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Characterization of Candlenut Shells and Its Application to Remove Oil and Fine Solids of Produced Water in Nutshell Filters of Water Cleaning Plant

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Abstract**—**Oilfields under waterflood often face the problem of plugging injectors either by internal filtration or external filter cake built up inside pore throats. The content of suspended solids shall be reduced to required level of filtration since corrective action of plugging is costly expensive. The performance of nutshell filters, where filtration takes place, is good using pecan and walnut shells. Candlenut shells were used instead of pecan and walnut shells since they were abundant in Indonesia, Malaysia, and East Africa. Physical and chemical properties of walnut, pecan, and candlenut shells were tested and the results were compared. Testing, using full-scale nutshell filters, was conducted to determine the oil content, turbidity, and suspended solid removal, which was based on designed flux rate. The performance of candlenut shells, which were deeply bedded in nutshell filters for filtration process, was monitored. Cleaned water outgoing nutshell filters had total suspended solids of 17 ppm, while oil content could be reduced to 15.1 ppm. Turbidity, using candlenut shells, was below the specification for injection water, which was less than 10 Nephelometric Turbidity Unit (NTU). Turbidity of water, outgoing nutshell filter, was ranged from 1.7-5.0 NTU at various dates of operation. Walnut, pecan, and candlenut shells had moisture content of 8.98 wt%, 10.95 wt%, and 9.95 wt%, respectively. The porosity of walnut, pecan, and candlenut shells was significantly affected by moisture content. Candlenut shells had property of toluene solubility of 7.68 wt%, which was much higher than walnut shells, reflecting more crude oil adsorption. The hardness of candlenut shells was 2.5-3 Mohs, which was close to walnut shells' hardness. It was advantage to guarantee the cleaning filter cake by fluidization process during backwashing.

Keywords**—**Candlenut shells, walnut shells, pecan shells, nutshell filter, filtration.

I. Introduction

THE produced water re-injection becomes one of solution of scale tendency and water management since last decades. The aquifer as natural drive mechanism is sufficiently weak, resulting in small contribution to primary recovery from natural water influx. In 1993, the reservoir of Zamrud field has been waterflooded to sweep the oil and to maintain reservoir pressure. The produced water is used as injection water. Pressure of injection water was three times of initial bubble point pressure. Keeping injection pressure above initial bubble point pressure results in higher oil production due to miscible gas preferential flow [1]. The upper and lower sand, which were separated 70 ft in depth, had initial bubble point pressure of 192 psi and 292 psi, respectively [40]. Before peripheral waterflood started breakthrough, the number of production wells inside boundary reservoir were increased. Nowadays, 49 injection wells are injecting cleaned water of 148,500 BPD [41]. They are operated according to targeted flow rates of injection water and maximum allowable injection pressure, which is lower than fracture pressure.

The reservoir is sandstones and is oil-wet, indicated by high capillary pressure. The salinity of formation water is 5,700 ppm, which can precipitate asphaltenes present in the crude oil [2]. Precipitation of asphaltenes, which is polar, can alter wettability from water-wet to oil-wet [3], [4]. The average pore throat size of 21 μm produces fine sands of 1-63 μm, which is contributed by feldspar and quartz [5]. Larger size of suspended solids than pore throats impacts on formation of internal filtration and external filter cake near wellbore of injection wells [6]. The well injectivity decline, i.e. strongly positive skins are achieved either by fine solids migration or coarse solids mobilization, can effect on field-scale waterflood operation [7], [8]. The injection wells can use any cleanup chemicals such as acid treatment and pressurized solvent washer in order to improve their injectivity index. In order to avoid progressive particle plugging, which impacts on injectivity decline, produced water is cleaned prior to be used as injection water. Scale growth, corrosion, and bacteria, which can also decline injectivity, are carefully controlled by injecting some sub-surface line inhibitors and biocide.

Some tests using filter membrane can be carried out to answer the question on the required specification of injection water by assuming pseudo-homogenous pore sizes of rocks [9], [10]. However, tests of coreflood and on-site injectivity are needed to determine water quality on heterogeneous and complex porous rock, containing solid content [11]-[13]. The impairment mechanisms and filter cake properties from the coreflood tests data can be predicted [14]. Selecting acceptable degree of filtration varies from one oil operator to others. Very high degree of filtration causes high investment and operating costy, without directly returning on increasing production.

Cleanup of injection water can be accomplished either by combination nutshell filter and cartridge filter for onshore or screen deck and cartridge filter for seawater injection [15]. Desanding hydrocyclone, which combination with deoiling hydrocyclone, is commonly selected for removing solid

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particle in the platform from standpoint of view foot print [16], [17]. The usage cartridge filter standalone can reduce solids of 50-100 ppm to 2-5 ppm, but it was difficult in operational due to clogging [18]. Nutshell filters can be equipped with internal or external vertical screen for backwashing purpose [19]. For good coalescing and filtration, the ratio filter media of pecan and walnut shells was 4:1 [20]. More amount of walnut shells shall be added to pecan shell if there is an increase in solid size. The best filter media for capturing oil, as determined by wet retention testing, was pecan shells, followed by walnut shells [21]. Although nutshell filters are widely used in oil industry, the evaluation of performance of nutshell filters using pecan and walnut shells have very little publications. Nutshell filter using pecan and black walnut shells with 4 inch diameter equipment with 48 inch bed depth was investigated by [22]. They concluded that filter media at flux of 13.5 GPM/ft^2 can remove solid of 5 μm size. Unfortunately, their experimental work was not run on industrial-scale nutshell filter, so it lose the effect of hydrodynamics when fluidization during backwashing. Most-uniform distribution of fluidization with higher backwash flow of scrubber pump and moderate jet flow in computational fluid dynamics (CFD) simulation took place at the bottom of internal vertical screen due to smaller shape at its end [23].

In this paper, candlenut shells (*Aleurites moluccana*) were used, there are no previous works reported. Some parameters affecting the performance of nutshell filter using candlenut shells will be further discussed at the same flux rate limit as pecan and walnut shells, which were previously used. The industrial-scale nutshell filters were run by actual conditions, which are injecting scale inhibitor, corrosion inhibitor, and biocide. In addition, field data of cumulative wellhead pressure and flow rate of injection water were plotted to predict the injectivity-decline-rate curves.

II. Experimental Section

A. Materials

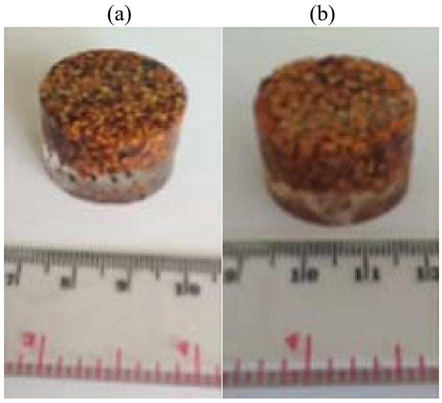
Pecan shells (*Carya illinoinensis*) and black walnut shells (BWS) (*Juglans nigra* L) were bought from Composition Materials Co. Inc., 1375 Kings Higway East, Fairfield, Connecticut, US. Pecan and BWS shells with ratio of 4:1 were first used in nutshell filters. Then, candlenut shells were used to replace pecan shells and BWS as filter media. Candlenut shells (*Aleurites Moluccana*) were bought from CV. Bumi Riau. Candlenut, pecan, and walnut shells were subjected to sieve analysis according to ASTM D422-63 [24]. Fig. 1 shows candlenut shells, which was passed on mesh of 8 and was 97% retained on mesh of 12. The pecan and walnut shells were passed on mesh of 10 and were 97% retained on mesh of 20.

The hygroscopic nature of biological materials enables it to absorb or desorb moisture until equilibrium is reached with its surrounding conditions. The amount of water to fill the voids of those filter media was measured as moisture content by drying at 105 ^{o}C for 16 hours, cooling, and weighting according to ASTM D2216-92 [25]. The ratio of loss in weight and sample weight before drying was used to calculate moisture content. Specific gravity was measured as bulk density, which is density of granular media including its voids was referred to procedure reported by [21]. This specific gravity was measured without drying process, so that the filter media contains inherent free water. The nitrogen and ash contents were determined by ASTM D5291 and ASTM D3174, respectively [26], [27]. The amount of acid-insoluble lignin was measured according to TAPPI T 222 om-11 [28]. Acid-soluble lignin for this measurement was not considered. The determination of cellulose was carried out by applying methods according to TAPPI T 203 cm-9, IDT [29]. The extractives content, which was soluble in solvents of sodium hydroxide, alcohol-benzene, acetone, hot water, and toluene, were measured by using milli-pore filtration. The mixture of filter media and solvents at certain ratio were heated at 70 ^{o}C for 10 minutes, filtered, oven-heated at 120 ^{o}C, and weighted.

(a) (b) (c)

Fig. 1 Filter media. (a) Candlenut shells, (b) Pecan shells, (c) Walnut shells

(a) (b)



(c) (d)

Fig. 2 Hardness testing: (a) Leco hardness tester, (b) Candlenut shells composite, (c) Pecan shells composite, (d) Walnut shells composite

Vickers hardness was tested for candlenut, pecan, and walnut shells according to ASTM E92-82 using LECO hardness tester, model M-400-H1 (USA) [30]. Olympus GX51 inverted microscope (LECO, USA) was used to get the image analysis of candlenut shell after 50 times magnification as shown in Fig. 4.

B. Equipment Setup

The flare stack was seldom online because of waterflood breakthrough. Gathering station (GS) was composed of de-gas boot, wash tank, and shipping tank (see Fig. 7). Free oil and water were separated in two phase wash tank, which was designed to remove oil droplets ≥ 100 μm.

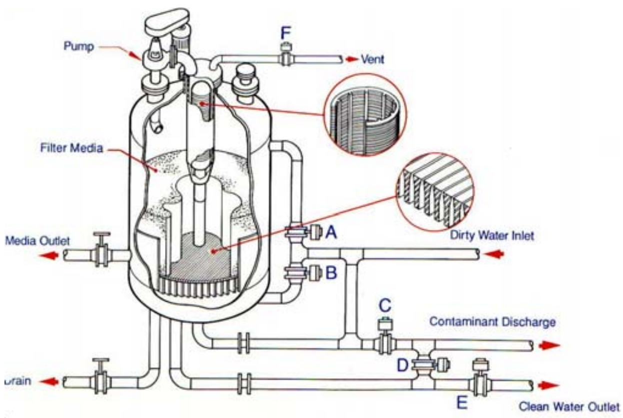
Waters effluent wash tank, where dispersed oils and suspended solids, are fed to Water Cleaning Plant (WCP) for further oil and solid removal. WCP is composed of oil skimming tank and nutshell filters as secondary and tertiary stage of oil and solid removal, respectively. Oil droplets, which have size less than 125 μm, are removed from the water in the oil skimming tank by a combination of coalescence and settling by gravity. This unit can reduce oil content of 595.8 ppmv to 99.3 ppmv. Nutshell filter was designed using design basis of 98% solid removal efficiency or maximum 2 mg/L TSS and minimum oil content. Prior to send to injection wells, cleaned waters were through cartridge filters as polishing unit. The injection water can contain high oil content as long as the oil droplet size is less than or equal to average pore throat diameter [31].

If one-third of pore throat diameter is used as basis of cartridge design, therefore the maximum solids size allows to invade formation of Zamrud field is less than 7 μm [32]. In Table III, upper sand of Pedada field has permeability of 280 md and hence pore throat diameter is 16.7 μm, which is the square root of its permeability [33]. Therefore, the maximum solids size is 6 μm. Cartridge filters with retention rating of 10 μm is reasonable selection to avoid reservoir plugging. As comparison, the allowable solids size for Bangko field, which has 530 md permeability and 23 μm pore throat size, is less than 8 μm [34]. Otherwise, for Bekasap field with 1,000 md permeability and 31.6 μm pore throat size, the allowable solids size is less than 11 μm [35].

Fig. 2 shows the full-scale nutshell filters, located in Zamrud field, used for the investigation. Six nutshell filters are operated in parallel. They have diameter of 13.5 ft (4.11 m) and height of 8 ft (2.44 m) with maximum capacity of 72,500 BPD (WEMCO, model of Silver Band SB1485). They are operated on 33% of their maximum capacity. The deep of nutshell bed is 121.92 cm (or 48 inch) with maximum flux limit of 11.1 GPM/ft^2. If nutshell filter is run above maximum flux limit, the quality of filtration will significantly reduce. Otherwise, the inlet stream of nutshell filter, which is outgoing oil skimming tank, is pressured to 40-50 psig to increase the filtration rate. The usage of candlenut shells for nutshell filter #A, #F and pecan and walnut shells for nutshell filter #B to #E were aimed at comparing them.

For filtration mode, the actuator valves A and E are normal opened using pneumatic with pressure of 20 psig while valves B, C, D are in normal closed position. The inlet stream is from valve A and the stream will be filtrated through bed of candlenut shells, which can foul and clogging. If filter cake builds up, causing in increasing pressure drop and lowering flow rate of inlet stream, the candlenut shells need to be backwashed for 15 minutes fluidization. The alarm will be triggered if differential pressure reaches 16 psi as pre-caution alert. Mudballing, when oil causes filter media agglomeration, will occur if backwash is not sufficient.

(a)



(b)

Fig. 3 Nutshell filters. The pecan and walnut shells 10/20 mesh was replaced by candlenut shells of 8/12 mesh. (a) Photograph of nutshells filters capacity of 74,250 BPD for each unit, (b) Schematic drawing of nutshell filter for normal and back-washing operating mode. The deposited contaminants are scrubbed from the filtration media by circulating media along a toroidal flow path within nutshell filter

In order for rejuvenating the filter media, nutshell filter can be operated reverse flow by opening valve B and closing valve A, C, D, E; we called as backwash mode. The water outgoing discharge of a scrubber pump will flow through a nozzle on the top of nutshell filter and then continuous downflow through bed of candlenut shells for fluidization by creating radial flow along internal vertical screen. After backwashing is finished, valve B is closed and valve C is opened for draining dirt water to pit, while valves D, E, and A are still closed.

Automatic backwash is triggered by flow rate of 1,000,000 barrels or 10,000 minutes. Piping and instrumentation diagram (P&ID) of the nutshell filter can be seen in Fig. 8.

III. Results and Discussion

A. Chemical Composition of Candlenut Shells

Candlenut, pecan, and walnut shells contain the same constituents; cellulose, hemicelluloses, lignin, ash, and a small amount of other extractives such as furans, phenols, carbonyls, alcohol, and acids. However, proportions of lignin can vary among these materials. Table I shows composition of lignin and cellulose percentages of candlenut, pecan, and walnut shells.

TABLE I
Physical Characteristics and Chemical Analysis of Candlenut, Pecan, and Walnut Shells

		Unit	Candlenut	Pecan	Black Walnut
Chemical Analysis			**Constituents:**		
	Nitrogen	wt%	0.22	0.39	0.09
	Chlorine	wt%	0.01	0.01	0.01
	Alpha Cellulose	wt%	20.17	22.7	40.60*
	Lignin	wt%	44.10	43.6	20.30*
	Ash	wt%	2.248	1.32	0.31
			Solubility In:		
	1 % Sodium Hydroxide	wt%	10.24	23.30	8.64
	Alcohol - Benzene	wt%	7.81	8.14	8.14
	Acetone	wt%	5.14	9.8	4.05
	Hot Water	wt%	9.4	12.15	9.45
	Toluene	wt%	7.68	-	0.65
Physical Property	Specific Gravity	-	1.54	1.20	1.40
	Charring Temperature	^{0}F	437	-	380*
	Moisture content	wt%	9.95	10.95	8.98
	Hardness	Mohs scale	2.5 - 3	2	2.5
	Color	-	Black brown	Dark brown	Light brown

* [36]

Table I shows that the hardness of candlenut shells was ranging 2.5 to 3 Mohs. Candlenut shells have higher hardness compared to pecan and walnut shells. Detail testing results shown in Table IV. It seems that candlenut shells had more good pressure resistance when scrubbing off solids accumulate in the interstitial between the filter media during backwash. The candlenut shells replacement was minimum and each nutshell filter makes up 10 to 25% per year of its total bulk media volume. The specific gravity of candlenut shells was the highest among them, resulting in more complete sink in water compared to others. Toluene, which was hydrocarbon and water-insoluble, was also tested to measure the affinity of candlenut shells to adsorb crude oil. The extractives contents soluble in toluene for candlenut shells and BWS were 7.78 wt% and 0.65%, respectively. The solubility in toluene was not affected by aging, otherwise, age is only influenced by solubility in ethanol. In addition, moisture content of candlenut shells was 9.95 wt%, which was between moisture content of BWS and pecan.

The biggest diameter of candlenut shell is 1,717 μm, resulting in candlenut shell retained in 12 mesh as can be seen in Fig. 4. This mesh was adjusted to match with screen in the nutshell filters.

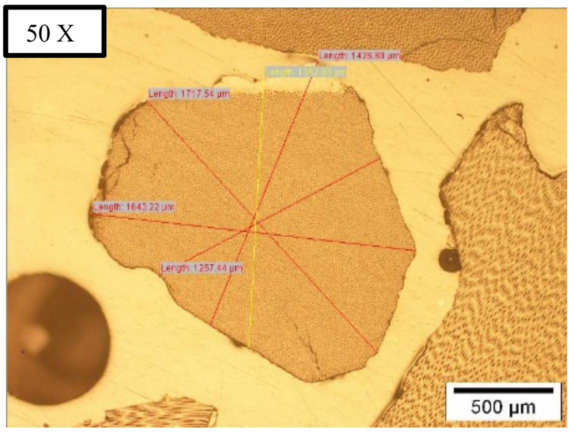


Fig. 4 The image analysis of candlenut shell (after 50x magnification)

The filtration using nutshell filters does not remove dissolved ions, and its performance is not affected by high salt content, therefore they can be used for all Total Dissolved Solid (TDS) of produced water. Dissolved ions are removed to avoid fouling and heat transfer reduction in boilers when producing steam quality of 80% and 100% for steamflood and Steam Assisted Gravity Drainage (SAGD), respectively [37], [38]. The treated water is injected to injector and the remaining water is injected to disposal well. The produced and injected water are closed-loop and no water is discharged to environment.

B. Filtration Performance of Pecan and Walnut

The performance of different type of filter media to reduce turbidity, oil content and total suspended solid will be discussed in the following. Turbidity of produced water after filtration in nutshell filter is shown in Fig. 5. The data were collected for 1 month after filling up pecan and walnut. It shows that the turbidity was ranged of 2.5-8 Naphelometric Turbidity Unit (NTU), which was less than acceptable specification of injection water.

C. Filtration Performance of Candlenut Shells

After filtered by pecan and walnut shells, the filter media were changed to candlenut shells. Fig. 6 shows the turbidity of filtered water. The turbidity was ranged of 1.7 to 5.0 NTU. It shows that candlenut shells are affordable as filter media, giving good filtration.

Longer monitoring shows that there was no stable flow rate of produced water due to some disturbances. Less flow rate is due to producer shut-in due to some reasons such as downhole scale formation, pump failures or fine sand production [39]. After rig service of 2-4 days, the flow rate can be back to normal. Therefore, the trend data of treated produced water has followed Fig. 6 until September 2020.

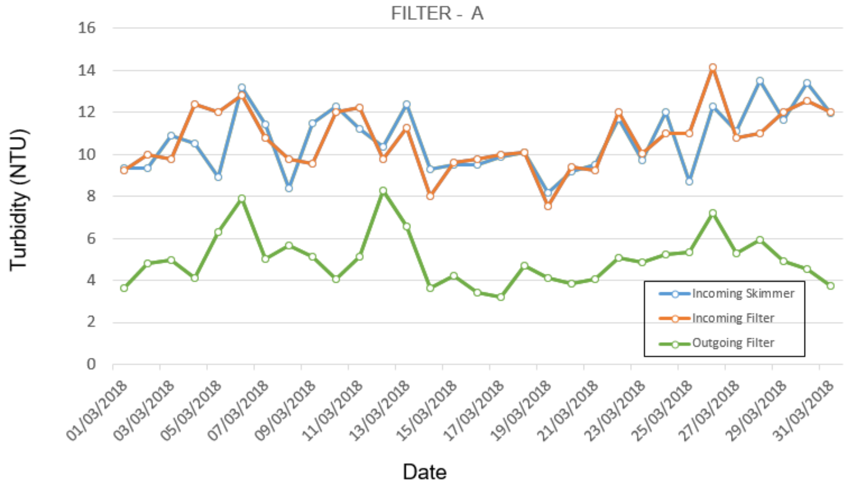


Fig. 5 Turbidity of produced water incoming and outgoing nutshell filter

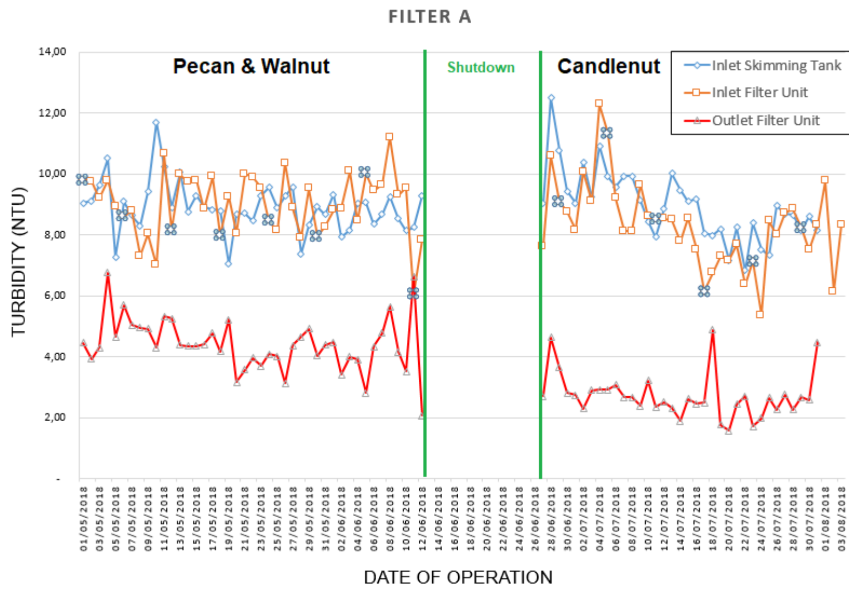


Fig. 6 Turbidity of produced water incoming and outgoing nutshell filter using pecan and walnut compared to candlenut shells

The detail performance of candlenut shells was shown in Table II. The inlet stream of each unit of nutshell filter was coming from the same main header as shown in Fig. 7 in Appendix A. Nutshell filters #A and #F were filled up with candlenut shells, whereas nutshell filters #B to #E were using pecan and walnut.

Oil removal efficiency of nutshell filter #F was similar to nutshell filter #B. In nutshell filter #B, oil content of 99.3 mg/L reduced to 14.9 mg/L with oil removal efficiency of 84.9%. Walnut shells had maximum oil sorption capacity for lower oil viscosity [36].

Solid removal efficiency of nutshell filter #F, using candlenut shells, was much higher compared to nutshell filter #B and #C, using pecan and walnut shells. Nutshell filter #F was able to reduce TSS of 39 mg/L to 17 mg/L with solid removal of 56.4%. Unfortunately, nutshell filter #A had the lowest solid removal efficiency. Low solid removal efficiency of candlenut shells might be caused by bigger mesh size of candlenut shell compared to pecan and walnut. Smaller mesh resulted in bigger void of filter media, so that small particle size could not be filtered. The best solid removal efficiency of pecan and walnut shells was 64.1%, which reduced TSS of 39 mg/L to 14.0 mg/L in Nutshell filter #D.

In order to evaluate the quality of treated produced water, which was injected to reservoir and to reduce uncertainty in expected well injectivity, Hall's plot was used. There was good indication of Hall's plot and there was no case of either plugging or fracture.

IV. Conclusion

1. Candlenut shells at flux of 11 GPM/ft^2 were able to remove 1-63 μm solid size, indicated by turbidity, which

was ranged of 1.7-5.0 NTU.

2. Using candlenut shells, total suspended solid of 39 mg/L and oil content of 99.3 mg/L were reduced to 17 mg/L and 15.1 mg/L, respectively.
3. Moisture contents of walnut, pecan, and candlenut shells were 8.98 wt%, 10.95 wt%, and 9.89 wt%, respectively.
4. Toluene solubility of candlenut shells was 7.68 wt%, which was about a 7-fold walnut toluene solubility, resulting in higher adsorption rate of crude oil.
5. The hardness of candlenut shells was 2.5 – 3 Mohs, which was the highest compared to pecan and walnut shells.
6. Granulated candlenut shells with specific gravity of 1.54 pose a capability of coalescing of oil from produced water and accumulating the coalesced oil in the interstices of the filter media bed.

TABLE II
THE MEASUREMENT OF OIL CONTENT, TSS, AND TURBIDITY OF WASH TANK, OIL SKIMMING TANK, AND NUTSHELL FILTERS USING CANDLENUT SHELLS (JUNE 20TH, 2018)

Sampling point	Oil Content (mg/L)	TSS (mg/L)	Turbidity (NTU)	Solid Removal Efficiency (%)	Oil Removal Efficiency (%)
Inlet de-gas boot	-	2,290	>1,000	-	-
Outgoing wash tank	595.8	53.0	11.4	-	-
Outgoing oil skimming	99.3	39.0	8.6	26.4	83.3
Inlet nutshell filters	99.3	39.0	8.6	-	-
Outgoing Filter A	16.4	24.0	4.1	38.5	83.4
Outgoing Filter B	14.9	22.0	4.2	43.6	84.9
Outgoing Filter C	21.7	20.0	3.7	48.7	78,1
Outgoing Filter D	18.2	14.0	1.9	64.1	81.7
Outgoing Filter E	21.7	15.0	2.1	61.5	78.1
Outgoing Filter F	15.1	17.0	3.4	56.4	84.8

APPENDIX

Appendix A. Process Flow Diagram Surface Facility in Zamrud Field

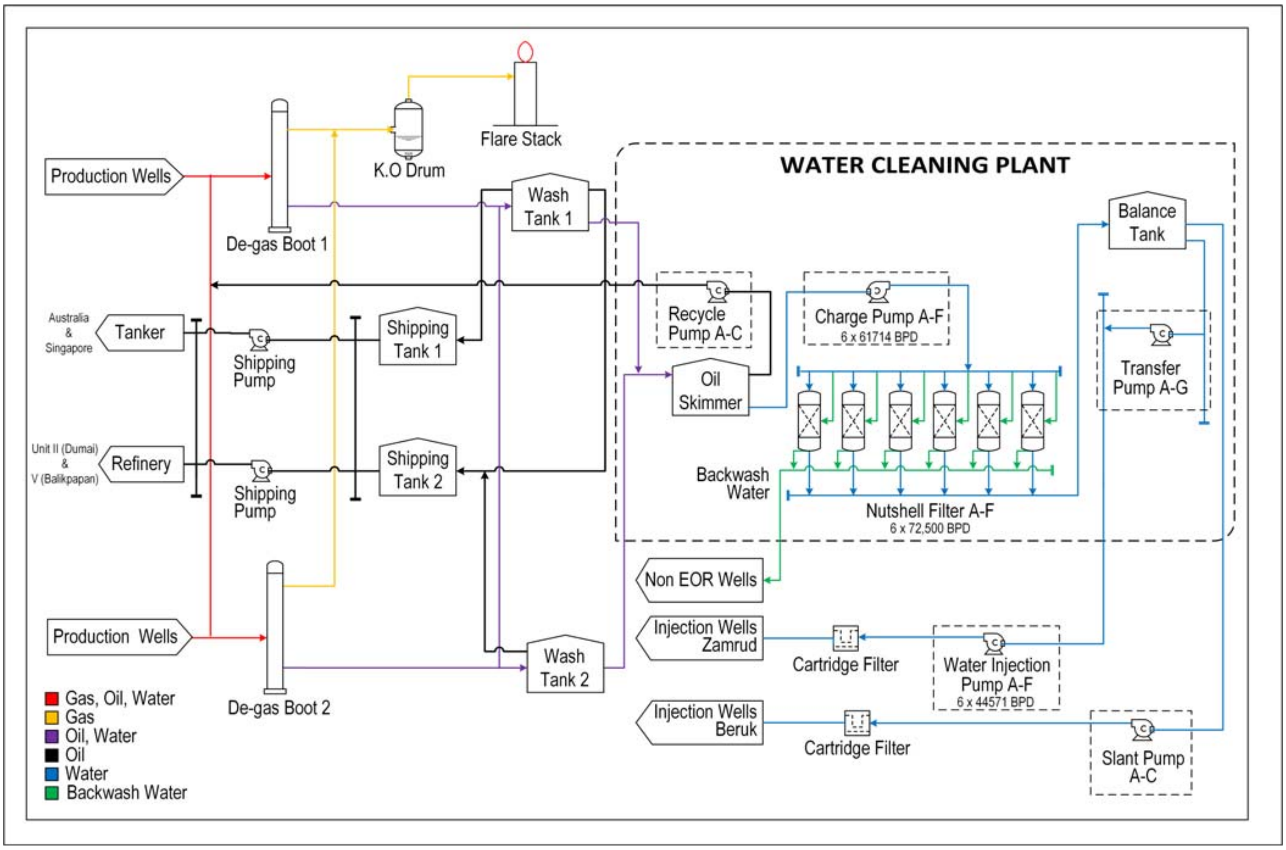


Fig. 7 Simplified process flow diagram for onshore GS and WCP

Appendix B. Reservoir Characteristics of Zamrud and Pedada

TABLE III
COMPARISON OF RESERVOIR CHARACTERISTICS OF ZAMRUD, PEDADA, BANGKO AND BEKASAP. ALL THESE FIELDS ARE LOCATED IN CENTRAL SUMATRA BASIN

Field Name		Zamrud	Pedada	Bangko*	Bekasap$
Country		Indonesia	Indonesia	Indonesia	Indonesia
Onshore/Offshore		Onshore	Onshore	Onshore	Onshore
Geologic Description		Sandstones	Sandstones	Sandstones	Sandstones
Natural Drive Mechanism		Aquifier	Aquifer	Aquifer	Aquifer
Permeability, md	Upper sand	480	280	530	250-1,000
	Lower sand	440	700		
Porosity, %		22-24	25-32	25	>22
Oil Gravity, °API		37.4	34	34	35.8
Oil Viscosity, cp		2.4	4.3	4.2	0.08
Initial Pressure, psi		1,250	284	770	-
Cumulative Oil, million STB		236,571	135,703	550	-
Water Injection Rate, BPD		148,500	50,237	415,000	-
W_{cut} (after breaktrough), %		97-99	97-99	94	-
No of Active Producers		120	78	210	107
No of Active Injectors		49	21	30	16
Injection Scheme		Peripheral	Peripheral	Peripheral	Peripheral

(*) [36], ($) [37]

Appendix C. Hardness Testing

TABLE IV
COMPARISON OF HARDNESSES OF CANDLENUT, PECAN, AND WALNUT SHELLS

Materials	Sampling Point	Vickers Hardness (HVN)	Average Hardness (HVN)	mohs Hardness
Candlenut	1	32.7	36.08	2.5 - 3.0
	2	33.6		
	3	34.3		
	4	40.1		
	5	32.7		
	6	34.8		
	7	40.4		
	8	36.6		
	9	37.8		
	10	37.8		
Pecan	1	14.2	15.2	~ 2.0
	2	15.8		
	3	15.7		
	4	15.5		
	5	17.5		
	6	16.6		
	7	16.7		
	8	13.0		
	9	11.9		
	10	14.3		
Walnut	1	23.9	20.59	~ 2.5
	2	24.7		
	3	17.7		
	4	21.3		
	5	21.4		
	6	18.8		
	7	18.1		
	8	18.6		
	9	22.5		
	10	18.9		

Appendix D. Simplified P&ID Nutshell Filter

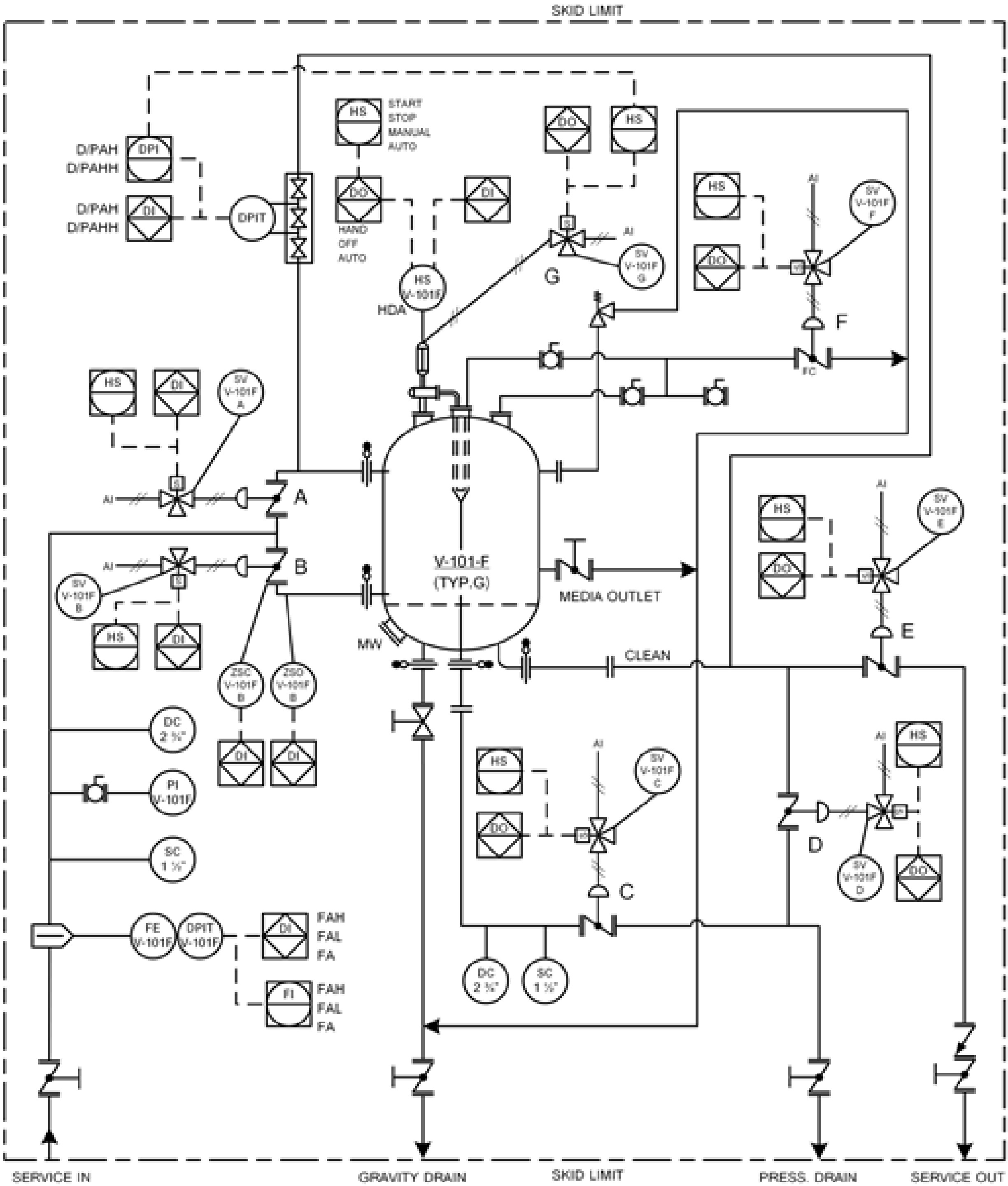


Fig. 8 Simplified P&ID typical nutshell filter

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