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Pollution Prevention Challenges in theProduction Process (Separation and Processing) of Oil and Gas Industry

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Abstract: During the oil and gas production process, a considerable amount of contaminated water is produced which is estimated to account about 70-90% depending on the geographical location and geological features of the oil field. This study describes the three stages of separation primary production, secondary recovery and tertiary recovery and discusses the challenges associated with the separation of produced water from oil and gas production. The study explores various hydrocarbons, produced solids, metals and radioactive materials as well as pollution issues related to the separation stage. Although, several technologies are used for the separation process, two techniques, three phase separation technology by using hydro cyclone and centrifugal separators are discussed. The opportunities and challenges as they relate to disengagement and processing are discussed. It analyses pollution prevention strategies and suggests incorporating life cycle assessment and process integration in resolving P2 issues related to produced water. Recommendations have been made for the constitution of a P2 committee involving professionals with chemical engineering, mechanical engineering, environmental scientists and economic realm. The study suggests for aggressively pursuing P2 strategy by conducting LCA (process to process) and carrying out studies on process integration for reducing the volume of produced water.

Key words: Pollution prevention, oil and gas, hydrocarbons, separation and processing, crude oil, natural gas

INTRODUCTION

The US EPA has classified the oil and gas extraction process into four distinct stages: exploration, well development, production and site abandonment. The Exploration stage involves searching oil and natural gas deposits and consists of geophysical prospecting and exploratory drilling. The good development stage starts only after finding economically recoverable fields. At this juncture, one or more wells are constructed which are either abandoned in the absence of adequate quality of hydrocarbons or else completed to recover hydrocarbons provided they are available in sufficient quantities. To reduce infrastructure cost, usually, several production wells are drilled from one pad which also, reduced land requirements. The size and number of wells also vary depending upon the hydrocarbon reserves, the size of reservoirs and its geological features. Large oil fields may contain more than a hundred wells while small areas may have around ten wells to be drilled.

The production process involves the extraction of hydrocarbons and the separation of the hydrocarbon liquid into the gas, water and solids. During this process, non-saleable substances are removed, so that, liquid hydrocarbons and gas could be commercially sold. While oil shall be treated at a refinery, natural gas is refined at a natural gas processing plant. The site abandonment stage becomes involved when it is determined that wells do not have the economically viable quantity to drill oil and gas.

According to Ekins and Vanner (API., 1997), the oil and gas production process generates a considerable amount of contaminated process water which is estimated to account for nearly 70% of the total volume (Ali *et al*., 1999). The process water after a preliminary treatment is termed as “produced water” which is either discharged or injected into aquifers. Due to growing environmental concerns and considerations, disposal of these waters after adequate treatment could be considered for utilization in agriculture and industrial sectors (All Consulting Tusla, 2003). A report by the Pacific Northwest Pollution Prevention Research Centre suggests that the produced water is the largest water stream which constitutes 95% of the total water in most of the oil fields.

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Asserts that at the end of the productive life of oil wells, water constitutes nearly 98% of material generated and brought to the surface during the oil and gas production process. According to the American Petroleum Institute (API., 1997) annual water production can exceed 15 billion barrels. However, natural gas wells tend to produce considerably less quantity of water compared to oil wells. Produced water which is a mixture of oil, salts, chemicals, solids and trace metals is the largest constituent by volume in the Gulf Coast region. It is estimated that in 1991, Louisiana (the US) generated over 1 billion barrels and texas (the US) generated approximately 7.5 billion barrels of produced water associated with oil and gas production (Cline, 1998).

The objective and scope of this study are to identify waste generated in the form of produced water, its quality parameters, environmental concerns associated with the water and the steps to be taken as pollution prevention measures to reduce the volume of produced water. The study will examine the current practices and strategies pursued by the oil and gas industry in reducing the produced water and also, the challenges the industry faces regarding pursuing pollution prevention strategies. Although, several technologies are used in the processing and separation process to separate produced water, this study briefly discusses two popular and profitable technologies.

MATERIALS AND METHODS

Petroleum production: Petroleum production involves, first, bringing the fluid to the surface, separation of the liquid and gas compounds and finally removing impurities. Oil and natural gas are produced from the same reservoir. With the passage of time and drilling, wells deplete the reservoir which increases the gas to fuel ratio and also, the ratio of water to hydrocarbons. The increase of gas over oil is attributed to the natural gas property of being on top of the oil during formation. However, wells are drilled from the bottom portion to recover liquid hydrocarbons.

Primary production: The first stage in hydrocarbon production involves using natural reservoir pressure to extract oil. However, when natural pressure is not adequate to lift oil to the surface, artificial lifting equipment is used. When oil is lifted by using pumping equipment, motors are employed on the surface or inside the walls for lifting the fluid to the surface. This production stage is capable of providing <25% of the actual quantity of oil in place.

Challenges in primary separation process: As shown in Fig. 2, a mixture of oil, gas and water including some solid particles enter a three-phase separator vessel from the left. Since, gas and liquid have different densities, the separation of gas is easy. However, it is quite likely that a mixture of gas and oil in the form of foam may be carried over to provide micron-size liquid droplets in the gas (Davies *et al*., 1996).

Rowley and Davies observe that horizontal separator vessels suffer from a problem related to the presence of emulsion which is a mixture of oil and water. They maintain that the physics associated with the oil and water separation is based on two primary mechanisms: settling and coalescence and both of them depend on the droplet diameter of the dispersed phase (Halwagi, 1998).

Davies *et al.* (1996) and Halwagi (1998) point out that the separation of oil and water pose a difficulty due to the difference in the density of oil and water. In the droplet coalescence mechanism, drops join each other to become bigger in size which facilitates in a quick separation process. Production of Bioethanol from Papaya and Pineapple Wastes using marine associated microorganisms (Abraham *et al*., 2017). However, various chemical compounds present in the crude oil often create hindrance in the ability of the droplets to coalesce.

Secondary recovery: Secondary recovery is used to recover liquid hydrocarbons by repressurizing the reservoir and re-establishing the natural water. At this stage, water which is produced with the oil is re-injected (Fig. 3). However, additional quantities of water may also be used. Produced water which is injected for the other recovery of crude oil and natural gas is regarded as recycling of water as waste. In some reservoirs, gas is injected to improve gas cap drive.

Tertiary recovery: The final stage for removing the last extractable oil and gas is carried out by using chemicals, gases or heat to enhance the efficiency of oil recovery. For example US EPA in 2000.

Thermal recovery (heating reservoir fluid) by injection of steam or a controlled burning of tank to turn the fluid into less viscose.

Miscible injection which involves CO_2 or alcohol to be injected to minimize the oil density and to enable it to reach the surface more quickly.

Microbial recovery requires particular organic digesting microbes to be injected with oxygen to digest heavy oil and asphalt and lighter oil to flow.

Crude oil separation: The fluid brought to the surface is composed of several substances, e.g., natural gas, water, sand, salt and additives that may have been used for improving the extraction process. The separation process of oil includes the separation of gaseous compounds, the removal of solids and water and the breaking up of oil-water emulsions.

When volatile components are removed to separate natural gas from the liquid, gaseous contaminants such as Hydrogen Sulfide (H_2S) may also be present in some field. The gases are separated using passing through one or two decreasing chambers. The remaining liquid and solid constitute a complex mix of water, oil and sand. During the extraction process, water and oil form an emulsion which may contain either small deposits of oil in the water or droplets of water in oil. Fluid separation provides a layer of sand, a layer of water with minimum oil contents, a layer of emulsion and a small layer of relatively pure oil. Then water and sand or basic sediment and water are removed by a process called free water knockout. According to Arnold and Stewart, emulsions are broken by heating the fluid up to 100-160°F or by using chemicals. At this stage, oil is approximately 98% pure which can be stored or sent to refining. A comparative study of saline and non-saline water in an application of tomato yield by using photonic sensor has explained (Roy *et al*., 2016).

Natural gas conditioning: Natural gas conditioning involves removing impurities from the gas to make it worthy of a transportation system. However, sometimes natural gas which is free from impurities is obtained and thus does not require any conditioning. Since, the natural gas is separated from the liquid, it may carry pollutants which are often quite hazardous and pose considerable problems. One of the most dangerous substances is Hydrogen Sulfide (H_2S) which is likely to be present in natural gas. H_2S is known to have potential health impacts at individual concentrations on humans in addition to creating corrosion in pipes. Another problem is associated with water vapor. Manning and Thompson point out that when water is reacted at high pressure with components in gas, it converts into gas hydrates which are in solid form and are capable of clogging pipes, valves and gauges. Furthermore, water can freeze due to low temperatures which also can clog pipes and valves.

Conditioning processes such as dehydration and sweetening are used in natural gas conditioning process. The total quality of water produced from gas fields is significantly less than the oil production area.

Produced water from oil production: Reservoir rocks contain petroleum hydrocarbons liquid and gas as well as water. The physical and chemical composition of produced water greatly varies depending on the geographical location of the field, the geological formation and the production of specific hydrocarbon products.

A report by the US EPA illustrates the concentrations of pollutants in treated offshore produced water samples obtained from the Gulf of Mexico as shown in Table 1. The first column of the table provides the performance at a fundamental level of treatment by using Best Practicable Technology (BPT). The data in the second column shows a greater standard of therapy by applying Best Available Technology (BAT).

According to Tibbetts *et al.* the organic and inorganic compounds of produced water discharged from offshore wells can be found in different states such as solution, suspension, emulsion, absorbed particles and particulates. Cline (1998) argues that the produced water from oil production may also, contain groundwater or seawater which is injected to generate or maintain additional reservoir pressure. He contends that the produced waters are more saline than sea water. Also, produced water may also, contain chemical additives used in drilling and manufacturing operations associated with the oil/water separation process.

Produced water from gas production: Jacob *et al.* observe that the produced waters from gas production tend to have greater contents of low-molecular-weight aromatic hydrocarbons such as Benzene, Toluene, Ethylbenzene and Xylene (BTEX) compared to oil production. They point out that produced waters discharged from gas/condensate platforms are approximately ten times more toxic than the produced water discharged from oil platforms. They also note differences between offshore oilfields provided water and offshore gas produced water for other parameters, e.g., they observed that in the North Sea ambient pH is 8.1 and chlorides are about 19 g/L. Produced water released from oil platforms in that area have pH levels of 6-7.7, however, produced water from gas platforms were found to be more acidic, i.e., approximately 3.5-5.5. Similarly, chloride concentrations range from about 12-100 g/L in produced water generated from crude oil production while <1-189 g/L in produced waters generated from natural gas production.

Constituents in produced waters from conventional oil and gas production: It is noted that organic substances are either dispersed or dissolved in produced water which includes oil and grease and several other dissolved components. Stephenson observes that dispersed oil consists of small droplets suspended in the aqueous phase and they can contaminate not only the accumulation of oil on ocean sediments but can also, disturb the benthic community. Bansal and Candle (1999) point out that the size of precipitated droplets is approximately 4-6 μ while the treatment system currently available is not capable of removing droplets smaller than 10 μ. PLI 2 and *Aeromonas hydrophilia* co-infection in pacu, *Piaractus brachydomes* is detailed in (Abraham *et al*., 2017).

Dissolved or soluble organic components: Glickman asserts that hydrocarbons that are naturally present in produced water include organic acids, Polycyclic Aromatic Hydrocarbons (PAHs), phenols and volatiles. He argues that while individually these hydrocarbons may not contribute to toxicity levels in produced water, their cumulative impact on toxicity can be significant.

Ali *et al.* (1999) contend that, since, soluble organics can not be easily removed from produced water, they are discharged to the ocean or re-injected at coastal locations. They point out that organic compounds which are highly soluble in produced water have been found to have low molecular weight (C2-C5) carboxylic acid (fatty acids), ketones and alcohols. They note that these organic compounds also, include acetic and propionic acid, acetone and methanol. They go on to assert that the concentration of these compounds in some produced waters is often greater than 5,000 ppm.

Naphthalene is the most pure PAH which is usually present in higher concentrations than other PAHs. For example in the Norwegian fields, naphthalene consists of over 95% of the total PAHs in offshore produced water. PAHs are believed to increase biological oxygen demand are highly toxic to aquatic organisms in addition to being carcinogenic to man and animals.

Produced solids: Cline (1998) suggests that produced water tends to contain precipitated solids, sand, silt, carbonates, clays, proppant, corrosion products and other suspended solids generated during production and well bore operations. He points out that the fine-grained solids can directly affect the efficiency of oil/water separators, thus leaving excessive oil and grease in discharged produced water.

Metals: Frost *et al.* (1998) argues that the concentration of metals in produced water depends on the type of oil field, its age and the geology of formation from where oil and gas are extracted. Produced waters contain zinc, lead, manganese, iron and barium.

Naturally Occurring Radioactive Material (NORM): Frost *et al.* (1998) maintains that the most common NORM compounds in produced water are radium-226 and radium-228 which are generated due to the radioactive decay of uranium and thorium associated with certain rocks and clays in the hydrocarbon reservoir.

Sodicity: According to, the soil structure and plant growth have significant adverse impact associated with the excessive amount of sodium in irrigation water. Sodicity is measured regarding Sodium Absorption Ratio (SAR). Thus, high SAR causes reduced permeability which in turn reduces infiltration, reduces hydraulic conductivity and also, causes surface crusting.

Technology considerations in produced water separation from crude oil: According to Otto and Arnold, several techniques that are used by the oil and gas industry for removing contaminant include, hydro cyclone, reverse osmosis, membrane filtration, gas flotation, carbon adsorption, bioreactors, chemical oxidation, stripping/extraction and UV oxidation. However, these processes are expensive and complicated. Veil suggests for reinjection or using in-well separators for the recycling of produced water. He points out that although reinjection has been gaining popularity, enhanced treatment is often needed to remove oil and gas particulate matter to get rid of damaging rock formations. He asserts that the suitability of produced water for reinjection depends on the water quality and the rock formation properties.

Veil *et al.* observe that in a typical oil well, the ratio of water-to-oil varies from near zero (100% crude oil) to near infinity almost 100% water, usually salt water. Currently, two types of technologies are commercially used. The first uses hydro cyclone to separate oil and water and gravity separation point out that hydro cyclone based technology is preferred for wells with water-to-oil ratio of 5:1-100:1 and produces fluids with a water to oil ratio 1:1-2:1 which contains oil concentrations of <100-500 ppm in the separated water. Fluids are pumped through or pulled through the hydro cyclone after installing a dual pumping system.

The gravity separator-based technology is based on the oil-water separation device which is installed in the underground structure. The most common gravity separator uses a rod pump which has two pumping chambers, the upper house is located near the oil-water interface which takes a mixture of oil and water and pumps to the surface. The lower house is situated below the oil-water interface through which water enters and is injected on the down stroke.

Veil *et al*. assert that hydro-cyclone and gravity separators have limitations due to the following: they cannot handle oil/gas/water mixtures, they are capable of removing only 75% of the water per stage and they are unable to operate in the oil-rich phase or the transition phase. Due to these shortcomings, hydro cyclone and gravity separators have been used only for on-shore application where the cost of transportation/treating water is considerably high, high water production restricts the overall well production capacity, e.g., reducing the volume of water pumped to the surface can increase the incremental oil production.

Efficient separation technologies are required to be used where surface treatment could have a significant difference, e.g., zero discharge and offshore platform where water pumping costs are significantly higher compared to on-shore locations and also, involve considerable initial construction costs related to separation equipment.

Three phase separation technology: Significant research has been conducted on hydro cyclone used for solid-liquid separation in the oil industry. Downhole separation is used to separate oil and water in the oil-bearing media derived from the oil field. Perkins maintains that hydro cyclone-based Downhole Oil-Water Separation (DOWS) systems (Fig. 4) are meant to be used commercially in wells with water-to-oil ratios of 5-100 which provide 1-2 water-to-oil ratio. However, downhole separation systems are not found reliable for offshore. He points out that hydro cyclone has turned out to be a useful device for solid-liquid separation which has been accepted in other downhole applications. According to him, a liquid-liquid hydro cyclone is used to separate two immiscible liquids while a solid-liquid hydro cyclone is designed to separate solid particles from the fluid stream. *In vitro* Assessment of Antimicrobial Properties in Different Concentration Crude Extracts of Ascidian (Jayaprakashvel *et al*., 2014; Sri Kumaran *et al*., 2014). He reports that the liquid-liquid units have a length-to-diameter ratio of 20-40. However, solid-liquid units possess a length-to-diameter ratio of 5-8 (Haas *et al*., 1957).

Perkins finds that hydro cyclones are capable of separating particles in the range of 40-400 mm but can be used for separating particles in the range from 5-1000 mm with particular applications. Perkins *et al*. (2003). Svarovsky finds that the density of these particles can range from 1.5-2.0 g/mL. He points out that that hydro cyclone makes use of centrifugal forces and drag forces. For example, when the centrifugal force is greater than the drag force, the particle moves outward towards the wall of the hydro cyclone. However, if the centrifugal force is less than the drag force, the particles move towards the center of the hydro cyclone (Haas *et al*., 1957). It is observed that due to the centrifugal force, massive particles tend to accumulate at the wall of hydro cyclone during the operation. The liquid-liquid hydro cyclone is used to separate two immiscible liquids when the fluids pass through the hydro cyclone unit, the lighter fluid moves towards the center of the hydro cyclone. In this process, the heavier phase is to the wall of the separation unit and exists out of the bottom of the hydro cyclone (Haas *et al*., 1957).

Centrifugal separations: Leonard points out that centrifugal of various sizes ranging from 2-25 cm rotor diameter have been in use in the US Department of Energy applications. According to Walker and Cummins, these separators have distinct advantages and make their claim viable in the downhole separation of oil and produced water.

In centrifugal separators, the oil/water mixture enters the spinning rotor which is separated by the centrifugal force, segregating water in the outer layer and oil in the inner layer (Fig. 5). The center of rotor contains a column of air. The oil and water are pushed over their respective weirs and slung out from the rotor.

Centrifugal force is applied in separating oil and water in a rotor of the unit. An experiment at the Oak Ridge National Laboratory found that the centrifugal force is related to the diameter of the rotor, i.e., the larger diameter of the rotor provides greater radial strength and better separation process. Also, higher rotational speed provides greater centrifugal force at enhanced efficiency in separation process.

Pollution issues related to separation and processing

Produced water: While many impurities are separated from produced water, some components and impurities remain as they are water-soluble and therefore cannot be easily removed. Water may contain high concentrations of chloride, sodium, calcium, magnesium and potassium. Produced water may also, include organic compounds such as benzene, naphthalene, toluene, phenanthrene, bromodichloromethane and pentachlorophenol. Inorganic substances may include, lead, arsenic, barium, sulfur and zinc. Radionuclides may include uranium, radon and radium. However, the concentration of these pollutants significantly varies from one geographical location of the well to another and also, the treatment methodology used for treatment. Moreover, contaminants from produced water from offshore and onshore pose different sets of risks and challenges.

Produced water mainly comes from oil bearing reservoirs but may also include seawater which is injected to enhance reservoir pressure. The volume of produced water discharged to the North Sea has become a cause of concern (Henderson, *et al*., 1999). According to the Energy Report, the produced water in the North Sea increased from 187 million tons in 1993-234 million tons in 1997 (Henderson *et al*., 1999). North Sea fields generate 2,400-40,000 m^3/day of produced water for oil installation and 2-30 m^3/day for gas production. The OPSI (2002) report indicates that PAH concentration level in the North Sea exceeded toxicity threshold levels within 500 m from the discharge point .

Menzie points out that process water contains some pollutants in varying degree which largely depend on the location, the age of oil and gas field and geological features. According to the OPSI (2002) report, produced water contains dispersed oil and dissolved organic compounds including light aromatic hydrocarbons such as BTEX, PAH, heavy aromatic NPD organic acids, phenols and inorganic compounds. The chemical composition of produced water varies from on location to another depending on the reservoir's geology. Also, after few years of use, wells tend to produce the greater amount of water. Since, the water is injected into the reservoir to maintain pressure, the composition of produced water also, changes due to dilution.

Hudgins argues that the majority of oil platforms use two or three types of production chemicals to separate oil, gas and water from the reservoir fluids. The use of these chemicals has grown considerably which may include corrosion inhibitors, emulsifiers, defoamers and biocides (Henderson *et al.*, 1999).

Produced water during onshore operations: Produced water generated during onshore operations with high saline concentration can cause considerable environmental risks at coastal and shallow offshore areas. The saline concentration, however, varies from one location to another. Stephenson suggests that in some places, the salt concentration in produced water can be as high as 200,000 mg/L. A US EPA report, however, points out that in some areas salt concentration in produced water is so low that the water can be used, after meeting regulatory limits for irrigation purposes or livestock watering.

The release of produced water onto soil can considerably increase salinity levels which in turn can damage plant growth. The concentration of metals and organic compounds present in produced water are also a cause of concern. According to Smith, more than 90% of onshore produced water is injected for disposal or greater recovery.

Produced water during offshore operationsl: Produced water, if not adequately treated can cause immediate impact in the area surrounding the platform. The pollutant's in the form of metals, radionuclides, extra oily materials and high BOD in the produced water may be greater than the surrounding water. Neff and Sauer, however, point out that the impact of produced water is considerably reduced at greater distances from the well. For example in the Gulf of Mexico, it is observed that "produced water can be diluted 100 fold within 100 m of the discharge".

Air emission: The production process also involves several sources of air emissions, e.g., leaking tubing, valves, tanks or open pits release Volatile Organic Compounds (VOCs). When the gas produced is not sold, it is flared and consequently releases carbon monoxide, nitrogen oxides and also, sulfur dioxide if the gas happens to be sour. Machinery used during production are also a source of emissions in the form of nitrogen oxides, sulfur oxides, ozone, carbon monoxide and particulates. Emissions generated from natural gas processing plants are greater than field production operations.

Other wastes: The sand which is separated from produced water if not disposed of properly is contaminated with oil and traces of metals. For the temporary storage of oil, natural gas or produced water, tanks are used. These containers form the sludge on the bottom of the reservoir due to a mixing of small solid particles in the liquid. These sediment and water need to be periodically removed from the bottom of the tanks. Some of the tanks may require frequent cleaning several times in a year while others may require one every 10 years or so.

Produced water management: The management of produced water poses a considerable challenge due to its volume and handling cost. Veil *et al.* point out that according to API sources, exploration and production activities take place at nearly 900,000 separate locations in 33 states of the US and on the Outer Continental Shelf.

However, there is no authentic mechanism for tabulating the volume of produced water generated by the oil and gas industry.

Due to the no discharge criteria for produced water in the US coastal areas, produced water from conventional oil and gas operations onshore is being injected. A study conducted by API reveals that nearly 71% of all produced water is being injected for beneficial use and 21% is being injected for disposal. Thus, "92% of all produced water generated is being returned to the subsurface from whence it came". The remaining 5% produced water is either treated and discharged or is used for irrigation, livestock, wildlife watering, etc. The other 3% of the produced water is disposed of via evaporation ponds or percolation. In 2002, the US onshore operations generated nearly 14 billion barrels which indicated that it requires concerted efforts for the proper management of produced water.

Veil discusses water management technologies and strategies in light of three tiered pollution prevention hierarchy. The first tier involves water minimization procedure which requires processes to be modified by adopting suitable technologies or substituting products to reduce the volume of water being generated. Water minimization approach not only provides monetary savings for operations but it also, contributes to environmental protection. However, despite water minimization, the water produced needs to be reused or recycled in line with the second tier strategy. The remaining quantity of water that cannot be recycled or reused needs to be injected or discharged to dispose of.

Pollution prevention in separation and processing opportunities and challenges: According to US EPA, pollution prevention can be achieved by "reducing material inputs, re-engineering processes to reuse by-products, improving management practices and employing substitution of toxic chemicals". The report goes on to assert that "if source reduction is not feasible, the next alternative is recycling of wastes, followed by energy recovery with waste treatment as a last alternative".

The American Petroleum Institute (API, 1991) has proposed ten steps for waste management plans which also include pollution prevention strategy. The 10 steps plan, proposed by API includes the following.

Company management approval: Management should establish goals for the waste management plan, identifying key personnel and resources that are committed to planning and develop a mission statement for its environmental policies.

Area definition: The waste management plan should be designed for a particular field to account for differing regulations and conditions in most cases, the area would be limited to within one state.

Regulatory analysis: Federal, state and local laws as well as landowner and lease agreements, should be evaluated. Based on these evaluations, operating conditions and requirements should be defined.

Waste identification: The source, nature and quantity of generated wastes within the plan's area should be identified and a brief description of each type of waste should be written.

Waste classification: Each waste stream should be classified according to its regulatory status including whether it is a hazardous waste subject to regulation under the Resource Conservation and Recovery Act.

List and evaluate waste management and disposal options: List all waste management practices and determine the environmental acceptability of each option. Consider regulatory restrictions, engineering limitations, economics and intangible benefits when determining their feasibility.

Waste minimization: Analyze each waste-generating process for opportunities to reduce the volume generated or ways to reuse or recycle wastes. The waste minimization or pollution prevention opportunities that are presented in this study can be used for this step.

Select preferred waste management practices: Choose the preferred management practices identified in step 6 and incorporate waste minimization options from step 7 wherever feasible. Specific instructions for implementation should be developed.

Prepare and implement an area waste management plan: Compile all preferred waste management and minimization practices and write waste management summaries for each waste. Implement the plan on a field level.

Review and update waste management plan: Establish a procedure to examine and revise the plan periodically.

Pollution Prevention Strategies

Life-cycle assessment as pollution prevention tool: Life Cycle Assessment (LCA) is involved in the evaluation of the environmental loads caused by product, process or unusual activity. The evaluation is carried out by quantifying the energy and material consumption and waste generated into the environment (Halwagi, 1998; M.M.E., 2007).

Three types of LCA are used for process or product development: cradle-to-grave, cradle-to-gate and gate-gate LCA. Cradle-to-grave LCA is usually used for product development. It defines the system boundary from materials extraction to disposal. Cradle-to-gate and gate-to-gate LCA are used for process development. Cradle-to-gate takes account of all the environmental burdens starting from materials extraction until the final production while gate-to-gate LCA only considers the duties within the plant boundary, i.e., from plant input gate to delivery gate (Halwagi, 1998).

LCA is intended to achieve two primary objectives. First, it quantifies and evaluates the environmental performance of a process from ‘cradle-to-grave’ and thus, to help decision makers in choosing alternative processing routes or materials. In this context, LCA provides a useful tool for identifying the Best Practicable Environmental Option (BEPO). Azapagic proposes a methodology for process design based on the life cycle analysis. The method uses LCA throughout the process design and thereby, environmental consideration has been incorporated from the early stage of conception. Khan *et al*. proposed GreenPro, a systematic methodology for process design using LCA. They considered the minimization of environmental impact of a process by integrating the LCA technique within a standard process design and optimization approach. It used the LCA tool for assessing the environmental implications of a process or product through its complete life cycle (Halwagi, 1998).

Another objective of LCA is related to identifying the improvement opportunities at different stages of a life cycle for improving the environmental performance of a processing system. Clift and Longley maintain that LCA can be instrumental on its own or by combining with other pollution prevention assessment tools in identifying the pollution prevention opportunities over a broader environmental domain (Halwagi, 1998). However, despite several benefits associated with LCA, it suffers from the following drawbacks (Halwagi, 1998):

- LCA is a highly data-intensive method and the success of any given study depends on the access of accurate data which is often quite a challenging task
- LCA system is very time consuming and expensive
- Life Cycle Inventory (LCI) data are not available for wide sectors in particular for chemical process units
- LCA does not tell the investigator what the ultimate limit of the environmental performance that can be achieved and thus is it does not facilitate in attaining the target
- Significant uncertainties exist in LCA studies which are very likely to create complexity in decision making

Process integration: Halwagi (1998) argues that pollution control strategies have been based on two approaches. End of pipe treatment which involves “the application of the chemical, biological and physical process to reduce toxicity or magnitude of environmentally undesirable compounds in process waste streams before their release to the environment” (Halwagi, 1998).

Disposal is carried out as a “post-process activities” to tackle waste, i.e., good deep injection and offsite shipment by transporting hazardous substance to waste management facilities. He maintains that the pollution control decisions are rarely based on process which in his view is often the leading cause of generating waste. He goes on to stress that often pollution prevention solutions can be found in existing process equipment instead of installing new equipment. He, however, warns that solutions can not be directly copied from one process to another without taking into considerations subtle differences between methods. He, therefore, suggests for a process integration which provides solutions for coping with challenges that relate to the use of technologies for pollution prevention.

Halwagi (1998) describes pollution prevention as “holistic approach to process design” which involves “determining its attainable performance targets.”. He suggests three key components of any effective process integration include, synthesis, analysis and optimization. Process synthesis provides designer a framework for developing the design by taking into consideration various process technologies, alternatives, configurations and operating conditions. Process analysis “involves the decomposition of the whole into its constituent elements for individual study of performance” (Halwagi, 1998). It requires a detailed analysis and prediction with regards to flow rates, compositions, temperature and pressure. This involves the use of mathematical modeling, empirical correlations and computer-aided process simulation tools. Further, it also, includes experiments at a lab or pilot plant scale or even within the existing facility for predicting and validating of performance (Halwagi, 1998).

Synthesis and analysis continue till the process objectives are achieved. The realization of process goals suggests that a solution has been found which may not, however, provide an optimum result regarding solution.

Optimization requires choosing the "best solution among the set of available options. This requires the justification of selecting a particular solution and quantifying the selection regarding objective function, e.g., cost (Halwagi, 1998).

There are several questions that need to be answered to ensure that the selected solution is an optimum solution. Halwagi (1998) outlines the following issues:

- Which process stream should be intercepted?
- Which phase (s), i.e., gaseous, a liquid is required to be blocked to remove the pollutants?
- To what extent should the pollutants be removed from each process stream?
- Which separation operations should be used for the interception?
- Which did separating agents need to be selected for the interception?
- Which units should be manipulated for source reduction and by what means?
- Should a stream be segregated? Which one?
- Which stream needs to be recycled/reused?

The answers to the above questions can provide several alternatives. An engineer can be entrusted the responsibility to come up with answers to these issues. Subsequently, the designer is assigned the responsibility to develop a simulation model by conducting an economic analysis and identifying the most suitable and cost effective solution from the selected options that have been examined (Halwagi, 1998). Halwagi (1998) argues that such a solution does not justify to be termed as "Optimum" solution. He asserts that a solution can be justifiably called optimum provided it is less expensive. He maintains that mass integration and energy integration can facilitate in identifying best performance targets of the process and in finding an optimal solution for improving process efficiency including pollution prevention. He goes on to emphasize that an effective pollution prevention can result by applying a combination of a stream to include:

- Segregation
- Mixing
- Recycling
- Interception and
- Sink/Generator manipulation

Segregation involves separation of streams. That is, segregating waste streams at the source can reduce the pollution prevention cost. Also, this reduces the cost of eliminating pollutants from a segregated stream.

Recycling implies "the utilization of pollutant-laden stream (a source) in a processing unit (a sink)" (Halwagi, 1998). A source-sink mapping diagram provides a practical and useful means for recycling strategies. This involves drawing a diagram for each pollutant load.

Interception requires the "utilization of separation unit operations to adjust the composition of the pollutant-laden streams to make them acceptable for sinks" (Halwagi, 1998). These separations can be accelerated by either using Mass-Separating Agents (MSAs) or Energy Separating Agents (ESAs) or by using both.

Sink/generator manipulation involves making necessary operating changes in design which can provide positive changes in flowrate or "composition of pollutant-laden streams entering or leaving the process units" (Halwagi, 1998). These steps involve making changes in "temperature/pressure, replacement of unit, altering catalyst, feedstock substitution, reaction-path changes" (Halwagi, 1998).

RESULTS AND DISCUSSION

It is evident that during the oil and gas production process, produced water is the largest segment and is estimated to account about 70-95% depending on the geographical location of the field, the geological formation of the site, the age of oil well, etc. However, these percentages can be taken as the rough guide as there seems to be no credible mechanism in place for tabulating the volume of produced water generated by the oil and gas industry. Natural gas wells, however, produce significantly less quantity of water compared to oil wells. The separation of oil and water poses a challenge due to differences in density of oil and water. Pollutants from produced water from offshore and onshore pose different sets of risk and challenges. Although, there have been considerable efforts regarding improving operational techniques to reduce pollution in the form of produced water by imbibing technologies, the outcome of these efforts have not been up to the mark.

Produced waters from gas production have been found to contain greater contents of low-molecular-weight aromatic hydrocarbons such as Benzene, Toluene, Ethylbenzene and Xylene (BTEX) compared to oil production. Also, produced water discharged from gas/condensate platforms are found to be ten times more toxic than the produced water discharged from oil platforms. Small precipitated droplets present in dispersed oil are about 4-6 microns while the currently available treatment system is not capable of removing droplets less than 10 μ.

Hydrocarbons present in produced water such as organic acids, Polycyclic Aromatic Hydrocarbons (PAHs), phenols and volatiles may not contribute to toxicity level, their cumulative impact, however can be significant. Produced water usually contains higher concentrations of naphthalene than other PAHs. In some of the fields, naphthalene has been found to consist over 95% of total PAHs in offshore produced water. PAHs are believed to contribute to increasing biological oxygen demand are highly toxic to aquatic organisms and are also carcinogenic to man and animals. Produced water contains solids in the form of sand, salt, carbonates, clays, corrosion products and other suspended solids. These fine-grained solids can reduce the efficiency of oil/water separations and lease excessive oil and greases in discharged produced water. The metals found in produced waters include zinc, lead, manganese, iron and barium.

Hydrocyclone based technology is preferred for wells with water-to-oil ratio 5:1-100:1 which produces fluids with water to oil ratio 1:1-2:1 containing oil concentrations of <100-500 ppm in separated water. Hydrocyclones have been found to be efficient in separating particles in the range of 40-400 mm but can be used for separating particles range from 5-1000 mm with particular applications. The centrifugal separators are technologically simple but provide satisfactory results and are widely used due to their simplicity and efficiency.

CONCLUSION

LCA related to separation and processing stage can provide a useful tool to determine energy consumption and waste generated. It can also, assist in process design and minimize adverse environmental impacts associated with a process. A pollution prevention strategy to reduce the volume of produced water will require modifying processor suitably improving technologies rather than installing new equipment. Also, to addressing environmental concerns associated with produced water, pollution prevention strategy can contribute to monetary savings for operations. Process integration can substantially help to reduce a volume of produced water and evolving a viable means of pollution prevention. Process integration design tools can also contribute to improving productivity in addition to resource conservation and strategic planning.

RECOMMENDATIONS

A facility involved in the oil and gas production should take the following proactive steps for pollution prevention regarding minimizing the volume of produced water.

Constitute a pollution prevention committee comprising of professionals in chemical engineering, mechanical engineering, environmental science and economic realm.

Carry out life cycle assessment (gate to gate) of separation and processing phase of oil production. Adopt process integration approach to find the viable solution for pollution prevention regarding reducing a volume of produced water and contaminants that are constituents of the water.

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