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DETERMINATION OF MERCURY IN ACID GAS TREATMENT PROCESS AND ITS ENVIRONMENTAL IMPACTS

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ABSTRACT

Mercury occurs naturally in unprocessed hydrocarbon streams, which can damage the equipment and contaminate the treatment fluids as well as pose a health risk to workers and the environment. Mercury was determined in all stream fluids for sweetening process (Benfield solution process) and composition analysis also determined to evaluate the performance of the process. Fourteen samples were collected from natural gas, Benfield solution, water, sludge and solid samples. Mercury was measured on-site for gas streams using cold vapor atomic absorption (CV-AAS) technique. Total Hg concentrations were measured for liquid streams and solid samples with AAS after digestion with a different technique. Vent gases (composed mainly of carbon dioxide) have high Hg concentration reached to 21.6 μg/Sm^3 for Train2, emitted to the atmosphere without treatment. This study suggests that separate carbon dioxide and install Claus process for remove H$_2$S and periodically monitor Hg for the treatment process and environment. Moreover, mercury contaminates the Benfield solution where the total Hg concentration of rich Benfield solution reached to 175.4 ng/g for Train2 but the lean Benfield solution free of mercury due to the regeneration process. Although water collected from reflux is condensed water, but it has high mercury content reached 122.1 ng/g for train1. Finally, solid and sludge samples collected from regeneration package contain mercury sulfide, which reached to 8.2 weight% of sludge sample. Therefore, the workers when cleaning the vessel from solid and sludge must take all safety precaution.

INTRODUCTION

Natural Gas is a vital component of the world's supply of energy and considered as an environmentally friendly clean fuel, offering important environmental benefits when compared to other fossil fuels. The superior environmental qualities over coal and crude oil are the negligibility of sulfur dioxide and carbon dioxide emissions. This helps to reduce problems of acid rain and greenhouse gases (Mokhatab, 2006). Egypt's estimated proven gas reserves stand at 77 trillion cubic feet (Tcf) and the fourth–largest amount in Africa (EIA, 2015). Natural gas is a mixture of hydrocarbon and non–hydrocarbon compounds (impurities). The hydrocarbon compounds normally found in natural gas are methane, ethane,

propane, butane, pentane, and small amounts of the heavier hydrocarbons that are mainly hexane, heptane, and octane. Some aromatics can also be present such as benzene, toluene and xylenes. The non–hydrocarbon gasses are nitrogen, carbon dioxide, helium, hydrogen sulfide, water vapor, and other sulfur compounds such as carbonyl sulfide and mercaptans (Speight, 2007). Mercury is also being present in produced and processed natural gas, hydrocarbon liquids and wastewater in various forms. The mercury removal unit (MRU) must be installed in gas plant even for the low concentration levels of mercury, especially when the gas processing plant consists of the aluminum heat exchanger**.** Raw natural gas must be processed before moving into high pressure pipeline systems for use by consumers. Natural gas processing means the separation of undesirable components, such as water, acid gases (CO$_2$ and H$_2$S) and heavy hydrocarbons. This is in order to facilitate its transportation and meet specifications for commercial use.

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The composition of raw natural gas is the most important issue in choosing a processing scheme. The natural gas must be within a specific gross heating value content of 1035 ± 50 Btu/ft^3 and a specified hydrocarbon dew point temperature level of ~ 15 °F at 800 psig maximum. Mercury occurs naturally in trace amounts, where, the concentration of mercury in crude oil and natural gas varies between 0.01 ppb and 10,000 ppb (wt/ wt) depending on the geologic location. The various chemical forms of mercury in natural gas processing are appearing as an elemental metal in the vapor phase or as an organo– metallic compound in liquid fractions and ionic mercury (II) in waste water fractions (Wilhelm and Kirchgessner, 2001; Shafawi et al., 1999; Wilhelm and Bloom, 2000).

Mercury must be removed to satisfy environmental concerns and to ensure the safe transport and efficient processing of these products. In natural gas and condensate production areas, the elemental mercury damages aluminum alloy heat exchangers and pipelines by corrosion. In chemical manufacturing and refining, mercury poisons catalysts and pollutes waste water, thus influence the regulatory compliance. Contamination of primary gas treatment systems (amine, glycol and carbonate solution) and aggregation of toxic sludge deposits in separators generate waste streams that are difficult to dispose of. Maintenance operators in the petroleum manufacture can be at risk due to inhalation of mercury vapor and dermal absorption of organic mercury compounds unless proper reservations are implemented. Therefore, mercury must be removed below the concentration 0.01 μg/m3, in order to avoid previous mentioned problems (Wilhelm, 1999). To date, little research has been published on the determination and monitoring of mercury in natural gas processing plants, especially in carbonate solution (Benfied solution). In this study, mercury was determined in produced and processed gases as well as carbonate solutions itself. Moreover, study the impact of the gaseous elemental mercury on health, safety and the environment. Afterward, the obtained data could help us to take the safety precautions if needed.

Experimental

Description of the Studied Area

Our study was conducted at the largest gas plant in the Western Desert of Egypt and designed to produce a daily contract quantity (DCQ) of 360–420 MMSCFD of sales gas at an export pressure of 101 bars. The diagram of the gas plant shows in Fig. 1. The produced gases from the wells are introduced into two parallel trains. First, it enters a three phase horizontal separator where the separation of gas, condensate and water takes place. Then, the gas flows from the three–phase separator to the gas sweetening systems. The first system is an acidic gas removal unit that contains the hot potassium carbonate solution (Benfield solution), which reduce CO_2 and sulfur compounds (H_2S and mercaptans) in the export gas. The second system is a dehydration unit containing Tri-Ethylene Glycol (TEG) that remove water from the gas, in order to avoid hydrate formation and to reduce water content, hence the best gas specifications can be achieved for export. After the glycol unit, the gas is then diverted to the dew pointing package, whose function is to separate entrained traces of condensate and heavier hydrocarbons that condense as liquids from the gas at the low temperature separator (LTS).

This step is a final step to export the gas, achieving hydrocarbon dew point specifications, via the export compressors. Condensate collected from the various processing steps move to stabilize before being stored in the storage tanks.

Studied samples

The study aims to monitor and determine mercury in all streams entering and outlet from the sweetening process (gas, Benfield solution, water and solid). In this study, fourteen samples were collected from the process shown in the Table 1. The samples were collected and measured at the short-term period.

Bulk Composition of the Studied Samples

Gas samples

Collection of the high pressure gas samples from the gas plant carried out according to ISO 10715 (1997). Also, the composition of gas was done according to ASTM-1945 (2003) using gas chromatography technique. The gas chromatograph is Varian Natural Gas Analyzer type C model CP-3800 equipped with thermal conductivity detector (TCD) and flame ionization detector (FID). Three columns were used to accomplish the single channel analysis of natural gas. Firstly, molecular sieve column (4 ft in length, 1/8 inch in internal diameter and Molsieve 13X with 45/60 mesh size) for oxygen and nitrogen separation, secondly, Hayesep P column (6 ft in length, 1/8 inch in internal diameter and Heyesep P with 80/100 mesh size) for separation of methane, carbon dioxide, ethane and hydrogen sulfide if present in detection limit of TCD and finally, capillary column (CP Sil 5, 60 meter in length, 0.25 mm in internal diameter and 1 μm in film thickness) for separation of methane till nonane hydrocarbon. Two packed columns Molecular sieve and Hayesep P were attached with TCD, while, the capillary column was attached with FID. Helium gas was used as carrier gas with constant pressure 20 psi, 23.5 psi and 13.4 psi for CP Sil 5, Hayesep P and Molsieve columns, respectively. The elution of the studied gas mixture was achieved by temperature programming ranging from 50 °C up to 200 °C at a rate of 10 °C min^{-1}. The injector and detector temperatures were 200 °C and 250 °C, respectively.

Varian gas chromatograph CP 3800 was attached with computer having star chromatography workstation software. The gas chromatograph response was calibrated using a certified standard gas samples with known composition closed to the composition of the studied sample. This was done to calculate response factor of each individual component of gas sample. The heat value of the investigated gas was calculated according to ASTM D 3588 (2003) method. Hydrogen Sulfide in gas samples was determined by Portable H_2S Analyzer (Trace 050, TRACE Techonolgy, USA). H_2S reacts with lead acetate to form a brown stain on the paper. The rate of reaction and the resulting rate of color change is proportional to the concentration of H_2S in the sample, This test according to ASTM D4084-07 (2012).

Analysis of Water and Carbonate Solution

Cations and anions were determined by ion chromatography (IC) manufactured by Dionex IC model DX 600 equipped with high capacity columns according to ASTM D 4327 (2003).
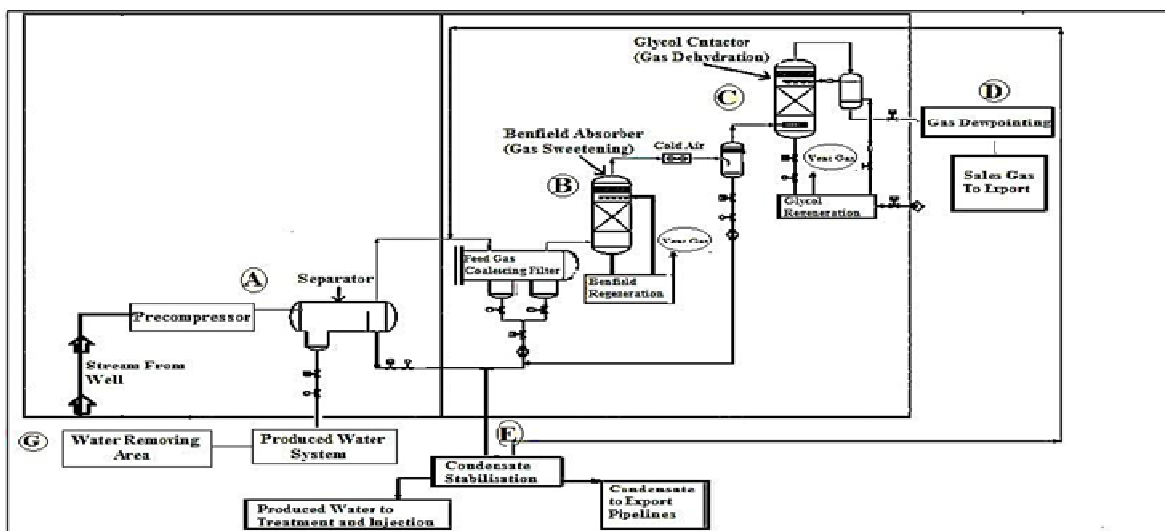
Fig. 1. Schematic Diagram of Gas Processing Plant

Table 1. Description the collected samples and sampling conditions of the sweetening process

Type of Sample	No.	Code of Sample	Description of Sampling Point	Temp. (°C)	Pressure (bar)
Gas	1	G-OIS-Tr1	Gas stream from inlet separator Train -1 (V-2011)	70.5	69.7
	2	G-OIS-Tr2	Gas stream from inlet separator Train -2 (V-2021)	69.2	69.5
	3	G-BSA-Tr1	Gas outlet from Benfield solution absorber Train-1 (C-2611)	40	68.2
	4	G-BSA-Tr2	Gas outlet from Benfield solution absorber Train-2 (C-2621)	40	68.3
	5	VG-BR-Tr1	Vent gas from Benfield regenerator Train-1	25	0.3
	6	VG-BR-Tr2	Vent gas from Benfield regenerator Train-2	25	0.3
Potassium	7	LCS-Tr1	Lean carbonate solution inlet absorber Train-1	110	68.4
Carbonate	8	RCS-Tr1	Rich carbonate solution outlet absorber Train-1	102	0.8
Solution	9	LCS-Tr2	Lean carbonate solution inlet absorber Train-2	110	68.4
	10	RCS-Tr2	Rich carbonate solution outlet absorber Train-2	102	0.8
Water	11	W-BRD-Tr1	Water stream from Benfield reflux drum Train 1	23	0.4
	12	W-BRD-Tr2	Water stream from Benfield reflux drum Train 2	22	0.4
Solid and	13	S-SCR	Solid from steam condensate reboiler (E2623) in regeneration package of sweetening process	-	-
Sludge	14	S-SACTr1	Sludge from sweetening absorber column Train-1 (C-2621)	-	-
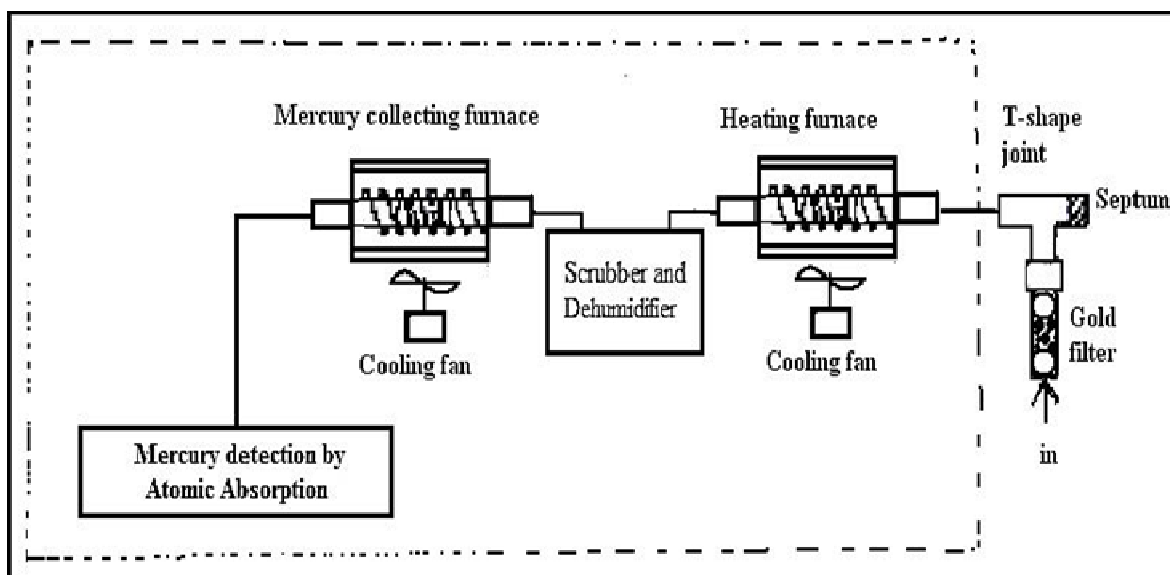
Fig. 2. Flow chart of Nippon Mercury Analyzer Model WA–4 (NIC, Japan)

Also, hydrogen sulfide (H_2S) in carbonate solution samples was achieved by potentiometric titration method (Titrando Meterohm 836 potentiometer) equipped with silver electrode was used in such analysis using $AgNO_3$ as titrant according to ASTM D 3227.

Total mercury analysis in natural gas

Quantitative determination of elemental mercury in natural gas was performed using a mercury analyzer (WA-4, Nippon instrument Co., Japan).

Fig. 3. Schematic Diagram of Sweetening Process

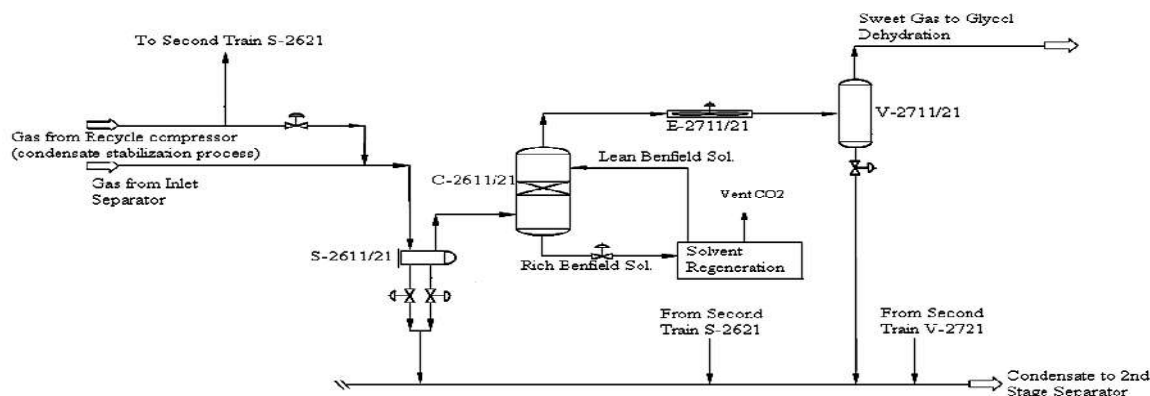The analyzer was equipped with a low pressure Hg discharge lamp as light source at a wavelength at 253.7 nm and two programmable thermal desorption units (heating furnaces) capable of heating quickly to 700 °C and 800 °C. The furnaces were attached to two collector tubes (gold-coated sand trap) as shown in Fig.2. The Analyzer was calibrated by injection of known concentrations of mercury gaseous standard using a Nippon mercury standard gas box model MB-1 (Hg STD Gas Box).

This box contains a drop of pure metallic Hg, which vaporizes to produce saturated Hg vapor, which is dependent on the ambient temperature, thus the concentration of Hg° in the gas can be determined. Four ranges of Hg detection levels, namely 0-2 ng, 0-20 ng, 0-200 ng and 0-1000 ng were applied according to Hg concentration in gas samples. The samples from the high pressure pipeline (up to 100 bar) were collected using a specially designed high-pressure sampling box (M&C Co., Germany). The sampling box equipped with two electrical heaters to prevent liquid condensation and loss of mercury adsorption. Moreover, it contains three flow meters with a control valve to adjust the flow rate entering to the Hg collector tube. This design used to reduce the pressure of gas without changing the Hg concentration, the sampling and analysis of gas were done according to ISO 6978-2 (2003) method.

Total mercury analysis in Benfield solutions and process water

For total Hg determination in Benfield solution and water, the samples were manually shaken for 10 min to homogenize. Accurately weighed amounts of approximately 1 mL of sample were mixed with 5 mL of HNO_3 (70%) in 22 mL glass vials with Teflon-lined caps, and left for pre-digestion for 120 min. The pre-digested samples were then digested in an autoclave at 90 °C for 150 min. The resulting digest was allowed to cool to room temperature and stored at 4 °C until further use (Ezzeldin et al., 2016).
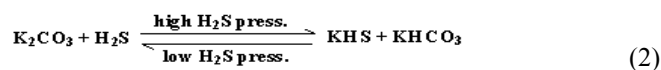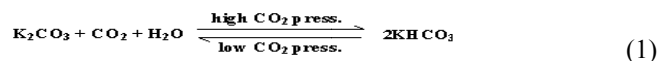
Total Hg measurements were done using Atomic absorption model ZEEnit 700 (Analytik Jena, Jena, Germany) equipped with the hydride system, Hg° was collected and introduced into the absorption cell for measurement at a wavelength of 253.7 nm. The digested samples mixed with 10% $SnCl_2$ to reduce Hg^{2+} to Hg° and swept out of solution and collected into the absorption cell for measurement. The standard calibration curve was prepared prior to the analysis of the samples by using serial dilution of the mercury chloride stock solution 1000 ppm.

Total mercury analysis in solid and sludge samples

The digestion of mercury in solid and sludge samples carried out according to SW-846 EPA method 3051. The microwave (MLS-1200 MEGA, Milestone, USA) equipped with temperature and pressure control as well as a closed vessel made from fluorinated polymer. Microwave power was 1600 Watt and the sample was digested according to the following program (Power in W/time in min): 300/2.0, 0/0.5, 450/10.0, 0/0.5, 450/10.0, 0/0.5, 300/9.5, 0/0.5, 400/3.0, ventilation 2.0 min. The internal temperature was limited to 250 °C and the pressure to 50000 KPa. Finally, the analysis of total mercury in digesting sample carried out by Atomic absorption model ZEEnit 700 (Analytik Jena, Jena, Germany) as mention above.

RESULTS AND DISCUSSION

Sweetening process is a process at which removes acid gases (CO_2 and H_2S) from raw natural gas stream to meet natural gas specification, where sales gas is required to be sweetened to contain no more than 4 ppm and 3 mole% of H_2S and CO_2 respectively. Sweetening process achieved by several methods based on absorption, adsorption, membrane and biological processes. Several factors must be considered in each process, such as types and concentrations of contaminants in the gas, the degree of contaminant removal desired, the selectivity of acid gas removal required, and the carbon dioxide-hydrogen sulfide ratio in the gas (Mokhatab, 2006). The acidic gas removal unit (Tr-1 and Tr-2) in the gas plant under investigation contains Benfield solution of K_2CO_3. Hot potassium carbonate (Benfield solution) process is a mild alkali for removing acid gases (Yi et al., 2009; Faramawy et al., 2016), which has been used in more than 700 plants worldwide. This process is originally intended to remove CO_2, but H_2S is also absorbed. It can also remove reversibly COS and CS_2. The mechanism of the reaction occurs is as follows (Klinkenbijl et al., 1999):

$$K_2CO_3 + CO_2 + H_2O \underset{\text{low } CO_2 \text{ press.}}{\overset{\text{high } CO_2 \text{ press.}}{\rightleftharpoons}} 2KHCO_3 \qquad (1)$$

$$K_2CO_3 + H_2S \underset{\text{low } H_2S \text{ press.}}{\overset{\text{high } H_2S \text{ press.}}{\rightleftharpoons}} KHS + KHCO_3 \qquad (2)$$

It is worth mentioning that diethanolamine (DEA) has been mixed with the Benfield solution in order to increase the efficiency of the removal process. The absorption and regeneration steps have been carried out at 110 °C and the reactions are reversible, based on the partial pressures of the acid gases.

Table 1. The composition of gas samples along sweetening process

Compound	Produce gas		Sweet gas		Vent gases	
	G-OIS-Tr1 Mole %	G-OIS-Tr2 Mole %	G-BSA-Tr1 Mole %	G-BSA-Tr2 Mole %	VG-BR-Tr1 Mole %	VG-BR-Tr2 Mole %
Nitrogen	0.767	0.768	0.552	0.556	0.05	0.051
Methane	76.656	76.484	79.949	79.807	3.831	4.057
Carbon Dioxide	9.660	9.767	3.12	3.14	94.54	94.285
Ethane	7.939	7.992	8.921	8.934	0.416	0.424
Propane	3.015	3.036	3.902	3.895	0.194	0.203
i-Butane	0.48	0.589	0.621	0.725	0.057	0.057
n-Butane	0.746	0.579	1.005	1.025	0.148	0.145
i-Pentane	0.22	0.23	0.497	0.497	0.078	0.092
n-Pentane	0.191	0.202	0.356	0.361	0.094	0.104
Hexanes plus	0.326	0.353	1.077	1.060	0.592	0.582
Total	100.000	100.000	100.000	100.000	100.000	100.000
Gross Calorific value, Btu/ft^3	1063.7	1063.8	1210.6	1212.4	96.4	99.3
H_2S, ppm (V)	10.2	9.7	1.2	1.5	158.2	142.5

Table 2. Total mercury concentration in gas samples along sweetening process

Sample Point	Location	Total mercury, $\mu g/Sm^3$
G-OIS-Tr1	Production separator Tr1	6.2 ± 0.56
G-OIS-Tr2	Production separator Tr2	5.6 ± 0.31
G-BSA-Tr1	Sweet gas Tr1	11.2 ± 0.73
G-BSA-Tr2	Sweet gas Tr2	10.6 ± 0.45
VG-BR-Tr1	Vent gas Tr1	15.3 ± 1.2
VG-BR-Tr2	Vent gas Tr2	21.6 ± 0.64

Table 3. Physical and chemical properties of carbonate solution

	Rich Benfield Solution		Lean Benfield Solution	
	RCS-Tr1	RCS-Tr2	LCS-Tr1	LCS-Tr2
Density at 60 °F, g/ml	1.2119	1.2199	1.2375	1.2529
CO_3^{2-}, wt%	4.501	6.886	13.679	13.005
HCO_3^-, wt%	15.559	11.044	5.75	3.474
H_2S content, ppm	34.9	58.0	12.902	14.632

Table 4. Total mercury concentration in Benfield solution and water samples along sweetening process

Sample Point	Location	Total mercury, ng/g
LCS-Tr1	Lean Benfield Tr1	< 0.1 (Nil)
RCS-Tr1	Rich Benfield Tr1	151.4 ± 5.6
LCS-Tr2	Lean Benfield Tr2	< 0.1 (Nil)
RCS-Tr2	Rich Benfield Tr2	175.4 ± 7.2
W-BRD-Tr1	Water Reflux Drum Tr1	122.1 ± 3.2
W-BRD-Tr2	Water Reflux Drum Tr1	118.0 ± 4.7

Table 5. Concentration of the major phases in sludge and solid samples collected from sweetening process

Phase	Sludge Tr1	Solid
	S-SACTr1, Wt %	S-SCR, Wt %
Moisture	10.53	5.4
Organic Matters	50.36	0.59
$CaCO_3$	3.83	0.0
$MgCO_3$	0.40	1.39
HgS	8.22	1.12
FeS	9.35	72.86
Silcates	4.44	3.22
Carbonceous matter	12.87	15.42
Total	100.00	100.00

The schematic diagram of the acidic gas removal unit is shown in Fig. 3. As shown in Fig. 1, the sour gas outlet from inlet separator enters into the bottom of the absorber and flows to the potassium carbonate. The sweetening has been occurring at 110 °C. The acid–rich potassium carbonate solution from the bottom of the absorber is flashed to a flash drum in regeneration package, where much of the acid gas is removed. The solution then proceeds to the stripping column, which operates at approximately 100 °C and near-atmospheric pressure. The low pressure combined with a small amount of heat input leads to drive off the remaining acidic gases, and the lean potassium carbonate from the stripper is pumped back to the absorber (Mokhatab, 2006).

Gases from Sweetening Process

The gas outlet from production separator (G-OIS-Tr1 and G-OIS-Tr2) contain high concentrations of CO_2, which is the main component of the acid gases. The concentrations of CO_2 are 9.660 mole% and 9.767 mole % in train-1 and train-2, respectively. Also, The concentrations of H_2S for the two trains about 10 ppm as reported in Table 1. Therefore, these gases refer as sour gas that must be treated to remove excess of acid gases to meet natural gas specifications. Moreover, the total mercury concentration of producing gases are 6.2 $\mu g/Sm^3$ and 5.6 $\mu g/Sm^3$ for train-1 and Train-2, respectively. These Hg° concentrations of inlet separators are higher than the

previous study, it may be due to entering a new wells to process or as resulting of variation of the wells (Ezzeldin *et al.*, 2016 and Ryzhov *et al.*, 2003). CO_2 concentrations in treating gases (sweet gas) as shown in table 1 decrease from 9.767 mole% to 3.140 mole% Tr-2, also, H_2S contents decease from 10 ppm to 1.2 ppm. The concentrations of CO_2 and H_2S in treating gas samples are in agreement with the pipeline specification limits. In other words, the Benfield solution removes up to 65 % of the original CO_2 and 88% of H_2S. Accordingly, one may conclude that calorific value increases and the sweetening process are working properly. Total Hg° concentrations of treated gases are 11.2 µg/Sm^3 and 10.6 µg/Sm^3 for Tr-1 and Tr-2, respectively. These Hg° concentrations of sweet gases are higher than those of gas outlets from the inlet separators, these data agree with the previous results due to Hg° transferring from the condensate processing area into gas processing line (El Naggar *et al.*, 2015; Ezzeldin *et al.*, 2016; Mohamed B. Masod, 2011). Also, Foster *et al*. reported that mercury can be transferred throughout the plant during the processing of hydrocarbons.

In the regenerator, CO_2 is driven out of the carbonate solution because of its lower partial pressure in the acid gas relative to the corresponding equilibrium pressure of the carbonate solution. The regenerator column runs at near atmospheric pressure and is heated to 112 °C using hot oil. The sudden reduction in pressure in the regenerator flashes a large amount of the acid gases on the tray of the regenerator. The steam from the reboiler passes up the packed column and strips CO_2 and H_2S from the solution. The steam provides heat to convert $KHCO_3$ back to K_2CO_3 as shown in equation (1). The vent gases are composed mainly of carbon dioxide (94.540 mole% and 94.285 mole% for Tr-1 and Tr-2 respectively). Moreover, H_2S contents for vent gases Tr-1 and Tr-2 are 158.2 ppm and 142.5 ppm, respectively.

The acidic gases (CO_2 and H_2S) have been vented to atmosphere without any further treatment, which reflects the bad impact on the environment. Accordingly, one may recommend that vent gases must be separated CO_2 to decrease its impacts on the environment and also removed H_2S by conversion to elemental sulfur by built the process achieving this function (Claus process). Total Hg° concentration for vent gas samples VG-BR-Tr1 and VG-BR-Tr2 are 15.3 µg/Sm^3 and 21.6 µg/Sm^3, respectively. The high content of mercury could be attributed to the low solubility of elemental mercury in Benfield solution. Moreover, the adsorbed mercury on metallic surfaces, solid materials, and sludge could be desorbed by heating and depressurizing of the rich solution in the regeneration process. This leads to the association of the elemental mercury with the vent gases. Moreover, these vent gases, which are emitted directly to an atmosphere, could cause an environmental pollution problem.
It is known that nature of mercury, even in minimum quantities, has an extremely toxic effect on humans and endangers the entire ecological system (Špiric *et al.*, 2000 and Wilhelm, 1999)

Carbonate solution and water from sweetening process

The rich carbonate solution (RCS) obtained after passing the sour gas over it. The Physico-chemical properties of rich carbonate solutions are shown in Table 3. The RCS is composed mainly of bicarbonate ions (HCO_3^-) and a small amount of carbonate ions (CO_3^{2-}) for the both trains as shown

in table 3, RCS also contains trace amount of dissolved H_2S. This reflects the efficiency of the Benfield carbonate solution. Therefore, these solutions must be regenerated to convert the bicarbonate to carbonate and liberate CO_2 and H_2S as vent gases. The lean carbonate solution (LCS) is that obtained after regeneration and able to remove acid gases. From Table 3, It is obvious that carbonate ions are predominate ions. This means that, the regeneration process is working properly and this carbonate solution able to recycle in the absorber tower to eliminate acid gases. H_2S content in LCS is less than its content in RCS due to H_2S is stripped in the regeneration by emitting with vent gases and could be absorbed in solids.

Total Hg concentrations of rich Benfield solution are 151.4 ng/g and 175.4 ng/g for RCS-Tr1 and RCS-Tr2 respectively as shown in Table 4. But, lean Benfield solution samples (LCS-Tr1 and LCS-Tr2) free of mercury due to the regeneration process. This indicates that, mercury removes or adsorbs in the regeneration process via vent gas and water. The major redistribution of mercury compounds in the process occurring by the pressure and temperature changes (Edmonds *et al.*, 1996). The water outlet from the reflux drum (W-BRD-Tr1 and W-BRD-Tr2) is a water of condensation from the overhead reflux system at the Benfield regeneration package. This water is returned to the wash trays on the top of the column. Total Hg concentrations of W-BRD-Tr1 and W-BRD-Tr2 are 122.1 ng/g and 118 ng/g as shown in Table 4. Although the water sample is due to condensation, but it has high mercury concentration. This is because water is washing the regeneration column, which may be highly contaminated with mercury.

Solid samples collected from sweetening process

Sludge from absorber column Tr-1 (C-2621) and solid from steam condensate reboiler (E2623) in the regeneration package of sweetening process are shown in Table 5. The sludge and solid samples have a significant amount of mercury sulfide reaches to 8.22 weight% in S-SACTr1. Also, ferric sulfide reaches to 72.86 weight% for solid sample. It found that the major phases, in inorganic matrices, were ferric sulfide, mercuric sulfide and silicates. These results proved Leeper *et al* mechanism, where H_2S can react with iron oxide (resulted from the corrosion of pipes). Afterwards, mercury sulfide precipitates and adsorbs onto the pipe wall.

$$H_2S + Fe_2O_3 \rightarrow 2FeO + S + H_2O \tag{3}$$

$$Hg + S \leftrightarrow HgS \tag{4}$$

Conclusion

Mercury was determined in fourteen samples (gas, Benfield solution, water, solid and sludge), which is all stream fluids in the Benfield solution process. Moreover, the bulk composition also determined for all samples for evaluating the performance of the process. The high mercury content in gas for this process found in vent gas (21.6 µg/Sm^3 for Train2 and 15.3 µg/Sm^3 for Train1). Vent gas, mainly composed of carbon dioxide and contaminates with H_2S and mercury, emitted to the atmosphere without treatment. Therefore, vent gas must be treated to control the emission of the impurities into the environment. Vent gas could be treated by separating carbon dioxide then remove H_2S using Claus process. Although, rich Benfield solution (composed mainly bicarbonate) was contaminated with mercury (175.4 ng/g for Train2 and 151.4 ng/g for Train1), but the lean Benfield solution free of

mercury, this indicates that mercury transfer from Benfield solution to another fluid. Total Hg concentrations in water samples collected from reflux drum are 122.1 ng/g and 118.0 ng/g for train1 and train2, respectively. In addition, the solid sample collected has 72.86 weight% ferric sulfide and 1.12 weight% mercuric sulfide. Finally, the sludge sample collected from the regeneration stage has 8.2 weight% mercuric sulfide. Therefore, the workers must take all safety precaution when work in the sweetening process area.

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