# The effects of water reclamation technologies on biological stability of industrial water

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**Abstract** A modified Assimilable Organic Carbon (AOC) procedure was adopted in conjunction with Heterotrophic Plate Count (HPC) method to assess the effect of Single Effect Distillation (SED) and Reverse Osmosis (RO) lab-scale systems on the biological stability of industrial water. Industrial water was collected from a local Industrial Water Works, pre-treated with alum coagulation and cartridge filtration, before being subjected to advanced water treatment. The results obtained in this study indicated that AOCs in the SED product water were in the range of 70–80 μg acetate-C/L, while those in the RO product water ranged from 30–40 μg acetate-C/L in the 15-min permeate to 55–65 μg acetate-C/L in the 3-hr permeate. The above findings suggested that product water of both systems were potentially biologically unstable and would likely lead to bacteria regrowth during its distribution and storage. Removal efficiencies of lab-scale RO and SED systems on AOC were as high as 90%, dependent on the concentration of AOC-NOX in the industrial water. The RO system had much higher organic removal efficiencies in terms of AOC and DOC than the SED system. Organics removed from both feed waters were found to be concentrated in the brine water and rejected water in SED and RO systems respectively.

**Keywords** Assimilable organic carbon (AOC); biological stability; industrial water; reverse osmosis (RO); single effect distillation (SED); water reclamation

## Introduction

The hygienic, technical and aesthetic significance of biological stability in drinking water and the problem of bacterial re-growth have gained renewed attention after several phenomena of high colony counts were discovered pertaining to water supply treatment processes. Although biological stability of the drinking water had been investigated widely, its effects and implications in relation to reclaimed water are still remained relatively unexplored. With the present trend of reclamation and reuse of industrial and domestic wastewaters, the issue of biological stability of the reclaimed water is becoming increasingly important. In general, reclaimed sewage for industrial purpose meets the quality requirements for cooling, washing and process applications of industries. However, it has been widely noted that bacteria re-growth in the downstream could occur which in turn would lead to deterioration of water quality and failure to meet the desired water quality standard. An industrial water was reported to encounter bacteria re-growth problem previously even with effective disinfection when leaving the treatment facility (Chin, 1986). Problems associated with water reclamation and reuse also include growth of waterborne microbes, biofouling as well as concomitant microbial induced corrosion. Biologically stable water would minimize re-growth of micro-organisms and prevent contamination of treated water with micro-organisms during storage and distribution.

For controlling and reducing re-growth in a practical situation, information such as the concentration of carbon compounds that can be used as energy and carbon sources for bacteria in water leaving the treatment facility should be carefully analyzed. A bioassay determining the concentration of easily Assimilable Organic Carbon (AOC) was used in this study in conjunction with the Heterotrophic Plate Counts (HPC) method for evaluation of

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biological stability of water before and after reclamation. This study investigated the performance of two advanced treatment processes, namely Single Effect Distillation (SED) and Reverse Osmosis (RO) systems, in terms of their effectiveness for controlling biological stability in the industrial water.

## Materials and methods



### AOC assay

The AOC determination, originally proposed by van der Kooij (1982), is based on measuring the maximum level of growth (maximum colony count, $N_{max}$ in colony-forming units per ml) of a selected pure bacterial culture in a representative water sample, in which the indigenous bacteria have been killed or inactivated by heat treatment. The AOC method was further modified and simplified according to recommendation by Kaplan *et al*. (1988) and Lechevallier *et al*. (1993). Generally, a water can be defined as biologically stable if its AOC value is less than 10–20 μg acetate-C/L without disinfection or less than 50–100 μg acetate-C/L if it had been disinfected (Lechevallier *et al*., 1993).

*Pre-treatment of water samples*. The samples were filtered using a 0.2 μm diameter pore filter paper to remove suspended solids which can contain large numbers of spore-forming bacteria that may survive pasteurisation, grow and interfere with the enumeration of P17 and NOX on spread plates. The cellulose acetate membrane was rinsed with 1 L carbon-free water before being used to avoid the inherent contamination (Noble *et al*., 1996). Dilution of samples according to DOC level is needed so that AOC level is within the detectable limit of the bioassay.

*Combination inoculation*. The samples were inoculated with strains P17 and NOX, resulting simultaneous growth of these micro-organisms. This is for avoiding the overestimation of AOC level.

*Increased incubation temperature*. Temperature adopted was increased to room temperature (23°C) to take advantage of the higher ambient temperature in tropical region (Ng *et al*., 1998). This method will shorten the whole period for testing because both strains of bacteria reached their respective stationary phases by the end of the 3rd or 4th incubation day under room temperature instead of the 7th to 8th days proposed in *Standard Methods* (1995). It was noted that the higher incubation temperature could reduce the time needed to perform the AOC bioassay and yet yielding results that were comparable to the corresponding values obtained under the temperature of 15°C proposed by the *Standard Methods*.

### Water reclamation technologies

Water reclamation is becoming important in a region facing water shortage problem. With the present trend in water reclamation and reuse, technologies such as distillation and reverse osmosis are gaining popularity as advanced treatment processes. Two lab-scale SED and RO systems were employed to investigate the effect of SED and RO on the biological stability of reclaimed industrial water.

Figure1 shows the schematic diagram of treatment trains and the sampling points used in this study. A total of 7 samples were collected and analysed at the various stages of the treatment process. HPC was used to determine the number of living heterotrophic bacteria. The samples were filtered with a 0.2 μm filter paper and the filtrate was analyzed for DOC and AOC.

To prevent degradation of membrane and deterioration of permeate quality as membrane is sensitive to chlorine, dechlorination of feed industrial water was conducted as the

first step of pre-treatment. Coagulation and filtration were also employed in this study as they were reported as an effective pre-treatment in the removal of suspended, colloidal solids as well as AOC (van der Kooij, 1990). 40 litres of industrial water were collected each time and then dechlorinated with 2.5 ml sodium thiosulphate solution (30g/l $Na_2S_2O_3$) per litre of collected water. The dechlorinated sample was then coagulated with a dosage of 20 mg/l of aluminium sulphate. The sample was further filtered with a 5 μm cartridge filter, and the filtrate was used as feed water for the subsequent SED and RO systems. The diagrams of lab-scale SED and RO system were shown in Figures 2 and 3, respectively.



As shown in Figure 2, feed water was pumped into the evaporator reservoir before it was further pumped into the distillation column by the recirculation pump, in which impurities such as salts and ions in feed water were separated to recover clean water. Concentrate would flow back to the evaporator reservoir and recycle to distillation column or be discharged as overflow. The concentrate was discharged by an overflow pipe from the evaporator reservoir to prevent over-concentration of the feed. Product vapour was condensed into condensate by cooling water. The steam was provided by the boiler to the distillation column. Condensed steam was recycled back to the boiler and reused again.

It could be seen from Figure 3 that incoming feed water, pressuried by a pump, entered one end of the RO membrane module, travelled and crossed the membrane surfaces. Treated water permeated through the membrane to the product tube. A portion of feedwater, enriched by the rejected salts, flew out of the module as brine or reject stream and was recycled back to feedwater. The operating pressure was self-regulated within a level of 5–6 bar.

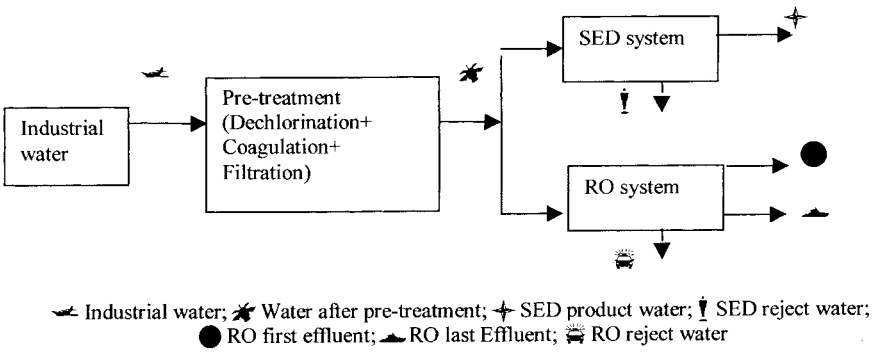


**Figure 1** Schematic diagram of treatment trains and sampling points

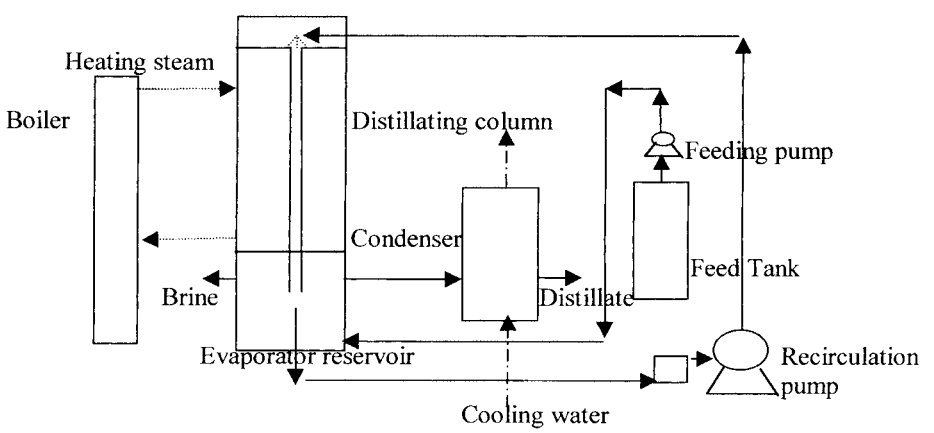


**Figure 2** Schematic diagram of the laboratory SED set-up

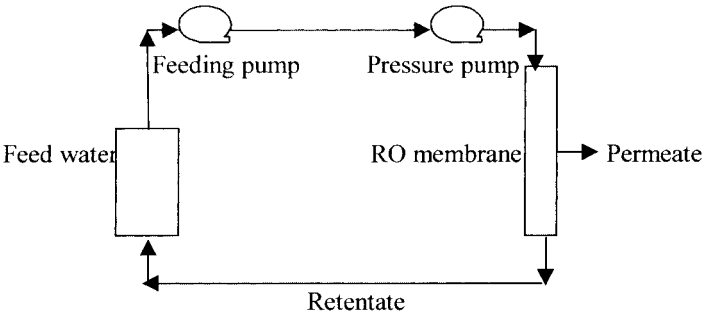


**Figure 3** Schematic diagram of the laboratory RO set-up.

## Results and discussion

A total of 3 sets of investigations were carried out to estimate the effects of SED and RO on the biological stability of reclaimed water in the period of Dec. 98 to Feb. 99. The results obtained are summarised in the following tables and figures.

### HPC and its removal

It was noted from Table 1 that with free chlorine content as high as 0.2 mg/l, living HPC bacteria could not be detected in the water samples. This observation was consistent with the findings of Chin (1986), in which it was identified that the industrial water had a coliform count of 0 after chlorination but an increased number in the downstream distribution system. HPC levels increased dramatically after dechlorination, due to the recovery of dormant bacteria or bacteria injured during treatment, as reported by Gibbs *et al.* (1993).

Undetectable levels of HPC bacteria in the product water of SED system after 5-day incubation of the enumerated plates were also reported. This is expected due to the principle of separation of SED system. The high temperature (97°C) in the distillation column was sufficient to destroy or inactivate most of the bacteria strains originally present in the water. The high level of HPC in one of the product water (first run) might be due to either an accidental introduction into the enumeration stage of HPC test or possible contamination from the SED system itself.

The RO system was able to remove HPC bacteria of more than 90% in this study. However, it was relatively unsatisfactory considering the potential performance of a RO membrane. The high HPC level in the RO product water shown in Table 1 might be a result of bio-fouling of the RO membrane. Similar findings were also reported by Chin (1986), in which one-fold decrease in HPC level was noted and replacement of RO membrane was suggested after 8 months of operation in dealing with sewage reclamation. HPC levels of the last product water consistently lower than that of the first product water might also sug-

**Table 1** HPC and free chlorine in water samples

| Water samples | pH | Free Chlorine (mg/l) | HPC density (CFU/ml) | HPC removal efficiencies (%) |
|---|---|---|---|---|
| Industrial water | 7.4–7.5 | 0.04–0.2 | ND*–$1.84\times10^8$ | – |
| Pre-treated water | 7.3–7.4 | 0 | $4.15\times10^5$–$5.65\times10^5$ | – |
| SED product water | 6.7–7.0 | 0 | ND*–$1.7\times10^7$ | 100 |
| SED reject water | 8.8–9.0 | 0 | ND*–$2.1\times10^7$ | – |
| RO first product water | 6.4–6.5 | 0 | $2.3\times10^4$–$1.4\times10^6$ ($4.9\times10^5$) | 93.6–94.5 (94.1) |
| RO last product water | 6.5–9.5 | 0 | $1.1\times10^4$–$1.0\times10^5$ ($4.7\times10^4$) | 94.5–97.3 (95.9) |
| RO reject water | 8.0–8.4 | 0 | $1.2\times10^6$–$9.4\times10^7$ ($3.3\times10^7$) – | |

*ND: not detectable at 5 days incubation period
Data in bracket are average values

**Table 2** DOC in water samples

| Water samples | DOC (mg/l) | DOC removal efficiencies (%) |
|---|---|---|
| Industrial water | 22.5–24.7 (23.6) | – |
| Pre-treated water | 17.4–17.7 (17.6) | 22.7–28.7 (25.6) |
| SED product water | 3.5–5.9 (4.4) | 66.5–80.2 (74.8) |
| SED reject water | 29.7–39 (33.2) | – |
| RO first product water | 2.3–2.6 (2.5) | 85.2–86.8 (86.0) |
| RO last product water | 3.5–7.6 (5.4) | 57.1–80.1 (69.1) |
| RO reject water | 45–63 (54.7) | – |

Data in bracket are average values



gest that bacteria attached to biofilm could have been sheared and detached at the beginning of running, when permeate flew across the RO membrane.

#### DOC and its removal

As shown in Table 2, DOC of industrial water varied in the range of 22.5–24.7 mg/l. The pre-treatment processes reduced approximately 25.6% of DOC, to the levels of 17.4–17.7 mg/l. Removal of DOC was significantly higher when the pre-treated samples were further treated by the SED and RO systems. In general, RO first product water had a better removal efficiencies of DOC than that of SED. Concentrations of DOC in the RO first product water ranged from 2.3–2.6 mg/l, while those in SED product water ranged from 3.5–5.9 mg/l. Potentially RO system was capable of producing permeate of a higher quality. However, as discussed above, there might be a possibility of bio-fouling of RO membrane, and a consequence of bio-fouling, as widely characterized, was the decrease of permeate quality. As expected, the reject water of both systems remained high levels of DOC, expressing the concentrating effect of the processes themselves.

RO last product water was consistently poorer as compared to RO first product water with respect to DOC value. This could be due to the recycling of reject water into the feed stream of RO system, which had the effect of increasing the subsequent DOC concentration in feed water. The phenomenon of decreased rejection of target substrate at increased osmotic pressure has been explained by Todtheide *et al*. (1997). They reported that increasing the osmotic system might increase or decrease the rejection of the target substances, due to the influence of substance-specific parameters such as molar mass, hydrogen bonds, functionality, and steric hindrance in a multi-component system.

#### AOC and its removal

*AOC in industrial water*. The AOC levels in the industrial water samples were detected ranging from 2550–3720 μg acetate-C/L (Table 3). This was indicative of biological instability even with disinfection. The phenomenon of biological re-growth at the downstream

**Table 3** AOC in water samples

| Water samples | AOC-T (μg acetate-C/L) | AOC-NOX/AOC-T (%) | AOC/DOC ratio (%) |
|---|---|---|---|
| Industrial water | 2550.0–3720.0 (3152) | 22–34 (28.7) | 10.8–15.5 (13.8) |
| Pre-treated water | 934.0–1020.5 (979.0) | 42–73 (39.0) | 5.4–5.8 (5.6) |
| SED product water | 70.0–225.6 (124.6) | 80–91 (87.0) | 2.0–3.8 (2.6) |
| SED reject water | 2170.0–5428.3 (3379.4) | 25–32 (28.0) | 7.0–13.9 (9.8) |
| RO first product water | 32.7–76.9 (49.9) | 67–98 (84.7) | 1.4–3.0 (2.0) |
| RO last product water | 55.1–92.9 (71.1) | 57–68 (61.7) | 0.9–2.2 (1.4) |
| RO reject water | 1536.0–3462.5 (2716.2) | 34–48 (42.7) | 3.4–6.3 (4.9) |

Data in bracket represent average values

**Table 4** AOC removal efficiencies

| Water samples | Removal efficiencies (%) | | |
|---|---|---|---|
| | AOC-P17 | AOC-NOX | AOC-T |
| Pre-treated water | 76.6–90.7 (83.0) | 9.3–67.8 (29.5) | 60.0–73.6 (68.7) |
| SED product water | 95.7–97.3 (96.4) | 50.5–91.9 (77.3) | 77.0–93.1 (87.2) |
| RO (first product water) | 95.6–99.7 (98.0) | 87.5–95.3 (92.6) | 92.2–96.5 (94.9) |
| RO (last product water) | 92.0–93.0 (92.7) | 87.1–94.5 (92.0) | 90.5–94.1 (92.7) |

Data in bracket represent average values



has indeed been confirmed by Chin (1986). It is also noted from Table 3 that AOC-P17 contributed to 71.3% of AOC-T, which suggested that industrial water contained a great percentage of high molecular weight P17-assimilable compounds. The finding further indicated that the organics present in the industrial water could be easily utilized by P17, which in turn suggested that compounds like alcohols, hydrocarboxylic acids and carbohydrates rather than carboxylic acids could be the major contributors to the AOC.

*AOC removal by treatment processes*. The results shown in Table 4 suggested that coagulation with alum followed by filtration with a 5 μm cartridge filter could remove 60–73.6% of AOC. Similar findings concerning the effectiveness of coagulation for reduction of AOC in drinking water have also been reported by van der Kooij (1990) and Huck *et al*. (1991). The removal efficiencies of AOC-P17 were generally much higher than those of AOC-NOX. This observation could be explained by the mechanism of coagulation, as such treatment process is effective for removing large molecular weight organics.

AOC levels in SED effluent were generally in the range of 70.0–80.0 μg acetate-C/L, except for the first run which was 225.6 μg acetate-C/L. This high AOC value associated with the first run was suspected to be due to a contamination of SED system itself. Contamination of product water would occur if the system was not cleaned thoroughly. AOC-NOX contribution to AOC-T increased to about 80–91% in SED product water. The phenomenon agreed with van der Kooij's observation (1990, 1992) that strain NOX usually grow much more rapidly and attained higher colony counts than strain P17 in product water. The observation of the lower AOC-NOX removal efficiencies associated with the SED system could be due to the relatively volatile characteristics of carboxylic acids which were the major contributing organic compounds to AOC-NOX. In addition, the proportion of AOC-NOX in feed water, which were relatively more volatile, had more influence on removal efficiency of SED system. One could deduce that a lower AOC-NOX/AOC-T ratio corresponded to a higher AOC removal efficiency. This is because AOC-NOX removal efficiency was typically lower than that of AOC-P17 in a SED system.

AOC levels in RO first product water were consistently much better than those of SED system, with a range of 32.7–76.9 μg acetate-C/L. Different mechanisms were responsible for the differences in terms of AOC removal. AOC-NOX contributed about 84.7% of AOC-T in RO product water and AOC removal efficiency was also dependent on the ratio of AOC-NOX in RO feed water. Todtheeide *et al*. (1997) reported that rejection of targeted carboxylic acids was in the range of about 30–40%. This observation suggested a high proportion of AOC-NOX present in the RO product water. This latter point could explain the difficulties in reduction of low molecular weight organics by RO membrane. An increasing of AOC-P17 in the effluent was noted as recycling continued, because AOC-P17 retained in reject stream probably could lead to a corresponding increase in the product water. Removal efficiencies of RO system were typically greater than 90%.



High AOC levels in both reject waters showed that AOC removed in feed water were

**Table 5** Mass balance of DOC and AOC

| Parameters | SED system | | | RO system | | |
|---|---|---|---|---|---|---|
| | In | Out | Recovery ratio (%) | In | Out | Recovery ratio (%) |
| DOC (mg) | 194.7 | 164.7 | 84 | 424.8 | 439.9 | 104 |
| AOC (μg acetate-C) | 10643.8 | 11850 | 111 | 24492 | 18298.1 | 75 |



concentrated in the reject stream, consistent with the findings in DOC test. It was interesting to note an increase of AOC-P17 proportion and a decrease of AOC-NOX proportion in reject waters. Both product waters possessed an unacceptable AOC level without disinfection. This finding suggested that there are potential difficulties related to bacteria re-growth during distribution or storage of product waters.

*AOC/DOC ratio*. As shown in Table 3, there was a decrease in the AOC/DOC ratio after pretreatment, from 10.8–15.5% to about 5.4–5.8%. SED product water had AOC/DOC ratios of 2.0–3.8%, while those of RO product water were in the range of 0.9–3.0%. Similar findings were also reported by Huck *et al*. (1994) in their study on drinking water treatment system. A decrease in the ratio would suggest that the removal of AOC was better than that of DOC. This would also explain why the reduction in AOC/DOC ratio was more significant in the RO system than that of the SED system. This result was in agreement with the observed higher AOC removal efficiency of the former system.

#### Mass balance

Mass balance was performed to verify the mechanism of organics removal assumed. Table 5 summerizes the results obtained from the mass balance analyses performance in this study. It is noted from Table 5 that the recovery rates were all around 80% or above, which confirmed that organics (DOC & AOC) removed from the product waters were concentrated in the reject waters.

## Conclusions

The following conclusions could be drawn from this study.

1. A residual chlorine concentration of 0.2 mg/l might not be sufficient to inhibit re-growth of bacteria in the industrial water with a significant AOC level.
2. SED system could potentially destroy and inactivate all HPC bacteria, however high HPC in the RO product water displayed the possibility of bio-fouling of the RO membrane.
3. DOC as well as AOC removals were more efficient for the RO system as compared to the SED system. Reject of both systems showed a concentrating effect.
4. AOC levels were in the range of 70–80 and 30–77 μg acetate-C/L in product water of SED and RO respectively, demonstrating a potentially biological instability without disinfection.
5. AOC-P17 was the major contributor to AOC in industrial water. The proportion decreased after coagulation followed by filtration, showing that coagulation had a better removal efficiency of AOC-P17. Thus, coagulation could be effectively used for removal of AOC prior to advanced treatment.
6. AOC removals in SED and RO systems were dependent on the proportion of AOC-NOX in the feed stream, which represent organics low in molecular mass and relatively more volatile. Proportion of AOC-NOX was high in SED and RO product water.
7. AOC constituted about 0.9–3.8% of DOC in both product waters. The decreasing

AOC/DOC ratio after advanced treatment processes implied the removal of AOC was more efficient than that of DOC.


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