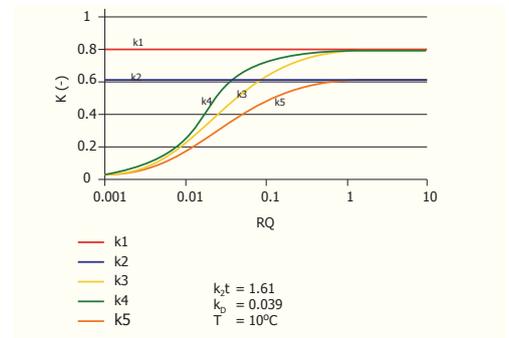
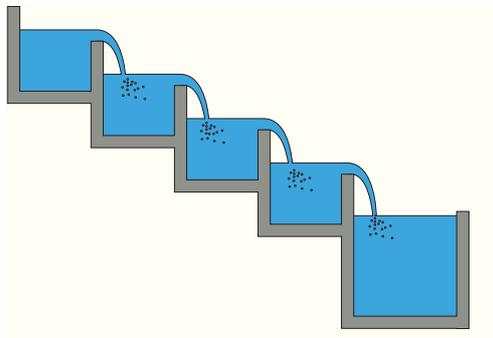
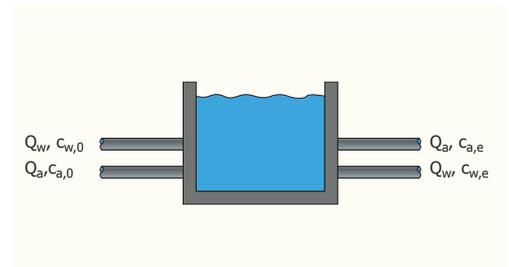
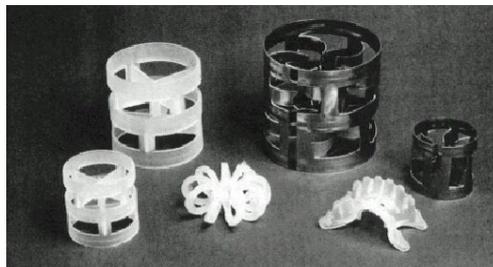


# Aeration and gas stripping



**Framework**

This module explains aeration and gas stripping.

**Contents**

This module has the following contents:

1. Introduction
2. Theory of gas transfer
  - 2.1 Equilibrium
  - 2.2 Kinetics
  - 2.3 Mass balance
  - 2.4 Solutions for the basic equations
3. Practice
  - 3.1 Cascade
  - 3.2 Tower aerator
  - 3.3 Plate aerator
  - 3.4 Spray aerator
  - 3.5 Alternative aeration systems

## 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 ( $O_2$ ) and the removal of carbon dioxide ( $CO_2$ ), methane ( $CH_4$ ), hydrogen sulfide ( $H_2S$ ), and other volatile organic compounds (for example 1,2-Dichloropropane (1,2 DCP), Trichloroethene (TRI), Tetrachloroethene (PER) and Trichloromethane (chloroform)).

Gas transfer is seldom applied in the treatment of surface water because surface water has been in contact with air for a prolonged period. Consequently, surface water contains sufficient oxygen, and other gases, like methane and hydrogen sulfide, are absent.

The addition of oxygen is required for the oxidation of bivalent iron ( $Fe^{2+}$ ), manganese ( $Mn^{2+}$ ) and ammonium ( $NH_4^+$ ). These substances are present in dissolved form in groundwater. Due to chemical and biological oxidation, the substances can be removed by following a filtration step. This will be discussed in the chapter on granular filtration.

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 has negative influences on the filtration processes.

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

Volatile organic compounds are usually toxic; some of them are even carcinogenic. Obviously, these compounds are not allowed in drinking water.

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

One of the oldest systems is the cascade (Figure 1). The water falls in several steps. In each step,



Figure 1 - Cascade aeration

the water falls over a weir into a lower placed trough. When the falling stream enters the water body, air is entrapped in the form of bubbles, providing for a mixture of water and air in which gas transfer will occur.

The tower aerator (Figure 2) consists of a cylindrical vessel of steel or synthetic material that is filled with packing material, usually consisting of elements of synthetic material. Water falls down and air is blown in a co-current or counter-current direction.

A plate aerator (Figure 3) is a horizontal perforated plate. Water flows over the plate and air is blown through the orifices, creating a bubble bed of air and water above the plate.

Sprayers (Figure 4) are typically used because of their simple implementation in existing treatment plants. By spraying, a contact surface between the air and water is created for the gas exchange.

## 2 Theory of gas transfer



Figure 2 - Tower aeration

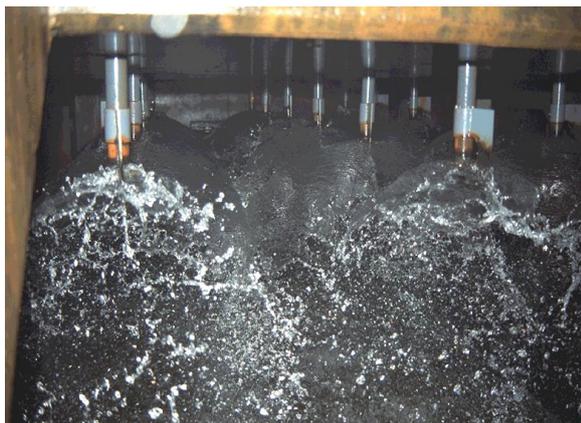


Figure 4 - Spray aeration

## 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 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:

$$c_w = k_H \cdot c_g$$

in which:

$c_w$  = 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>]

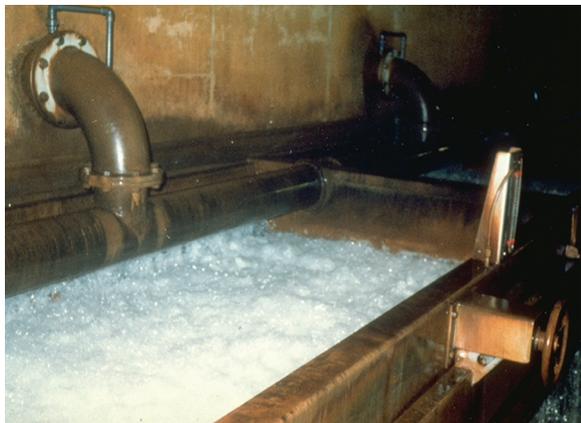


Figure 3 - Plate aeration

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. This issue will not be discussed here.

In literature, many different forms of Henry's law are found.

Often partial pressure is used instead of the gas concentration in air, and/or molar concentration in the water instead of weight concentration. Consequently this results in a different unit for the distribution coefficient, or Henry's law constant (ie. [mol/(m<sup>3</sup> Pa)] or [mol/l/atm]).

For gas stripping, often the volatility is given instead of the solubility of a gas. In this case, the distribution coefficient is inverted (gas/water, instead of water/gas).

### Distribution coefficient

In Table 1 for a number of gases a list of values is given of the distribution coefficient 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 they can, therefore, be easily removed.

The other gases have high  $k_H$ -values and dissolve easily, which makes it difficult to remove them from the water or easy to add them to water.

### Gas concentration in air

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:

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

in which:

$p$  = 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]

Table 1 - Distribution coefficient for gases and the molecule weight

Gas	Distribution coefficient ( $k_H$ )			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> )	5000	2900	1800	17

<sup>1</sup> These substances are still in the liquid phase at a temperature of 0°C and therefore the  $k_H$  is not known

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

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

in which:

MW = molecular weight of a gas [g/mol]

### Partial pressure

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

$$p = p_o \cdot V_f$$

in which:

$p_o$  = standard pressure at sea level (=101,325) [Pa]

$V_f$  = 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  $c_g$  equal to zero and also a  $c_w$  equal to zero (for example, methane).

In Figure 5 the equilibrium (saturation) concentration of oxygen is given as a function of water temperature. With an increase in water temperature, the saturation concentration decreases because less oxygen can be dissolved in warm water.

The saturation concentration  $c_w$  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>.

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

Table 2 - Volume fractions of gases

Gas	Volume fraction <sup>1</sup> [%]	Saturation concentration <sup>2</sup> $c_w$ [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

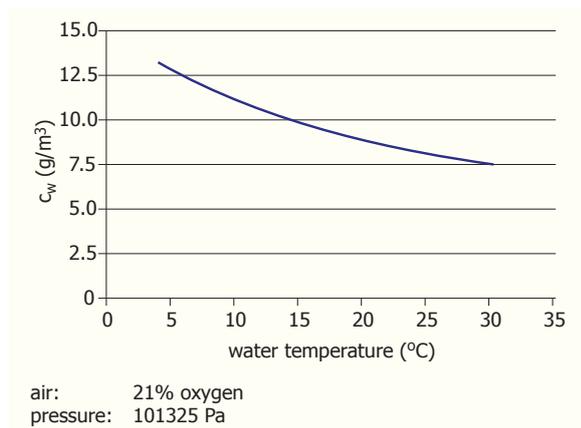


Figure 5 - Saturation concentration of oxygen as a function of the water temperature

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 6 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 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.

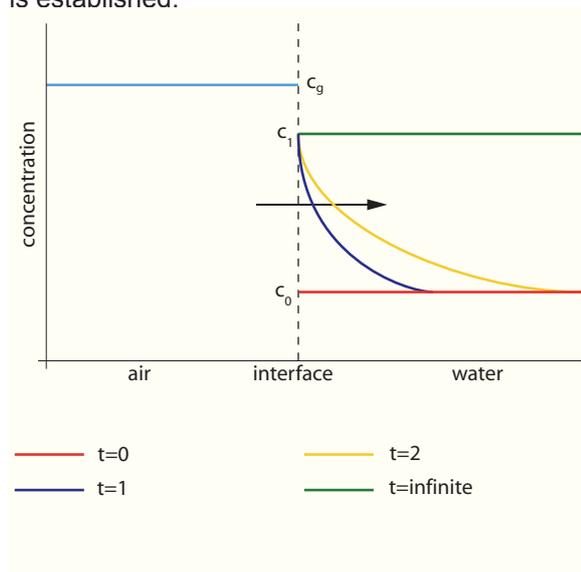


Figure 6 - Gas transport from air to water

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

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

in which:

$$c_w = \text{concentration of a gas in water} \quad [\text{g/m}^3]$$

$$k_2 = \text{gas transfer coefficient} \quad [\text{s}^{-1}]$$

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, 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 7 for a constant  $c_s$  (10 mg/l) and an initial oxygen concentration of 0 mg/l. In the beginning, when the difference between the  $c_s$  and the  $c_w$  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  $t=\infty$  the oxygen concentration in water equals the saturation concentration  $c_s$ .

For a batch reactor the differential equation can be solved by integration, with  $c_w=c_{w,0}$  at time  $t=0$ , taking into account that  $c_s$  is constant:

$$c_w = c_s - (c_s - c_{w,0}) \cdot e^{(-k_2 \cdot t)}$$

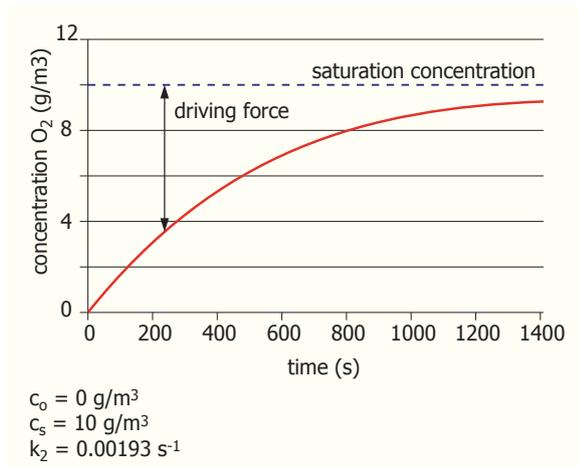


Figure 7 - Oxygen concentration in water as a function of contact time

or:

$$\frac{c_s - c_w}{c_s - c_{w,0}} = e^{(-k_2 \cdot t)}$$

### 2.3 Mass balance

In the preceding paragraph it is assumed that the oxygen concentration in air is constant. This is a simplification that is not always applicable. For situations in which the gas concentration changes in air are important, a mass balance needs to be formulated.

In Figure 8 a mass balance for a gas transfer system is schematically presented.

A water flow ( $Q_w$ ), with a gas concentration in the water phase ( $c_{w,0}$ ), and an airflow ( $Q_a$ ), with a gas concentration ( $c_{a,0}$ ), enter the system. The same water flow ( $Q_w$ ), with a gas concentration in the water phase ( $c_{w,e}$ ), and the same airflow ( $Q_a$ ), with a gas concentration ( $c_{a,e}$ ), leave the system.

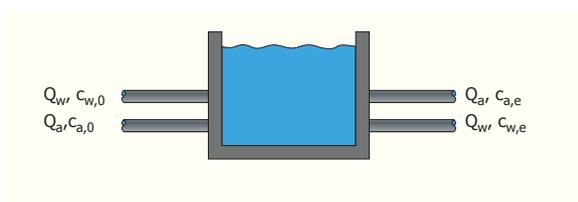


Figure 8 - Gas transfer system with in- and outflow of water and air

For the gas transfer system, the law of continuity is valid: the total amount of gas that enters and leaves the system must be equal and a mass balance can be set up:

$$Q_w \cdot c_{w,0} + Q_a \cdot c_{a,0} = Q_w \cdot c_{w,e} + Q_a \cdot c_{a,e}$$

By using the mass balance, the gas concentrations in the air and water are linked and can be applied in the gas transfer equations presented below.

The RQ is the relationship between the airflow and the water flow. Using the mass balance RQ, that relationship can be defined as follows:

$$RQ = \frac{Q_a}{Q_w} = \frac{c_{w,e} - c_{w,0}}{c_{a,0} - c_{a,e}}$$

### 2.4 Solutions for the basic equations

For gas transfer systems three equations are derived:

- equilibrium equation
- kinetic equation
- mass balance

With these equations it is possible to calculate the changes in the gas concentrations in water and air.

Combining the equilibrium equation and the mass balance results in two equations with two unknown variables,  $c_w$  and  $c_a$ . With different initial conditions, different solutions for these equations can be obtained.

In the following section a number of equations are presented that form the basis for the calculation of gas concentrations in water for different gas transfer systems.

If the variation in the gas concentration in the air cannot be neglected, the mass balance needs to be taken into account. The efficiency of a gas transfer system can be calculated by dividing the

realized gas transfer by the maximum achievable gas transfer:

$$K = \frac{c_{w,e} - c_{w,0}}{c_s - c_{w,0}}$$

The following basic systems can be distinguished:

- plug flow with a constant gas concentration in air
- complete mixed system with a constant gas concentration in air
- plug flow, co-current flow and a variable gas concentration in air
- plug flow, counter-current flow and a variable gas concentration in air
- complete mixed system with a variable gas concentration in air

#### Plug flow with a constant gas concentration in air

A characteristic of a plug flow is that the water is supposed to flow as a "frozen volume" through the gas transfer system. Thus, all water particles in the system will have the same retention time. The efficiency equation, then, can be written into the following equation:

$$K_1 = 1 - e^{(-k_2 \cdot t)}$$

An example of a plug flow where the gas concentration in air and thus  $c_s$  is supposed to be constant is a falling droplet from a spray aerator into a large open space. The change in the gas

Table 3 - 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	O <sub>2</sub> , CH <sub>4</sub>	-
Tower aerator	5-100	CO <sub>2</sub>	CHCl <sub>3</sub>
Plate aerator	20-60	CH <sub>4</sub> , CO <sub>2</sub> , O <sub>2</sub>	-
Spray aerator	0.5	O <sub>2</sub> , CO <sub>2</sub>	-
Deep well aerator	0.1-0.4	O <sub>2</sub>	O <sub>2</sub>
Cone aerator	>5	-	O <sub>2</sub>

concentration in air as a result of gas transfer can then be neglected.

#### Complete mixed system with a constant gas concentration in the air

The opposite of a plug flow is a complete mixed system. In such a gas transfer system the water drops are mixed extensively. Consequently, the retention time of the water drops is variable. Some water drops leave the system directly (short-circuit flow) and others stay for a prolonged period of time in the system (eddy formation). The efficiency is calculated with:

$$K_2 = \frac{1}{1 + \frac{1}{k_2 \cdot t}}$$

#### Plug flow, co-current flow and a variable gas concentration in air

The equation for co-current flow can be found with the following initial conditions:

$$c_w = c_{w,0} \quad \text{at time } t=0;$$

$$c_a = c_{a,0} \quad \text{at time } t=0$$

The following solution can be derived:

$$K_3 = \frac{1 - e^{(-k_2 \cdot t \cdot (1 + \frac{k_d}{RQ}))}}{1 + \frac{k_d}{RQ}}$$

#### Plug flow with counter-current flow and variable gas concentration in the air

The equation for counter-current flow can be found with the following initial conditions:

$$c_w = c_{w,e} \quad \text{at time } t=t_e;$$

$$c_a = c_{a,e} \quad \text{at time } t=t_e.$$

The following solution can be derived:

$$K_4 = \frac{1 - e^{(-k_2 \cdot t \cdot (1 - \frac{k_d}{RQ}))}}{1 - \frac{k_d}{RQ} \cdot e^{(-k_2 \cdot t \cdot (1 - \frac{k_d}{RQ}))}}$$

**Complete mixed system with variable gas concentration in air**

The following solution can be derived:

$$K_5 = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_d}{RQ}}$$

In Figure 9 the efficiencies for oxygen ( $k_H = 0.039$  at  $T=10^\circ\text{C}$ ) for the 5 basic equations are plotted against the RQ with a  $k_2 \cdot t$  of 1.61.

The lines for  $K_1$  and  $K_2$  are obviously constant, because, in this case, RQ is not of importance. The lines for  $K_3$ ,  $K_4$  and  $K_5$  climb at increasing values of RQ. When RQ approaches infinity, the lines for the different plug flow systems  $K_1$ ,  $K_3$  and  $K_4$  and for the mixed systems  $K_2$  and  $K_5$  coincide.

It can be concluded that a counter-current flow reactor has a higher efficiency than a co-current flow reactor, and plug flow reactors have a higher efficiency than a complete mixed system.

The RQ is an important factor for the gas transfer systems.

During the design of a gas transfer system, the RQ value must be chosen. This depends on the required efficiency and the type of gas that needs to be removed (Example 1).

The example to the right shows that the RQ necessary for a 90% removal efficiency of chloroform is 200 times greater than the value of RQ for methane. This means that for the same water flow the airflow through the system and the capacity of the ventilator must each be at least 200 times greater.

A general rule that is applicable for the influence of the type of gas on the efficiency is: the higher the value of  $k_H$ , the more air is needed for removal, resulting in an increased RQ. Different gas transfer systems have different characteristics with respect to RQ.

A cascade, for example, has an RQ of approximately 0.4 and is therefore suitable for the removal of methane and the addition of oxygen, but is not used for the removal of chloroform.

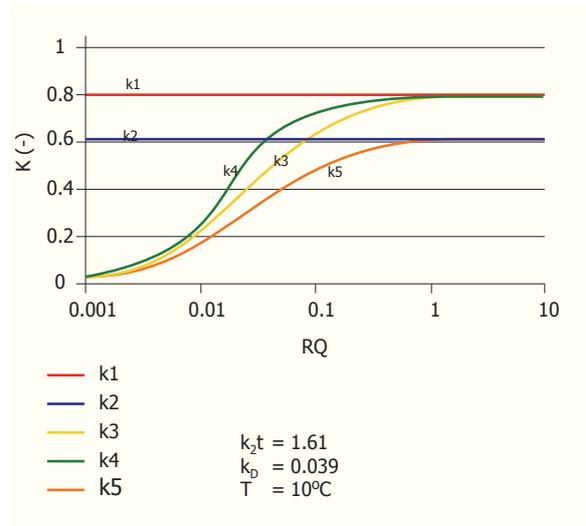


Figure 9 - Efficiencies of the different basic equations Tower aerators are operated under different RQ values and can be used for gases that are either easy or difficult to remove, like tetra- and trichloroethene. Deep well aerators have the same characteristics as cascades.

**Example 1: The effect of RQ on the efficiency**

Calculate for a gas transfer system, that can be represented by a complete mixed system, the RQ that is necessary for a gas removal efficiency of 90% for methane, carbon dioxide and chloroform. Assume that the contact time in the reactor is infinite and that the water temperature is  $10^\circ\text{C}$ . The efficiency for a complete mixed system can be calculated with the following equation:

$$K_5 = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_d}{RQ}}$$

The contact time is infinite, so  $1/k_2 \cdot t = 0$ . The above equation can be simplified as:

$$K_5 = \frac{1}{1 + \frac{k_d}{RQ}}$$

Gas	Efficiency [%]	$K_5$ [-]	$K_D$ [-]	RQ
Methane	90	0.90	0.043	0.39
Carbon dioxide	90	0.90	1.23	11.1
Chloroform	90	0.90	9.62	86.6

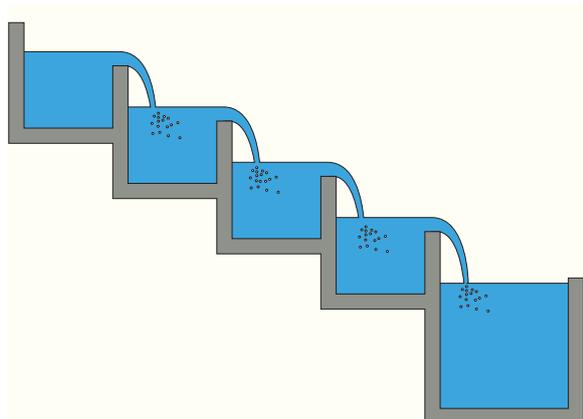


Figure 10 - Scheme of a cascade

### 3 Practice

#### 3.1 Cascade

The water in a cascade is falling onto several steps. Each step contains an overflow weir and a receiving gutter. When water passes over a weir, an interface between air and water is created. 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, which leads to an excessive transfer of gases.

The gas transfer takes place at the interface between the water and the air bubbles (Figure 10). Because the amount of air that is entrained is limited, the RQ is also limited. According to practical measurements and model investigations, the RQ of cascades is approximately 0.4.

The energy consumption of a cascade is 10-30 Wh/m<sup>3</sup>.

#### Efficiency

An estimate of the efficiency for a cascade can be made, assuming that there is a relationship between the measured fall height and the efficiency. The efficiency of a cascade depends on the fall height of each cascade step and the num-

ber of steps:

$$K = \frac{c_{we} - c_{w0}}{c_s - c_{w0}} = 1 - (1 - k)^n$$

in which:

$k$  = efficiency for each step [-]

$n$  = number of steps

In Table 4 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 4 and the equation mentioned above, the efficiency of a cascade with  $n$  steps can be calculated.

In practice, the total fall height of all the cascade steps together varies between 2 and 7 meters.

From Table 4 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 RQ value for cascades. Carbon dioxide removal requires a higher value of RQ. The interface between air and water gets saturated rapidly with carbon dioxide, regardless of the retention time of air bubbles in the water, which is dependent on the fall height. The greater the fall height, the deeper the penetration in the trough, and the longer the retention time.

#### 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 11):

$$q_w = \frac{Q_w}{L_{\text{nett}}}$$

in which:

Table 4 - Efficiency coefficient  $k$  of different gases as a function of the weir height

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

$q_w$  = weir loading [m<sup>3</sup>/m·h]  
 $L_{\text{nett}}$  = 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.

With cascades the weir loading is generally 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 tray depth must be more than two-thirds of the fall height.

**Trough width**

The trough width must be large enough to receive the falling water jet (Figure 12).

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

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

or

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

The distance x can be calculated when the water

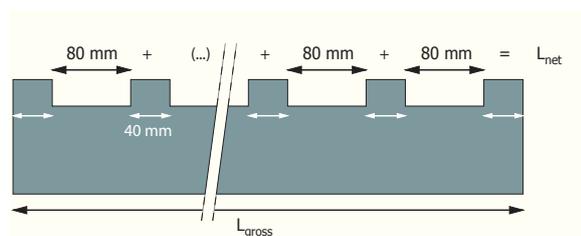


Figure 11 - Weir loading of a cascade aerator

velocity  $v_o$  is known. To calculate the velocity, the equation of the complete overflow is used:

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

and

$$v_o = \frac{Q_w}{L_{\text{nett}} \cdot d}$$

in which:

$Q_w$  = discharge [m<sup>3</sup>/s]

$d$  = thickness of the falling water jet [m]

$v_o$  = velocity of the falling water jet [m/s]

The distance can be calculated with the equation:

$$x = v_o \cdot t$$

With the distance x the trough width can be calculated.

As a rule of thumb, the trough width is at least twice the distance x:

$$B = 2 \cdot x$$

It is obvious that the trough width must be calcu-

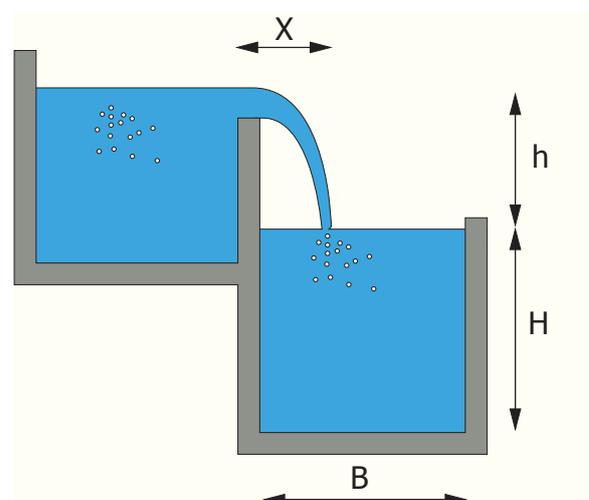


Figure 12 - Scheme of the width of a cascade trough

lated using the maximum flow that is discharged over the weir.

### Configurations

The cascade troughs can be placed in two different ways. They can be placed next to each other or on top of each other (Figure 13).

Placing them next to each other is advantageous because it looks attractive.

The advantage of putting them on top of each other is that less space is used. The disadvantage, however, is that this makes maintenance more difficult.

### 3.2 Tower aerator

A tower aerator 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.

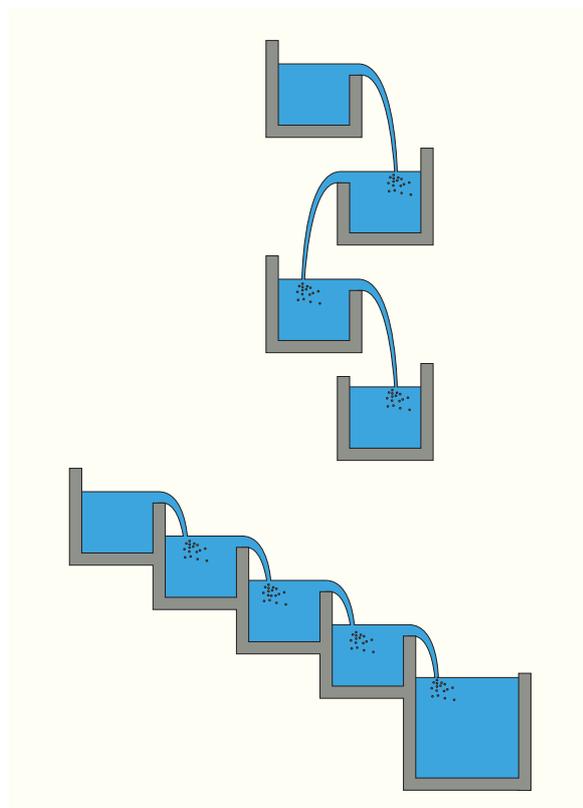


Figure 13 - Cascades beside each other and on top of each other

In the top section of the tower the water is divided 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, continuously 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 14 a tower aerator with counter-current flow is represented.

In Figure 15 different types of packing material are represented. The packing material can be produced from synthetic material, metal, carbon or ceramic material.

The dimensions of the individual pieces vary from 6 mm to 75 mm. In practice, installations used for purifying drinking water use mostly synthetic packing material with a dimension of 25-50 mm.

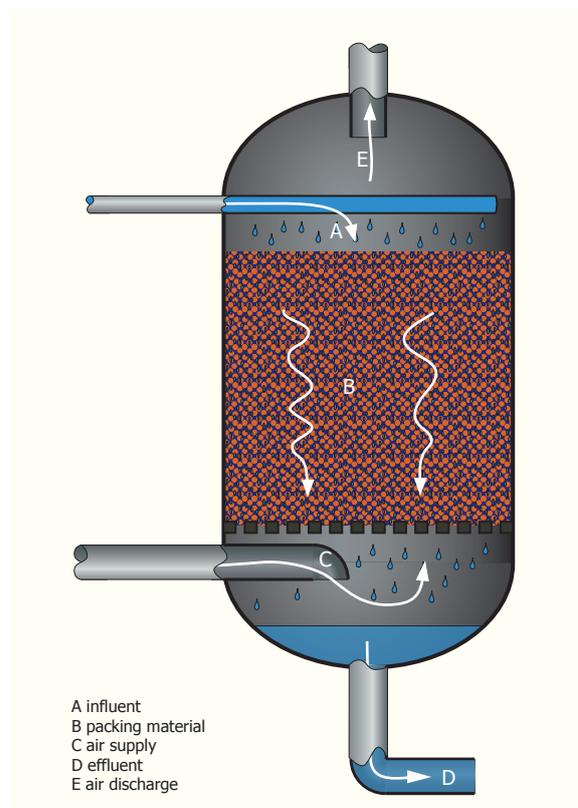


Figure 14 - Representation of a counter-current tower aerator

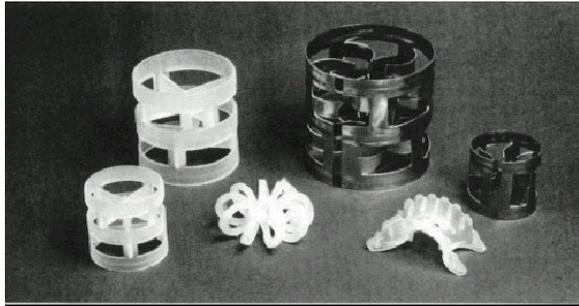


Figure 15 - Different types of packing material

### Surface loading

The surface loading (flow divided by surface area) that in practice is used in tower aerators is 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%.

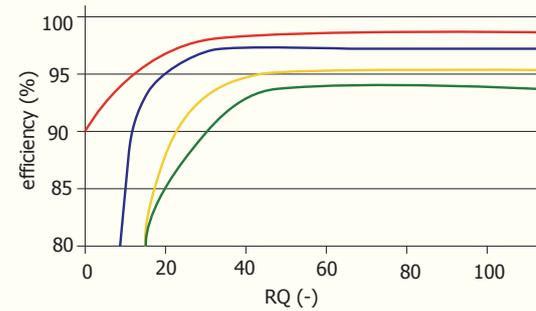
The applied RQ depends on the gases that need to be removed.

In Figure 16 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 is considered remarkable. In most gas transfer systems, a larger flow results in a greater flow rate, resulting in a shorter retention time for the water, and a lower efficiency.

This insensitivity to the surface loading with a tower cascade can be explained by the fact that the retention time in a tower aerator is practically independent of the water flow. The water falls under the influence of gravity, so the retention time is mainly determined by the type of packing material used and the height of the bed. It is indifferent if more or less water falls through the tower because the retention time remains unchanged.

In Figure 17 more results from the removal efficiency experiments are given.



— 18  $\text{m}^3/(\text{m}^2 \cdot \text{h})$       — 54  $\text{m}^3/(\text{m}^2 \cdot \text{h})$   
 — 36  $\text{m}^3/(\text{m}^2 \cdot \text{h})$       — 72  $\text{m}^3/(\text{m}^2 \cdot \text{h})$

#### trichloro ethene

packing material: hy-pack steel 30mm  
 height packing material 3m  
 temperature: 11 °C

Figure 16 - Removal efficiency of a tower aerator as a function of RQ at different surface loadings

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 periodically 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 18).

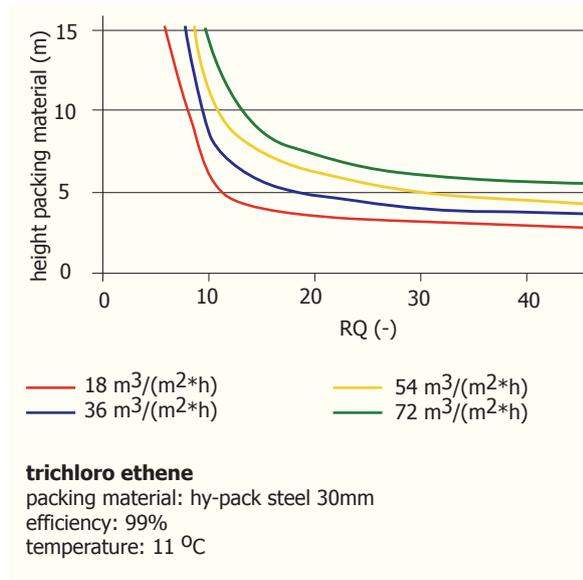


Figure 17 - Required packing height and RQ to achieve an efficiency of 99% at different surface loadings

In the paragraph on theory it was explained that 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 needed 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, which can even result in the tower aerator filling up with water.

### 3.3 Plate aerator

A plate aerator consists of a horizontal perforated plate. Water flows over the plate and air is blown through its orifices, creating a bubble bed of air

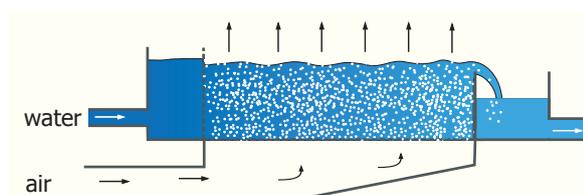


Figure 19 - Representation of a plate aerator

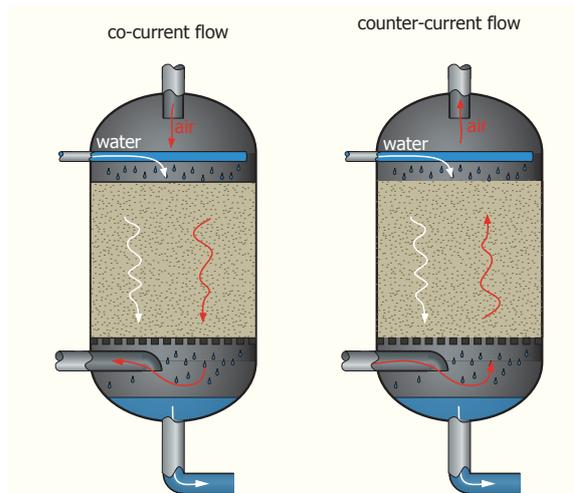


Figure 18 - Design alternatives for tower aerators

and water above the plate (Figure 19).

This results in intense contact between the air and the water.

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 varies from 1.5 % to 3% of the total plate surface area.

The energy consumption of a plate aerator is 30-40 Wh/m<sup>3</sup>.

Due to the reduced construction height and head loss, this technique offers good possibilities for incorporating it in existing treatment plants. Sometimes it is possible to place the plate aerators in the filter building 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, unlike the co- and counter-current flows.

In practice, the applied RQs vary from 20 to 60 and the applied surface loading varies from 30 to

40 m<sup>3</sup>/(m<sup>2</sup>.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 once a month or once every other month. It might also be necessary to clean the plate chemically once or twice a year.

### 3.4 Spray aerator

Spray aerators divide water into small droplets, which results in a large air-water interface (Figure 20). The energy consumption of spray aerators is 10-50 Wh/m<sup>3</sup>, depending on the type of aerator.

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:

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

The efficiency for the addition of oxygen can vary from 65 to 80%, for the carbon dioxide removal the efficiency varies from 60 to 80%.

In Figure 21 the efficiency of the Dresden-nozzle for carbon dioxide removal as a function of the fall height is shown.

It is remarkable that after a certain fall height the efficiency remains more or less constant. The reason is that after some time the interface be-



Figure 20 - Spraying small droplets of water

tween air and water is saturated. Because the droplet remains intact during the fall, the interface is not renewed and the gas transfer stops.

### Energy consumption

Spray aerators need a certain pressure to guarantee an equally distributed spray. For sprayers that produce fine droplets (mist), the pressure is the greatest, about a 10-meter water column.

The energy consumption of these high pressure spray aerators is, therefore, the largest.

### Clogging

A disadvantage of sprayers is their high sensitivity to clogging.

### Alternatives in practice

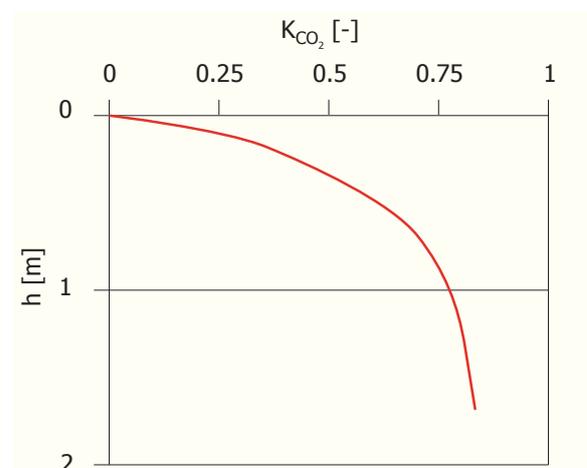


Figure 21 - Efficiency Dresden-nozzle as a function of the fall height

Spray aerators can be divided into two groups:



Figure 23 - Dresden sprayer

upward- and downward-directed spray aerators. An example of the first type is the 'Amsterdam' spray aerator (Figure 22). In this type of spray aerator, two jets are directed perpendicular to each other, dispersing the water. This results in many droplets in the air. During the fall of the water droplets, the gas transfer takes place.

An example of the second type of sprayer is the Dresden sprayer (Figure 23), or the plate sprayer. Here, the water flows through a plastic tube and strikes a disc (plate), shaping the water like an umbrella, and eventually disintegrating into droplets.

### 3.5 Alternative aeration systems

#### Vacuum gas transfer system

A vacuum gas transfer system is usually execut-



Figure 22 - Amsterdam sprayer

ed as a tower aerator filled with a packing material in which the pressure is lowered by a vacuum pump (Figure 24).

Due to the vacuum pump, gas is removed from the tower, resulting in lower gas concentrations and a decreased pressure there. Because the gas concentrations in the tower are lower than in the atmosphere, the saturation concentrations in the tower are also lower. Because of the low saturation concentrations, it is possible to remove higher levels of gas from the water than is possible under atmospheric conditions. This makes a vacuum gas transfer system ideal for removing dissolved nitrogen and oxygen from the water and is frequently applied before the denitrification process.

The efficiency of the vacuum gas transfer system depends on the vacuum pressure that is maintained in the tower. In the absence of an air flow, the RQ equals zero. Since oxygen is not brought into the system, oxidation of iron cannot occur. This allows the water to be pumped to the next treatment process, contrary to a cascade. In a cascade oxidation of iron does occur, which, when the water is pumped to the next treatment

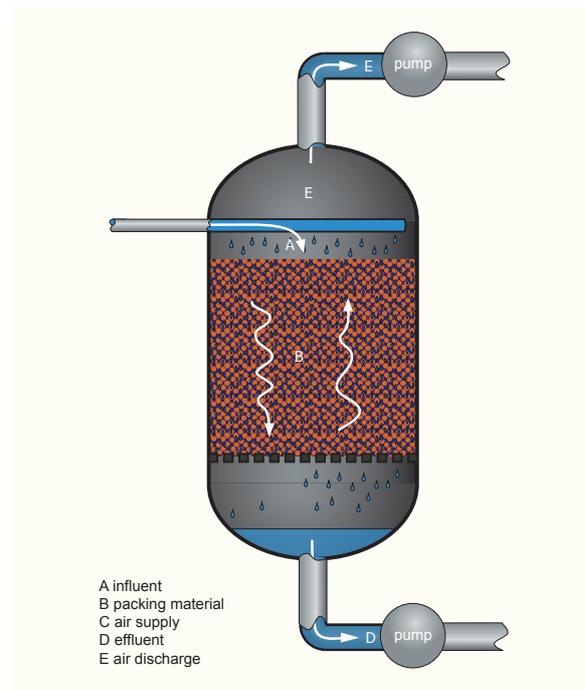


Figure 24 - Representation of a vacuum liquid-gas exchange

process, causes the iron flocs to break up making them harder to remove in the filter.

Like the tower aeration system, the vacuum system is not very sensitive to surface loading. The applied surface loading varies from 50 to 100  $\text{m}^3/(\text{m}^2 \cdot \text{h})$ .

A great disadvantage of the vacuum gas transfer system is its high energy consumption, requiring approximately  $1,600 \text{ Wh/m}^3$  to maintain it.

### Deep-well aerator

Water flows through the deep well, entraining air by a venturi (Figure 25 right), or air is supplied at the bottom of the well (Figure 25 left).

Due to the high water pressure at the bottom of the well, an increase in air pressure is established, which results in a higher oxygen concentration. With a higher saturation concentration, more oxygen can be dissolved into the water than at atmospheric conditions.

Deep well aerators are mainly used in the treatment of wastewater, because the oxygen consumption of wastewater is normally high.

The advantage of a deep well aerator is that large amounts of water can be treated against relatively low energy costs. The energy consumption for the deep well aerator is approximately  $5 \text{ Wh/m}^3$ .

### Venturi aerator

The venturi aerator consists of a tube with a reduced cross-sectional area, where the increased water velocity occurs. At the place where the water velocity is the highest (through orifices in the tube), air is entrained. Due to the strong turbulence, an intensive mixing of the entrained air with the water leads to the dispersion of fine bubbles.

Since the amount of air that can be entrained is relatively small, the RQ of a venturi aerator is rather small, varying between 0.2 to 0.4.

The efficiency for oxygen addition ranges from 80

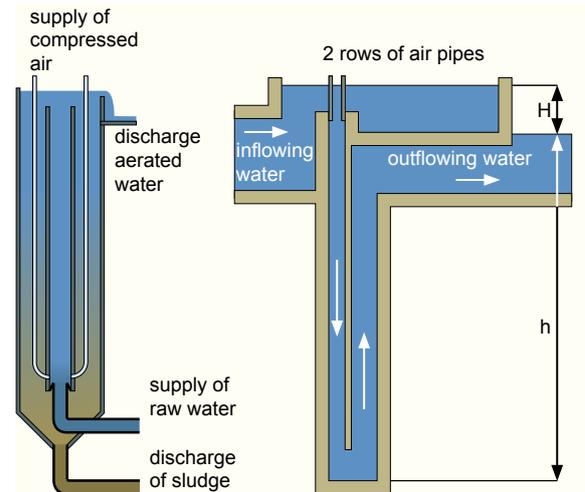


Figure 25 - Design alternatives for a deep-well aerator to 95%.

The advantage of the venturi aerator is that it requires little space and the system is not expensive. A disadvantage is that only limited flow variations can be allowed for an optimal effect. The energy consumption is approximately  $20\text{-}30 \text{ Wh/m}^3$ .

### Bubble aeration

The transfer of gas by means of a bubble aerator is accomplished by injecting compressed air through orifices of various sizes into the water (Figure 27). Air is distributed by perforated pipes at the bottom of a tank. During the rise of the formed bubbles, gas transfer takes place. This system is mainly used in wastewater treatment. The principle of gas transfer by bubble aeration is the same as in cascades.

### Cone aerator

A cone aerator is used as a gas transfer system for the treatment of wastewater.

The cone aerator consists of a large rotating

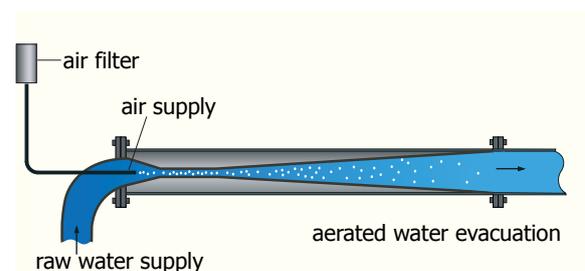


Figure 26 - Representation of a venturi aerator

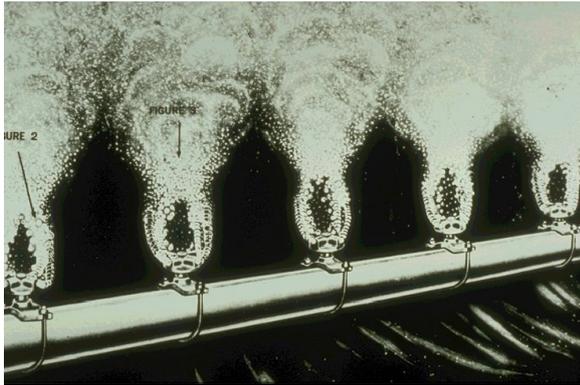


Figure 27 - Bubble aeration system



Figure 28 - Cone aerator

blade in the form of a cone, situated in a basin on the water's surface (Figure 28). Through the blade, water is abstracted from underneath the cone and sprayed laterally over the water's surface. Because water droplets are formed and air is entrained, gas transfer can be achieved.

As a result of the suction of water from underneath and the horizontal distribution of the water, a circular flow is created and the water in the basin is aerated.

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## Further reading

- Water treatment: Principles and design, MWH (2005), (ISBN 0 471 11018 3) (1948 pgs)
- Modelling van intensieve gasuitwisselings-systemen (in Dutch), A.W.C. van de Helm (MSc thesis)