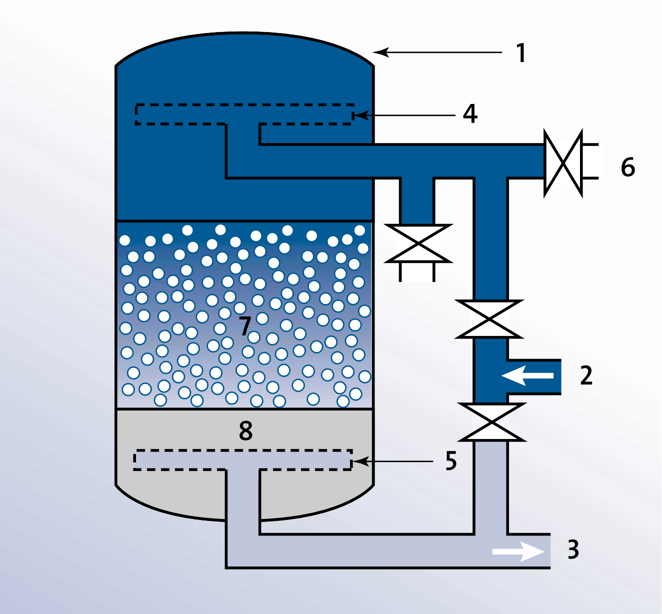


***Fig. 34:** Standard ion exchange vessel*

4.2.4 Application of ion exchange

Ion exchange is widely used today...

- for softening of water (calcium and magnesium are replaced with sodium)
- for the production of demineralised (deionised) water (such as feedwater for high-pressure boilers)
- for production of pharmaceutical products
- for purification of chemicals
- in analytical chemistry
- for process water in general.

In rare cases ion exchange is used for treatment (softening) of drinking water.

For softening only cation exchange is used, whereas for demineralisation both cation and anion exchange is used.

Using a suitable combination of softening, cation and anion exchanger and degasification of carbon dioxide an extremely high degree of purity can be achieved for the purified water. Measured by the water's conductivity, it can be as low as 0.1 µS/cm.

As the ion exchange resin, as mentioned, becomes saturated and must be regenerated now and again, ion exchange is not suitable for desalination of water with a high content of salts, as is the case with brackish water and sea water. In such cases reverse osmosis and distillation will be used.

4.3 ion exchange systems for industrial purposes

Two-bed systems consist of two separate pressure vessels; one holding the cation resin, and the other holding the anion resin. This design results in longer service between regenerations, and simpler operation. Installed in multiple units, two-bed systems can provide continuous service without down-time for regeneration. When one system is regenerating, the others can provide 100% of the required flow.

Pos.	Description
1	Vessel
2	Inlet for raw water
3	Outlet for treated water
4	Raw water distribution unit
5	Collection conduit for treated water
6	Inlet for regeneration liquid
7	ion exchange resin
8	Base (gravel)

The installation of mixed-bed ion exchange units after two-bed systems also increases system capacity and further raises water purity. See section "4.3.2 Total desalination of water in mix-bed ion exchanger".
Standard packaged deionizers are supplied with either manual or automatic regeneration controls. Standard packaged deionizers are skid-mounted, fully assembled and include the necessary piping and valves to begin immediate operation.

4.3.1 Total desalination of water (demineralisation, deionisation)

The most common purpose of the application of ion exchange is desalination of water containing not too large a quantity of salts, e.g. production of boiler feed water from drinking water.

The schematic sketch in Fig. 35 shows this type of system with a deaerator for carbon dioxide positioned between the cation and anion exchanger. The carbon dioxide is released in the acidic environment in the cation exchanger and is subsequently degassed so that the anion exchanger is not unduly overloaded. From the boxes on the sketch you can see the chemical sequences involved in the process. The result is pure, desalinated water [H_2O]. It can produce demineralised water with a conductivity of less than 0.1 µS/cm.
For comparison with this, drinking water typically has a conductivity of 100 – 800 µS/cm and sea water a conductivity of 50,000 µS/cm.

4.3.2 Total desalination of water in mix-bed ion exchanger

Total desalination can also take place in mix-bed ion exchangers. Here both a cation exchanger and an anion exchanger are incorporated into the same tank. During operation the two ion exchange resins are mixed, but before regeneration takes place they are separated, and each regenerated with their own chemical reagent. Separation is performed by directing water in at the bottom of the tank at such a rate that the ion exchange resin floats (fluidises). As the small ion exchange beads differ in buoyancy, depending on whether they are cation or anion exchangers, they will stratify into two layers, and regeneration can now proceed by means of a manifold ("split flow system") centrally located in the tank. Before the tank begins normal operation again the cation and anion exchangers are mixed by adding air at the bottom of the tank. See Fig. 36.

4.3.3 Removal of silica

Silica [SiO_2] has historically created problems for water treatment because of its stability as an un-ionized compound, making it difficult to remove using ion exchange processes. It can even cause a certain level of resin fouling. As a result, silica can only be effectively removed if the ion exchange resins are completely and properly regenerated.
For heavy-duty steam boilers for turbine operation the content of silica [SiO_2] is particularly critical (silica can form undesirable

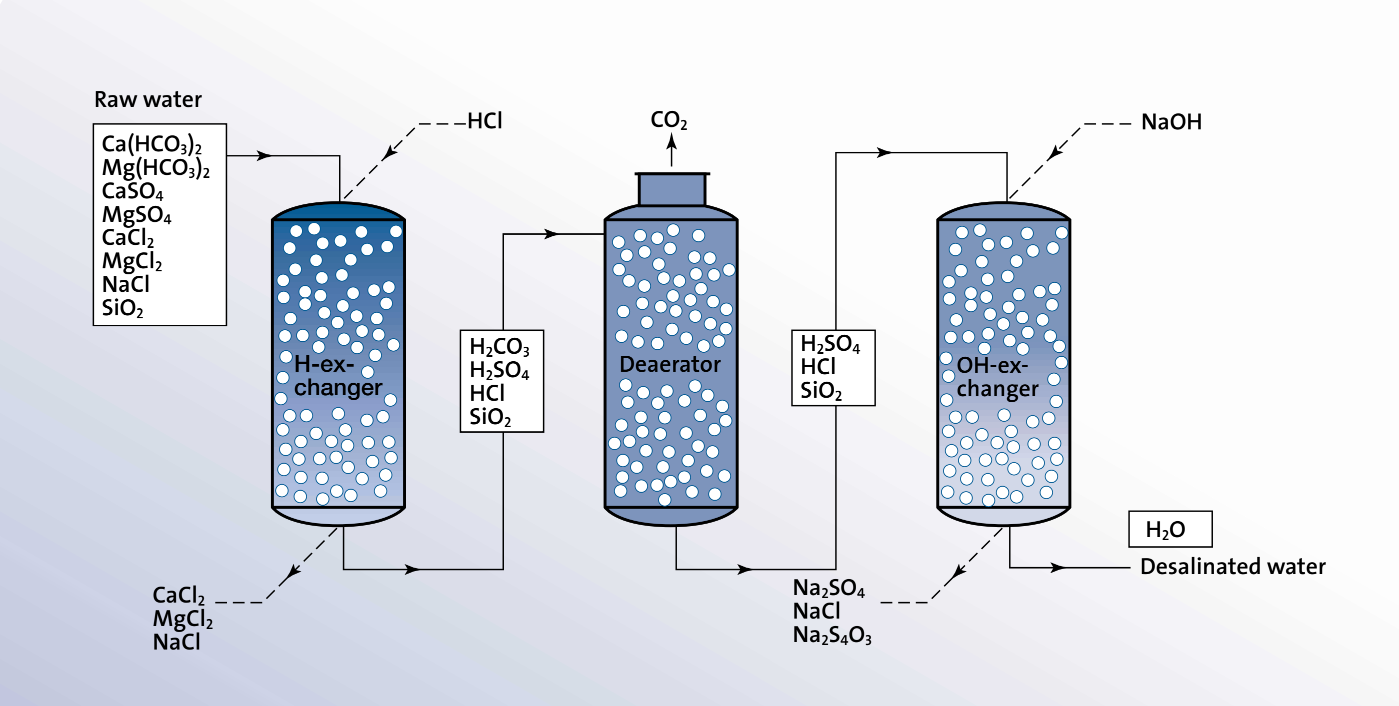


Fig. 35: Schematic sketch of a cation and anion exchanger with CO_2 deaerator

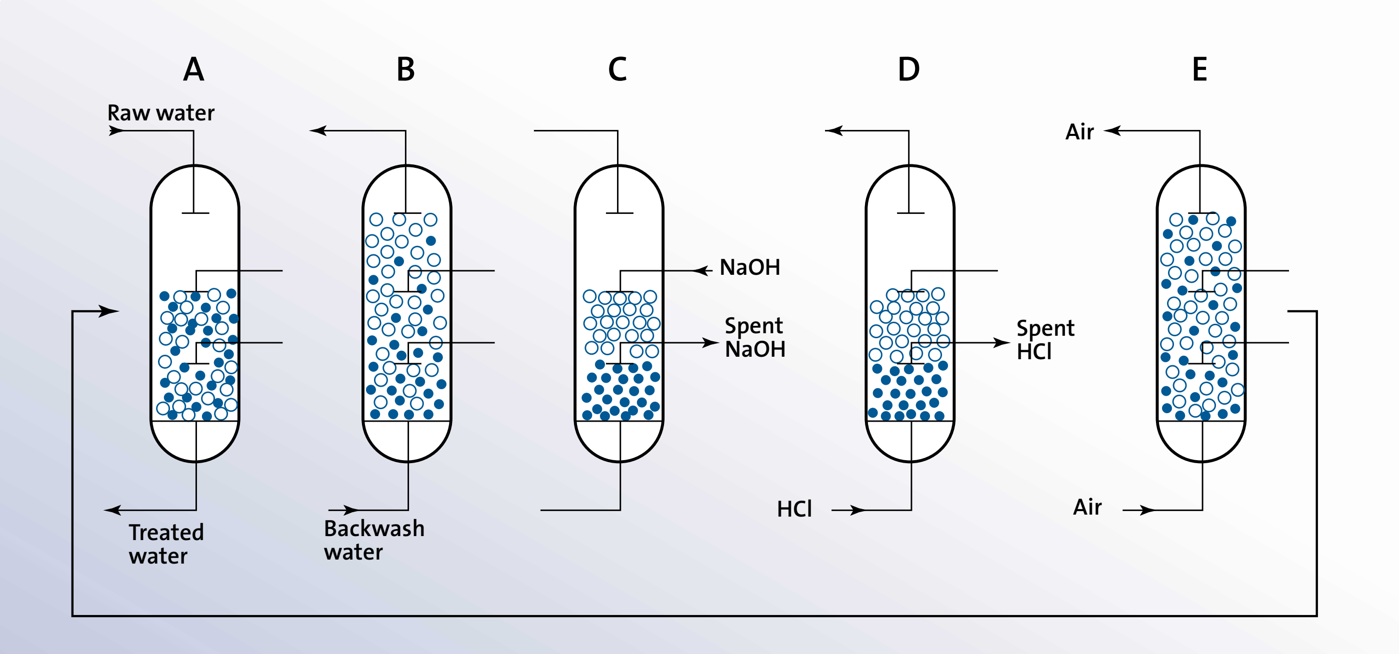


Fig. 36: *Cycle in a mix-bed ion exchanger*

Pos.	Description	Pos.	Description
A	Operation	D	Regeration of cation exchange using hydrochloric acid
B	Seperation (statification) of resin with water	E	Mixing of resin with air
C	Regeneration of anion exchanger using sodium hydroxide		

deposits on the turbine blades), so the ion exchanger contains extra ion exchangers positioned in series for the purpose of reducing the silica content as much as possible.

4.3.4 Structure of industrial ion exchangers

Large-scale ion exchange systems: Standard ion exchange systems for industrial purposes, once they reach a certain size, will be constructed from several tanks connected in parallel (a number of cation exchangers in parallel with a number of anion exchangers in parallel). The anion exchangers are connected in series with the group of cation exchangers. In this way the system can be kept in continuous operation, as there will always be one or more of the tanks in each group in the regeneration process. With an appropriate system of pipes and valves you can direct the liquid flow of raw water, deionate (treated water) and regeneration liquid to the required locations at the same time without disrupting operation.
With fully-automatic operation, valves are often all air-operated and controlled from a panel with accompanying gauges for achieving the correct quality and quantity of water.

Fig. 37 shows an industrial system of this type with CO_2 deaerator.

Fig. 37: *Standard ion exchange system for 2 x 10 m^3/h for industrial application. The pumps in the foreground ensure the pressure after the deaerator and before the anion exchangers. The pumps are stainless steel, as the water is aggressive.*

Fig. 37: The system's air-operated adjustment valves are partially hidden between the two rows of tanks. There are 12 fibre-glass tanks in total with 4 valves each.

Very large ion exchangers: The very large ion exchange systems can be equipped with a large number of parallel and series-connected strong and weak cation exchangers, strong and weak anion exchangers, deaerators and mix-bed ion exchangers, plus traditional treatment of the raw water consisting of a variety of mechanical filtration, flocculation and sedimentation.
This can result in demineralised water of a high quality:

- conductivity of 0.05 – 0.1 µS/cm
- a silica [SiO_2] content of 5 – 55 µg/l, and
- a pH value of 7.

The capacity of large systems can be up to several hundred cubic metres per hour.

4.3.5 Drawbacks of standard ion exchange systems

The aforementioned ion exchange processes have all involved fixed resin and been intended for batch operation, i.e. the resin remains in its tank during both operation and regeneration and the tank is out of operation during the regeneration. The tank is always designed as an upright cylindrical vessel. An ion exchanger of this type typically undergoes a cycle characterised as follows: Service cycle, backwash cycle, regeneration and rinsing, after which it returns to its starting point and is ready for a new cycle.

An ion exchange system like this has several drawbacks:

- The need for large quantities of resin, particularly with increasing content of salts in the raw water.
- Interruption of water production during regeneration.
- Complex regeneration process.
- High consumption of water for backwash and rinsing of ion exchange resin.

Nevertheless these standard systems are the most common, probably due to the price.

4.3.6 CIE systems

There are other types of ion exchange system that are capable of performing the ion exchange process continuously, i.e. without the aforementioned cycle. These systems are called CIE systems (Continuous Ion Exchanger), and there are several variants available. The most simple are used for ion exchangers that only contain one type of ion exchange resin. More complicated CIE systems are also produced, for example mix-bed ion exchangers.

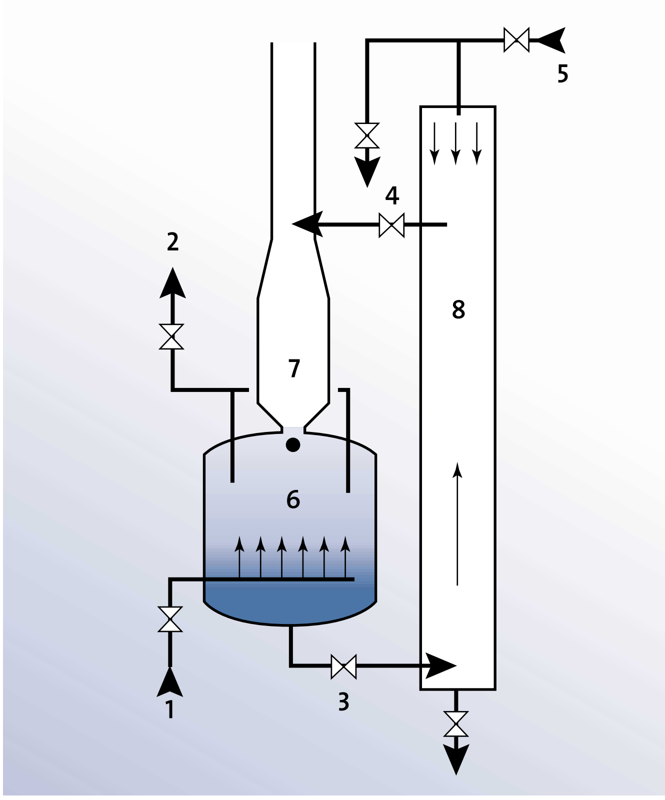


Fig. 38: *CIE system*

Pos.	Description
1	Inlet for raw water
2	Outlet for purified water
3	Valve for used ion exchange resin
4	Valve for regenerated resin
5	Inlet for regeneration liquid
6	Tank for ion exchange
7	Flushing tank
8	Tank for regeneration of ion exchange resin

Fig. 38 shows a CIE system with only one type of ion exchange resin, also known as a "single exchanger". The ion exchange resin is regenerated in the tank on the right (8), where, during fluidisation in countercurrent, it receives the regeneration liquid from above via a pipe (5).
The regenerated resin is conveyed via a valve (4) into the flushing tank (7), where an upward water flow rinses the ion exchange resin clean of residue of regeneration liquid and impurities. The contaminated rinsing water leaves the system out above the large pipe (above 7). The ion exchange resin subsequently "sinks" down past the ball (below 7) and ends up, still fluidising, in the tank (6) where the actual ion exchange takes place. In the tank (6) the resin settles in countercurrent with the raw water, which is added to the system via a pipe (1). Finally the resin is conveyed via a valve (3) back to its starting point in the regeneration tank (8). The purified water (deionate) is drawn off via a pipe (2).
To ensure that the CIE system's extra sub-processes (fluidisation, liquid flow and separation) proceed satisfactorily, setting up the system must be carried out with greater precision than is

the case with at standard ion exchange system.

4.4 Pumps in ion exchange systems

In ion exchange systems, if the raw water pressure is not high enough, it will be necessary to install a feed pump. The aim is partially to overcome the pressure drop throughout the ion exchange system, and partially to comply with possible system pressure after the system.

In some systems it is preferred to have a 2nd pump after the ion exchange unit, a clean-water pump. However, in this situation you must be careful not to create a vacuum in the anion exchanger. There is a risk of it collapsing in the event of too low pressure (vacuum).

4.4.1 Material requirements

The feed pump will normally convey fairly ordinary water (drinking water) and therefore only needs to fulfil the requirements for this. A cast-iron design will often be suitable, but it is very common to use stainless steel, or composite pumps, as this is required at other points in the system.

4.4.2 Pressure drop in ion exchange systems

The pressure drop across an ion exchange tank changes very little over time, as, unlike sand filters, it accumulates very little “dirt” during operation. In addition, the pressure drop is not used as the criterion for start of regeneration, but rather the fact that the ion exchange resin is saturated.

Saturation of the ion exchange resin: When designing the system the capacity is calculated based on the chemical composition of the raw water (water analysis), and from simple water quality measurement (water meter) it can be determined when the system must be regenerated. You should also keep an eye on the conductivity of the deionate. The conductivity will increase rapidly once the ion exchange resin is saturated.

Calculation of required head across ion exchange system:
Head equals number of tanks multiplied by (0.5 – 1 bar (7.25 – 14.5 p.s.i.)) plus pressure after system minus inlet pressure before feed pump.

The pressure drop across a single ion exchange tank is typically 0.5 – 1 bar (7.25 – 14.5 p.s.i.), so it is merely a question of a multiple of the number of tanks in series and pressure after the system plus correction for inlet pressure.

Deaerator: If a deaerator for carbon dioxide is installed between a group of cation exchangers and a group of anion exchangers the pressure after the deaerator will be zero, i.e. atmospheric, and an extra pump will therefore be needed. See Fig. 37.

4.4.3 Flow rate in ion exchange systems

The filtration rate is very wide-ranging: From 2 m/h for raw water with a high salt content to 80 m/h for condensate that only requires supplementary purification (polishing).
If the flow varies, and there is no storage tank for purified ewater, it can be advantageous to use a frequency-controlled pump.

4.4.4 Pumps for regeneration liquids

If we look at the feed of regeneration liquid for ion exchange systems, there are several pump options:

- Stainless steel or titanium pumps if the liquid does not contain acid, otherwise a composite pump should be used. The pressure is fairly low and the flow depends on the type of system. The pump can be controlled in accordance with level in chemical tank.
- An ejector driven by the regeneration water (deionate is normally used for this) sucks chemical solution from a tank. The pump that powers the ejector must provide additional pressure compared to the pump mentioned above.
- To have optimum control of the quantity of regeneration chemicals for the ion exchanger, dosing pumps are often used. The dosing quantity can be altered according to varying requirements, e.g. for varied raw water composition. Optimum automatic operation of the ion exchange system can be achieved by using programmable dosing pumps.

4.4.5 Pumps in very large ion exchange systems

In very large ion exchange systems pumps will be located at several points in the system for internal transport of water between the individual subgroups. These will typically be large pumps made of corrosion-resistant material.

5. Membrane filtration

5.1 Introduction

Membrane filtration is physical separation of a substance by means of a semi-permeable membrane. The presence of a gradient, i.e. a propelling force, across the membrane drives the process. The propelling force can be electrical, chemical or may use pressure. This force pushes the smallest molecules (the substances' "building blocks") in a given solution through the membrane and keeps back the larger molecules.

Membrane filtration has been known for many years, but was not worked on seriously until after 1960. The reason was that until that time the membranes would block up to a great extent or "foul", as it is called in technical jargon, when a layer builds up on membranes. In addition, the familiar membrane materials in chemical terms were so sensitive that they were practically impossible to clean.

In 1960 two students, Loeb and Sourirajan, at the University of California successfully produced membranes of cellulose acetate. These membranes showed satisfactory retention (filtration ability) of various salt solutions, and the capacity was also acceptable.

5.2 Membrane filtration is "cross-flow" filtration

A common feature of all membrane filtration is the "cross-flow" principle: The raw water, which is under pressure, flows across the membrane. Some of the water goes through (penetrates) the semi-permeable membrane as purified water (permeate), and the remainder leaves the membrane as concentrate. When the raw water flows at a high rate across the membrane, it keeps the membrane clean.

Fig. 39 shows the three currents. The permeate is at right angles to the course of the raw water concentrate. Hence the expression "cross-flow" filtration. "Cross-flow" filtration is also known as tangential filtration. Standard filtration is called "dead end" filtration, as the feed water ends up at a dead end in the filter. The dirt remains on the filter and only one water flow (the filtrate) leaves the filter.

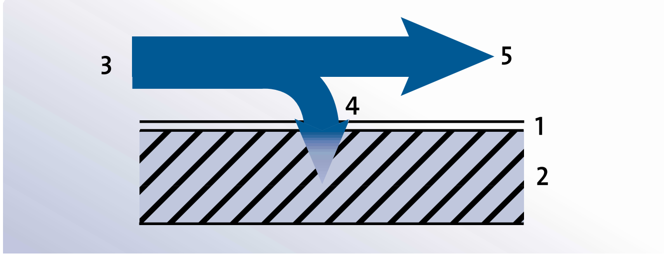


Fig. 39: *"Cross-flow" filtration*

Pos.	Description	Pos.	Description
1	Membrane	4	Permeate
2	Porous base	5	Concentrate
3	Raw water		

5.3 Application of membrane filtration

Membrane filtration is very widely used, including the following areas:

- desalination of salt water
- purification of drinking water (e.g. removal of pesticides)
- purification of water collected from rubbish dumps
- the food-processing industry
- the electronics industry (production of ultra-pure water)
- the pharmaceuticals industry
- the petrochemical industry.

5.4 The propelling force in membrane filtration

The propelling force in membrane filtration can be electrical, chemical or be by means of pressure. These three types are described in brief in the following sections.

5.4.1 Electrical propelling force in membrane filtration

Over forty years ago, the American compagny Ionics invented and introduced ion-exchange membranes and the electrodialysis (ED) process, which incorporates such membranes. ED is a process in which solutions are desalted or concentrated electrically. Salts in water dissociate into positively and negatively charged ions. The key to the ED process is a semi-permeable barrier that allows passage of either positively charged ions (cations) or negatively charged ions (anions) while excluding passage of ions of the opposite charge. These semi-permeable

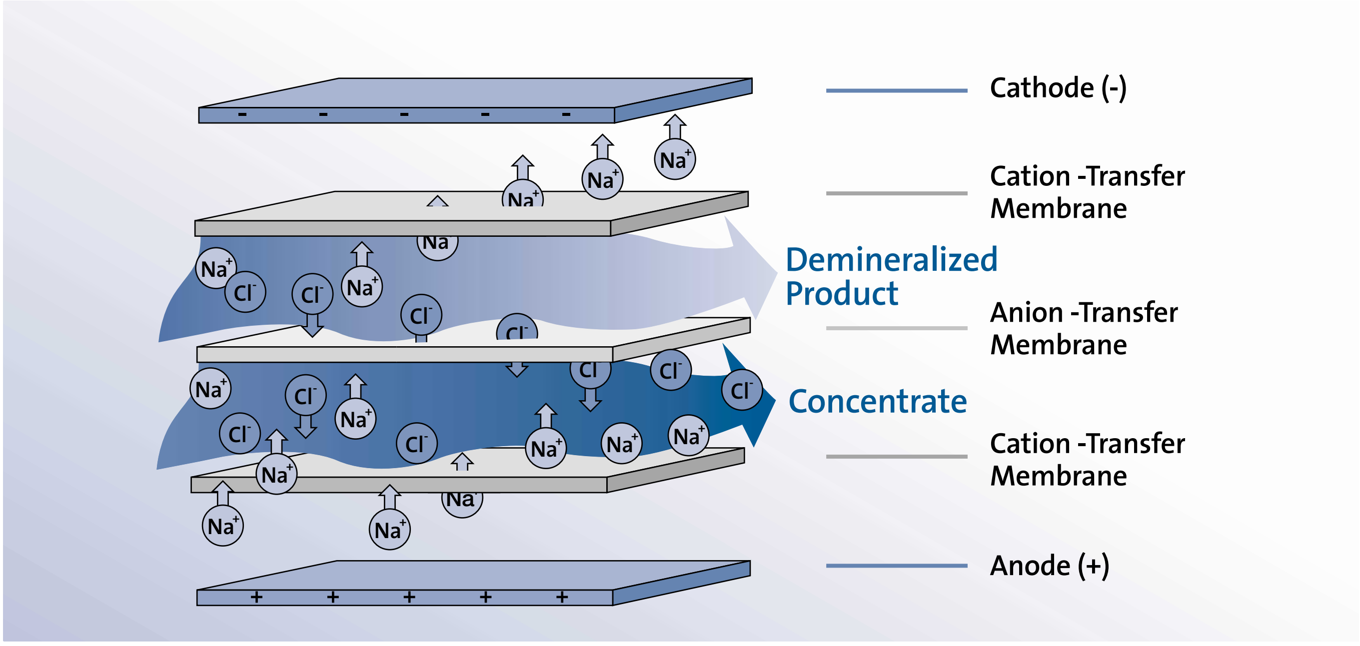


Fig. 40: *Electrodialysis principle*

barriers are commonly known as ion-exchange, ion-selective or electrodialysis membranes. See Fig. 40.

One of the problems in water desalination processes is that membranes and other active surfaces tend to become "fouled" or "scaled" over time by organic and inorganic substances present in the water. The electrodialysis reversal (EDR) process was developed and introduced by Ionics in the early 1970's to deal with this problem. By reversing the electrical current and exchanging the fresh product water and the concentrate wastewater streams within the membrane stack several times per hour, fouling and scaling constituents that build up on the membrane surface in one cycle are removed in the next reversing cycle.

This process was formerly very widely used for drinking-water production, but due to the high electricity consumption and corrosion problems it has now been replaced by reverse osmosis.

5.4.2 Chemical propelling force in membrane filtration

Propelling force as a result of a difference in concentration (concentration gradient) across a membrane is a phenomenon that is known from nature. The process is called osmosis, see Fig. 59, and occurs throughout the natural world in the cell walls of animals and plants. The cell wall is the semi-permeable membrane, and substances are transported through it to supply nourishment to sustain the cell (life).

5.4.3 Applied pressure as the propelling force in membrane filtration

Pressure as the propelling force is literally membrane filtration. Hydraulic pressure (i.e. pressure created by a pump) forces the smaller molecules through the membrane.
For example the process of reverse osmosis requires a driving force (application of pressure in excess of the osmotic pressure) to push the liquid through the membrane. See section "5.10.2 Liquid flow in nano and reverse osmosis filtration". The higher the pressure, the greater the driving force.
Reverse osmosis is capable of rejecting for example bacteria, salts, sugars, proteins, particles and dyes.
The hydraulic pressure required to drive the process varies greatly, from approx. 1 bar (14.5 p.s.i.) with the most open membranes (micro filtration) to over 100 bar with the dense membranes (reverse osmosis).

The following section of this chapter solely describes membrane filtration with hydraulic pressure as the propelling force.

5.5 Types of membrane filtration

Membrane filtration is divided into the following four types, depending on the size of the molecules to be filtered:

- Micro filtration (MF)
- Ultra filtration (UF)
- Nano-filtration (NF), and
- Reverse Osmosis (RO).

The chart in Fig. 42 shows the ion/particle sizes and typical media that fall within each of the four types of membrane filtration. For the sake of comparison standard filtration, "particle filtration", as described in chapter "3. Standard filtration", has also been included. Ion exchange belongs to the left of the superfine filtration, which involves sizes of less than 1 millionth of 1 mm (1 nanometer).

Fig. 43 also shows a comparison of the four types of membrane filtration. You can see what is retained and what goes through the membrane.

Another parameter that distinguishes the four types of membrane filtration from one another is the pressure under which they normally operate. Fig. 41 shows four curves, one for each type, where the flux (the capacity of purified water, "permeate", measured in l/m^2 membrane per hour) is depicted as a function of the feed pressure. In the case of micro filtration (MF) and ultra filtration (UF) the optimum pressure (1 and 4 – 5 bar (14,5 and 58 – 72.5 p.s.i.)) can also be observed, while nanofiltration (NF) and reverse osmosis (RO) come much higher up (20 – 40 bar (290 – 580 p.s.i.) and 40 – 100 bar (580 – 1450 p.s.i.). Above the optimum pressure clogging of "pores" occurs and the membrane is compacted.

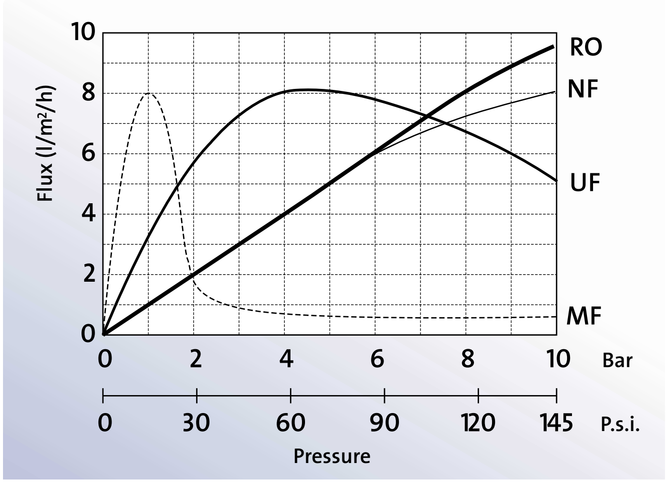


Fig. 41: Flux as a function of pressure for the four types of membrane filtration

5.5.1 Materials in membrane filters

In addition to the membrane material cellulose acetate, there are a considerable number of synthetic membrane materials available today. The two most important are polysulphone and polyvinylidene difluoride. The various membrane materials each offer benefits in filtration of different media.

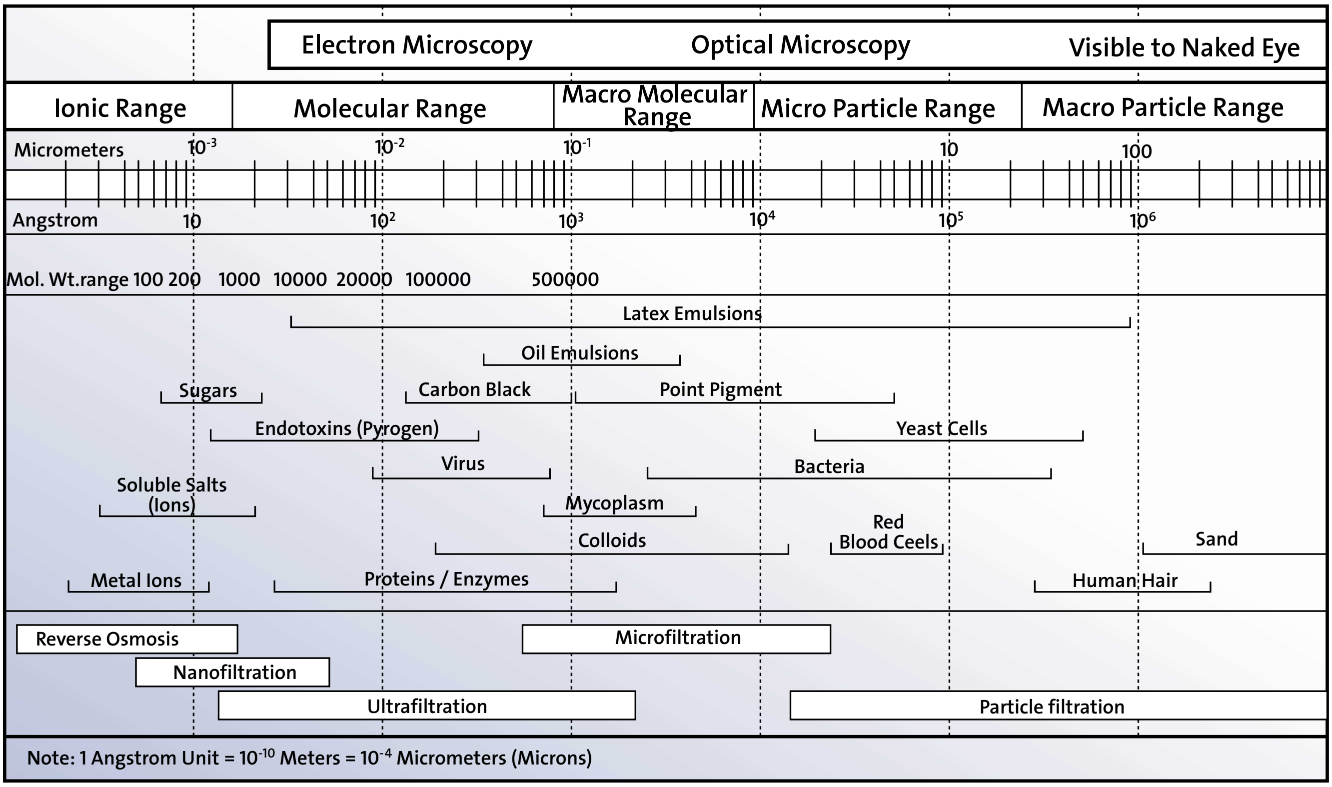


Fig. 42: Comparison of filtration grade for the different types of membrane filtration

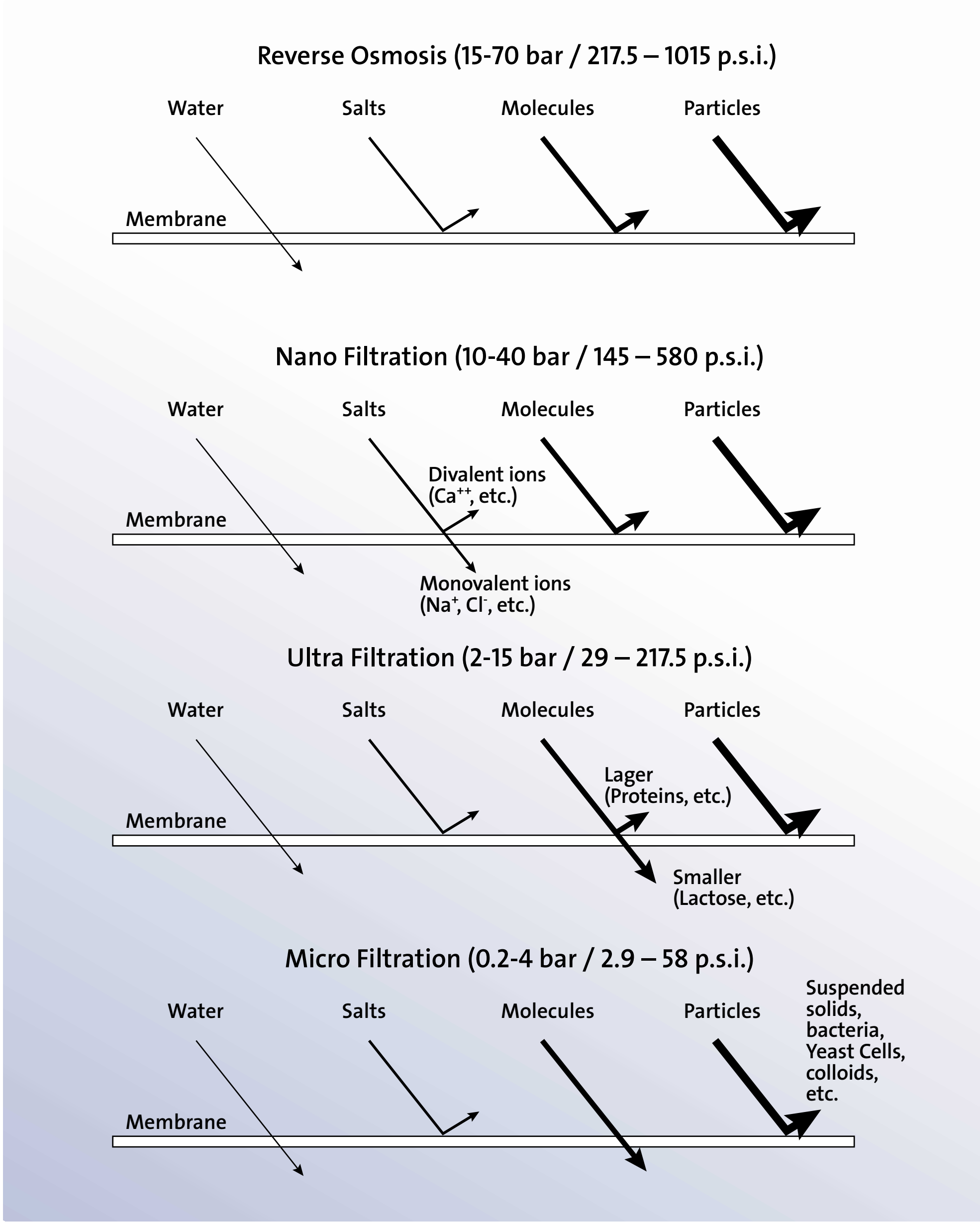


Fig. 43:
Comparison of filtration grade for the four types of membrane filtration

5.6 Membrane filtration modules

If we consider a membrane filtration system in its entirety it is clear that the membrane is the most important component. The membrane must be in a frame, i.e. it is part of a unit called a module. Membrane filtration modules are available in many designs, each with advantages and drawbacks. The four most important types of module are:

- “Tubular” module
- “Hollow fiber” module
- “Spiral wound” module, and
- “Plate and frame” module.

5.6.1 “Tubular” module

Structure: A “tubular” module consists of a perforated stainless steel tube on the outside with a diameter of 10 – 40 mm. Inside it is installed another tube, of a porous material, with the membrane on its internal side.

Fig. 44 shows a schematic sketch of a “tubular” module. The complete system consists of many such modules assembled in a tube bundle with all the tubes in parallel.

The raw water is added under pressure to the internal side of the tube, and the purified water (permeate) passes through the membrane and the porous tube to finally drip from the outside of the perforated steel tube.

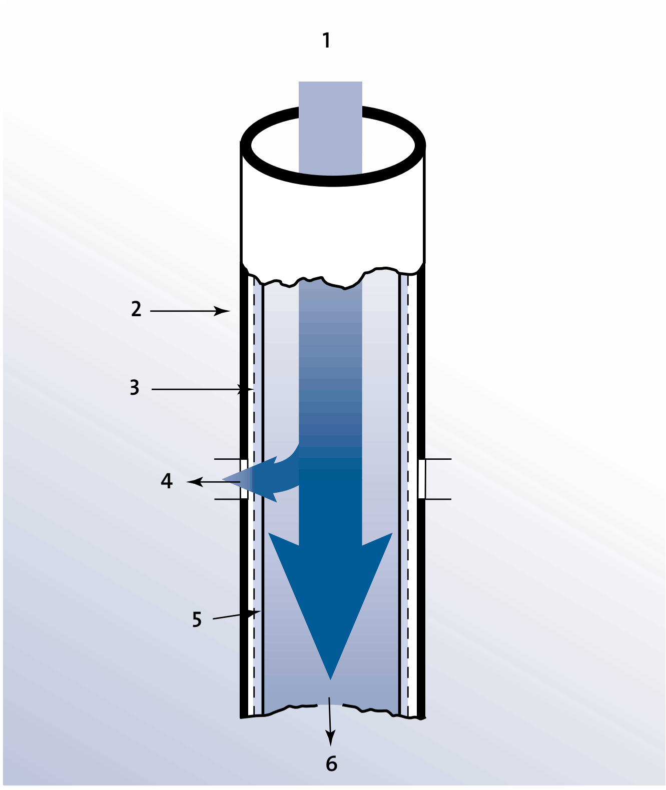


Fig. 44: "Tubular" module

Pos.	Description	Pos.	Description
1	Inlet for raw water	4	Outlet for permeate
2	Perforated tube	5	Membrane
3	Porous base	6	Outlet for concentrate

Application: The "tubular" module is used in the food-processing industry, as the system is easy to clean.

Due to the tube-shaped membranes the pressure drop, even with a flow rate of 6 m/s, will be limited, and it will therefore also be possible to filter viscous liquids. Drawbacks are that the system requires a high volume flow rate, is not particularly compact and has a high price per installed square metre of membrane.

5.6.2 "Hollow fiber" module

Structure: "Hollow fiber" modules consist of numerous small tubes with diameters ranging from less than 1/10 mm up to several mm and so the direction of flow of the permeate can also be in both directions. The completed system consists of large bundles of these small tubes, set up in larger pressure vessels. See Fig. 45.

The system has very high integrity with up to several thousand square metres of membrane surface per cubic metre. The pressure drop in the raw water – concentrate direction is as low as for the "tubular" module. The module can tolerate backwashing, i.e. against normal permeate flow direction. Therefore it is often easier to clean than other module types, which cannot tolerate this treatment without the membranes being damaged.

Application: The "hollow fiber" module is very popular within drinking-water production.

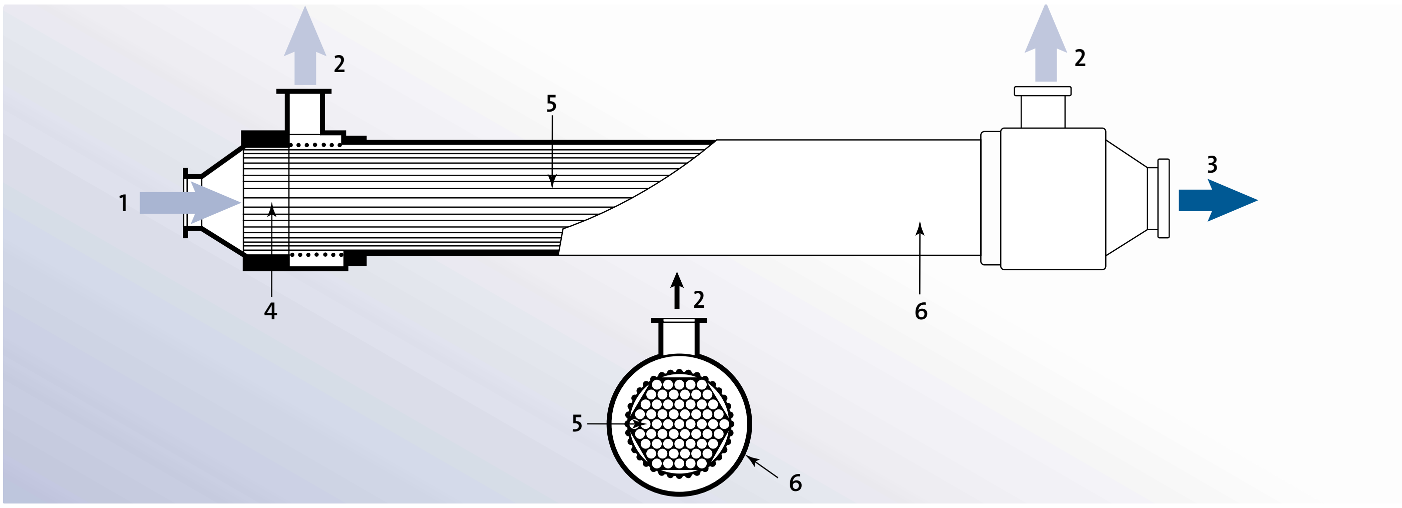


Fig. 45: "Hollow fiber" module

Pos.	Description	Pos.	Description
1	Inlet for raw water	4	Fibre support
2	Outlet for permeate	5	Hollow fibres
3	Outlet for concentrate	6	Pressure vessel

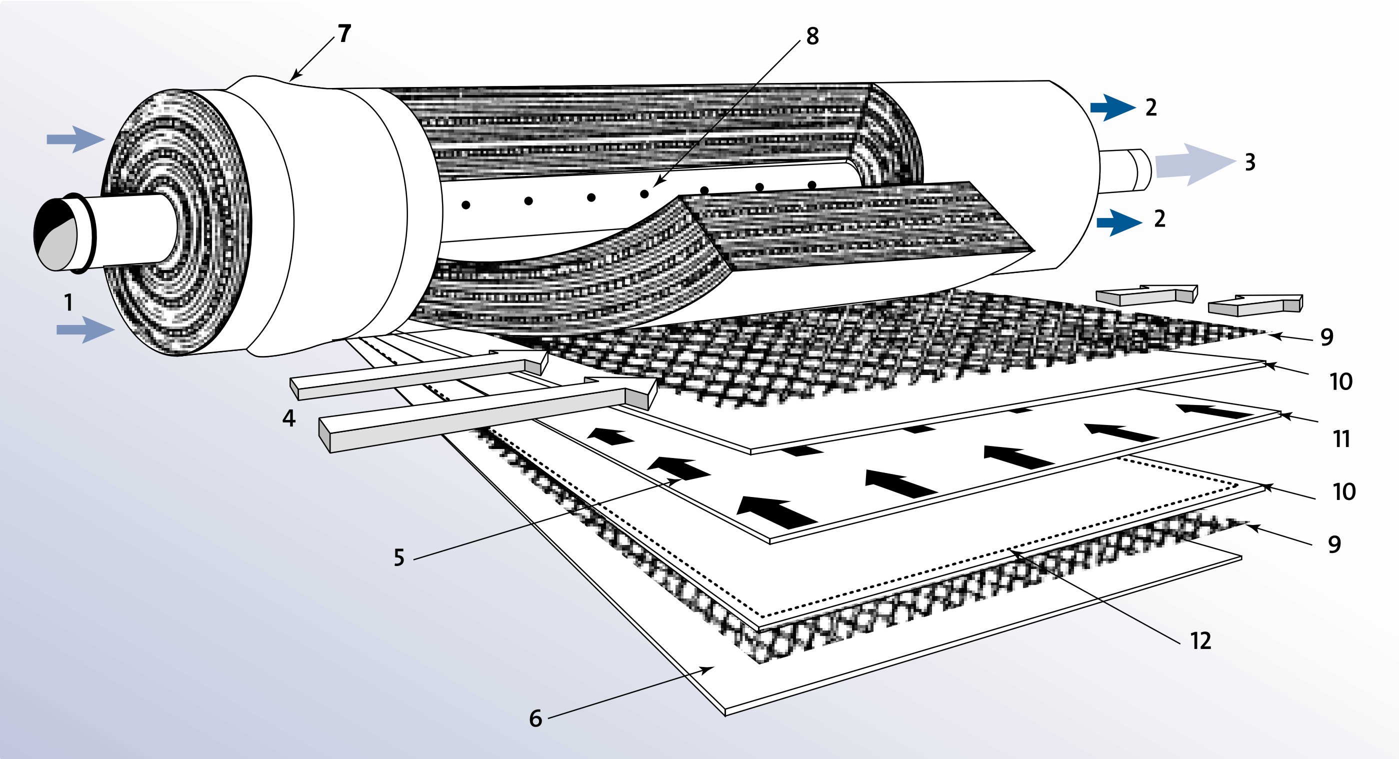


Fig. 46: *“Spiral wound” module*

Pos.	Description	Pos.	Description	Pos.	Description
1	Inlet for raw water	6	External housing cover (sleeve)	10	Membrane
2	Outlet for concentrate	7	Seal ring between module and pressure vessel	11	Permeate spacer
3	Outlet for permeate	8	Perforation in central pipe	12	Glue joint of “envelope“
4	Flow direction for raw water	9	Concentrate spacer		
5	Flow direction for permeate				

5.6.3 “Spiral wound” module

The “spiral wound” module is currently the dominant module on the drinking-water market and easily the most widely-used module type on the whole.

Structure: Its structure is substantially more complicated than the other types: The filter consists of a large “envelope”, which is glued tightly along three edges, with a porous mesh, “the letter”, inside, and with the actual membrane surface on the two external sides of the envelope. A mat, “spacer”, of fairly open mesh is on top of the envelope. After that is another envelope, as above, and another mat and so on. Each of the open ends of the envelopes is glued to a perforated tube, the permeate tube, so that the openings are right against the rows of perforations. All the layers are then rolled up around the permeate tube so that the whole thing resembles a rolled carpet. Finally a tubular housing cover, supporting sleeve, is placed round the whole “carpet”.

The modules are installed in series’ of up to 7 in a pressure tube, “pressure vessel”. This is crucial in order for the modules to be able to withstand the often very high system pressures.

Fig. 46 shows a cross section of a coiled “spiral wound” module.

During operation the raw water is directed into the end of the module and flows axially through the module in the aforementioned spacers. The permeate penetrates the membranes and into the spacer inside the “envelopes”, where it flows in a spiral until it reaches the central permeate pipe, from which the permeate can be drained from the ends (3).

As the spacers in the module are not very thick (0.75 – 2.2 mm), and the meshing in the spacer produces great resistance, the flow resistance is very high.

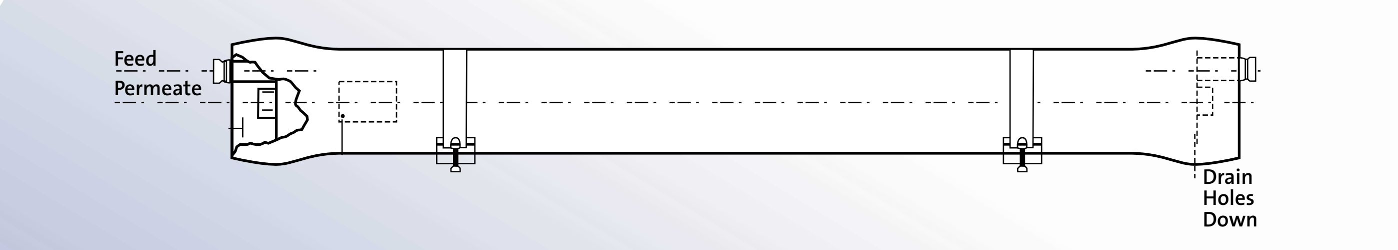


Fig. 47: Pressure vessel for "spiral wound" modules

Fig. 47 shows a complete standard pressure vessel of glass-fibre reinforced plastic for 8" (200 mm) "spiral wound" modules including two supports.

Application: "Spiral wound" is the most widespread membrane filter module within water treatment.

5.6.4 "Plate and frame" module

The plate and frame system is about the oldest within membrane filtration. The first trials with membrane filtration were carried out using this exact type of filter, and at the beginning of the 60s Europe was already among the pioneers.

The Danish company Danisco (former DDS, RO Division) became involved from 1965. They developed cellulose acetate membranes and carried out trials involving filtration of sugar-beet juice in "plate and frame" modules. The experiment was not attractive financially or in terms of energy consumption and was abandoned. However, they looked around for other applications for the filter. This led to filtration of dairy products and pharmaceutical products. And later also water treatment.

Structure: A "plate and frame" module is constructed from membrane sheets supported by perforated "plates" that are stacked and clamped between two flanges in a "frame", looking like a large sponge cake. Plates, "spacers", with flow channels for delivery of the raw water, are inserted between the membranes. In cross section the module/layers can be circular, rectangular or oval. Externally the module is sealed around its periphery with the actual membranes as the seal element. See Fig. 48.

The raw water is usually directed into the module at the bottom and zigzags up through the layers. See Fig. 48.

En route a certain amount of the raw water penetrates the membranes and flows into the membrane support plates and on to a small drain pipe. The concentrate leaves the module at the top. The "spacers" provide flow channels for the raw water-concentrate flow.

The flow rate across the membranes falls somewhere between the rates for "spiral wound" and "tubular" modules, i.e. around 3 m/s. As the pressure drop across the membranes is relatively large, the module is divided into several parallel courses, so you achieve greater raw water flow and a lower pressure drop. The fact that the liquid flows fairly easily across the membranes means that the "plate and frame" module is more suitable for viscous liquids than, for example, the "spiral wound" module.

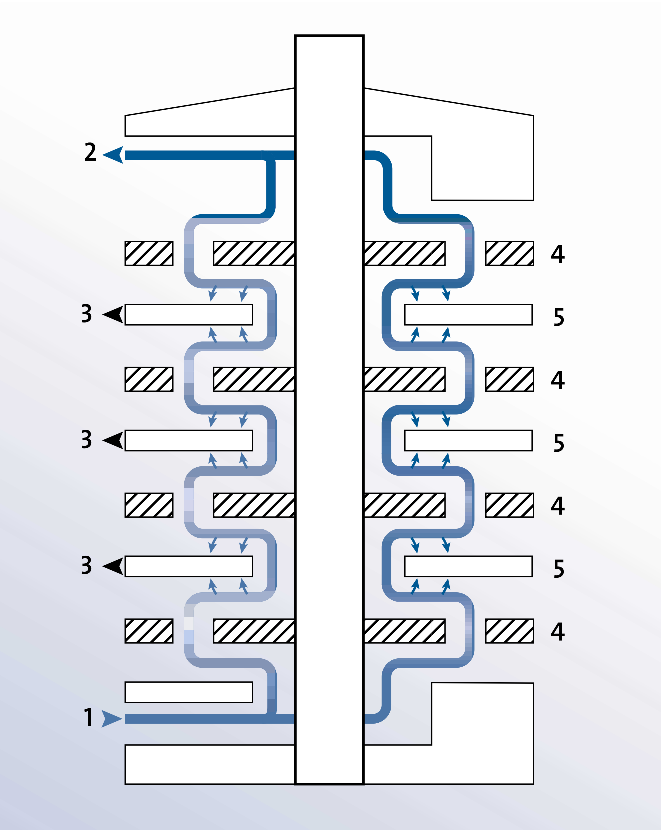


Fig. 48: Typical "plate and frame" module

Pos.	Description	Pos.	Description
1	Inlet for raw water	4	"Spacer" with flow channels
2	Outlet for concentrate	5	Perforated membrane support plate
3	Outlet for permeate		

Application: Sanitary purposes, e.g. within the food-processing industry, as the membranes are easier to clean after use. One market where "plate and frame" systems are currently in evidence is for clarification of process water and process wastewater.

5.7 Membrane filtration systems

5.7.1 Single membrane filtration system

A pump feeds the system with suitable pressure and flow. The permeate goes through the membrane and flows from the system unpressurised, while the concentrate is kept under pressure by means of a pressure-control valve before finally also leaving the system, unpressurised. See Fig. 49.

In Fig. 49 and 50 the symbol for "membranes" represents one or more modules/pressure vessels positioned in parallel and in series.

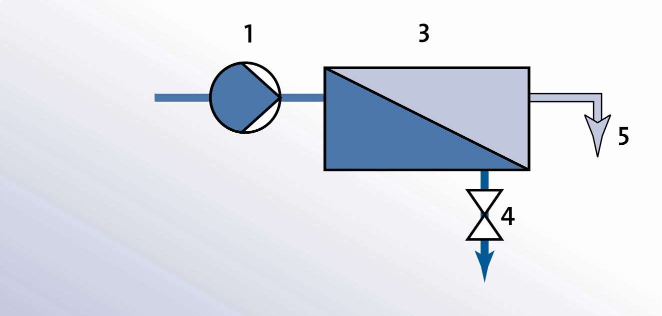


Fig. 49: *Single membrane filtration system*

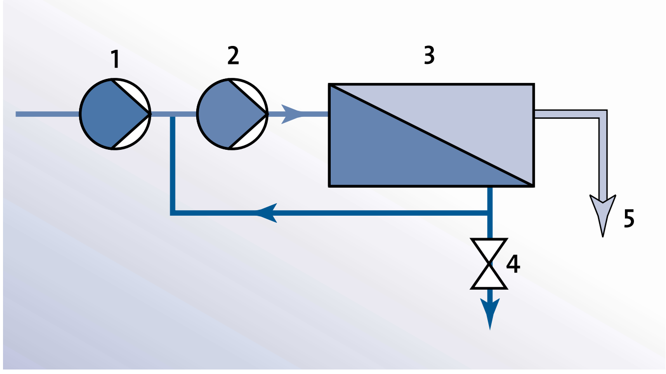


Fig. 50: *Membrane filtration system with recirculation*

Pos.	Description	Pos.	Description
1	Feed pump	4	Concentrate pressure relief valve
2	Recirculation pump		
3	Membranes (modules)	5	Permeate

A membrane must be kept clean by means of a certain flow rate across the membrane. The flow supplied by the feed pump, see Fig. 49, is not always sufficient. Therefore an extra pump, with greater flow than the feed pump, is often incorporated. This pump is called a recirculation pump, see Fig. 50. Increased flow can also be established by conveying some of the concentrate back to the suction side of the feed pump. In this instance the feed pump must be made correspondingly larger in flow terms.

The system shown in Fig. 49 is very widely used for nano-filtration and reverse osmosis. The system in Fig. 50 is mostly used for micro filtration and ultra filtration, where the water often displays a greater tendency for fouling. See section "5.10.4 Membrane capacity".

Recirculation is also used because it makes the system more flexible, so it is better able to tackle variations in capacity and chemical composition of the raw water. For example, reduction of the raw water flow with capacity control will be less significant for maintaining the necessary flow across the membrane.

In reverse osmosis systems for sea water it is unnecessary to have recirculation pumps. The water utilisation factor (permeate flow/raw water flow) here is so low (~ 0.3) that the "flush flow", even in a long series of modules (6 – 7), is still adequate in the last module in the series.

5.7.2 "Christmas-tree layout" of membrane filtration system

In very large systems, e.g. for treatment of brackish water, where one does not wish to install recirculation pumps, a special layout is used, involving a mixture of series and parallel runs. By graduating the number of modules/pressure vessels in the parallel groups through the line of series connections you achieve a fairly constant flush flow across the membranes. You only need to know the quantity of permeate that runs from one parallel group to be able to calculate the raw water flow and the number of parallel runs in the next group. This setup is shown in Fig. 51 and is popularly called a "Christmas tree". Like the single installation in Fig. 49, this setup belongs to the "plug-flow" type (i.e. one through-flow), as opposed to the systems with recirculation.

5.7.3 "Loop" setup of membrane filtration system

Another type of layout for modules/pressure vessels is a series of "loops", where several successive groups of parallel runs are positioned in series. Each of the parallel groups has its own recirculation pump. This setup is widely used in ultra filtration for very polluted liquids, where very high concentrations are also required. Fig. 52 shows a system like this consisting of a feed section and three loops.

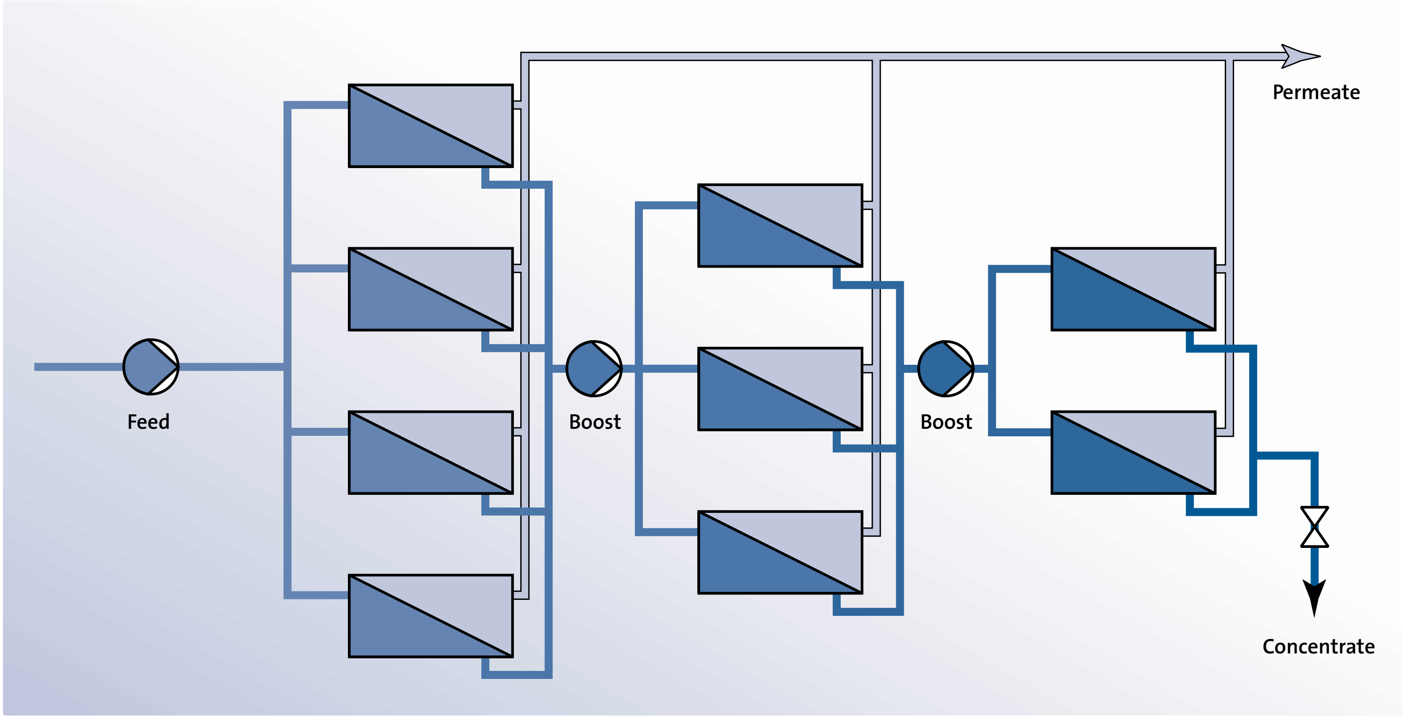


Fig. 51: Membrane filtration: Pressure vessels in "Christmas tree layout"

5.7.4 Calculations for membrane filtration systems

There are computer programs available for calculations for membrane filtration systems. However, they are only valid for nano-filtration and reverse osmosis systems. Many membrane suppliers send out diskettes with this type of calculation program at regular intervals.

Information on raw water analysis, required capacity, water utilisation factor, temperature and estimated number of filtration modules is entered in the program. The program will then state raw water flow, raw water pressure, pressure drop across modules and chemical composition of permeate and concentrate.

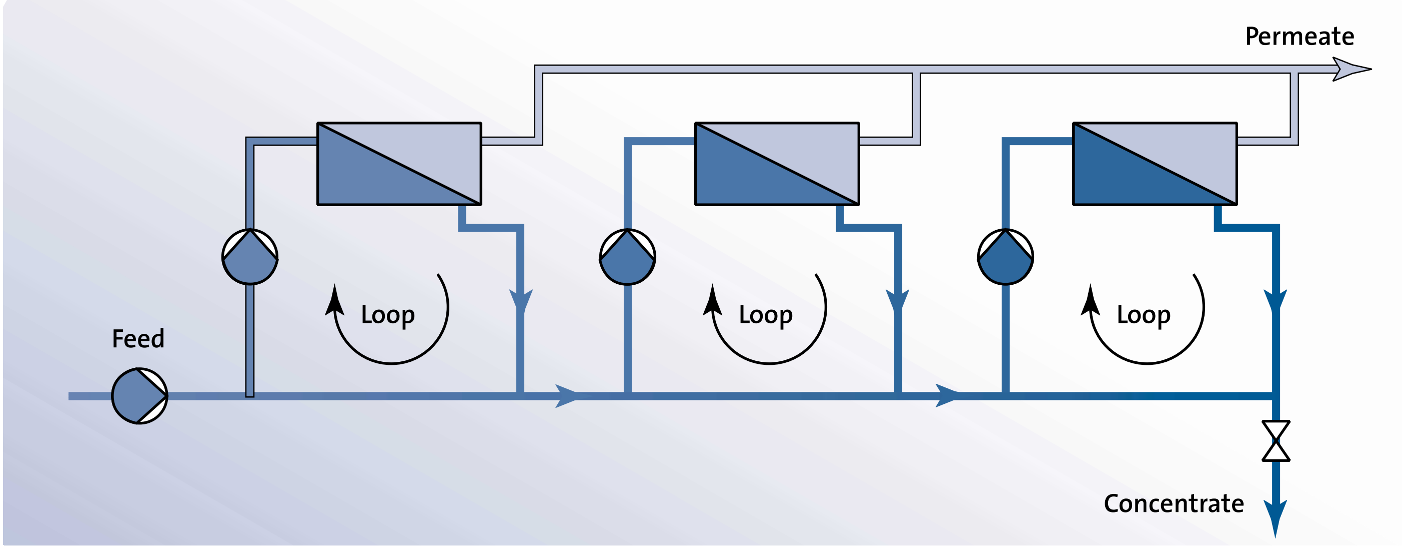


Fig. 52: Membrane filtration with "loops"

5.8 Pumps in membrane filtration

5.8.1 Material selection for pumps in membrane filtration

Many membrane filtration systems are used within the food-processing industry and in the pharmaceuticals industry, and so the pumps for this must fulfil certain standards, such as being of sanitary design.

Pumps for membrane filtration must generally be corrosion-resistant, so cast iron, for instance, cannot be used. Even bronze can be a dubious material selection.

The content of chloride (common salt) in the raw water is not the only decisive factor in material selection. Also decisive is the fact that various acids are used, during CIP, i.e. when the filter is cleaned. See section “5.10.4 Membrane capacity”. These make it necessary for the pumps to be either composite or stainless steel.

There are some systems where for particular reasons it has been decided to install a separate CIP pump, e.g. in composites. In systems like this a bronze pump can be used as raw water pump during normal operation of the system, if there is nothing else in the raw water (e.g. acid) to prevent it. In cases of high raw water pressure, i.e. above 10 bar (145 p.s.i.), composite pumps are generally out of the question due to the mechanical force.

Chloride-bearing media: For media containing chloride, the section “1.3 Corrosion” analyses choice of stainless steel type. Stainless steel (904 L) as a pump material is used for media containing chloride, but also aluminium bronze, nickel alloys (e.g. hastelloy) and titanium are very suitable for such media. Many pump manufacturers use these materials today in pumps for the chemical industry and others. Titanium is offered by Grundfos in the CRT range and would be an excellent alternative for reverse osmosis systems for brackish water, where the pressure is generally below 30 bar (435 p.s.i.). For reverse osmosis systems for sea water with a feed pressure above 40 bar (580 p.s.i.), Grundfos offers the BM and BMET ranges in 904 L (indicated by “R”).

Shaft seals: Shaft seals for reverse osmosis of brackish water rarely cause major problems. In the event of crystallisation on the atmospheric side of the seal, a Grundfos type Q (Quench) shaft seal with external flushing can be used. In the case of the BM range, the pump is hermetically sealed in a stainless steel sleeve.

Micro and ultra filtration systems operate in the range from 1 - 6 bar (14.5 – 87 p.s.i.), see Fig. 41, and often with recirculation, see Fig. 50 and 52, while nano-filtration and reverse osmosis go right up to 100 bar (1450 p.s.i.) pressure.

5.8.2 Membrane filtration of process wastewater

A new area for application of micro and ultra filtration is filtration of process wastewater. See Fig. 53. Increasing requirements from the authorities mean that effluent must be cleaned before discharge to the sewer. If the effluent contains valuable substances, these will be present in greater concentrations in the concentrate after filtration. This means that it can be advantageous to possibly reuse the effluent in the industry concerned or somewhere else.

The filtered water (permeate) can also be reused in several instances, as wash/flush water, for example, instead of being sent to the sewer. The permeate, as a result of micro and ultra filtration, can also be further-treated in a subsequent reverse osmosis system, the result of which is pure water.

Fig. 53: *Membrane system for filtration of brewery wastewater including two dosing systems*

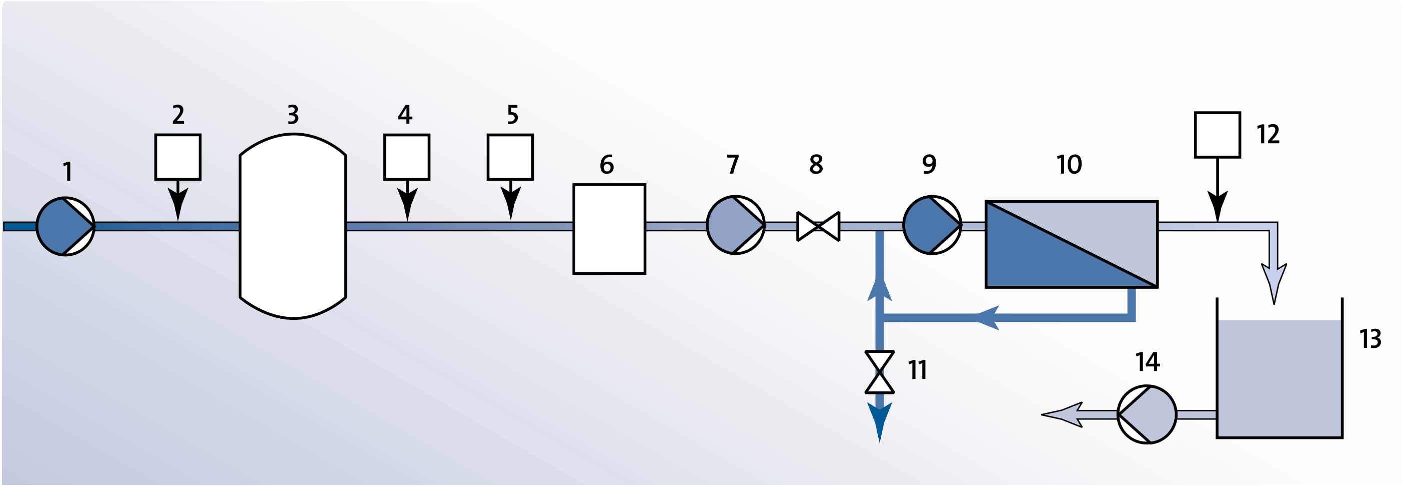


Fig. 54: Reverse osmosis system for brackish water with sand filter (preliminary filtration) and recirculation

Pos.	Description	Pos.	Description	Pos.	Description
1	Raw water pump	6	Microfilter (e.g. bag filter)	11	Concentrate pressure relief valve
2	Dosing of flocculating agent	7	High-pressure feed-water pump	12	Dosing of leaching solution (for adjustment of pH valve)
3	Sand filter	8	Feed-pressure control valve		
4	Dosing of acid	9	Recirculation pump	13	Permeate tank
5	Dosing of “antiscaling“ agent	10	Modules/pressure vessels	14	Permeate pump

5.8.3 Example: Pumps in brackish water systems

Fig. 54 shows a brackish water system, which includes...

- a raw water pump (1)
- four dosing pumps (2, 4, 5, 12)
- a high-pressure feed-water pump (7)
- a recirculation pump (9), and
- a permeate pump (14).

Raw water pump and high-pressure feed-water pump: CRN (CRN-SF) pumps will typically be used for a system like this. Small-scale systems will have one pump at each of the four pump locations, and there are larger systems with three CRN pumps in parallel at each of the four pump locations. If the system requires more than three pumps in parallel, a BME may come into the picture, for the high-pressure pump at least, Fig. 54, pos. 7. Large CRN pumps will be fine to use for raw water pump and permeate pump. Not all manufacturers of reverse osmosis systems will accept the use of NK pumps due to the bronze.

Recirculation pump: The recirculation pump, Fig. 54, pos. 9, can be a CRN or a BM. A CRN pump can be used for inlet pressure up to 10 bar (145 p.s.i.), and as the feed pressure in a reverse osmosis system for brackish water will typically be greater than 15 bar (217.5 p.s.i.), we would recommend choosing a BM for the recirculation. The BM module 4 – 6” can operate up to 60 bar (870 p.s.i.) system pressure. Calculation of the differential pressure across the recirculation pump will, as stated above, be included in the computer calculation. Friction loss is not added to the computer calculation, so this must be included in the total calculation for the system.

Many manufacturers neglect using a recirculation pump. In this case it is the high-pressure feed-water pump that must be able to achieve a discharge pressure equal to the calculated inlet pressure on the membranes.

Dosing pumps: Most membrane filtration systems, like the system shown, include several dosing pumps. Fig. 54 shows the following four dosing points:

- dosing of flocculating agent before sand filter (2)
- dosing of acid and “anti-scaling” agent after sand filter (4, 5), and
- adjustment of pH value with leaching agent (sodium hydroxide) in the permeate (12).

Several of the dosing pumps shown could advantageously be controlled by either flow or pH value.

Capacity regulation: If you wish to regulate the capacity of a system as shown in Fig. 54, there are two options:

- by means of a pressure control valve (pos. 8) on the discharge side of the high-pressure feed-water pump.
- by means of a frequency-controlled high-pressure feed-water pump, e.g. controlled by the permeate flow or by a level transmitter in the permeate tank.

Fig. 55 shows a reverse osmosis system for filtration of brackish water.

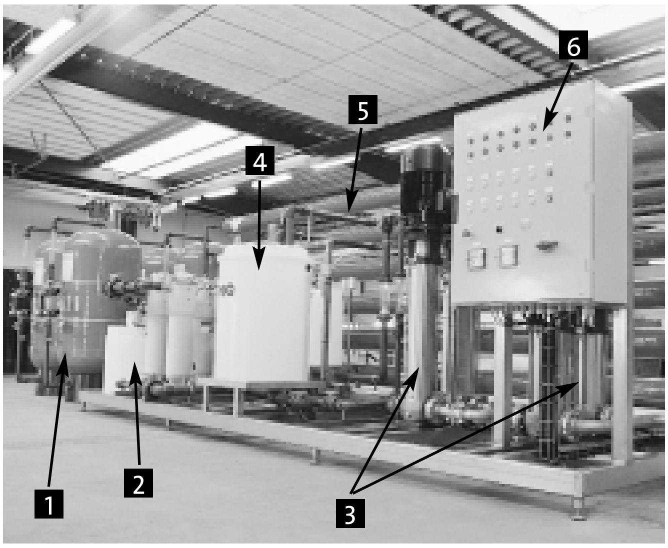


Fig. 55: *Reverse osmosis system for brackish water*

Pos.	Description
1	Sand filter (preliminary filter)
2	Dosing unit
3	Stand with feet pump and recirculation pump
4	CIP tank
5	Pressure vessel with actual membrane filter
6	Control panel

5.9 Membrane filtration of sea water

A reverse osmosis system for treatment of sea water is always constructed in accordance with the single installation shown in Fig. 49. The sea water can either be retrieved direct from the sea through a preliminary filter, or preferably from a borehole on the beach. The borehole is no more than 10 to 15 m deep, but the large quantity of sand that the sea water must pass through on its way down to the bottom of the borehole provides excellent preliminary filtration. Before the sea water reaches the reverse osmosis system, like brackish water, it must be pre-treated, as shown in Fig. 54. Pre-treatment of sea water is generally more complicated than pre-treatment of brackish water, where the raw water typically comes from deep boreholes with the consequent better natural preliminary filtration.

After pre-treatment and diverse dosing the high-pressure pump raises the sea water's pressure to 60 – 70 bar (870 – 1015 p.s.i.). In the membrane filter the sea water is divided into permeate (approx. 30 – 45% of the raw-water flow) and concentrate (the remainder, approx. 55 – 70%). The concentrate is directed either to a pressure release valve or to an energy recovery system. After this the unpressurised concentrate is conducted back to the sea.

5.9.1 Energy recovery in sea water systems

The quantity of energy stored in the concentrate is very large. Using an energy recovery system between 50 and 60% of the energy in the concentrate can be retrieved. Newer methods for energy recovery, which follow the pressure exchange principle, can reduce consumption even further. Using this principle, approx. 95% of the energy in the concentrate can be recovered.

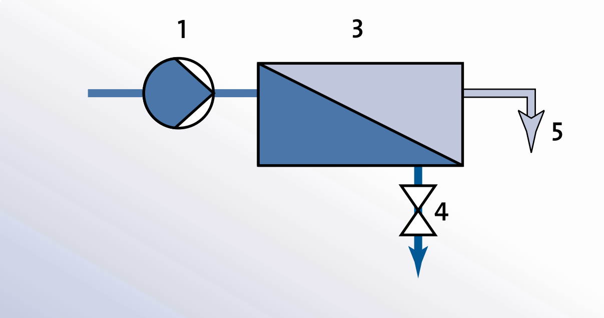


Fig. 56*: Reverse osmosis system without ERT, "Energy Recovery Turbine"*

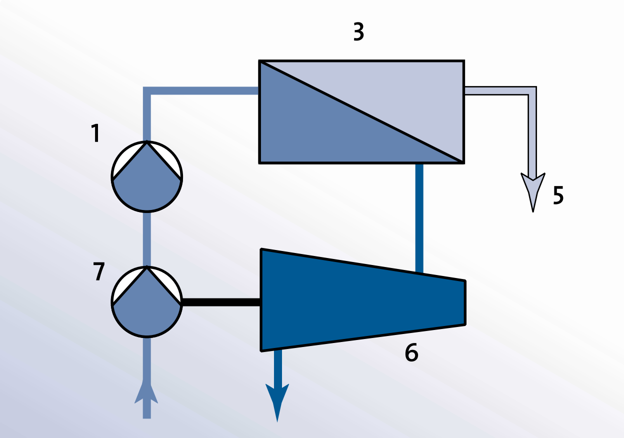


Fig. 57: *Reverse osmosis system with ERT, "Energy Recovery Turbine"*

Pos.	Description	Pos.	Description
1	Main pump (BME)	5	Permeate
3	Membranes	6	Turbine
4	Concentrate relief valve	7	Turbine-operated pump (BMT)

Fig. 56 and 57 are diagrams of a simplified reverse osmosis system for salt water with and without energy recovery for the concentrate. The energy recovery process shown follows the ERT principle, "Energy Recovery Turbine", where a turbine is driven by the concentrate. The turbine either powers a separate feedwater pump, e.g. Grundfos BMET, or supplements the motor for the main pump, i.e. pulls on the same pump shaft.

Energy consumption without and with ERT system is as follows:

Pump/system type	Energy consumption
Piston pumps	From approx. 7.5 kWh per m^3 permeate
Centrifugal pumps	9 – 10 kWh per m^3 permeate
ERT system, dependent on size of centrifugal pump	5 – 7 kWh per m^3 permeate

Table 8: *Energy consumption of pump/system types*

5.9.2 Pumps in sea water systems

The calculations for Grundfos BME-type pumps, and in particular for the turbine version BMET, are complicated. So Grundfos has issued a program for calculation on computer.
The material selection for all BME and BMET modules is 904 L or equivalent quality, and the modules are therefore suitable for use in reverse osmosis systems for sea water.

Grundfos booster modules, types BM 6" and BM 4", are also available in 904 L. They are used for reverse osmosis systems for sea water and offer an elegant design, low noise level and maintenance benefits (sealless type). For small capacities, i.e. up to approx. 15 m^3/h, piston pumps are often used. For larger capacities BME and BMET are usually beneficial due to the compact design and energy recovery turbine.

5.9.3 Sea water systems built into a container

It is common for reverse osmosis systems to be built into a container. A system like this is completely built by the manufacturer and supplied as a turnkey system ready for connection of raw water, concentrate, permeate (drinking water) and electricity. Fig. 58 shows a sea water system built into a container with a Grundfos BMET-type pump in the foreground.

5.10 Theory: Membrane filtration

In membrane filtration you differentiate between micro and ultra filtration on the one hand and nano and reverse osmosis filtration on the other hand. Micro and ultra filtration are similar to standard filtration and follow Darcy's law, as described under chapter "3. Standard filtration", while nano and reverse osmosis filtration are also dependent on the osmotic pressure of the liquid.

Fig. 58: *Reverse osmosis system built into a container with a Grundfos BMET pump*

5.10.1 Liquid flow in micro and ultra filtration

The liquid flow in micro and ultra filtration can be expressed by the following equation:

$$J_w = \frac{C}{\eta} \times \Delta p$$

Where:
J_W is the liquid's (water's) flux (capacity measured in $l/m^2/h$)
C is a constant
η is the liquid's viscosity
Δp is the pressure drop through the membrane
(Δp = pump pressure – permeate pressure (~ 0))

After a minor revision the equation resembles Darcy's law:

$$\Delta p = \frac{1}{C} \times J_w \times \eta$$

The equation expresses the fact that the pressure drop through the membrane is directly proportional to the flux and viscosity.

It can be said that micro and ultra filtration proceed like standard filtration, but in contrast to this they handle much finer "grain sizes". It is a question of molecule sizes, i.e. large molecules like proteins and carbohydrates (e.g. starch and sugar).

5.10.2 Liquid flow in nano and reverse osmosis filtration

Before analysing the equation for the liquid flow in nano and reverse osmosis filtration, we will examine the term osmotic pressure.

The term osmotic pressure can be explained by the following experiment, as shown in Fig. 59:
If the beaker on the left is filled with completely pure water on the left side of the membrane and a salt solution on the right side, you will be able to observe that the liquid level rises on the side of the membrane containing the salt solution (see middle beaker). This is because the pure water pushes through the semi-permeable membrane in an attempt to equalise the difference in concentration. As the membrane is not permeable for salt the difference in concentration cannot be equalised by the salt from the solution in the right side pushing through the membrane and mixing with the pure water.
This phenomenon is called osmosis and, as mentioned previously, is a natural phenomenon.
After a while the process will come to a standstill and a state of equilibrium will occur. The difference in the level of the two liquid levels is designated the osmotic pressure head (π) or the osmotic pressure for the salt solution in question in relation to water.
If hydraulic pressure greater than the osmotic pressure (π) is exerted on the salt solution (see the beaker on the right), the process will reverse and go in the opposite direction, i.e. the pure water will leave the salt solution and the liquid level of the pure water on the left side of the membrane will rise. This phenomenon is called reverse osmosis and does not occur naturally.

The liquid flow in nano and reverse osmosis filtration can be expressed by the following equation:

$$J_w = A \times (\Delta p - \Delta \pi)$$

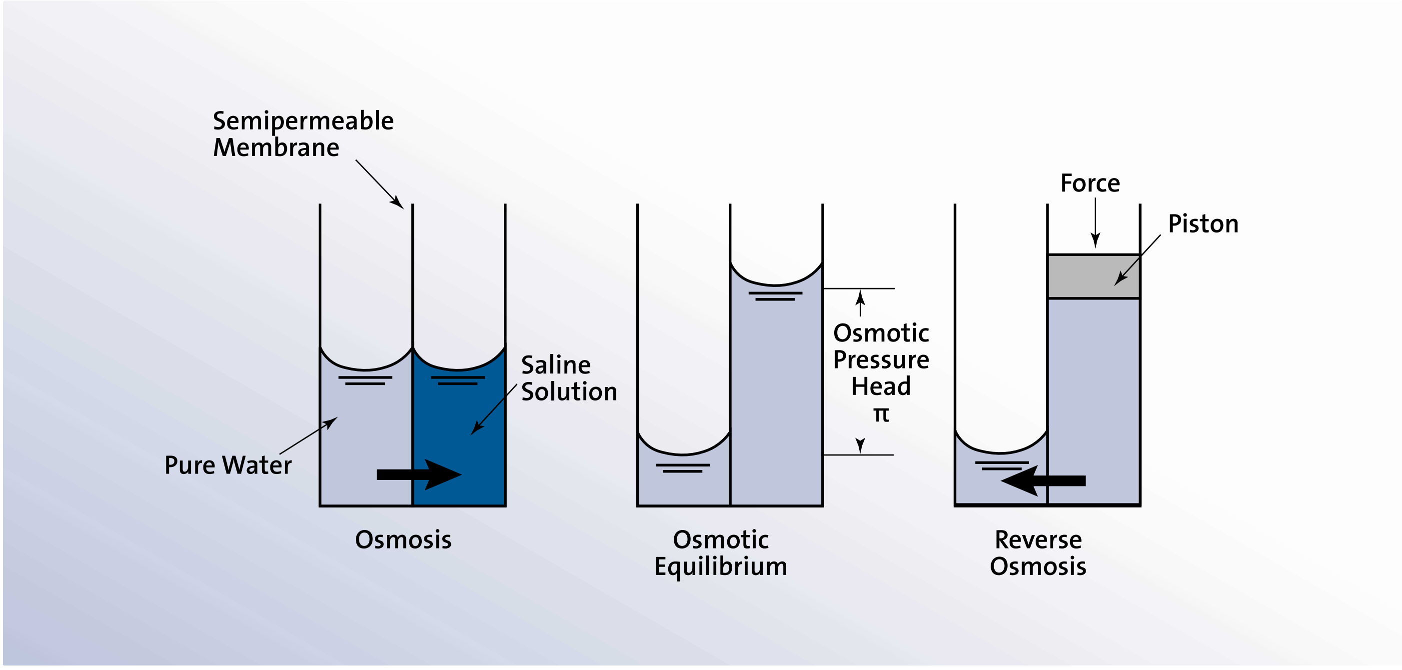


Fig. 59: *Osmosis and reverse osmosis*

The viscosity dependence is gone, and instead Δπ, which is the difference in osmotic pressure on the feed water and the permeate, appears. A is a constant.
The viscosity will naturally also have an effect on nano and reverse osmosis filtration, but this will only be reflected in the pressure drop across the membrane, i.e. in the feed water – concentrate direction.

Retention of dissolved substances: J_W is the flux of the pure water (water flux), which goes through the membrane, but a little of the dissolved substance also goes through the membrane with the water. In nano-filtration quite a lot of the dissolved substance may go through with the water, while in reverse osmosis, which is a much denser membrane, only a little goes through. Common salt [NaCl] is at around 50% with nano-filtration and around 2% with reverse osmosis. This property is called retention of dissolved substances or ions. Retention (filtering ability) for various other substances is shown in Fig. 42 and 43.

It is by and large true that the membrane capacity (flux) for nano and reverse osmosis filtration depends on the feed pressure and the osmotic pressure in the solution and the retention depends on physical conditions in the membrane (its density).

5.10.3 Technical specifications for filters

Technical specifications for a spiral module, see Fig. 60, (also known as an element) for reverse osmosis will include the following:

- Capacity in m^3/24 hours
- Diameter and length
- Max. feed-water flow [m^3/h]
- Max. operating pressure [bar]
- Max. operating temperature [°C]
- Max. tolerance to chlorine [mg/l]
- Max. turbidity in feed water [NTU]
- Max. undissolved substance in feed water [SDI]
- Membrane type
- Minimum salt retention in % measured in chloride [Cl^-]
- pH value limits
- Type designation
- Typical salt retention in % measured in chloride [Cl^-].

The technical specifications for a nano-filter's membrane are often supplemented by information on retention of larger molecules, such as sodium nitrate, calcium bicarbonate, magnesium sulphate and glucose.

5.10.4 Membrane capacity

Fig. 61 shows curves for osmotic pressure for various solutions as a function of the solution's concentration. The "sea water" curve is used for brackish and sea water.

Note that the osmotic pressure for salt water with 4% salt is approx. 25 bar (362.5 p.s.i.), i.e. the reverse osmosis system for sea water only begins to produce water once the high-pressure feed-water pump achieves a pressure of more than 25 bar (362.5 p.s.i.) (see above: $J_W = A \times (\Delta p - \Delta\pi)$).

Another factor that affects a membrane's capacity is the temperature dependence. The capacity increases with the temperature: 2 – 3% per degree (C). This is because the membrane opens up with the temperature. It also results in poorer retention, and therefore more salt in the treated water.

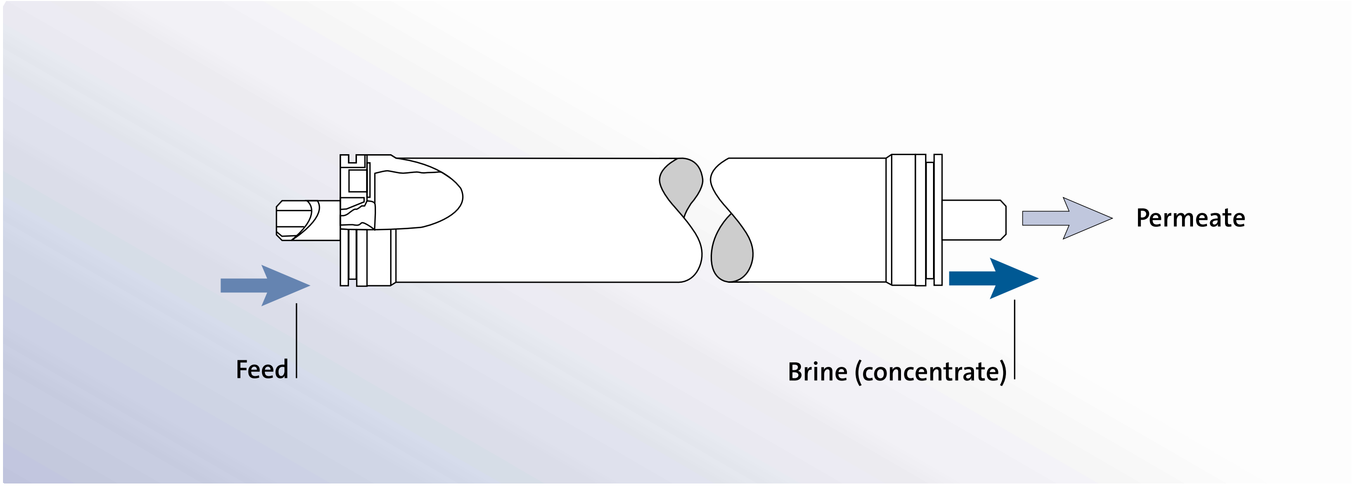


Fig. 60: Typical spiral module (element)

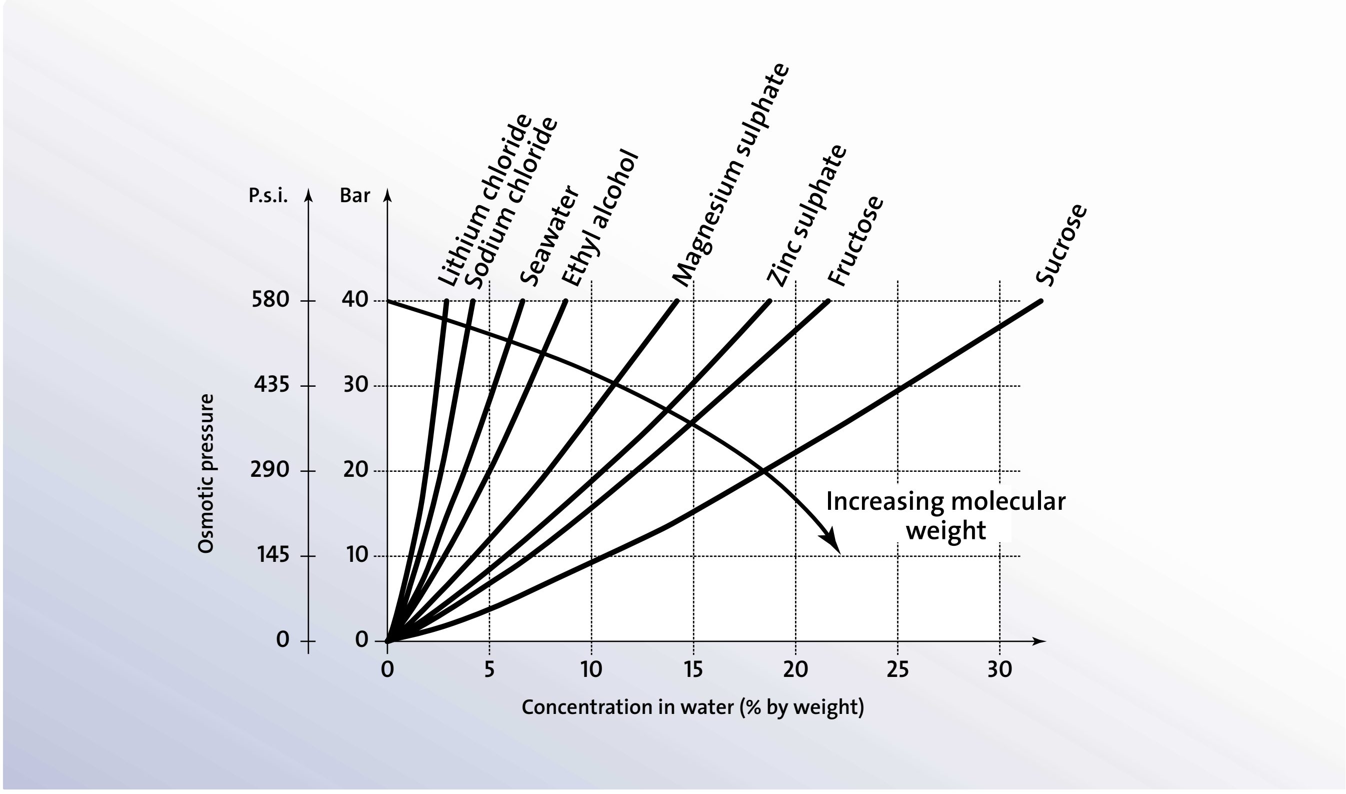


Fig. 61: *Osmotic pressure for various solutions*

It is not just concentrations and membrane conditions that determine the capacity, not in the long term anyway. In every form of membrane filtration concentration of the raw water across the membrane takes place, and solutions thus approaching their saturation point will display a tendency to deposit. Across the membrane the pure water will leave the solution to continue more or less alone through the membrane, and the solution remaining will therefore be even more concentrated. The result is (can be) precipitation of solid substances across the membrane. In nano and reverse osmosis filtration this is called “scaling”, and in micro and ultra filtration “fouling”.

Scaling is often a hard layer of lime and gypsum, while fouling passes more into a softer layer (sludge) of the substance that may now be in the solution. With both types the result is reduced capacity over time. Once the capacity becomes too low, CIP-type cleaning must be carried out by recirculation of a cleaning agent, which can be acid, leaching solution, detergents (surfactants) or enzymes.
With nano and reverse osmosis filtration it is possible to extend the intervals between CIP by dosing the anti-scaling agents into the feed water. Computer programs are available for calculating the dosing quantity of anti-scaling agent based on water analyses, raw water flow and concentration grade.

6. Distillation

6.1 Definition

Distillation refers to a process where concentration intensification takes place in a solution, as the solvent is removed by boiling off. The boiled-off solvent is subsequently condensed on a cold surface and is collected. With water treatment the solvent will be water and the solution will normally be salt water.

In an industrial enterprise the solution may be effluent, from which the water is evaporated, for recovery for process water, for instance.

Other types of solution, where the solvent is not water, fall outside the subject of water treatment.

6.2 The distillation process

Distillation processes are used in many places for production of drinking water, where the raw water is salt water or brackish water. The process requires a supply of heat energy for evaporation and cooling energy for condensation. Distillation plants are therefore often close to large combined heat and power plants by the sea in order to be near a relatively cheap energy source. A supply of cooling energy is thus present in the form of relatively cold salt water.

Supply of heat energy takes place in several different ways. It can be in the form of waste heat from a thermal power station or a diesel engine or by direct heating. There is a difference between sea and land-based systems.

Sea-based systems: A diesel engine on a ship generates large quantities of heat energy (cooling water and exhaust gas), which is simply discharged into the sea and the atmosphere. A "freshwater generator" is a distillation system that utilises this waste heat for vaporisation of salt water, and where the cooling salt water is on hand for use during the condensation. If the heat source is hot enough (above 100°C), e.g. in the form of exhaust gas and steam, the process can take place at atmospheric pressure. When using cooling water from a diesel engine as the heat source the temperature will be below 100°C, and the distillation process will then take place at a pressure below atmospheric pressure (vacuum system).

Land-based systems: Land-based systems function like sea-based systems. The heat source is typically warm cooling water, exhaust gas and waste steam from a thermal electricity generating station.

There are other types that use vapour compression in a single-stage or multi-stage system, and even in combination with input of thermal energy. With the latter the steam is added by a steam ejector, which simultaneously sucks in and compresses the low-pressure steam that comes from the last stage in the multi-stage system.

6.3. Distillation systems

There are four types of distillation system:

- Distillation system with steam compression, type VVC (Vacuum Vapour Compression).
- Single-stage (single-effect) distillation system, type "Single".
- Multi-stage distillation system, type MED (Multiple-Effect Distillation).
- Multi-stage distillation system, type MSF (Multi-Stage Flash).

6.3.1 Distillation system with steam compression, type VVC

Fig. 62 shows a diagram of a distillation system of the type VVC, Vacuum Vapour Compression, and Fig. 63 shows a picture of the same type of system.

6.3.2 Single-stage (single-effect) distillation system, type "Single"

Fig. 64 shows a single-stage distillation system of the type "Single", which is typically used for distillation of salt water for production of drinking water and process water on ships and drilling rigs and in connection with small-scale electricity generating stations. These systems can be either with or without a vacuum system, i.e. operate both around and below 100°C. The two plate heat exchangers (evaporator and condenser) are installed in a globe-like housing to prevent collapse in vacuum. The material selection is stainless steel (spherical housing), bronze (pipes, valves, pumps and ejector) and titanium (plate heat exchangers).

The system size goes up to approx. 100 m^3 drinking water per 24 hours (~ 4 m^3/h), and the quality of the distilled water is around 2 mg salt/l. Energy consumption is approx. 760 kWh/m^3 drinking water.

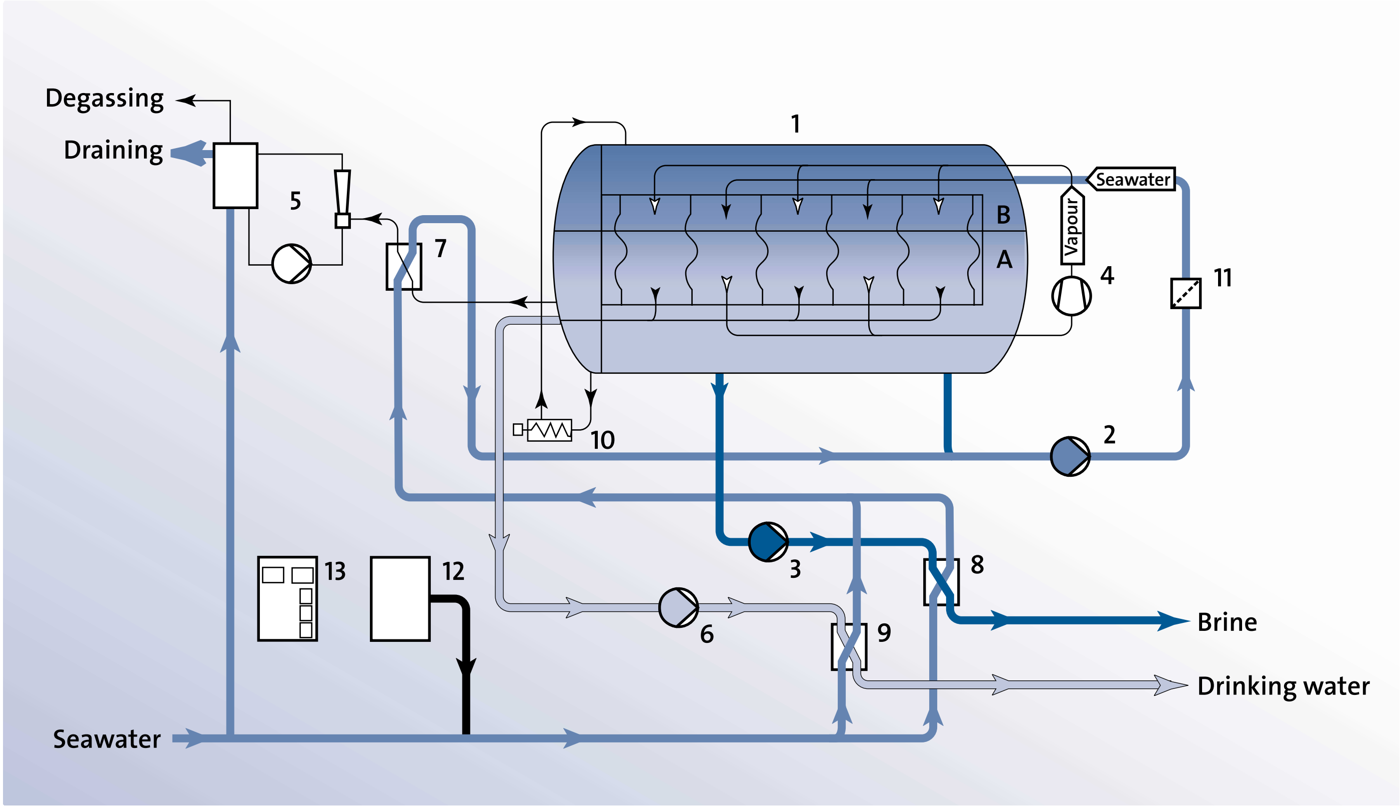


Fig. 62: *Diagram of distillation system with steam compression, type VVC*

Pos.	Description	Pos.	Description	Pos.	Description
1	Distillation boiler (consisting of A + B)	4	Stream compressor	10	Electric heater (only for start-up of system)
		5	Vacuum system		
A	Evaporation chamber	6	Distillate pump	11	Automatic self-purifying filter (0.5 mm)
B	Condensation chamber	7	Condenser for ventilation	12	Anti-scaling dosing unit
2	Brine circulation pump	8	Brine/sea water preheater	13	Control panel
3	Brine transport pump (“blow down pump”)	9	Distillate/sea water preheater		

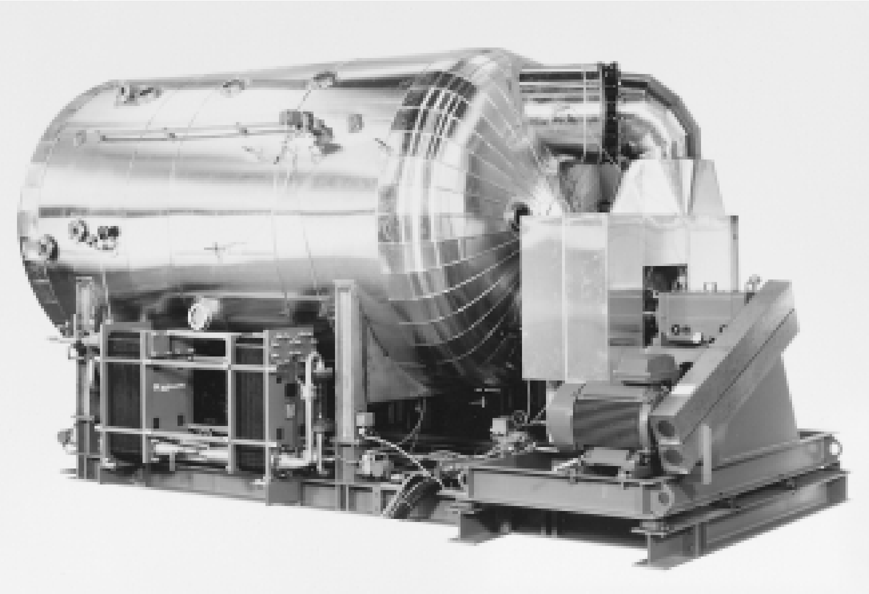


Fig. 63: *VVC distillation system for 400 m³ drinking water per 24 hours*

Fig. 64:
Single-stage (single-effect) distillation system of the type "Single"

6.3.3 Multi-effect distillation system, type MED

In large distillation systems of the MED type, series of two or more distillation units are integrated in one plant. In this way lower energy consumption is achieved as the supplied heat energy is reused several times on its way through the plant. Stage by stage the distillation takes place at a lower and lower temperature and pressure. See Fig. 66 and section 6.5.2.

6.3.4 Multi-stage distillation system, type MSF

For many years very large distillation plants have been in use in some places e.g. in the areas around the Persian Gulf. They are all located close to the sea and are supplied with waste heat from a nearby thermally-driven electricity generating station. This type is called an MSF system (Multi-Stage Flash).

The largest of the plants have capacities up towards 50,000 m^3/24 h with heat-energy consumption of around 50 kWh per m^3 drinking water.

Outwardly the systems look like one large box, which contains a large number of evaporator stages arranged in series.

6.4 Pumps in distillation systems

The size of the pump in a distillation system depends on the system's capacity. Distillation systems of the "Single" and MED type range from 5 – 20,000 m^3/24 h, and VVC-type systems are available from 20 – 2000 m^3/24 h.

6.4.1 Sea water pumps

Sea water pumps handle input of salt water for distillation and/or for cooling purposes. The type depends on the type of sea water intake, i.e. whether the pump is submerged or not, and the size of the system. The delivery pressure is typically 2 – 3 bar (29 – 43.5 p.s.i.).

Pump requirements: The flow for a MED system is 5 – 50 times the drinking-water capacity. For the pump this is equivalent to from 1 to several 1000 m^3/h. For VVC-type systems the flow is 2 – 3 times the drinking-water capacity. For the pump this is equivalent to from 2 – 250 m^3/h.

Pump types: Can be SPR (904 L) and/or CRT.

6.4.2 Brine transport pump ("blow down pump")

The brine transport pump ("blow down pump") is typically exposed to brine with a salt concentration of 1.5 – 2 times the concentration in the sea water and a temperature of 60 – 80°C. The flow is 1 to 2 times the system's drinking-water capacity, which is from 0.2 – 1,600 m^3/h. As the pump is only a transport pump, only a low head is needed.

Pump requirements: The pump should run with a large vacuum on the suction side, equivalent to the low pressure in the evaporation boiler. However, you usually position the pump 1 – 2.5 m lower than the distillation system so that the pressure on the suction side is minus 0.7 – 0.9 bar (10.15 – 13.05 p.s.i.).

Under these conditions (low pressure and relatively high temperature) the pump must run slowly and have good flow conditions. The following are recommended:

- **Speed:** Max. 1,400 min^{-1} (i.e. a pump with disproportionately large dimensions)
- **Flow rate:** Max. 0.5 m/s in delivery pipe.
- **Piping:** Reduction of pipe diameter just before pump.
- **NPSH:** 0.5 – 2 m.

Material selection: The medium contains up to approx. 10% salt at approx. 50°C, and stainless steel type 904 L and sea water-resistant bronze can be used. In practice stainless steel of the type AISI 316 L is used. The reason that this is possible is probably that the brine is deficient in oxygen due to the deaeration that takes place during the evacuation. In addition, the corrosion hazard to stainless steel peaks at a salt content of around 5%. With distillation of salt water the salt content in the brine is typically above 5%.
Shaft seals function well, even standard versions. Only in rare instances have double seals with barrier fluid (type Q - Quench) been used.

Pump type: Can be CRN, CRT and NK in bronze.

6.4.3 Brine circulation pump

The brine circulation pump is used in VVC systems and in other types of system to maintain efficient mixing of raw water and brine and to ensure turbulence on the heating surfaces.
The medium has the same concentration as for the brine transport pump, but the temperature is somewhat higher: 45 – 80°C.

Pump requirements: The pump requirements are the same as for the brine transport pump.
See section “6.4.2 Brine transport pump” above.
The flow is 5 – 10 times the drinking-water capacity, i.e. the pump must be able to produce 4 – 800 m^3/h, and for VVC systems the differential pressure across the pump is approx. 2.5 – 3 bar (36.25 – 43.5 p.s.i.).

Pump type: Can be CRN, CRT and NK in bronze.

6.4.4 Drinking-water pump/distillate pump

Like the brine transport pump, the drinking-water pump, or distillate pump, is a transport pump.
The medium has a salt content of 2 – 20 mg/l, and the pH value is between 5.5 and 7 (depending on carbon dioxide content). The temperature is typically 40 – 50°C.

Pump requirements: The pump requirements are the same as for the brine transport pump.
See section “6.4.2 Brine transport pump” above.
The flow is equivalent to the drinking-water capacity, i.e. the pump must be able to produce 0.2 – 800 m^3/h, and the head will often be a few metres.

Material selection: The material selection is generally bronze, but stainless steel is also used, type AISI 304.

Pump type: Can be NK, CRN and CHI. Shaft seals in standard version.

6.4.5 Condensate pump

The condensate pump is used in systems that utilise steam as the energy source.
The condensate has a salt content of 2 to 5 mg/l, and the temperature is typically 65 – 90°C.

Material selection: The material selection is as for the drinking-water pump.

Pump requirements: The pump requirements are the same as for the brine transport pump.
See section “6.4.2 Brine transport pump” above.
The condensate flow is equal to the steam consumption and depends on the system’s capacity and efficiency.
An approximate calculation of the flow from the smallest systems, “Single” type, to the largest, MED type, gives roughly from 0.2 – 125m^3/h.

Pump type: Can be NK, CRN and small CHI types. It is important to remember the special version with low speed and consequent reduced head and flow.

6.4.6 Dosing pump

In a distillation system for evaporation of salt water there is, on the whole, no pre-treatment of the sea water. A simple filter removes the worst of the dirt before the water reaches the evaporation boiler. However, dosing anti-scaling agent into the raw water is carried out. The dosing reduces the risk of scaling on the heating surfaces. The types of chemicals and dosing quantities per cubic metre of raw water are nearly the same as for reverse osmosis systems.
See chapter “8. Chemical treatment (dosing pumps)”.

6.5 Theory: Distillation

The quantity of steam (which ends up as drinking water) generated in a distillation system is proportional to the input heat quantity and the heating surfaces’ ability to transfer heat from one medium to the other, i.e. from engine cooling water to salt water, for example. The following equation expresses the ratio in a heat transfer like this:

$$\frac{Q}{\tau} = U \times A \times \Delta t$$

Where

Q is the quantity of heat [kWh (Kcal)]

τ is the time unit [hours]

U is the thermal transmittance [KWh (Kcal) /m^2 x h x °C]

A is the area of the heating surface [m^2]

Δt is the temperature difference across the heating surface [°C]

6.5.1 Schematic sketch of single-stage distillation system

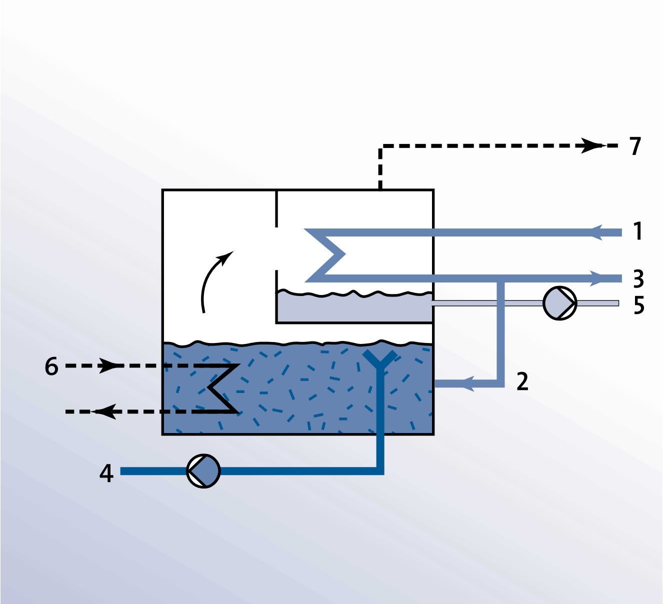


Fig. 65: Schematic sketch of single-stage distillation system.
Energy consumption: Approx. 750 kWh/m^3 distillate

Pos.	Description
1	Inlet for salt water
2	Salt water for evaporation
3	Excess of salt water
4	Drain for concentrated salt water (brine)
5	Drain for distillate (drinking water)
6	Input of heating medium
7	Outlet for non-condensable gases

6.5.2 Multi-effect distillation system, type MED

The number of stages for a specific distillation is determined on the basis of the total temperature drop involved, i.e. the temperature difference between the heating medium and the available cooling medium divided by 7 – 10°C. Another aspect is the costs connected to the number of stages. The initial costs increase almost in proportion to the number of stages, while the heat saving for each new stage becomes less and less.
See Fig. 66.

A MED plant produces 1 m^3 drinking water using between approx. 400 kWh (two stage model) and approx. 60 kWh (ten stage model).

6.5.3 Distillation system with steam compression, type VVC

It is different with distillation systems where mechanical steam compression is used, see Fig. 67. A single-stage system produces 1 m^3 drinking water for approx. 11 kWh, and a three-stage system produces 1 m^3 for approx. 8 kWh. Distillation systems can achieve high levels of efficiency, equivalent to reverse osmosis systems.

Mode of operation: See Fig. 67. The steam from the steam zone (4) is compressed in the compressor (5), increasing the temperature of the steam. In the heat exchanger (6) the steam condenses at the same time as the brine is heated for boiling in the boiling zone (3). The recirculation pump (2) recirculates a mixture of brine and salt water (1). Drinking water is removed via a pipe (7), and excess brine is removed via a pipe (8). The ratio between drinking water and brine is typically one to one, i.e. the water utilisation ratio is 50%.
The schematic sketch does not show all necessary pumps and external heat exchangers. See these in Fig. 62.

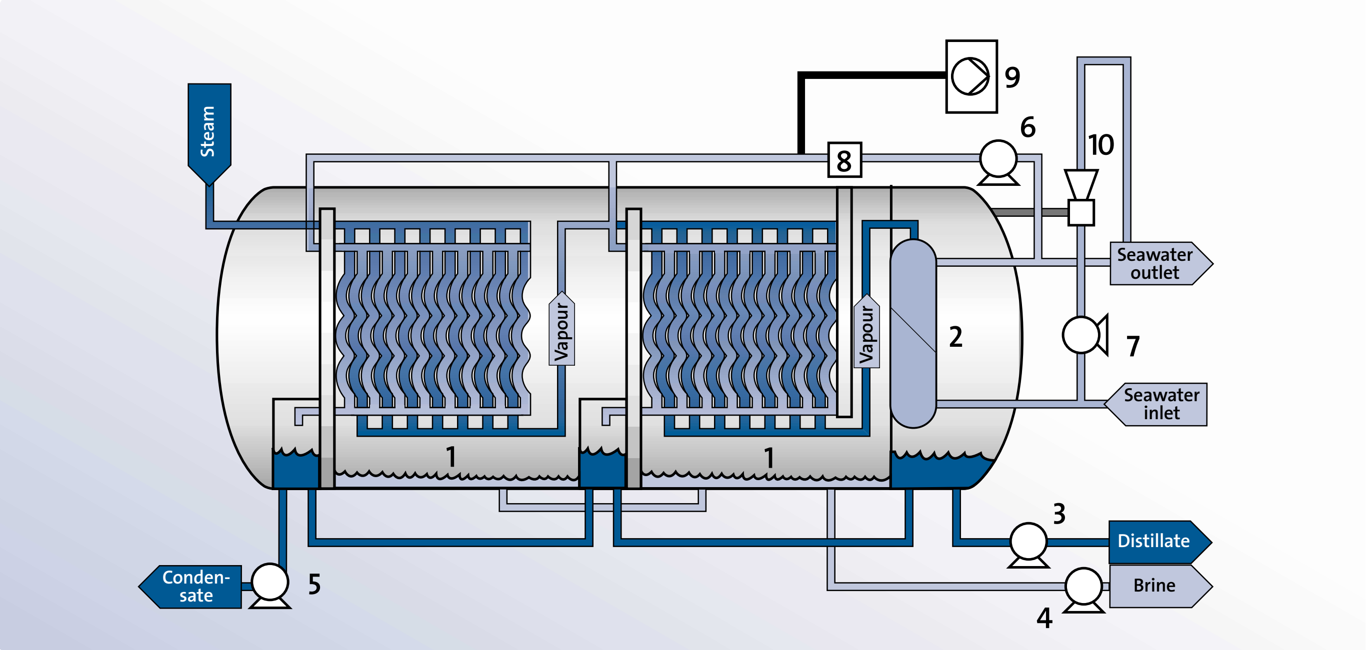
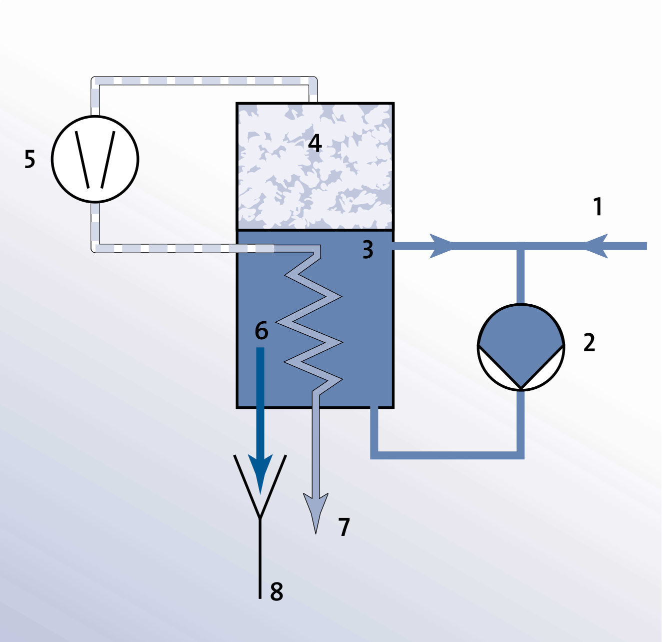


Fig. 66: Multi-effect distillation system, type MED, with two stages

Pos.	Description	Pos.	Description
1	Heat exchanger	6	Feed-water pump
2	Condenser	7	Ejector pump
3	Distillate pump	8	Feed-water filter
4	Brine pump	9	Dosing system
5	Condensate pump	10	Air ejector



Pos.	Description
1	Inlet for salt water
2	Recirculation pump
3	Boiling zone
4	Steam zone
5	Steam compressor
6	Heat exchanger
7	Outlet for drinking water
8	Outlet for brine

Fig. 67: Distillation system with steam compression, type VVC

7. UV and ozone

7.1 Introduction

UV refers to water treatment by means of irradiation with ultraviolet light, and ozone refers to water treatment by dosing of O_3 (ozone).

UV and ozone can be used for disinfection of water, i.e. to kill the microorganisms that are present in almost all types of surface water, and, in rarer cases, also in ground water.

The presence of microorganisms will generally impair the quality of the water. Drinking water may become undrinkable, even directly toxic. UV is often used in combination with reverse osmosis and ion exchange for production of “ultra-pure water” for use in the pharmaceutical industry, for example.

There are a number of different alternatives for disinfection of water, such as ...

1. removal of microorganisms by filtration, e.g. micro filtration and slow sand filtration.
2. inactivation of microorganisms by chemical means, e.g. treatment with chlorine, chlorine dioxide and ozone.
3. inactivation of microorganisms by physical means, e.g. boiling and UV irradiation.

Filtration through micro filters and sand filtration, pt. 1, and dosing of chlorine and chlorine dioxide, pt. 2, are dealt with under chapters 2, 3 ,5 and 8.

7.2 Water treatment with UV

The disinfecting effect of ultraviolet rays has been known since 1878, when sunlight’s bactericidal effect was discovered. 1910 saw the first attempt to use UV irradiation for disinfection of water. It is currently being used in many places as time goes on, but has never been able to outstrip the use of chlorine. One of the reasons is that UV irradiation is short-acting, as an infection of the water (e.g. due to unclean pipes) after irradiation with UV renders the irradiation no longer effective. Chlorine, on the other hand, will remain in the water and be effective for a long time after the dosing has taken place.

A major advantage of UV systems is low investment costs and a single, inexpensive operation without the addition of chemicals. Maintenance consists of cleaning fittings occasionally, and replacing the lamp roughly once a year.

7.3 Water treatment with ozone

Dosing of ozone [O_3] in water was used for the first time in 1906. The ozone is created in ozonisers, from where it is dosed and mixed in the water. Ozone is very fast-acting. Compared with chlorine it is roughly twice as effective in relation to the dosing quantity. In addition to having an immediate bactericidal effect, ozone also has a positive effect on the taste and smell of the water, and a strong oxidising effect that increases the reaction rate of many chemical processes in the water, e.g. in connection with the presence of iron, manganese, humus and organic substances. The process must generally be followed up by filtration due to deposited substances that cause the water to be cloudy.

Mode of operation for ozone system: From the ozoniser the ozone is directed to a dosing system for mixing with the water to be disinfected. As the ozone is in a gaseous state the most efficient way of adding it is as small bubbles (approx. 3 mm in diameter) through a system of nozzles and then ensuring a long residence time and/or good agitation in the water. Many traditional systems act in this way, but the most efficient method has proved to be the use of the “U-tube” reactor.

7.4 Water treatment with both UV and ozone

Finally, there is also a combination of UV and ozone. It has been found that UV light from a mercury lamp with a light-wave length of around 172 nm is capable of creating ozone (“FOTOZON”). The UV light converts the water’s content of free oxygen into ozone by photochemical means. The discovery of this process is relatively recent (approx.1980) and it is not yet very widely used. It is used, for example, to inhibit organic growth in water tanks for animals (fish, seals and sea lions). It may be possible to develop the process sufficiently to enable it to compete with traditional ozonisers, which in relation to the UV/ozone method are very expensive in initial cost.

7.5 UV systems

Fig. 68 shows a sectional drawing of a U-shaped UV irradiation chamber with a UV lamp in each branch of the U-pipe. The actual lamp is either like an ordinary fluorescent tube (low-pressure mercury lamp), but without the fluorescent coating on the internal side of the tube, so the UV light escapes directly, or a special version (medium-pressure mercury lamp). The lamp is installed in a protective tube of quartz glass. The water to be irradiated flows around the protective tube at a depth of only a few cm. Greater depths can cause problems with the penetration capability due to possible cloudy water. A photoelectric cell is mounted alongside the outer tube (external wall), to monitor the light intensity of the lamp and report if either the light intensity is too weak (cleaning of quartz tube necessary) or the lamp is not lighting at all (replacement).

In large systems many lamps are positioned in parallel operation in the same pipe or housing.

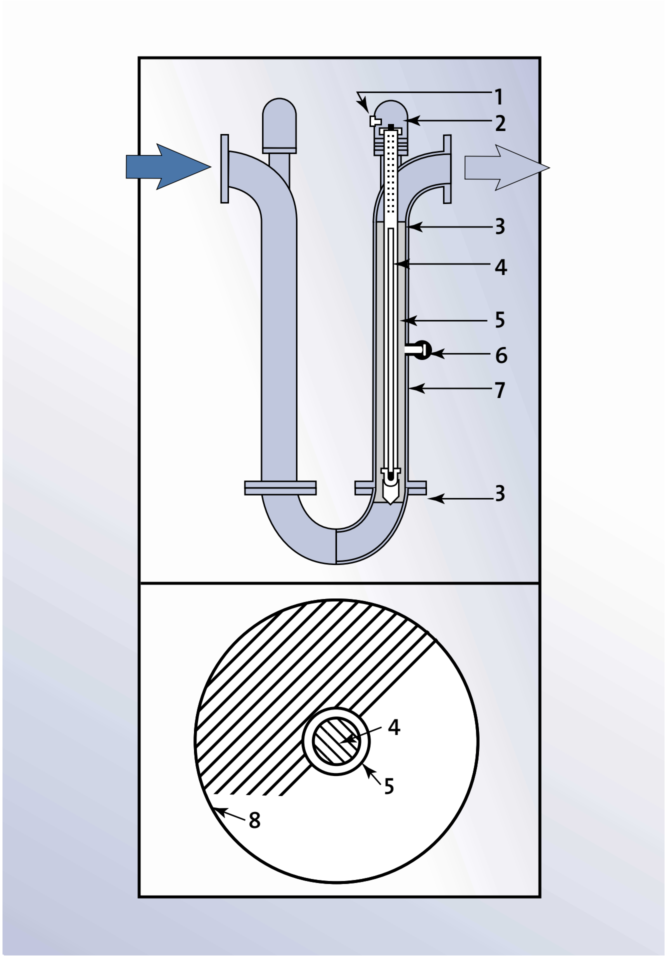


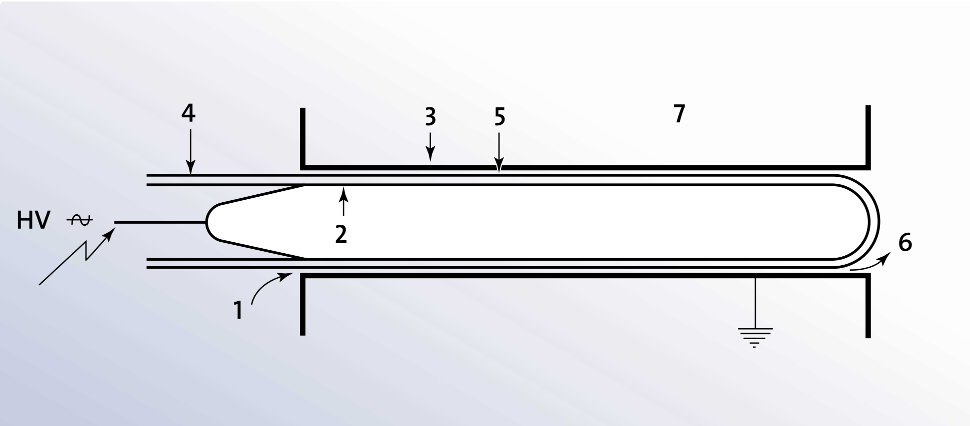
***Fig. 68:** UV irradiation in U-pipe*

Pos.	Description	Pos.	Description
1	Plug	5	Quartz tube
2	Protective cap	6	Photoelectric cell
3	Turbulence device	7	Irradiation chamber
4	UV lamp	8	External wall

7.6 Ozone systems

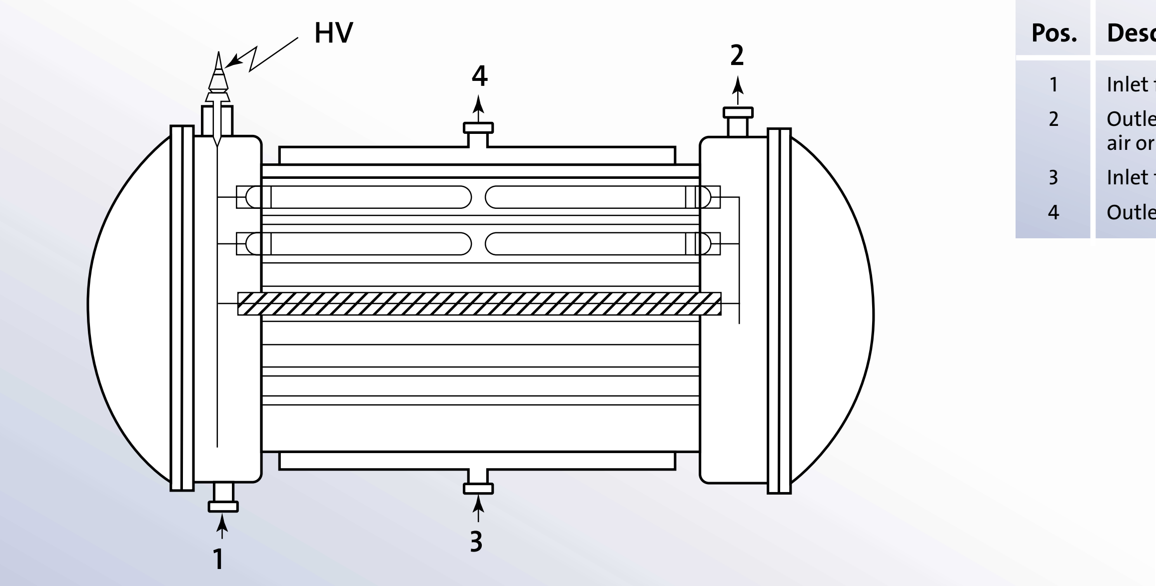
In the majority of cases ozone systems are produced with tubular electrodes, see Fig. 69 pos. 2 and 3, where the high voltage is applied to the central pipe (2). The dry air or oxygen is conveyed in a fairly narrow gap (1 and 5) between the two electrodes. A mixture of ozone-containing air and oxygen is removed at (6). A dielectric medium (4) is located between the two electrodes. This is an insulating material that prevents direct current passage (short circuit) between the two electrodes. Due to the huge outputs imparted between the electrodes (~ 5 kW/m^2) a certain amount of heat is generated, which is conducted away with the cooling water in the outer earthed electrode (7).

As with UV apparatus, ozone elements are integrated in larger units in parallel operation for greater capacities. Fig. 70 shows a unit like this with the elements positioned as a tube bundle in a drum-shaped container. The capacity is 15 – 25 kg ozone/h, depending on supply of air or oxygen.



Pos.	Description
1	Gap between the two electrodes
2	Central pipe electrode
3	Electrode
4	Dielectric medium between the two electrodes
5	Gap between the two electrodes
6	Removal of ozone-containing air and oxygen
7	Cooling water

***Fig. 69:** Tubular ozoniser element*



Pos.	Description
1	Inlet for air or oxygen
2	Outlet for ozone-containing air or oxygen
3	Inlet for cooling water
4	Outlet for cooling water

Fig. 70: *Large unit with ozoniser elements positioned as a tube bundle in a drum-shaped container*

Description of the "U-tube" reactor ozone system: The "U-tube" reactor is constructed from two concentric pipes, see Fig. 71. The raw water enters the system at (6) via a pipe and has an ozone/air mixture added via the nozzles (3). During the descent through the pipe (1) the gas bubbles will become less and less due to the increasing static pressure in the water. By these means a gas/water emulsion with good contact area between water and ozone is achieved. After leaving the inner pipe (4) water and gas rise in the outer pipe (2), where the bubbles become larger and larger before finally being released at the surface (5). The ozone-treated water flows from the system via a pipe (7). For the system to run at optimum the relations between the downward rate in the inner pipe, the gas/water ratio and the pressure drop through the entire system must be precisely adapted. It is therefore necessary to have a recirculation pump positioned between outlet (7) and inlet (6) to keep a constant flow. Without this the system would not be able to operate satisfactorily with varying loads.

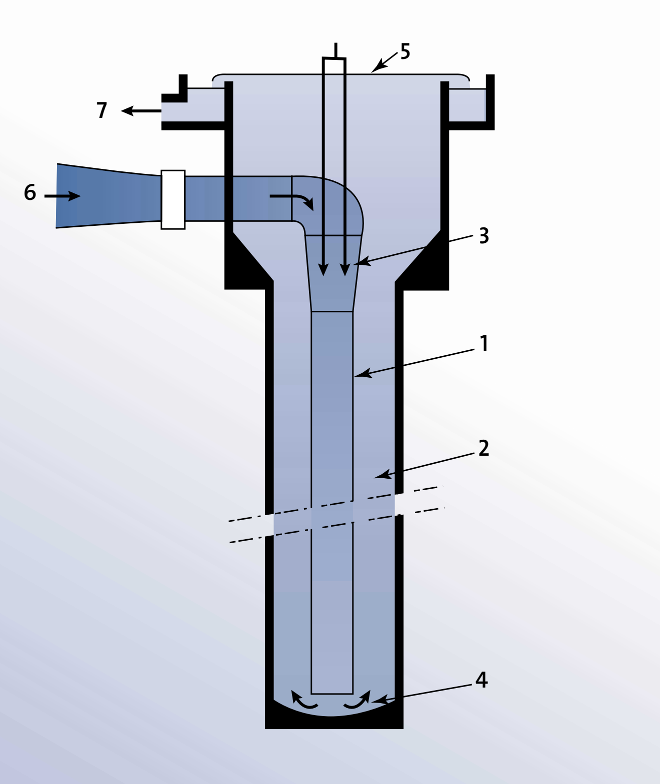


Fig. 71: *U-tube reactor*

7.7 Pumps in UV and ozone systems

Apart from the aforementioned "U-tube" reactor, there will not be any special pump requirements for UV and ozone systems, besides the demands made by the medium.

Pos.	Description
1	Pipe
2	Water and gas rise in the outer pipe
3	Nozzle for ozone/air mixture
4	Water and gas leaves the inner pipe
5	Surface
6	Inlet for raw water
7	Outlet for ozone-treated water

The pumps are usually transport pumps, as the drops in pressure through the systems are slight.

If ozone residue is present in the water around rubber components in the pump (including shaft seals) elastomers resistant to ozone should be selected.

7.8 Theory: UV and ozone

7.8.1 Ultraviolet light

Ultraviolet light from an electric fluorescent tube with a wavelength of 200 to 300 nm has a powerful destructive effect on microorganisms. This effect peaks at approx. 260 nm, where the organisms' DNA molecules display the greatest absorption of the ultraviolet light, see Fig. 72, UV-C.

The effect results from the fact that UV light (photons) destroys the organisms' DNA molecules, as it attacks the building blocks (nucleic acid) in the molecule, deactivating the tissue cells and halting the capacity for cell division.

7.8.2 Ozone

Ozone is an unstable gas created by the effect of oxygen in a powerful electric field. By supplying a high voltage (up to 20 kV) from a generator, an electric field (corona) is formed between two electrodes, by which means dry oxygen [O_2], which is passed between the electrodes (plates), undergoes a partial separation into atoms [O] and almost immediately after combines in threes to form ozone [O_3].

The disinfecting influence is due to the fact that ozone (like chlorine) has powerful oxidising properties that cause all organic material to decompose, including infectious bacteria.

The normal ozone dosage in drinking water is up to 0.4 g/m^3, and for river water up to 2 g/m^3. With it the energy consumption is significantly greater than with application of UV irradiation (approx. 0.02 kWh/m^3 water against approx. 0.001 for UV). However, ozone's disinfecting properties are also much greater than those of UV irradiation.

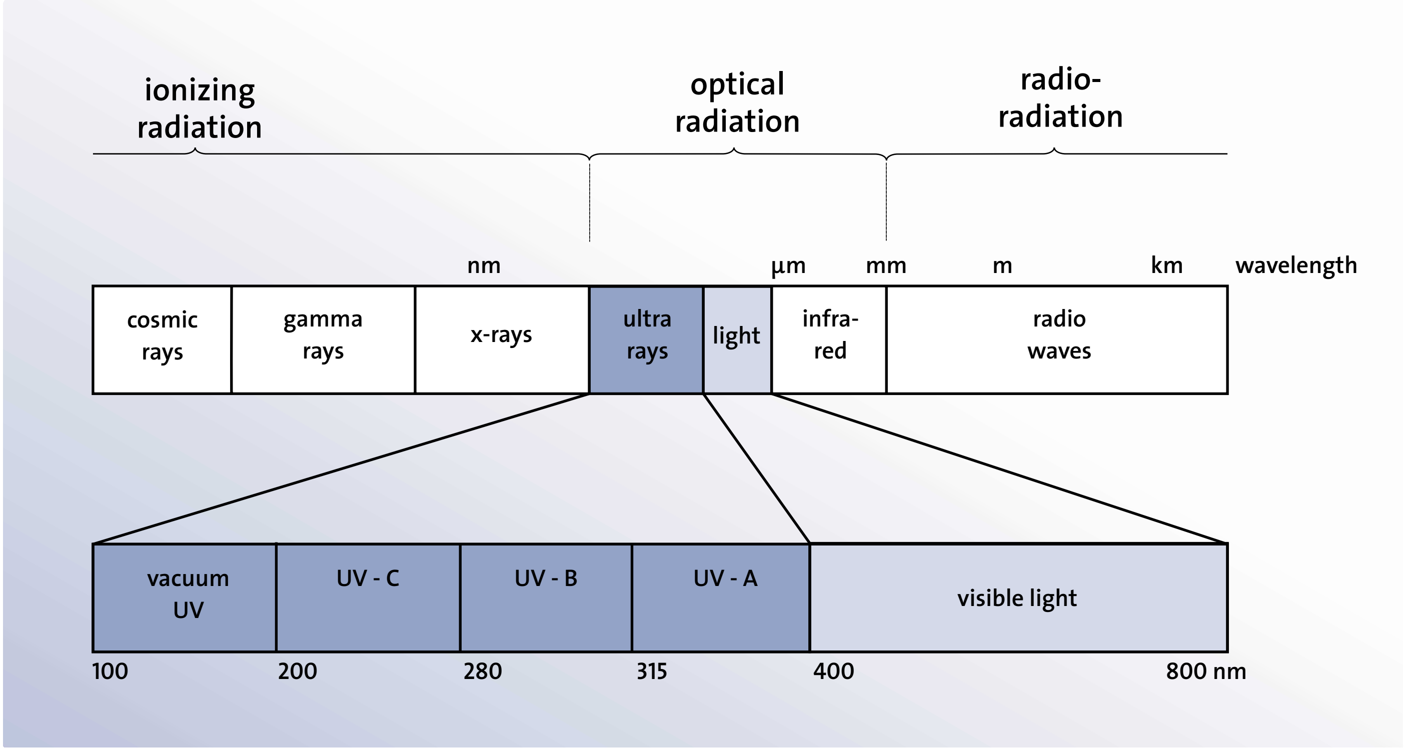


Fig. 72: The ultraviolet spectrum compared with other electromagnetic waves

8. Chemical treatment (dosing pumps)

8.1 Introduction

Most types of water treatment require some form of chemical treatment in order to achieve the best possible quality of water in the shortest possible treatment time. Therefore the construction of chemical dosing systems, including handling, storage and mixing of the chemicals, is extremely important. A correctly-designed dosing system will be able to improve the effectiveness of a specific water treatment and thus assist in reduction of operation and maintenance expenses.

In principle three basic forms of chemicals are used: solid matter, liquid and gas. Dosing of chemicals in liquid state (dissolved substance) is best, as it is more compact, more precise in the dosing and easier to handle. In general dosing systems must be able to handle a wide variation in capacity to enable it to live up to the corresponding variation in the water treatment system's capacity and requirements for dosing of chemicals.

As this section only deals with the application of dosing pumps in water treatment, focus will be on dosing of chemicals in a liquid state (i.e. in solution).

Chemicals for water treatment systems, and especially when the end product will be drinking water, must be pure and of a quality that has been approved by the local health authorities. In the case of dosing in wastewater the needs of the recipient (watercourses and sea) are paramount, i.e. consideration for plants and animals (protection of the environment).

Metering pump: In English-speaking countries the term "Metering pump" is often used for a dosing pump.

8.2 List of the most important chemicals

The list below shows some of the most important chemicals, classified according to typical fields of application. The typical concentration in aqueous solution for delivery is shown (max. concentration).

Coagulation and flocculation (precipitation):

Chemicals	Typical concentration in water on delivery
Aluminium sulphate (alum), $[Al_2(SO_4)_3]$	49%
Polyaluminiumchloride (PAC)	5 – 10%
Ferric chloride, $[FeCl_3]$	35 – 45%
Iron sulphate, $[Fe_2(SO_4)_3]$	59%
Cationic polymer (e.g. polydimethyl-diallyl-ammonium chloride)	Up to 100%
Anionic polymer (e.g. polycarboxylates)	Up to 100% (normally supplied as solid matter)
Noionic polymer (e.g. polyacrylamides)	Up to 100% (normally supplied as solid matter)

Disinfectants:

Chemicals	Typical concentration in water on delivery
Sodium hypochlorite, $[NaClO]$	15% (~7% active chlorine)
Sodium chlorite, $[NaClO_2]$	Approx. 30%
Ammonium sulphate, $[(NH4)_2SO_4]$	4% (normally supplied as solid matter)
Calcium hypochlorite, $[Ca(ClO)_2]$	Not suitable, as lime will deposit on valves in dosing pumps
Sodium hydrogensulphite, $[NaHSO_3]$ (preservation)	50% (removes oxygen and chlorine)
Quaternary ammonium compounds	– (not relevant)
Diverse biocides (e.g. bromine compounds)	– (not relevant)

pH control:

Chemicals	Typical concentration in water on delivery
Hydrated lime (calcium hydroxide), [$Ca(OH)_2$]	20% (supplied as solid matter of 82 – 95%)
Soda lye (sodium hydroxide), [NaOH]	50% (or as solid matter of 100%)
Sodium carbonate, [Na_2CO_3]	10% (supplied as solid matter of 99%)
Sulphuric acid, [H_2SO_4]	62 – 93%
Hydrochloric acid, [HCl]	30% (often available with corrosion inhibitor)

Taste and smell control:

Chemicals	Typical concentration in water on delivery
Potassium permanganate, [$KMnO_4$]	approx. 5% (supplied as solid matter of 97 – 99%)

Corrosion control:

Chemicals	Typical concentration in water on delivery
Zinc orthophosphate	8% as zinc
Soda lye (sodum hydroxide) [NaOH]	50% (or as solid matter of 100%)

Drinking-water improvement (health):

Chemicals	Typical concentration in water on delivery
Fluosilicic acid, [H_2SiF_6]	20 – 30%
Sodium fluoride, [NaF]	approx. 4%
Sodium fluorosilicate, [Na_2SiF_6]	0.5 – 1%
Solution of sodium, potassium and iodate salts	– (not relevant)

Algae control:

Chemicals	Typical concentration in water on delivery
Copper sulphate, [$CuSO_4$]	20%

“Scaling” control:

Chemicals	Typical concentration in water on delivery
Sodium hexametaphosphate, [$NaPO_3]_6$	67% as [P_2O_5] (particularly for RO and evaporation)
Trisodium phosphate, [Na_3PO_4]	25%

Particularly for ion exchange:

Chemicals	Typical concentration in water on delivery
Sodium hydroxide	50% (or as solid matter of 100%)
Hydrochloric acid	30% (often available with corrosion inhibitor)
Salt (saturated NaCl-solution, brine)	Approx. 30%

Particularly for cooling-water treatment:

Chemicals	Typical concentration in water on delivery
Biocide:	
- Sodium hypochlorite	15% (~7% active chlorine)
- Benz-iso-thiazolinon	–
- Poly-hexamethylene-biguanide	20%
Corrosion inhibitor:	
- Zinc salts	–
- Phosphonates	–
- Polycarboxylates	–
- Tolytriazole (TTA)	–

Particularly for boiler water:

Chemicals	Typical concentration in water on delivery
Scaling control:	
- Tannins	–
- Phosphates	–
Oxygen scavenger:	
- Sulphites	–
Corrosion inhibitors:	
- Sodium hydroxide	50% (or as solid matter of 100%)
- Amines	–
- Phosphonates	–

Before designing a dosing unit, it is important to find out about the quality of the raw water (composition), the requirements for the finished water and this water's ability for being treated at all. These factors will determine what type(s) of chemicals must be used, and how much must be dosed into the raw water (e.g. in mg/l). Many suppliers of chemicals have simple computer programs for calculation of dosing quantities: The input required for the computer is the composition of the raw water and required treatment, and the output is type and quantity of chemical.

Other factors that should be considered are the characteristics of the individual chemicals, effective life, storage temperature, salubrity, combustibility and danger of explosion, local conditions, delivery method, safety directions during transport, ability to supply, price, local safety regulations and storage facilities. On the whole, in the case of chemicals in general, you must be sure that your conduct in these matters is correct.

8.3 Dosing pump application

8.3.1 Dosing in distillation systems

Fig. 73 shows a dosing unit consisting of a dosing tank with a dosing pump on top of the tank. An appropriate quantity of the solution is dissolved in pure water in the tank and the dosing pump is set to the required dosing quantity. Distillation systems generally operate with fixed capacity, so flow-proportional control of the dosing pump is not necessary.

Fig. 73: *MED distillation system with dosing unit for anti-scaling agent (front right)*

8.3.2 Installation of dosing pumps

Before installing a dosing pump in a specific application the following points should be considered:

Type:	Diaphragm pump. Note: This description refers to diaphragm pumps only.
Capacity:	As a starting point a dosing pump should be set up with a maximum capacity equivalent to approx. 2 times the required dosing flow.
Counter pressure:	From 1 to 10 bar (14.5 – 145 p.s.i.). In exceptional cases, up to 16 bar (232 p.s.i.).
Precision:	$^{+}$/-1.0% of maximum capacity is preferable.
Variation:	The minimum requirement is usually from 1 to 100 % of maximum capacity.
Control mode:	The best is either: • flow-proportional control by a water meter, cf. Fig. 74, or • closed-loop control where the pump is controlled by an instrument (such as a pH controller) based on a water quality measurement, cf. Fig. 75. Manual setting of the dosing quantity should also be possible.
Material selection:	Dosing pumps are typically used for corrosive media and the materials will therefore be polymers such as PP, PVDF, PTFE and elastomers such as EPDM and FKM.

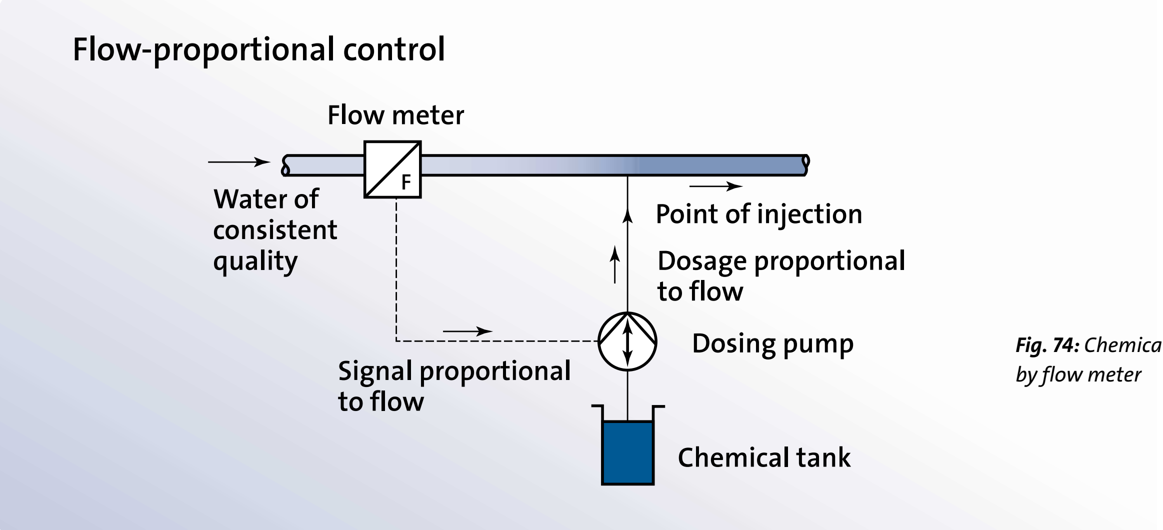


Fig. 74: Chemical dosing controlled by flow meter

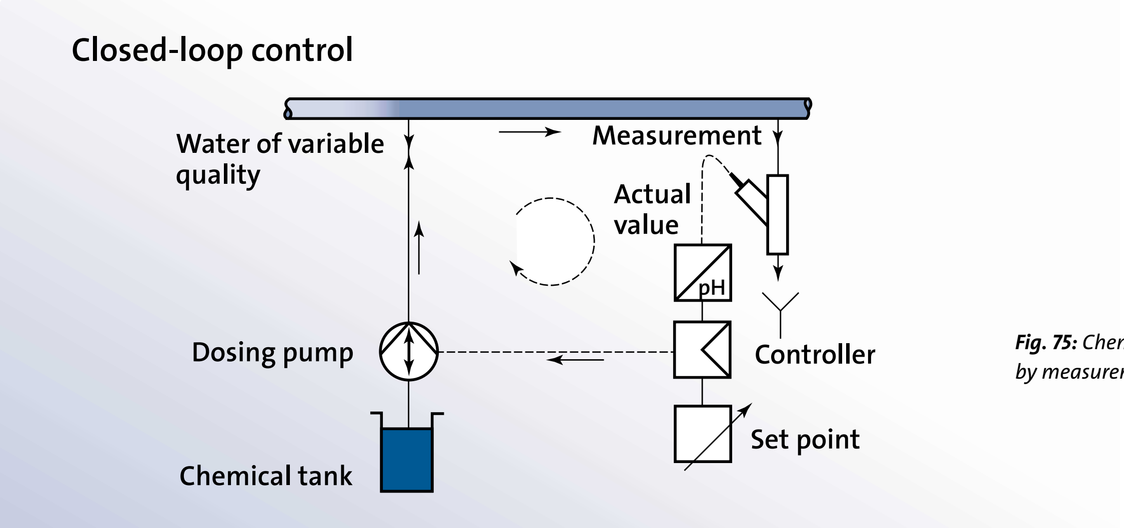


Fig. 75: Chemical dosing controlled by measurement of water quality

Chemical tank: Corrosion-resistant materials. Stainless steel is sometimes used, but plastic (e.g. polyethylene, PE) is most common. Remember to take into consideration frost and venting in the event of unpleasant odours or discharge of toxic vapours.

The volume of the tank should be equivalent to approx. 15 days' consumption, unless the chemical solution does not have an effective life of 15 days.

The tank should be equipped with level indicator to signal an 'almost empty' tank via an alarm connected to the central control panel.

If the solution in the tank has a tendency to settle, or the solid matter is difficult to dissolve during the actual preparation of the solution in the tank, an electrically-operated agitator should be used.

Suction line: The suction line (PE or PVC) will often be fitted with a nonreturn valve in the bottom of the chemical tank, and a filter as well, if the dosing liquid contains suspended substances.

The suction pipe should be no longer than 2 m, and the internal diameter is adjusted for a flow of max. 0.8 m/s, measured by the flow during the suction stroke.

Discharge line: The discharge line (PE, PTFE or stainless steel) has the same flow as the suction line. The pressure will be substantially higher than in the suction line, due to the counter pressure at the dosing point and pressure drop in any injection valve. To prevent ruptures of the equipment from any blockage of the discharge line or valve, a pressure relief valve with back-flow to the chemical tank can be installed, see Fig. 76. To dampen pressure peaks, pulsation dampers can be installed. Pulsation dampers are primarily used in very long discharge lines.

For information on accessories in general refer to the technical documentation.

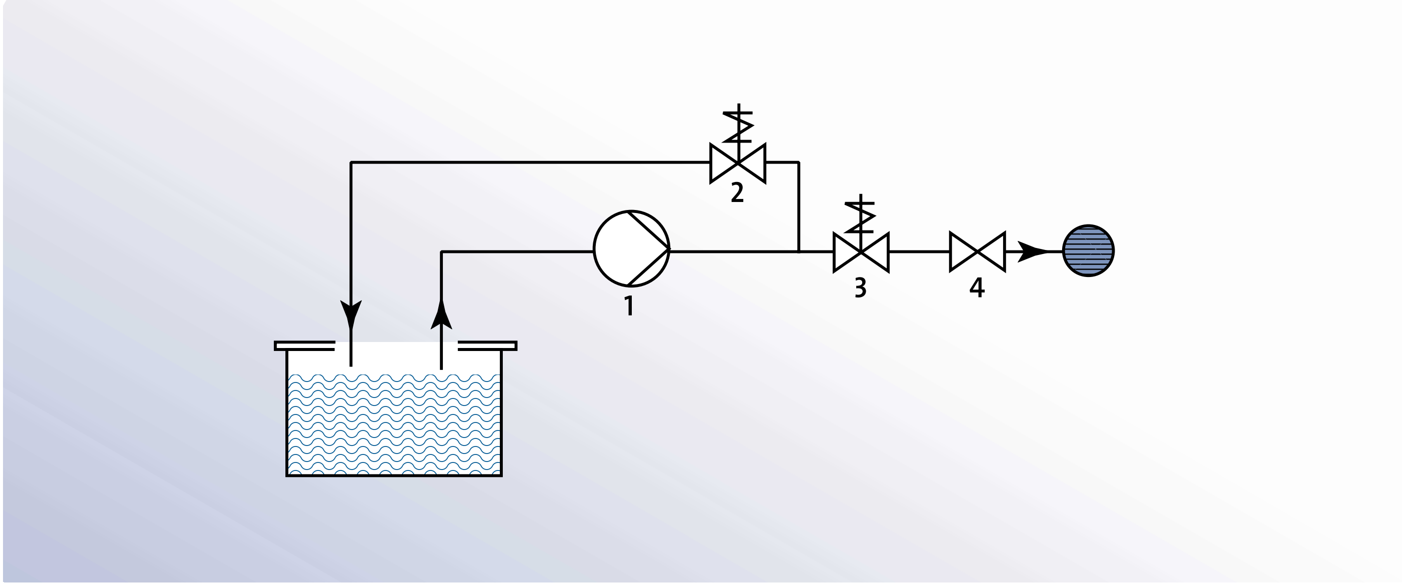


Fig. 76: Dosing system with pressure relief valve (2) and counter pressure valve (3)

Pos.	Description	Pos.	Description
1	Dosing pump	3	Counter pressure valve
2	Pressure relief valve	4	Isolating valve

8.4 Sample calculation

A customer has a water treatment system in which he wishes to dose 10 mg soda lye/l in a pipeline with a flow of 6 m^3/h and system pressure of 4 bar (58 p.s.i.). His dosing solution of soda lye [NaOH] must be a 25% solution.

Which dosing pump should we offer him?

In a 25% [NaOH] solution there is approx. 25 g [NaOH]/100 ml = 250 mg [NaOH]/ml. In 6 m^3 water with 10 mg [NaOH]/l there is in total: 6000 x 10 = 60,000 mg [NaOH].

In one minute the quantity dosed must be: 60,000 / 60 = 1,000 mg [NaOH] equivalent to 1,000 / 250 = 4.0 ml [NaOH] solution, i.e. the dosing pump must supply 4.0 ml/min (0.24 l/h).

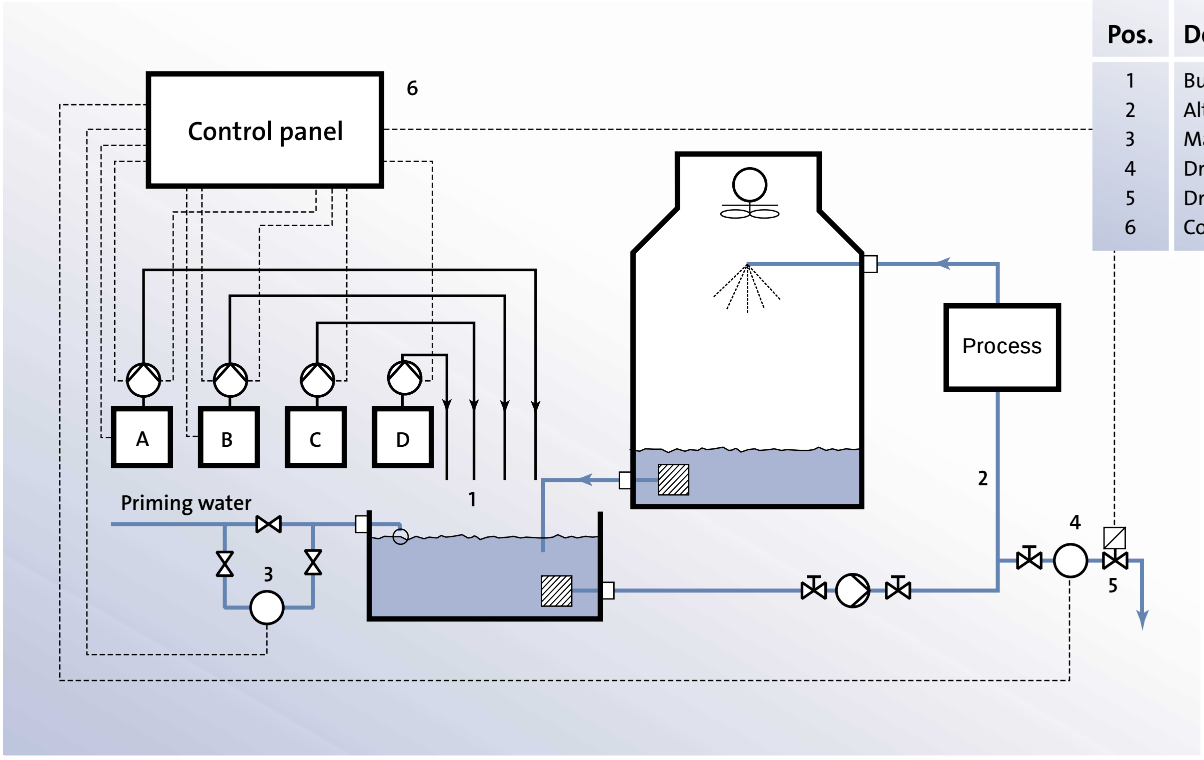
An appropriate choice of dosing pump could be a Grundfos type DME 2 – 18, which has a setting range between 0.0025 and 2.5 l/h. To avoid uncontrolled overdosing the pump's maximum output can be restricted electronically, to 0.5 l/h, for example, whereby the pump will be customised for this precise application.

If the water treatment system is fitted with a flow meter, with either a pulse or an analog signal (4 – 20 mA), in the pipeline where the dosing is to be performed, the dosing pump can be set so that the dosing quantity is always flow-proportional. The same applies if a similar signal from an instrument controlling the quality of the treated water (e.g. pH) is used. In both cases the dosing pump must nevertheless be dimensioned as shown above.

The materials PP and EPDM are suitable for a 25% sodium hydroxide solution.
Discharge and suction tubing of PE and PVC are also suitable. At temperatures above 40°C PTFE or stainless steel should be used.

The question of material resistance in a dosing pump should be dealt with by means of a material resistance list.
The correct choice of material is crucial to avoid pump failure.

***Fig. 77:** Dosing of base for pH control of the water in district heating system and boiler*



Pos.	Description
1	Buffer tank
2	Alternative dosing spot
3	Make-up water meter
4	Drain water meter
5	Drainage valve
6	Control panel

Fig. 78: *Application of dosing in a cooling tower system: One dosing of acid, one dosing of inhibitor and two dosings of biocides*

Example of dosing in cooling tower system
Schematic sketch of structure of dosing systems in a cooling tower application is shown in Fig. 78.

Illustrated chemical treatment:

Pos.	Description
A	Dosing of acid (generally sulphuric acid) for minimisation of lime precipitation.
B	Dosing of corrosion inhibitor to protect steel components from attack by acid.
C and D	Dosing of biocide for inhibiting growth of various types of microorganisms.

The variety of chemicals within the category of biocides is huge, as the type of microorganisms can vary from cooling tower to cooling tower. Local ratios and conditions for the microorganisms also play a part.

Dosing of the chemicals should be carried out either directly into the buffer tank/cooling-tower tank (1) or alternatively directly into the circulating cooling-water pipe on the pressure side of the circulator pump (2).
If dosing acid directly into the pipeline, we recommend “linking” the circulator pump and the dosing pump (A), so that A cannot run without the circulation pump running.
(3) is a make-up water meter and (4) is a drain water meter. Both assist in controlling the dosing pumps by means of flow signals to the control panel.
The dosing tanks are all equipped with alarm/stop for low level (not shown for C and D).

8.5 Theory: Chemical treatment

The purpose of chemical treatment of water is to achieve a reaction between the chemical and the water. The result is a change in the composition of the water and/or its effect on its surroundings. Dosing with acid or alkaline solution can alter the pH value of wastewater to a value more appropriate for the conditions, dosing of scale inhibitor into raw water for a reverse osmosis system will inhibit the tendency for lime precipitation to form on the diaphragm, dosing of sodium hypochlorite in drinking water can keep down the quantity of microorganisms, etc.
The most interesting processes in chemical treatment of water are coagulation and flocculation. These processes are also some of the most widely-used within dosing technology.
The fields of application include clarification of drinking water,

see section “2.3 Surface water”, by which dissolved metallic compounds (e.g. calcium, magnesium and iron) and also microorganisms (BOD) are removed by subsequent sedimentation and filtration. In the treatment of wastewater the spectrum of undesirable substances is even greater: It includes fairly fine particles (suspended substances), chemical residue from fertilisers, phosphates, toxic metallic compounds (heavy metals) and microorganisms.
The terms coagulation and flocculation are often confused and used indiscriminately for the same thing.

Coagulation is the process of destabilisation of the charge (predominantly negative) on particulates and colloids suspended in water. Destabilisation lowers the repelling character of particulates and colloids and allows them to become attached to other particles so that they may be removed in subsequent processes. See Fig. 79. The particulates in raw water (which contribute to colour and turbidity) are mainly clays, silt, viruses, bacteria, fulvic and humic acids, minerals (including asbestos, silicates, silica, and radioactive particles), and organic particulate.

Flocculation means a process to enhance agglomeration of destabilised particles and colloids toward settleable (or filterable) particles (flocs). Normally flocculation involves an intentional and defined process of gentle stirring to enhance contact of destabilised particles and to build floc particles of optimum size, density, and strength to be subsequently removed by sedimentation or filtration.

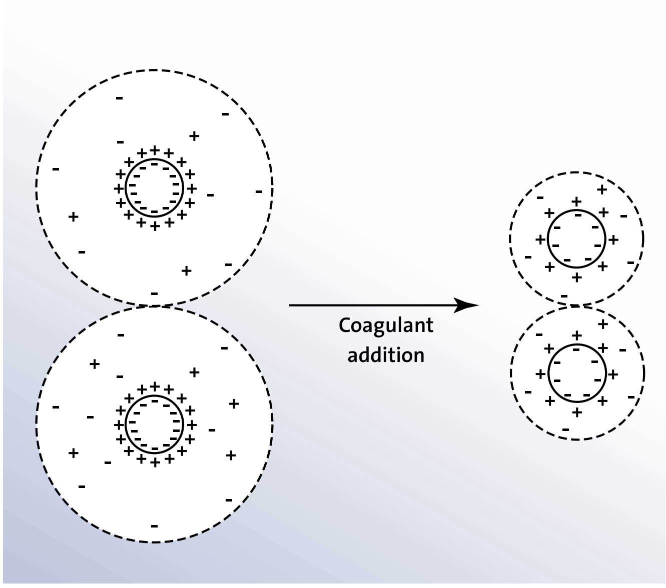


Fig. 79: *Addition of a coagulant compresses the repellent double layer between the particles, after which they bunch together*

Addition of too much polymer can reverse the situation back to the smaller particles again, see Fig. 80. Therefore it is important that the dosing quantity of polymer flocculating agents is correct.

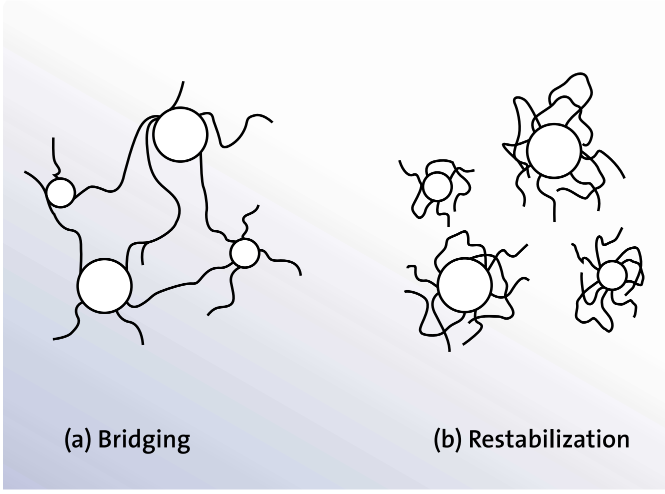


Fig. 80: *(a) Large flocs are formed by means of polymer bridging. (b) Small particles are re-formed by overdosing of polymer, called restabilization*

8.6 Theory: Dosing Pumps

In the case of dosing pumps the theory concerns which type of pump is best suited for the specific purpose and how the dosed quantity can best be controlled. Displacement pumps are generally preferable, because the accuracy in the dosing is usually the dominant feature. With very large dosing quantities, where there are no major requirements for accuracy, a centrifugal pump would be a possibility. A piston or diaphragm pump would be preferable. Fig. 81 shows typical Q-H curves for centrifugal pumps, diaphragm pumps and piston pumps. It is clear that for accuracy in dosing, piston pumps are best, as they come closest to the theoretical potential, i.e. that the flow/dosing quantity (Q) is independent of the pressure (H). Since diaphragm pumps are more user-friendly than piston pumps with regard to maintenance, they are generally chosen as being the most suitable for dosing pumps. The point is that the dosing pump should supply a carefully measured volume per pump stroke, revolution or time. Or, in other words, that it is possible, independently of the counter pressure, to dose a specific volume dependent on e.g. the flow in the pipeline in which the chemical is to be dosed.

The fact that there is a difference between a piston pump and a diaphragm pump for dosing purposes is chiefly due to the fact that there is more elasticity/flexibility built into the diaphragm pump. In a diaphragm pump, the higher the counter pressure the greater the yield from the diaphragm etc. will be.

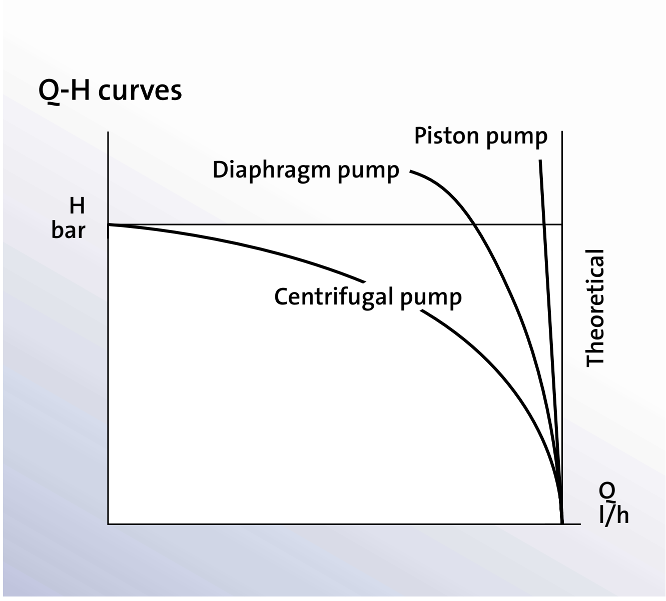


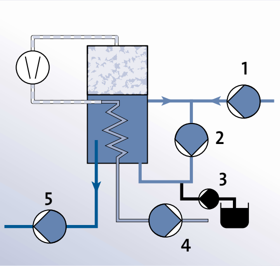
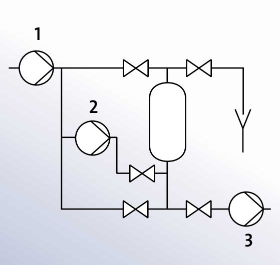
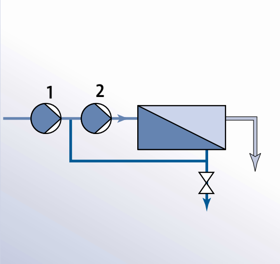
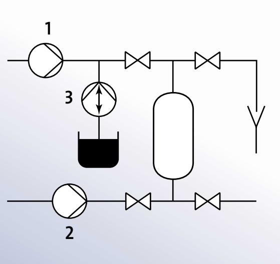
Fig. 81: Correlated Q-H curves for piston, diaphragm and centrifugal pumps

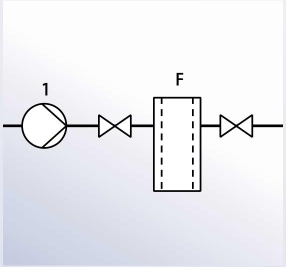
Therefore in Fig. 81 we see that the flow output (Q) e.g. per pump stroke becomes less and less, the higher the counter pressure: The Q-H curve bends as with a centrifugal pump, but to a much lesser extent.

A piston/diaphragm pump, in which a piston activates the diaphragm via a parting liquid (e.g. oil), generally provides the optimum dosing pump solution, combining the advantages of both pump types.

9. Overview of pumps in water treatment applications

The table below provides an overview of the types of pump that are typically used in the various forms of water treatment applications.

Water treatment application	Pump function	Grundfos pump type	Reference chapter
Evaporation  	1. Sea water pump 2. Brine recirculation pump 3. Dosing pump 4. Drinking-water pump/distillate pump 5. Brine transport pump	SPR (904 L), CRT CRN, CRT, NK/NB bronze version DM NK, CRN, CHI CRN, CRT, NK/NB bronze version	Chapter 6
Ion exchange  	1. Feed pump 2. Regeneration pump 3. Clean-water pump (if needed)	CR, CRN CR, CRT (if liquid does not contain acid) CR, CRN, BMQ, BM	Chapter 4
Membrane filtration  	1. Raw water pump High-pressure feed water pump 2. Recirculation pump **Other pumps:** Permeate pump Dosing pump (pre-treatment and post-treatment)	CRN, CRT, BM CRN (CRN-SF), BME, CRT CRN, BM, CRT CRN DM	Chapter 5
Sand filtration  	1. Raw water pump 2. Backwash pump 3. Dosing pump (flocculant)	SP NK/NB DM	Chapter 2

Water treatment application	Pump function	Grundfos pump type	Reference chapter
Standard filtration 	1. Transport pump	CR, CRN, CHI, BM	Chapter 3
UV and ozone	Transport pump	CR, CHI, BM	Chapter 7

10. Overview of Grundfos pumps

The list below provides an overview of the types of Grundfos pumps mentioned in this book.

Pump name	Description
BM / BM-R	Booster Module with SP pump. BM-R in AISI 904 L.
BME/T	Booster Module with External motor, with/without recovery Turbine
CHI	Multistage Centrifugal pump, Horizontal, for Industrial application.
CLM	Single-stage Centrifugal pump, in-Line, M = 4-pole.
CR	Multistage Centrifugal pump.
CRK	Centrifugal pump, Condensate.
CRN	Multistage Centrifugal pump, Niro (316 L).
CRT	Multistage Centrifugal pump, Titanium.
DM	Dosing/Metering pump.
NK/NB	Single-stage standard (Norm) pump.
SPK	Submersible pump, Condensate.
SP / SP-R	Submersible pump. SP-R in AISI 904 L.

Source references

The following sources have been used in the writing of this book:

"Brief introduction into the technics of dosage", JESCO Dosiertechnik.

"Coagulants and Flocculants", Yong H. Kim.

"Drikkevand en truet resurse", NOAH.

"Integrated Design of Water Treatment Facilities", Susumu Kawamura.

"Ion Exchange", Rohm & Haas.

"Kemiske Enhedsoperationer", L. Alfred Hansen and P. Søltoft.

"Membrane Filtration Handbook", Jørgen Wagner.

"Water Treatment Handbook", Degrémont.

"Stahlschussel", 18. Auflage, 1998

"General Chemistry", McQuarrie and Rock

"Corrosion", Volume 13, Metals Handbook, Ninth Edition

"BetzDearborn Handbook of Industrial water Conditioning", Ninth Edition 1991

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Glossary

BOD	Biological Oxygen Demand. - Method of measuring the content of (some) oxidable organic substances in the water.
CIE	Continuous Ion Exchanger.
CIP	Cleaning in Place. Washing carried out with the filtering medium still in place.
Coagulation	The process of destabilisation of the charge (predominantly negative) on particulates and colloids suspended in water.
COD	Chemical Oxygen Demand. - Method of measuring the content of all oxidable substances in the water.
Corrosion	The deterioration of a metal or its properties caused by a reaction with its environment.
Cross-flow filtration	Filtration by which the flow-off is divided into two streams, whereby the suspended particles are continuously washed away.
Dead end filtration	Filtration by which the suspended particles end up in the filter.
Distillation	Distillation refers to a process where concentration intensification takes place in a solution, as the solvent is removed by boiling off. The boiled-off solvent is subsequently condensed on a cold surface and is collected. With water treatment the solvent will be water and the solution will normally be salt water.
ED process	Electrodialysis process.
EDR process	Electrodialysis reversal process.
ERT	Energy Recovery Turbine. Reverse osmosis system principle according to which a turbine is driven by the concentrate.
Flocculation	The process of enhancing agglomeration of destabilised particles and colloids toward settleable (or filterable) particles (flocs).
Flux	The capacity of purified water, "permeate", measured in l/m^2 membrane per hour.
Fouling	Precipitation of solid substances on the membrane in micro and ultra filtration.
FTU	Formazin Turbidity Units. – Unit of measurement for the content of inorganic substances in the water. Similar to NTU.
Inorganic substance	A substance that does not contain carbon chemically bound to hydrogen. Carbonates, bicarbonates, carbides and carbon oxides are considered inorganic substances, even though they contain carbon.
Ion exchange	A reversible process in which ions are released from an insoluble permanent material (resin) in exchange for other ions in a surrounding solution; the direction of the exchange depends upon the affinities of the ion exchanger for the ions present, and the concentrations of the ions in the solution.
MED	Multiple-Effect Distillation system.
Membrane filtration	Membrane filtration is physical separation of a substance by means of a semi-permeable membrane. The presence of a gradient, i.e. a propelling force, above the membrane drives the process. Membrane filtration is cross-flow filtration.
MF	Micro filtration. Type of membrane filtration.
MSF	Multi-stage Flash. Multi-effect distillation system.
NF	Nano-filtration. Type of membrane filtration.
NTU	Nephelometric Turbidity Units. – Unit of measurement for the content of inorganic substances in the water. Similar to FTU.
Organic substance*	A substance that contains carbon chemically bound to hydrogen. It often contains other elements (particularly O, N, halogens or S).
Ozone	Ozone refers to water treatment by dosing of O_3 (ozone). Ozone can be used for disinfection of water, i.e. to kill the micro-organisms that are present in almost all types of surface water, and, in rarer cases, also in ground water.
Permanent hardness of water	The difference between total and temporary hardness of water, explained as the quantity of calcium and magnesium that corresponds to sulphate $[SO_4^{2-}]$ and chloride $[Cl^-]$. Permanent hardness is characterised by the fact that it cannot be removed by boiling etc.
PRE	Pitting Resistance Equivalent.
RO	Reverse Osmosis filtration. Type of membrane filtration.
SCC	Stress Corrosion Cracking. Corrosion characterised by cracking caused by the simultaneous effects of mechanical tensile stresses and corrosion.
Scaling	Precipitation of solid substances on the membrane in nano and reverse osmosis filtration.
SDI	Silt Density Index. – Index expressing the cloudiness of the water caused by suspended, undissolved substances, such as clay.
SS	Suspended Solids. Small undissolved particles.
Standard filtration	Standard filtration is a process in which solid particles are separated from either a gas or a liquid.

<table>
<tr><td>TDS</td><td colspan="3">Total Dissolved Solids. – The total content of dissolved substances in water, other than dissolved gases.</td></tr>
<tr><td rowspan="5">Treated water</td><td>Treated water is called...</td><td>when water treatment takes place as...</td><td>After the treatment the water contains...</td></tr>
<tr><td>deionate (or deionised or demineralised water) or softened water</td><td>ion exchange.</td><td>other, fewer or very few salts.</td></tr>
<tr><td>distillate</td><td>distillation.</td><td>no salt.</td></tr>
<tr><td>filtrate</td><td>standard filtration.</td><td>many salts.</td></tr>
<tr><td>permeate</td><td>membrane filtration.</td><td>a few salts.</td></tr>
<tr><td>UF</td><td colspan="3">Ultra filtration. Type of membrane filtration.</td></tr>
<tr><td>UV</td><td colspan="3">UV refers to water treatment by means of irradiation with ultraviolet light.
UV can be used for disinfection of water, i.e. to kill the microorganisms that are present in almost all types of surface water, and, in rarer cases, also in ground water.</td></tr>
<tr><td>VVC</td><td colspan="3">Vacuum Vapour Compression. Evaporation system with steam compression.</td></tr>
</table>

Units used in this book:

µS/cm	(microSiemens per cm); Siemens = mho = ohm^{-1}
mg/l	(equal to ppm)
AISI	(American Iron and Steel Institute)
mval	(millivalens)

Subject index

Subject index