# Aerated biological filtration for the removal of ammonia and manganese in a major new water treatment works under construction in Hong Kong

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**Abstract** Construction is currently under way in Hong Kong of a US$ 575 million water treatment and transfer scheme including the first 250 Ml/d stage of a new water treatment works at Tai Po, with an ultimate capacity of 1,200 Ml/d. The design incorporates primary aerated biological filters for ammonia and manganese removal as a key element of the treatment strategy.

Pilot filter work was carried out for a period of over twelve months covering seasonal variations. The work included investigations into "start up" times; ammonia removal efficiency at different filtration rates; effects of flow changes; ammonia peaks and temperatures; aeration and chemical dosing requirements; recovery after a "kill" and operation in both downflow and upflow modes. The pilot filters demonstrated the process to be effective and robust and provided design parameters for the sizing of the process units and for the provision of chemical dosing and aeration equipment.

The paper sets the context to the scheme, describes the pilot filter work and the results, discusses the reaction kinetics and shows how the design parameters obtained from the pilot filter work were used in the development of the engineering design of the treatment works.

**Keywords** Ammonia removal; bio-filters; manganese removal; nitrification; reaction kinetics

## Introduction

Hong Kong has a population of 6.6 million with a current water demand of about 2,500 million litres per day; 99.8% of the population are provided with potable water by the Water Supplies Department of the Government of the Hong Kong Special Administrative Region. There is a highly developed and innovative system of catchwaters, tunnels and reservoirs to make maximum use of the rainfall over the limited land area but since the 1960s an increasing amount of water has been taken from the Dongjiang (East River) in Guangdong Province north of Hong Kong. This source now supplies 80% of the demand. In order to meet forecast increases in demand for potable water, construction is currently under way of the US$ 575 million Stage I of the 1,200 Ml/d Tai Po water treatment and transfer scheme. This first stage includes the 250 Ml/d tranche of a new water treatment works at Tai Po. The treatment works design incorporates primary aerated biological filters as a key element of the process strategy.

## Raw water characteristics

Dongjiang raw water is a soft, aggressive water, generally low in dissolved solids. Average values for pH are close to neutral at 7.2. Turbidity showed a maximum reading of 38 NTU with an average value for the period 1989–1994 of 11.3 NTU. A maximum of 80° Hazen (true colour) was reported with an average value of 21° Hazen (1989–1994). Water temperatures range from 12 to 34°C with a mean of 24°C. Since 1992, the water from Guangdong has shown increases in ammonia, manganese and oxygen absorbed values and decreases in dissolved oxygen levels.

Peak levels of ammonia in the raw water have exceeded 3 mg/l. To date satisfactory

treatment of the ammonia has been able to be achieved by break point chlorination. However with a chlorine demand of approximately 10 mg/l per mg/l of ammonia the quantity of chlorine to be handled and stored is considerable. For a 1,200 Ml/d treatment works the peak chlorine demand would equate to over 35 tonnes/day. The corresponding quantities of chlorine to be transported, stored and handled would result in the assessed risks being above acceptable levels for a site close to a densely populated area. Such dose levels also carry the potential for formation of undesirable disinfection by-products. Following a review of options for the removal of ammonia, Binnie Black & Veatch proposed the use of aerated biological filtration.

## Pilot filter trials

Biological nitrification of ammonia is not new to potable water treatment although it has not been in widespread use. Previous experience has generally been in Europe and under different conditions to those experienced in Hong Kong. In order to gain sufficient confidence to adopt the process as a key treatment element on a scheme the size of Tai Po it was necessary to demonstrate the process and to determine fundamental design parameters under local conditions. The Water Supplies Department, Hong Kong agreed to a programme of pilot filter work which was carried out by Binnie Black & Veatch at an existing water treatment works in Hong Kong, fed from the same raw water source as the proposed new works.

## Description of pilot filtration system

The pilot plant comprised three perspex columns with the following characteristics.

### Column No. 1

4.0 m × 0.25 m dia Perspex column for the biological removal of ammonia (and soluble manganese) through a deep-bed coarse media (initially 1.5 m but later increased to 2.0 m depth) of 2.75 mm effective size proprietary media. Dosing with alkali (sodium carbonate); phosphorus (sodium dihydrogen phosphate); air (injection at base of column).

### Column No. 2

3.5 m × 0.15 m dia Perspex column for the biological removal of ammonia (and soluble manganese) through a deep-bed uniformly graded sand media (1.0m depth of 0.8 to 0.9 mm effective size sand). Dosing with alkali (sodium carbonate); phosphorus (sodium dihydrogen phosphate); potassium permanganate; air (injection at base of column).

### Column No. 3

3.5 m × 0.15 m dia Perspex column for the removal of soluble manganese using a catalytic manganese dioxide ore (150 mm depth) mixed with coarse sand filter media (0.8 to 0.9 mm effective size) to a total depth of 1.0m. Dosing with alkali (sodium carbonate); potassium permanganate.

The principal features of the filter columns were:
  (i) individual flow control and in-line flow metering;
 (ii) water backwash facility;
(iii) chemical dosing (see above);
(iv) manometer board and tappings monitoring loss of head at 5 points per filter;
 (v) flexibility for Column No. 2 to be operated in downflow or upflow modes;
(vi) Column No. 3 operated in series or in parallel with Column No. 1.

## Programme of testing

The pilot filtration tests were carried out for 18 months within the period between March 1995 to September 1996. Flows on to the filters were generally started at 5 m/h and increased to 10 m/h once nitrification was established. Thereafter flow rates were varied with test conditions but were generally maintained within the range 10 to 15 m/h in downflow mode. When Column No. 2 was operated in upflow mode the rate of flow was increased from an initial rate of 15.5 m/h up to a maximum of about 30 m/h. Upflow was tested for 4 weeks.

## Raw water quality during the tests

During the period of pilot plant operation ammonia concentrations in the raw water ranged from 0.02 to 2.13 mg/l as N and averaged 0.75 mg/l. Soluble manganese concentrations varied from 0.001 to 0.36 mg/l as Mn and averaged 0.046 mg/l as Mn. Raw water quality during the tests is summarised in Table 1. For a period of 4 days ammonia concentrations were artificially increased to approximately 3.3 mg/l as N by dosing ammonium sulphate in order to test the response of the filters to sudden changes in ammonia concentration.

## Pilot filter performance

Nitrification is a two stage process, the first involves the oxidation of ammonia to nitrite by the *Nitrosomonas* bacteria and the second the oxidation of nitrite to nitrate by *Nitrobacter*. The second stage takes longer to develop than the first and as a result high nitrite concentrations may be present during the initial stages of filter operation.

The nitrification process developed rapidly (2 to 3 days) without "seeding" in the aerated biological filter Column No. 1 containing new proprietary media and when receiving raw water within the temperature range 18 to 31ºC. Ammonia removal of about 25% was recorded 40 hours after startup, although none was converted beyond nitrite to nitrate. Over the following eight hours this increased to 40% removal. By the beginning of the second week of operation about 85% removal was achieved and nitrite values had dropped significantly to an average value of 0.022 mg/l as N indicating that the second stage of the nitrification process was also fairly well established. The start up time for Column No. 2 (sand media) was longer with 20% removal after about 72 hours and 80% after 10 days of operation. The second stage of biological oxidation (nitrite to nitrate) took considerably longer to become established, still being incomplete after 3 to 4 weeks.

Column No. 1 performance of with respect to ammonia removal is shown in Figure 1. During the initial 6 days of operation ammonia in the filtrate fluctuated around 0.5 mg/l. After 11 days the daily average had fallen below 0.1 mg/l as N where it remained until the

**Table 1** Summary of raw water to pilot plant data 11 Jan to 4 Oct 1996

|  |  | Count | Average | Minimum | Maximum | Std Dev |
|---|---|---|---|---|---|---|
| Temperature | °C | 275 | 24.175 | 12.500 | 34.000 | 6.056 |
| pH | pH units | 179 | 6.767 | 6.160 | 7.350 | 0.257 |
| Eh | MV | 160 | 91.433 | 4.300 | 254.000 | 33.909 |
| Dissolved Oxygen | % saturation | 169 | 52.124 | 8.000 | 89.000 | 20.744 |
| Turbidity | NTU | 176 | 4.239 | 1.600 | 15.000 | 2.127 |
| E. Conductivity | µS/cm | 179 | 149.497 | 112.000 | 205.000 | 22.818 |
| Alkalinity | mg/l CaCO3 | 179 | 29.077 | 21.400 | 37.400 | 3.383 |
| Ammoniacal Nitrogen | mg/l | 1179 | 0.750 | 0.020 | 2.130 | 0.410 |
| Nitrite Nitrogen | mg/l | 163 | 0.205 | 0.005 | 0.896 | 0.139 |
| Nitrate Nitrogen | mg/l | 151 | 3.064 | 1.200 | 5.400 | 0.659 |
| Ortho-Phosphate | mg/l | 149 | 0.071 | 0.000 | 0.150 | 0.030 |
| Total Manganese | mg/l | 177 | 0.152 | 0.025 | 0.512 | 0.078 |
| Soluble Manganese | mg/l | 209 | 0.046 | 0.001 | 0.362 | 0.066 |
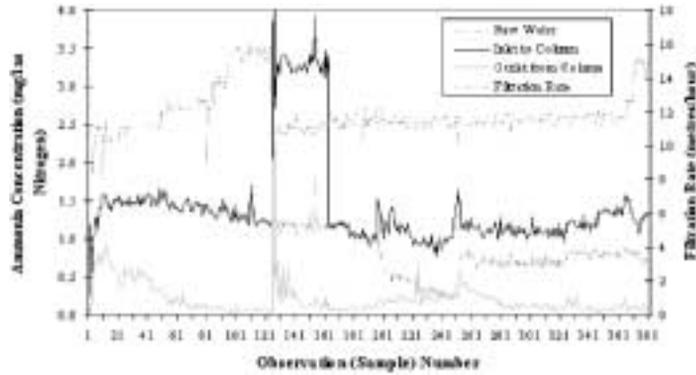
**Figure 1** Performance of Column 1 with respect to ammonia removal (11th January 1996 to 1st March 1996)

influent ammonia concentration was enhanced from the 1.2 mg/l present in the raw water to about 3.3 mg/l as N by the addition of ammonium sulphate. Initially when the ammonium sulphate was dosed the average daily concentration in the effluent increased to 0.80 mg/l but by the second day had dropped to 0.32 mg/l and by the third day to 0.13 mg/l. During this period the hydraulic loading on the column was increased steadily from 10 to 15.5 m/h.

During the period of enhanced ammonia dosing Column No. 1 required more frequent backwashing due to the increased growth of biomass. The frequency was increased from once per week to every two days. Backwashing consisted of seven minutes combined air and water wash with a water wash rate of 60 m/h followed by a period of 3 minutes of water alone. The media was not fluidised but expanded by about 7 percent. The performance of the filters was not adversely affected by washing.

The oxidation of ammonia results in the production of acid thus some alkalinity is destroyed. In order to neutralise the acidity and ensure that the pH of the filtrate from the column did not fall excessively, sodium carbonate was dosed to the inlet of the filter columns. It has been shown (Groeneweg *et al*., 1994) that the oxidation of ammonia is pH dependent, with the maximum rate of oxidation occurring in the range 7.0 to 8.5. Below a value of 6.5 the efficiency of the nitrification process is considerably reduced. The sodium carbonate was therefore dosed in order to maintain the pH of the filtrate above 6.5 and preferably at about 7.0. During the tests the pH value was generally within the range 6.4 to 7.3 and averaged 6.85. In fact no loss of efficiency was noted at pH values of 6.2 and above. From the test data it has been calculated that 8.05 mg/l of alkalinity (as $CaCO_3$) is destroyed for every 1 mg/l of ammoniacal nitrogen oxidised. This compares with a theoretical value of 7.14 mg/l. The test data also show that the dissolved oxygen requirements are 5.2 mg/l for every 1 mg/l of ammoniacal nitrogen oxidised. The theoretical value is 4.6 mg/l. A reduction in nitrification efficiency was noted when dissolved oxygen levels dropped to 15 to 20% saturation (1.2 to 1.6 mg/l).

The consumption of ortho-phosphate by the biomass was very low at approximately 0.01 mg/l as P. It was therefore concluded that the dosing of phosphate would not be necessary so long as the ortho-phosphate phosphorus concentration in the raw water did not fall below 0.02 mg/l as P.

During periods of stable operation both Columns Nos. 1 and 2 consistently achieved between 80% and 90% ammonia removal with raw water ammonia concentrations of up to 2.4 mg/l as N and when operating at a hydraulic loading equivalent to 14 m/h. Rapid changes in hydraulic loading were not detrimental to the volumetric performance of the process, although some short-term deterioration in ammonia removal can be expected if the flow changes are abrupt and large. Similarly, large increases in influent ammonia

concentrations did not cause long term deterioration in performance but a short term decline in effluent quality can be expected if the increase in inlet ammonia concentration is large. During this study only two such natural events occurred with step increases of 0.5 and 0.7 mg/l as N between the two-hourly interval between measurements, neither of which gave rise to a measurable increase in filtrate ammonia concentration. When ammonia as ammonium sulphate was dosed at the inlet to Column 1 to give a concentration of 3.3 mg/l as N, the degree of removal increased from 1.2 mg/l to 2.2 mg/l as N over 1 hour. Over the subsequent five hour period ammonia removal averaged approximately 2.85 mg/l as N producing a filtrate concentration of 0.45 mg/l as N.

On one occasion Column No. 2 suffered from complete loss of nitrification. The column recovered 7 days after the event with complete recovery taking a further 5 days. Subsequent tests showed that recovery could be speeded up by seeding the column with biomass from another column.

Typically the biological filters removed about 65% of turbidity when supplied with a low turbidity raw water (3 to 4 NTU). During the trials turbidity values in the raw water were consistently below 7.5 NTU thus it was not possible to assess the performance of the biological filters under conditions of higher solids loadings.

### Upflow mode

The sand media in Column No. 2 was replaced with proprietary media (effective size 2.75 mm) and run in upflow mode for a period of 4 weeks. Comparison of the performance with Column No. 1 indicates that greater removal of ammonia can be achieved by running the columns in upflow mode. The calculated kinetics for the two columns suggest that upflow is approximately 60% more efficient in the oxidation of ammonia compared with downflow mode. It should however be noted that Column No. 2 was only operated in upflow mode for a relatively short period and that the long-term viability of such a process would need to be proven by a more detailed study. The performance of Column No. 2 is shown in Figure 2.

### Manganese removal

Manganese concentrations in the raw water varied from 0.025 to 0.51 mg/l as Mn and averaged 0.15 mg/l. For most of the test period the metal was present in particulate form with the average value for the soluble form being less than 0.02 mg/l as Mn. Soluble manganese concentrations in the filtrate from Column No. 1 ranged from 0.001 to 0.085 mg/l as
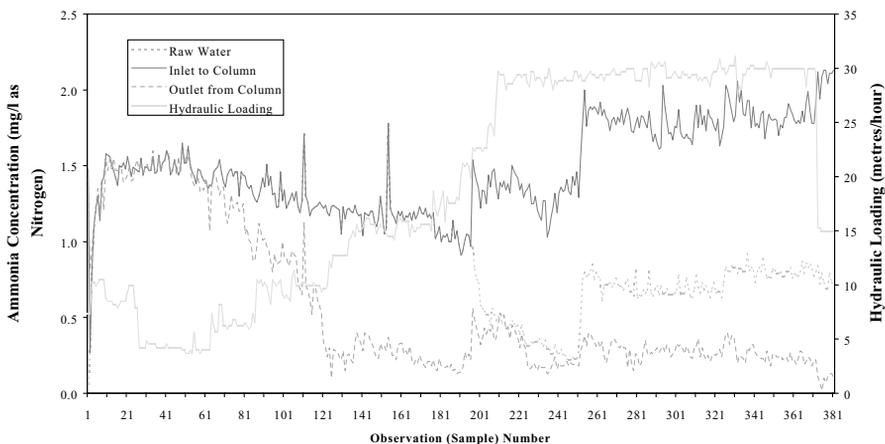


**Figure 2** Performance of Column 2 with respect to ammonia removal (11th January 1996 to 1st March 1996)

Mn and averaged 0.014 mg/l, this represents a 75% reduction over the inlet concentration. During September 1996 soluble manganese concentrations increased to 0.36 mg/l (average 0.155 mg/l) for a short period, permitting a more detailed investigation to be carried out. Over this latter period Column No.1 filtrate showed a maximum value of 0.085 mg/l and averaged 0.009 mg/l.

It has been reported in technical literature that manganese can only be removed biologically once ammonia removal has been completed. However, a review of residual ammonia concentrations in Column No. 1 filtrate shows that significant manganese removal was achieved whilst residual ammonia concentrations in Column No. 1 filtrate ranged from 0.01 to 1.10 mg/l as N, and averaged 0.11 mg/l as N over the relevant period.

Further removal of soluble manganese was achieved on Column No. 3 (catalytic media) when operated in series with Column No. 1 although the concentrations in the incoming water did not exceed 0.06 mg/l. On average the metal concentrations were reduced from 0.016 to 0.006 mg/l.

Manganese removal on Column No. 3 containing the catalytic media was also successful with the peak soluble manganese concentration of 0.36 being reduced to 0.006 mg/l. The average manganese concentration in the filtrate was 0.003 mg/l. The catalytic media was regenerated intermittently with potassium permanganate.

### Reaction kinetics and effects of temperature

The kinetics of many chemical treatment processes may be described by reaction order. The concept of classifying reactions on the basis of order is generally applicable to the following types of reactions.

(a) Essentially irreversible reactions, where a stoichiometric combination of reactant chemical species is totally or almost totally converted to product.

(b) The initial stages of most reversible reactions, where the reactant concentration-to-product concentration ratio is large.

(c) Reversible reactions, where the position of equilibrium lies far to the right, i.e. where the equilibrium product concentration-to-equilibrium reactant concentration ratio is large.

Many reactions encountered in process chemistry will be one of these three types.

For a particular chemical reaction, the order, $n$, with respect to a specific reactant species, A, may be defined in terms of the concentration of A, $C_A$, and its rate of change with respect to time, $-dC_A/dt$, by the equation:

$$\log[-dC_A/dt] = \log K + n\log C_A \tag{1}$$

By applying this equation, experimental results may be interpreted to establish a reaction order and rate. For any constant order reaction, if the log of the instantaneous rate of change of reactant concentration at any time is plotted as a function of the log of the reactant concentration at that instant, a straight line will result and the slope of the line will be the order of the reaction.

During the monitoring of the influent and effluent for Column 1 two sets of four profiles were made of the ammonia removal through the Column by taking samples at the manometer tappings. Both plots suggested that the removal of ammonia in the column follows an exponential decay. This indicates that the removal of ammonia may be described by a first-order reaction, i.e. one in which the rate of reaction is directly proportional to one of the reactants (in this case ammoniacal nitrogen), and has the form:

$$\ln [C_o/C] = Kt \tag{2}$$

where $C_o$ is the inlet concentration of ammonia, $C$ is the outlet ammonia concentration, $K$ is the reaction constant (which will be temperature dependent) and $t$ is the time of contact with the Column.

To confirm the order of reaction for the oxidation of ammonia the data obtained from the profiles through the column have been plotted (Figure 3) in the form given in Equation 1 (i.e. as log of the rate of change of ammonia against log of ammonia concentration) with $t$ calculated as the time of travel through the empty bed volume.

The linear regression lines for the plotted data have slopes of 1.0 which confirms that the reaction for the oxidation of ammonia follows a first order. A first-order reaction is one in which the reaction proceeds at a rate directly proportional to the concentration of one of the reactants, in this case ammonia. Since the rate of oxidation depends on the concentration of ammonia and since the concentration of ammonia will be decreasing with time, an arithmetic plot of the variation in the concentration of ammonia with time will give an exponential decay curve. Such curves were obtained with the data from the ammonia profiles through Column 1.

As first-order reaction kinetics are followed, the rate of disappearance of ammonia can be described by the rate equation:

$$-dC/dt = K(C)^1 = KC$$

where $-dC/dt$ = rate of change in the concentration of ammonia with time $(MV^{-1}T^{-1})$
$C$ = concentration of ammonia at any time, $t$ $(MV^{-1})$
$K$ = reaction rate constant $(T^{-1})$

Integrating this equation and letting $C = C_0$ at $t = 0$ gives an integrated rate equation of the form:

$$\ln[C_0/C] = Kt$$

This integrated rate equation has been used to look at the changes in the rate constant that occurred for both Columns 1 and 2. A plot of the calculated rate constants for the two columns is given in Figure 4.

### Reaction rate constants for the two columns

From Figure 4 the reaction rate constant $(K)$ that can be achieved using a column in down-flow (filtration) mode has been calculated to be 0.373 $min^{-1}$. This value of "$K$" is based on the average reaction rate constant for Column 1 during the period 24 to 28 January 1996. During this period there appeared to be no further growth in biomass and after
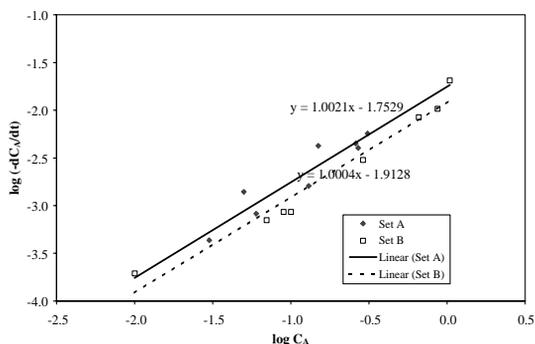
**Figure 3** Reaction order

this period there were several factors (in particular low ammonia concentrations and alum dosing) that affected the performance. The water temperature for the period over which the reaction rate constant was calculated ranged from 17°C to 20°C, and averaged 18.4°C. Also from the figure the reaction rate constant ($K$) that can be achieved using a column in upflow mode is estimated to be 0.599 s$^{-1}$. This value of "$K$" is based on the average reaction rate constant for Column 2 during the period 10 to 29 February 1996. During this period the derived "$K$" value appeared to be fairly constant indicating that the biomass was no longer increasing. The water temperature for the period over which the reaction rate constant was calculated ranged from 12.5°C to 20.5°C, and averaged 15.5°C. The reaction rate constant achieved in upflow conditions is some 60% higher than achieved in downflow mode in spite of the average water temperature being some 3°C lower.
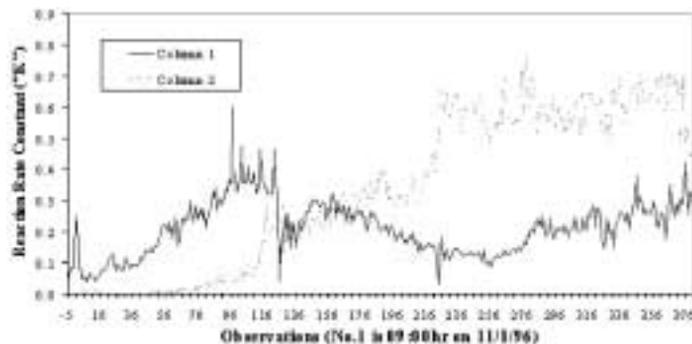
### Growth in biomass

Growth of biomass can be estimated from the plots of the reaction rate constants where the value of "$K$" is increasing. These periods have been replotted in Figure 5 for both Columns 1 and 2 on an actual time-scale. Both sets of data give a straight line correlation with general slope equal to 0.024 indicating that there was no apparent difference in growth pattern between the two columns. The slopes give a rate of increase in the reaction rate constant under growth conditions of 0.0244.

### Overall treatment strategy

The treatment strategy developed for Tai Po Water Treatment Works has three main treatment stages, with provision for the future addition of ozone. As described elsewhere (McMeekan *et al.*, 1996; Hieatt, 1997; Hieatt and Herber 1997; Ng *et al.*, 1998) the main features under normal operating conditions are:

- No pre-chlorination
- *when turbidity high*, pH adjustment for coagulation and DAF clarification
- *when turbidity low*, bypass DAF (raw water data indicates 8 or 9 months/year)
- Primary Aerated Biological Filtration to reduce ammonia and manganese
- Chlorination to remove remaining ammonia and oxidise soluble manganese
- *if DAF bypassed*, coagulation and flocculation for Direct Filtration
- Secondary Rapid Gravity Filtration by physical filtration for "polishing"
- Catalytic media as back-up for the removal of soluble manganese
- Chlorination within a Contact Tank for final disinfection
- Final pH correction and Fluoridation.



**Figure 4** Calculated reaction rate constants (based on first order reaction kinetics)
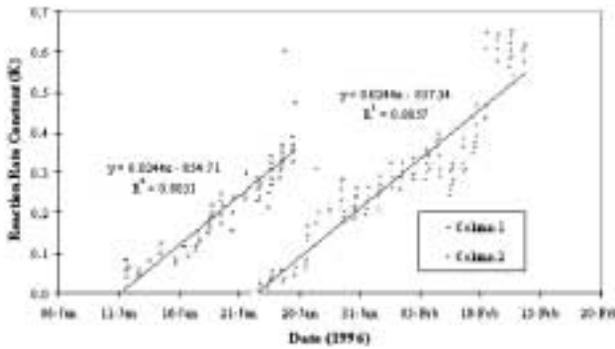
**Figure 5** Increase in reaction rate constant with growth in biomass

## Use of pilot filter data in the design

One requirement of the design brief was to maximise the treatment capacity of the available site area. Whereas previously available information from European experience indicated design filtration rates of below 10 m/h the pilot filter work demonstrated that in the Hong Kong context adequate performance of the biological filters could be achieved in down flow mode at rates of up to about 10 to15 m/h. The increased design rates allowed a greater capacity per unit area.

In general, for a large works there are benefits in using the largest possible unit sizes subject to considerations of how many units need to be taken off-line at any one time, however there is also a need for confidence that the unit size will perform satisfactorily. In order to maintain a steady work output during filter washing it is necessary to consider an upper bound for filtration rates for filters in service whilst other filters are being drained or washed. It is also necessary to consider the configuration of the units within the overall layout and in relation to other process units and the shape of available site. In the case of the Primary Aerated Biological Filters (PABF), the final configuration adopted 10 filters per stream with the three streams set adjacent to each other to form a single block. An individual filter area of 150 m$^2$ (15 m long × 10 m wide) was selected, the size being towards the upper bound of known satisfactory potable water applications for rapid gravity type filters. The pilot plant work allowed the adoption of relatively high design filtration rates of up to 10.4 m/h at Stage I (with one filter out of service for washing) and up to 13 m/h for the ultimate development of 400 Ml/d per stream. The depth of media is to be 2 m with provision within the structures to accommodate an additional 0.5 m should additional ammonia removal be found necessary.

The overall scheme includes a 1.2 km 3.8 m dia raw water transfer tunnel and 80 m vertical shaft rising into the treatment works inlet works; site formation and ancillary structures for a 1,200 Ml/d treatment works at Tai Po with construction of the first treatment stream equipped at Stage I for 250 Ml/d output; a 250 Ml/d Stage I treated water pumping station; 12 km steel lined treated water tunnel and a 40,000 m$^3$ Stage I service reservoir perched on a hilltop above the metropolitan area of Kowloon and Hong Kong.

Construction began in 1997 with contractors Leighton-Kumagi JV (Tunnels), Gammon Construction Ltd (Treatment Works) and Gammon Kværner JV (Service Reservoir). As at July 2000 the tunnels have been driven and lined and civil works at the treatment works and service reservoir sites are well advanced. Further information on the scheme can be found in the references and on the project website at http://www.bbv-taipo.com.hk/ including pictures of progress to date.

## Acknowledgements

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