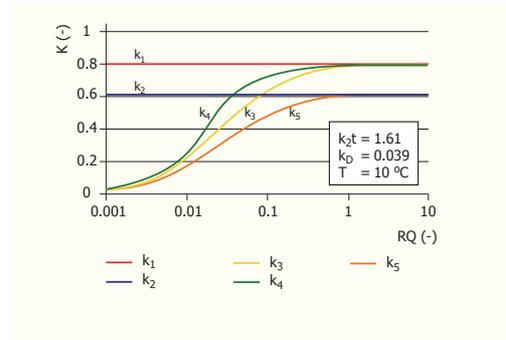
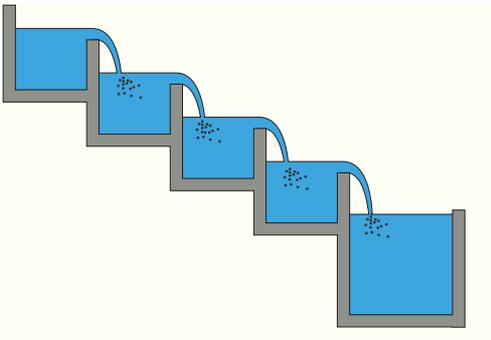
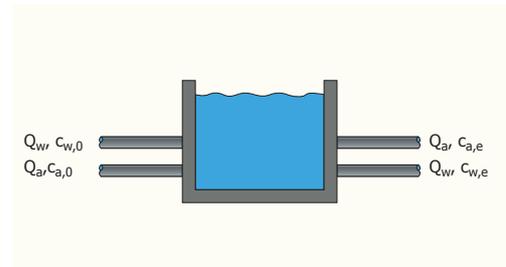
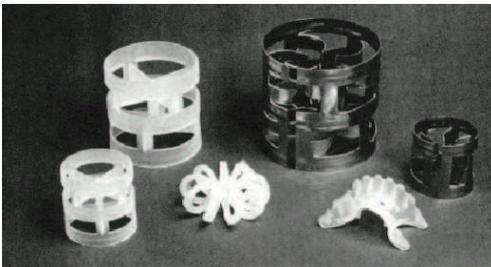


# Aeration and gas stripping



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This handout is based on *Drinking Water, Principles and Practices* by de Moel et al.

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## 1. Introduction

Aeration (gas addition) and gas stripping (gas removal) are normally the first treatment steps during the production of drinking water from groundwater or riverbank water. This artificially induced gas transfer aims at the addition of oxygen (O<sub>2</sub>) and the removal of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), hydrogen sulfide (H<sub>2</sub>S), and other volatile organic compounds (for example 1,2-Dichloropropane (1,2 DCP), Trichloroethene (TRI), Tetrachloroethene (PER) and Trichloromethane (chloroform)).

The addition of oxygen is required for the oxidation of bivalent iron (Fe<sup>2+</sup>), manganese (Mn<sup>2+</sup>) and ammonium (NH<sub>4</sub><sup>+</sup>). These substances are present in the dissolved form in groundwater and after chemical and biological oxidation, they can be removed in a subsequent filtration step.

Reducing the carbon dioxide concentration leads to a rise in pH and a reduction of aggressive carbon dioxide that is able to disintegrate (concrete) pipes. Methane should be removed because its presence results in excessive growth of bacteria in filtration processes.

Hydrogen sulfide has an unpleasant odor (rotting eggs) and therefore needs to be removed from the water.

Volatile organic compounds are usually toxic; some of them are even carcinogenic and therefore not allowed in drinking water.

To achieve gas transfer, a number of systems have been developed over the years.

They include cascade and tower aerators, which divide the water in thin layers; spraying, in which water is dropped in fine droplets through the air; and air bubbling, in which bubbles of air are blown in the water. The air bubbling can be performed through deep well aerators, plate aerators or compressor aerators.

## 2. Theory of gas transfer

### 2.1 Equilibrium

#### Henry's law

Water contains dissolved gases. In a closed vessel containing both, gas (e.g., air) and water, the concentration of a volatile component in the gas phase will at last be in equilibrium with the concentration in the water phase, according to Henry's law.

The equilibrium concentration can be calculated using the following form of Henry's law:

$$C_s = k_H \cdot C_g$$

where:

$C_s$  = equilibrium concentration of a gas in water (g/m<sup>3</sup>)

$k_H$  = Henry's constant or distribution coefficient (-)

$C_g$  = concentration of the gas in air (g/m<sup>3</sup>)

The distribution coefficient,  $k_H$ , depends on the type of gas, and the temperature.

In addition, pollution and impurities in the water influence the equilibrium concentration.

In Table 1, a list of values of the distribution coefficient,  $K_H$ , is given for a number of gases at different water temperatures, (intermediate values can be obtained with linear interpolation).

In the table it is shown that nitrogen, oxygen and methane have low  $k_H$  values. This means that these gases hardly dissolve in water and therefore, they can easily be removed.

The other gases have high  $k_H$  values and dissolve easily, when sufficient gas is present in the air. This makes it difficult to remove them from water (or easy to add them to water).

In addition, the gas concentration in the air  $c_g$  must be known before the equilibrium (or saturation) concentration can be calculated. This concentration can be determined using the universal gas law:

$$p \cdot V = n \cdot R \cdot T$$

Table 1 - Distribution coefficient for gases and the molecular weight

Gas	Distribution coefficient ( $k_{H,i}$ )			Molecular weight (MW) [g/mol]
	T = 0 °C	T = 10 °C	T = 20 °C	
Nitrogen (N <sub>2</sub> )	0.023	0.019	0.016	28
Oxygen (O <sub>2</sub> )	0.049	0.041	0.033	32
Methane (CH <sub>4</sub> )	0.055	0.043	0.034	16
Carbon dioxide (CO <sub>2</sub> )	1.71	1.23	0.942	44
Hydrogen sulfide (H <sub>2</sub> S)	4.69	3.65	2.87	34
Tetrachloroethelene (C <sub>2</sub> HCl <sub>4</sub> )	-1	3.20	1.21	167
Tetrachloroethene (C <sub>2</sub> HCl <sub>3</sub> )	-1	3.90	2.43	131.5
Chloroform (CHCl <sub>3</sub> )	-1	9.0	7.87	119.5
Ammonia (NH <sub>3</sub> )	-	0.94	0.76	17

<sup>1</sup> These substances are still in the liquid phase at a temperature of 0 °C and therefore the  $k_{H,i}$  is not known

where:

- p = partial pressure of gas in gas phase (Pa)
- V = total gas volume (m<sup>3</sup>)
- n = number of moles of a gas (mol)
- R = universal gas constant (= 8.3142 J/(K.mol))
- T = (air) temperature (K)

The gas concentration can be calculated by multiplying the molar gas concentration in air [mol/m<sup>3</sup>] with the molecular weight of the considered gas:

$$c_g = \frac{n}{V} \cdot MW = \frac{p}{R \cdot T} \cdot MW$$

where:

MW = molecular weight of a gas (g/mol)

The partial pressure of a certain gas is proportional to the volume fraction of that gas in air:

$$p = p_o \cdot V_f$$

where:

- p<sub>o</sub> = standard pressure at sea level (=101,325) (Pa)
- V<sub>f</sub> = volume fraction (-)

In Table 2 the volume fractions of different gases that occur in air are given.

These values are valid for dry air with a standard pressure of 101,325 Pa. With these volume fractions the partial pressures of all gases in air

can be calculated. Gases that do not occur in air have a partial pressure equal to zero and thus a c<sub>g</sub> and a c<sub>s</sub> equal to zero (for example, methane).

In Figure 1 the equilibrium (saturation) concentration of oxygen is given as a function of water temperature. With an increase in water temperature, the saturation concentration decreases, which means that less oxygen can be dissolved in warm water.

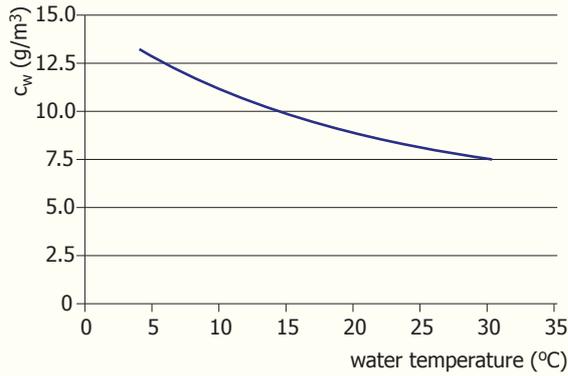
The saturation concentration c<sub>s</sub> is linearly dependent on pressure. The saturation concentration for oxygen at the standard pressure of 101,325 Pa is 11.3 g/m<sup>3</sup>.

At a height of 8,000 meters (for example, Mount Everest), the air pressure is only 10,000 Pa which means that the saturation concentration for oxygen is 1.1 g/m<sup>3</sup>.

Table 2 - Volume fractions of gases

Gas	Volume fraction <sup>1</sup> (%)	Saturation concentration <sup>2</sup> c <sub>w</sub> (g/m <sup>3</sup> )
Nitrogen (N <sub>2</sub> )	78.084	17.9
Oxygen (O <sub>2</sub> )	20.948	11.3
Argon (Ar)	0.934	-
Carbon dioxide (CO <sub>2</sub> )	0.032	0.79
Other gases	0.02	-

<sup>1</sup> In dry air at a standard pressure of 101,325 Pa  
<sup>2</sup> Water and air temperature of 10 °C



air: 21% oxygen  
 pressure: 101,325 Pa

Figure 1 - Saturation concentration of oxygen as a function of the water temperature

In the sea at a depth of 100 meters below sea level, the pressure is 1,100,000 Pa. This results in a saturation concentration for oxygen of 113 g/m<sup>3</sup>.

## 2.2 Kinetics

As soon as water and air are in contact, gas molecules will be exchanged continuously. The direction of the net gas transport depends on the gas concentration in the water ( $c_w$ ) and the equilibrium concentration  $c_e$ .

In Figure 2 the gas concentration in the water at time  $t=0$  is smaller than the equilibrium concentration. This means that more gas can be dissolved in the water than is present at time  $t=0$ . A net gas transport from air to water occurs, as indicated by the arrow in the Figure. The net gas transport

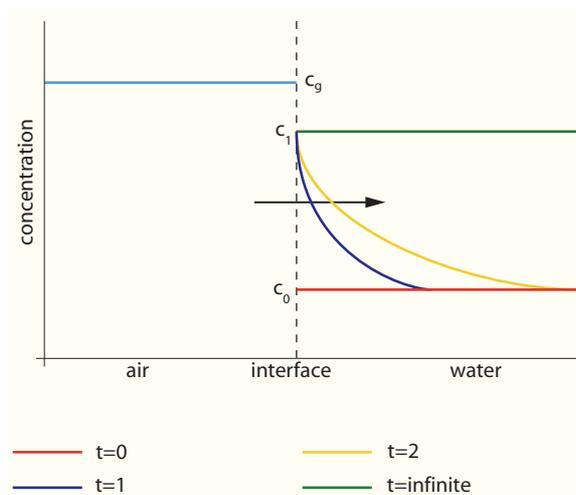


Figure 2 - Gas transport from air to water

continues until time  $t=\infty$  and the gas concentration in the water is equal to the equilibrium (or saturation) concentration. Then, the gas transport from water to air and vice versa are equal. Hence, no net gas transport occurs and the gas concentration in the water and air do not change. In that case, a dynamic equilibrium is established.

The velocity of gas transfer is determined by the kinetic equation:

$$\frac{dc_w}{dt} = k_2 \cdot (c_s - c_w)$$

where:

$C_w$  = concentration of a gas in water (g/m<sup>3</sup>)

$k_2$  = gas transfer coefficient (s<sup>-1</sup>)

The time-dependent gas concentration change in water is represented by the term  $dc_w/dt$ . The changes in concentration are determined by the magnitude of the gas transfer coefficient  $k_2$  and the driving force ( $c_s - c_w$ ).

The gas transfer coefficient  $k_2$  is a device-dependent parameter. The larger the contact surface area between the air and water and the renewal of this surface area, the better the gas transfer and the higher the gas transfer coefficient.

The driving force is defined by the amount of gas that can maximally be dissolved in a volume of water, the saturation concentration  $c_s$ , and the amount of gas that is present in a volume of water,

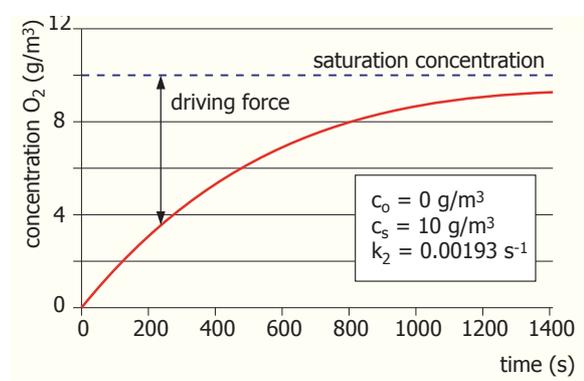


Figure 3 - Oxygen concentration in water as a function of contact time

the concentration  $c_w$ . The larger the driving force, the faster the gas transfer.

The increase in the oxygen concentration in time is shown in Figure 3 for a constant  $c_s$  (10 mg/l) and an initial oxygen concentration of 0 mg/l.

In the beginning, when the difference between  $c_s$  and  $c_w$  is the largest, the gas transfer occurs at maximum velocity. As time passes, the gas concentration in water increases and the driving force decreases, which gradually results in a lower gas transfer rate. For  $t \rightarrow \infty$  the oxygen concentration in water equals the saturation concentration  $c_s$ .

### 3. Practice

#### 3.1 Cascade

The cascade (Figure 4), one of the oldest aeration systems, is robust and consists of several steps. In each step, the water falls over a weir into a lower placed trough, creating an interface between air and water. When the jet submerges into the receiving body of water, significant amounts of air are entrained. The entrained air is then dispersed in the form of bubbles throughout the receiving body of water, leading to a mixture of gas and water in which gas transfer will occur (Figure 5).

The gas transfer efficiency in a cascade can be estimated, based on the fall height of each cascade step and the number of steps:

$$K = \frac{c_{w,e} - c_{w,0}}{c_s - c_{w,0}} = 1 - (1 - k)^n$$



Figure 4 - Cascade aeration

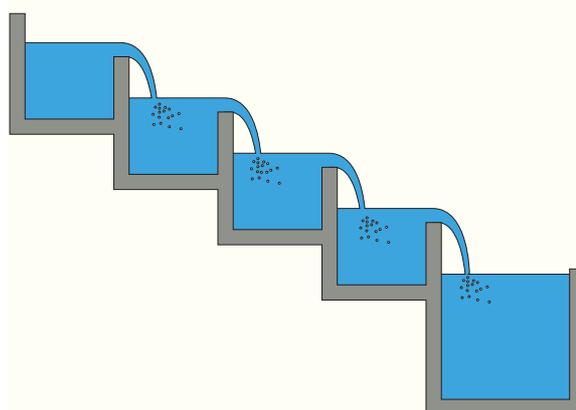


Figure 5 - Scheme of a cascade

in which:

$k$  = efficiency for each step (-)

$n$  = number of steps

In Table 3 the efficiency is given for oxygen, carbon dioxide and methane as a function of the fall height of a step. With the data from Table 3 and the equation mentioned above, the efficiency of a cascade with  $n$  steps can be calculated.

In practice a maximum fall height of 1 meter per step is chosen. The efficiency barely increases above this height. A higher efficiency can be obtained by using more steps. For a very thorough removal of  $CH_4$ , cascades with 4 - 5 steps and a total fall height of 4 - 5 m are used.

From Table 3 it can be seen that oxygen and methane efficiencies increase with an increase in fall height, but that the carbon dioxide efficiency remains constant. This is a result of the low amounts of air that are present in the cascade system. The interface between air and water gets rapidly saturated with carbon dioxide, regardless of the retention time of the air bubbles in the water.

#### Weir loading

Weir loading is the amount of water per meter per hour that flows over the weir.

The weir loading can be calculated by dividing the flow by the net weir length (Figure 6):

Table 3 - Efficiency coefficient  $k$  of different gases as a function of the weir height( $h$ )

K (%)	$h = 0.2$	$h = 0.4$	$h = 0.6$	$h = 0.8$	$h = 1.0$	$h = 1.2$
O <sub>2</sub>	14	25	36	46	51	55
CO <sub>2</sub>	14	14	15	15	15	15
CH <sub>4</sub>	14	27	37	48	56	62

$$q_w = \frac{Q_w}{L_{net}}$$

where:

$Q_w$  = weir loading (m<sup>3</sup>/m.h)

$L_{net}$  = total weir length (m)

From various experiments it can be concluded that the efficiency of a cascade is almost independent of the weir loading. The advantage of this is that the gas transfer is still satisfactory at production flows that are lower than the design flow.

Cascades generally have a weir loading between 50 and 100 m<sup>3</sup>/(m.h).

### Trough depth

The trough depth of a cascade is chosen in such a way that the falling water jet will not reach the bottom. Air bubbles are dragged to a maximum depth and this results in a maximum contact or retention time and a maximum gas transfer time. As a rule of thumb, the trough depth must be more than two-thirds of the fall height, to obtain sufficient contact time.

### Trough width

The trough width must be large enough to receive the falling water jet (Figure 7).

The fall time of the water jet can be calculated with the following equation:

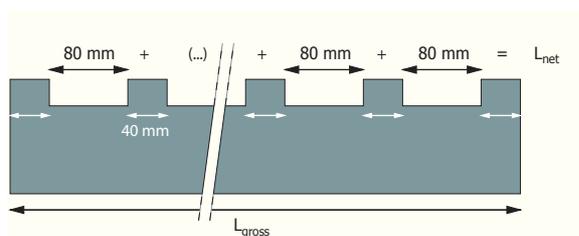


Figure 6 - Weir loading of a cascade aerator

$$h = \frac{1}{2} \cdot g \cdot t^2$$

which results in:

$$t = \sqrt{\frac{2 \cdot h}{g}}$$

The distance  $x$  can be calculated when the water velocity  $v_0$  is known. To calculate the velocity, the equation of the complete overflow is used:

$$d^3 = \frac{Q_w^2}{g \cdot L_{net}^2}$$

and

$$v_0 = \frac{Q_w}{L_{net} \cdot d}$$

where:

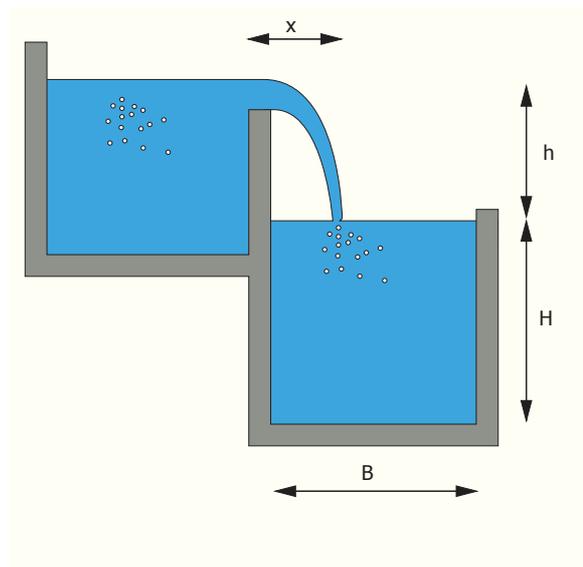


Figure 7 - Scheme of the width of a cascade trough

$Q$  = discharge ( $\text{m}^3/\text{s}$ )  
 $d$  = thickness of the falling water jet (m)  
 $V_0$  = velocity of the falling water jet (m/s)

The distance can be calculated with the equation:

$$X = V_0 * t$$

With the distance  $x$  the trough width can be calculated.

As a rule of thumb, the trough width is about twice the distance  $x$ :

$$B = 2 * x$$

### 3.2 Tower aerator

A tower aerator (Figure 8) consists of a cylinder of steel or synthetic material that is filled with a packing medium. Packing media can consist of stacked slats or tubes, or specially designed packing material like the Pall-ring and the Berl-saddle.

In Figure 9 different types of packing material are represented.

In the top section of the tower the water is distributed over the packing medium and flows down over the medium surface. As a result of the flow of water over the packing medium, a large contact surface between the air and water is created for gas transfer. In addition, the water falls in drops from one packing element to the other, contin-



Figure 8 - Tower aeration

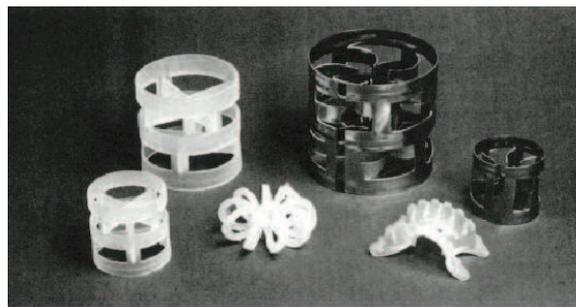


Figure 9 - Different types of packing material

uously forming new drops thus renewing the air-water interface.

The air can be renewed by natural ventilation or with the help of a ventilator. In case a ventilator is used, the air can have a co or counter-current flow in the tower. In Figure 10 a tower aerator with counter-current flow is represented.

#### Surface loading

The surface loading (flow divided by surface area) used in tower aerators is in practice 40 to 100  $\text{m}^3/(\text{m}^2 \cdot \text{h})$ .

The applied packing height, that determines the retention time of the water in the tower aerator, varies between 3 and 5 meters.

#### Efficiency

With tower aerators, removal efficiencies can be as high as 95%.

The applied air to water ratio (RQ) depends on the gases that need to be removed (Table 4).

In Figure 11 the results of a pilot experiment using a tower aerator are represented.

It can be concluded that the efficiency hardly changes when the surface loading is increased. This insensitivity to the surface loading can be explained by the fact that the retention time in a tower aerator is practically independent of the water flow.

In Figure 12 more results from the removal efficiency experiments are given.

For all points in the graph, with the combination of packing height and RQ, an efficiency of 99% is reached. From this graph it can be concluded that, at a certain point, an increasing RQ value does not lead to a reduction of the packing height. At that point the amount of air is not decisive but the

minimum necessary retention time for removal of 99% is reached.

### Clogging

A disadvantage of the tower aerator is that the system is sensitive to clogging. If iron ( $\text{Fe}^{2+}$ ) is present in groundwater, it will oxidize in the tower aerator ( $\text{Fe}^{3+}$ ) and remain on the packing material ( $\text{Fe}(\text{OH})_3$ ). Because the oxidized iron influences the gas transfer negatively, it will be necessary to back flush the tower aerator. Water with a high velocity, or a combination of water and air, is then flushed through the tower aerator, removing the iron contamination from the packing material. In addition to flushing, it will be necessary to periodically clean the packing material chemically. In this case, the packing material must be removed from the tower aerator.

### Co- or counter-current flow

A tower aerator can be operated in both co-current flow and counter-current flow (Figure 13).

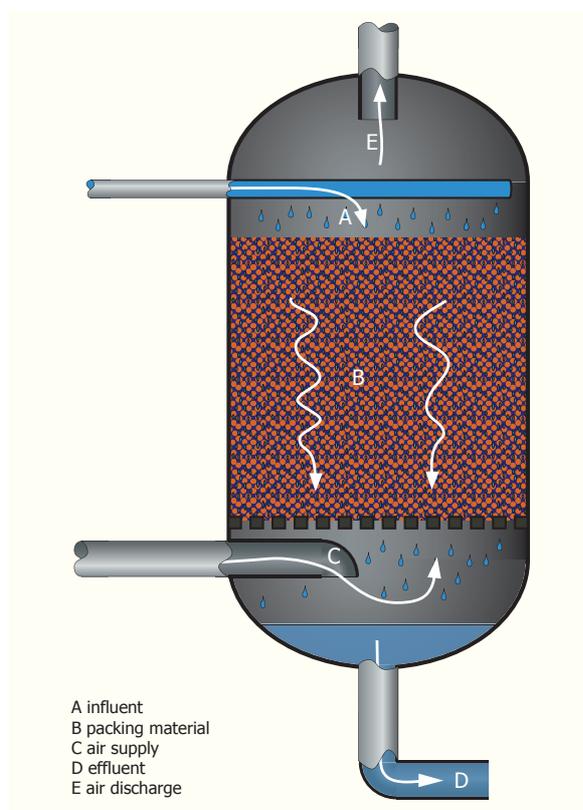


Figure 10 - Representation of a counter-current tower aerator

Counter-current flow results in a higher efficiency than co-current flow. Still, co-current flow is applied. The reasons for this are:

- to avoid high carbon dioxide removals which will cause limestone scaling. Using a co-current aerator with low values of RQ, the addition of oxygen and the removal of methane are sufficient while carbon dioxide removal will be limited.
- to apply high surface loadings. Using counter-current flow, "flooding" can occur. This means that a water layer is created in the column because of the buoyancy of air.

### 3.3 Spraying

Spray aerators (Figure 14) divide water into small droplets, which results in a large air-water interface where gas exchange occurs (Figure 15).

An advantage of spray aerators is the ease of incorporation into existing installations. The spray aerators can be placed directly above the filters.

### Efficiency

When the air is intensively renewed, the efficiency of spray aerators can be calculated with the following equation:

$$K = 1 - e^{(-k_2 \cdot t)} = 1 - e^{(-k_2 \cdot \sqrt{\frac{2h}{g}})}$$

Table 4 - Air/water ratio for different gas transfer systems and the gases that can be removed by the system

System	RQ	Application drinking water	Application wastewater
Cascade	0.4	$\text{O}_2$ , $\text{CH}_4$	-
Tower aerator	5-100	$\text{CO}_2$	$\text{CHCl}_3$
Plate aerator	20-60	$\text{CH}_4$ , $\text{CO}_2$ , $\text{O}_2$	-
Spray aerator	0.5	$\text{O}_2$ , $\text{CO}_2$	-
Deep well aerator	0.1-0.4	$\text{O}_2$	$\text{O}_2$
Cone aerator	>5	-	$\text{O}_2$

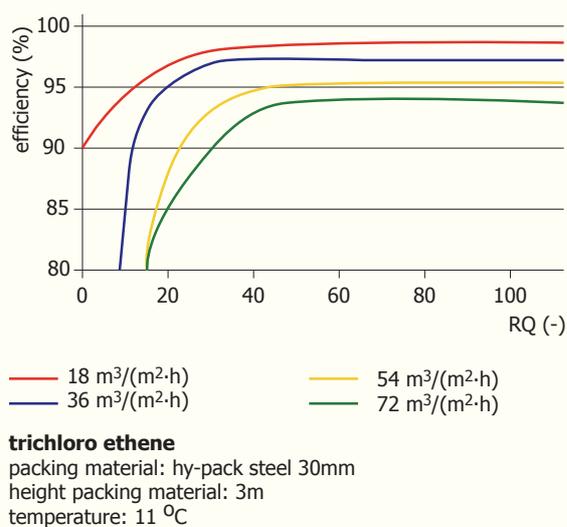


Figure 11 - Removal efficiency of a tower aerator as a function of RQ at different surface loadings

Spraying is efficient for the addition of oxygen and the removal of CH<sub>4</sub> (for both 80 - 90%), but less efficient for the removal of CO<sub>2</sub> (40 - 50%).

In Figure 16 the efficiency of the Dresden-nozzle for carbon dioxide removal as a function of the fall height is shown.

Most systems have a capacity of 1 - 3 m<sup>3</sup>/h per sprayer. If 2 - 4 sprayers are placed per m<sup>2</sup>, this results in a surface loading of 2 - 12 m/h, which is the same order of magnitude as the filtration rate

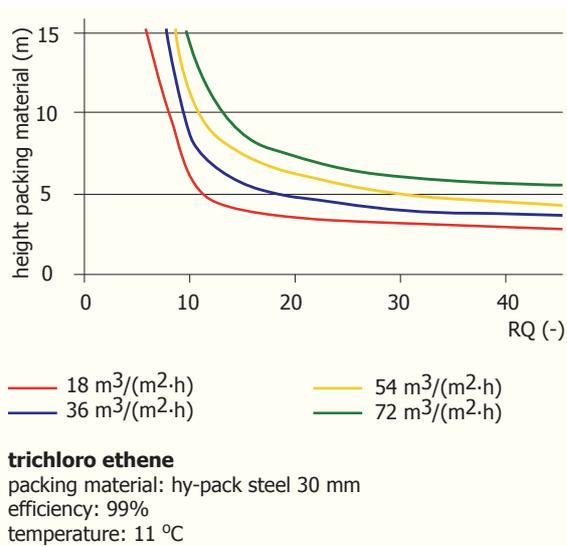


Figure 12 - Required packing height and RQ to achieve an efficiency of 99% at different surface loadings

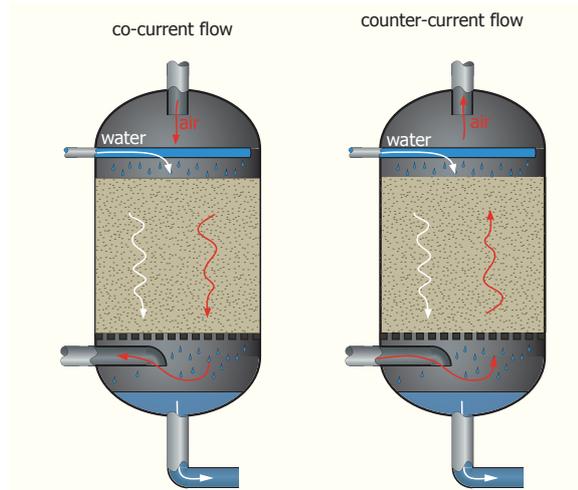


Figure 13 - Design alternatives for tower aerators

of the filters. However, sprayers have a limited flow range and at low flows, the water distribution is poor).

The spraying room has to be ventilated with a flow that results from the desired water to air ratio (RQ-value) for the aeration/gas transfer. This air is filtered in advance to avoid contamination of the microbiologically reliable groundwater by contaminants in the atmosphere (aerosols, etc.).

A disadvantage of sprayers is their high sensitivity to clogging. The addition of oxygen results in the oxidation of dissolved iron. Therefore, on the walls and pipes of the spraying systems, iron deposits can be found, which affects a good distribution during spraying. Spray systems will have to be cleaned a few times per year.

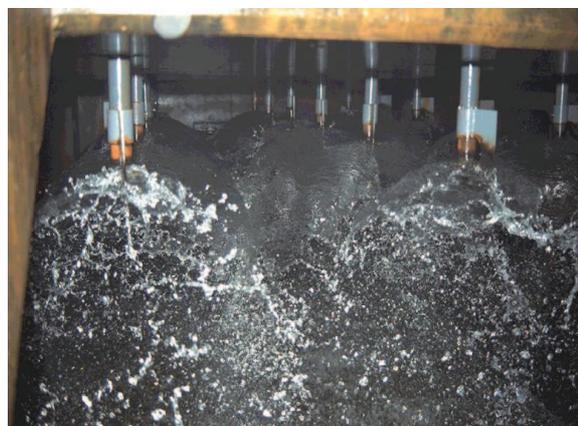


Figure 14 - Spray aeration



Figure 15 - Spraying small droplets of water

### 3.4 Air bubbling

Air bubbling consists of injecting compressed air through orifices of various sizes into the water (Figure 17). Air is distributed by perforated pipes at the bottom of a tank. During the rise of the formed bubbles, gas transfer takes place.

Bubble aeration for groundwater treatment occurs mainly through plate aeration.

A plate aerator (Figure 18) consists of a horizontal perforated plate. Water flows in a thin layer (ca. 25 - 30 cm) over the plate and a large flow of air (RQ of 30 - 60) is blown through its orifices, creating a bubble bed of air and water above the plate (Figure 19).

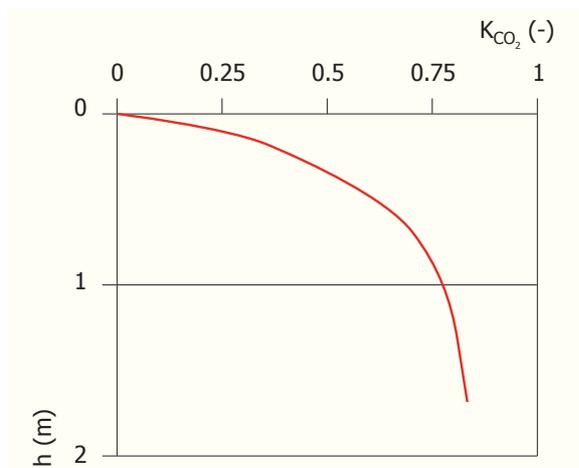


Figure 16 - Efficiency Dresden-nozzle as a function of the fall height

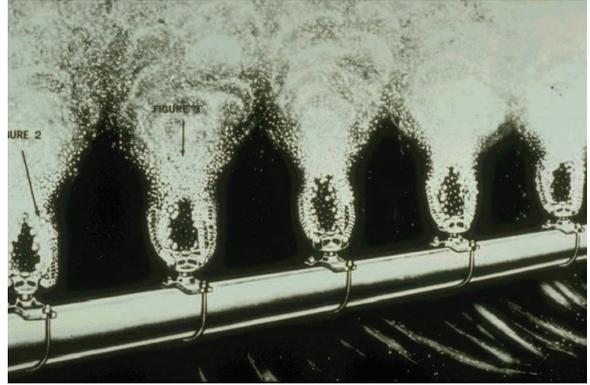


Figure 17 - Bubble aeration system

The large air flow causes strong turbulence and a good gas transfer, despite the short residence time (10 - 20 s).

The combination of horizontal water flow and vertical airflow (i.e., the flows are perpendicular), is called cross-flow aeration.

The height of the bubble bed is determined by adjusting the height of the weir at the end of the plate.

The diameter of the holes in the perforated plate is usually 1-1.5 mm. The open surface area (i.e., the total area of the holes) varies from 1.5% to 3% of the total plate surface area.

With this system a very good methane removal is possible (90 - 95%) and considerable  $CO_2$  removal (60 - 70%).

Due to the reduced construction height and head loss, this technique is easily incorporated in exist-

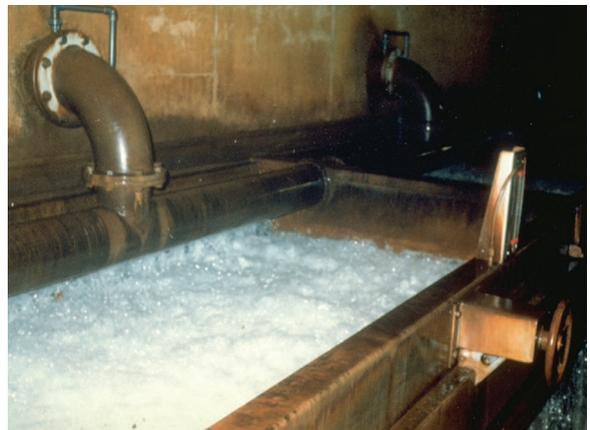


Figure 18 - Plate aeration

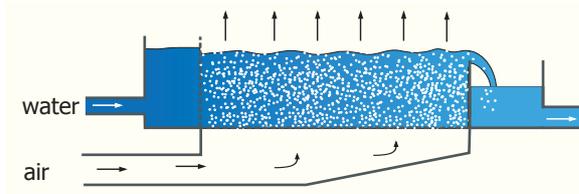


Figure 19 - Representation of a plate aerator

ing treatment plants. Sometimes it is possible to place the plate aerators directly above the filters.

### Efficiency

The efficiency of plate aerators is mainly determined by the applied RQ and the retention time of the water on the plate. There is no analytical equation for calculating the efficiency.

In practice, the applied RQs vary from 20 to 60 and the applied surface loading varies from 30 to 40  $\text{m}^3/(\text{m}^2 \cdot \text{h})$ .

### Clogging

Plate aerators are sensitive to clogging because of the small orifices in the plate. Iron deposits found on the plate can block the orifices and affect the flow through the plate.

Short-circuit flows can occur, influencing negatively the gas transfer.

Depending on the iron loading, the plate has to be cleaned frequently. It might also be necessary to clean the plate chemically once or twice a year.