WRC WATER RESEARCH CENTRE

A LITERATURE REVIEW OF CO_2 REMOVAL BY AERATION

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SUMMARY

Removal of carbon dioxide from water by aeration is an economic method of pH adjustment for water of high alkalinity. It has importance in corrosion control as applied to some groundwaters and has been examined as part of treatment methods which may be relevant to reduction of lead in water from lead pipes.

The basic physical principles governing the transfer of CO_2 from water to air and their practical implications for CO_2 removal from water are considered first. The importance of providing an adequate air:water volume ratio for any aeration method is discussed; and the relative merits of co-current and counter-current operation are compared. It is concluded that counter-current operation may only be justified where almost complete CO_2 removal is required and data are given from plant operation described in the literature to support this.

The various aeration methods that have been used in practice for CO_2 removal are described and their performances compared. Most methods, apart from some sprays, are capable of at least 70 per cent removal. Cascades of simple construction and towers containing lightweight grids, lattices or packings have proved to be both effective and relatively inexpensive.

The highest surface loading rates were achieved using very open types of grids and packings, when it was often found that the percentage of CO_2 removed was independent of loading rate over a wide range of flows.

The majority of the literature reviewed was from Continental sources and it was not, therefore, possible to arrive at any detailed conclusions on the relative costs of different aeration methods. Most aeration methods involve breaking head; but this consideration apart, capital depreciation would outweigh energy costs for aeration processes.

CONTENTS

1. INTRODUCTION

This report comprises two parts:

The first presents the physical principles governing the aeration process and the limits that they set to the performance that can be achieved in practice. The performance that can be expected for CO_2 removal by aeration is also compared with that attained for oxygenation by aeration.

The second part compares the performances for CO_2 removal attained by a number of different aeration systems in practice, on the basis of published information. Finally, the energy consumption and costs of different systems are compared briefly.

2. THE PHYSICAL PRINCIPLES OF CO_2 MASS TRANSFER BETWEEN AIR AND WATER

2.1. EQUILIBRIUM CONSIDERATIONS(1,2)

Carbon dioxide is present in air to the extent of 0.03 to 0.04 per cent by volume. The concentration of free CO_2 present in water in equilibrium with air at ambient temperatures lies between 0.4 and 0.7 mg/l. Since this concentration is small, in relation to the concentrations present in water undergoing aeration for CO_2 removal, it is usually neglected in calculations of CO_2 transfer behaviour.

Within the concentration ranges found during aeration, CO_2 obeys Henry's Law: so that at equilibrium there is a constant ratio between the concentration of CO_2 in the water and the concentration of CO_2 in the surrounding air at any given temperature. This is shown in Fig. 1 by the linear plots of the CO_2 concentration in water in equilibrium with its concentration in CO_2-enriched air, at a series of temperatures. Figure 2 shows (plotted on different scales) the corresponding solubility relationships for oxygen in equilibrium with air and oxygen-depleted air, over a range of temperatures.

Carbon dioxide is much more soluble in water than oxygen. At 10 °C, for instance, it can be seen from Fig. 1 that 60 mg/l of CO_2 in air is in equilibrium with 75 mg/l of CO_2 in water, thus exhibiting a water:air 'partition coefficient' of 1.25. 240 mg/l of oxygen in air, on the other hand, are in equilibrium with only 10.2 mg/l of oxygen in water. Thus oxygen shows a water:air partition coefficient of 0.0425. Therefore at 10 °C, carbon dioxide is about 30 times more soluble than oxygen.

The practical consequences of this solubility difference may be seen by reference to Fig. 3 (Ideal co-current case). It is possible to achieve 75% saturation of 1 volume of deoxygenated water with oxygen by bringing it into equilibrium with only about 0.12 volumes of air. But to achieve 75% removal of CO_2 from water by the same means requires nearly 4 volumes of air (i.e. about 30 times as much).

Any aeration system will therefore require a much greater air:water volume ratio to achieve a given CO_2 removal performance than would be required to achieve a comparable oxygenation performance. A spray aerator, for instance, that achieves 98% oxygenation may be found to give only 66% CO_2 removal efficiency. These performances are consistent in each case with the water having reached equilibrium with about 2.5 times its own volume of air.

In aeration systems where the air and water flows are counter-current, much smaller air:water volume ratios are needed to achieve a given performance than is the case for batch-mixed or co-current systems. The heavy line in Fig. 3 shows this and was plotted on the assumption that equilibrium was attained instantly between the incoming water and outflowing air. This cannot, of course, be achieved in practice and the kinetics of (i.e. rate of attainment of equilibrium during) CO_2 or oxygen transfer become important in determining the performances that can actually be achieved by counter-current systems.

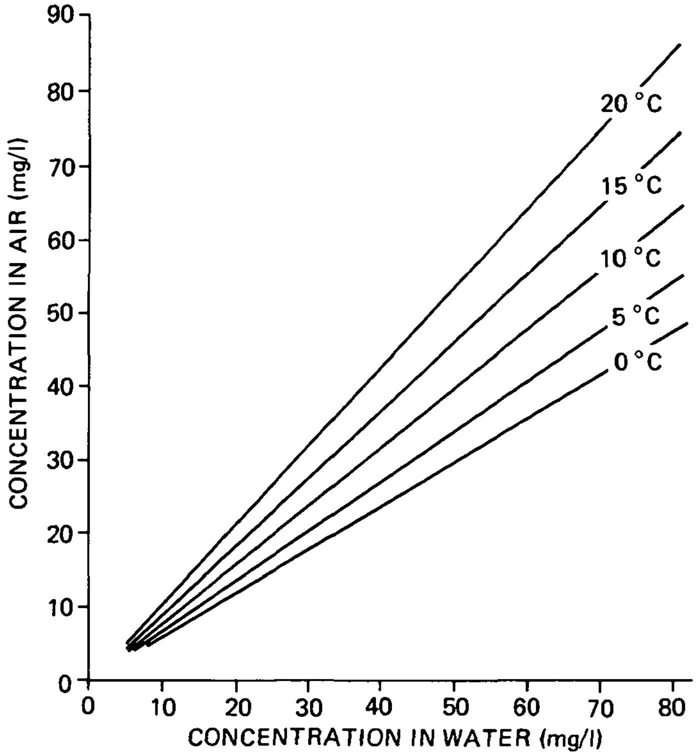

Fig. 1. Partition of CO_2 between air and water

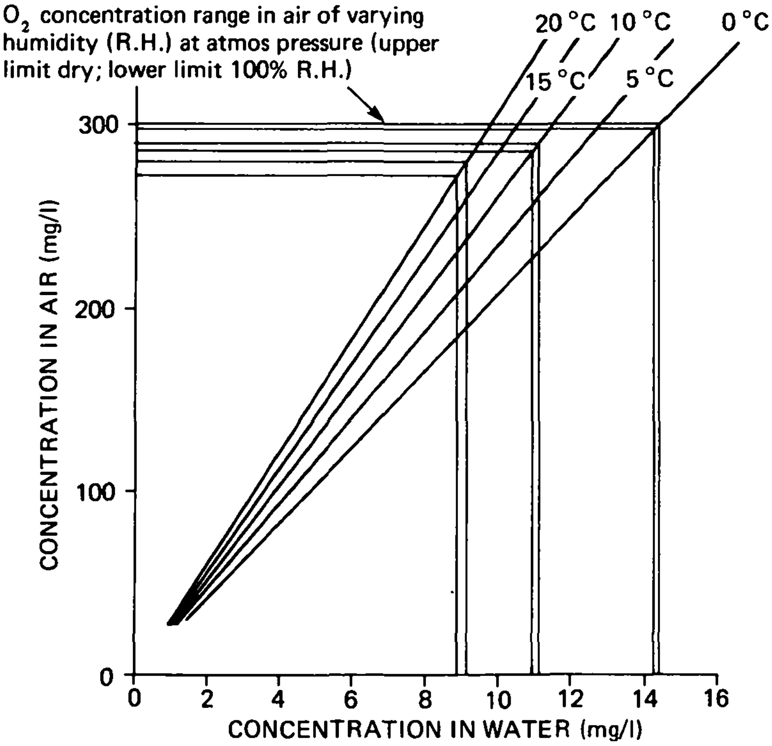

Fig. 2. Partition of O_2 between air and water

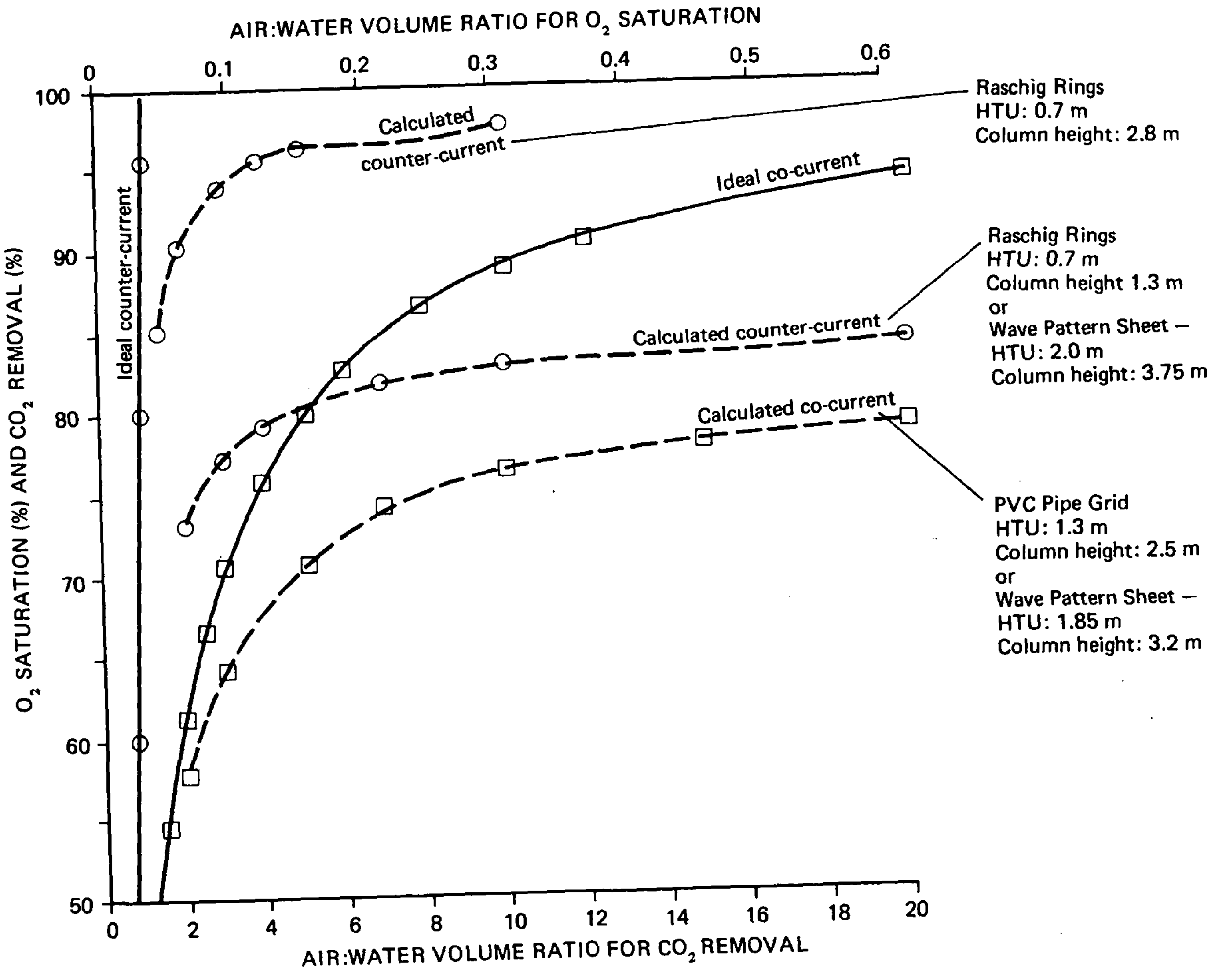

Fig. 3. Aeration column performance (10 °C)

2.2. KINETIC CONSIDERATIONS(3)

The previous section has shown what degree of oxygenation or carbon dioxide removal can be achieved if equilibrium between air and water is reached for both co- and counter-current systems (Fig. 3, Ideal cases). The transfer kinetics determine in each case how nearly equilibrium is attained under the conditions of flow, contact time etc., that prevail.

Firstly, it has been shown that under practical conditions, less than 0.5% of the carbon dioxide dissolved in water is in the form of carbonic acid (H_2CO_3). The remainder is unhydrated CO_2 gas. The fact that the total dissolved CO_2 concentration is used for the carbonic acid concentration in calculations involving the first dissociation constant, K_1, of carbonic acid, is merely a convention and has no physical reality. Thus, in considering the rate of transfer of carbon dioxide from water to air, only the diffusion of CO_2 gas need be considered. The rate of chemical reactions, such as the hydration or dehydration of carbon dioxide, will have a negligible effect; and provided no solid calcium carbonate is either dissolved or precipitated during the aeration process, very little interchange between the combined and free carbon dioxide in solution takes place.

Like other relatively insoluble gases such as hydrogen and oxygen, the rate of transfer of CO_2 is governed by its rate of diffusion in the liquid film at the air/water boundary. Since the diffusivities of carbon dioxide and oxygen in water are very similar, their rates of transfer per unit driving force* (i.e. Mass Transfer Coefficients) are also very similar. Sherwood(3) has verified this experimentally, using a packed tower. It has been found, using packed towers(4) and bubble columns(25), that there is no difference in the rate of transfer of CO_2 when comparing its DEsorption from water with its ADsorption into water under identical conditions (but using opposite driving forces). Thus kinetic data obtained for ADsorption should be equally applicable to DEsorption by the same system; and the same value for the Mass Transfer Coefficient can be used in each case.

The mathematical expressions relating the performance of co-current and counter-current systems with the Mass Transfer Coefficient and residence time are given in Appendix A. The Mass Transfer Coefficient relates to the rate of transfer taking place per unit volume of the desorption unit per unit driving force. Its value is dependent on the interfacial surface area between the air and water per unit volume of aerator and on the flow conditions. A large Mass Transfer Coefficient is favoured

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* The driving force ($C-C_e$) is the difference between the actual concentration (C) of the gas in the water and the concentration (C_e) that would be present if the CO_2 or O_2 in the water were in equilibrium with that present in the surrounding air. (For example, for CO_2 at 10 °C: $C_e = 1.25\ C_{air}$ where C_{air} is the CO_2 concentration (mg/l) in the air next to the water.)

by a large interfacial surface area and flow conditions that promote a continual renewal of the water at the water/air interface. This is usually achieved either by bubbling air through the water (e.g. Inka system) or by allowing water to flow over a grid or packing surrounded by air (Packed Tower). Systems relying solely on spraying water into the air are able to attain a high value of the Mass Transfer Coefficient but are limited in performance by the air:water volume ratio and by the flowrates that can be used.

The expressions given in Appendix A take into account the effects both of kinetic factors and of the relative air:water volume flowrates on the systems' performance. Their applicability in practice depends on the accuracy of the figure taken for the Mass Transfer Coefficient. This figure is dependent both on the system used (e.g. bubble or packing sizes) and on the operating conditions (e.g. water and/or air flowrates). It is, therefore, a practically, rather than theoretically, determined figure.

2.3. BASIS FOR COMPARISON OF PERFORMANCES OBTAINED IN PRACTICE

In reviewing the different types of aeration systems, the performances obtained in practice will be compared; and wherever possible, the values to be expected for the Mass Transfer Coefficient will be given. This is of practical importance because the superficial residence time (T) required for a given percentage CO_2 removal to take place within the aerator is inversely proportional to the value of the Mass Transfer Coefficient (Appendix A). Thus the larger the Mass Transfer Coefficient, the smaller the aerator need be. This approach can only be applied to closed aeration systems where not only the water flowrate but also the air flowrate is measurable. For open air aeration systems (e.g. sprays, cascades) the air flow is difficult to estimate and varies with wind conditions. No reliable estimate of the Mass Transfer Coefficient can therefore be made under such conditions.

As an alternative to the Mass Transfer Coefficient (K_La), the height of a Liquid Transfer Unit $(HTU)_L$ can be used to compare column performances. $(HTU)_L$ is a particularly useful concept in cases where K_La is found to be directly proportional to the water flowrate. This is discussed more fully in Section 4.1, and the significance of $(HTU)_L$ together with its relation to K_La is fully explained in Appendix D.

Besides wind conditions, which may be expected to influence the performance of open air aerators, temperature will also have an effect on the performance of any aeration system (see Appendix B). As a first approximation it may be stated that to maintain the same percentage CO_2 removal after a 10 ^{o}C temperature drop, residence time will need to be increased by 25% and the air:water volume ratio by 40%. Unfortunately the temperature is not always stated when performance figures for CO_2 removal are given (e.g. Refs 13 and 18).

3. PERFORMANCE OF OPEN-AIR AERATORS

The most simply constructed aerators are generally those which are open to the atmosphere and rely on natural air currents for their air supply. A comparison of several different types of open-air aerators has been carried out by Donaldson(5), prior to adopting one of them for an 18 m.g.d. treatment plant. He measured their performance on a water containing 28 mg/l of free CO_2 over a wide range of flowrates. Approximately 50% CO_2 removal could be achieved by a perforated pan placed 5 ft above a collector tray. The same result was also obtained from a single 1 ft deep coke bed with a perforated base, and by free flow from a 5 ft high 2 inch diameter riser pipe. About 75% CO_2 removal was achieved by a stack of three perforated coke trays, with intervening air spaces, and also by spray nozzles.

Spray nozzles were not, however, chosen for the final design because of the ground area and pressure head required, and the possible risk of contamination from atmospheric dust etc. Stacks of four superimposed coke trays with intervening air spaces were chosen instead. The stacks would have a height of about 2 m and be operated at a loading of 90 m^3/m^2 h.

3.1. SPRAYS

Spray nozzles can be either upward-pointing or downward-pointing. There is a wide variety of each type(6). The upward-pointing types generally work at a pressure of up to 7 m head and are arranged to give a surface loading of 10 to 30 m^3/m^2 h(7). They provide a high surface area between the water and the air but a contact time of only about 2 seconds.

Performances of 70 to 80% CO_2 removal are attained using sprays at several municipal water plants in the USA.

The performance of spray nozzles was investigated at Bundaberg, Australia(8) where CO_2 removals of 50 and 75% were attained at 1.5 m and 3.0 m water pressures respectively. However, assuming a temperature of 30 °C at that location, the corresponding CO_2 removals at 10 °C would be unlikely to exceed 35 and 60%.

Measurements carried out between 5 °C and 15 °C to find the effect of temperature on sprays have shown(9) that a 5 °C temperature drop causes a relative fall in performance of 10%. An effect of similar magnitude was observed for cascades.

Of the downward-facing nozzles, the 'Dresden' impact-plate nozzle has received most attention(6,9-11), and been found to have low energy requirements and good performance. Between 70 and 75% CO_2 removal has been reported(6) as a result of practical experience of their use in Belgium. Tests carried out(10) with a single nozzle of this type, at water pressures of 0.35 to 0.6 m, have shown that performance was almost independent of the pressure at the nozzle, but that it was much affected by the distance of the collecting surface below the nozzle. With the collector 1 m below the nozzle, removals of 70 to 80% were obtained at 16 °C. The performance fell sharply when the distance was reduced below about 0.75 m.

It is probable that when an array of nozzles is used, the resulting reduction in the effective air:water volume ratio would lower this performance. Sixty per cent CO_2 removal was found(11) at 10 °C when using arrays giving a surface loading of 10 m^3/m^2 h with a 2 m fall below the nozzles. It has been claimed(9) that plant performances show variations of only ± 10% attributable to changes in atmospheric conditions.

3.2. CASCADES

The work of Donaldson(5), using a stack of superimposed coke trays with perforated bases and intervening air spaces, has already been mentioned. A stack of three 0.3 m deep coke trays separated vertically by 0.3 m air spaces, for instance, was found to give 75% CO_2 removal at surface loadings up to 240 m^3/m^2 h.

Another simple type of cascade consists(6,9) of several superimposed troughs, each having a ½ inch wide slit in the bottom through which the water falls into the trough below. A cascade of six such troughs occupying a total height of 3 m resulted(6) in a 60% CO_2 removal at a loading of 70 m^3/m^2 h, although a better performance has also been claimed(9).

Tests on a third type of cascade consisting of superimposed perforated plates(9) showed that 80% CO_2 removal was achieved after the seventh plate. Each plate had about 1200 7 mm diameter holes per m^2 and the vertical spacing was 0.33 m. A surface loading of 50 m^3/m^2 h was used for the test.

The performances achieved for each of the three types of cascade were obtained on a laboratory scale (about 0.25 m^2). On plant scale performances could well be lower if the horizontal flow of air becomes restricted.

Tests have been carried out on a larger scale(12) with fountain cascades. Water containing 46 mg/l of free CO_2 issuing from a 3 inch diameter riser pipe was allowed to cascade down over the edges of ½ inch deep circular trays of increasing diameter (0.7 to 2 m). Performance was found to improve slightly with throughput over the range 8 to 27 m^3/h (i.e. up to 0.15 m.g.d.). Seventy per cent CO_2 removal was achieved at a flow of 24.5 m^3/h using the following arrangements:

3 trays in a total vertical distance of 2.25 m
or 4 trays in a total vertical distance of 1.75 m
or 3 trays in a total vertical distance of 1.37 m using air injection.

In the latter case, air was injected at an air:water volume ratio of 1:2 into the feed pipe at ground level.

On a still larger scale, a 12 inch diameter riser was used with a flow of 560 m^3/h (3 m.g.d.) cascading down over five 1 inch deep trays from 1.5 to 6 m diameter within a vertical distance of 3.2 m. This arrangement also gave a CO_2 removal of 70%, rising to nearly 80% when air was injected into the riser through eight ½ inch nozzles at an air:water volume ratio of 1:2.

A stepped cascade operated at a flowrate of 60 to 80 m^3/h per m length was also investigated(12). Each step was 0.3 m high, 0.3 m wide and had a ½ inch sill. After seven steps, about 66% CO_2 removal was attained. This performance was raised to about 74% removal when air was injected into the 3 inch riser pipe feeding the cascade (at an air:water volume ratio of 1:1). Thus, the vertical drop required to achieve a given performance was very similar to that required for a fountain cascade with similar throughput. The surface loading rates would, however, be about 30 m^3/m^2 h for the stepped cascade and under about 10 m^3/m^2 h for the fountain cascades.

Plant cascades treating about 400 m^3/h (2 m.g.d.) at Witharen and Brucht in Holland have been described(13). They consisted of Dresden nozzle distributors spraying water at loading rates of up to 140 m^3/m^2 h on to two 0.5 m deep packs of PVC pipes. Each pack contained 10 layers of 25 mm PVC pipes laid horizontally with 33 mm gaps. Air was free to enter above the packs which had a 1 m vertical distance separating them. At Brucht CO_2 removals of 80 to 85% were obtained at a loading of 50 m^3/m^2 h, falling to 75 to 80% removal at 100 m^3/m^2 h.

4. PERFORMANCE OF ENCLOSED AERATORS

Enclosed aerators comprise aeration systems in which the air supply can be controlled and measured. Packed towers, air bubble or foam aerators and enclosed cascades fall into this category. Their advantage lies in the greater degree of control that can be exercised over their performance, and as a result of this much more detailed and accurate information is available on their performance and the factors affecting it than is the case for open air aerators.

For a desorption process, there can be no advantage to be gained by operating under pressure. Thus, although the air may have to be introduced into the aerator under some pressure to effect its proper distribution, the aerators themselves are always operated at atmospheric pressure.

4.1. PACKED TOWERS

The type of packing used affects both the Mass Transfer Coefficient ($K_L a$) and the maximum gas and water flowrates that can be used before a drop in transfer efficiency and, finally, flooding occurs. In general, packings that are coarse and open allow high flowrates but give low $K_L a$ values, and conversely, so that a compromise has to be found. In practice, a packing is chosen that allows a high surface loading rate (i.e. m^3/m^2 h of water) without resulting in a tower of unacceptable height.

In counter-current operation, for instance, it is found that as the liquid surface loading is increased, a point is reached where the pressure required to maintain the airflow starts to increase rapidly. This usually limits surface loading that can be used with 1 inch Raschig rings to under 50 m^3/m^2 h. Another type of column packing, originally proposed for biological wastewater treatment, consisting of wave pattern sheets hung vertically at 3 cm intervals, has been found$^{(2,14)}$ to allow the use of surface loadings up to 400 m^3/m^2 h.

For any given column packing, the value of $K_L a$ has been found to increase with the water flowrate$^{(3,14-16)}$; and further details of this are given in Appendix C. It is also to some extent dependent on the air flowrate$^{(16,17)}$, but this is usually ignored for design purposes. Where $K_L a$ has been found to be directly proportional to the water flowrate, as has been the case for both Raschig rings$^{(16)}$ and wave pattern sheet$^{(14)}$, it becomes possible to specify the height of column required to effect a given percentage CO_2 removal, without regard to the water flowrate. That is to say, the column height required is, within limits, independent of the water flowrate as explained in Appendix D.

For counter-current operation using air:water volume ratios greater than about 10:1 it can be shown that for 1 inch Raschig rings a column height of 0.7 m would be required to remove 63% of the CO_2 at 10 °C, whereas the corresponding height for wave pattern sheet was found to be 2 m. Doubling these heights would effect 86.5% CO_2 removal in each case (see Appendix D). Co-current operation would require higher air:water volume ratios and/or longer columns to achieve the same CO_2 removal. This is shown with an example in Appendix D and illustrated in Fig. 3.

The performance of some packing materials will now be considered in a little more detail.

4.1.1. Raschig rings

It could be expected that the K_La value would depend on the size of rings used. Sherwood(3) has given data relating K_La values to the sizes of both Raschig rings and Berl saddles. He found that whereas there was no appreciable difference between ½ inch and 2 inch saddles, ½ inch rings gave a K_La value 3.25 times greater than did 2 inch rings at the same water flowrate. However, Koch *et al.*(15) could find no appreciable difference between ⅜ and 1¼ inch rings.

4.1.2. PVC pipe grid

This type of aerator, extensively tested and used in Holland, comprises a tower in which water is sprayed through Dresden nozzles onto layers or stacks of PVC pipes. A co-current flow of air is provided by fans installed at the top.

A tower has been operated(18) containing 40 layers of 50 mm diameter pipes. In each layer the pipes were laid parallel to each other with a gap width of 60 mm between pipes. The pipes in each layer were laid at right angles to those in the layer above and the total height of the 40 layer stack was 2 m.

Using an air:water ratio of 20:1 and loading rate of 140 m^3/m^2 h, a CO_2 removal of 78% was attained.

The same performance was found(18) when only 4 or 5 *single* layers of 50 mm diameter pipe, with 25 mm gap width, evenly spaced down the length of the tower, were used. Further tests carried out using three single layers in the top part and one 10 layer stack at the bottom of the tower still gave the same result. Provided an air:water ratio of 20:1 was maintained, 78% CO_2 removal was obtained over a surface loading range of 120 to 260 m^3/m^2 h. Higher loadings were not tried. By reducing the loading from 100 to 30 m^3/m^2 h, the percentage CO_2 removal was increased to about 88%. The equilibrium (i.e. maximum obtainable) percentage CO_2 removal at the air:water ratio of 20:1 was calculated to be 93 (Fig. 3). Reduction of the ratio to 10:1 still resulted in a removal of at least 75% CO_2.

The derivation of the Mass Transfer Coefficient (K_La) and Transfer Unit Height $(HTU)_L$ from this performance data is given in Appendix E. From this it can be seen that the pipe grid tower has K_La and $(HTU)_L$ values intermediate between the Raschig ring and wave pattern sheet packings.

Some suggestions have been made(13) for improving the performance of the pipe grid tower. Counter-current operation was one. However, it was found that fans capable of supplying adequate air co-currently for loadings up to 250 m^3/m h, could not supply air at sufficient pressure for counter-current operation beyond loadings of about 50 m^3/m h through a 40 layer stack. This approach was not pursued further.

A second suggestion was partially tested. This was to vent the air halfway down the tower, and introduce a fresh supply of air to the water after it had passed an airlock and been resprayed into the bottom half of the tower. That is to say, one long tower was effectively converted into two short sections operated in series. In this manner, a CO_2 removal of 87% was achieved in a tower of total height 2.5 m, each section of which contained one 10 layer stack of 25 mm diameter pipes with 12.5 mm gap width and an inter-layer spacing of 25 mm. The air in the bottom section was drawn in by the fall of water without the aid of fans.

It was also shown(13) that spraying followed by free fall did not result in such effective CO_2 removal as spraying followed by a pipe grid. Test results indicated that a 10 layer pipe stack 500 mm deep gave the same CO_2 removal as 2 m free fall.

A comparison of the performances of four Dutch pipe grid tower installations has been made(13) showing that, whereas in two instances (Engelse and Denekamp) CO_2 removal performance became independent of surface loading above 120 m^3/m^2 h; in other cases (Brucht and Manderveen) this was not so. The reasons for this difference were not found, but it is not clear whether the necessary air:water ratio was maintained at the higher loadings in the latter cases. Failure to maintain it could account for the observed decrease in CO_2 removal performance throughout the loading rate range of 50 to 250 m^3/m^2 h.

The Brucht installation, consisting of two 10 layer pipe stacks, was originally operated as an open cascade with free access of air to each stack. Problems with algal growth necessitated enclosure and the installation of fans. The performance of the open and enclosed cascade was compared(13). At a loading of 100 m^3/m^2 h, for instance, 75 to 80% CO_2 removal was achieved when open. This increased to 85% removal after enclosure. At another site, Witharen, removal efficiencies of 65 to 70% without a fan were increased to 75 to 80% by using a fan, in the loading range 50 to 150 m^3/m^2 h.

4.1.3. Wave pattern sheet

The counter-current operation of this system has already been discussed (see Section 4.1). On a small-scale experimental unit using only two sheets 3.75 m high(14), CO_2 removals of 80 to 85% were achieved at 10 °C using loading rates from 100 to 400 m^3/m^2 h. The figures for the Mass Transfer Coefficent (K_La) and Transfer Unit Height $(HTU)_L$ in Appendices C and D were derived from these results.

The co-current operation was also investigated(14) at 10 °C *without* the use of fans or blowers. The ratio of the entrained air:water volume decreased with increasing loading rate from 24 at 160 m^3/m^2 h to 8 at 700 m^3/m^2 h. As a result the CO_2 removal performance decreased from 81% to 73%. The value of $(HTU)_L$ for this mode of operation was about 1.85 m - slightly less than for counter-current operation.

These performances were reproduced to within 5% on a larger scale using a 14 sheet unit of 0.2 m^2 cross-section for loadings up to 400 m^3/m^2 h (0.4 m.g.d.).

The co-current operation of a two-stage 0.15 m^2 co-current operated unit has also been described(19). No fans were used and fresh air was entrained at the top of each 2 m high section and vented at the end of each. The overall CO_2 removal at 12 °C from water containing 30 mg/l ranged from over 90% at a loading of 100 m^3/m^2 h to 82% at a loading of 600 m^3/m^2 h. At the higher loading, the throughput was 90 m^3/m^2 h (0.5 m.g.d.). The small cross-section area of the unit was somewhat offset by the overall height of almost 8 m. However, just one section would have been adequate for most purposes: for instance, 75% removal was achieved by one section at 400 m^3/m^2 h loading.

5. AIR BUBBLE AND FOAM AERATORS

Two approaches have been taken in applying bubble aeration: the first involves the production of small air bubbles (4 mm diameter or less), using relatively low air:water ratios (<10:1); while the second employs a foam of larger air bubbles, requiring air:water ratios of between 40:1 and 200:1.

The first method can be carried out in two ways: either the air is forced under pressure (150 g/cm^2) through a fine porous frit(20) on which the bubbles tend to grow in size before becoming detached, or the air is injected through orifices in a rotating vane or shaft which disperses the bubbles before they grow too large. Mechanical rotation is used in the Vogelbusch-Dispergator(20) and the Pista aerator(6). Both devices also impart a swirling motion to the water which increases the time taken by the air bubbles to escape. This has been found(20) to result in better performance than aeration through a porous frit. The second method, relying on the production of a foam, is used in the Inka aerator(9,21,22), which although requiring large air volumes, operates at a relatively low air pressure (10-15 g/cm^2).

Schäfer(20) has found the influence of temperature on bubble aeration to be greater than was reported for packed towers(3) (see Appendix B) or for spraying(9). At 20 °C, CO_2 removal by a Vogelbusch-Dispergator proceeded 1.64 times faster than at 10 °C; and data presented(22) for the performance of an Inka aerator between 8 °C and 18 °C indicate a very similar temperature effect. Schulman however, has found(25) a very similar temperature effect for bubble aeration to that reported for packed towers (Appendix B(b)). This, however, only applied for air flowrates below about 150 m/h, when air flow through the water was streamlined. At higher flowrates where the flow became turbulent he found the rate of CO_2 desorption actually *decreased* with increasing temperature.

Considering each bubble aeration system in more detail: tests carried out in a 0.1 m^3 container with 0.54 m depth of water have shown(20) that with an air flow of 0.2 m^3 per minute, 75% CO_2 removal was achieved in 6 minutes at 20 °C. Increasing the air flow to 0.67 m^3/min reduced the required aeration time to 2 minutes. The corresponding aeration times were 4 minutes and 1.5 minutes respectively, when a Vogelbusch-Dispergator rotating at 600 rev/min was used instead of a porous frit. When a continuous flow of water was applied, the performance of the two aeration systems became very similar. With an air:water volume ratio of 4:1, a 6 minute residence time gave about 75% CO_2 removal in each case.

Schulman and Molstad(25) have studied bubble aeration in sufficient detail to enable the performance of a plant scale unit to be estimated although the CO_2 concentrations they worked with were much higher than those found in natural waters. They used columns up to 4 inches diameter in which the water flowed downwards while the air was introduced through a porous plate at the bottom. They showed that no advantage was to be gained from the use of fine porosity plates and recommended the use of a coarse grade to reduce the air pressure drop across the plate. In practical application, where the head of water in the column would be several feet, the pressure drop across the plate would then be a small fraction of the total air pressure required.

They found that the behaviour of the aeration columns differed according to whether the air flow through the water was streamlined or turbulent and that $(HTU)_L$ depended on both the air and water flowrates. $(HTU)_L$ increased linearly with water flowrate from around 0.3 m at 50 m/h (at 15 °C) to around 0.75 m at 200 m/h, the precise values depending on the air flowrate. Since the flow conditions resulted in some vertical mixing taking place, $(HTU)_L$ was found to be dependent on column height. The $(HTU)_L$ values just quoted for a 0.6 m high column increased by about 25% when a 1.2 m high column was used.

It may be concluded that a bubble column exhibited an $(HTU)_L$ of about half that of a Raschig ring column at low (50 m/h) water flowrates. At high water flowrates (say, 100 to 200 m/h), the $(HTU)_L$ of a bubble column rose, but still remained about half that of a PVC pipe grid or about a third that of a wave pattern sheet column (see Appendices D and E). A bubble column would, however, consume more energy on account of the higher air pressure required to operate it.

The performance of Vogelbusch-Dispergators used on plant scale have been reported(23). Two cases were cited where about 80% CO_2 removal was achieved with residence times of 3 and 4.5 minutes, using air:water ratios of 3:1 and 4.5:1. The submerged depth of the rotating injectors was 1.5 m and the surface loadings applied were between 20 and 30 m^3/m^2 h. A degree of counter-current effect can be obtained by arranging for the water to enter at the top of the aerator tank and leave at the base.

The Inka aeration system uses much larger air:water volume ratios, as already mentioned. The air is introduced through a perforated plate (with 2 mm diameter holes) into the water stream flowing horizontally across its surface. A foam layer up to 0.3 m high is produced which provides a short period of intensive aeration. Tests carried out at Tolkewitz waterworks(9), using a small 0.2 m^2 Inka aeration unit, have shown CO_2 removals of between 75 and 85% at 10 °C. The corresponding surface loadings ranged from 70 to 10 m^3/m^2 h; and since the air flowrate remained constant throughout, the air:water volume ratio varied between 30 and 200. Another series of tests carried out with a larger 1.14 m^2 unit(21), to determine the influence of the foam layer height on CO_2 removal, also gave CO_2 removals of between 75 and 85% (at 7 °C). In these tests, however, the surface loadings were between 17.5 and 26 m^3/m^2 h in each case, and the respective air:water volume ratios were 25 and 34. Similar results have again been obtained with this unit(22) using air:water ratios of between 40 and 80 and with similar surface loadings.

6. ENERGY CONSUMPTION

The relative efficiencies of the various aeration systems can be expressed in terms of the number of watt-hours of electrical energy consumed per m^3 of water treated. The electrical energy is used in pumping the water and in providing a forced-draught of air where necessary. All the aeration systems described work at, or near, atmospheric pressure and necessitate breaking head. In considering the energy required to pump the water, any penalty incurred by breaking head will be ignored, and only the energy required to run the aeration system itself will be taken into account.

A pump of average efficiency will consume 5 watt-hours per m^3 of water treated per metre of head required. Most of the column and cascade processes will achieve 70 to 80% CO_2 removal within a height of 3 metres. Thus 15 to 20 watt-hours per m^3 would suffice for them in most cases. Only those methods using counter-current operation would require a significant additional expenditure of energy for air blowers.

A Raschig ring column, for instance, requires only about an additional 5 watt-hours per m^3 for the counter-current air flow(2). A 3.75 m high column with wave pattern sheet packing operated at a surface loading of 250 to 300 m^3/m^2 h would still require slightly less energy for the counter-current air flow than for pumping the water(14), thus consuming a total energy of about 30 to 40 watt-hours per m^3 treated. At the other extreme, the Inka aerator operates with almost negligible head of water but requires a considerable forced air flow. Energy consumptions of 18 to 36 watt-hours per m^3 treated have been found(9), using air:water volume ratios of 35:1 to 70:1.

The aerator having the highest energy requirement is the Vogelbusch-Dispergator(23), with a consumption of about 50 watt-hours per m^3; most of this is used for mechanical rotation of the air distributor which sweeps round the 1.5 to 2 m diameter circular base of the aeration tank.

An expression enabling the air blower energy consumption per m^3 of water treated to be calculated is given in Appendix F. The only initial data required are the air pressure and the air:water volume ratio being used.

From a cost point of view, energy consumption is unlikely to be the most important factor in deciding which type of aerator to install. The depreciation on capital cost, when calculated at rates of about 10 per cent per annum, is certain to exceed the operating costs in every case.

Comparisons of the energy consumptions of aeration systems in relation to their performance are given in a number of the references already mentioned. Table 1 lists the references together with the types of aeration system compared in each case:

Table 1. References containing comparisons of performance and energy consumption

System	Ref: 2	9	11	22	24
Pressure sprays	✓	✓		✓	(✓)
Dresden sprays		✓	✓		✓
Open cascades				✓	
Perforated plate cascade		✓	✓		
PVC pipe grid	✓		✓	(✓)	(✓)
Raschig ring column	✓				✓
Wave pattern sheet column	✓				✓
Inka aerator		✓	✓	(✓)	(✓)
Vogelbusch-Dispergator	✓				✓
Chemical methods			✓	✓	✓
Costs (Continental currency)		✓	✓	✓	✓

Reference 24 is a review paper, deriving its data from the other references mentioned previously. It compares aerator efficiencies in terms of K_La value per unit energy consumption. This concept is difficult to relate to performance in practice, particularly for systems such as spraying or the Inka aerator, where the meaning of K_La value is doubtful. Hence allusions to these systems under Reference 24 in Table 1 are bracketed. Allusions to the PVC pipe grid in References 22 and 24 are also bracketed because the energy consumption was unnecessarily high due to the use of high pressure spray nozzles instead of Dresden impact plate nozzles for the inlet distributor; the PVC pipe grid can, in fact, be one of the most efficient aerator systems(2,9). For some reason, also, the Inka aerator tested in Reference 22 had almost twice the energy consumption of others(9,11). Hence it is clear that performance, energy consumption and cost comparisons can only be useful after critical evaluation of the data.

7. CAPITAL COSTS

The capital costs of several aeration systems have been compared in relation to throughput(11). In most cases the capital cost per m^3 throughput became independent of throughput for plants capable of treating 300 m^3/h (1.5 m.g.d.) and above. The least costly plant of those compared (see Table 1, Ref. 11) was the PVC pipe grid column. It is probable that the wave pattern sheet column would have a similarly low cost since both these types of aerator are capable of high surface loading rates. They also have very light packings which enable the construction costs of the columns to be lower than would have been the case for a Raschig ring column(2).

The information available on capital costs is, however, too incomplete to allow a comprehensive cost comparison of all the aeration systems described in this report to be made.

All the capital costs contained in the quoted references are given in Continental currencies; and where they were used to calculate total aeration treatment cost(9,11), the depreciation rates used were well below those currently applicable in this country.

Further work to determine capital costs would be well justified since they are likely to be the major item in the overall cost of an aeration system.

8. COMPARATIVE SUMMARY OF AERATION METHODS

An overall comparison of the performance and relative costs of different aeration methods, which will prove useful in deciding which to choose in a given practical instance, is difficult to make. As Table 2 shows, almost all aeration methods can achieve at least 75% CO_2 removal. Mechanical aeration can be supplemented by alkali dosing when over 80% CO_2 removal is required, or where accurate control of the final pH and CO_2 content is necessary. Thus, the system finally chosen for CO_2 removal might involve a combination of mechanical aeration and chemical dosing. However, in compiling this survey of aeration methods several conclusions do emerge which could reduce the number of alternatives to be considered in a given case. Table 2 summarises the performances of most of the aeration systems reviewed. They differ mainly in the surface loading rates that can be used.

Table 2. Performance of aeration systems for CO_2 removal

System	Co-current (CO) Counter-current (CTR)	Surface loading (m^3/m^2 h)	Head required (m)	CO_2 removal (%)
Sprays		10 - 30	2 - 7	60 - 70
Fountain Step } cascades		10 - 30	2 - 3	Up to 75
Open PVC pipe grid cascade	CO	50 - 100	2 - 3	Up to 80
Forced draught PVC pipe grid column	CO	50 - 250	2 - 3	Up to 80
Raschig ring column	CTR	25 - 50	2 - 3	85+
Bubble aerator*	CTR	50 - 200	1 - 2	75 - 85
Wave pattern PVC sheet	CO, CTR	100 - 400	3 - 4	75 - 85
Inka aerator		10 - 70	-	75 - 85
Vogelbusch-Dispergator		20 - 30	1.5 - 2	Up to 80

NB. Higher columns will give greater CO_2 removals, particularly if:

a) operated with counter-current air draught

or b) composed of separate co-current sections operated in series

* Estimated performance from data in Reference 25

Considering the main aeration methods: systems relying solely on sprays tend to remove only moderate amounts of CO_2 (60 to 70%) and only allow low surface loadings to be used. Simple open air stepped or fountain cascades can remove about 70% of the CO_2 and also have rather low surface loading rates (up to 30 m^3/m^2 h). Such systems might, however, be justified where no better performance is required and where capital costs could be shown to be low.

Packed trays or columns enable greater CO_2 removal to be achieved at higher surface loadings. The packings that allow the highest surface loading rates and permit the lowest column construction costs are made of light materials having an open structure (e.g. PVC pipes or wave pattern sheet). Any rigid packing material that will operate at high liquid flowrates without flooding (e.g. as designed for aerobic biological treatment processes) would merit consideration for use in an aeration column.

To achieve above 80 to 85% CO_2 removal, a counter-current forced draught packed column is usually required. Any desired degree of CO_2 removal up to 98% can then be obtained by using a sufficiently high column (e.g. 2.8 m Raschig ring column in Fig. 3). Bubble aeration can also give good CO_2 removal performance (see Table 2) provided the water flow is counter-current to the air flow. This may not be easy to achieve merely by installing air diffusers on existing plant. Otherwise experience suggests(13,19) that co-current operation can achieve the desired result. Forced draught may then not be necessary if the hydraulic conditions are such that an adequate volume of air is entrained with the down-flowing water. To improve the co-current CO_2 removal performance, the column can be divided into two sections in series, each having its own air inlet and exhaust.

Where the degree of CO_2 removal requires to be closely controlled, there is a choice between removing the last part of the CO_2 by alkali addition, and carrying out the whole process by an aeration system whose air flow can be regulated. The effect of temperature on aeration performance must always be taken into account, as well as that of possible fluctuations in the CO_2 content of the supply water.

APPENDIX A – EXPRESSIONS FOR THE EFFECT OF RESIDENCE TIME AND MASS TRANSFER COEFFICIENT (K_La) ON CO_2 REMOVAL

a) For co-current systems
b) For counter-current systems
c) For cross-current systems
d) For sprays and cascades.

Expressions relating residence time (T) to:

The Mass Transfer Coefficient	(K_La)
The Water:Air volume flow ratio	(R)
The initial CO_2 concentration	(C_1)
The final CO_2 concentration	(C_2)

The initial assumption will be that the equilibrium and operating lines for the process are linear and therefore that the following relationship holds:

$$\text{Overall } CO_2 \text{ Transfer Rate} = K_La \left[\frac{(C_1 - C_1^e) - (C_2 - C_2^e)}{\ln\left(\frac{C_1 - C_1^e}{C_2 - C_2^e}\right)} \right] V$$

where:	V	is the total volume of the aerator
	C_1^e	is the concentration of CO_2 in the water at the *inlet* which would be in equilibrium with the CO_2 in the air at that point
	C_2^e	is the concentration of CO_2 in the water at the *outlet* which would be in equilibrium with the CO_2 in the air at that point.

If this is now applied to CO_2 desorption at 10 °C for which the partition coefficient, $\frac{\text{mg/l } CO_2 \text{ in water}}{\text{mg/l } CO_2 \text{ in air}}$ is 1.25, we get:

a) For co-current or batch-mixed systems ($C_1^e \approx 0$):

$$\frac{C_2 - 1.25\, R(C_1 - C_2)}{C_1} = \left[\exp \quad - K_La\ (1 + 1.25R)\ T \right]$$

Another useful form of this expression is:

$$\frac{C_2 - C_2^e}{C_1 - C_2^e} = \exp\left[- K_La\ (1 + 1.25R)\ T \right]$$

where C_2^e, the equilibrium concentration of CO_2 in the water at $T = \infty$, is given by:

$$C_2^e = \frac{1.25\ RC_1}{1 + 1.25R}$$

as plotted in Fig. 3.

b) For counter-current systems ($C_2^e \approx 0$):

$$\frac{C_2}{C_1 - 1.25R(C_1 - C_2)} = \exp\left[- K_L a\ (1 - 1.25R)\ T\right]$$

In circumstances where $C_1 \gg C_2$, this simplifies to:

$$\frac{C_2}{C_1} = (1-1.25R)\ \exp\left[- K_L a\ (1-1.25R)\ T\right]$$

and if $R \ll 1$, it becomes:

$$\frac{C_2}{C_1} = \exp\left[- K_L a.T\right] .$$

c) For cross-current systems where the water flows horizontally across a perforated plate through which air is blown upwards:

Assuming complete mixing of the aqueous phase in the vertical direction and plug flow in the horizontal direction:

$$\frac{C_2}{C_1} = \exp\left[\frac{1}{1.25R}\left(\frac{1 - \alpha}{\alpha}\right)\right]$$

where $\alpha = \exp\left[K_L a\ 1.25R\ T\right]$

when $R \ll 1$, this also becomes:

$$\frac{C_2}{C_1} = \exp\left[- K_L a.T\right] .$$

d) Spray and cascade systems open to the atmosphere:

No strictly applicable mathematical model can be used, because the effective air:water volume ratio cannot be determined in practice. However, an expression, similar to that given above for co-current systems, has been derived$^{(26)}$ and can be used as a basis for interpreting results:

$$\log \frac{C_2 - C^e}{C_1 - C^e} = -K\left(\frac{A}{V}\right) t$$

where k is a transfer constant dependent on temperature,
$(\frac{A}{V})$ is the air/water interfacial surface area, per unit volume of water,
t is the contact time.

APPENDIX B – EFFECT OF TEMPERATURE ON CO_2 REMOVAL

Temperature affects both the partition coefficent of CO_2 between water and air and the value of the Mass Transfer Coefficient:

a) Temperature effect on Partition Coefficient: $\left(= \dfrac{CO_2 \text{ conc. in water } (mg/l)}{CO_2 \text{ conc. in air } (mg/l)} \right)$

Temp. °C:	0	5	10	15	20	25	30
Partitn Coeff:	1.79	1.49	1.25	1.06	0.91	0.80	0.70

The effect of a change in Partition Coefficient on aerator performance may be found by inserting the appropriate value from Table B1 in place of the figure 1.25 in the expressions given in Appendix A (which apply at 10 °C).

Where equilibrium between the air and water is closely approached, any increase in the Partition Coefficient, due to falling temperature, must be compensated for by a corresponding increase in the air:water ratio if the same percentage CO_2 removal is to be maintained.

b) Temperature effect on Mass Transfer Coefficient (K_La).

According to Sherwood and Holloway$^{(3)}$ from work done using packed towers:

$$K_La \propto \exp\left[.023\ t\right] \quad \text{where t denotes } ^{\circ}C$$

Thus:

$t\ ^{\circ}C$:	0	5	10	15	20	25
$\dfrac{K_La \text{ at } t\ ^{\circ}C}{K_La \text{ at } 0\ ^{\circ}C}$:	1	1.12	1.26	1.41	1.58	1.78

Lowering the temperature reduces the rate of CO_2 desorption and increases the time needed for equilibrium to be approached. The effect of changes in K_La on aerator performance may be deduced from the expressions given in Appendix A.

Where high air:water volume ratios are used, (>20:1 say), the residence time must be increased in inverse proportion to the value of K_La, as temperature falls, to achieve the same percentage CO_2 removal.

APPENDIX C – DEPENDENCY OF MASS TRANSFER COEFFICIENT K_La (h^{-1}) ON WATER FLOWRATE (L)

a) In packed towers containing 1 inch Raschig rings:

Ref. 3: $K_La = 0.092\ L^{0.78}$ at 25 °C for 1 inch rings.
($= 0.080\ L^{0.78}$ at 20 °C)
Ref. 15: $K_La = 0.0156\ L^{0.96}$ at 20 °C for ½ to 1¼ inch rings.
Ref. 16: $K_La = 0.0085\ L$ at 15 - 20 °C for 1 to 1½ inch rings.

In each case, L was measured in units of $lbs/ft^2\ h$. Converting L into units of $m^3/m^2\ h$ ($1\ m^3/m^2\ h = 205\ lbs/ft^2\ h$) we get:

Ref 3: $K_La = 5.85\ L^{0.78}$ at 25 °C
($= 5.09\ L^{0.78}$ at 20 °C)
Ref. 15: $K_La = 2.22\ L$ at 20 °C
Ref. 16: $K_La = 1.74\ L$ at 15 - 20 °C

b) In columns containing wave pattern sheets: (derived from data presented in Ref. 14)

$K_La = 0.5\ L$ at 10 °C (L: $m^3/m^2\ h$).

c) In columns containing PVC pipe grids: (derived from data presented in Ref. 18 - See Appendix E)

$K_La = 0.76\ L$ (L: $m^3/m^2\ h$).

APPENDIX D – THE SIGNIFICANCE OF LIQUID TRANSFER UNIT HEIGHT $(HTU)_L$ AND ITS RELATION TO K_La

The height of a Liquid Transfer Unit $(HTU)_L$ for a given packing and liquid flowrate (L) is given by:

$$(HTU)_L = \frac{L}{K_La}$$

where $(HTU)_L$: m
L : m^3/m^2 h
K_La : h

Examples: i) 1 inch Raschig rings:

Taking $K_La = 1.74\ L$ (see Appendix C)

$$(HTU)_L = \frac{L}{1.74\ L} = 0.575 \text{ m at } 20\ ^{\circ}C$$
$$(= 0.7 \text{ m at } 10\ ^{\circ}C)$$

ii) Wave pattern sheets:

Taking $K_La = 0.5\ L$

$$(HTU)_L = \frac{L}{0.5\ L} = 2.0 \text{ m at } 10\ ^{\circ}C.$$

Note that where K_La is proportional to L, $(HTU)_L$ must be independent of L.

The practical significance of $(HTU)_L$ is found as follows:

$$(HTU)_L = \frac{L}{K_La} = \frac{H}{T.K_La}$$

where H : Column height
T : Superficial residence time of water

Hence if a column of height $(HTU)_L$ is set up, we find:

$H = (HTU)_L$ and hence $K_La.T = 1$

Thus from Appendix A we get:

a) For co-current operation:

when $H = (HTU)_L$

$$\frac{C_2 - C_2^e}{C_1 - C_2^e} = -1$$

for $R \ll 1$, (i.e. for air:water volume ratios greater than 10, say)

$$\frac{C_2 - C_2^e}{C_1 - C_2^e} = 0.37$$

Thus 63% of the CO_2, that would have been removed had equilibrium been reached, is in fact removed within a distance equal to $(HTU)_L$.

Example:

For an air:water ratio of 10:1 at 10 °C, the CO_2 removal at equilibrium (i.e. by an infinitely long column) is 88% of the initial concentration (see Fig. 3).

In a column of length $(HTU)_L$, the overall CO_2 removal will be:

$$0.63 \times 88 = 55.5\% \text{ of the initial } CO_2.$$

In a column of length $2(HTU)_L$, overall CO_2 removal will be:

$$\left[0.63 + (0.63 \times 0.37)\right] 88 = 0.863 \times 88$$

$$= 75.9\% \text{ of the initial } CO_2$$

b) For counter-current operation:
when $H = (HTU)_L$,

$$\ln \frac{C_2}{C_1} = -1$$

for $R \ll 1$ (i.e. for air:water volume ratios greater than 10, say)

$$\frac{C_2}{C_1} = 0.37$$

Thus 63% of the initial CO_2 will be removed in a column length equal to $(HTU)_L$.

In a column length of 2 $(HTU)_L$, the overall CO_2 removal will be:

$$63 + (0.63 \times 37)$$

$$= 86.3\%.$$

The effect of column height on counter-current performance is also shown in Fig. 3. In the case calculated for a wave pattern sheet column of height 3.75 m (= 1.87 $(HTU)_L$), the CO_2 removal approaches 85% at high air:water ratios. If the column height is increased to 4 $(HTU)_L$, as with the Raschig ring column, the CO_2 removal performance approaches 98%.

APPENDIX E – DERIVATION OF K_La AND $(HTU)_L$ FROM PERFORMANCE DATA

Derivation of K_La and $(HTU)_L$ for PVC pipe grid tower for the surface loading range 100 to 260 m^3/m^2 h:

Taking the case where the air:water ratio is 20:1
the equilibrium CO_2 removal is 93%
the actual CO_2 removal is 78%
the tower height is 2.25 m.

Using the co-current expression from Appendix A:

$$\frac{C_2 - C_2^e}{C_1 - C_2^e} = \exp\left[-K_La\ (1 + 1.25R)T\right]$$

$$\ln\left(\frac{100 - 7}{22 - 7}\right) = K_La\ .\ 1.0625\ T$$

Now: $T = \frac{H}{L}$ where T : residence time (h)
H : height of tower (m)
L : loading rate (m/h)

$$\therefore K_La = \frac{L}{2.25 \times 1.0625} \ln\left(\frac{93}{15}\right)$$

$$= 0.76\ L\ h^{-1}$$

Thus $$(HTU)_L = \frac{L}{K_La} = 1.3\ m$$

APPENDIX F – ENERGY CONSUMPTION FOR FORCED AIR FLOW

Energy consumption for forced air flow:

Assuming 100% blower efficiency:

$$E = 0.027 . \frac{\text{air vol}}{\text{water vol}} . p \quad \text{watt-hours per } m^3 \text{ of water treated}$$

where p is the air pressure in cm of water head.

In practice, with a blower efficiency of 50 to 60%, we could take:

$$E = 0.05 . \frac{\text{air vol}}{\text{water vol}} . p$$

Example:

Using a porous frit, 75% CO_2 removal can be obtained(20) with an air:water volume ratio of 4, for which an air pressure of 0.14 kg/cm^2 is required.

$$E = 0.05 . 4 . 140 = 28 \text{ watt-hours per } m^3.$$

APPENDIX G – LIST OF EQUIPMENT SUPPLIERS

The following list gives some equipment manufacturers or suppliers. It is not comprehensive and does not imply any particular recommendation of the companies or their products. It should be remembered that even the simplest devices, e.g. PVC pipe grids, can give good CO_2 removal when suitably mounted and installed.

SPRAYS:

Delavan-Watson Ltd.,
Gorsey Lane, Widnes,
Cheshire. (051-424 6821)

Spraytec Engineering Ltd.,
Matilda St., Sheffield.
(0742 25163)

CERAMIC GAS DIFFUSERS:

Doulton Industrial Products Ltd.,
Filbeybrooks, Stone, Staffs.
(078-583 3241)

Naylor Bros. Ltd.,
Denby Dale, Nr. Huddersfield,
Yorks. (0226 790591)

BUBBLE CAPS AND SIEVE TRAYS:

ETA Process and Effluent Plant Ltd.,
The Levels, Brereton, Rugeley,
Staffs. (08894 6524)

A.J.G. Waters Ltd.,
8-28, Milton Ave., Croydon,
Surrey. (01-689 5521)

METAL OR PLASTIC MESH:

Knitmesh Ltd.,
Knitmesh House, Standerstead,
South Croydon, Surrey.
(01-657 0921)

Expamet Industrial Products Ltd.,
1, Butler Place, London, SW1H OPS.
(01-222 7766)

Netlon Ltd.,
Kelly St., Mill Hill,
Blackburn. (0254 62431)

RANDOM COLUMN PACKINGS (Rings, Saddles, etc.):

Norton Chemical Process Products Ltd.,
King St., Fenton, Stoke-on-Trent.
(0782 45561)

Matthews Engineering Ltd.,
Sycamore Trading Estate,
Squires Gate Lane, Blackpool.
(0253 42095)

(See also manufacturers listed under 'Bubble Caps and Sieve Trays'.)

REGULAR COLUMN PACKINGS:

Flocor E (3D Plastic 'Honeycomb')

ICI Pollution Control Systems,
P.O. Box 15, Hyde, Cheshire.
(061-368 4000)

Cloisonyle (Stacked tubes)

Air Products Ltd.,
Coombe House, St. Georges Sq.,
New Malden, Surrey. (01-942 2424)

Satec Ltd.,
P.O. Box 12, Weston Rd.,
Crewe. (0270 583111)

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