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PRODUCED WATER MIDDLE EAST

SUNDAY 12TH & MONDAY 13TH NOVEMBER 2017

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WATER STANDARD

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Application of Flotation for Removing Fine Particles from Iron-Containing Produced Water

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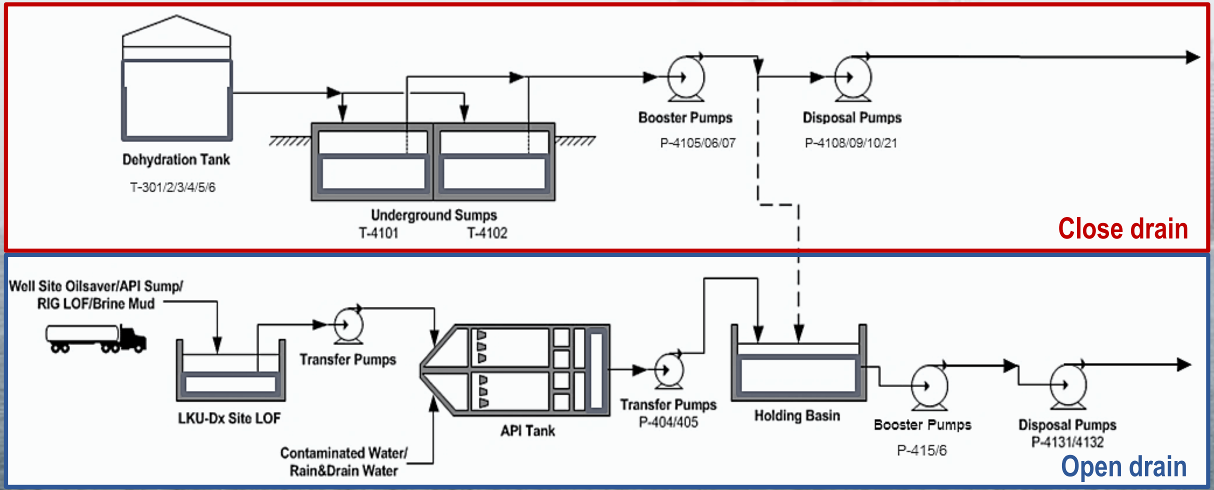
PRODUCED WATER
MIDDLE EAST

Background

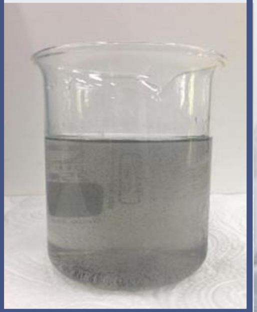
- Produced water characteristics depend on subsurface formation
- PW in onshore production is similar to groundwater properties
- Iron (soluble form, Fe^{2+}) and sulfate (SO_4^{2-}) are commonly found in groundwater from various areas in Thailand



- Produced water management
  - Re-injection
  - Improved oil recovery
- Problems
  - Clogging
  - Equipment damage

Characteristics

Open drain

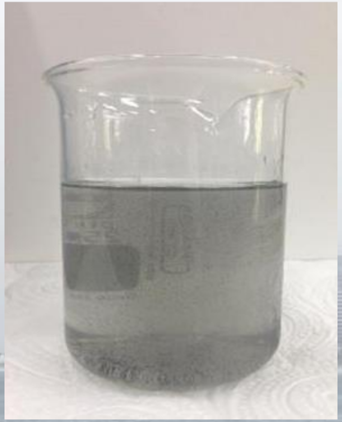


Close drain

Parameter	Unit	Produced water		Groundwater
		Open drain	Close drain	
Turbidity	NTU	31.0 ± 2.58	13.0 ± 0.46	-
Conductivity	µS/cm	575	264	108 – 461
pH		7.16	7.65	6.4 – 8.8
Oil & Grease	mg/L	35.2 – 71.5	47.5 – 69.1	-
Suspended Solids	mg/L	130 ± 12	20 ± 7	-
Chloride (Cl^-)	mg/L	21,800	6,270	3 – 21
Sulfate	mg/L	15.0	12.0	-
Sulfide	mg/L	0.22	0.12	-
Iron (Fe)	mg/L	11.8	2.08	0.2 – 81
Manganese (Mn)	mg/L	2.50	0.30	-
Mercury (Hg)	mg/L	0.036	0.007	-
Arsenic (As)	mg/L	0.11	0.01	-

Characteristics

Open drain



Particle size (µm)	Number	Number fraction (%)	Volume fraction (%)
<5	5,347,172	99.81	93.41
5 – 10	6,342	0.12	0.89
10 – 15	1,541	0.03	0.73
15 – 20	777	0.02	0.87
20 – 25	594	0.01	1.29
>25	745	0.01	2.81

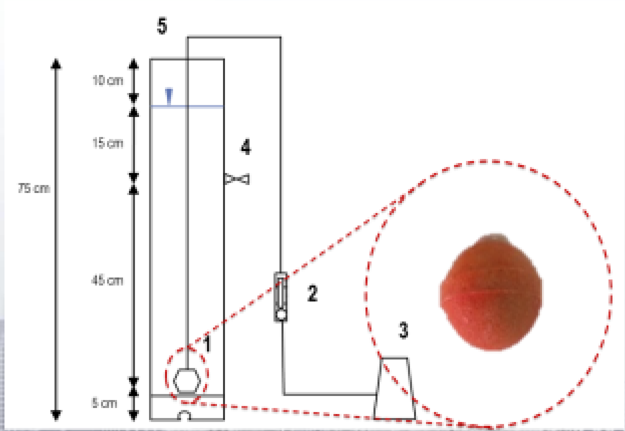
- Technology/process for removing <5 µm particles and oil

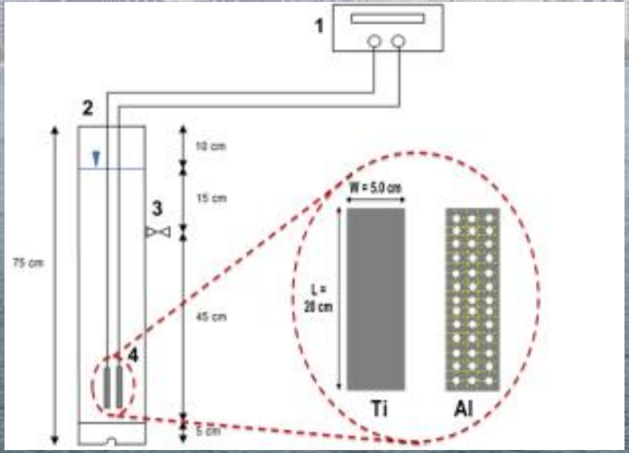
Separation technology

Process	Minimum size of particles removed (µm)	Advantages	Drawbacks
Chemical treatment	1	• Applicable for a large amount of wastewater with high suspended solid	• High chemical cost • Require proper sludge management
Gas flotation	3-5	• No moving parts • High efficiency • Easy operation	• Chemical required for particle aggregation • Sensitive for fluctuation in inlet flow rate or concentration • Most effective with smaller gas bubbles than droplet/particle sizes
Electrocoagulation-flotation (ECF)	<1	• High efficiency without chemical required • Produces less sludge volume that is easier for dewatering • Capable in treatment of oil in dissolved or emulsion forms	• Need to replace new electrode regularly due to electrode corrosion • Electric power consumption

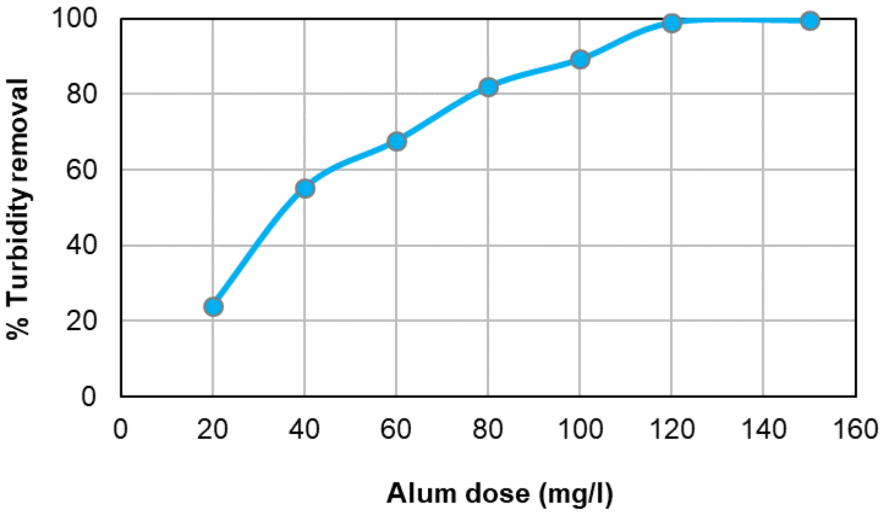
Methodology

- **Chemical treatment**:
  - Aluminum sulfate ($Al_2(SO_4)_3$ or alum) in jar test experiment
- **Flotation**
  - Induced air flotation (IAF)
  - Induced air flotation with chemical (MIAF)
- **Electrochemical process**
  - Electroflotation (EF)
  - Electrocoagulation-flotation (ECF)





Chemical treatment



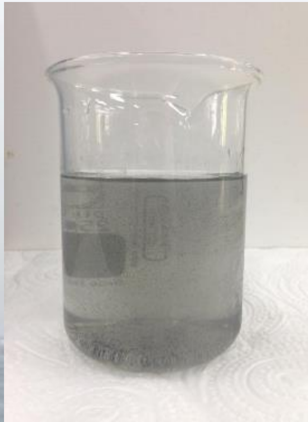
pH of 6.3–6.8 at all applied dosages of alum ($Al_2(SO_4)_3$)

Parameters	Unit	Initial	Treated
pH	-	7.16	6.50
Turbidity	NTU	31.80	1.12
Total suspended solids	mg/L	134	41
Oil and Grease	mg/L	69.7	13.5

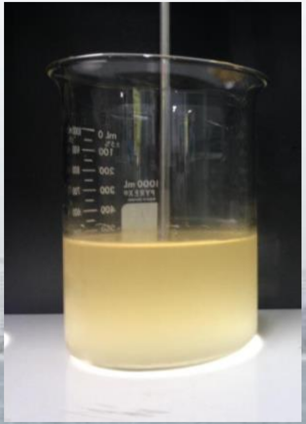
Alum dosage >120 mg/L

- 96% turbidity removal
- 70% SS removal
- 60% oil and grease removal

Chemical treatment



After mixing



Parameter	Unit	Initial	After mixing
pH	-	7.16	7.09
Turbidity	NTU	31.0 ± 2.58	233.3 ± 4.93
Suspended solid	mg/L	130 ± 12	171 ± 8

Changes in appearance and characteristics of produced water due to oxidation

$$Fe^{2+} + O_2 \rightarrow Fe^{3+} + O_2\cdot$$

$$2O_2\cdot + 2H^+ \rightarrow H_2O_2 + O_2$$

$$Fe^{2+} + H_2O_2 \rightarrow HO\cdot + HO^- + Fe^{3+}$$

Characteristics

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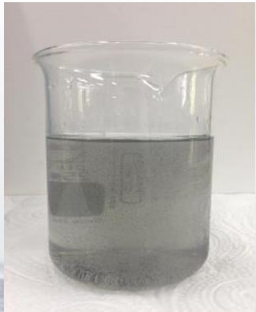

Close drain

2 hours

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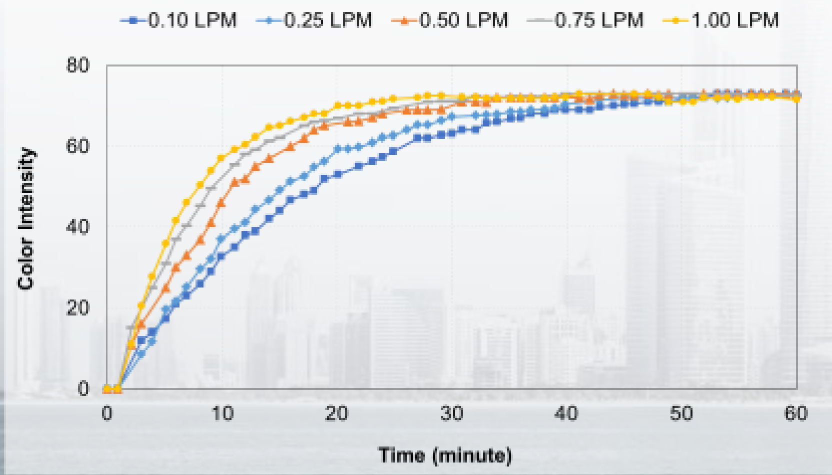
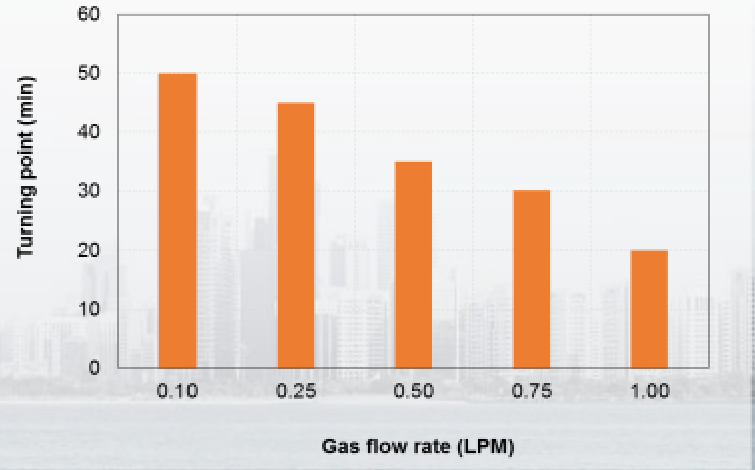
Flotation

Color transition during flotation





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Flotation

Produced water **after 60-minute treatment** with Q_g of 0.05 LPM

IAF

MIAF
(50 mg/l alum)

Processes	Efficiency (%)	
	Suspended solids	<5 µm particles
IAF	88	65
MIAF	98	76

- Limited separation from difference in sizes between large bubbles and small particles
- Slight turbid and yellowish color after flotation
- Ferrous oxidation affects the performance

Electroflotation (EF)

Produced water **after 60-minute treatment by EF** (2 cm electrode gap and 1.25 A electric current)

Rusty sludge on the surface

Anode (oxidation)	$2H_2O_{(l)} \rightarrow 4H^+_{(aq)} + \boxed{O_{2(g)}} + 4e^-$
Cathode (reduction)	$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$

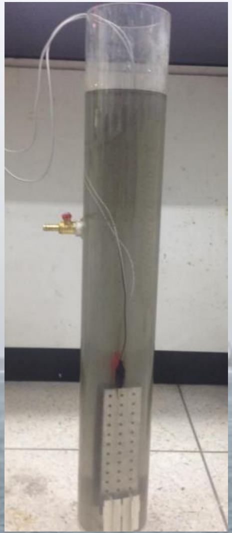
- Yellow turbid water from ferrous oxidation
- With oxygen is continuous produced, iron rust is formed

$$Fe^{2+} + 2H_2O \rightleftharpoons \boxed{Fe(OH)_2} + 2H^+$$

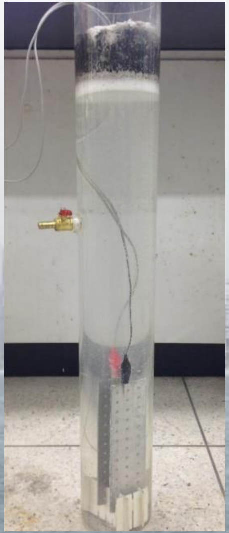
$$Fe^{3+} + 3H_2O \rightleftharpoons \boxed{Fe(OH)_3} + 3H^+$$

Electrocoagulation-Flotation (ECF)

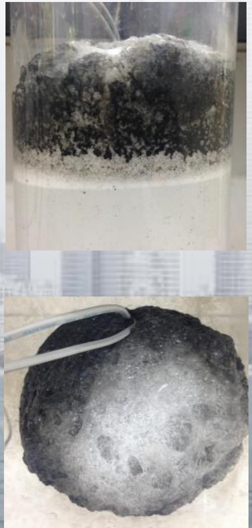
Appearance of produced water **after 30-minute treatment by ECF** at electrode gap 2 cm and current 1.25 A



Initial



After 30 minutes



Sludge layer

Anode (oxidation)	$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^-$ $2H_2O_{(l)} \rightarrow 4H^+_{(aq)} + O_{2(g)} + 4e^-$
Cathode (reduction)	$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$

- 99% removal efficiency of particles larger and smaller than 5 μm
- Clear and unchanged color water after treatment
- 2 layers of sludge on the surface of produced water
    - Thick black layer
    - White layer

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Efficiency comparison

Criteria	Jar test (150 mg/L alum)	IAF	MIAF (150 mg/L alum)	EF	ECF
Appearance	Slight turbid	Turbid	Turbid	Rusty	Slight turbid
>5 µm removal (%)	99	88	98	N/A	97
Retention time (min)	35	60	60	30	30
<5 µm removal (%)	99	65	76	N/A	99

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Conclusion

- Effectively separation of both larger and smaller than 5 μm from produced water by chemical coagulation and ECF
- Oxidation of iron in produced water greatly affects treatment performance and process selection
- Handling of iron in produced water in necessary for preventing clogging from
    - Particle generation
    - Scaling (petroleum schmoo)
- Development of process (or combined processes) for dealing with iron-containing produced water is necessary


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