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The performance of the "Dresden" nozzle in the aeration of water

1. Introduction

Of spray aerators used in the treatment of ground-water the "Dresden" nozzle is very suitable for expelling CO_2 — and thus attenuating the aggressiveness of the water — and raising the dissolved oxygen content. This has been established by Carrière [1] having investigated this type of spray aerator. A similar result has been obtained by Kittner [2]. Presumably, its effect on the removal of free CO_2 as well as on the uptake of O_2 is such as to justify a further investigation into such matters as the efficiency of the nozzle in the transfer of gases. Also with respect to other requirements the "Dresden" type is advantageous among spray aerators, as has been pointed out by Louwe Kooymans [3]. It is noted that Carrière's results have been obtained on natural ground-water. In the present research use was made of tap water being enriched with CO_2. Typical test-water quality characteristics are shown in table I.

TABLE I - Ionic concentrations in m mol. l-1 of water used in this study.

Ca²+	2.19	HCO₃⁻	2.33
Mg²+	0.49	SO₄²⁻	0.62
Na+	4.1	Cl⁻	5.8

2. The nozzle (see fig. 1a)

The tested specimen constitutes a renewed type of nozzle being used most frequently in the Netherlands nowadays. It consists of a 37 mm ID plastic tube that is mounted vertically. The tube, having a length of 0.25 m, is fitted with a circular flow deflector at the outer end of it so that the water will be issued horizontally and spread to assume the shape of an "umbrella".

The latter is, in fact, a thin film of water extending some 0.25 to 0.3 m below the flow deflector, which film will be soon disintegrated into drops due to gravity. The distance between the flow deflector and the end of the tube is chosen in accordance with the flow rate and may be varied from 0.02 to 0.03 m. The nozzles are usually embedded in a concrete floor which is part of a shallow spreading basin and enough water depth is provided herein to allow of sufficient head for a proper functioning of the nozzles.

3. Basic considerations

The rate of escape of a gas from water is governed by those factors which also apply to the rate of absorption of a gas. In both cases the differences between the partial pressures of gases in water and in the atmosphere are important. In general, the partial pressure of CO_2 in the atmosphere is low (0.04 %) resulting in a low concentration of CO_2 in water being in equilibrium with a normal atmosphere (about 1 ppm). It has been mentioned by Boorsma [4] and Louwe Kooymans [5] that the ultimate CO_2-content to be obtained after aeration of natural ground-water is higher than the value following from Henry's law. According to Kleijn [6] and Schäfer [8] equilibrium is seldom reached in aeration. It is noted that practical conditions do not allow to determine the equilibrium value very precisely and therefore the author will confine himself to an ultimate CO_2-

Fig. 1a - Dresden nozzle.

a. spindle-holder
b. plastic tube of 37 mm ID
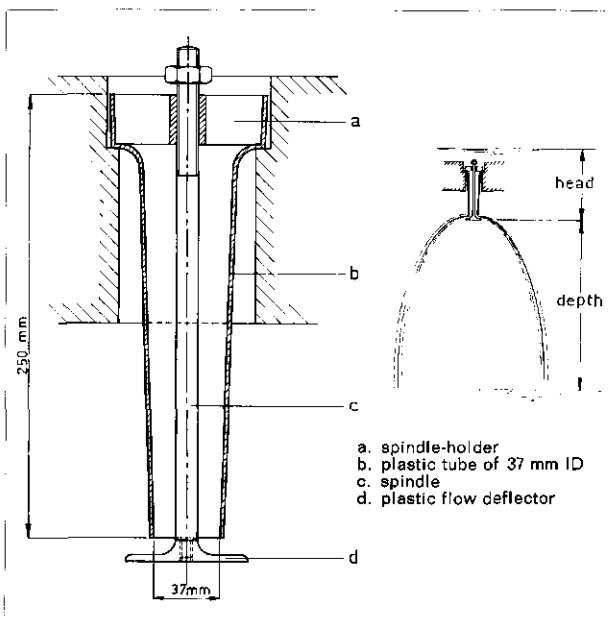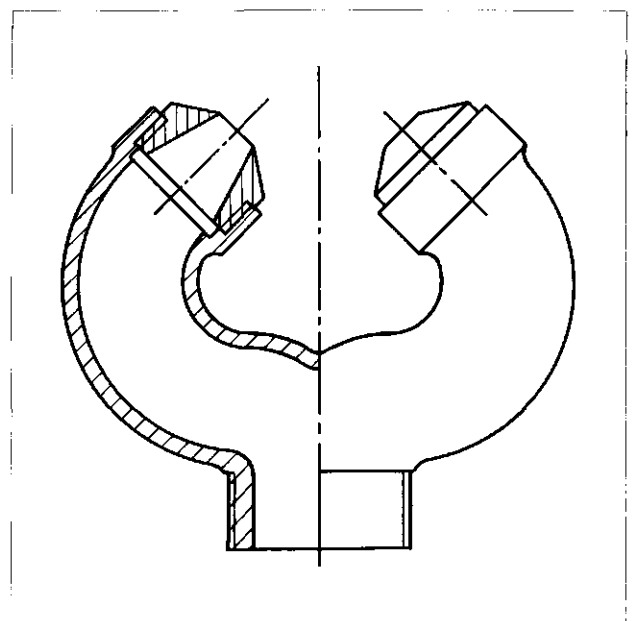c. spindle
d. plastic flow deflector

Fig. 1b - Amsterdam nozzle.

content of the water tested, which may be obtained from a graphic method. This method will be mentioned later. When the CO_2-content is in excess of the equilibrium value C_e, the water is supersaturated and aeration will then result in a drop of CO_2 being proportional to the degree of supersaturation. This may be expressed by the following relationship:

$$C_a — C_b = K_1 (C_a — C_e) \quad (1)$$

where C_a and C_b are the CO_2 concentrations before and after aeration and K_1 is a coefficient of escape.

The raise of the dissolved oxygen content is proportional to the oxygen deficit and may be expressed by:

$$C_b — C_a = K_2 (C_s — C_a) \quad (2)$$

where C_b and C_a are the dissolved oxygen concentrations after and before aeration, C_s is the oxygen saturation value and K_2 is a coefficient of absorption.

It is sometimes convenient to express the aeration capacity in terms of the raise of the O_2-content under the condition of oxygen-free water supplied to the nozzle. The aeration capacity will then follow from:

$$C_o = K_2 C_s \quad (3)$$

CO_2 is present almost completely as a gas so that no chemical factors are involved and K_1 and K_2 are related to physical and hydrodynamical factors only. Their influence, however, is uncertain as conditions during the free fall vary so much, so that we are obliged to relate K_1 and K_2 to parameters like depth below the deflector (see fig. 1a) and flow rate to characterize the effect of the nozzle. Of the physical factors only the influence of diffusivity may be traced by comparing K_1 and K_2. This question is of practical importance since investigations on several nozzles in the past concern the transfer of one gas — either O_2 or CO_2 — and predictions as to the effect towards the other gas would complete our knowledge. In chemical industry various concepts regarding the rate of gas transfer have been developed, two of which — the Higbie and Danckwerts models — predict that K_1 and K_2 are proportional to the square roots of the diffusivities, $\sqrt{D_1}$ and $\sqrt{D_2}$, of both gases.

4. The influence of temperature

Temperature is likely to be of consequence to K_1 and K_2 and the influence may be estimated from the variations of $\sqrt{D_1}$ and $\sqrt{D_2}$ with temperature. To this purpose the values of D_1 for CO_2 and D_2 for oxygen obtained at 18° C. have been taken from the Int. Crit. Tables [7]. For oxygen various values are available and a mean value of 1.80×10^{-5} cm^2 s^{-1} has been adopted in this paper. D's at other temperatures are assumed to obey the Nernst-Einstein equation $\dfrac{D\eta}{T}$ = const., where η is the viscosity of water and T the absolute temperature. The results are summarized in table II. From this it is clear that the values increase when temperature increases. For practical purposes CO_2-removal is often expressed by:

$$C_a — C_b = K_1 C_a \quad (1a)$$

This simplification is of little consequence to the estimation of the temperature effect so long as C_e is small in comparison with C_a. From the above-mentioned arguments it would follow that the removal efficiency

TABLE II - Variations of $\sqrt{D_1}$ (CO_2) and $\sqrt{D_2}$ (O_2) with temperature.

Temperature °C	$\sqrt{D_1} \times 10^3$ cm s$^{-\frac{1}{2}}$	$\sqrt{D_2} \times 10^3$ cm s$^{-\frac{1}{2}}$
5	3.38	3.46
6	3.44	3.52
7	3.50	3.58
8	3.55	3.63
9	3.62	3.70
10	3.68	3.77
11	3.73	3.82
12	3.80	3.89
13	3.84	3.94
14	3.90	4.00
15	3.96	4.07
16	4.02	4.12
17	4.09	4.19
18	4.14	4.25

expressed as a percentage depends on temperature and will increase with increasing temperature. This may be verified on the basis of data furnished by Kittner [2]. In his paper removal efficiencies are given at various temperatures for Dresden nozzles of 19 and 25 mm. These data are reproduced in table III together with computed ratios. The ratios, which are the ratios of the

TABLE III - CO_2-removal efficiencies of Dresden nozzles at 6 m^3. m^{-2}. hr^{-1} capacity and at various temperatures (after Kittner [2]).

Temperature °C	Removal efficiency in %		Ratio of removal efficiency to $\sqrt{D_1} \times 10^{-4}$	
	19 mm	25 mm	19 mm	25 mm
5	57	52	1.69	1.54
10	63	58	1.71	1.57
15	69	64	1.74	1.61

removal efficiencies to the values of $\sqrt{D_1}$, appear to be fairly constant indeed, approving the concepts of gas transfer to be applicable to spray aerators. The influence of temperature on O_2-uptake is quite different. It has been mentioned elsewhere [9] that the variation with temperature of C_0 according to eq. 3 is small, provided not too wide a temperature range is considered.

5. Experimental

Laboratory investigations were carried out concerning the CO_2-removal and O_2-uptake by a single Dresden nozzle as shown in fig. 1a. The nozzle was mounted below a supply tank of about 0.15 m^3 capacity. Water being artificially enriched with CO_2 was pumped from a storage tank of about 100 m^3 capacity into the supply tank at rates varying from about 2.5 to 6 m^3. hr^{-1}. The heads allowed to the nozzle expressed in m water column above the flow deflector were varied from 0.35 to 0.6 m. The inlet CO_2-content was varied from about 30 to 120 ppm. To obtain a substantial change in dissolved oxygen content in the system the water was deoxygenated by addition of a solution of sodium sulfite. The solution was dosed continuously into the supply line at some distance upstream from the installation together with a small quantity of cobalt chloride as a catalyst to permit
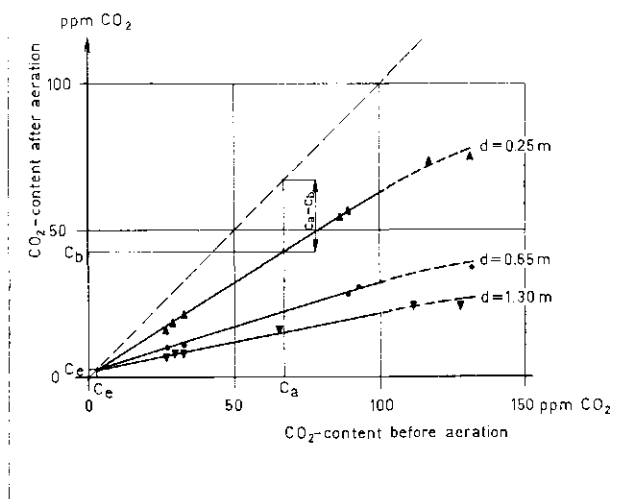
Fig. 2 - *Established relationship between CO_2-content before and after aeration by a single 37 mm Dresden nozzle at 2.9 m^3 hr^{-1} capacity and different depths below the flow deflector (16 - 17° C).*

Fig. 3 - *CO_2-removal by a single 37 mm Dresden nozzle over the depth below the flow deflector. Results obtained at 2.9 m^3 hr^{-1} capacity and at 16 - 17° C.*

sulfite to be oxidized completely before reaching the nozzle. The aerated water was collected in two shallow trays of 5 dm^2 that were moved mechanically along the circumference of the spray. The mechanism for driving the trays allowed samples to be taken at any depth below the flow deflector. Great care was exercised in taking the samples from the trays to prevent loss of CO_2. It is noted that samples were taken after conditions had become steady. The temperature of the water ranged from 16 to 17° C.

Analyses

The CO_2-content was calculated from the pH-value and total alkalinity. The dissolved oxygen content was determined by the Winkler-method.

Results

CO_2-removal was tested at various inlet concentrations C_a. It may be seen from fig. 2 that for $C_a <$ 100 ppm and for depths of 0.25, 0.65 and 1.3 m the plots become a straight line. The lines intersect at a point that is very near the origin and that may well represent the equilibrium value C_e (about 3 ppm). There is no explanation why the lines should deviate at C_a-values > 100 ppm. It is quite possible that the technique of sampling becomes inaccurate in this range of CO_2-content. The line at an angle of 45° indicates that no removal of CO_2 would have occurred. The biggest removals occur in the first 0.65 m below the flow deflector. The influence of depth on CO_2-removal is further illustrated in fig. 3. There are two explanations for the form of the curve. Firstly, the degree of supersaturation decreases with increasing depth resulting in a lowering of the rate of CO_2-escape. Secondly, the water droplets which are formed at a depth of about 0.3 m will be accelerated due to gravity, resulting in shorter contact times of the water with the air per unit depth. An important factor is the head to be applied to the nozzle for a proper functioning of it. Carrière has found that for an economic handling of the water a small head should be practised. It was therefore interesting to investigate the effect of
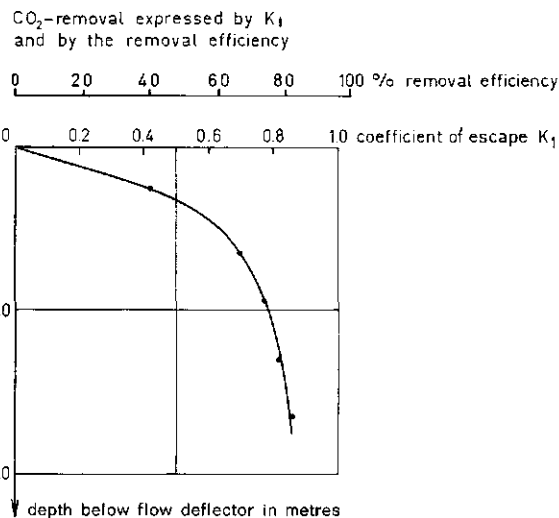
the nozzle at the lower range of head. 0.35 and 0.6 m were chosen which heads appeared to correspond with minimum flow rates of about 2.9 and 2.3 m^3. hr^{-1}. At 2.9 m^3. hr^{-1} the removal efficiencies at both heads differed so slightly as to make it advisable to avoid heads being in excess of 0.35 m. From this it may be concluded that the economy in CO_2-removal can be obtained by provision of depth only, which is in agreement with Carrière's finding. Further investigations into the effect of flow rate have therefore been carried out at a head of 0.35 m. To this purpose the distance between the flow deflector and the end of the nozzle tube was adapted. The results have been collected in table IV and it is obvious that the removal efficiencies over the total range of depth will decrease when the rate of flow is augmented.

TABLE IV - 37 mm Dresden nozzle - Influence of flow rate on CO_2-removal expressed by K_1 at 0.35 m inlet head an at 16° C.

Flow rate in m^3. hr^{-1}	Depth below flow deflector			
	0.65 m	0.95 m	1.30 m	1.65 m
2.9	0.70	0.77	0.82	0.86
3.7	0.65	0.76	0.80	0.83
4.8	0.61	0.65	0.75	0.76
5.8	0.62	0.70	0.73	0.74

K_2 was determined by aerating water containing a low dissolved oxygen content at a rate of about 2.9 m^3. hr^{-1}. Obtained data have been collected in table V, together

TABLE V - CO_2-removal and O_2-uptake by a 37 mm Dresden nozzle at 2.9 m^3. hr^{-1} capacity and at 16° C.

Coefficient	Depth below flow deflector		
	0.65 m	0.95 m	1.30 m
K_1 (CO_2)	0.70	0.77	0.82
K_2 (O_2)	0.75	0.78	0.83
Ratio of K_2 to K_1	1.075	1.01	1.01

with K_1-values for CO_2-removal at the same flow rate. The mean ratio of K_2 to K_1 appears to be 1.03 and when comparing this result with the ratio of $\sqrt{D_2}$ to $\sqrt{D_1}$ it may be concluded that the ratios are the same. We may therefore predict O_2-uptake from K_1-values and in order to obtain the aeration capacities C_0 at the various flow rates, the results in table IV should be multiplied by 1.03×10.0, 10.0 being the oxygen saturation value in ppm at $16°$ C. The aeration capacity expressed in kg O_2 per net kWh may be very useful when comparing the performance of various types of aerators.

It may be calculated from:

$$\frac{3600}{9.81} \cdot \frac{C_0}{h} \quad \text{kg of oxygen per net kWh}$$

where h is the sum of the head and the depth in metres. For the lower range of flow rate and a head of 0.35 m data are given in table VI. From this it may be concluded that Dresden nozzles may provide a very efficient aeration. At the upper range of flow rate the aeration capacity may be expected to be some 10 to 15 % lower.

TABLE VI - Aeration capacity per net kWh of 37 mm Dresden nozzle at 2.9 m³. hr⁻¹ capacity and 0.35 m inlet head.

Aeration capacity	Depth below flow deflector			
	0.25 m	0.65 m	0.95 m	1.30 m
kg O_2 per net kWh	3.0	2.75	2.2	1.85

6. The "Amsterdam" nozzle (see fig. 1b)

It may be of interest to compare the effect of the Dresden nozzle with that of the Amsterdam nozzle. Therefore, investigations were carried out on this type of spray aerator applying various outlet openings and heads of 1.75, 2.75, 3.75 and 4.75 m. From this study it became clear that the CO_2-removal efficiencies were almost independent of head. In testing outlet openings of 6, 7 and 8 mm the efficiencies did not vary much either, as is indicated in table VII. When the result obtained at the biggest outlet opening and a head of 1.75 m is chosen as a reference it would follow that the effect of the Amsterdam nozzle is inferior. Furthermore, the head applied to the nozzle did not allow to achieve a better aeration capacity than about 1.6 kg O_2 per net kWh.

7. Results

From the experimental study on a single Dresden nozzle it appeared that:

7.1. the economy in CO_2-removal may be best attained by provision of depth below the flow deflector;

7.2. the CO_2-removal expressed as a percentage of the inlet CO_2-content amounts to 80 % at 3.0 m³. hr⁻¹ and a depth of 1.3 m. At a capacity of about 6.0 m³. hr⁻¹ the CO_2-removal is some 8 to 12 % lower;

7.3. the O_2-uptake may be predicted from data obtained on CO_2-removal. The aeration capacity at the lower range of flow rate and a depth of 1.3 m amounts to 1.85 kg of O_2 per net kWh.

References

1. Carrière, J. E. (1950). *Voorlopige uitkomsten van de door het KIWA verrichte sproeiproeven* - Mededeling No. 9 van het KIWA - The Hague, The Netherlands.

2. Kittner, H. (1963). *Die mechanische Entsäuerung und Belüftung in der Wasseraufbereitung,* Wasserwirtschaft-Wassertechnik, 13, 124-127 and 160-163.

3. Louwe Kooymans, L. H. (1955). *Aeration and deferrisation,* IWSA Congress, London, Subject no. 4, 283-347.

4. Boorsma, H. J. (1952). *Ontijzering enz. door droogfiltratie,* 4de vakantiecursus, Delft.

5. Louwe Kooymans, L. H. (1952). *Ontzuring,* 4de vakantiecursus, Delft.

6. Kleijn, H. F. W. (1965). *Buffer capacity in water chemistry,* Int. J. Air Wat. Poll., 9, 401-413.

7. "Int. Crit. Tables" (1929). Vol. V, 64-65.

8. Schäfer, W. (1966). *Die Entsäuerungsverfahren,* Veröffentlichung der Abt. und des Lehrstuhls für Wasserchemie der TH, Karlsruhe, Heft 1, 29-46.

9. v. d. Kroon, G. T. M. and Schram, A. H. (1969). *Weir aeration,* H₂O, 2, 528-45.

TABLE VII - CO_2-removal by Amsterdam nozzle at $16°$ C.

Head in m	6 mm		7 mm		8 mm	
	Capacity m³. hr⁻¹	Removal eff. %	Capacity m³. hr⁻¹	Removal eff. %	Capacity m³. hr⁻¹	Removal eff. %
1.75	1.12	76.5	1.51	74.0	1.97	75.5
2.75	1.40	81.5	1.90	85.0	2.48	76.0
3.75	1.66	82.0	2.21	79.5	2.88	79.0
	av.	80.0		78.5		77.0