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# Recent developments in the application of sequencing batch reactor (SBR) technology for the petroleum industry wastewater treatment

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A B S T R A C T

Oily wastewater treatment in the petroleum industry may generally be classified as process wastewater pretreatment, primary treatment, secondary treatment, and tertiary treatment or polishing. In secondary treatment, dissolved oil and other organic pollutants may be consumed biologically by microorganisms. Biological treatment of complex chemicals in the petroleum industry wastewaters is specially challenging due to the inhibition and/or toxicity of these compounds when they serve as microbial substrates. Processes such as sequencing batch reactor (SBR) technology which promote the mineralization of the petroleum industry wastewaters containing toxic compounds seem to be promising. In this study, principles of SBR, modifications in SBR technology, effective parameters on SBR process, and recent developments in the application of SBR technology for the petroleum industry wastewater treatment have been reviewed.



**Capsule Summary:** In present study, principles of SBR, modifications in SBR technology, effective parameters on SBR process, and recent developments in the application of SBR technology for the petroleum industry wastewater treatment are discussed.

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## INTRODUCTION

Large quantities of effluents containing oil, water and sludge can be generated from the activities and processes in the petroleum industry which draining of these effluents not only pollutes the environment but also reduces the yield of oil and water (Zhong et al., 2003; Jafarinejad, 2014a; 2014b; 2015a; 2015b; 2015c; 2015d; 2017).

Generally, oily wastewater pollution can affect drinking water and groundwater resources and crop production; endanger aquatic resources and human health; pollute atmosphere; and destruct the natural landscape, and even probably because of coalescence of the oil burner safety issues may arise (Yu et al., 2013; Jafarinejad, 2017).

Oily wastewater treatment may generally be classified as process wastewater pretreatment, primary treatment, secondary treatment, and tertiary treatment or polishing (U.S. EPA, 1995; Benyahia et al., 2006; IPIECA, 2010; European Commission and Joint Research Center, 2013; Goldblatt et al., 2014; Jafarinejad, 2015d; 2017). In secondary treatment, dissolved oil and other organic pollutants may be consumed biologically by microorganisms (U.S. EPA, 1995; Jafarinejad, 2017). Microorganisms (naturally occurring, commercial, specific groups, and acclimatized sewage sludge) oxidize organic matter into simple products ($CO_2$, $H_2O$, and $CH_4$) under aerobic, anaerobic or semi aerobic conditions. A C:N:P ratio (100:5:1) can be adequate for microorganisms to grow (Ishak et al., 2012; Jafarinejad, 2017). Biological treatment processes can be classified into two categories:

- Suspended growth processes such as activated sludge process (ASP), sequencing batch reactors (SBRs), continuous stirred tank bioreactor (CSTB), membrane bioreactors (MBRs), and aerated lagoons; and
- Attached growth processes such as trickling filters (TFs), fluidized bed bioreactor (FBB), and rotating biological contactor (RBC) (EPA, 1997, IPIECA, 2010, Ishak et al., 2012; Jafarinejad, 2017).

Petroleum industry wastewaters usually contain oil, toxic organic compounds, etc. (Mohan et al., 2005; Jafarinejad, 2017). These wastewaters need treatment with suitable treatment processes due to the compliance with the regulations set by regulatory agencies and the prevention the related harm on the surrounding environment (Ghorbanian et al., 2014). In the petroleum industry, the biological treatment is the most widely applied technique for the removal of dissolved oil from wastewaters (Stringfellow and Alvarez-Cohen, 1999; Pajoumshariati et al., 2011; Jafarinejad, 2017) which ASP has been the most common employed biological treatment process (Pajoumshariati et al., 2011; Jafarinejad, 2017). The wastewater variability on both flow and composition naturally inhibits the treatment process and makes it difficult to treat using traditional biological processes (Mohan et al., 2001; 2002; 2005). Conventional continuous flow systems such as ASP may have serious difficulties to meet the regulated discharge limits. Biological treatment of complex chemicals is specially challenging due to the inhibition and/or toxicity of these compounds when they serve as microbial substrates. Alternative approaches like discontinuous processes such as SBR technology, which promote the mineralization of the petroleum industry wastewaters containing toxic compounds seem to be promising (Mohan et al., 2005). In this study, principles of SBR, modifications in SBR technology, effective parameters on SBR process, and recent developments in the application of SBR technology for the petroleum industry wastewater treatment have been reviewed.

## Principles of sequencing batch reactor (SBR)

SBR technology is applied all over the world and has been around since the 1920s. With its growing popularity in Europe and China as well as the USA, this technology is being employed successfully to treat both municipal and industrial wastewaters, especially in areas characterized by low or varying flow patterns (New England Interstate Water Pollution Control Commission (NEIWPCC), 2005; Dohare and Meshram, 2014).

The SBR is one of the potential options for aerobic and anaerobic treatment of wastewaters (Mane and Munavalli, 2012). In real, the SBR is a fill-and draw activated sludge system for both municipal and industrial wastewater treatment that aeration, sedimentation and clarification can all be achieved using a single batch reactor. It operates without a clarifier and in this system, wastewater is added to a single batch reactor, treated to remove undesirable components, and then discharged. To optimize the performance of the system, two or more batch reactors are applied in a predetermined sequence of operations. Typical cycles in SBR process are shown in Fig. 1. The operation of an SBR is based on a fill-and-draw principle, which consists of five steps: fill, react, settle, draw, and idle. These steps can be altered for different operational applications. SBRs are typically used at flow rates of 219 L/s (5MGD) or less. The more sophisticated operation required at larger SBR plants tends to discourage the use of these plants for large flow rates. The SBR technology is particularly attractive for treating smaller wastewater flows. The majority of plants were designed at wastewater flow rates of less than 22 L/s (0.5MGD) (Metcalf and Eddy, 1991; U.S. EPA, 1999; Gurtekin, 2014; Jafarinejad, 2016; 2017).

In the SBR technology, the reactor volume varies with time, whereas it remains constant in the conventional continuous flow system (Mohan et al., 2005). Accommodation of large fluctuations in the incoming wastewater flow and composition without failing is the major advantage of SBR technology. Furthermore, SBR technology is more flexible. In real, the wastewater residence time in SBRs can be extended until the microbial population has recovered and completed the degradation process. Similarly, the settling time can be changed to allow complete settling before discharging. (Oliveira et al., 2008; Fakhru'l-Razi et al., 2010; Awaleh and Soubaneh, 2014). The cycles, hydraulic retention time (HRT), and sludge retention time (SRT) can be varied and hence it provides wide scope for treatment that is too in a single reactor which is most advantageous factor Mane and Munavalli, 2012).

SBRs can be applied as pre or post treatment options along with other treatment facilities successfully (Mane and Munavalli, 2012). Also, they may be utilized in denitrifying application (Oliveira et al., 2008; Fakhru'l-Razi et al., 2010; Awaleh and Soubaneh, 2014).

## Modification in SBR technology

To provide secondary, advanced secondary treatment, nitrification, denitrification and biological nutrient removal, SBR technology may be modified (Mahvi, 2008; Dohare and Meshram, 2014). In recent years, some modifications of SBR have been applied by researchers, such as continuous flow SBR (Mahvi et al., 2004), sequencing batch biofilm reactor(SBBR) (Speitel and Leonard, 1992), anaerobic sequencing batch reactor (ASBR) (Dague et al., 1992), anaerobic-aerobic SBR (Bernet et al., 2000), and membrane sequencing batch reactor (MSBR) (Bae et al., 2003; Fakhru'l-Razi et al., 2010; Pajoumshariati et al., 2017).

## Effective parameters on SBR process

Organic loading rate, HRT, SRT, dissolved oxygen (DO), and influent characteristics such as chemical oxygen demand (COD), solids content, C/N ratio are the main parameters affecting SBR performance. Depending on the controlling of these factors, the SBR can be designed to have function such as carbon oxidation, nitrification and denitrification, and phosphorus removal (Mahvi, 2008; Dohare and Meshram, 2014).

Economic feasibility, design considerations, regulatory requirements, sludge generation rates, sludge transporting requirements, and site applicability are the factors that require to be assessed prior to the procurement and installation of a SBR treatment system (Maga and Durlak, 2004).

**Application of SBR technology in the petroleum industry wastewater treatment**

Several laboratory and pilot-scale studies have demonstrated that SBR technology can be useful for the petroleum industry wastewater treatment (Freire et al., 2001; Lee et al., 2004; *González et al., 2007;* Fakhru'l-Razi et al., 2010; Kutty et al., 2011; Pajoumshariati et al., 2011; Ghorbanian et al., 2014; Frank, 2016; Pajoumshariati et al., 2017). SBR system has been practiced in some refineries, but its use is not common and has limited application in the petroleum industry wastewater treatment (IPIECA, 2010; Jafarinejad, 2017).

BP refinery Ltd utilized SBR technology for upgrading of a lagoon system applied for secondary treatment of petroleum refinery wastewater during a major expansion of an existing refinery; using a HRT of 36 h and SRT of 40 days the total COD in the petroleum refinery wastewater was decreased to 50–150 mg/L (Hudson et al., 2001; Pajoumshariati et al., 2011).

In real, SBR technology was selected for the lagoon upgrade based on the following; SBR technology allowed a retro-fit of the existing earthen lagoon without the requirement for any additional substantial concrete structures, a dual lagoon system allowed partial treatment of wastewaters during construction, SBRs gave substantial process flexibility, SBRs had the ability to easily alter process variables without any physical modifications, and considerable cost benefits (Hudson et al., 2001).

Freire et al. (2001) studied biological treatment of a mixture of oilfield wastewater and sewage, in different percentages (10 to 45% v/v) in a SBR operated under 24 hour cycles. The removal of ammonium and phenols reported not to change considerably in the experimental runs, achieving average values of 95% and 65%, respectively.

Chemical oxygen demand (COD) removals of 30 to 50% were reported in dilution percentages of 45 and 35% (v/v), respectively. A test performed with a lower proportion of produced water (15% v/v), keeping the salinity level corresponding to a higher proportion of industrial effluent (45% v/v), resulted in an improvement in the COD removal, demonstrating that the recalcitrance of the organic compounds found in the effluent is the major cause of the moderate COD removal efficiencies achieved in the SBR system. With regard to the composition of the microbial flocs, no considerable alteration was seen in the polysaccharide (PS)/protein (PTN), PS/volatile suspended solids (VSS) and PTN/VSS ratios while the effluent composition varied (enhanced salinity and levels of organic material) (Freire et al., 2001).

Yoong and Lant (2001) investigated biodegradation of high strength phenolic wastewater using SBR. A SBR loading rate of 3.12 kg phenol/$m^3$.d (2.1 g COD.$g^{-1}$ MLVSS $d^{-1}$) with a COD removal efficiency of 97% at a SRT of 4 days and a HRT of 10 hours was reported. The SBR was conducted at 4 hours cycle, including 3 hours react phase and the synthetic wastewater of 1300 mg/L phenol was the sole carbon source. The oxygen mass transfer coefficient, $K_{La}$, of 12.6 $h^{-1}$ was reported (Yoong and Lant, 2001). Uygur and Kargi (2004) studied phenol inhibition effects on biological nutrient removal in a four-step SBR operation including anaerobic/oxic/anoxic/oxic steps with 1 h/3 h/1 h/1 h hydraulic residence times, initial phenol concentration between 0 and 600 mg/L, and the sludge age at 10 days. Phenol concentrations below 400 mg/L did not adversely affect nutrient (COD, $NH_4$-N, and $PO_4$-P) removals and effluent nutrient concentrations, because phenol was almost completely degraded at such phenol levels.

Percent COD, $NH_4$-N,and $PO_4$-P removal was above 95, 90, and 65%, respectively for initial phenol levels below 400 mg/L demonstrating no considerable phenol inhibitions due to the complete degradation of phenol. However, for initial phenol levels above 400 mg/L, phenol degradation was not complete and the residual phenol caused inhibition on nutrient removal leading to low levels of nutrient removals. The sludge volume index (SVI) values were reported to be nearly 45 mL/g for phenol concentrations below 400 mg/L which enhanced to 90 mL/g for initial phenol level of 600 mg/L. They mentioned that the residual phenol seemingly caused cell inactivation or disintegration and leaded to high SVI values at phenol levels above 400 mg/L; thus, initial phenol levels should be kept below 400 mg/L for effective nutrient removal from phenol containing wastewaters (Uygur and Kargi, 2004).

Lee et al. (2004) applied a two-stage SBR system for treatment of oily wastewater with COD and oil and grease (O&G) concentrations ranging from 1,722–7,826 mg/L and 5,365–13,350 mg/L, respectively. They developed an appropriate start-up protocol by gradual increase in oily wastewater composition with methanol as the co-substrate which this strategy provided a short acclimation period of 12 days for the sludge in the two-stage SBR to adapt to the oily wastewater. After acclimation, the first stage and second stage SBRs were reported to be able to attain COD removals of 47.0±2.4% and 95.3±0.5%, respectively. The first stage SBR was reported to be able to reach 99.8± 0.1% of O&G removal and effluent O&G from the first stage SBR was reported to be only 6±2 mg/L. The second stage SBR was applied to further remove COD in the effluent from the first stage SBR which the final effluent from the second stage SBR had a COD concentration of 97±16 mg/L with no detectable O & G content. They concluded that a two-stage SBR system could be feasible for processing high strength oily wastewater to meet the local discharge standards (Lee et al., 2004).

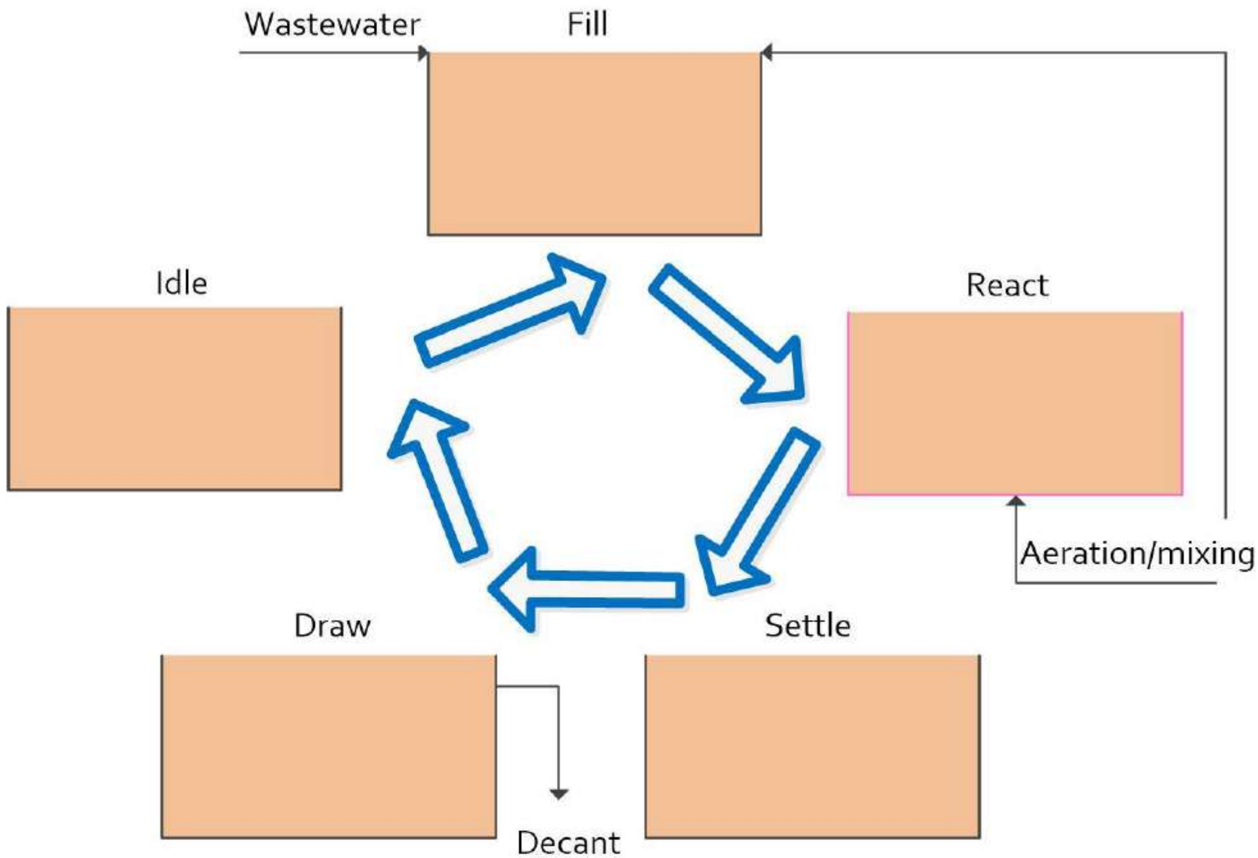


**Fig. 1:** Typical cycles in sequencing batch reactor (SBR) process (modified from EPA, 1997; U.S. EPA, 1999; Mane and Munavalli, 2012; Jafarinejad, 2017).

González et al. (2007) treated oily wastewaters from the Tank-Yard Ulé in the west cost of Lago de Maracaibo of Petroleum Venezuelan industry in aerobics conditions by SBR to evaluate the organic matter (hydrocarbons and phenols) removal efficiency. The COD, totals phenols and totals hydrocarbons removal seen in Light Petroleum Extraction effluent (EEPL) and the Heavy Petroleum Extraction effluent (EEPP) were reported to be maximum 96% and 72%, respectively (González et al., *2007)*.

Because of the adversely affected settleability of the activated sludge and some process perturbation such as toxic shock loading, the suspended solids (SS) content of the effluent of SBRs cannot be decreased to near zero and can be significant (Pajoumshariati et al., 2011). The incorporation of membrane separation technology (e.g. micro- or ultra-filtration unit) instead of the settling phase of the SBR (i.e. MSBR technology) could be useful (Pajoumshariati et al., 2011, 2017). Utilization of MSBR will result in an effluent with negligible SS content which may directly be fed into a reverse osmosis unit for the generation of potable water (Pajoumshariati et al., 2011). In comparison with SBRs, MSBRs: i) can provide higher treatment quality because of complete biomass retention; ii) can yield higher SRTs which will result in increase of nutrient removal; and iii) are more compact because of the elimination of the settling phase (Pajoumshariati et al., 2017). Fakhru'l-Razi et al. (2010) studied and compared the performance of a MSBR (Fig. 2) and MSBR/reverse osmosis (RO) process treating produced wastewater. Different HRT of 8, 20 and 44 h were investigated in the MSBR operations and operation results demonstrated that for a HRT of 20 h, the combined process effluent COD, TOC and O&G removal efficiencies were 90.9%, 92% and 91.5%, respectively. The MSBR effluent concentration levels met the requirements for oil well reinjection. The RO treatment decreased the salt and organic contents to acceptable levels for irrigation and different industrial re-use. Foulant biopsy indicated that the fouling on the membrane surface was principally because of inorganic (salts) and organic (microorganisms and their products, hydrocarbon constituents) matters (Fakhru'l-Razi et al., 2010).

Kutty et al. (2011) treated the petroleum refinery effluent wastewater using bench scale biological SBR systems. Six SBRs each of 2L liquid volume were operated at a 24 hours cycle in various anaerobically stirred and aerobic modes. The average COD removals for the aerobic reactor, combined anaerobic-aerobic reactors and aerobic mixed with domestic wastewater were reported to be approximately 91%, 91%, and 88% respectively, with its final average effluent COD of 63 mg/L, 65 mg/L, and 44 mg/L, respectively.

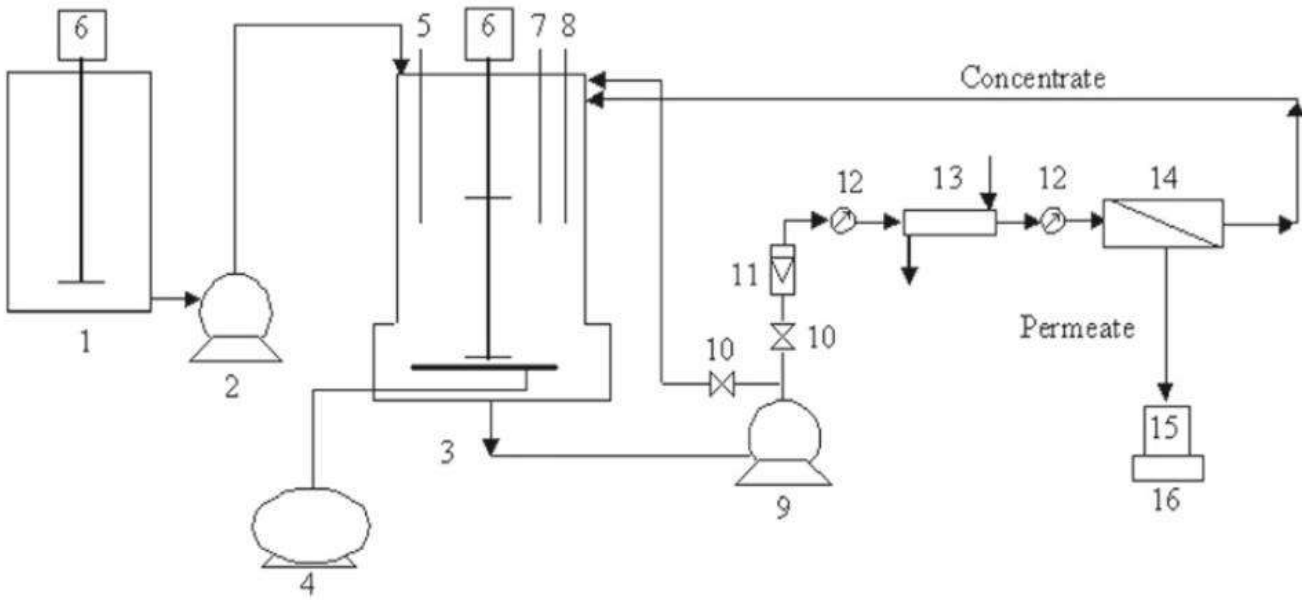


**Fig. 2:** Schematic of the membrane sequencing batch reactor (MSBR) system applied in Fakhru'l-Razi et al. (2010) work (1: raw wastewater tank, 2: peristaltic pump, 3: fermenter, 4: air compressor, 5: pH probe, 6: mixer, 7: temperature probe, 8: DO probe, 9: centrifugal pump, 10: valve, 11: flow meter, 12: pressure gage, 13: heat exchanger, 14: membrane, 15: permeate, and 16: balance) (Fakhru'l-Razi et al., 2010).

In the other work, Ahmed et al. (2011) reported that the effluent soluble COD (sCOD), ammonia-nitrogen, nitrate-nitrogen, total suspended solids (TSS), and VSS for aerobic SBR treating raw petroleum refinery wastewater could be 54 mg/L, 5.9 mg/L, 1.47 mg/L, 66 mg/L, and 19 mg/L respectively. Also, these parameters for two-stage anaerobic-aerobic SBR treating raw petroleum refinery wastewater could be 49 mg/L, 0.8 mg/L, 3.1 mg/L, 60 mg/L, and 17 mg/L, respectively. In addition, these parameters for the aerobic SBR treating mixed raw petroleum refinery wastewater with domestic could be 53 mg/L, 0.8 mg/L, 1.9 mg/L, 76 mg/L, and 52 mg/L, respectively. They concluded that combined anaerobic-aerobic SBR treating petroleum refinery wastewater gave pathway for maximum biodegradation and demonstrated relatively better performance (Kutty et al., 2011).

Pajoumshariati et al. (2011) evaluated the pollutant removal performance and membrane fouling characteristics of MSBR for the treatment of a synthetic petroleum refinery wastewater as a function of HRT (HRT of 8, 16, and 24 h). Increase in HRT led to statistically significant reduction in mixed liquor suspended solid (MLSS). Removal efficiencies >97% were reported for the three model hydrocarbon pollutants at all HRTs, with air stripping making a small contribution to overall removal. Decrease in the protozoan populations was reported in the activated sludge with decreasing HRT and a higher proportion of larger and smaller sized particles was reported at the lowest HRT. The membrane fouling and soluble microbial products (SMP) especially carbohydrate SMP, and mixed liquor apparent viscosity enhanced with decreasing HRT; whereas the concentration of extracellular polymeric substance (EPS) and its components decreased. Organic compounds were reported to be the main component of membrane pore fouling (Pajoumshariati et al., 2011). In the other work, Pajoumshariati et al. (2017) reported mean COD, O&G and total petroleum hydrocarbons (TPH) removal efficiencies of 80%, 82% and 93.4%, respectively during more than three-month operation of the MSBR with real petroleum refinery wastewater of varying composition. They mentioned that compared to the utilization of air scouring alone, relaxation (a hydraulic membrane cleaning method) leads to a significant drop in the rate of membrane fouling in MSBRs and affects the way mixed liquor physicochemical properties influence membrane fouling (Pajoumshariati et al., 2017).

Leong et al. (2011) have studied the sludge characteristics and the treatment performances of the SBR in the removal of varying influent phenol concentrations. Results showed that almost complete phenol removal can be achieved with sufficiently long react step and the change of sludge morphology did not affect the phenol removal efficiency in the SBR with increase phenol loading. However, with increasing influent phenol concentration to 400 mg/L, microfloc was prevailed resulting in poor sludge settleability and deteriorated the quality of effluent with discharged suspended solids (Leong et al., 2011). Ishak et al. (2012) have concluded that activity and biological performance in treatment plant may be affected by toxic compounds such as phenol that leads to constant drop in bacterial count during acclimatization period (Ishak et al., 2012).

Ghorbanian et al. (2014) studied the performance of a sequencing anoxic batch reactor for the biodegradation of hydrocarbons in petroleum-contaminated saline water as a function of inlet concentration at a HRT of 24 h. The average TPH removal rates for concentrations of 950, 1450, and 2500 mg/L were reported to be 99.7%, 98.5%, and 87.7%, respectively and the highest rates of TPH biodegradation at a loading rate of 104 g/m$^3$.h in the sequencing anoxic batch reactor was 91.3 g/m$^3$.h (Ghorbanian et al., 2014).

of the influent by volume, nitrification was lost, showing the threshold at which removal is effected by produced water dose lies between 6% and 20% by volume. Over this time, the biological community in the bioreactors remained stable providing evidence of a robust system (Frank, 2016).

Siemens Water Technologies Corp (2009) has introduced OMNIFLO® SBR to manage wastewater in the petroleum refining and petrochemical industries which is a fill-and-draw, non-steady state ASP, in which one or more reactor basins are filled with wastewater during a discrete time period, and then operated in a batch treatment mode. The SBR fulfills equalization, aeration and clarification in a timed sequence, in a single reactor basin. The OMNIFLO system can handle influent flows ranging from zero to four times design, and a wide range of organic loads and industrial pollutants (Siemens Water Technologies Corp, 2009).

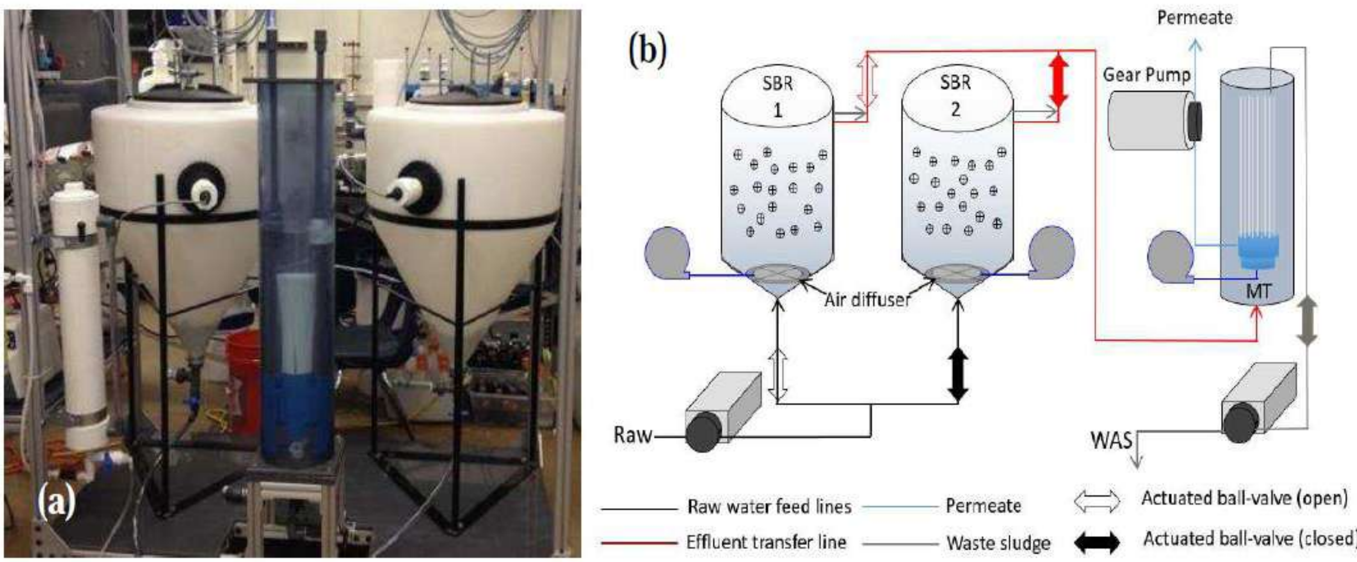


**Fig. 3:** (a) Picture and (b) process flow diagram of the SBR-MBR system in Frank (2016) work (Frank, 2016).

Xie et al. (2016) studied the microbial community in a full scale anaerobic baffled reactor and SBR system for oil-produced water treatment in summer and winter. According to their results, COD effluent concentration reached lower than 50 mg/L level after the system in both summer and winter, however, COD removal rates after anaerobic baffled reactor treatment system were significant higher in summer than that in winter, which complied with the microbial community diversity. Detection of *Saccharomycotina*, *Fusarium*, and *Aspergillus* were reported in both anaerobic baffled reactor and SBR during summer and winter. Compared to summer, the total amount of the dominant hydrocarbon degrading bacteria reduced by 10.2% in anaerobic baffled reactor, leading to only around 23% of COD was removed in winter. Although microbial community remarkably changed in the three parallel sulfide reducing bacteria, the performance of these systems had no considerable difference between summer and winter (Xie et al., 2016). Frank (2016) used a pilot-scale SBR-MBR hybrid treatment system (Fig. 3) to remove organic compounds, primary nutrients, and suspended solids from a mixture of municipal and oil and gas wastewaters for beneficial reuse. According to this study, by use of 6% by volume produced water, the SBR-MBR system reached comparable removal of primary (i.e., COD, ammonia) and secondary constituents (i.e., trace organic compounds, inorganic contaminants) to control conditions. As produced water was enhanced to 20%

## CONCLUSIONS

In the petroleum industry, the biological treatment is the most widely applied technique for the removal of dissolved oil from wastewaters which ASP has been the most common employed biological treatment process. The wastewater variability on both flow and composition naturally inhibits the treatment process and makes it difficult to treat using traditional biological processes. Conventional continuous flow systems such as ASP may have serious difficulties to meet the regulated discharge limits. Alternative approaches like discontinuous processes such as SBR technology, which promote the mineralization of the petroleum industry wastewaters containing toxic compounds seem to be promising.

To provide secondary, advanced secondary treatment, nitrification, denitrification and biological nutrient removal, SBR technology may be modified. Continuous flow SBR, SBBR, ASBR, anaerobic-aerobic SBR, and MSBR are some modifications of SBR technology.

Organic loading rate, HRT, SRT, DO, and influent characteristics such as COD, solids content, C/N ratio are the main parameters affecting SBR performance. Depending on the controlling of these factors, the SBR can be designed to have function such as carbon oxidation, nitrification and denitrification, and phosphorus removal.

Economic feasibility, design considerations, regulatory requirements, sludge generation rates, sludge transporting requirements, and site applicability are the factors that require to be assessed prior to the procurement and installation of a SBR treatment system.

Several laboratory- and pilot-scale studies have demonstrated that SBR technology can be useful for the petroleum industry wastewater treatment. SBR system has been practiced in some refineries, but its use is not common and has limited application in the petroleum industry wastewater treatment.

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