REMOVAL OF VOLATILE SUBSTANCES FROM WATER

František Vašák and Zdeněk Brož
Institute of Chemical Process Fundamentals AS CR
Rozvojová 135, 165 02 Prague 6, Czech Republic

In this paper the rotating disk stripper (RDS) for removal of volatile contaminants from water has been modeled mathematically. For experimental verification two model systems have been used, namely desorption of CO_2 from water and desorption of radon from ground water. As a result of the performed study the new apparatus suitable for volatile organic contaminants (VOC) removal has been designed.

Introduction

The number of water sources polluted with volatile contaminants, namely crude-oil and chlorinated hydrocarbons or radon, increases. The shortage of water sources suitable for drinking water preparation results in the necessity to use polluted ones even if the water processing costs are higher.

There exist numbers of suitable methods for removal of volatile contaminants from water. We discussed one of them in our latest contribution [1]. The air stripping of radon, crude-oil and chlorinated hydrocarbons in vertical columns with packing is wide-spread. If we select an efficient packing with low pressure drop, the high ratio of air to water flowrates G/L can be applied and even substances with lower volatility can be effectively removed. We successfully realized this arrangement in cooperation with Neptun Bylany join-stock company in approx. 50 plants, so far.

Recently we often meet the requirement to apply this technology to old water sources with low throughput. But old water works with a low building height make it impossible to situate a high desorption column inside. And the cost of building reconstruction is often higher than the designed separation column. The miscellaneous operating conditions and trials to make the water processing as effective as possible made it necessary to explore another method based on application of a rotating disk stripper (RDS). RDSs have been already successfully used in analytical chemistry and in processing of waste waters as carriers of bacteria or aerators in biofilters.

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The principle of RDS function

A rotating disk stripper consists of circular disks fixed equidistantly on the motor driven shaft carried on ball-bearings. The disks with diameter d are partially immersed in a channel with half-circular or rectangular crossection, where polluted water is flowing. By rotation of the disks the water is carried up as a film adhering on their surface. This water film is brought in contact with air blown in in a perpendicular direction to the axis of rotation by a fan. A volatile pollutant transfers from water to the stream of air which leaves the RDS. An interval of applicable rotation frequencies is limited from above by a value when a considerable amount of water begins to spirt on the apparatus walls due to centrifugal forces. RDS design follows from requirements concerning its capacity.

For distribution coefficient K of pollutant in water-air equilibrium we can write eq. (1)

$$c_L = K \cdot c_G \quad , \tag{1}$$

where c_L and c_G are pollutant concentrations in water and air. The overall mass transfer coefficient can be defined by eq. (2)

$$K_L = \frac{1}{\frac{1}{k_L} + \frac{K}{k_G}} \quad . \tag{2}$$

For low values of K/k_G ratio the eq. (2) transforms to eq. (3)

$$K_L = k_L \quad . \tag{3}$$

The liquid side mass transfer coefficient can be calculated on the basis of Higbie's penetration theory [2], eq. (4)

$$k_L = \sqrt{\frac{4.D}{\pi.\tau}} \quad , \tag{4}$$

where D is the diffusion coefficient of a volatile pollutant in water and τ is the time of contact of water film element with the air. This time of contact can be calculated as the ratio of one half of the disk perimeter and its circumferential velocity, eq.

(5), where n means the frequency of rotation

$$\tau = \frac{1}{2 \cdot n} \quad . \tag{5}$$

The size of interfacial area A formed by z disks with diameter d on a shaft with diameter d_0, can be calculated by eq. (6)

$$A = 0,25 \cdot \pi \cdot z \cdot (d^2 - d_0^2) \quad . \tag{6}$$

For the number of transfer units N_{OL} we obtain eq. (7),

$$N_{OL} = \frac{k_L . A}{L} \quad , \tag{7}$$

where L means the flowrate of water through the RDS.

Experimental

During the development of RDS four experimental set-ups labelled as RDS-D, RDS-H, RDS-I-H and RDS-I-D have been designed. Their characteristics are in Table 1.

Table 1. - Description of experimental set-ups

Set-up	Material of disks	Number of disks	Disk diam. [mm]	Shaft diam. [mm]	Length of RDS [mm]	Number of sections
RDS-D	polynet	37	290	10	300	1
RDS-H	PVC ≠ 1 mm	30	300	10	300	1,4,7
RDS-I-H*	PVC ≠ 2 mm	32	265	110	600	4
RDS-I-D*	PVC ≠ 3 mm	32	265	110	600	4

*Between the disks the squares 200mm by 200mm of sinusoidally corrugated polynet netting were inserted

RDS was tested on two systems: water saturated with carbon dioxide and water containing radon (from Vepřová site in the Czech Republic), both for stripping by air at 25°C. The concentration of carbon dioxide in water was evaluated by titration. The measurement of radon concentration in water was arranged by the Neptun Bylany joint-stock company. Both the input and output concentrations in water c_1 respective c_2 were measured. Number of the transfer units can then be calculated by eq. (8)

Table 2.

Results of measurements on the RDS-I-H arrangement (c_1,c_2- input and output concentration, for CO_2 [mol/m^3], for Rn [Bq/ℓ], n - frequency of rotation [min^{-1}], S1-S4 - section with 8 disks each, P - overflow, /VV - outdoor air, /Ox- CO_2 was exhausted out of room, x=1, 2, ... repetitions, L - flowrate of water [ℓ/min], G/L=10)

Desorption of CO_2 - L = 2 ℓ/min

n	45		66		107		150	
c_1	33.0		30.0		30.1		30.4	
	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}
S1	19.4	0.53	14.2	0.75	8.5	1.26	8.1	1.32
S2	11.9	1.02	7.95	1.33	4.8	1.83	3.17	2.26
S3	7.3	1.5	4.42	1.91	3.3	2.2	1.64	2.92
S4	4.8	1.93	2.76	2.38	1.2	3.22	1.2	3.23
n	106		106/VV		106/01		106/02	
c_1	32.8		33.3		32.0		33.0	
	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}
S1	12.1	1.0	11.1	1.1	11.9	1.0	-	-
S2	6.0	1.7	5.2	1.8	5.7	1.72	-	-
S3	3.1	2.36	2.9	2.44	3.0	2.36	-	-
S4	2.2	2.7	2.1	2.76	1.67	2.95	1.89	2.86
P					1.45	3.09	2.12	2.75
n	106/03		106/04		106/05		106/06	
c_1	32.2		33.0		31.0		31.0	
	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}
S1	11.0	1.07	-	-	10.9	1.04	-	-
S2	5.0	1.86	-	-	5.8	1.68	-	-
S3	2.67	2.5	-	-	3.2	2.26	-	-
S4	1.67	2.96	1.89	2.86	2.0	2.74	2.0	2.74
P	1.34	3.18	2.12	2.75	2.0	2.74	2.0	2.74

Desorption of CO_2 - L = 4 ℓ/min

n	45		66		107		150	
c_1	33.0		31.3		30.9		31.8	
	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}
S1	23.8	0.33	20.8	0.4	13.7	0.8	11.6	1.0
S2	18.8	0.56	14.2	0.79	9.4	1.2	5.14	1.82
S3	13.7	0.88	9.7	1.17	7.0	1.5	2.95	2.38
S4	10.4	1.15	7.1	1.48	5.0	1.82	1.2	3.28
n	106		106/01		106/02			
c_1	32.2		33.0		33.0			
	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}		
S1	17.7	0.6	17.7	0.62	-	-		
S2	10.8	1.1	10.5	1.14	-	-		
S3	6.77	1.64	6.57	1.61	-	-		
S4	4.66	1.93	3.68	2.19	4.35	2.03		
P	-	-	4.0	2.11	4.35	2.03		

Table 2 (continued)

Desorption of CO_2 - L = 4 ℓ/min   Desorption of CO_2 - L = 1 ℓ/min

n	106/03		106/04		106/03		106/04	
c_1	32.2		33.0		29.2		29.0	
	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}	c_2	N_{OL}
S1	16.4	0.67	-	-	6.7	1.48	-	-
S2	9.6	1.21	-	-	2.7	2.4	-	-
S3	5.57	1.75	-	-	1.22	3.17	-	-
S4	3.57	2.2	4.35	2.02	0.66	3.8	0.66	3.8
P	3.57	2.2	4.35	2.02	0.66	3.8	0.66	3.8

Desorption of Rn - L = 2 ℓ/min   Desorption of Rn - L = 4 ℓ/min

n	107		107	
c_1	303		350	
	c_2	N_{OL}	c_2	N_{OL}
S2	123	0.9	186	0.63
P	26	2.45	83	1.44

Data presented in Table 2 are taken from the report by Kuthan at al [3].

$$N_{OL} = \ln(c_1/c_2) \quad . \tag{8}$$

This relation is a special case of a general one which can be transformed to eq. (8) for low values of the absorption factor $K \cdot L/G$, where G means the flowrate of air. This condition was fulfilled for both radon ($K \doteq 0.3$) and carbon dioxide ($K \doteq 1$). In Table 2 data are presented covering the influences of rotation frequency, length of apparatus, flowrate of liquid and of the G/L ratio.

Analysis of experimental data

As follows from eq. (7), the number of transfer units is directly proportional to the mass transfer coefficient k_L, the interfacial area A and inversely proportional to the flowrate of water L. The same dependencies follow from our experimental data. *Frequency of rotation:* Fig. 1 shows in logarithmic coordinates the dependence of N_{OL} on the frequency of rotation for a constant flowrate and for four different sizes of interfacial area given by the number of disks. At the beginning of RDS (8 and 16 disks) the influence of backmixing can be seen, the slope b of dependence $\log(N_{OL}) \sim b \cdot \log(n)$ is higher at the beginning than at the end

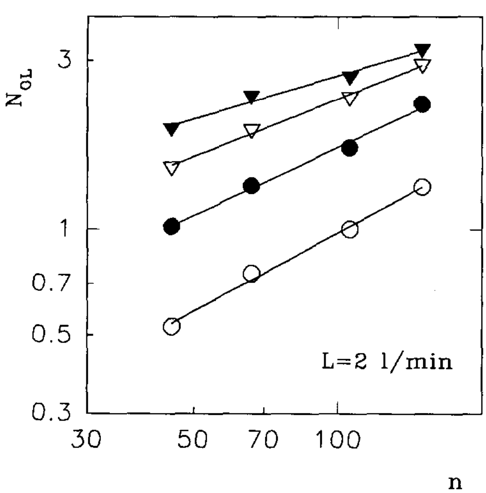

Fig. 1 - Dependence of number of transfer units on frequency of rotation and length of RDS

▼ 32 disks ▽ 24 disks
● 16 disks ○ 8 disks

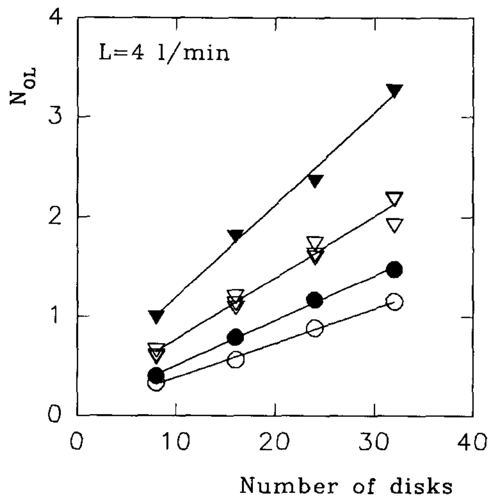

Fig. 2 - Dependence of numbe of transfer units on length RDS and frequency of rotatio

▼ n=150 min^{-1} ▽ n=106 min
● n=66 min^{-1} ○ n=45 min^{-1}

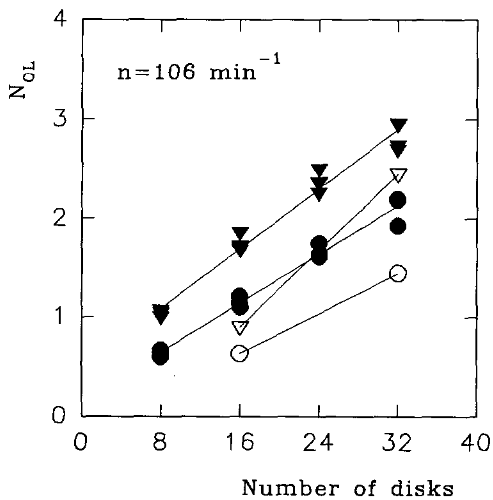

Fig. 3 - Influence of water flowrate and diffusivity on number of transfer units

▼ CO_2:L=2 l/min ▽ Rn:L=2 l/min
● CO_2:L=4 l/min ○ Rn:L=4 l/min

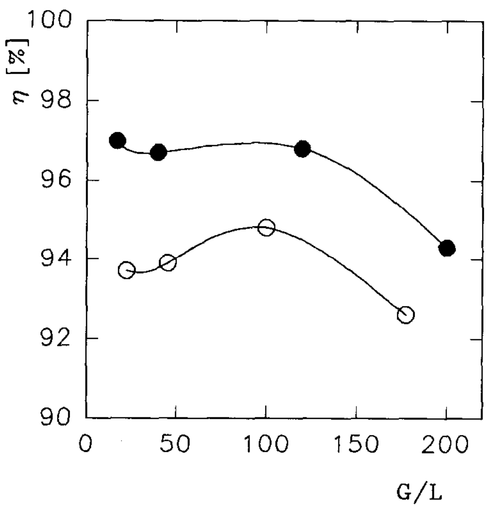

Fig. 4 - Dependence of effectivity of RDS on air to water flowrates ratio

○ n=32 min^{-1} ● n=66 min^{-1}

of RDS. With increasing length of RDS the influence of backmixing subsequently vanishes.

Length of apparatus: It follows from Fig. 2 that the number of disks is crucial for the overall efficiency. The slope of experimental data expresses the influence of interfacial area and frequency of rotation on the number of transfer units given by eq. (7).

Water flowrate: Eq. (7) predicts the decrease of N_{OL} values with increasing water flowrate. The expected decrease of efficiency of RDS with increasing flowrate of water can be seen in Fig. 3, where the data for radon and carbon dioxide desorption are plotted.

Influence of G/L ratio: Fig. 4 shows the efficiency of RDS η calculated by eq. (9)

$$\eta = (1-c_2/c_1)\cdot 100 \quad , \qquad (9)$$

in dependence on the air to water flowrates ratio G/L, for data measured on RDS-D arrangement. The water flowrate was 2 ℓ/min and frequency of rotation 32 a 66 min^{-1}. It can be noticed, that in a considerable part of the measured interval of G/L values the influence of G/L on RDS efficiency is not important. Only for very high values of G/L ratio the decrease of efficiency can be seen, which is likely given by the change of hydrodynamics. It can be stated that for a given set-up the value G/L=10 is sufficient for efficient desorption of carbon dioxide from water. Fig. 4 also shows, that with the increasing frequency of rotation the efficiency of RDS increases.

Mathematical model for the RDS-I-H set-up

In the preceding part the results of stripping of carbon dioxide and radon obtained from laboratory and semi-pilot plant measurements were presented. The size of interfacial area A for the RDS-I-H set-up equals

$$A = 0,25\cdot\pi\cdot z\cdot(d^2-d_0^2)=0,25\cdot 3,14\cdot 32\cdot(0,265^2-0,11^2)=1,46\ m^2 \quad .$$

The water flowrates L=2 and 4 ℓ/min correspond to 0,033 and 0,066 $l\cdot s^{-1}$, respectively. The velocity of water in axial direction equals to $L/S=33\cdot 10^{-6}/35,3\cdot 10^{-4}=9,35\cdot 10^{-4}$ $m\cdot s^{-1}$ and $1,87\cdot 10^{-3}$

$m \cdot s^{-1}$, respectively. The number of transfer units N_{OL} for the most often used frequency of rotation, approx. 100 [min^{-1}], is N_{OL}=2,9 for 2 ℓ/min and N_{OL}=2 for L=4 ℓ/min. Time of contact τ by Higbie [2] can be calculated as the ratio of one half of disk perimeter $\pi D/2$=0,416 m and its circumferential velocity $v = n\pi d/60 = 1{,}39\ m \cdot s^{-1}$

$$\tau = 0{,}416/1{,}39 = 0{,}28\ s \quad .$$

For the liquid side mass transfer coefficient it follows

$$k_L = (4D_{CO_2}/\pi/\tau)^{0.5} = (4 \cdot 1{,}9 \cdot 10^{-9}/\pi/0{,}28)^{0.5} = 9{,}3 \cdot 10^{-5}\ m \cdot s^{-1}.$$

Using this calculated (modeled) value of k_L, the size of interfacial area A=1,46 m^2 and water flowrate L we obtain the following number of transfer units

$$N_{OL} = 9{,}3 \cdot 10^{-5} \cdot 1{,}46/33 \cdot 10^{-6} = 4{,}11 \text{ pro } L=2\ \ell/min \quad ,$$

$$N_{OL} = 9{,}3 \cdot 10^{-5} \cdot 1{,}46/66 \cdot 10^{-6} = 2{,}06 \text{ pro } L=4\ \ell/min \quad .$$

The agreement between calculated and measured values is good.

Scale-up

The number of transfer units N_{OL} attained for flowrates of water 2 and 4 ℓ/min is acceptable from the point of efficiency for radon or volatile organic contaminants stripping. But the apparatus throughput is very low (0,033 and 0,066 ℓ/s, respectively). The capacity of RDS can be increased by enlarging the interfacial area, by increasing the number of disks or their diameter or by both ways. Increasing the disk diameter, the circumferential velocity can become as high that the spirting of separate drops, filaments or coherent films (which disintegrate to drops before they reach the wall) occurs at the perimeter of the disks. The spirting of drops at the perimeter of the disk is influenced by the centrifugal, gravitational and superficial forces. The velocity of flow on the disk at the direction to its perimeter or at the direction of gravitational force is controlled by viscous forces. For water film element with a thickness t at the disk surface the following equations can be derived

$$\text{gravitational force } F_g = m \cdot g = \rho \cdot t^3 \cdot g \quad , \tag{10}$$

$$\text{centrifugal force } F_o = 2 \cdot m \cdot v^2/d = 2 \cdot \rho \cdot t^3 \cdot v^2/d \quad , \tag{11}$$

$$\text{superficial force } F_\sigma = 4 \cdot t \cdot \sigma \quad , \tag{12}$$

$$\text{viscous force } F_\mu = - \frac{\mu}{S} \cdot \frac{dv}{dx} \quad . \tag{13}$$

At the position on the disk where the water film element is at its top dead centre it follows from the equilibrium of gravitational and centrifugal forces

$$2v^2/d = g \quad . \tag{14}$$

Using the frequency of rotation in equilibrium of forces n^*, $v = d \cdot \pi \cdot n^*$, we get eq.(15)

$$2\pi^2 d^2 n^{*2}/d = g \tag{15}$$

and for n^*

$$n^* = 60 \sqrt{\frac{g}{2.\pi^2.d}} = 42,298/\sqrt{d} \ \text{min}^{-1}, \text{m} \ .$$

Table 3 shows the calculated frequencies of rotation for the equilibrium of centrifugal and gravitational forces for selected diameters of disks. For the water film thickness t=1 mm we obtain

$$F_\sigma = 4 \cdot t \cdot \sigma = 4 \cdot 10^{-3} \cdot 0,072 = 2,9 \cdot 10^{-4} \ \text{N} \quad ,$$

$$F_g = \rho \cdot t^3 \cdot g = 1000 \cdot 10^{-9} \cdot 9,81 = 0,98 \cdot 10^{-5} \ \text{N} \quad .$$

The superficial force is quite high and it can contribute to keep the water film on the disk even for higher frequencies of rotation than for those calculated from the equilibrium of centrifugal and gravitational forces. The disk region going through the top dead center down in direction to water level provides from the point of addition of forces the best conditions for water spirting. The direction of drops flying away follows the tangent of the disk perimeter which indicates the place of likely incidence of water drops.

If there are more disks close to each other, then the formation of a meniscus between them and the velocity of its outflow back to water level determines the rotation frequency for which the water will be carried above the water level and around the perimeter of disk. But for our experimental set-up it is not likely to occur. This is of importance for viscous liquids and for extremely low disks pitch.

For evaluation of k_L the time of contact has to be known. Time of contact depends on the circumferential velocity and with respect to the spirting of drops, on the disk diameter. After substitution of the necessary quantities to eq. (4) we get the following proportionality

$$k_L \sim n^{0,5} \sim d^{-0,25} \quad .$$

This proportionality is shown in Fig. 1 ($N_{OL} \sim k_L$), where the slope of experimental data for the length of RDS 24 and 32 disks reached values of 0,53 and 0,41.

So far all calculations concerned with carbon dioxide used during laboratory measurements. Using e.g. radon the coefficient k_L and the number of transfer units N_{OL} decrease due to the low radon diffusivity in water. This fact can be noticed from the trend of experimental data in Fig. 3.

Table 3 shows the calculated values of A, k_L, $k_L A$ and N_{OL} for the desorption of radon. The flowrate of water was 4 ℓ/min and the disks pitch was 5 mm (i.e. 200 disks/m). We supposed that the whole surface of the disks was wetted and that the mass transfer coefficient could be modeled by an equation based on Higbie's penetration theory [2].

Table 3. - Calculated values of parameters

d [m]	A [m^2]	$k_L \cdot 10^5$[m/s]	$k_L A \cdot 10^5$[m^3/s]	N_{OL}	n^*[min^{-1}]
0,265	9,1	6,7	61	9,2	82,2
0,3	12,2	6,5	79,3	12	77,2
0,4	23,2	6,0	139,2	21,1	66,9
0,5	37,4	5,7	213,2	32,3	59,8

As follows from the last row of the Table 3, the number of transfer units N_{OL} calculated for the water flowrate 0,066 $l \cdot s^{-1}$ is so large that we can increase the flowrate for example five times to the value 0,33 $l \cdot s^{-1}$, having still sufficient number of transfer units, approx. 6,5. This value corresponds to the efficiency of radon removal 99,8 %. To increase the efficiency and throughput a set-up with high interfacial area and low resistance for passing the disks through the liquid has to be selected.

Construction

Fig. 5 shows a new segment of the RDS 140 mm long formed by 29 disks with a diameter 285 mm manufactured from a 1 mm thick

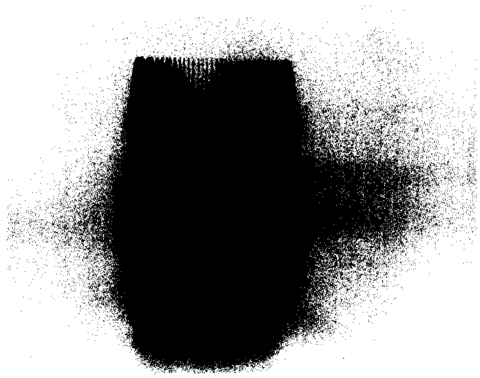

Fig. 5

PVC foil. Its length is approximately four times shorter than that for the RDS-I-H set-up. At the disk 6 draw bars are situated which using a system of washers fix the disks around their perimeter. By increasing the diameter of the disks it is convenient to increase the number of draw bars. The units of RDS can be arranged in parallel to increase the throughput or in series to increase the efficiency of removal of volatile contaminants from water. RDS can also be combined with a short column which works as a preprocessing stage.

References

1. Brož Z., Kuthan K., Vašák F.: Air Stripping of Volatile Organic Compounds from Water, CHISA'90, Prague 1990
2. Higbie R.: Trans. AIChE 31, 368-389 (1935)
3. Kuthan K., Vašák F., Brož Z.: Testing of Rotating Disk Stripper Prototypes and Fan Water Drive (in czech), ÚTZCHT Report No. 33/91, Prague 1991