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KLM Technology Group P. O. Box 281 Bandar Johor Bahru, 80000 Johor Bahru, Johor, West Malaysia	Kolmetz Handbook of Process Equipment Design OIL AND GAS PRODUCTION PRODUCED WATER TREATMENT UNIT SELECTION, SIZING AND TROUBLESHOOTING (ENGINEERING DESIGN GUIDELINES)	Co Author: Rev 01 Robert Thomas Rev 02 Apriliana Dwijayanti Editor / Author: Karl Kolmetz

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INTRODUCTION

Scope

Water tends to become the dominant produced fluid as an oil field matures. With ever increasing water cut, up to 90% or higher, the volume of produced water that a facility must process often far exceeds that of the hydrocarbons. At the same time, concern for the environment has resulted in more stringent standards for discharged water quality. An increasing awareness of the impact of oil field discharges by the industry has accelerated the cleanup efforts. In some cases, self imposed corporate guidelines are more stringent than those allowed by governmental regulations.

The combined effect of larger volumes and higher level of polishing has driven up the cost of of produced water disposal. Conventional produced water treatment (PWT) systems, consisting of a low pressure separator, CPI and flotation units are highly space and weight intensive. These system usually require costly chemicals and constant attention to be effective. For offshore operations where weight, space and manpower come at a premium, PWT facilities have become a high profile and costly component of major projects.

Furthermore, operating experience has shown that conventional PWT systems do not work well on floating structures. Platform movements tend to induce excessive turbulence for good gravity settling in CPI'S, and there is too much wave motion for effective skimming in flotation cells.

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General Design Consideration

Produced water is a term for reservoir water that is separated during the oil and gas production process. Oil and gas reservoirs normally contain amounts of water, oil, solids, condensates and gas. Produced water (PW) is an undesirable product of hydrocarbon production from oil and gas reservoirs.

The PW is in contact with hydrocarbons in reservoir, well or surface pipelines, so that it is a very complex mixture comprising of polar and non-polar organic components, cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Ba^{2+} , Sr^{2+} , Fe^{2+}), anions (Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^-) and other substances such as heavy metals (cadmium, chromium, copper, lead, mercury, nickel, silver, and Zinc).

When the oil and gas is processed, water is separated and pumped back into the reservoir in order to maintain the right pressure in the well. Alternatively, the water is discharged to the sea or sewerage. Both methods involve a set of conditions and strict regulations aimed at preventing well contamination and water pollution.

When the oil and gas reservoirs are depleted, water content may be as much as 98% of the total fluids being produced. As a result, the handling and treatment of produced water up to the required quality levels becomes an increasing cost factor in the total Life Cycle Cost of an operated asset.

The treatment of produced water is a major cost component of the oil and gas production industry. Initially, wells produce little water; eventually however, all oil wells can produce the same as, or a larger volume of water than the recovered oil. The ability to efficiently treat and economically dispose of this water is critical to success in the oil production business.

The purpose of this design instruction is to provide the basic guidelines to develop Produced Water Treatment, Equipment Data Sheets for various types of Installations, as well as assist in the evaluation of the equipment required for Produced Water

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Treatment. The equipment discussed is for use in the treatment of produced water prior to discharge overboard or disposal by other means.

Treated produced water can be disposed of by reinjection for downhole pressure maintenance. However, this, until recently, has not been a general practice utilized. Pressure maintenance is accomplished mainly by sea water injection. The sea water is always available and is easier to prepare for injection than is produced water.

Be aware however that with the advent of sub-sea production work now becoming more and more prevalent, reinjection is now becoming more commonplace. Sub-sea separation and treatment of produced water can now be accomplished on the sea floor. The basic design principles of the equipment will still be the same, but the location of the equipment will be either buried on the ocean floor or skid mounted on the ocean floor. The more equipment installed sub-sea means smaller platform footprints and less platform CAPEX.

The equipment included in this guide is mechanical equipment capable of removing free oil from produced water, preferably without the need of chemical additions to assist in the free oil removal. Further, this mechanical equipment will not break any type of emulsion and will not perform successfully if any type of emulsion is present, unless chemical addition is used to break the emulsion.

As major oil fields mature and the water cut rises, the issue of processing and disposal of increasing volumes of produced water has become a priority.

In offshore operations, overboard dumping of untreated produced water was the most economic and expedient method of offshore disposal. However, performance standards for the disposal process and regulations limiting discharges now mandate the standards for treatment of produced water offshore. Produced water must be treated offshore so that it can be discharged overboard without affecting the surrounding environment. The Standards for produced water disposal are determined by State, National and international regulatory bodies.

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The effluent from a Produced Water System is monitored constantly using an Oil in Water Monitor. The monitor normally has several settings to alert the operators of any problems. If high oil in the effluent remains a problem for some time, the produced water will be diverted to the platform Dead Oil Tank until the effluent quality is returned to its process guarantee level. The monitors should be IMO certified.

Table 1 shows the existing discharge limits for free oil in water, ranging from 10ppm to 40ppm, for a number of locations. Compliance with such limits has an economic cost which can be minimized by an integrated approach to the subject of treatment and disposal. The IMO free oil concentration is highlighted in the table, since this international standard is being adopted by more and more countries and oil companies when they are specifying Produced Water Equipment.

Table 1: Free Oil Discharge Levels in Produced Water for Various Locations

LOCATION	MAXIMUM FREE OIL CONCENTRATION PPM
International Maritime Organization (IMO)	15
NE Atlantic and Arctic Oceans	40
NORTH SEA (PARIS COMMISSION)	40
USA OFFSHORE EFFLUENT GUIDELINES (EPA)	29
MEDITERRANEAN SEA	10-15
CASPIAN SEA	20
RED SEA	15
NIGERIA	10
BRAZIL	15
VENEZUELA	20

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Understanding What Is Produced Water

In the United States produced water as defined by the EPA, states in one version of the definition: "Produced Water" means the water (brine) brought up from the hydrocarbon bearing formation strata during the extraction of oil and gas, and can include formation water, injection water, and any chemicals added down-hole or during the oil/water separation process."

The physicochemical properties of produced water varies considerably depending on the reservoir type (e.g. oil, gas or coal), geographic location of the field, the geologic formation and the type of produced hydrocarbon (e.g. heavy oil, medium oil, light oil, lean gas, rich gas. Table 2 represents the summary of typical oil field produced water characteristics.

Table 2 Characteristics of typical oil field produced water

Parameter	Unit	Value
Density	kg/m ³	1014 - 1140
Surface tension	dynes/cm	43 - 78
TOC	mg/l	0- 1500
COD	mg/l	1220
TSS	mg/l	1.2 - 1000
pH	-	4.3 - 10
Total oil	mg/l	2 - 565
Volatile (BTX)	mg/l	0.39 - 35
Chloride	mg/l	80 - 200000
Bicarbonate	mg/l	77 - 3990
Sulphate	mg/l	2 - 1650
Sulphide	mg/l	10
Total polar compounds	mg/l	9.7 - 600
Higher acids	mg/l	1 - 63
Phenols	mg/l	0.009 - 23

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The produced water may also contain free oil, emulsified oil and suspended solids including precipitated solids, sand, silt, carbonates and clays which are suspended in the streams which can cause corrosion, and heavy metals which are less toxic compared to general organic constituents. It also contains various organic, inorganic compounds and some anaerobic bacteria. Furthermore, PW can contain These compounds can consist of the following:

- Dissolved Organic Compounds
- Dissolved and Free Oil Compounds
- Production Chemicals
- Produced solids, typically sand, silt, wax, asphaltenes, scale and
- Corrosion Products
- Dissolved gas such as CO₂ and H₂S

The amount of dissolved compounds will depend on the pH, salinity, temperature, suspended solids, oil loading, shear history and the type and quantity of the production chemicals used. Further, these may affect the ability of the separation equipment to separate the oil and water, and may require additional chemical treatment in order for the produced water equipment to meet its free oil process guarantee. Typical organic compounds that may be found in produced water are shown in Table 3.

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Table 3: Typical Organic Content of Produced Water From Oil and Gas Fields

Components	Concentration –Oil Field		Concentration –Gas Field	
	Typical ppm	Range-ppm	Typical ppm	Range-ppm
Aliphatics- ≤C ₅	1	0-6	1	0-6
Aliphatics- ≥ C ₅	5	0-30	10	0-60
Aromatics BTEX*	8	0-30	25	0 ≥ 50
Naphthalene's	1.5	0-4	1.5	0 - 4
Polar Compounds				
Phenols	5	1-11	5	0-22
Fatty Acids	300	30-800	150	0-500

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Produced Water has other properties that are frequently not well understood. Ignorance of them can complicate the treatment of Produced Water. Some of these are:

- a. Produced Water contains chemical equilibrium systems that shift with changes in temperature and pressure, causing reactions to occur. These reactions may result in mineral scales being formed, solid hydrocarbon deposition (paraffin formation) and changes in pH.
- b. Produced Water does not normally contain oxygen and some of its components are in a chemically reduced state. These will react with oxygen if the water is allowed to contact air. This can result in deposition of iron compounds and elemental sulfur. Closed systems are required.

Problems associated with produced water include:

- a. Plugging of disposal wells by solid particles and suspended oil droplets,
- b. Plugging of lines, valves, and orifices due to deposition of inorganic scales, Growth of bacteria that plug lines and valves or result in the formation of harmful products.
- c. Produced solids, typically sand, silt, wax, asphaltenes, scale and corrosion products.
- d. The salinity and pH of produced water can range from 40,000 ppm to 250,000 ppm with a pH of 5.0 - 6.5. As the life of the production well ages the salinity and pH of the water will change.

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To give a single 'Best Practice' guideline is therefore not possible. More appropriate is a common approach to design, and to identify and diagnose problems in a system. Jointly solve water treatment problems stepwise approach is as follows (Frankiewicz, 1999):

1. Review all aspects of the facility's mechanical operations; fix mechanical problems first, add chemicals second
2. Correlate appearance of separation problems with operational factors.
3. Conduct mechanical and chemical diagnostic field testing.
4. Take fluid samples for laboratory characterisation and analysis.
5. Review data with operators, field engineers and chemical experts.
6. Provide data to equipment and chemical suppliers; work with them to select candidate solutions; remain involved.
7. Pilot test; contribute to design, engineering and implementation of proposed solution(s).

Below are the factors that can affect the amount of produced water production on the life of a well (Reynolds and Kiker, 2003):

- 1) Method of well drilling: a horizontal well can produce at a higher rate than a vertical well at similar drawdown, or can produce similar production rate at lower drawdown.
- 2) Location of well within homogeneous or heterogeneous reservoirs: for homogeneous reservoirs, use of horizontal wells reduces water production but in homogeneous reservoirs, the increase in production of horizontal versus unstimulated vertical wells is proportional to the reservoir's area contacted by the wells.
- 3) Different types of completion: the open hole method permits testing of drilling zones and avoids drilling into water. On the other hand, the perforated completion method

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offers a much higher degree of control since the interval can be perforated and tested.

- 4) Single zone and commingled: most wells are initially completed in a single zone. As oil rate declines because of maturing of the well, other zones may be opened to maintain the oil production rate, as a result water production too increases.
- 5) Type of water separation technologies: different methods are used to reduce costs of lifting and/or water handling for wells that produce large quantities of saline water. These methods are water shut-off treatment using gelled polymers, reducing beam pump lifting costs, power options to reduce electrical costs and separation technologies.
- 6) Water injection or water flooding for enhancing oil recovery: the aim of water flooding is getting the well-treated water to the oil level to increase production rate. Because of water flooding, an increasingly higher percentage of water is produced. As a flood progresses, the volume of required water for injection increases. In this case, makeup water with suitable chemical characteristics is necessary. The poor quality of treated produced water, or makeup enables sealing, clay swelling, and brine incompatibilities.
- 7) Poor mechanical integrity: many water entries are caused by mechanical problems of the casing holes caused by corrosion or wear, and splits caused by flows; excessive pressure can allow unwanted reservoir fluids to enter the casing and increase water production.
- 8) Underground communications: underground communications problems happen near wellbores or reservoirs. Both these problems generate increase in produced water. Near wellbore problems are the channels behind casing, barrier breakdowns, and completions into or near water. Reservoir related problems are coning, cresting, channeling through higher permeability zones or fractures, and fracturing out of zone.

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DEFINITIONS

Hydrocyclone: A device to classify, separate or sort particles in a liquid suspension based on the densities of the particles. A hydrocyclone may be used to separate solids from liquids or to separate liquids of different density, i.e. produced water and oil. A hydrocyclone will normally have a cylindrical section at the top where liquid is being fed tangentially, and a conical base. The angle, and hence length of the conical section, plays a role in determining operating characteristics.

Skim Tank: A vertical or horizontal vessel used to separate free oil from produced water. The skim tank depends on the difference in specific gravity between oil and water, lighter oil eventually floating to the top of the denser water content, where it can easily be skimmed off. These tanks are normally designed to provide long residence time during which coalescence and gravity separation can occur.

CPI Separator: The CPI is “Corrugated Plate Interceptor” and is sometimes termed *coalescing plate interceptor* because it encourages coalescence of oil droplets to improve the rise rate and performance as the effective droplet sizes are increased. CPI separators are counter current separators. Oily water enters the plate pack at the top and flows between the parallel plates in a downward direction. Separated oil droplets adhere to the plate surface, coalesce and move upward, counter to the downward moving main flow. The separated oil droplets leave the CPI plate pack at the top.

DGF - Dissolved Gas Flotation: When properly operated, gas flotation units can reduce oil concentrations of wastewater effluents to well below 40 mg/l. Gas flotation is particularly valuable for heavy oils (oils having a density close to that of water). The flotation process relies on the attachment of gas bubbles to the dispersed oil droplets. This attachment is heavily dependent on the complex processes involving the surface characteristics of the oil droplets and their interaction with gas. The attachment mechanisms include the oil/bubble contact, the interactions of chemical additives (usually surfactants) in aiding this contact and the spreading of the oil around the gas bubble.

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IGF - Induced Gas Flotation: A vessel which removes free oil from produced water using induced gas bubbles to assist in coalescing the oil. Very much like dissolved gas except that the gas is introduced into the vessel rather than dissolved in the vessel.

Fixed Offshore Platform: An offshore structure that sits on the seafloor and is usually held in place by piles. (See Diagram 1)

FPSO: Floating Production Offshore Storage and Offloading- an offshore production facility that is typically ship-shaped and stores crude oil in tanks located in the hull of the vessel. The crude oil is periodically offloaded to shuttle tankers or ocean-going barges for transport to shore. FPSO's may be used as production facilities to develop marginal oil fields or fields in deep water areas remote from the existing OCS pipeline infrastructure. FPSO's have been used to develop offshore fields around the world since the late 1970's. They have been used predominantly in the North Sea, Brazil, Southeast Asian/South China Seas, the Mediterranean Sea, Australia, and off the West Coast of Africa.

SPAR's or Tension-Leg Platform (TLP's): These are floating platforms held in position by centrally located multiple cables anchored to the ocean floor. The constant tension of the cables makes the platform immune to heave, pitch, and roll caused by wave action, conditions that typically affect conventional semisubmersible platforms.

Free Gas: Is in a gaseous phase in the subsurface reservoir and remains in a gaseous phase when produced.

Dissolved Gas: Is in solution within the subsurface reservoir, but bubbles out of solution when temperature and pressure drops.

Slug Flow: A multiphase fluid flow regime characterized by a series of liquid plugs (slugs) separated by a relatively large gas pockets. In vertical flow, the bubble is an axially symmetrical bullet shape that occupies almost the entire cross-sectional area of

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the tubing. The resulting flow alternates between high-liquid and high-gas composition. The word slug normally refers to the heavier, slower moving fluid, but sometimes to the bubbles of lighter fluid. There are also small bubbles within the liquid, but many of these have coalesced to form the large bubbles until they span much of the pipe. In gas-liquid mixtures, slug flow is similar to plug flow, but the bubbles are generally larger and move faster. As flow rates increase, slug flow becomes churn flow.

Coalescence: Gravity separation utilizes the difference in specific gravity between the oil and water. Oil separates from a fluid at a rate explained by Stoke's Law. The formula predicts how fast an oil droplet will rise or settle through water based on the density and size of the oil droplet size and the distance the object must travel.

Free Oil: A Non-emulsified oil droplet of about 150 microns that will separate from water and which will float immediately to the surface due to its large size and high rise velocity. The free phase oil can also be "dispersed" or spread out throughout the body of the water due to being broken into a range of droplet sizes.

Dissolved Oils:The oils that are dissolved in the produced water due to their innate characteristics, nature and external influences.

Emulsions:Oil which is dispersed in the water in a stable fashion due to its small diameter and its low rise velocity.

Oil Droplet Shear- The breaking up of larger oil droplets into smaller ones, primarily due to pressure drop.

NEAT - A term used to describe how a chemical is being injected - straight,meaning it is not diluted.

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NOMENCLATURE

$\%OF_{solid}$	percent of overflow solid
$\%circulating$	Approx Circulating Load
$\%F_{solid}(v)$	percent of feed solid by volume
$\%UF_{solid}$	percent of underflow solid
D	Pipe Internal Diameter (Inches)
d	the diameter of the oil-droplet
F	the separation force
L	Pipe length (feet)
Q	Flow rate (BPD)
$SG_{Fslurry}$	specific gravity of feedflow slurry
$SG_{OFslurry}$	specific gravity of overflow slurry
$SG_{UFslurry}$	specific gravity of underflow slurry
SG_{solid}	specific gravity of solid
SG_{liquid}	Specific gravity of liquid
T	Time (seconds)
V	the velocity of the particle or droplet being separated from the bulk fluid
$W_{Fslurry}$	Feed flow of slurry (MTPH),
W_{Fsolid}	Feed flow of Solids (MTPH),
W_{Fwater}	Feed flow of water (MTPH),
$W_{OFsolid}$	Overflow of Solids (MTPH)
$W_{OFwater}$	Overflow of water (MTPH)
$W_{UFsolid}$	Underflow of Solids (MTPH) ,
$W_{UFwater}$	Underflow of water (MTPH),
$W_{UFslurry}$	Underflow of slurry (MTPH)

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Greek Letters

ρ_{water}	the density of the water.
ρ_{oil}	the density of the oil.
η_{water}	the viscosity of the bulk phase (water),
ΔP	pressure drop (kPa)

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