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Comparison between oily and coal seam gas produced water with respect to quantity, characteristics and treatment technologies: a review

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ABSTRACT

Oil and gas are significant sources of energy worldwide, and their importance increases due to the ever increasing global demand for energy. The production of conventional oil, atural gas, and unconventional gas, for example, of coal seam gas (CSG) or coal bed methane, is usually accompanied with contaminated water. This article reviews the similarities and differences between the water produced during exploitation of conventional hydrocarbon and unconventional CSG resources in terms of quantity, characteristics, current treatment and a promising alternative treatment that can be used. The volume of produced water from conventional oil and gas exploitation increases during the operating life of a well. In contrast, in CSG exploitation, produced water is generated from an early stage in large volumes. Characteristics of oily and CSG produced water differ considerably from each other in terms of organic content (e.g. the occurrence of oil and grease and specific petroleum organic contaminants such as benzene, toluene, ethylbenzene, and xylene or BTEX), ionic composition and total dissolved solids. In general, methods for treating and disposing oily produced water are more established but somewhat less stringent given the long history of conventional oil and gas extraction. On the other hand, the treatment of CSG produced water requires a more comprehensive and stringent treatment train and almost always involves reverse osmosis filtration, particularly if the treated water is for beneficial reuse. Membrane filtration technologies have played and will continue to play a major role in the treatment of produced water. Several new membrane processes, particularly forward osmosis, have also emerged as notable candidate technologies for sustainable management of produced water from the oil and gas industry.

Keywords: Produced water; Forward osmosis; Reverses osmosis; Coal seam gas; Produced water

1. Introduction

During the production of oil or natural gas, a large volume of water can also be brought to the surface along with crude oil and methane gas. This is called produced water, which is the largest by-product in volume associated with oil and gas production. In the case of oil production, the oil-to-water volume ratio is about 1:3 [1–4]. Produced water associated with oil production generally contains liquid and gaseous

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hydrocarbons. As such, it is often called oily produced water. Oily produced water can also contain dissolved or suspended solids, sediments such as sand or silt, and injected fluids and additives placed in the formation during the exploratory phase and subsequent production activities [5]. On the other hand, the extraction of coal seam gas (CSG), which is also known as coal bed methane [6], requires the removal of formation water to decrease the pressure thus allowing the methane gas to desorb from the coal seams and to migrate to the collection wells and subsequently the surface. As such, CSG produced water is essentially groundwater, which occurs within the coal seams [5]. Both oily and CSG produced waters must be carefully managed to avoid any adverse impact on the environment.

In general, oily produced water contains a large range of organic compounds (e.g. emulsified oil and organic acids) and dissolved salts. Oily produced water can also contain benzene, toluene, ethylbenzene and xylenes (which are commonly referred to as BTEX). BTEX are toxic [7], and thus, there are public health guidelines and standards of these chemical in drinking water. BTEX chemicals occur naturally in crude oil and can be found in ground or sea water in the vicinity of petroleum deposits. The chemistry of CSG produced water can differ significantly from that of oily produced water. There have not yet been any reports of significant BTEX concentrations in CSG produced water; however, it is prudent to note that these chemicals may also occur naturally in natural deposits. CSG produced water is usually saline and is dominated by sodium. Direct application of CSG produced water for irrigation without adequate treatment or chemical amendment may cause damage to soil structure. In other words, soil salinity increases and makes it difficult for vegetation to absorb water from soil [8] Thus, prior to environmental discharge or irrigation of CSG produced water, the sodium adsorption ratio that determines soil permeability and water penetration should be kept below 1.5 (dS/m) and 6 ($meq^{-0.5}$), respectively [9]. Overall, neither oily nor CSG produced water is suitable for direct discharge or irrigation. When selecting treatment options, high efficiency, water recovery, cost, and brine or residual disposal are the main objectives of most of the current treatment methods, and any future alternative method or combination of methods that is recommended.

CSG extraction is still emerging, and thus, the management of CSG produced water has not been fully established. On the other hand, oily produced water management has a long history. A number of treatment techniques and disposal options such as re-injecting it into the producer reservoir to enhance the recovery of oil and to maintain pressure in the reservoir have been applied for managing oily produced water. This article reviews the similarities and differences between the oily and CSG produced water in term of quantity, characteristics and treatment technologies. This review aims to evaluate whether the advanced technologies used to treat oily produced water can also be used for CSG produced water.

2. Volume of oily and CSG produced water worldwide

2.1. Volume of oily produced water

Oily produced water is the largest waste stream by volume in the petroleum industry—roughly three barrels of water for every barrel of oil [10] (one barrel is approximately 159 L). It results from the production of oil and natural gas from underground reservoirs, which contain formation water [11]. The global estimated average of produced water is 210 million bbl/d, resulting in an annual production of 77 billion bbl/year [12]. The estimate of produced water in offshore platforms worldwide is approximately 107 million bbl/d, while the estimation of total offshore oil production is 120 million bbl/d. Fig. 1 shows a comparison between onshore and offshore oily produced water since 1990. The quantity of produced water from the petroleum industry has increased dramatically, and it does not remain constant during an oil well's operation time [1]. In some older oil fields, the water cut exceeds 95% of the well production [10,12]. Most of the off-shore produced water is discharged directly into the ocean with little or no treatment [13]. On the other hand, adequate treatment is required for on-shore oily produced water prior to environmental discharge or beneficial reuse. The volume oily produced water worldwide is expected to increase in the future, which means that

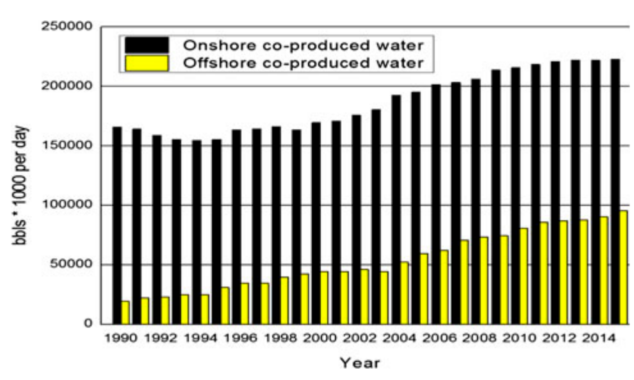

Fig. 1. Global onshore and offshore produced water production [1].

the effect of discharging produced water into the environment will be increased due to the increasing the produced water quantities [10].

2.2. Volume of CSG produced water

CSG produced water is different from conventional oil and natural gas produced water in term of the way it is generated as well as its composition and its environmental impacts. CSG produced water is created when the water that permeates the coal beds that contain methane is pumped out to reduce the pressure and to allow desorption of methane and its flow and exploitation to the surface [5]. Unlike to conventional oil and gas production, the produce water from CSG wells is pumped in large volumes in the early stages of production, although during the productive life of a well the volume of produced water decreases significantly while the production of gas increases. The quantity of water produced during the lifespan of a well can be one to three barrels of water/million cubic feet (bbl/mcf) of gas [14]. The total of CSG produced water can be estimated based on the total amount of CSG worldwide, as is shown in Table 1 [8].

CSG produced water can be beneficially reused in arid areas to reduce the pressure on existing resources. For instance, in Australia 2010, approximately 450 GL/year of groundwater is extracted from the entire Great Artesian Basin (GAB) for agriculture, industrial and domestic purposes. In contrast, the total volume of CSG produced water extracted from Surat and Bowen Basins is estimated to be between 125 and 350 GL/year [15,16]. This means CSG produced water may reduce 77% of the annual groundwater extraction from the GAB.

3. Characteristics of produced water

The characteristics of oily and natural gas produced water are a combination of physical and chemical properties that vary significantly, based on the location of the oil and gas field, the geological formation from which the produced water has been in contact, and the type of hydrocarbon product being produced whether it is heavy of light crude oil. The properties and volumes of oily produced water can vary during the lifespan of a reservoir, and water injection (to increase oil productivity) plays a large role in affecting the properties and volume of produced water [5]. The total dissolved solids (TDS), oil and grease, inorganic, organic compounds and naturally occurring radioactive materials are the main concerns with oily produced water. Total oil production can be increased if the characteristics of produced water are well understood; understanding parameters such as contents of suspended solids and concentrations of chemical constituents of produced water that may cause scaling in the pipes is important to design countermeasures such as the addition of scale inhibitors and chemical treatment, as well as helping to identify down-hole problems such as plugging [17].

Exploring and better understanding the chemical constituents of oily produced water enhances the ability to select the proper options for better managing its treatment and disposal and for optimising the recovering the oil. One of the most important constituents of onshore and offshore oily produced water is oil and grease, stemming from the presence of many organic chemicals, since the average oil and grease content of oily produced water ranges between 40 and 2,000 mg/L [18]. Salinity is also considered to be an important constituent in onshore produced water because a concentration of dissolved salts; in many cases, it is more saline than seawater. The TDS content of oily produced water from the western USA varies from 1,000 mg/L to 400,000 mg/L [18].

Additional chemical constituents are usually found in oily produced water due to several operational treatments and developments in oil production and recovery. Water injection is used to maintain pressure

Table 1
Total CSG production and the estimation of CSG produced water from the stated countries [8]

Country	Production in billion m^3	CSG total produced *GL/year**
USA	52	1,355–4,066
Australia	6.2	162–485
China	1.4	36–109
Canada	0.85	22–66
India	0.056	1.5–4.4
Europe	4.6	110–330
Total	+65.1	1,696–5,090

*Calculated based on the total CSG production and methane gas to water ratio.

in the reservoir to increase oil production. The injected water, which is usually supplied by a different aquifer, may contain suspended solids and microorganisms [19], while additive chemicals such as coagulants, emulsion breakers, scale inhibitors, corrosion inhibitors and solvents are usually used during the production and operational stages. The aim of adding these chemicals is to improve the productive capacity of the oil well [17], but they may reappear in the oily produced water and can affect its overall toxicity. Table 2 outlines the characteristics of oily produced water, also it includes the major inorganic constituents and concentration in oily produced water based on the International Association of Oil and Gas Producers [20].

Based on Tables 2 and 3, all the inorganic constituents in oily produced water are at a higher level than in CSG produced water, except for bicarbonate ($CaCO_3$), which appears as higher than average compared to the oily produced water but the inorganic constituents in oily produced water may not be always higher than in CSG. It is highly dependent on the location and geochemical characteristics of the formation. The USGS database showed some CSG produced water having TDS between 11 and 26 g/L, which is much higher than the TDS concentration in some oily produced water [23].

In contrast, CSG produced water entails an environmental and technological challenge due to its unique characteristics [24–27]. The characteristic of CSG produced water is determined by the geological and hydrogeological pattern of the coal seam reservoirs [15]. To extract CSG, pumping of the water above and within the coal seams is essential in order to decrease pressure as needed to allow the methane gas to desorb from the coal and rise to the surface. This water may in some cases continue entire lifespan of the well (which estimated to be up to 15 years) [15,28], depending on the geological formation of the coal seam basin. On other hand, CSG production increases and reaches a stable production stage followed by a declining stage (Fig. 2) [28].

Table 2
An example of oily produced water characteristics [21,22]

Oily produced water characteristics	Quantity
Oil-in-water	Up to 3,000 mg/L
Total suspended solid (TSS)	Up to 3,000 mg/L
pH	5.1–7.0
Specific gravity at 15˚C	1.03–1.15
Sulphide (H_2S)	Up to 1,000 mg/L
Dissolved CO_2	Up to 2,000 mg/L
Salinity	Up to 300,000 mg/L
Bicarbonate	771
Chloride	60,874
Sulphate	325
Sulphide	140
Nitrate	1

The salinity of CSG produced water varies, but in general it is less than oily produced water (Tables 2 and 3); for instance, in Queensland, Australia, the salinity of CSG produced water, which usually measured as dissolved solids, is varying from 200 to over 10,000 mg/L (limit for drinking water: 500 mg/L) for comparison: seawater salinity varies from 36,000 to 38,000 mg/L [29]. However, the average salinity of CSG produced water in Australia is varying from 1,200 to 6,000 mg/L, which is similar to those of brackish water (5,000 mg/L) Table 3. In some cases, drilling or fracking during completion of a CSG production well may cause the presence of additional chemical contaminants [15]. The TDS of CSG produced water from the western USA show are about 170,000 mg/L [30]. Several factors affect the TDS of CSG produced water, such as the depth of the coal bed, the composition of the rocks surrounding the coal beds, the amount of time the rock and water react, and the origin of the water entering the coal beds. Table 3 shows the TDS values of CSG produced water in some basins.

From 2003 to 2005, a comprehensive survey was held in the Powder River Basin in terms of evaluating the trace element concentration in CSG produced water, and they have concluded that the concentrations of minor trace elements in CSG produced water such as iron (Fe), aluminium (Al), chromium (Cr), manganese (Mn), lead (Pb), copper (Cu), zinc (Zn), arsenic (As), boron (B), selenium (Se), molybdenum (Mo), cadmium (Cd) and barium (Ba) are commonly considered to be low [28]. Nevertheless, concentrations of all trace elements except Al and Cu, which were found to exceed the standard for drinking water, are low enough not to pose any significant risk to aquatic life [33,34].

Oily produced water contains mixture of organic and inorganic, and its concentration are vary based on the location and over the lifespan of a producing field [35,36]. Average levels of some critical organic are shown in Table 4. Whereas in CSG produced water, the concentration of all volatile organic compounds is typically less than 1 mg/L [23], but continuous monitoring of these compounds is essential as precautionary measures to avoid any future environmental impact caused by the appearance of these components in CSG produced water.

Table 3
Characteristics of CSG produced water in some different basins worldwide [28,31,32]

Parameter	Surat Basin, Australia (Basin wide)	Surat Basin, Australia (Tipton)	PRB, USA (47 samples)	PRB, USA (Mitchell Draw)	Walsenburg, USA	Waterberg, South Africa
pH	9–8	7.6–8.9		8.2	8.41–8.52	7.8
Salinity, mg/L	1,200–4,300	4,500–6,000	370–1,940	3,460	588–722	5,125
Sodium adsorption ratio (SAR), meq$^{-0.5}$	107–116	69–131	4.9–30.4	25	9.5–11.9	85.4
Sodium, mg/L	300–1,700	1840–3,461	130–800	880	250–314	2,023
Potassium, mg/L				35.2	1.2–1.3	16.5
Magnesium, mg/L				14.6	0.01	10.4
Calcium, mg/L			5.9–57	28.0	1.7–2.4	25.1
Chloride, mg/L	590–1,900	2060	6.3–64	28.4		278.1
Sulphate, mg/L	5–10	2	0–12	1.0		418
Bicarbonate (as $CaCO_3$), mg/L	580–950	1,030	290–2,320	2,416		4,712
Iron, mg/L		0.07–4.50				0.99
Manganese, mg/L		0.07–1.00				0.3
Silica, mg/L				12		
Fluoride, mg/L		0.77–1.00		1.0		4
Boron, mg/L				0.2	0.21–0.26	

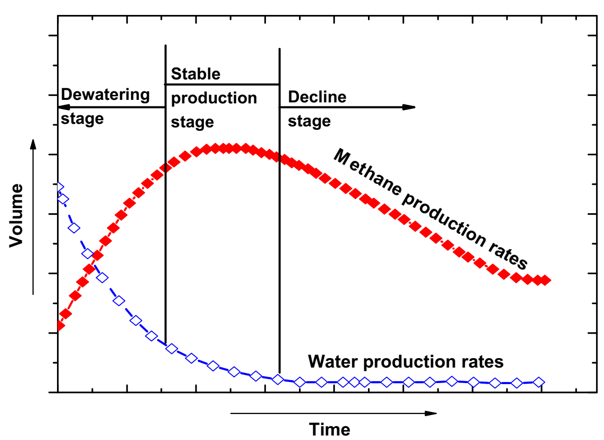

Fig. 2. Typical changes of CSG produced water and gas production (adopted from [15]).

4. Current management of produced water

4.1. Discharge of produced water at surface

On offshore platforms, there is neither space nor time to allow a long retention time for oily produced water that must be treated prior to disposal. Processes that require significant treatment time, such as oil skimming and biological reactors, are therefore not suitable for offshore platforms. Fig. 3 illustrates the final stage of oily produced water and shows the affected area around the discharge disposal point. Fig. 3(a) shows the oily produced water pits used in Wyoming to separate oil from produced water. Produced water pits are used for further separation after heater-treater (which is an item of production equipment used to increase the temperature of the crude oil in order to remove contaminants from the oil during the processing treatment) stage. Fig. 3(b) illustrates another view of the pond in Park County Wyoming [41]. Oily produced water discharged offshore may contain up to 10 times more oil and grease than that discharged from onshore facilities because in onshore space and time are not challenge in terms of treating oily produced water. Globally, most of produced water in offshore operation is discharged into the sea [5].

Considerable advances in the treatment of CSG produced water have been made in recent years. For instance, in Queensland, Australia, until the year 2010, most untreated CSG produced water was disposed of in evaporation ponds that ranged from 1 to 100 hectares in area, as shown in Fig. 4 (a). Fig. 4 (b) illustrates the evaporation method and working principle. In 2010, these evaporation ponds were discontinued as a primary source for disposing of CSG water because of concerns over any leakage of saline waters into soils, shallow aquifers and rivers located nearby [42]. Nevertheless, limited use of these ponds might be permitted as temporary evaporation ponds necessary for water aggregation and storage of brine from treatment facilities, provided the ponds are fully lined to a standard determined by the relevant authority [15,28].

Table 4
Organic content in oily produced water, adapted from [37]

Components (mg/L)	Norway [38]	Gulf of Mexico [39]	Campos Basin [40]
Benzene, toluene, ethylbenzene and xylene (BTEX)	8	B: 1.318 T: 1.065	T: 0.990 0-X: 0.135
Naphthalene	1.5	0.132	0.106
Phenols	5	1.049	4.3
Total organic carbons (TOC)		70–650	386

Fig. 3. Oily produced water ponds in created for further separation in Wyoming (adopted from [41]).

4.2. Re-injection of produced water into underground

The re-injection of produced water has been routinely used in the petroleum industry for oily produced water management [44–46]. The technical and regulatory framework as well as economic feasibility of conventional deep well disposal of oily produced water has been established. Nonetheless, unconventional gas produced from coal seams in low-permeable layers does not ease injection of significant water volumes in these layers or in deeper layers as permeability is generally decreasing with depth; this significantly increases the cost of disposal well drilling due to the high pressures needed to inject CSG water into these formations. In addition,

Fig. 4. Coal seam gas produced water ponds in Australia (adopted from [43]) & evaporation ponds in Wild Turkey system (adopted from [31]).

CSG produced water cannot be re-injected into the producing formation to improve recovery of production such as oil fields. Injection in shallower better permeable layers is mostly restricted as they impose a contamination risk for aquifers, which is in particular important when these are used for water supply or if they discharge in springs or into surface water bodies. Thus, re-injecting CSG produced water into the coal basin is impractical either in terms of its cost and productivity. These economic and technical limitations of re-injection make the fast adaption and/or development of an economic method for managing CSG produced water to a key challenge [28].

4.3. Produced water treatment

Separating oil-in-water emulsion is considered to be the primary method of separation in the oil industry. A large amount of liquid waste in the form of either oil-in-water or water-in-oil emulsion is generated by the petrochemical and other industries [47], and therefore, demulsification has become a critical process associated with them. Thus, the separation of water from water-in-oil emulsions is important in industries involved in the recovery of solvents and the desalination of oil [48]. Hence, water-in-oil emulsions are also encountered in liquid membrane processes for metal extraction or wastewater treatment. Multimedia filtration has been successfully used to remove solid particles and droplets of oil larger than 10 μm. A multimedia filter uses a variety of media types that are distinctly layered, with the coarsest medium at the top and the finest at the bottom. This layering structure of the media allows larger particles to be removed near the top of the bed while the smaller particles are filtered out towards the bottom. It has been reported that the most efficient multimedia filters can efficiently remove large solid particles and oil droplets [49]. If they are not removed, these large solid particles can foul the injection well and cause formation damage due to the plug near the well bore. Nevertheless, multimedia filtration systems are not effective at removing small oil droplets (less than 10 μm) and dissolved contaminants [1]. Hence, several studies have been conducted to develop suitable technologies for the treatment of oily produced water [1,50–56]. Treatment processes such as oxidation, stripping, adsorption, membrane technologies have been widely investigated. Table 5 shows the comparison of oily produced water treatment technologies with their advantages and disadvantages.

Due to the strict regulations (which is similar to the oily produced water in terms of surface discharge options), treatment and monitoring after disposal of CSG produced water are compulsory. Several treatment technologies can be considered for treating CSG produced water such as reverse osmosis (RO), nanofiltration (NF) [8,57], ion exchange (IX), capacitive desalination (CD), electrodialysis reversal distillation (EDR), freeze-thaw/evaporation, ultraviolet light, chemical amendment, artificial wetlands [28] and evaporation ponds [63]. Furthermore, an evaluation of the economic feasibility of several desalination technologies was carried out in Australia in 2004, and they concluded that RO technology is considered to be the most competitive technology in terms of the cost effect [28]. CSG produced water treatment is considered to be unique due to a variety of quality characteristics, and hence, pre-treatment is required to avoid membrane fouling. In the treatment of CSG produced water, both concentrate management and pre-treatment are considered to be the most challenging aspects due to the alkalinity of this water, and the fact that it contains a high percentage of bicarbonate compared to oily produced water (see Tables 2 and 3) indicates that a high potential for scaling is expected. Furthermore, soluble iron can cause membrane fouling, and thus, some pre-treatment techniques such as media filtration and coagulation flocculation are required in terms of removing the iron from CSG produced water [28]. Table 5 illustrates the comparison of CSG produced water treatment technologies with their advantages and disadvantages, in order to give a better understanding of the similarity and differences of the existing methods that used to treat such as this contaminant water to see whether the advancement technologies of treating oily produced water can be used in CSG produced water in terms of achieving the ultimate goal of zero pollutant discharge.

5. Pre-treatment of CSG produced water

Pre-treatment is required when treating CSG produced water to avoid membrane fouling and scaling. Brine management and pre-treatment are considered to be the most challenging aspects due to the alkalinity of this type of water in CSG produced water. In addition to that, soluble iron has the ability to cause fouling, and hence, pre-treatment techniques such as coagulation flocculation and media filtration are required to remove the suspended solids and that will avoid any membrane fouling [28]. A combination of coagulation and sand filtration followed RO is often introduced in these cases. In the water reclamation process using RO, microfiltration (MF) or ultrafiltration is generally used as a pre-treatment.

Table 5
Comparison of oily produced and CSG produced water treatment technologies with their advantages and disadvantages

Treatment	Advantages	Drawback	Energy consumption	Life cycle	Ref.
Oxidation	• It requires minimal equipment, and no waste is generated from this method • No pre- or post-treatment is required, and it has 100% recovery rate	• Cost effect in terms of the chemical and periodic calibration and maintenance of chemical pumps • Chemical metering equipment is considered as critical for this method	• Approximately 18% of the total cost of the operation and maintenance of this method	• Life span of this method is around 10 years	[4]
Stripping	• Practical treatments for oily wastewater are especially for volatile components, and it is cheap in terms of the cost	• Highly cost and it impractical to be used in small area such as oil platforms because a large stripping column is usually required	• N/A	• N/A	[13]
Adsorption	• Compact packed bed modules, cheap and efficient • It has the ability to reduce TOC, BTEX, metal and oil content in produced water	• High retention time, less efficient at higher feed concentration	• Minimal requirement	• It is based on the media type	[4,21]
Gas flotation	• High recovery of produced water (nearly 100%) • Does not require post-treatment	• In efficient if the produced water temperature is high • Sludge generation requires solid disposal	• Energy required	• N/A	[4]
Microfiltration (MF)	• High recovery of fresh water, compact modules	• High energy required, less efficiency for removal of divalent ions, viruses etc.	• N/A	• Ceramic MF more than 10 years • Polymeric MF more than 7 years	[4,21]

(Continued)

Table 5
(*Continued*)

Treatment	Advantages	Drawback	Energy consumption	Life cycle	Ref.
Ultrafiltration (UF)	• High recovery of fresh water, compact • Modules, viruses and organics etc. removal	• High energy demand, membrane fouling, low molecular-weight MW organics, salts etc.	• N/A	• Minimum 7 years for ceramic UF and minimum 10 years for polymeric UF	[4,21]
Reverse osmosis	• An effective method for removal of monovalent • Considered as competitive technology in terms of capital investment and operating cost	• High pressure is required to separate contaminations from water through the porous membrane	• For sea water SW, it is vary from 0.46 to 0.67 KWh/bbl • BW less energy required ~0.02 up to 0.13 KWh/bbl	• From 3 to 7 years	[28,57,58]
Nano-filtration	• Has the ability to remove divalent salts at lower pressure compared to RO	• It is efficiency with low dissolved solids content water only	• It is considered as less energy requirement compared to RO, and it is approximately 0.08 KWh/bbl	• Similar to RO from 3 to 7 years	[57–59]
Electrodialysis	• Clean technology, no chemical addition, mobile treatment possible, less pre-treatment	• Inefficient with high concentration as well as removing dissolved compounds such as aromatic hydrocarbons and high energy is required	• It is vary from 0.14 up to 0.2 KWh/lb	• The lifespan is 4 to 5 years	[21,60]
Ion exchange	• High efficient in removing salt	• Cost effect when applied for large scale applications	• Energy used for the pumps only and its commonly 0.07 KWh/bbl	• An anion resin is varying from 4 to 8 years, while the cation resins vary from 10 to 15 years	[57,61]
Electrodialysis reversal distillation (EDR)	• High efficiency of salt removal from solution	• Cost effect due to chemical additive required in this method	• It is vary from 0.14 up to 0.2 KWh/lb	• The lifespan is 4 to 5 years	[57,61]

(*Continued*)

Table 5
(*Continued*)

Treatment	Advantages	Drawback	Energy consumption	Life cycle	Ref.
Capacitive distillation and rapid spray evaporation	• New methods under development process	• New methods under development process	• N/A	• N/A	[8,57]
Freeze-thaw/evaporation	• Zero liquid discharge is achievable • Does not need high professional observers	• It is in efficient is very low for high concentration of methanol produced water • It is high efficiency in winter season only and when the temperature is below freezing temp • Secondary treatment is required • It is efficiency is considered as moderate if the TDS are around 1,000 mg/L	• Approximately 20 years	• N/A	[57,62]
Evaporation pond	• Very cheap and it does not require any chemical additions	• concerns over any leakage of saline waters into soils, shallow aquifers and rivers located nearby	• Energy is limited, only pumps used to pump the water in to the ponds	• Long lifespan.	[42,57]
Media filtration (Sand filter)	• Removal efficiency exceeds 90% when proper pre-treatment steps are followed	• Cannot remove small oil droplets less than 10 μm, dissolved elements and microbes	• It is considered as a minimal, and the energy required for the backwash filtration	• It is based on the media type	[1,4]

5.1. Coagulation

Coagulation is generally used to remove suspended particles and some dissolved matters. The process is based on neutralisation followed by the formation of aggregation. Negatively charged suspended particles are neutralised by positively charged coagulants to form aggregates called flocs, which can absorb other materials such as heavy metals and dissolved matters. Large flocs settle down in the sedimentation tank and thus can easily be separated. For instance, chlorine was used in the pre-treatment stage to remove the iron in Wild Turkey (Fig. 5) [31]. While increasing the concentration of bicarbonate of the CSG produced water feed requires an essential addition of acid to reduce feed water pH, and hence, the high potential for scaling expected due to the precipitation of carbonate. In contrast, reductions in pH cause a reduction in the solubility of silica, which influences recovery of the RO system due to the variability of silica in the CSG, as was experienced in the Wild

Turkey project. Ion exchange was deployed at the Mitchell Draw plant for the removal of some soluble cations such as calcium, magnesium, barium and strontium (Fig. 5) [28,31].

The Langelier saturation index can be controlled by ion exchange at (−1.3), whereas the feed water pH remains constant, and hence, both silica and carbonate scaling can be mitigated [64]. While in Australia at the Spring Gully plant, which is considered to be one of the most particular in terms of treating CSG produced water, several pre-treatment options such as air filtration, sand filtration and coagulation were investigated. As a primary stage, they combined the sand and air filtration with an addition of coagulation, but the turbidity measurement exceeded five, which was recommended by the RO manufacture as a minimum value of SDI, so an additional pre-treatment stage (MF) was added to meet the specifications of SDI recommended by the manufacture to be less than five [28,65], but the biggest challenge faced by either the Mitchell Draw plant or the Wild Turkey was the cost of pH adjustment. Thus, all major treatment units at Spring Gully are skid mounted, to enable future relocation [28,65].

5.2. Media filtration

Multimedia filtration has been successfully used to remove solid particles larger than 10 μm. A multimedia filter uses a variety of media types that are distinctly layered, with the coarsest medium at the top and the finest at the bottom. This layering structure of the media allows larger particles to be removed near the top of the bed while the smaller particles are filtered out towards the bottom. It has been reported that the most efficient multimedia filters can efficiently remove large solid particles [49]. If they are not removed, these large solid particles will cause fouling and then formation damage will occur due to the plug near the well bore in the injection wells. Furthermore, these particles will cause membrane fouling if membrane technologies are used to treat produced water. Nevertheless, multimedia filtration systems are not effective at removing small particles (less than 10 μm) and dissolved contaminants [1]. Multimedia filters are used as pre-treatment stage in the Wild Turkey facility in order to remove the iron (Fig. 6) [64].

6. Produced water and membrane technologies

Membrane technologies can play a major role in the treatment of produced water. Membrane processes including MF, UF, NF and RO have been increasingly used to treat oily wastewater [66–68]. For instance, MF membranes can be used to remove suspended particles, UF membranes can remove macromolecules, and RO membrane can remove dissolved components [69]. In addition to these pressure driven membrane processes, forward osmosis (FO) (which is an emerging process) may also be used for produced water treatment [70]. Heavy metals and dissolved organic compounds can be removed from oily produced water by using RO membranes, although the drawback of using them is the high energy demand to produce the high pressure (up to 5.5 MPa) necessary for their operation [13,71], whereas NF requires less energy (3.45 MPa) [72], but is less efficient than RO in terms of removing components with low molecular weight because the pores of NF membranes are larger [73]. Nevertheless, aromatic components such as BTEX and light phenols (C1–C3) can be removed with NF. The main disadvantage of both NF and RO is membrane fouling [36] the short lifetime of the membrane material is considered to be another drawback.

UF is considered to be one of the most successful techniques for treating oily produced water because it is very efficient at removing oil. In addition, UF does not need any chemical additives and only requires a small installation space and low energy [74]. Bilstad and Espedal [75] compared MF and UF membranes in terms of their removal efficiencies; the results showed that UF membranes could meet removal standards for SS and dissolved components. The total removal of hydrocarbon was 96%; BTEX were reduced by 54%, while heavy metals such as Cu and Zn were reduced by 95%. In contrast, dispersed oil was removal by MF was 90%, but MF did not separate dissolved hydrocarbons, and hence, MF was discontinued in this study [75]. A combination of MF and UF membranes could be used to remove oil droplets from produced water [13].

Electrodialysis (ED) is an industrial membrane separation process where the membranes are placed between two electrodes to allow cations or anions to pass through depending on the charge of the membrane [76]. This method is not recommended for oily produced water with a high concentration of TDS (~150,000 mg/L) [9,77]. Dallbauman and Sirivedhin [78] indicated in their results that ED is suitable for reclaiming oily produced water with a low TDS (~5,000 mg/L) [9], but it is not considered to be cost effective for high concentrations of oily produced water [9]. Hayes and Arthur [79] indicated that the major disadvantages of ED are its inefficient removal of dissolved compounds such as aromatic hydrocarbons and the high energy demand.

In addition to the above-mentioned membrane processes, FO (which is an emerging process) may also be used for produced water treatment [70]. The

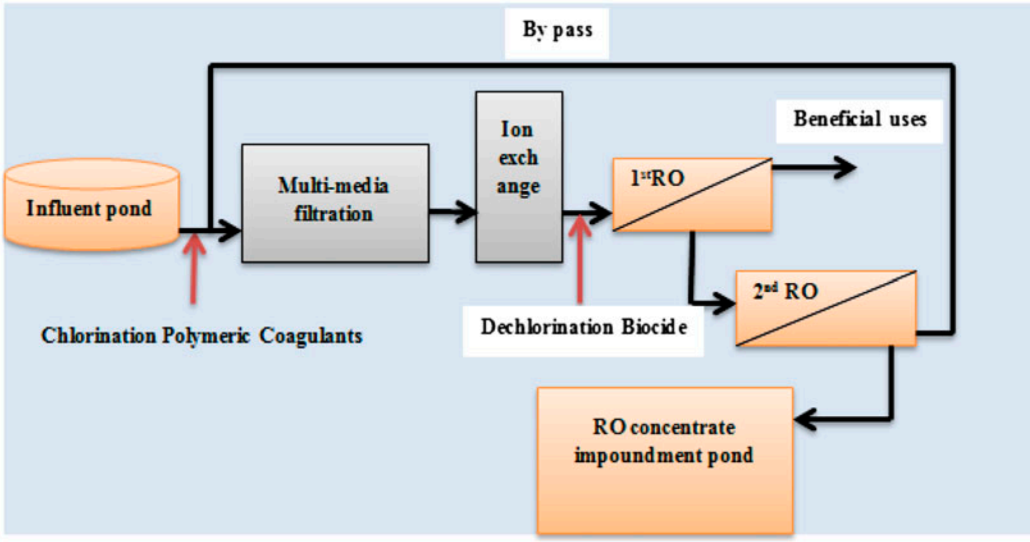

Fig. 5. CSG produced water treatment process in Mitchell Draw plant with ion exchange [64].

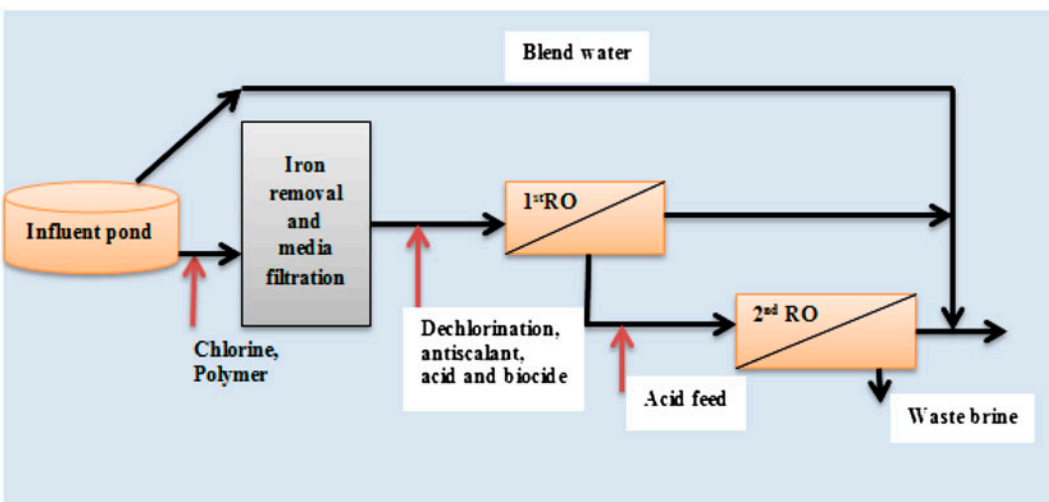

Fig. 6. CSG produced water treatment process in Wild Turkey [64].

FO process exploits the natural phenomenon of osmosis that occurs when two different solutions are placed on opposite sides of a semi-permeable membrane [80]. The osmotically driven process is not driven by any hydraulic pressure, and thus, it has an array of potential benefits [81]. If a draw solute is readily available, the FO process requires significantly less energy than the RO process (unlike RO, in FO membrane a concentrated draw solution used to generate an osmotic pressure gradient across the semi-permeable membrane) [81–83], and the FO process has a lower fouling propensity than the RO process. As a result, simple techniques such as rising without using chemical cleaning reagents can be enough to control fouling [84,85]. FO acts as a barrier to the transport of solute and also represents effective multiple approach barriers to removing contaminants, and furthermore, an FO membrane can effectively reject some organic contaminants, depending on the feed composition and duration of the treatment [86–88]. Several researchers have attempted to combine FO with RO to achieve a very high removal of different contaminants [89–92]. FO also has the ability to reject high amounts of salts, for example, more than 97% for NaCl, which is better than NF membranes (<85%) [93–95]. A high water recovery with low fouling propensity can be achieved by FO [81]. A range of advantages made FO a potentially promising process for many applications as a single process [96] or combine it with NF/RO membranes [97–99] for the treatment of produced water. A recent study that investigated the removal of dissolved organic components by FO concluded that a high removal of acetic acid, which is considered to be one of the organic dissolved contaminants in oily produced water, and thus due to the good results that were achieved, further investigations into using FO for treating oily produced water were recommended [100,101]. The previous discussion enhances the attractiveness of using FO in either oily produced water or CSG produced water as a practical FO oriented hybrid system.

7. Conclusion

The large volume of undesirable water associated with oily or CSG produced water raises a significant worldwide concern by regulatory bodies as well as by social and environmental organisations. Their main concern is the unsuitability of this water for direct release into the environment without adequate treatment. Both the energy demand and scarcity of water are the intrinsic factors which encourage investigation to develop treatment technologies that are suitable for produced water. In this article, we have reviewed the similarity and differences between the oily and CSG produced water in terms of its quantity, characteristics and the major treatment technologies that have been used and their application in future. The treatment and disposal of oily produced water is in general more established than those of CSG produced water. However, there are some similarities between these two forms of produced water in term of treatment requirement and disposal options. Membrane technologies are highly suitable for oily and CSG produced water treatment. RO is used in most cases for the treatment of CSG produced water treatment as widely demonstrated in the US and Australia. The ultimate goals in managing produced water are to achieve zero pollutant discharge, minimum energy consumption and beneficial reuse of the treated water. Further research will be needed to attain these goals for sustainable management of both oily and CSG produced water.

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