ENVIRONMENTAL TREATMENT SYSTEMS, INC.
ETS

25th ANNIVERSARY
Est. 1987

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Presented At

84th Annual Water Environment Federation
Technical Exhibition and Conference
Los Angeles, CA
October 15-10, 2011

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ABSTRACT

Dissolved gas flotation (DGF) is a feasible secondary clarification technology preceding a NPDES Permitted outfall. In 2009, a DGF was installed to separate mixed liquor suspended solids (MLSS) from wastewater originating from a petroleum refinery. Operational data indicates the technology can remove over 99% of influent suspended solids on a sustained basis. DGF clarification advantages, disadvantages, design considerations, and operational performance information are provided in this case study. Notable benefits of the technology are: low effluent suspended solids concentrations, concentrated recycle/waste activated sludge (RAS/WAS) solids, no sludge bulking concerns, compact footprint, and skid construction. The primary disadvantages are higher operating cost and more operator attention. Both conventional gravity (CGC) and DGF clarifiers should be considered viable technologies for separation of MLSS from biologically treated wastewater.

KEYWORDS: Dissolved Air Flotation, DAF, Dissolved Gas Flotation, DGF, Secondary Clarification, Activated Sludge, Refinery Wastewater, Solids/Liquids Separation

INTRODUCTION

Domestic petroleum refineries in the early 2000s were rapidly increasing their capacity and ability to process heavy and sour crude. As a result, the hydraulic and pollutant loading of associated industrial wastewater treatment processes were increasing. A 2007 engineering evaluation identified a hydraulic and solids loading bottleneck within a refinery's wastewater secondary clarification process. The observed peak hydraulic and solids loading rates on the CGCs were 44.8 m/day (1,100 gpd/ft^2) and 171 kg/day/m^2 (35 lbs/day/ft^2) respectively. The high wastewater loading rates were causing solids carryover decreasing the margin between the effluent concentrations and a 30 mg/L solids NPDES limit.

The addition of secondary clarification capacity was proposed to reduce the loading rates on the existing CGCs. The goal was to reduce the CGC's peak hydraulic and solids loading rates to 34.6 m/day (850 gpd/ft^2) and 97.8 kg/day/m^2 (20 lbs/day/ft^2) respectively. The following paragraphs describe the (1) technology selection, (2) process design and construction, (3) operational performance, and (4) conclusions associated with a non-conventional secondary clarification process.

TECHNOLOGY SELECTION

The three most widely used technologies for liquid/solids separation are: (1) gravity sedimentation, (2) flotation, and (3) filtration (Yeh, 1996). Of the three, Burns & McDonnell and THE STOVER GROUP considered CGC and DGF viable technologies for supplementary secondary clarification at the refinery. Filtration was omitted from further consideration based upon the high MLSS solids concentration. The two technologies were quantitatively evaluated based upon the parameters presented in Table 1.

Table 1. Comparison of CGC and DGF Technologies

Parameter	Units	CGC	DGF
RAS/WAS Concentration	% solids	0.5 to 1.5	1.5 to 7(1)
Effluent TSS	mg/L	< 30	< 30(2)
Surface Area	m^2	140	33
Mechanical Complexity	NA	Low	Moderate(3)
Capital Cost	NA	Parity	Parity
Coagulant Dose	mg/L	15	15
Polymer Dose	mg/L	5	10
Power Requirement	Hp	3	30
Labor	hrs/day	0-1	1-2

(1) (Metivier, 2002) and (Yeh, 1996); (2) (Environment Canada, 1981), (Zhang, 1985), (Jokela, 2002); (3) (Haarhoff, 1995)

A DGF was selected for secondary clarification of refinery wastewater following two-stage suspended and fixed film biological treatment. The technology was primarily selected because effluent limits were anticipated to relax in 2009 with changes in the refinery configuration and complexity. With less stringent limits, the DGF unit could be relocated for secondary oil/water separation before the biological treatment process. Other identified benefits of the DGF selection, relative to CGCs, are listed below.

1. Reduced hydraulic loading on the biological treatment process; attributed to concentrated RAS solids
2. Reduced hydraulic loading on the aerobic digester; attributed to concentrated WAS solids
3. Less congestion within the wastewater treatment unit
4. Low hydraulic residence time (WEF, 2008)
5. Better removal of fixed film biological solids during sloughing events
6. Less susceptibility to sludge bulking (Krofta, 1987)
7. Ability to handle 'mass-shock loading' from a bioreactor (Lavallee, 1997)
8. Higher effluent dissolved oxygen (Jenkins, 1982)
9. Reduced potential for denitrification in secondary clarification process
10. Increased aerobic MLSS microorganism viability (Krofta, 1983 and Metivier, 2002)
11. Better solids removal efficiency at low water temperatures (Arnold, 1995)

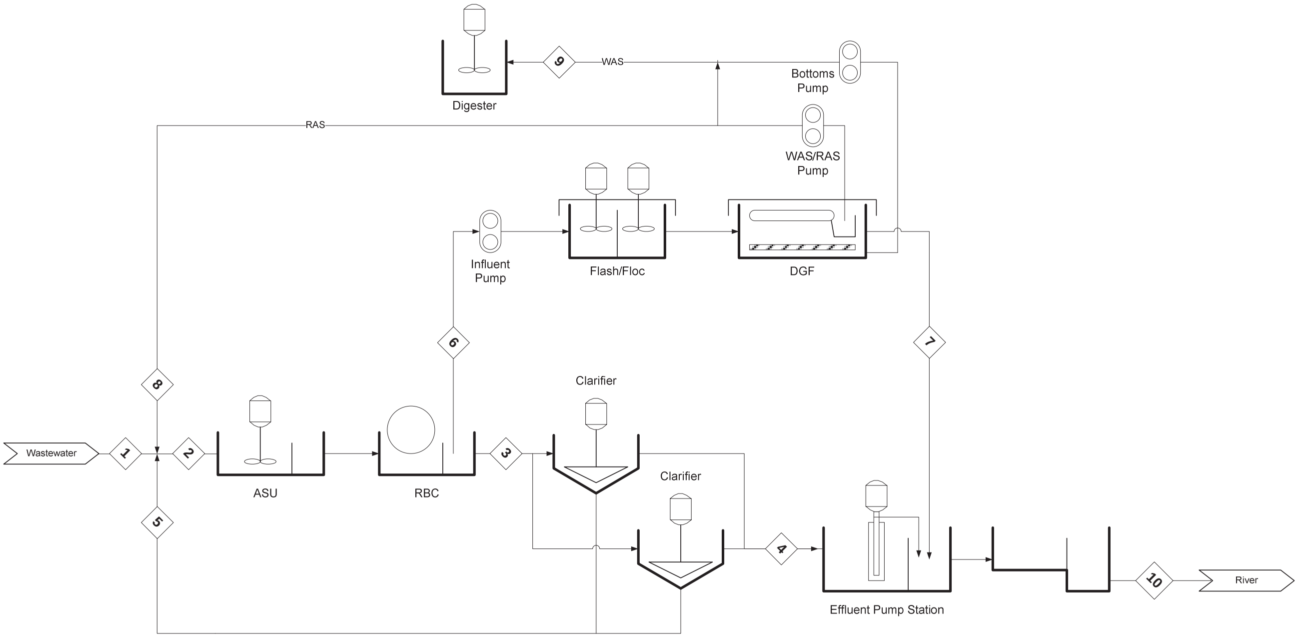
The regulatory agency expressed concern regarding the technology selection because no precedence for the technology application existed, there was a lack of published performance information (Jokela, 2002), and they were familiar with DGF sludge thickeners which typically had effluent TSS concentrations exceeding 30 mg/L. In addition, the USEPA (1981) reported median TSS removal rates of 88% for floatation which would not meet the NPDES effluent limit and a 1968 DGF wastewater application had been unsuccessful (Zhang, 1985). The selection was eventually approved based upon the understanding the DGF would be relocated as a secondary oil removal process within 18 months of installation. Providing published performance information to support future applications was a primary driver behind publishing this paper.

DESIGN AND CONSTRUCTION

Because a non-conventional process was being proposed for secondary clarification, Environmental Treatment Systems (ETS) was pre-selected to supply equipment based upon qualifications and a performance specification. As a result, the design of the secondary treatment process was a collaborative effort between Burns & McDonnell (Engineer-of-Record), ETS, and refinery employees. The secondary treatment unit process consisted of three components: (1) pump station, (2) chemical pre-treatment, and (3) DGF. A description of each component is provided in the following paragraphs.

Pump Station. The DGF influent pump station was designed to transfer biologically treated wastewater from a rotating biological contactor (RBC) basin to the DGF flash/floc tank. Maintaining a constant influent flow rate was recommended to minimize routine adjustments to chemical dose, mixing energy, rake speed, and other operational adjustments (Ross, 2003). The design capacity of the pump station was selected using a treatment plant mass balance and biological kinetic calculations. The design permits treatment plant Operators to set a constant DGF influent flow rate and shed flow variability to the existing CGCs. Figure 1 provides a mass balance for the maximum hydraulic and pollutant loading rates considered.

Figure 1. Wastewater Treatment Mass Balance



Stream Number		1	2	3	4	5
Description		Wastewater Influent	ASU Influent	CGC Influent	CGC Effluent	CGC RAS
Flow	m^3/min	5.47	7.43	3.65	2.13	1.52
TSS	mg/L	277	2,326	2,500	0	6,000
TSS Mass	kg/day	2,185	24,935	13,153	0	13,153

Stream Number		6	7	8	9	10
Description		DGF Influent	DGF Effluent	DGF RAS	DGF WAS	Wastewater Effluent
Flow	m^3/min	3.79	3.15	0.44	0.19	5.28
TSS	mg/L	2,500	0	15,000	15,000	0
TSS Mass	kg/day	13,647	0	9,597	4.050	0

The DGF was designed so the WWTP can treat the 100th percentile of flow without exceeding the maximum specified CGC hydraulic or solids loading rates of 34.6 m/day and 97.8 kg/day/m^2 respectively. At a MLSS concentration of 2,500 mg/L, the solids loading rate is the controlling design parameter. The hydraulic and solids loading rates of the CGCs are 17.1 m/day (420 gpd/ft^2) and 73.4 kg/day/m^2 (15 lbs/day/ft^2) at the design capacity of the WWTP and DGF. Therefore, there is some margin in the design to account for changes in MLSS, RAS, and WAS concentrations.

A positive displacement pump with a variable frequency drive (VFD) controlled motor was selected for the pump station. Positive displacement pumps provide constant flow, linear flow adjustment, and minimal shearing of biological floc. A rotary lobe pump was specified with a design capacity range of 1.89 m^3/min (500 gpm) to 3.79 m^3/min (1,000 gpm). Vogelsang USA supplied the rotary lobe pump for the DGF.

Chemical Pre-Treatment. The refinery historically used both coagulant and polymer to increase the solids removal efficiency of the CGCs. Cationic coagulant was added to the RBC influent at a dose of approximately 15 mg/L. Cationic polymer was added to the CGC flow splitter box at a dose of approximately 5 mg/L.

In September 2008, ETS ran a treatability test on a wastewater sample provided by the refinery. The sample was collected after coagulant had been added. ETS added 5 mg/L of polymer to the sample and ran a DGF bench test. The results of the test are presented in Table 2.

Table 2. Bench Test Results

Parameter	Influent	Effluent
Total COD	4,100 mg/L	30 mg/L
Soluble COD	100 mg/L	12 mg/L
TSS	4,600 mg/L	20 mg/L

Bench test polymer doses can underestimate field requirements; therefore, the design dose was double bench test results; consistent with other DGF installations (Lavallee, 1997). Laboratory data indicated the same chemistry could be used for the DGF and gravity clarifiers. In addition, all data indicated the combined treatment process using chemical pre-treatment and DGF could reliably meet the specified monthly average TSS effluent limitation of 30 mg/L.

The chemical pre-treatment unit was shipped in two skids: (1) chemical metering and (2) flash/floc tank. At a wastewater flow rate of 3.79 m^3/min, the chemical feed system can dose polymer at approximately 0.45 ppm to 45 ppm to the DGF flash/floc tank. A covered flash/floc tank with two treatment cells was installed preceding the DGF. The time required for solids flocculation is relatively short (Mally, 1991and Krofta, 1984) for DGF versus CGC applications. The minimum hydraulic retention times in the first and second cells are 2 minutes and 4.5 minutes respectively. The vessel cover and first compartment of the tank were specified for the secondary oil removal application; therefore, they were not needed in the initial application.

Coagulant is added to the DGF and CGC influent by the refinery; therefore, no chemicals are being fed into the first section of the tank and the mixer is energized to prevent the settling of solids. Polymer is added to the second compartment to flocculate biological solids. To minimize the sheering of floc, a mixer with a VFD controlled motor was installed in the second cell of the flash/floc tank.

Dissolved Gas Flotation. The DGF unit was designed for service as both a secondary clarifier (air) and a future oil removal process (nitrogen). As a secondary clarifier, the DGF unit was designed to separate biological solids from refinery wastewater following activated sludge and RBC biological treatment. The kinetic model used to evaluate the activated sludge unit (ASU) indicated acceptable treatment efficiencies at an MLSS concentration of 2,300 mg/L. The RBC is anticipated to contribute an additional 100 mg/L to 200 mg/L. Therefore, the design basis for the DGF influent TSS concentration is 2,500 mg/L. The specified maximum hydraulic and solids loading rates are 3.79 m^3/min and 569 kg/hr (1,251 pounds per hour) respectively. Table 3 provides a design envelope for the DGF installation.

Table 3. DGF Design Envelope

		Influent TSS (mg/L)														
		2,100	2,300	2,500	2,700	2,900	3,100	3,300	3,500	3,700	3,900	4,100	4,300	4,500	4,700	4,900
Flow (m^3/min)	1.3	167	183	199	215	231	247	263	279	295	310	326	342	358	374	390
	1.5	191	209	227	245	264	282	300	319	337	355	373	391	410	428	446
	1.7	215	235	256	276	297	317	338	358	379	399	420	440	460	481	501
	1.9	239	261	285	307	330	353	375	398	421	444	466	489	512	535	557
	2.1	263	288	313	338	363	388	413	438	463	488	513	538	563	588	613
	2.3	287	314	341	369	396	423	450	478	505	532	560	587	614	641	669
	2.5	310	340	370	399	429	458	488	517	547	577	606	636	665	695	725
	2.6	335	366	398	430	462	494	525	557	589	621	653	685	716	748	780
	2.8	358	392	426	460	495	529	563	597	631	665	700	734	768	802	836
	3.0	382	419	455	491	528	564	600	637	673	710	746	782	819	855	892
	3.2	406	445	483	522	560	600	638	677	715	754	793	831	870	909	947
	3.4	430	471	512	553	594	635	675	716	757	798	839	880	921	962	1,003
	3.6	454	497	540	584	627	670	713	756	800	843	886	929	972	1,015	1,059
	3.8	478	523	569	614	660	705	750	796	841	887	933	978	1,024	1,069	1,115

Values in green and red are DGF solids loading rates expressed in kg/hr

Solids loading rates in green are within the envelope; red values are outside the envelope

ETS provided a 30 mg/L effluent suspended solids performance guarantee to the refinery for the ETS RT-350LA DGF at the specified hydraulic and solids loading rates. The specified DGF uses recycled flow pressurization to minimize floc shear through the pressurization pump and pressure relief valve. The DGF system was assembled in Georgia and factory testing of the treatment unit and control system was witnessed by refinery employees before the unit was shipped to the refinery. A cover is installed to minimize disturbance of the floating solids by adverse weather conditions and to control air emissions when the unit is relocated as a secondary oil removal process. The DGF design parameters are presented in Table 4.

Table 4. DGF Design Parameters

Parameter	Units	Design	Literature
Recycle Pressure	kPa	724	276 to 483 (Metcalf & Eddy, 1991)
Recycle	%	29%	5% to 120% (Corbitt, 1999)
Hydraulic Loading	m/day	3.6	0.2 to 3.9- (Metcalf & Eddy, 1991)
Solids Loading	kg/m^2*day	422	94 to 234 (WEF MOP-8, 1992)
Air to Solids Ratio	mass/mass	0.0083	0.006 to 0.070 (WEF MOP-FD-3, 1994)

Published design parameters are provided in the preceding table. The DGF technology was patented by Peterson and Sveen in 1924 (Arnold, 1995) and has evolved over the past eight decades. It should be noted that many DGF design parameters in common literature do not consider recent advances in the technology (Ross, 2000) or are not applicable to secondary clarification (Ross, 2003).

An in-line TSS instrument manufactured by HACH was specified to continuously measure DGF effluent TSS quality. When the TSS concentration is below the lower set-point, effluent gravity flows to the NPDES outfall. If the TSS concentration exceeds an upper set-point, the DGF flow is automatically diverted to off-test holding and returned to the ASU.

Solids entering the DGF unit will either float or settle to the bottom of the unit. Floating solids are conveyed to an internal hopper with a variable speed chain-and-flight system. A minimum float TSS concentration of 15,000 mg/L was specified to minimize hydraulic loading on the ASU and digester. A positive-displacement float pump was designed to transfer the float solids to the ASU or aerobic digester. Solids that settle in the DGF are conveyed to an internal hopper using an auger. The settled solids are sent to the digester via a positive-displacement bottoms pump. This pump and auger are automatically controlled with a PLC timer.

OPERATIONAL PERFORMANCE

The refinery procured and installed the DGF unit in approximately seven months. In October 2009, the unit was commissioned and the performance of the unit was evaluated for approximately six months. Three sets of performance data are provided in the following paragraphs: (1) start-up and commissioning, (2) refinery operation, and (3) performance testing.

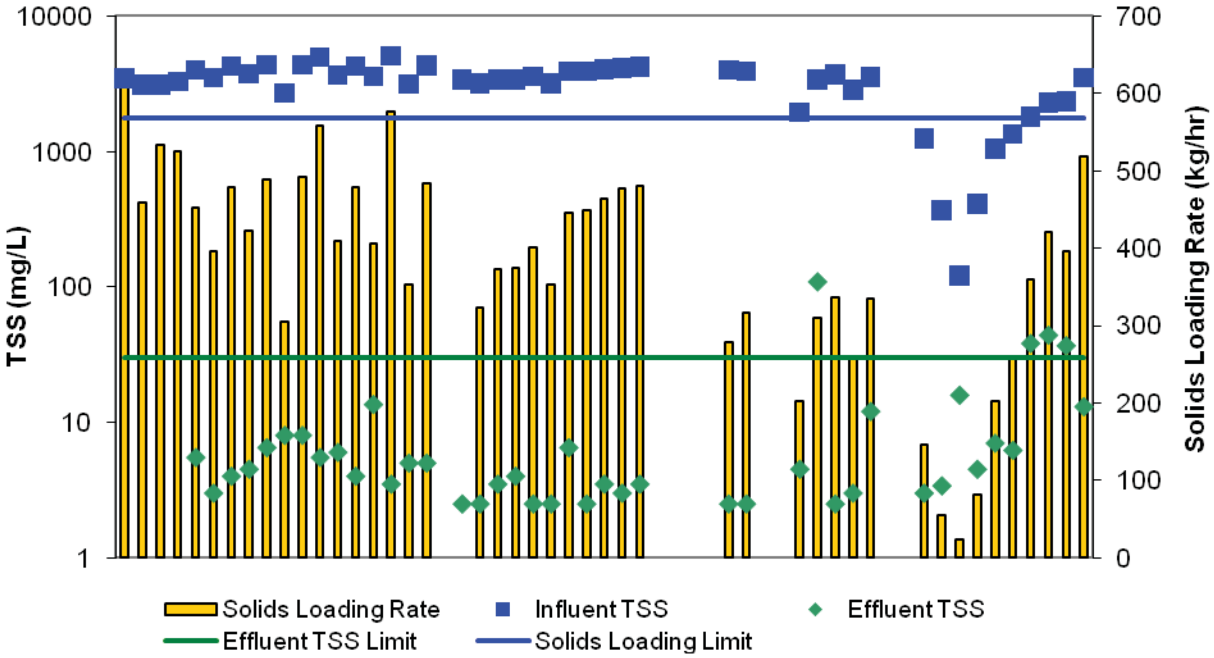
Start-up and Commissioning. The unit was started and commissioned by the refinery and ETS. The initial performance test was run at a solids loading rate exceeding 567 kg/hr and the effluent TSS remained below 5 mg/L. Due to the high TSS concentration in the influent flow, the test was performed at flow rates less than the design hydraulic loading rate of 3.79 m^3/min. Based upon testing results, both ETS and the refinery concluded the unit should be able to treat 3.79 m^3/min provided the influent solids concentration did not exceed 2,500 mg/L. Two noteworthy observations were made during start-up:

(1) Between design and construction, the refinery's chemical vendor replaced the cationic polymer with an anionic polymer. This change was not identified until significant floc formation problems were observed during start-up of the unit. To remove solids faster, ETS and the refinery increased the DGF effluent weir height; however, poor effluent quality continued. The anionic polymer was replaced with a cationic polymer and the effluent solids concentration decreased below 30 mg/L.

(2) During start-up, the cationic polymer dose was increased. The viscosity of the float solids increased resistance in the RAS line and caused the pressure relief valve to activate. Because solids could not be transferred to the ASU, solids accumulated in the DGF and effluent quality deteriorated. The refinery increased the pressure relief valve setting, reduced the polymer dosage, and cleaned solids from the DGF; the effluent quality returned to less than 30 mg/L.

Refinery Operation. The refinery operated the DGF without ETS assistance for approximately four months preceding the performance test. The solids loading rate was routinely higher than the design specification; however, the refinery remained compliant with NPDES Permit limits for TSS. DGF effluent samples collected and analyzed by the refinery laboratory averaged less than 10 mg/L TSS. DGF performance data is summarized in Figure 2.

Figure 2. First Four Months of Operating History



In 2011, ASU MLSS concentrations ranged from 3,000 mg/L to 5,000 mg/L and DGF is operated at a constant flow rate of approximately 1.89 m^3/min. The DGF has been operating for approximately 20 months and the effluent TSS concentrations remains consistently below 10 mg/L.

DGF Performance Test. During March 2010, performance testing protocol and criteria for the DGF equipment was developed by Burns & McDonnell, ETS, THE STOVER GROUP and the refinery. The goal was to operate the process between 3.41 m^3/min (900 gpm) and 3.79 m^3/min, for three days, provided the influent TSS concentration remained between 2,200 mg/L and 2,700 mg/L. Split six-hour composite DGF influent and effluent samples were analyzed by the refinery and a State certified laboratory to calculate daily averages and evaluate the performance of the solids removal process.

Before the test began, it became evident that the RBC effluent TSS concentration could not be maintained between 2,200 mg/L and 2,700 mg/L. The refinery identified solids originating from a new FCCU wet gas scrubber as the cause. The scrubber solids removal process was not operating as designed and scrubber blow-down water (containing solids) was being discharged directly to the wastewater treatment system. Despite the upset condition, Burns & McDonnell, ETS, THE STOVER GROUP and the refinery agreed to proceed with the performance test.

The refinery operated the DGF for approximately 92 hours with a short interruption to make equipment adjustments. ETS, THE STOVER GROUP, and Burns & McDonnell provided on-site operational advice to the refinery specific to the DGF. Upstream process units and the MLSS concentration were managed by the refinery. Results of the test are summarized below.

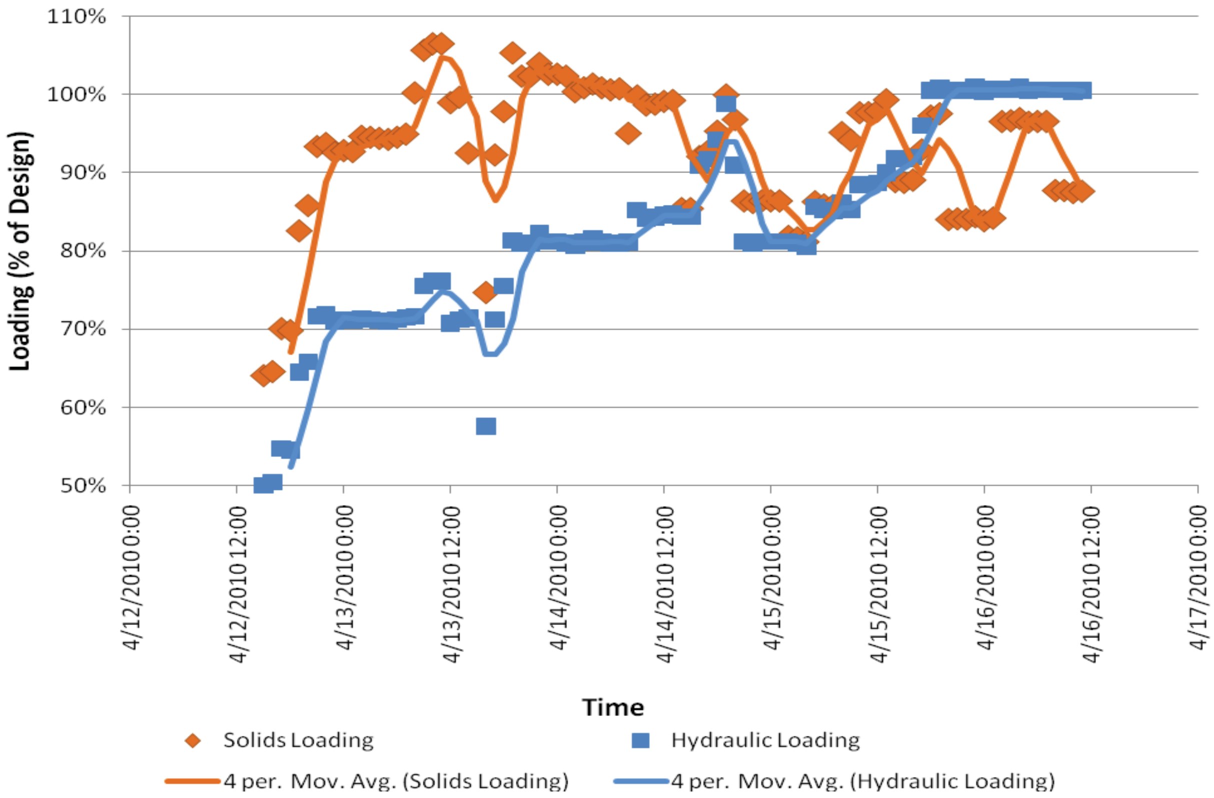
Table 5. DGF Performance Test Data

		Percentile					
Parameter	**Units**	**25%**	**50%**	**75%**	**95%**	**100%**	**Design**
ASU TDS	mg/L	3,993	4,100	4,388	4,938	5,050	NA
ASU TSS	mg/L	3,050	3,100	3,150	3,230	3,250	2,300
RBC Effluent TSS	mg/L	2,525	2,930	3,220	3,374	3,500	2,500
RBC Effluent VSS	mg/L	1,230	1,450	1,570	1,634	1,690	~ 1,625
DGF Flow Rate	m^3/min	2.82	3.08	3.47	3.81	3.82	1.89 – 3.79
Solids Loading Rate	kg/hr	339	537	563	587	606	< 569
Coagulant Dose	ppm	15	15	15	15	15	15
Polymer Dose	ppm	10	11	15	19	20	Jar Test
DGF Effluent TSS	mg/L	7	10	11	20.7	27	< 30
DGF Effluent VSS	mg/L	6	7	9.5	13.2	16	< 30
DGF RAS TSS	mg/L	22,563	37,675	44,088	46,038	46,300	> 15,000
Clarifier RAS TSS	mg/L	5,100	5,800	7,150	9,250	9,400	6,000

The RBC MLSS averaged approximately 2,900 mg/L over the testing period. Laboratory testing detected significantly more inert solids in the wastewater than anticipated during the process design. The volatile suspended solids (VSS) concentration was approximately equal to the amount originally anticipated. VSS typically represent 60% to 70% of the TSS in a biological treatment system. Therefore, the design basis mixed liquor (2,500 mg/L) would have a VSS concentration between 1,500 mg/L to 1,750 mg/L. The inert solids did not adversely affect the DGF solids removal efficiency; however, more polymer was required to flocculate the inert material relative to the original bench test conducted by ETS. The MLSS concentration, quantity of inert material, and required polymer are expected to decrease when the scrubber solids removal process operates as designed.

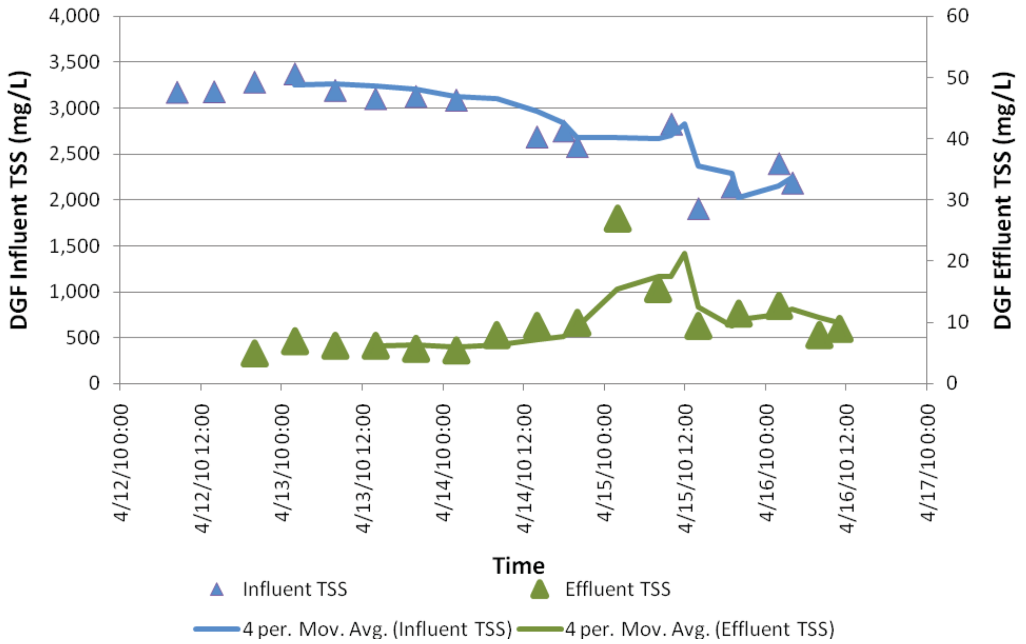
The operation of a DGF is constrained by both solids and hydraulic loadings rates. For the first portion of the test week, the solids loading rate was the controlling parameter and the refinery operated the DGF at or above the specified solids loading rate for 20 hours. Aggressive wasting of MLSS by the refinery was not effectively reducing the RBC effluent TSS concentration and almost no water was flowing through the CGCs. As a result, it became evident the DGF could not be operated for three days at 3.41 m^3/min and greater. Therefore, the refinery began recycling DGF effluent to the RBC to reduce the solids concentration and increase the amount of water available for treatment. Once the recycle system was installed, the DGF operated between 3.41 m^3/min and 3.82 m^3/min for 28 hours. The maximum solids and hydraulic loadings rates, as a percentage of design, were 107% and 101% respectively. A plot of the hydraulic and solids loading rates are presented in Figure 3.

Figure 3. DGF Solids and Hydraulic Loading Rates



The solids removal efficiency of the DGF was approximately 99.7% which exceeded the design basis of 98.8%. No effluent composite sample had a TSS concentration exceeding 30 mg/L. Figure 4 shows the DGF influent and effluent TSS concentration over the duration of the test.

Figure 4. DGF Influent and Effluent TSS



Based upon observations and data collected during the first six months of operation, the DGF can be operated at the specified hydraulic and solids loading rates while maintaining effluent TSS concentrations below 30 mg/L.

CONCLUSIONS

A DGF secondary clarifier was successfully designed and operated following ASU and RBC biological processes. The refinery unit was designed for maximum influent conditions of 3.79 m^3/min at 2,500 mg/L TSS (569 kg/hr). Based upon field observations and measurements, the DGF technology can routinely separate more than 99% of influent biological solids. Benefits of the technology are low effluent solids concentrations, high concentration of RAS solids, no sludge bulking concerns (Zhang, 1985), low footprint, and skid construction. The primary disadvantages are higher operating cost and more operator attention. At the conclusion of the project, the gravity clarifier loading rates were decreased and the margin between the effluent concentrations and the NPDES limit was increased. This case study illustrates the successful application of DGF technology for secondary clarification preceding a NPDES outfall.

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