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Produced water reuse enabling circularity in oil operations

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ABSTRACT

Saudi Aramco conducted comprehensive a field-testing program of produced water desalination technologies primarily targeted for produced water reuse as process/utility water and other industrial purposes with low total dissolved solids (TDS) (<1,000 mg/L). The main driver for the produced water re-use program was due to, firstly transition from linear model of economic growth, which is based on "take-make-dispose", which is not sustainable to circular economy model supporting "closing the loop" of recovering value from produced water considered waste stream and secondly the conservation of Saudi Arabia's precious non-renewable ground water resources which are currently used for crude washing in desalting across Saudi Aramco. The program will reuse produced water in its oil operations, with potential ground water savings up to several billion gallons annually post implementation and also enable circularity sustainably in its oil operations. The objectives of the program were to evaluate the produced water desalination with minimum 70% recovery factor as performance for two different configurations, that is, desalination of low salinity (TDS) produced water (<15,000 mg/L) and high salinity (TDS) produced water (<120,000 mg/L). A US patent 10,703,989 was also granted for the concept of produced water reuse. Produced water desalination testing was conducted at two different produced water streams in Arab Light crude oil at two different sites with gravities of 36–41 API, to determine the desalination performance and challenges with pre-treatment. Variation in feed conditions such as flow rate, temperature, inlet oil in water concentration and H_2S in water, recovery factor were introduced to establish operating envelopes for the produced water desalination systems. The performance of two field produced water desalination technologies was evaluated by determining the salinity (TDS) and oil in water concentration at different operating conditions. Prior to piloting the laboratory bench test were conducted at lab scale to characterize the performance of produced water. The lab test helped identify the challenges during pilot testing and demonstrated that produced water desalination for sustained flow conditions. This paper presents the key results of produced water re-use program along with two field tests as well as the path forward to deployment of these technologies to unlock the value for produced water as resource in circular economy. The implications of this program success extend beyond Saudi Aramco. By increasing produced water reuse in the oil and gas processing, more groundwater will be available for non-industrial applications in Saudi Arabia, which reduces reliance on seawater desalination.

Keywords: Produced water; Desalination; Sustainability; Produced water reuse; Circularity; Arab light

1. Introduction

Saudi Aramco has one of the largest integrated oil and gas supply chains in the world as shown in Fig. 1. The supply chain starts from onshore and offshore oil fields where the multiphase oil, gas and produced water is transported to oil processing facilities through pipelines. In oil processing facilities are also known as gas oil separation plants (GOSP) at Saudi Aramco, where crude oil is produced with

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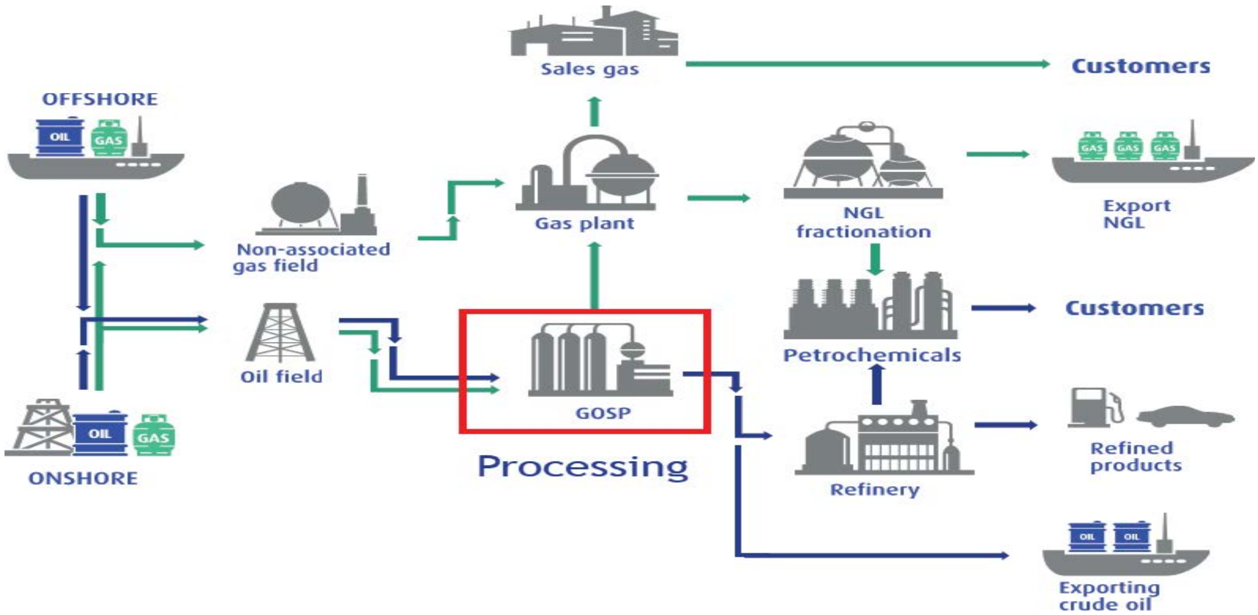

Fig. 1. Oil and gas supply chain at Saudi Aramco.

associated produced water and gas is processed to separate into three separate products – crude oil, gas and produced water. GOSPs are designed to meet each product quality specifications. The associated produced water is disposed to dedicated wells for removal and in some cases to wells for reservoir pressure maintenance. The associated gas is process to produce lean gas (methane) is sent to Master gas system for industrial needs such as desalination, power and feedstock to petrochemical plants. Natural gas liquids (NGL) recovered from gas plants are sent to NGL fractionation plants. The crude oil from GOSPs is either sent to terminals for export to global customers or to refineries for further processing into refined products.

In the crude supply chain, GOSPs are the heart of the process and represent large proportion of facilities (50+) at Saudi Aramco. There are 5 types of crude grades processed namely Arab Light, Arab extra light, Arab Super light, Arab Medium and Arab heavy. This paper will focus on Arab Light (36–41 API degree) processed at GOSPs which represents large proportion of the crude production.

2. Gas oil separation plant (GOSP)

The process scheme of the GOSP is shown in Fig. 2. In GOSPs, wild wet crude oil is routed through pipelines to production header which feeds the gravity separators. Gravity separators separate the crude, associated gas and water in three distinct phases with volume fractions of gas in liquids and vice versa. The separation is driven by stokes law and aided with oil field chemicals such as demulsifier. Wet gas is sent to the gas gathering system for processing. The two-phase oil and produced water is pumped through charge pumps to the wet crude handling (WCH) train which consists of two electrostatic vessels – dehydrator and desalter in series to meet the crude quality specs for un-stabilized crude to pipelines. Wash water and demulsifier are injected upstream of the mixing valve. Wash water used for crude desalting is obtained from natural aquifers. In electrostatic vessels, a high voltage electric field is generated between the electrode grids which coalesces the water droplets to drop to bottom for removal from the vessels. The crude is then pumped to crude stabiliser to further remove the light ends in the crude and meet H_2S specification in crude using steam reboilers. The crude oil is stabilised in the stabilizer column by removing H_2S and remaining gases using steam reboiler. The crude is then pumped by the crude export pumps to downstream facilities or stored in tanks for batching process.

The produced water separated in gravity separators/dehydrators/desalters and wash water used to “desalt” the crude oil are sent to produced water treatment equipment (API separator/WOSEP-water oil separator) to recover remaining oil in water before disposal to wells. The API separator is designed to treat produced water from with oil in water content from 1,000–2,500 to 50 ppm.

3. Water circularity and sustainability

Produced water is considered as waste product and is part of the current linear economy model of “take-make-dispose”. Produced water is injection after de-oiling into disposal reservoirs and not reused in any oil operations. In addition to this produced water disposal, wash water with low salinity (<1,500 mg/L) is obtained from non-renewable ground water aquifers for crude washing. This water once utilised in crude desalting is disposed along with the produced water as shown in Fig. 2. Given that most GOSPs in Saudi Aramco utilise precious non-renewable ground water resources which are currently used for crude washing. Saudi Aramco develop a plan in 2011 and committed to the conservation of Kingdom’s ground water resources. Corporate water conservation policy (CP-25) was developed which mandated a companywide drive to minimize groundwater use through optimizing water consumption, minimizing water losses, maximizing wastewater reuse and promoting the use of sustainable alternative to ground water [1,2]. The policy drove the development of ground water conservation program which eventually developed into the produced water re-use program.

4. Produced Water Reuse Program

The program aims to treatment produced water for reuse eliminating ground water utilization to promote water circularity and sustainability of oil operations. Produced Water Reuse program was developed on the principles of circular economy for water with the 3Rs – reduce, recycle and reuse in focus. This program will eventually conserve up to several billion gallons of non-renewable ground water currently used for crude desalting in Saudi Aramco GOSPs and Refineries. The program drove innovation to identify waste streams in oil operations and recycle them to be reused. The program mapped and identified two main waste stream as shown in Fig. 3. The desalter effluent stream with low salinity (<15,000 mg/L) after crude washing as ideal stream for de-oiling and desalination. The second stream identified was the API separator (Water Oil Separator) with higher salinity (<100,000 mg/L). These two streams were utilised by the in-house engineers to develop technology flow chart and screening of technologies for produced water reuse. The objective of the program was to determine treatment scheme with process equipment for implementation. The program was supported with bench scale verification

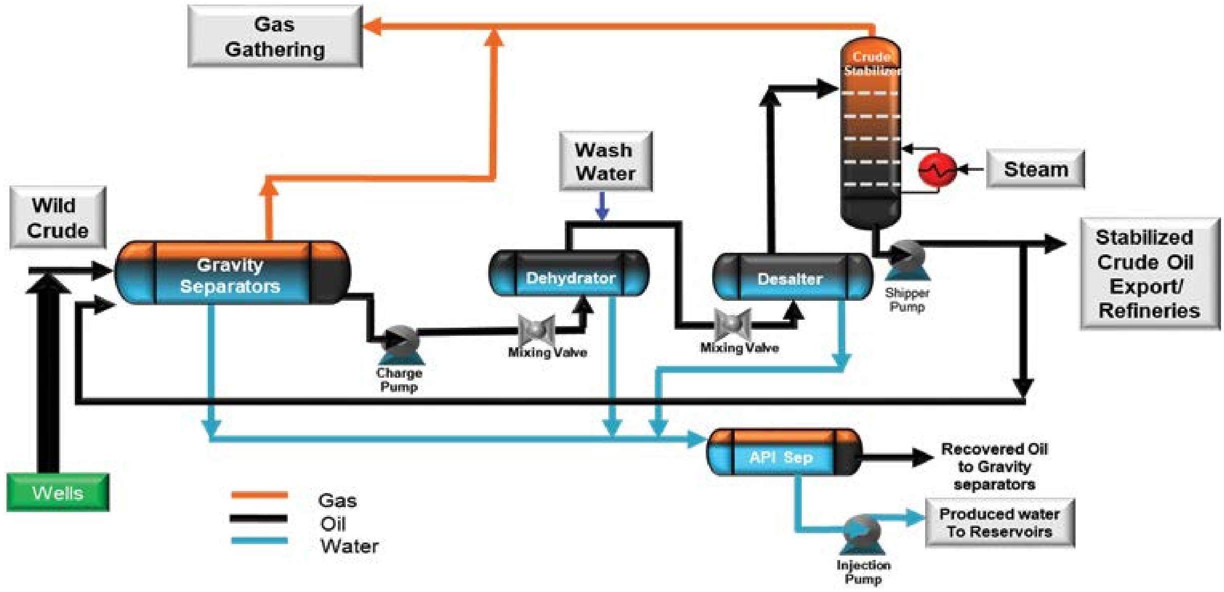

Fig. 2. Process scheme of gas oil separation plant (GOSP) at Saudi Aramco.

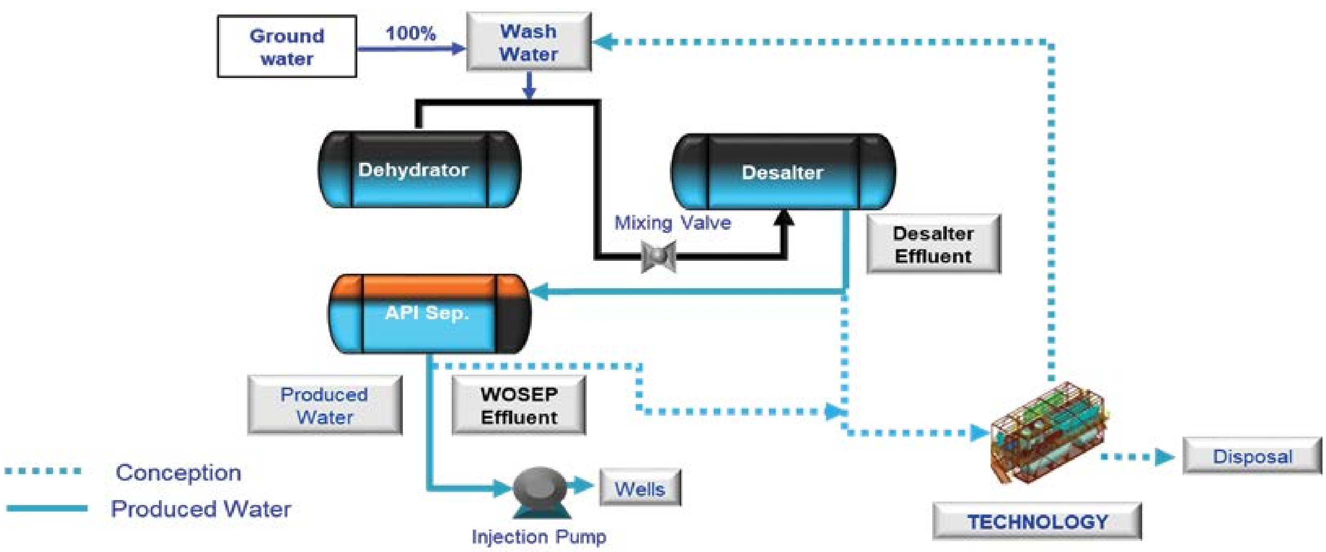

Fig. 3. Produced water reuse process schematic.

for produced water de-oiling and desalination. The program considered both summer and winter conditions and defined the limits for produced water desalination. Saudi Aramco was also recently granted US Patent Office No. 10,703,989 "Conserving fresh wash water usage in desalting crude oil" which is the guiding process for produced water reuse in oil operations.

5. Produced water desalination

The program identified several mature and emerging technologies to treat the two produced water streams – low salinity (<15,000 mg/L) and higher salinity (<120,000 mg/L). The technologies identified from literature survey were mapped on their sensitivity to oil in produced water and recovery factor. The technologies were evaluate to desalination produced water with minimum 70% recovery factor in terms of performance and along with energy and utility costs (chemicals) for desalination.

$$\text{Recovery Factor}(\%) = \frac{\text{Product flow}}{\text{Feed flow}} \times 100 \quad (1)$$

The technology selection was categorise based on technology readiness level (TRL): method of estimating technology maturity was developed by NASA in early 70s [5]. The use of TRLs as shown in Fig. 4 enables consistent, uniform, discussions of technical maturity across different types of technology. The TRL scale used in Saudi Aramco and utilised also by US DoD technology readiness assessment (TRA). Table 1 describes the different technology readiness levels from TRL 9 to TRL 1 adapted for technology deployment in produced water reuse program.

Table 2 lists all the technologies that were identifies by the program for pilot testing and deployment subject to entire lifecycle economic analysis with respect to net present value (NPV) The program also considered the reuse of membrane and other consumables with respect to circularity. Given the two waste streams low salinity (<15,000 mg/L) and higher salinity (<120,000 mg/L), the several technologies were shortlisted for de-oiling and desalination.

Based on the above technology maturity, the program develop a basic process scheme so that our produced water can be handled by any of the selected technologies. Fig. 5 is an example of the process scheme that contains two main sections: pre-treatment and desalination. Produced water desalination requires robust, reliable and compact equipment for use in existing brownfield applications both onshore and offshore. The performance testing is the recommended way to confirm the feasibility of produced water desalination technologies for produced water reuse and demonstrated that within given operating envelope the system can treat produced water stream with oil in water content of up to 400 ppm, reducing it down to 0 ppm level while reducing salinity which is our target specification. In addition, the issue of pre-treatment of sour water can be addressed by designing the de oiling system with H_2S strippers and packed beds for contaminants as BTEX and other organics. These sections are further explained with the objectives with respect to our produced water.

5.1. Pre-treatment

In this section is designed to condition the produced water feed to be processed by conventional desalination technologies. This subsection de-oiling removes the dissolved and dispersed oils with conventional technologies such as

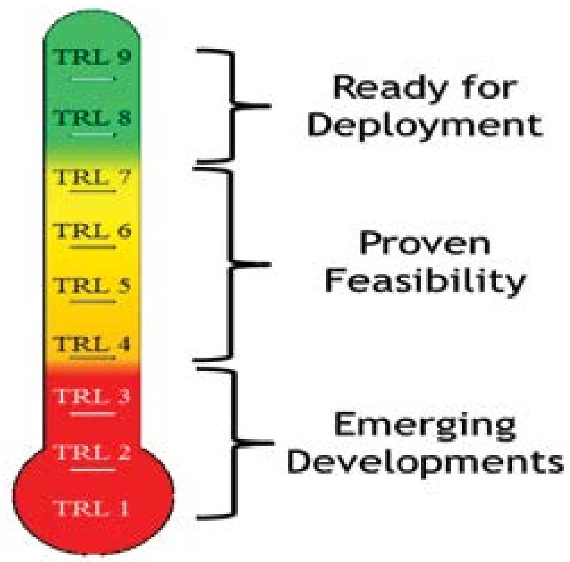

Fig. 4. Technology readiness level (TRL).

Table 1
Technology readiness level-maturity

TRL	Maturity level	Description
9	Ready for deployment	Proven technology with successful deployments in industry
8		Proven technology with demonstration in field conditions
7	Proven feasibility	Technology prototype in field conditions
6		Technology prototype in simulated field conditions at laboratories
5		Technology prototype validation in laboratories
4		Basic technology prototype testing
3	Emerging developments	Analytical and experimental concept
2		Technology concept formulation
1		Basic technology principles observed

hydrocyclone or induced gas flotation. The dispersed oil can also be removed using ultrafiltration membranes. H_2S is stripped from the produced water with chemicals and stripping column to prevent extensive scaling in the downstream process. The organic scavenger are used to reduce the total organic carbon content along with BTEX using packed beds.

5.2. Desalination

In this section, the produced water is subjected to desalination only and several technologies listed in Table 2 can be utilised to achieve the desired reduction in salinity. Each technology has it limitation dependent on the feed salinity expressed as total dissolved solids (TDS) in mg/L. Higher the salinity, greater would be the energy requirements to reduce the salinity and there have been advances in produced water treatment to reduce the OPEX for such treatment schemes.

6. Produced water feed quality and performance target

In this section, the produced water feed quality from both our case studies over last few years is listed with the defined target performance as shown in Table 3. This section will detail the complete geochemical analysis of the two produced water stream-low salinity (<15,000 mg/L) and high salinity (<120,000 mg/L). This will be basis used for the two pilot case studies conducted at Saudi Aramco. Tables 4 and 5 showcase the dissolved organics along with their geochemistry for low salinity (<15,000 mg/L) and high salinity (<120,000 mg/L) streams.

6.1. Case study 1: produced water low salinity desalination

The program shortlisted several GOSPs for the field testing based on the process scheme defined in Fig. 5. One technology supplier was shortlisted to provide and integrate all the components of the system for deployment. One of the largest onshore Saudi Aramco GOSPs located in Southern area was selected which processes 1,500 MBD of stabilised Arab Light (AL) crude oil with API 38. The GOSP is setup with five crude oil processing trains 300 MBD capacity besides gas trains, produced water treatme nt and injection pumps, utilities, crude storage tanks, crude shipping pumps and flare system. The GOSP processes wild wet crude oil and associated gas to separate them into stabilized crude oil and gas for transport through pipelines and injects their produced water to disposal reservoirs. The GOSP was also selected on account of centralised utilities (i.e., steam, N_2 gas and demineralised water) and lab support setup for field testing. The selected GOSP however posed a technical challenge of high temperature feed stream (160°F) as the crude oil desalting in this GOSP had crude preheating to break stable emulsions, unlike other GOSPs in Saudi Aramco. A high temperature desalination technology was required to avoid cooling water required during the field test phase. Fig. 6 is the process scheme at this GOSP with feed stream from the desalter effluent feeding the produced water reuse unit denoted in blue and the brine is sent to disposal pits.

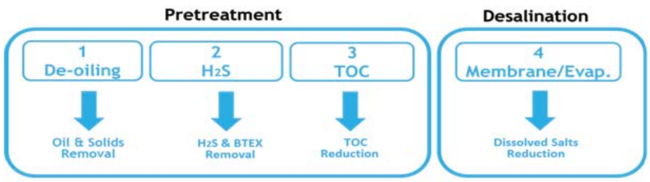

Fig. 5. Produced water reuse-pre-treatment (de-oiling) and desalination

Table 2
Produced water desalination technologies readiness level

Technology	Maturity	Salinity TDS (mg/L)	OIW limit	Oil removal requirement	Recovery factor %
Mechanical vapour compression	TRL 9	<150,000	No	N/A	70%–90%
Membranes	TRL 8	<100,000	Sensitive	Yes	70%–90%
Multiple effect distillation	TRL 8	<150,000	No	N/A	70%
Adsorption	TRL 9	<150,000	No	N/A	70%
Ion exchange	TRL 6	<1,000	Sensitive	Yes	<90%
Engineered wetlands	TRL 8	<15,000	N/A	N/A	Variable

Table 3
Produced water quality overview with target quality

Parameter	Case study 1 feed	Case study 2 feed	Performance target
Salinity: total dissolved solids (TDS), mg/L	10,962	94,157	<1,000
Oil in water, mg/L	10	1,000	<1
Total suspended solids (TSS), mg/L	202	263	<1
Temperature, °F	150	140	–
pH	7.7	7.4	6–7.5
Recovery factor, %	–	–	70

Table 4
Case study 1 feed water quality

Process parameters			
Process pressure, Psig			70
Process temperature, °F			90–150
H_2S content, ppm wt.			200–400
CO_2 content, ppm wt.			200
Basic parameters		**Cations**	
pH	7.7	Calcium (Ca), mg/L	641
Specific gravity	1.0289	Magnesium (Mg), mg/L	235
Total suspended solids TSS, mg/L	16.7	Sodium (Na), mg/L	2,400
Total dissolved solids TDS, mg/L	10,962	Potassium (K), mg/L	98.6
Bicarbonate alkalinity as $CaCO_3$, mg/L	202	Barium (Ba), mg/L	0.1
Bicarbonate HCO^{3-}, mg/L	186.7	Strontium (Sr), mg/L	8.9
Carbonate CO_3^{2-}, mg/L	19.7	**Anions**	
Total hardness as $CaCO_3$, mg/L	2,570	Chloride Cl^-, mg/L	5,330
Oil & grease, mg/L	28	Sulfate as SO_4^{2-}, mg/L	1,220
TOC, mg/L	12	Silica as SiO_2, mg/L	11.93
Total petroleum hydrocarbon (TPH)		**Volatile organic compounds – BTEX**	
$C_6 – C_9$ fraction, µg/L	34,800	Benzene, µg/L	27,200
$C_{10} – C_{14}$ fraction, µg/L	1,700	Ethylbenzene, µg/L	805
$C_{15} – C_{28}$ fraction, µg/L	1,820	Toluene, µg/L	4,720
$C_{29} – C_{36}$ fraction, µg/L	90	Meta and para-Xylene, µg/L	941
$C_{37} – C_{40}$ fraction, µg/L	<50	Ortho-xylene, µg/L	932
$C_{10} – C_{40}$ fraction, µg/L	3,610		
Volatile organic compounds – surrogates			
1,2-dichloroethane-d4, %	97.4	Toluence-D8, %	91.6
4-bromofluorobenzene, %	97.4		

The target for the unit was to produce water with salinity <1,000 mg/L [3,4].

Produced water reuse unit feed is defined in Tables 3 and 4 along with the performance target requirements. The process scheme in Fig. 7 was developed with the support of the technology and subject matter experts. The process scheme has several modules spread across pre-treatment and desalination which are briefly explained with their functions and individual performance. The field test was conducted for 3 months with continuous 24 × 7 operation with shutdowns to replace and test new membranes for ultrafiltration. Power was supplied by diesel generators and chemical used were caustic soda for pH adjustment, sulphuric acid to convert all sulphide ions to H_2S gas and anti-scalant for scale control.

Ultrafiltration (UF) membrane was the first module which was designed with inlet feed of 1,000–2,500 mg/L oil and 200 mg/L total suspended solids (TSS) and the outlet was <1 mg/L of oil and TSS. The module was able to achieve an average performance of 86% oil removal efficiency and 70% TSS removal efficiency. Ceramic membranes were used for UF module and both SiC and TiO_2 ceramic membranes were tested onsite and the regenerative performance of SiC membranes was better than TiO_2. H_2S Stripper module was able to strip the H_2S gas in sour feed and with injection of sulphuric acid upstream meet average performance of 1 ppm wt. while target was 0.2 ppm wt. as feed to reverse osmosis (RO) membranes. This was attributed to poor chemical management. The overall efficient was 99.5% and some volatile organic compounds such as BTEX were also reduced. The organic scavenger module selected was strong base anion resin which removes between 60%–80% of the dissolved organics. Polystyrenic resin was used due to greater reversible removal of organics on regeneration and can cope with higher levels of dissolved organics. They able to reduce the total organic carbon (TOC) from 12 mg/L down to 1 mg/L on average.

The next module was desalination, where high temperature reverse osmosis membranes were used. The RO module was designed with a recovery of 70%, (low TDS RO) permeate/product is produced. To achieve this recovery, the RO is designed as two stages RO unit with the configuration 2X–1X, that is two pressure vessels in the first stage, one pressure vessel in the second stage. Each pressure vessels contains 6 4-inch brackish water RO modules in series. The concentrate from the first stage is sent through

Table 5
Case study 2 feed water quality

Process parameters			
Process pressure, Psig			70
Process temperature, °F			90–140
H_2S content, ppm wt.			112
CO_2 content, ppm wt.			200
Basic parameters		Cations	
pH	7.4	Calcium (Ca), mg/L	10,000
Specific gravity	1.05396	Magnesium (Mg), mg/L	1,130
Electrical conductivity at 25°C, µs/cm	105,033	Sodium (Na), mg/L	39,000
Total suspended solids TSS, mg/L	265	Potassium (K), mg/L	1,335
Total dissolved solids TDS, mg/L	98,393	Barium (Ba), mg/L	1.8
Bicarbonate alkalinity as $CaCO_3$, mg/L	515	Strontium (Sr), mg/L	350
Bicarbonate HCO^{3-}, mg/L	628	Anions	
Carbonate CO_3^{2-}, mg/L	0	Chloride Cl^-, mg/L	45,331
Silica as SiO_2, mg/L	15	Sulfate as SO_4^{2-}, mg/L	618

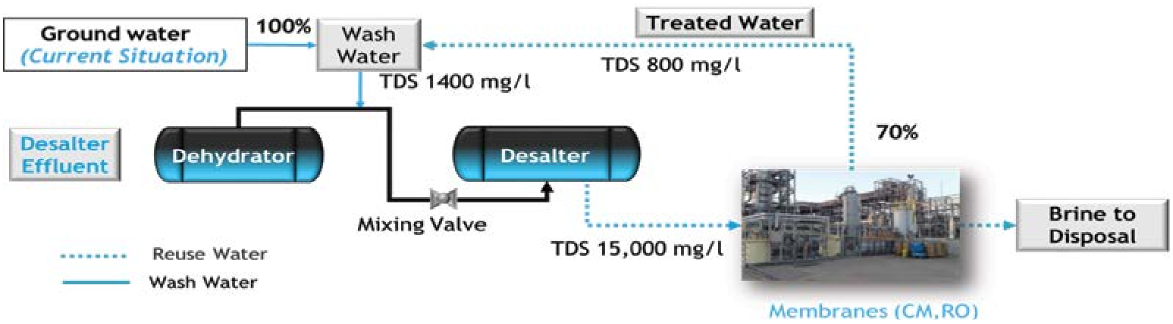

Fig. 6. Produced water desalination: membranes.

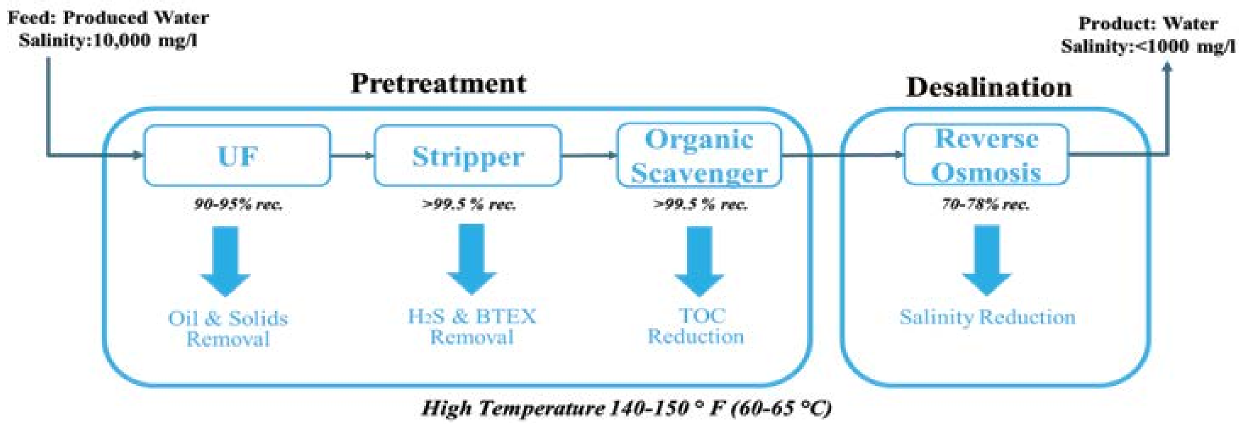

Fig. 7. Produced water desalination: membranes process scheme.

the second stage to maximize the recovery. The module was able to reduce the TDS inlet from 10,962 mg/L down to 800 mg/L average with target of TDS <1,000 mg/L.

The average recovery factor of 70% was achieved with this field testing with membranes and Fig. 8 is images of the field testing unit on site at the onshore GOSP with all the major equipment (RO membrane, H_2S stripper, organic scavenger (MPRA) shown along with feed and product.

6.2. Case study 2: produced water high salinity desalination

The program shortlisted several GOSPs for the field testing based on the process scheme defined in Fig. 5.

One technology supplier was shortlisted to provide and integrate all the components of the system for deployment. One of the onshore Saudi Aramco GOSPs located in Southern area was selected which processes 300 MBD of stabilised Arab Light (AL) crude oil with API 40. The GOSP processes wild wet crude oil and associated gas to separate them into stabilized crude oil & gas for transport through pipelines and injects their produced water to disposal reservoirs. The GOSP was also selected since it had the highest salinity produced water in the field and was located close to local laboratories for testing. Fig. 9 is the process scheme at this GOSP with feed stream from the water oil separator (WOSEP) effluent feeding the produced water reuse unit denoted in blue and the brine is sent to disposal pits. The target for the unit was to produce water with salinity <1,000 mg/L with feed of >100,000 mg/L.

Produced water reuse unit feed was defined in Tables 3 and 4 along with the performance target requirements. The process scheme in Fig. 10 was developed with support of the technology and subject matter experts. The process scheme has several modules spread across pre-treatment and desalination which are briefly explained with their functions and individual performance. The field test was conducted for 1 months with continuous 24 × 7 operation with shutdowns to clean heat exchangers. Power was supplied by diesel generators and chemical used were

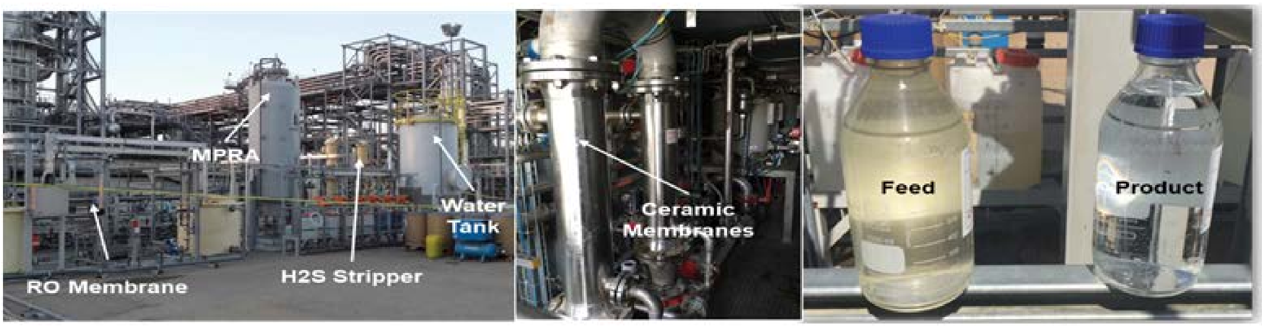

Fig. 8. Produced water desalination: membranes at field site.

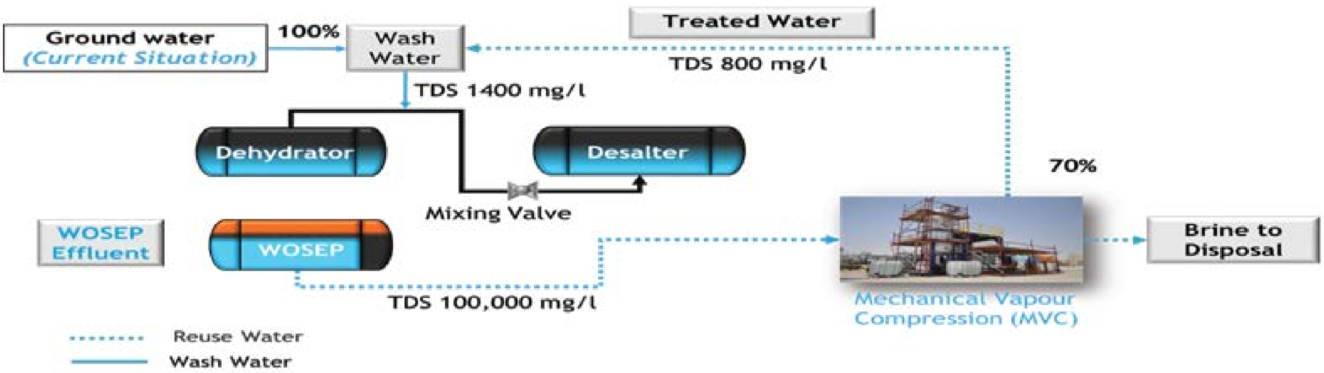

Fig. 9. Produced water desalination: high salinity (<150,000 mg/L).

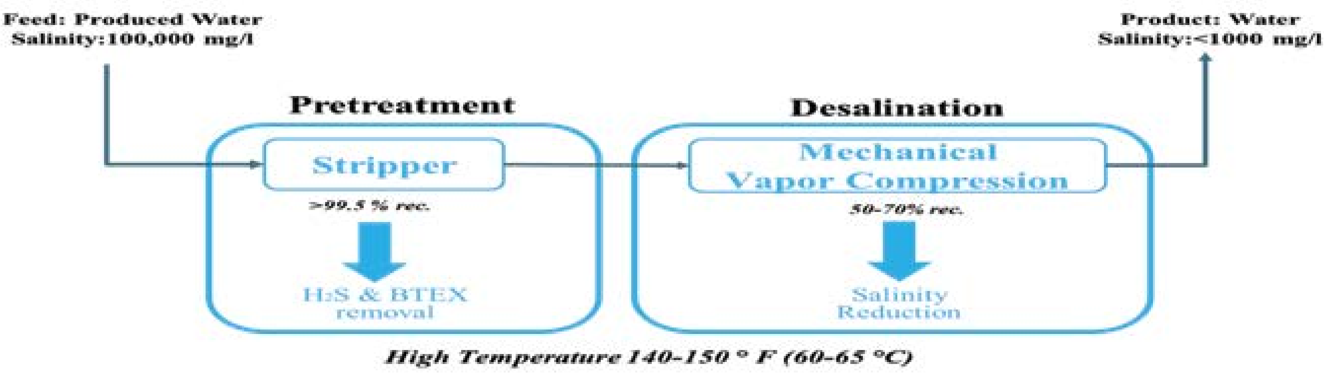

Fig. 10. Produced water desalination: mechanical vapour compression process schematic.

caustic soda for pH adjustment and anti-scalant for scale control.

Mechanical vapour compression (MVC) was selected for field testing technology after extensive review with technology suppliers to address the high salinity. In the pre-treatment module, stripper was used to remove the H_2S gas. Fig. 11 is the simplified operating principle for the MVC.

Produced water from WOSEP was routed to MVC unit and mixed with small volume of brine water at suction of circulation pump (CP). CP pumps brine water at high flow rate through primary heat exchanger in which brine is heated by compressed vapor flowing from rotary blower before it entered the flash vessel. At startup and during concentrate blow-down, an external heating from gas boiler is used as make up steam. Due to the low pressure, once the brine enters flash vessel, partial flash vapor is generated and sucked by the rotary blower and remaining water goes to bottom of vessel which is then circulated by the CP. Rotary blower compresses the generated vapor and increased its temperature. The compressed vapor is exchanging heat with circulated brine in primary plate heat exchanger and condensed as product. Cooling water is used to maintain the temperature of this product with salinity (<1,000 mg/L). The blow-down concentrate can be diluted with existing produced water and sent to the disposal well. The average recovery factor was 54% with variation between 45% and 70% vs. target of 70%. Fig. 12 shows the images of the field testing unit on site at the onshore GOSP with all the major equipment (flash vessel, distillate tank, compressors, pumps) shown along with feed, product and concentrate.

6.3. Case study summary: produced water desalination

The below Table 6 summaries the performance in terms of recovery factor, energy requirements and chemicals used in the two case studies.

6.4. Value opportunity: water circularity in oil operations

The program proved that technology was able to adeptly handle produced water with low (<15,000) and high salinity (<120,000 mg/L) levels and treat it to lower salinity (<1,000 mg/L) for reuse. The product water is of the ideal quality to use in Saudi Aramco's crude oil washing, well maintenance and drilling operations. This approach transitions from linear model of economic growth, which is based on "take-make-dispose", to circular economy model "closing the loop" of recovering value from produced water considered waste stream and also expedite the conservation of Saudi Arabia's precious non-renewable

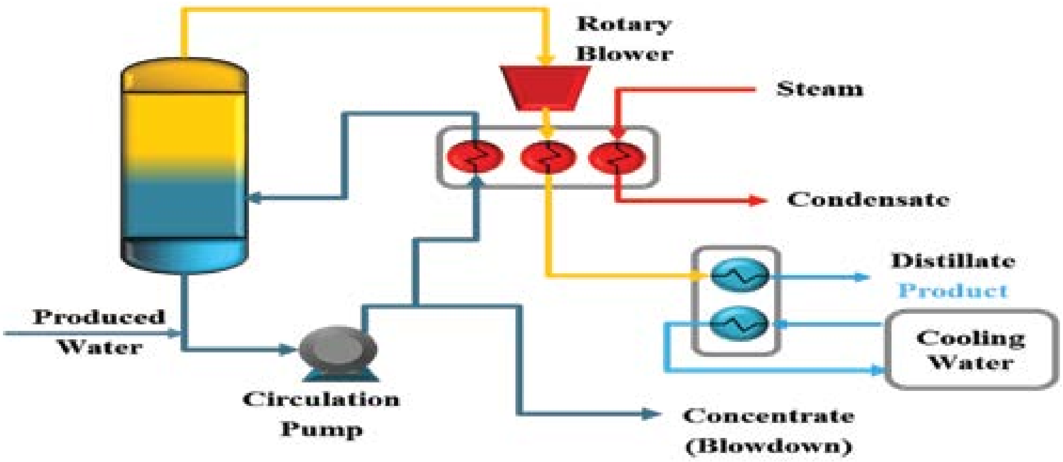

Fig. 11. Produced water desalination: mechanical vapour compression principle.

Fig. 12. Produced water desalination: mechanical vapour compression at field site.

Table 6
Produced water desalination comparison for salinities

Technology	Membranes (CM, RO)				Mechanical vapour compression (MVC)			
Feed salinity TDS (mg/L)	10,963	Recovery factor	70%	Feed salinity TDS (mg/L)	100,000	Recovery factor	54%
Unit capacity (m^3)	786	Concentrate (blow-down) m^3	235	Unit capacity (m^3)	786	Concentrate (blow-down) m^3	361
Energy, kWh/m^3	10			54			
Equipment	UF membranes H_2S stripper Oxygen scavenger RO membranes Pumps			H_2S stripper Rotatory blower Heat exchanger Flash vessel Chiller, pumps			
Chemicals	Caustic soda: 14 kg/d Sulphuric acid: 20 kg/d Anti-scalants: 5 ppmw Membrane replacement Every 7 years			Caustic soda: 14 kg/d Anti-scalants: 5 ppmw			

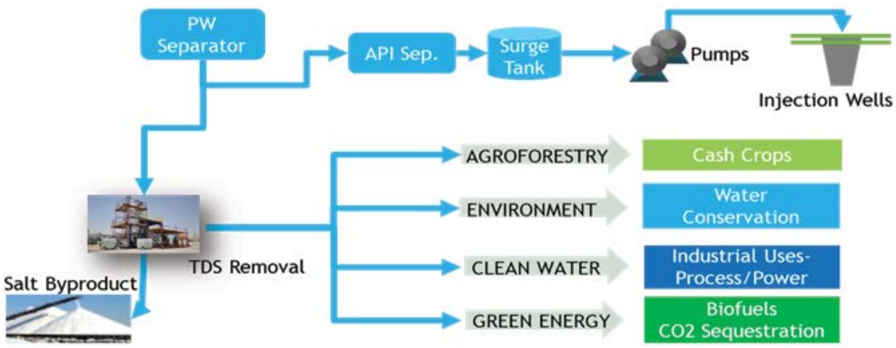

Fig. 13. Produced water reuse-water circularity.

ground water resources. The implications of this technology/program success extend beyond Saudi Aramco. As shown in Fig. 13 produced water reuse-water circularity, the water has applications across Saudi Aramco and Saudi Arabia. The water can be used in agroforestry for cash crops, from sustainability/environment point of view reduces reliance on ground water aquifers, clean water for industrial uses such as power and process water reducing reliance on sea water and finally water for use in the green energy program at Saudi Aramco to generate bio fuels and CO_2 sequestration.

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