Desalination and Water Treatment
www.deswater.com

51 (2013) 1804–1816
February

doi: 10.1080/19443994.2012.694231

Taylor & Francis
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SWRO pre-treatment design using high-rate dissolved air flotation including preliminary pilot-scale results

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Received 8 February 2012; Accepted 10 May 2012

ABSTRACT

The purpose of this paper is to present an overview of the design for both the full-scale and pilot-scale seawater reverse osmosis (RO) pre-treatment plant comprising dissolved air flotation (DAF) and dual-media filtration (DMF) proposed and operating, respectively, at the Ras Al Khair site in Saudi Arabia. This paper will deal with the design implications for a high-rate DAF and DMF plant, rated at a net loading of 30 m/h and up to 6.5 m/h, respectively, processing a proposed feed flow of approximately 1,010 Ml/d, and then how to replicate this using a pilot plant. In addition, how water conditions such as high salinity and temperature and the physical characteristics of the plant impact the process design. The basic water chemistry requirements and the physics when applying dissolved air will be discussed. In the latter case this involves both the dissolving and the subsequent efficient release as fine micro-bubbles of the air, to ensure that the required level of clarification is achieved ahead of filtration and that an SDI_{15} of <4 is consistently delivered to the RO plant.

Keywords: Highrate dissolved air flotation; Dual-media filtration; Process design; Algae; Seawater

1. Introduction

The application of both dissolved air flotation (DAF) and dual-media filtration (DMF) in the municipal water industry is regarded as well established; however the application of DAF to the treatment of seawater particularly at elevated temperatures, which is also prone to red tide events, is relatively new, and there is a limited amount of experience in this area.

The Ras Al Khair (RAK) Phase 1 power and desalination plant, formally known as Ras Az Zawr, comprises seawater intake, feeding two water treatment sections, the first and largest of which uses a multi-stage flash (MSF) whilst the second uses seawater reverse osmosis (SWRO), both systems producing desalinated water.

The plant located on the east coast of Saudi Arabia approximately 90 km north of the industrial city of

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Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

Jubail will draw its water from the Arabian Gulf known for its shallow nature with a reported average depth of 30 m and being surrounded by the large arid land masses of Saudi Arabia, the United Arab Emirates (UAE) and Iran. In addition to the circulation currents in the area, which tend to be anticlockwise, the water temperatures and salinity levels can vary significantly from one season to the next. These conditions combined with reported increased nutrient levels [1,2] arising from such sources as untreated sewage discharges, industrial effluent, agricultural run-off and even desalination plant discharges plus the relatively long flushing times in the Gulf of 3–5.5 years [3] have all probably contributed to the increased occurrence of algae blooms. These algae blooms vary in both nature and concentration, but the ones of keen interest are the harmful algae blooms typically referred to as "red tides" as seen in the widely reported events of 2008–2009 off the UAE coast and surrounding area. This algae bloom with counts reported in the local news media reaching as high as 27×10^6 cells/l had a major impact on the local environment and economy, with massive deaths in the local farmed and wild fish stocks and the forced shutdown of SWRO plants.

Partly because of the above and similar events there has been an increasing interest in the application of DAF technology. This is particularly so because of the need to ensure that plants such as the RAK SWRO can continue to operate during these bloom periods which can last, from the first appearance of the red discolouration in some areas through the times when the cell counts are at their highest and eventual decline and disappearance, for several months. The use of DAF technology has been seen as an additional requirement to the typically used DMF and even latterly the ultra-filtration (UF) systems, both of which have suffered from overloading by the mass of algae present at the works intake. As these systems have become overloaded, there is an increased risk of the release of internal cellular material due to cell lyses, as pressure differentials increase. This released material results in membrane fouling both by residual particulates and by it acting as substrate encouraging biological growth.

The following sections will focus on the pretreatment requirements of the SWRO and will describe the approach used in the design of the plant and early validation of the design by the results from large-scale pilot trials which at the time of writing continue after over seven months of virtually continuous operation.

2. Plant description

2.1. Design conditions

Tables 1–5 summarise the local ambient environmental conditions, raw seawater, proposed chemical dosing, design summary for both the main and the pilot plant plus the product water quality all of which have contributed to the design of both plants.

Table 1
Local environment, seawater flow and analysis

Environment	Unit	Flow scenarios	
Ambient air temperature	°C	4–49	
Ambient pressure	mbar	1,013	
Humidity	%	70	
Total feed flow	Ml/d	~1,010	
Seawater		Min	Max
pH		8	8.3
Turbidity	NTU	5	12
Temperature	°C	22	38
Conductivity at 25°C	μS	59,000	64,000
TDS at 180°C	mg/l	38,000	47,000
TSS	mg/l	20	40 (red tide)
Alkalinity (as $CaCO_3$)	mg/l	120	130
TOC	mg/l	–	10
Oil and grease	mg/l	–	1.2
SDI at 75%		7	~77
Total algae	Cells/l		~21,000,000 (>10^6 considered to be a red tide)

Table 2
Chemical dose rates

Chemical		Min	Design	Max
Chlorination (continuous)			1	
Chlorination (shock)			10	
Sulphuric acid[a]	mg/l	–	20	55
Ferric chloride	mg Fe/l	2	3.5	5.5
Polymer product (hydrex 6,794[b])	mg/l	–	–	3
Inter-stage ferric chloride	mg Fe/l	–	0	2.8

[a] The sulphuric acid dose has been estimated to achieve the coagulation pH of $\sim$6.4 when used together with the ferric chloride dose upto the maximum.

[b] Only product approved for use by the SWRO membrane supplier.

Table 3
Main plant DAF and DMF design summary

DAF design	Value	Units
Design inlet flow	42,335	m^3/h
Loading rate (net)	$\sim$30	m/h
Total no. of cells	16	
Minimum no. of cells	14	
Maximum flow/cell	3,024	m^3/h
Cell dimensions $L \times W \times WD$	10.1 × 10.1 × 4.6	m
Flotation area	102	m^2
Recycle	5–20	%
Nozzle type	Fixed orifice type	
Dual-media filter design		
Design inlet flow	41,952	m^3/h
Anthracite ES/depth	1.29/600	mm
Sand ES/depth	0.65/600	mm
Support gravel depth	500	mm
Maximum filtration rate	6.5	m/h
Total no. of filters	40	
Minimum no. of filters	37	
Maximum flow/filter	1,134	m^3/h
No. of filter beds/filter	2	
Filter bed dimensions $L \times W$	$\sim$5.2 × 17	m
Filtration area	$\sim$175	m^2
Wash regime	Combined air and water	
Washwater source	RO concentrate	
Underdrain type	Block floor	

2.2. Main plant

The main works raw water feed will be pumped via a seawater intake and screens and delivered to the pre-treatment plant comprising DAF and DMF. In an effort to avoid low water temperature flows entering the reverse osmosis (RO) system with the inherent impact that would have had on the design operating pressures for the system, "hot compensation" seawater will be added from the MSF plants cooling system. This compensation flow is to be returned at a controlled rate to ensure temperature of the seawater at the DAF inlet is always $\geqslant$22°C; other than maintaining this minimum temperature for design purposes, it was assumed that no further change to the seawater quality occurred.

The DAF and DMF together have a minimum design production capacity of $\geqslant$39,654 m^3/h which is required for the downstream RO process at all times. However, under normal operating conditions a small

Table 4
DAF & DMF product quality summary

		Unit
DAF product		
pH	$\sim$6.4	
Turbidity[a]	$\sim$2–4	NTU
TSS[a]	$\sim$4–12	mg/l
Iron (as Fe)[b]	$\sim$0.6–0.9	mg/l
Filtrate		
Turbidity	<0.5	NTU
Iron (as Fe)	$\leqslant$0.05	mg/l
SDI$_{15}$	<4	
Filter run times	24	h

[a] The target removal is at least 60 to $\geqslant$85% of the feed depending on the inlet conditions and includes precipitated solids arising from the coagulant dose.

[b] During red tide events, a supplementary dose of ferric chloride can be applied and this would increase to $\sim$2.8 mg Fe/l.

Table 5
Pilot plant DAF and DMF design summary

	Value				Units
Pilot plant DAF design					
Design inlet flow	61.2				m^3/h
Loading rate (net)	$\sim$30				m/h
Cell dimensions $L \times W \times WD$	1.7 × 1.2 × 4.8				m
Flotation area	2.04				m^2
Recycle	5–20				%
Nozzle type	Fixed orifice type				
Dual-media filter column design					
Design inlet flow	10				m^3/h
Number of filter columns	4				
Maximum flow/filter	2.5				m^3/h
Dirt bed LOH	2.5–3.0				m
Filter column number	1	2	3	4	
Anthracite size	1.18–2.5	1.18–2.5	1.0–2.0	1.0–2.0	mm
Anthracite depth	600	600	600	800	mm
Sand size	0.5–1.00	0.6–1.18	0.5–1.00	0.5–1.00	mm
Sand depth	600	600	600	400	mm
Support gravel depth	500				mm
Maximum filtration rate	6.5				m/h
Filter column diameter	0.7				m
Filtration area/unit	0.385				m^2

excess flow is produced, which will result in a continuous overflow at the DMF outlet channels of upto 990 m^3/h subject to the operating and raw water conditions.

The DAF plant was designed as two modules, which if necessary can be separated for maintenance purposes. Each module will be made up of eight individual DAF cells; and will be capable of producing upto 20,961 m^3/h. The actual flows to the DAF phase will be determined by the raw water conditions. This is particularly the case when a red tide or a similar event occurs; when the losses are expected to increase and therefore to maintain the feed requirements for the SWRO, there will be a corresponding increase in flow to the DAF plant. Design requirements meant that each DAF cell will operate as a pair; therefore, whilst the total number of cells is 16, the actual rating of each cell had to be based on 14 DAF cells in service and hence it is rated at ~3,024 m^3/h, which is equivalent to a total feed flow of ~42,335 m^3/h.

The common inlet section to the DAF plant is to be split into two streams, each comprising static mixer, where acid and ferric chloride will be dosed to ensure the correct coagulation conditions prior to a preliminary flocculation chamber where provision has been made for the dosing of a polyelectrolyte, if required, as a flocculant aid.

The flow after the dosing will be distributed to the individual DAF streams comprising two stages of flocculation providing a total retention time of at least 10 min and operated at a mixing intensity in the range of 25–100 s^{-1}.

The flocculated material will then flow directly to a DAF cell with a nominal area of 101 m^2 (10.1 m wide × 10.1 m long) and rated at a net loading of 26–30 m/h excluding any recycle. It should be noted that the DAF loading rate stated throughout this paper is based on cell surface area made up of the contact and clarification zone.

Each DAF cell will be fitted with a variable speed mechanical rotary scraper for the purposes of removing the accumulated sludge lifted to the surface by the release of dissolved air and collecting on the surface. The scraper can be operated either continuously or intermittently as required. Furthermore, to assist with the removal process and to maintain the cell walls relatively free of sludge, particularly at time of high algae load, sprays that are under automatic regulated flow have been provided.

A dedicated recycle system per pair of DAF cells is provided and is shown as part of Fig. 1 for one of the two DAF modules. The system comprising upto 16 recycle pumps and eight packed saturators will be capable of delivering 5–20% of recycle via up to three Enflo-Pi™ nozzle headers operated in the range of 4–6 barg. The air delivery system has been designed to provide on average an equivalent air dose of at least 10 gm/m^3.

The required clarified water as detailed in Table 4 will then flow to two separate blocks of 20 DMF units with each block further split into two banks of 10 filters, distributed either side of a pipework gallery running centrally between each bank.

Prior to the two blocks inline post-mechanically mixed flocculation chambers are installed at the inlet to the two blocks for mixing of a secondary dose of ferric chloride to aid the coagulation of any material that may escape from the DAF stage, particularly at the time of a red tide event.

The design details and filtrate quality requirements for these filters, etc. have been summarised in Tables 3 and 4, respectively. Furthermore, based on the anticipated water quality off the DAF filter run time of at

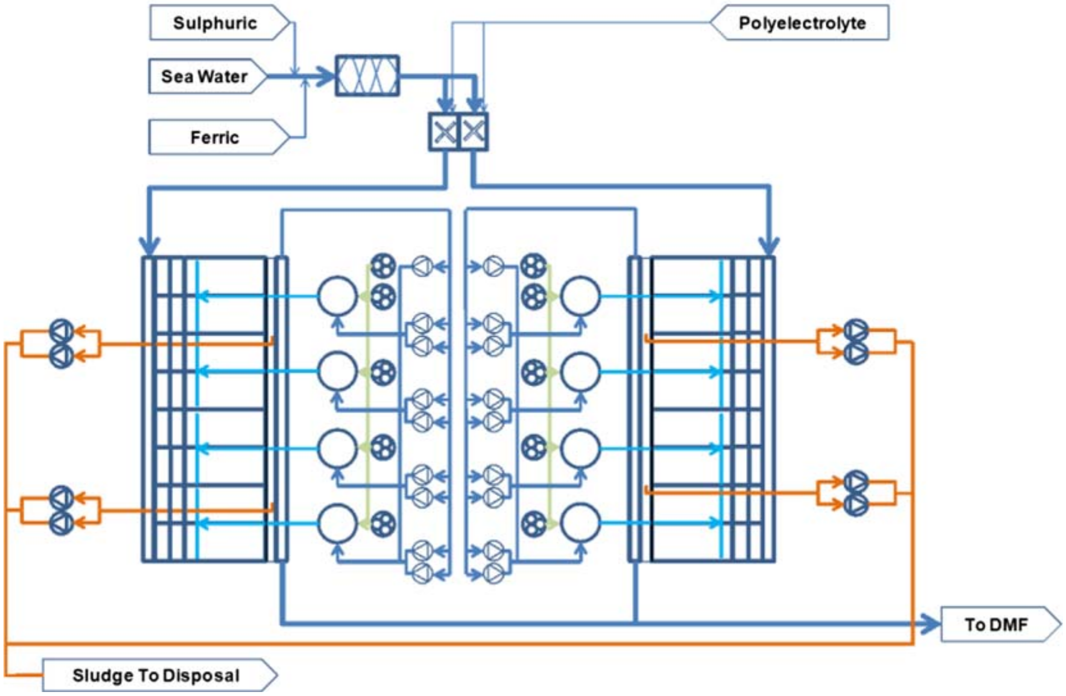


Fig. 1. Outline main plant process flow diagram.

least 24 h is envisaged. Due to the multimedia configuration in terms of both type and size, the washing regime to be employed will be a combination of air and water, with the latter being first at a low rate and then at a highrate to ensure a bed expansion of 40%, as specified, and restratification. As the washwater to be used is effectively RO concentrate with approximately a 50% increase in the TDS levels when compared with the raw seawater, a rinse period of ~30 min is provided before the washed filter is returned into service, and then together with the other filters in service, the filtrate will flow forward for further processing by the SWRO.

2.3. Pilot plant

A fully automatic pilot plant was supplied and was intended to not only validate the design for the main plant but provide operational experience in advance of the main plant commissioning phase. It was acknowledged that for the pilot results to have any value, the plant had to be purpose built and of a size that would be representative of the main plant, particularly as the latter was to be constructed at the same time as the trials were undertaken! Furthermore, as previously reported [4], the depths of the DAF cell together with the hydraulic loading are seen as an important part of any design. In the light of this, a plant of ~1/50th scale was proposed in terms of flow, that is, 61.2 m^3/h, but essentially full scale in terms of tank depths.

The treatment steps and rates were identical to those proposed for the main plant, and the process flow is detailed in Fig. 2. However, unlike the main plant, four different filters in terms of media configuration and potential wash regimes, each with a diameter of 0.7 m or ~0.4 m^2 bed area, were provided and operated at the same loading rate. The actual flow to each filter, for practical reasons, was set at 2.5 m^3/h, resulting in the balance of ~51 m^3/h being discharged to waste. Furthermore, the hydraulic driving head per filter was set to the same level as determined for the main plant to ensure that filter run times and loss of head (LOH) profiles did not need to be extrapolated.

It should be noted that whilst the total media depth of anthracite, sand and gravel of 1.7 m was to be supported on filter blocks on the main plant, a filter nozzle floor was used on the pilot plant, since for practical reason, should separate backwash trials cause severe disruption of the bed, it would be easier to return the filter back to its original state.

Of the four filter columns provided, only one, filter column No. 3, was considered at any one time as for "trial" and acting as feed to a separate RO pilot plant. It should be noted that the results from the other columns will not be covered herein. The concentrate from this RO pilot plant was as on the main plant used as the source of backwash water for all the filters.

The performance of the pilot plant was monitored online, remotely and by analysis of samples collected periodically.

The online monitoring of flow, turbidity, pH/ORP (oxidation reduction potential or redox), organics (using UV_{254}), temperature, conductivity, filter pressure drop and filtrate chlorine residual was logged

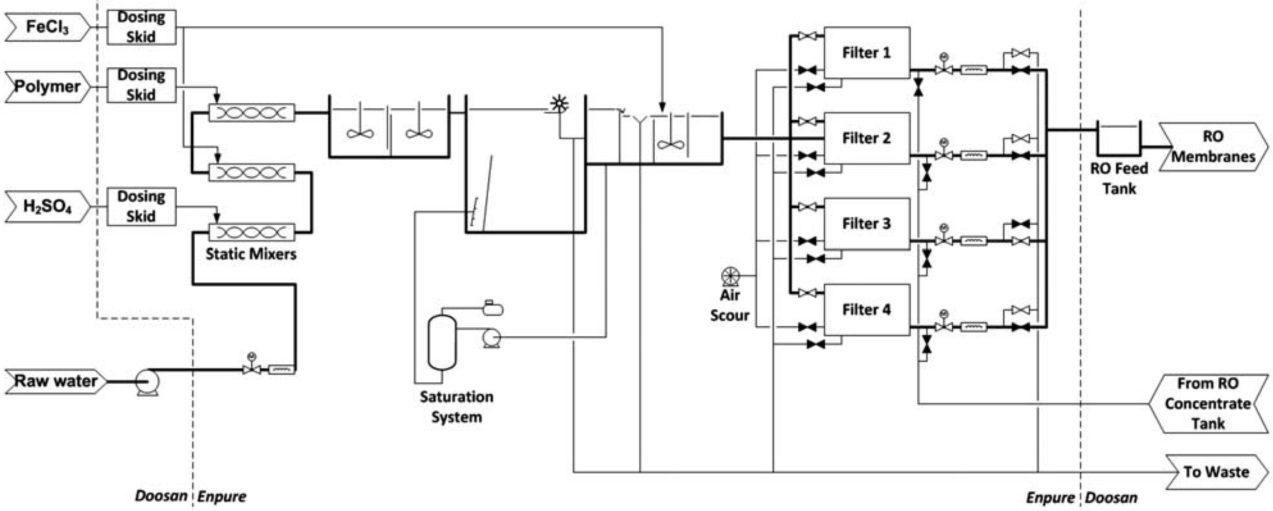


Fig. 2. Pilot plant: process flow diagram.

and trended using a PLC/SCADA system. In addition, a number of parameters such as suspended solids, UV_{254} absorbance, SDI_{15}, TOC and algae/chlorophyll A were measured off line.

3. Process issues

The application of DAF as reported in the literature [5] since its early wide scale introduction has primarily focused on non-saline water sources, and whilst the basic principles readily transfer to the treatment of brackish and seawater, a number of key process issues need to be addressed such as, but not necessarily limited to the seawater chemistry associated with treatment, the dissolving of the air required and tank design; these are briefly described in the following sections.

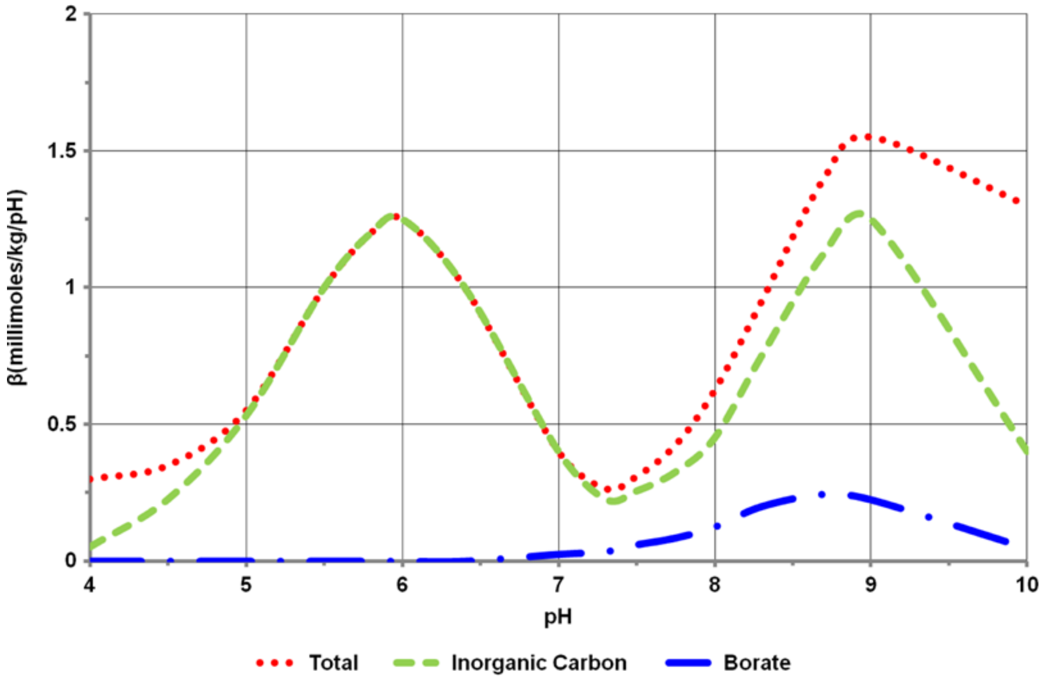
3.1. Seawater chemistry

A detailed description of this subject falls outside the scope of this paper, so the following merely summarises some of the basic points as they relate to DAF.

The basic parameters such as density and viscosity will be dependent on such things as temperature, salinity and even depth; for instance, at the surface, assuming a temperature of 30°C and a salinity (S‰) in the range of 35–47, the equivalent density and viscosity will be ~1,021–1031 kg/m^3 and ~0.861–0.886 $\times 10^{-3}$ kg/ms, respectively. In addition, chlorinity, a measure of the chloride and bromide components, plus the ionic strength are also of interest; generally, these are equivalent to $S/1.80,655$ and a sum of all the molar concentrations of ions in the solution, respectively.

When considering coagulation, the actual pH is significant both in terms of the alpha factor and bubble attachment efficiency [5], in determining the efficiency of the DAF clarification process and minimising subsequent coagulant residuals. Therefore, this respect there is a need to consider the buffer intensity of the water, which is defined as the resistance to change when either an acid or alkali is added to the water.

As can be seen from Fig. 3, the buffer intensity is high at two key pH values of ~6 and ~9, whilst with relatively low dosages of acid the pH can be readily depressed in the range of ~7.3–8. Outside of this narrow range, depression of the pH is more demanding in terms of the chemical dose rates required to reduce the pH to an ideal for the process requirements of the



Notes (1) Edzwald [6], Seawater at 20^0C, S‰=35 & $C_T=2.2\text{x}10^{-3}$ moles/kg & $B_T=4.1\text{x}10^{-4}$ moles/kg

Fig. 3. Seawater buffer intensity.

plant under consideration, or conversely, increasing the pH after coagulation beyond ~8 will require high levels of alkali.

The contaminants found in seawater are similar to those found in surface waters such as particulates both mineral and organic, the latter of which may comprise algae. These particles are generally stable due to a negative surface charge and hydration or steric effects with surface-bound water or spatial structures, respectively, preventing aggregation. In addition, some algae are mobile and able to swim away using flagella and they are self preserving, all of which prevent aggregation to occur and hence their removal.

The turbidity of seawater is generally low, that is, <1–2 NTU, unless close to shore or due to intense algae blooms.

The removal of particulates is necessary to prevent excessive load, and in the case of algae, their removal is important not only to reduce load but also to mitigate the risk of the release of extracellular material such as polysaccharides or cell lysis or rupture arising from differential pressure and shear within the system, all of which can encourage fouling.

The types of algae that can rupture are the dinoflagellates such as *Ceratium Tripos* and *Ceratium Furca* or *Protoperidinum* spp.; these can be readily removed by both DAF and media filtration.

In general, the coagulant of choice for the treatment of seawater to date would appear to be ferric chloride, and the efficacy of the dose will be dependent on both the nature of the particles and the coagulation pH. Taking into account the above, the dose rates will vary, and in the case of this particular project, a typical value anticipated was ~2 mg Fe/l though a design value of 3.5 mg Fe/l was used. However, in the presence of algae which may be excreting algae organic matter (AOM), then it was assumed that these dose rates would need to be increased at these times. In addition, pH conditions will vary subject to the nature of the contaminant. The literature [6] suggests that to minimise the increase in dose of coagulant to ~6 mg Fe/l, acid should be used to reduce the pH to ~6.0–6.8.

It should be noted that whilst the minimum solubility pH for iron is ~8 or even in the range 6–7, the theoretical residuals of iron would be ~1 μgm Fe/l [6].

In the case of the RAK project, the dose rates are as referred to in Table 2 whilst the target coagulation pH was in the range of 6.2–6.8.

3.2. The dissolving of air

As has been reported previously [4], the air dissolved and subsequently released has two functions: apart from the function needed to provide the buoyancy for the flocculated material produced, it also aids hydraulic stability within the DAF cell.

The way the air is dissolved, delivered and injected into the DAF cell will vary; however, here for both the main and pilot plant, the approach was and is to be the same: that is, the use of a packed saturator and proprietary nozzles. A general description of the principles can be found in the literature [5,8].

At this time, the saturator efficiency was assumed to be 90% whilst the salting out effect arising from seawater salinity was assumed to be the equivalent of ~25%. The bases for the latter value are best summarised in the following sample calculation, which is intended to demonstrate the techniques used whilst the actual figures were adjusted as part of the detailed design.

3.2.1. Example: the affect of salinity on the solubility of air in seawater

Air dissolved $c = k_H p_g$	
c = solubility of gas, k_H = proportionality constant, p_g = partial pressure of the gas	
Assuming a nominal water temperature of 25℃	
Oxygen $k_{HO} = 756.7$ atm/(mol/l)	Nitrogen $k_{HN} = 1{,}600$ atm/(mol/l)
mwt: $O_2 = 31.9{,}988$ g/mol	$N_2 = 28.0134$ g/mol
In air O_2:N_2 ratio = 0.21:0.79	In saturator O_2:N_2 ratio = 0.115:0.885
$c_O = (1 \times 0.115/756.7) \times 31.9988 = 4.86$ mg/kg	$c_N = (1 \times 0.885/1{,}600) \times 28.0134 = 15.5$ mg/kg
Total = 20.36 mg/kg into surface water	
Increasing salinity = "salting out effect"	$k_{Hs} = \frac{S_O}{S} k_H$
Setschenow equation	$\log \frac{S_0}{S} = k_s l$
Ionic strength (I)	$0.5 \sum_i (c_i z_i^2)$
where S_O = Solubility in pure water	k_S = salting coefficient (experimentally)
S = Solubility in electrolyte (i.e. seawater)	c_i = molar concentration of ion (mol/l)
k_{Hs}= Salinity modified k_H	z_i = charge of species i
$O_2 = k_{sO} = 0.145–0.6 \times 10^{-3} t + 0.65 \times 10^{-5} t^2 = 0.135$ [7]	
$N_2 = k_{sN} = 0.155–0.63 \times 10^{-3} t + 0.69 \times 10^{-5} t^2 = 0.144$ [7]	
Assuming temperature in the range of 0–40℃	
$O_2 = k_{sO} = 0.13–0.146$; Average = 0.138	
$N_2 = k_{sN} = 0.14–0.16$; Average = 0.150	
Assuming seawater	
SG = 1.023–1.03; Average = 1.027	Chorinity (Cl) = Sal/1.80655

(*Continued*)

Salinity (Sal) = 38–47; Average = 42.5

Volumetric ionic strength $I_V = 0.036 \times \mathrm{Cl} \times \mathrm{SG}$

$I_{\mathrm{VSea}} = 0.036 \times 42.5 \times 1.027/1.80655 = 0.8698$

$I_{\mathrm{VSea}} \times k_{\mathrm{sO}}$ or k_{sN} taking antilogs = 1.318 or 1.35

S or c_{O} for $O_2 = 4.86/1.318 = 3.687$ mg/kg

S or c_{N} for $N_2 = 15.5/1.35 = 11.482$ mg/kg

Total = 15.169 mg/kg into seawater

Reduction of solubility in seawater ~25%

3.3. DAF tank design

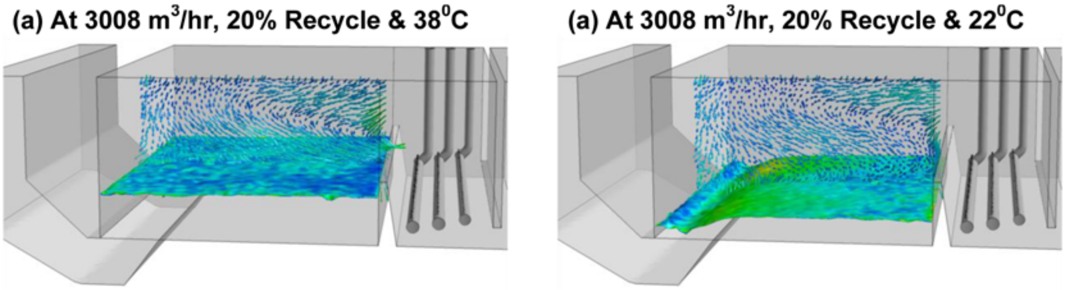
The basis generally used in the design of the DAF tank is to initially consider the hydraulic surface loading, based on net flow excluding the recycle into the tank divided by the total area provided by the contact and clarification zone. However, this approach takes no account of the water depth, and it could readily be seen that if a tank were too shallow, depending on the rate applied both the air released and the bubble floc agglomerates could escape the tank. In the past the tank depth was determined empirically from experience. The author first reported in 2007 [9] how a more scientific approach to determine the tank depth can be used, and these principles have been utilised in the design for this project.

The maximum loading considered for the RAK project was 30 m/h, and based on an operating temperature of 22–38 °C, where the worst case in terms of greatest risk of both whitewater and bubble flocc agglomerates escaping the tank is at the minimum temperature, a computerised fluid dynamic (CFD) model was completed of the tank proposed and summarised in Table 3. This is highlighted in Fig. 4 where it can readily be seen that at the maximum loading and recycle rate subject to the water temperature, the depth of the underside of the whitewater blanket below the surface, represented by the dark solid layer, will change but does not escape the tank. Furthermore, the vorticity magnitude [9] predicted, that is, the degree of turbulence, was low being in the range of 0.09–0.107 s^{-1}. Hence, it was concluded from this that the design proposed for the main plant should be acceptable, and on this basis, a pilot plant with a similar depth should confirm the CFD predictions in terms of performance and product quality; refer to the later sections for more details.

4. Pilot plant results

At the time of writing, the pilot plant has been running for approximately 6–7 months at a loading rate throughout of 30 m/h, and apart from the occasional interruptions in operations, arising from the fluctuations or failure of incoming generator power, the plant has operated continuously and automatically. Although the occasional storm gives rise to higher-than-specified turbidity at the inlet, comprising both sand and fibrous material, there has been no significant algal presence. Therefore, the results summarised in Table 6 and represented graphically in Figs. 5–9 highlight some of the key operating and performance parameters recorded to and from the DAF and filter column No. 3, the latter representing the actual configuration proposed for the main plant.

With reference to Tables 2 and 4, it can be seen that the performance of the DAF summarised in Table 6 operating together has readily achieved the desired quality requirements ahead of the SWRO. On those occasions, based on the 95 percentile values, where for instance the total iron residuals and suspended solids measured exceeded expectations off the DAF, there was in fact no significant impact on the performance of the overall plant, which continued to be fully compliant. On those occasions where the quality off the DAF was outside the desired limits, then this was primarily due to other operating conditions not being fully optimised, particularly when the raw water quality exceeded the design specification as highlighted in Fig. 5 for instance with an inlet turbidity of >12 NTU.



(a) At 3008 m^3/hr, 20% Recycle & 38^{0}C

(a) At 3008 m^3/hr, 20% Recycle & 22^{0}C

Fig. 4. CFD prediction of the main plant DAF tank hydraulics.

Table 6
Operating and performance summary

Source	Units	Range	95 percentile values
Raw water			
pH		8.0–8.8	8.28
Temperature	˚C	13.3–34.3	32.5
Turbidity	NTU	0.35–32	12.5
Flow	m^3/h	61–61.5	61.2
SDI$_5$	%/min	12–29	19
Chemical dosing			
Ferric chloride	mg Fe/l	0.8–3.1	$\sim$2.8
Sulphuric acid	mg H_2SO_4/l	14–53	$\sim$29
Polymer	mg product/l	0	0
Coagulation pH		6.4–7.3	6.67
DAF product			
Net loading	m/H	29.9–30.2	30
Recycle	m^3/h	6.8–10.1	10
Recycle	%	11–16.5	16.3
Turbidity	NTU	0.12–8.56	1.05
SDI$_{15}$	%/min	15.8–19.5	$\sim$19
Total iron residual	mg Fe/l	0.6–1.8	$\sim$1.1
Suspended solids	mg TSS/l	0.4–$\sim$31	18.5
Sludge flow	m^3/h	0.01–0.2	0.1
Filtrate			
Turbidity	NTU	0–0.13	0.1
SDI$_{15}$	%/min	1.2–4.15	3.9
Total iron residual	mg Fe/l	0–0.04	0.03
Filter run times	min	1,440–2,880	1900

It should be noted that during those periods when the raw water turbidity was high, it had coincided with storm conditions, with strong onshore winds that resulted in fine sand and coarse fibrous material passing the inlet screens ahead of the pilot plant.

In addition, it is clear from Fig. 6 that when recycle rates are less than ideal, the risk of higher-than-expected clarified suspended solids arising increases; however, when the recycle rates were increased, the suspended solids concentration reduced as capture rates improved. As suggested in Section 3.2 and as previously reported by the author [4], noting temperature and salinity effects, the recycle rate will impact the amount of air delivered and potential stability within the DAF cell.

The increase in recycle rate evident from Fig. 6 coincided with the first major storm experienced by the pilot plant; yet, it can be seen that this and later storms were readily handled with both suspended solids and turbidity, which reduced significantly across the DAF stage. However, what should be noted here is that in general for municipal water treatment practice, where it has been suggested [10] that there is a relationship between turbidity and suspended solids measurement which follows an empirical ratio of $\sim$1:2, in this particular trial, probably due to the characteristics of the solids, such a relationship needs to be used with care.

Furthermore, whilst the procedure falls outside the scope of this paper, the actual measurement of suspended solids in a highly saline water needs to be undertaken with care ensuring adequate flushing of any filtering medium is completed with distilled or similar water to clear any retained dissolved salts from the vessel and within the interstitial spaces of the filter membrane used. Failure to do so will mean that the values reported for suspended solids will be higher than is actually the case.

The potential impact of these higher-than-expected solids going forward onto the filter and in particular the headloss and run times obtained can be seen from Fig. 9 where two approximately 6-day periods are highlighted, these being during the storm events of August 2011 and the cooler period of late January 2012. In both cases, the air and water rates were the same though in the latter case the high-rate wash period had been extended from 6 to 7 min; the reasons for this change are covered later. In addition, the washing cycle was undertaken fully automatically with the wash frequency set at 24 h though the wash could be initiated if both the LOH and turbidity exceeded the desired values of $\sim$2.5 and 0.5 m, respectively. It is evident from Fig. 9 that whilst during August 2011 the headloss or the differential pressure (Dp) development was higher than for January 2012 at 5–6.5 and $\sim$3 cm/h, respectively, at no time the maximum head available exceeded.

In the case of Figs. 7 and 8 where the coagulant dose and pH were maintained essentially constant at $\sim$2 mg Fe/l and 6.6, respectively, the water temperature appeared to have the biggest impact on filtrate quality in terms of iron residual and SDI$_{15}$, particularly when this fell below the design minimum of 22˚C.

In fact, it was when the seawater temperature fell to $\sim$15˚C that it was decided to increase the duration of the wash period from 6 to 7 min in an attempt to minimise the fine residue remaining within the filter bed, hence ultimately impacting the SDI$_{15}$ values recorded. To date, the upward trend previously seen

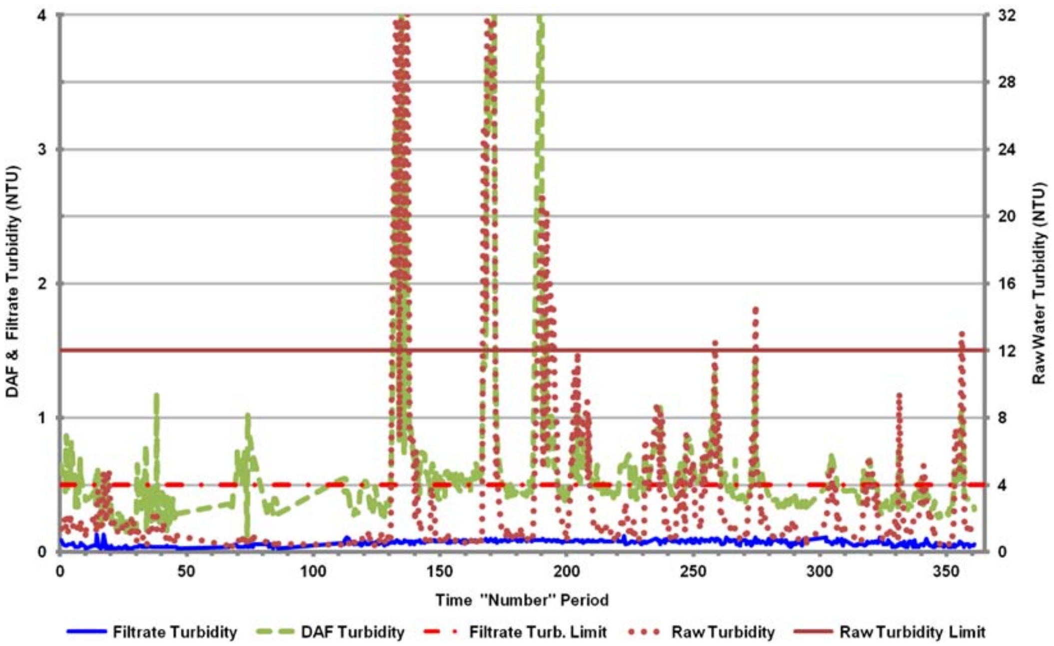


Fig. 5. Turbidity results summary July 2011–24th January 2012.

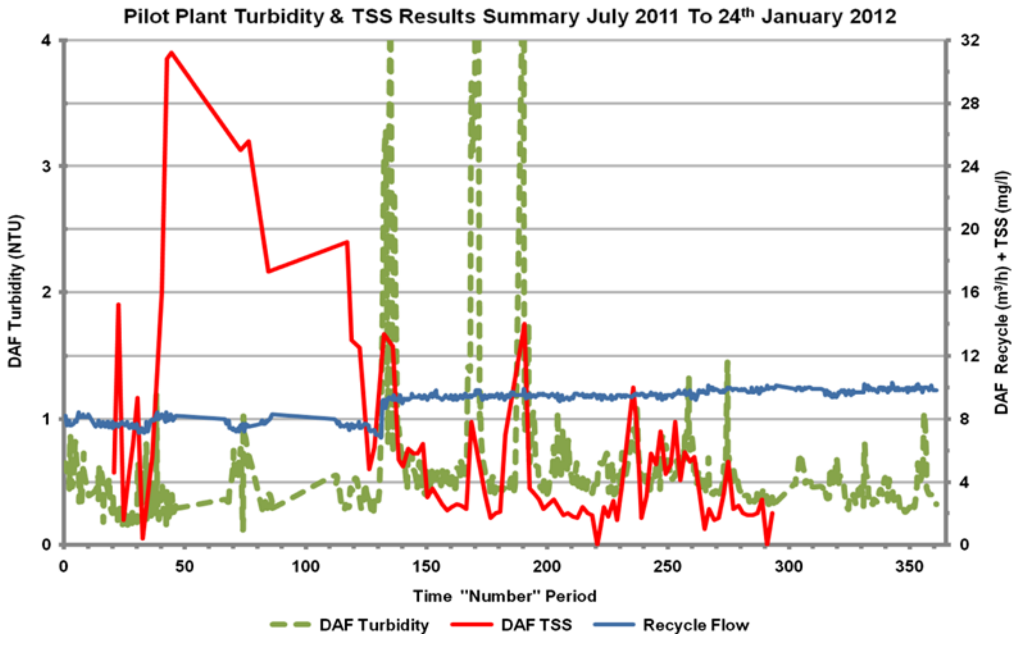


Fig. 6. DAF turbidity and TSS results summary July 2011–January 2012.

in the SDI_{15} values has been halted, as evident from Fig. 7, after the wash period was increased, highlighted by the vertical line.

A further point to note is that the SDI_{15} off the DAF remained fairly constant throughout this period at ~19.

5. Conclusions

As stated at the outset, the results reported here are preliminary and should be regarded as such since the trials continue, and therefore, some of the conclusions that follow may need to be adjusted in

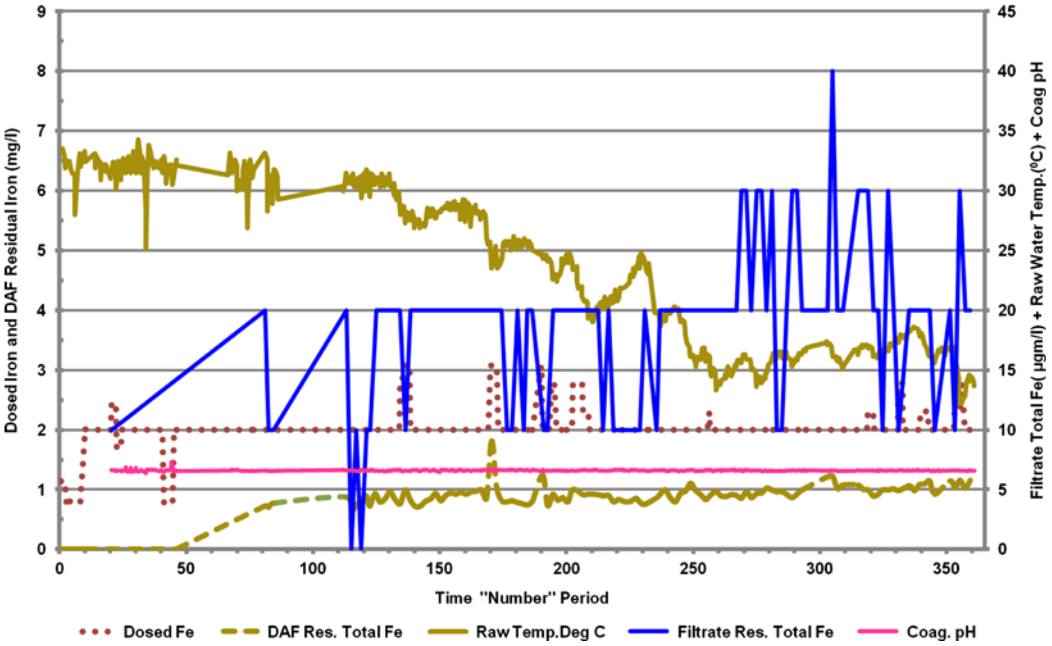


Fig. 7. Iron dose and residuals summary July 2011–January 2012.

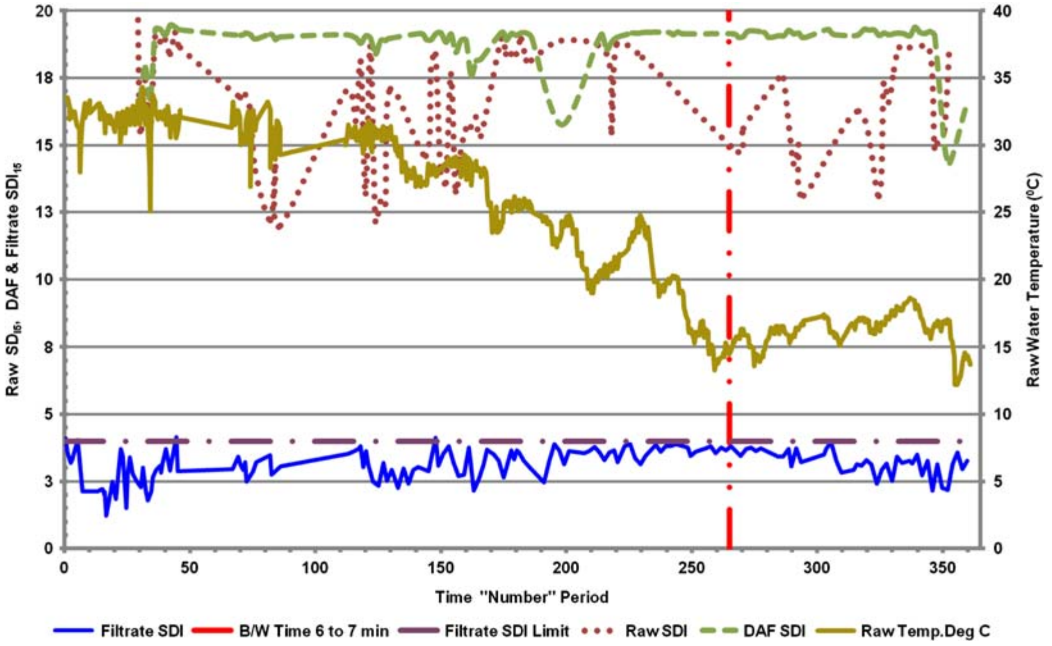


Fig. 8. SDI results summary July 2011–January 2012.

the light of later findings; that said, after approximately 6 months operation under constant hydraulic load, it is clear that the combination of high-rate DAF at 30 m/h and dual-media gravity filtration at 6.5 m/h provides a robust and reliable pre-treatment stage ahead of a SWRO plant.

It is clear that chemical dosing should be appropriate not only for the prevailing conditions, but also for the process to be employed, and that said, recycle rates have to be adjusted to cope with not only the solids load but also the high saline and temperatures characteristic of the Gulf seawater.

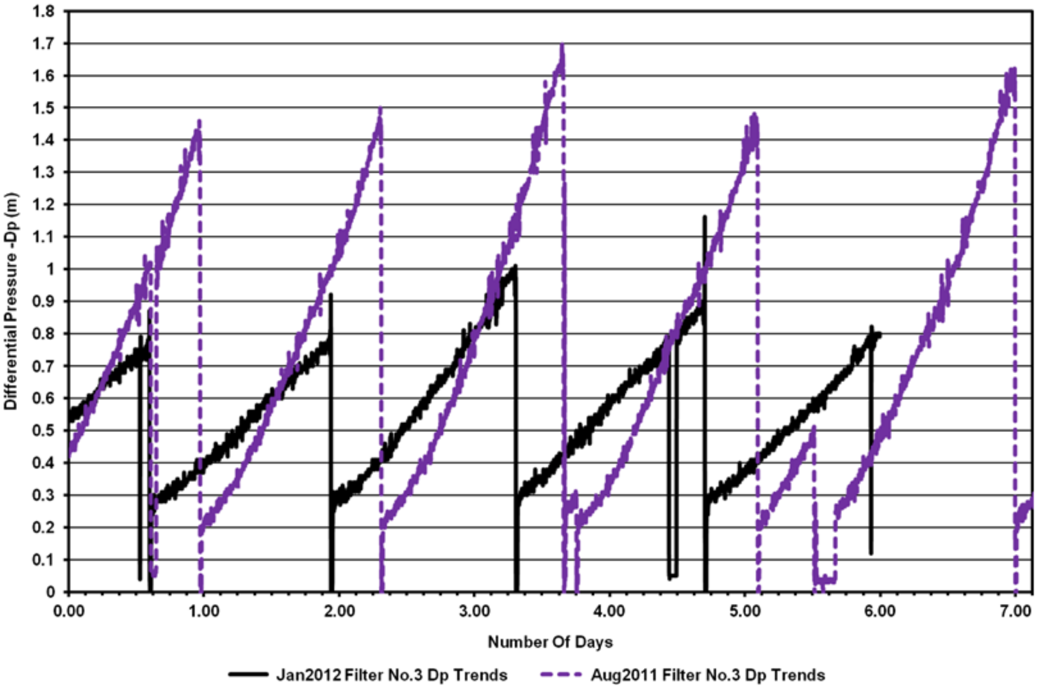


Fig. 9. Filter no. 3 Dp vs. run time during ~6 months of operation.

The design of the DAF cell with appropriate depths and vorticity values based on previously reported studies [4,9] has been shown to be appropriate, given the results recorded and reported above.

Acknowledgements

The authors thank those Doosan Heavy Industries and Construction and the operators on site who collected the results on a daily basis without whose commitment this paper could not have been produced.

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