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Research Article

Analysis Study of Available Alternatives for Mitigation of Aromatic Hydrocarbon Emissions from a Glycol Dehydration Unit

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A natural gas (NG) dehydration unit based on glycol absorption is considered one of the most important gas processing units, aiming to decrease water content and consequently adjust its dew point. However, during this process, not only water is absorbed by the glycol solvent, but also some aromatic compounds, including benzene, toluene, ethylbenzene, and xylene (BTEX), in addition to volatile organic compounds (VOC), are absorbed. These compounds are released during glycol regeneration into the atmosphere, resulting in environmental pollution and consequent catastrophic mental and physical health problems. This study aims to minimize BTEX emissions while ensuring efficient dew point control. Various strategies have been adopted to control BTEX emissions, but the present work focuses on optimizing operating conditions and investigating the influence of operational variables on BTEX emissions, as well as NG water content. LINGO optimization software and HYSYS (version 11) are used to find the plant's optimum conditions for minimizing BTEX emissions and satisfying efficient dew point control. Simulation results show that stripping gas, triethylene glycol (TEG) circulation rate, and inlet feed gas temperature significantly affect BTEX emissions. The proposed optimum operating conditions in this work resulted in a reduction in BTEX emissions by about 81% while satisfying the required NG dew point. Furthermore, two quadratic equations are developed based on regression analysis for efficient calculation of the BTEX emissions and water dew point at any operational variables.

1. Introduction

Dehydration aims to reduce natural gas water content, with environmental considerations focusing on reducing BTEX emissions. Efficient control of water content and hydrocarbon dew points in natural gas (NG) streams is crucial to prevent liquid drops and hydrate formation. Three primary methods include direct cooling, absorption, and adsorption with absorption are considered the most commonly used systems aiming to control the NG dew point [1–4].

Direct cooling using expansion or refrigeration with hydrate inhibitors is commonly used for pipeline gas production in mild-weather regions. Dehydration by adsorption, using porous solid desiccants like alumina, molecular sieves, and silica gels, removes water efficiently, though it has a high capital cost and significant pressure drop [5–7]. NG dehydration by glycol is a widely used process; it is a continuous liquid desiccant process involving selective absorption of water content from hydrocarbon streams, followed by thermal desorption of glycol, which is then regenerated or reconcentrated for further reuse [1, 3, 4].

Despite the wide spectrum of gas dehydration techniques, the glycol dehydration system is considered the most effective established gas dehydration technique due to the high hygroscopicity, low vapor pressure, excellent thermal performance, and moderate cost of glycols. It has been used in the industry for decades; the first commercial triethylene glycol (TEG) dehydration unit was developed and operated by a company in Texas known as BS&B in the early 1950s. TEG is proven to be the most efficient solvent for natural gas dehydration, making it a promising solvent in the industry [2, 7–18]. However, glycol NG dehydration process is usually associated with emissions of BTEX and VOCs. During the dehydration process, BTEX and VOC compounds present in wet gas are absorbed by glycol and consequently released to the atmosphere during the glycol regeneration process. The presence of small amounts of BTEX in the natural gas stream can result in very high concentrations in the vented stream [18–21].

BTEX compounds and VOC are irritants and carcinogens and they are considered hazardous air pollutants, as identified by the Environmental Protection Agency (EPA). These emissions have also been shown to cause blood disorders, in addition to considerable negative effects on central nervous system, reproductive system, and respiratory and neurological systems. Moreover, they cause severe foaming, flooding, a higher glycol loss rate, lower efficiency, and higher maintenance costs for absorbers during dehydration processes [22, 23].

BTEX compounds have been strictly monitored in several countries; the US government has included BTEX in its list of 189 hazardous air pollutants under the Clean Air Act Amendments of 1990. Different strategies could be applied to minimize BTEX emissions, such as incinerating emitted gases, adding a condensation unit, optimizing processes, and using less-absorbing glycol as a solvent [22, 24, 25]. Incineration is the most widely applied process used to eliminate BTEX gases [19, 25–27]. However, recent efforts focus on designing new processes, optimizing existing ones, and using less-BTEX absorbing solvents or alternative solvents instead of recovering BTEX compounds in water effluent due to the cost of post-treating of BTEX-containing water effluent [22, 24, 26, 28–31].

Many research studies have been done on gas dehydration units, but the previous research works were either focusing on increasing process efficiency or reducing emissions. Isa et al. [1] simulated three natural gas dehydration processes in an UAE industrial unit; they proposed adding potassium formate to the TEG solution as a new method to improve TEG-water absorption capacity. However, this increased the BTEX absorption rate and increased operational costs since it must be introduced externally. Abdulrahman and Sebastine [32] studied the use of different glycols to dehydrate natural gas; they found that TEG removes most water and absorbs more hydrocarbons. Their study highlighted the importance of controlling BTEX emissions in natural gas dehydration units due to their harmful effects on human health, but could not integrate the two objectives simultaneously. Hedayati Moghaddam [33] and Moghaddam et al. [34] investigated the performance of the wet natural gas dehydration process by absorption using liquid desiccant. Tazang et al. [35] presented an approach to accurately model the solubilities of BTEX in triethylene glycol (TEG).

Zong et al. [36] found that different recycling configurations for natural gas dehydration units do not significantly reduce water content or BTEX emissions, while requiring significant capital and operation costs. Their study also found that marginal reductions in total BTEX emissions are always accompanied by an increase in water content in dry product gas, while the total TEG loss rate is consistently reduced in all recycling configurations. Braek et al. [22] conducted a sensitivity analysis on five operating parameters (absorber temperature and pressure, regenerated TEG temperature, flash tank pressure, and regenerator reboiler temperature) of an NGDP in Abu Dhabi, UAE, revealing that optimal values have minimized emissions, resulting in 45–48% reduction in BTEX and VOC emissions. However, further reduction of these hazardous emissions is still needed.

Nemati Rouzbahani et al. [37] studied the impact of different operating parameters on BTEX emissions; they found that BTEX emissions from an NGDHP are highly sensitive to the lean DEG purity, while Darwish and Hilal [29] discovered that BTEX emissions are significantly influenced by lean TEG circulation rate and temperature. They also found that the stripping gas flow rate significantly impacts VOC emissions. Amouei Torkmahalleh et al. [38] examined the impact of solvent circulation rate, reboiler heat duty, stripping gas circulation rate, and lean TEG temperature on BTEX, VOCs, and CO2 emissions. Their results showed that increasing solvent circulation rate decreases dry gas moisture content to some extent, and if a solvent flow rate up to 9.25 GPM is used, the moisture content starts rising. On the other hand, Darwish and Hilal [29] found that increasing solvent flow rate could lead to a decrease in solvent purity due to chemical dissolution, and hence, moisture content decreases. Many works such as the research works of Amouei Torkmahalleh et al. [38], Hlavinka et al. [39], Braek et al. [22], and Sony et al. [40] have been directed toward studying the NG dehydration operating conditions. Siti et al. [41] studied the effect of operational parameters on the performance of natural gas dehydration process and an optimization of the operational parameters using symmetry process simulation software was carried out. Renanto et al. [42] described the process synthesis of a new configuration for natural gas dehydration using TEG, while Chong et al. [43] proposed a model based on an integrated simulation optimization approach for glycol dehydration systems aiming to reduce the total annual cost (TAC). Kharisma et al. [44] carried out an optimization of TEG dehydration process to minimize the TAC and improve the process efficiency. Mukherjee et al. [45] carried out an optimization of TEG dehydration process to determine the optimal operational conditions at which minimal BTEX emissions are obtained.

To date, no research work has succeeded to incorporate minimizing hazardous emissions with achieving the allowable percentage of water content efficiently. In the present study, the operating variables that affect water content and BTEX emissions are identified. A new optimization model is used to optimize NGDU operating variables in two technical ways using HYSYS V-11 and LINGO software V-18. The studied operating variables are TEG circulation rate, TEG reboiler temperature, stripping gas rate, and inlet feed gas temperature. Additionally, two novel correlations have been developed using regression analysis; the first correlation relates the water content in outlet gas to the studied operating conditions. The second correlation can facilitate the calculation of the amount of BTEX emissions evolved from the regenerator and the flash separator based on the operating conditions. The main objective of this work is to minimize BTEX emissions with efficient dew point control from NGDU, located in the Egyptian western desert. This study influences the operating conditions on BTEX emissions and the outlet gas dew point. The optimum operating conditions of the investigated NGDU aiming to minimize BTEX emissions and at the same time keep sales gas water dew point on spec have been identified. LINGO software version 18 is utilized for optimization in this study. LINGO is a robust tool specifically created for effectively constructing and solving linear and nonlinear mathematical optimization models. It boasts exceptional capabilities, being proficient in solving various types of optimization models.

Table 1: Wet gas compositions used as a feed of the investigated glycol unit.

Component	Mole %
Nitrogen	0.501
Methane	84.708
CO_2	1.753
Ethane	6.362
Propane	3.083
i-butane	0.740
n-butane	1.114
i-pentane	0.451
n-pentane	0.376
n-hexane	0.359
Benzene	0.011
n-heptane	0.162
Toluene	0.046
n-octane	0.088
E-benzene	0.004
p-xylene	0.005
m-xylene	0.005
o-xylene	0.003
n-nonane	0.081
n-decane	0.000
H_2O	0.148

2. Case Study

The case study on which this research paper is applied is NGDU located in the Egyptian Western Desert. The NGDU under consideration operates at an acceptable limit for each operating variable: stripping gas rate, TEG glycol circulation rate, inlet feed gas temperature, and glycol reboiler temperature. These variables are assumed to be varied in the range of 0.1–0.4 (MMSCFD), 2–10 (GPM), 25–40°C, and 190–205°C, respectively.

In the NGDU, the lean glycol and wet gas are contacted counter-currently in the contactor tower, where mass transfer takes place through eight bubble cap trays. The wet gas enters the tower from the bottom and exits from the top, while the lean glycol enters the tower from the top and exits from the bottom with absorbed water (water-rich glycol). Table 1 represents the gas composition of the wet gas that enters the glycol dehydration unit. The lean glycol is cooled prior to entering the top tray of glycol contactor by passing through the shell of the gas/glycol heat exchanger, where its temperature is reduced from 93.3°C to 57.78°C. The raising gas comes into intimate contact with the glycol as it flows across the bubble cap trays; as the gas flows from tray to tray ascending through the column, it comes into contact progressively with drier glycol, where the driest gas at the top of the column contacts the driest glycol. During this contact, TEG absorbs water as well as considerable amounts of BTEX from natural gas.

The dried gas leaving the contactor is passing through the tube side of the gas/glycol heat exchanger to cool down the inlet lean glycol. Consequently, the gas temperature is raised from 52 to 53°C, then left as dry gas with a water content in the range of 1–5 Lb/MMSCFD. The lean glycol is pumped to the gas/glycol heat exchanger via two triplex reciprocating plunger pumps. The rich glycol leaving the contactor is loaded with water vapor and should be regenerated. So, it is passed through the reflux coil in the still column; the water vapor coming out of the still column exchanges heat with the rich glycol passing through the reflux coil. The temperature of water vapor coming out of still column will decrease, and consequently, any contaminated glycol escaped with glycol will be condensed and recovered. The rich glycol will gain some heat at the same time, and its temperature will increase from 57 to 65°C; this temperature increase in the rich glycol in the reflux coil helps to flash off most of the soluble gases in the flash separator. The degassed warm glycol is first filtered through a particulate filter to remove any particulate matter and then flows through a full-flow charcoal filter to remove any trace amounts of hydrocarbon liquid.

The rich glycol goes through the tube side of lean/rich glycol exchanger to be heated up from 65 to 175°C. The rich glycol serves as a coolant for the regeneration equipment: firstly, to cool the overhead vapors in the still column and provide reflux liquid and secondly to cool the lean solution to a reasonable temperature for pumping. While providing process cooling, the rich glycol picks up heat, which reduces the heating load on the reboiler. In the regenerator, reboiling of the glycol takes place at atmospheric pressure, in which the temperature, ranged from 190 to 205°C, is maintained in the reboiler to establish the maximum concentration of TEG that can be attained thermally. The variation in reboiler temperature setting depends on glycol and sales gas periodic analysis, i.e., glycol concentration, sales gas dew point, and glycol pH.

The rich glycol that is preheated to approximately 163°C in lean/rich glycol exchanger flows into still column; a mixture of glycol and water vapor rising from the hot glycol in the reboiler flows through the stripping section of the packed distillation column. The hot vapor that is initially rich in glycol vapor strips the water from the inlet rich glycol. The vapors rising from the top of the stripper section are also very rich in glycol vapors; these vapors rise through the rectifying section of the column where the glycol and water streams are separated. Partial condensation of the overhead vapors by means of cooling coil at the top of the column generates reflux liquid, which establishes the correct temperature gradient in the still above the feed nozzle.

Since the operation of the still column is not sensitive to minor upsets or variations in conditions, the lean glycol of 99 wt% flows to stripping column where further stripping takes place. The lean glycol flows from top to bottom through packing media, and the striped gas flows from bottom to top for further stripping any trace of water to get a lean glycol with a concentration of 99.5 wt%.

At the completion of regeneration, the fully concentrated hot lean glycol flows to the shell side of the lean/rich glycol exchanger where the lean hot glycol of temperature ranging from 190 to 205°C gives some of the heat to the rich glycol that is coming out of the exchanger at 93°C. The lean glycol then flows to the accumulator above the reboiler, where the hot lean glycol flows to the suction of the circulation pump. Figure 1 shows the process flow diagram for the predescribed natural gas dehydration unit.

3. Research Methodology

The present study considered NGDU located in the western desert as a case study to obtain the optimum operating conditions that minimize BTEX emissions while keeping sales gas on specifications. The experimental data were collected from data log that summarizes different operating parameters of the mentioned NGDU throughout the year during summer and winter seasons. The HYSY program as a simulation tool was applied to the existing plant, and the sensitivity analysis was carried out to study the effect of different operational conditions on BTEX emissions and sales gas water content. Then, the simulation results will be validated to show the agreement degree between the experimental and simulation results. Optimization of the investigated operating variables will be done to achieve the optimum operating conditions, which correspond to the minimum BTEX emissions and keep the water content of sales gas within the required specifications.

The research methodology of the present work follows the following steps:

Step 1: experimental data are collected from an existing NGDU located in the western desert concerning the operating variables, natural gas water content, and quantity of BTEX emissions.

Step 2: simulation of the considered case study using HYSYS (version 11) simulation software carries out sensitivity analysis to study the effect of different operational conditions on BTEX emissions and sales gas water content.

Step 3: simulation results from the constructed model are validated by comparing these results with actual results collected from the field.

Step 4: the impact of operating variables on BTEX emissions and water content is studied.

Step 5: optimum operating conditions that correspond to the minimum BTEX emissions and keep the water content of sales gas within specifications are obtained using two different methods.

Step 6: developing two correlations to calculate the BTEX emissions and sales gas water content depends on the operating conditions.

4. Validation of Simulation Results

To ensure the accuracy and reliability of our simulation results for the case study, it is crucial to conduct a comparison between these results and the experimental findings. This analysis allows us to gain insights into how operational conditions impact BTEX emissions and the water dew point in the regeneration unit. By studying the influence of each operating variable while maintaining constant values for the others, a comprehensive understanding of their individual effects could be obtained. As mentioned before, stripping flow rate, TEG circulation rate, inlet feed gas temperature, and TEG regenerator temperature are varied in the range of 0.1–0.4 MMSCFD, 2–10 GPM, 25–40°C, and 190–205°C, respectively.

Figure 2 depicts the experimental results compared to the simulation results for sales gas dew points under the specified operating conditions. It is evident that the simulation accurately predicts the gas dew points, as indicated by the excellent matching between the experimental and simulated dew points. The fitting line (x nearly equals y) demonstrates a high R-squared value of 0.9992, which is further confirming that Aspen HYSYS (version 11) simulation software is highly effective in estimating dew points and consequently determining the amount of BTEX emissions from the regeneration unit in question, within acceptable operational limits.

5. Results and Discussion

The present work aims to study the considered dehydration unit to minimize BTEX emissions. This can be achieved by first identifying and investigating the effect of operating parameters on BTEX emissions. HYSYS simulation software V11 is used to study this effect, and sensitivity analysis is applied to identify the operating parameters that have great effects on BTEX emissions. Then, these operating parameters are optimized to minimize BTEX emissions from TEG regeneration unit taking into consideration that the treated gas must fulfill the sales gas specifications. Optimum operating conditions are identified using LINGO optimization software (version 18) and compared to the optimum results of the HYSYS Program. Thus, the first part of the results is directed to investigate the effect of the plant operational conditions on BTEX emissions and natural gas water dew point. The second part of this section introduces two correlations for calculating natural gas dew point and BTEX emissions at any operating parameters included in the simulation range.

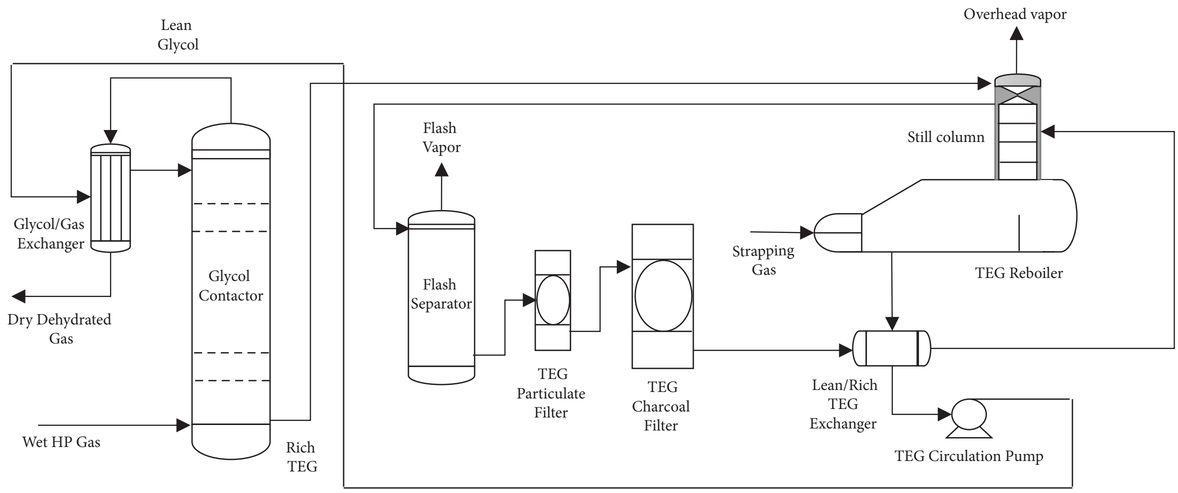

Figure 1: Process flow diagram for the considered natural gas dehydration unit.

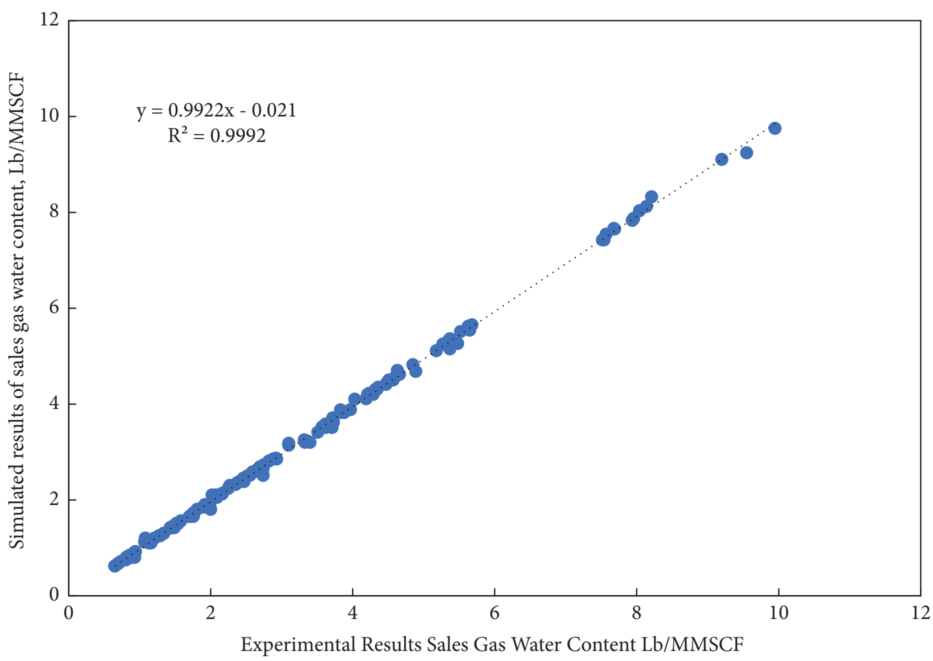

Figure 2: Comparison between experimental and simulated sales gas water content obtained at different operating conditions of the considered NGDU.

5.1. Effect of Operating Parameters on BTEX Emissions. To identify the optimum operating conditions of NGDU at which the BTEX emissions are minimized, the effect of the considered operating conditions on BTEX emissions and water dew point of the produced gases should be studied. These operating conditions include stripping gas rate, glycol circulation rate, inlet feed gas temperature, and glycol reboiler temperature. Regarding the considered case study, the effect of these operational conditions on BTEX emissions is studied using HYSYS V11 as a simulation tool. The studied stripping gas flow rates range from 0.1 to 0.4 MMSCFD (selected values are 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, and 0.4 MMSCFD). TEG circulation rate varies from 2 to 10 MMSCFD with selected values of 2, 4, 6, 8, and 10 GPM. Inlet-fed gas temperature selected values for this study are 25, 30, 35, 40, and 45°C, while TEG reboiler temperature is changed from 190 to 205°C with selected values of 190, 195, 200, and 205°C.

5.1.1. Effect of Stripping Gas Flow Rate. The utilization of stripping gas is essential for achieving exceptionally high glycol concentrations that cannot be achieved through conventional regeneration methods, which consecutively improve dehydration with more dew point depressions. After glycol regeneration, the stripping gas removes the residual water from the regenerated glycol. For the investigated case study, the introduction of stripping gas into the system is accomplished by utilizing a packed tower positioned between the reboiler and the storage tank. This allows the dry gas to effectively strip away any remaining water from the regenerated glycol. The glycol is heated in the reboiler, then flows downward through this section, coming into contact with the stripping gas, which facilitates the removal of excess water before being collected in the storage tank. The stripping gas is normally taken from the reboiler fuel gas (dry gas) line.

Figure 3 shows the effect of stripping gas flow rate on the BTEX emissions at different TEG flow rates with an inlet feed gas temperature of 25°C and TEG regenerator temperature of 190°C, while Figure 4 presents the effect of stripping gas flow rate on BTEX emissions at different TEG flow rates with an inlet feed gas temperature of 35°C and TEG regenerator temperature of 195°C. Regarding the simulation results of Figures 3 and 4, it is clear that the rate of emissions is increasing gradually with increasing TEG circulation rate and increasing the stripping gas flow rate leads also to increase these emissions. This behavior can be explained as increasing the stripping gas flow rate in the stripping column decreases the glycol vapor pressure and reduces the water vapor mixture, which facilitates the release of vapors including BTEX emissions. Also, recycling more quantity of glycol saturated with BTEX components will increase the chance of increasing BTEX emissions with the existence of stripping gas.

Additionally, the effect of stripping gas flow rate on BTEX emissions is studied at different values of inlet feed gas temperature as indicated in Figures 5 and 6. According to the simulation results of these two figures, it is noticed that by increasing stripping gas flow rate, BTEX emissions are increased, and in the same manner, increasing inlet feed gas temperature leads to increasing BTEX emissions. This can be interpreted as increasing the inlet gas temperature facilitate converting BTEX emissions from liquid to vapor state in which it can be easily separated in the regeneration package. It is also noticed that BTEX emissions are related to other operating conditions such as TEG rate and regenerator temperature. From Figures 4–6, it is clear that increasing TEG rate and inlet feed gas temperature leads to more BTEX emissions.

The effect of stripping gas flow rate on BTEX emissions at different values of TEG regenerator temperature is studied and the simulation results are presented in Figures 7–9. It is obvious that increasing stripping gas flow rate results in an increase in BTEX emissions. It is also noticed that TEG regenerator temperature has a small effect on gas stripping flow rate-BTEX emissions relationship at a lower TEG rate and a lower feed gas temperature as indicated in Figure 5. By increasing both TEG rate and feed gas temperature, BTEX emissions are highly increased by increasing the stripping gas flow rate. In addition, the effect of TEG regenerator temperature is noticeable until 0.25 MMSCFD stripping gas flow rate. At higher values of stripping gas flow rate, there is an insignificant effect of TEG regenerator temperature on BTEX emissions as described in Figures 7 and 9.

5.1.2. Effect of TEG Circulation Rate. TEG circulation rate is one of the most important parameters that have a great effect on BTEX emissions. The sensitivity analysis of TEG circulation rate influence on BTEX emissions is studied using HYSYS simulation results. Figure 10 displays the effect of TEG glycol circulation rate on BTEX emissions at different values of stripping gas flow rates with an inlet feed gas temperature of 30°C, and TEG regeneration temperature of 195°C. It is noticed that by increasing TEG circulation rate, BTEX emissions are increased. Furthermore, increasing of stripping gas flow rates leads to more increase in these emissions at all circulation rates as discussed earlier in section 5.1.1. Numerous studies, including those conducted by Nemati Rouzbahani et al. [37] and Braek et al. [22], have demonstrated the significant impact of solvent circulation rate, such as TEG, on BTEX emissions. Additionally, Braek et al. [22] and Amouei Torkmahalleh et al. [46] observed a similar relationship between solvent flow rate and BTEX emissions. These findings highlight the importance of careful managing the circulation rate of solvents to minimize BTEX emissions effectively. This effect can be attributed to that recycling more quantity of glycol saturated with BTEX components raises the chance of increasing BTEX emissions with the existence of stripping gas. It is also obvious from Figure 11 that BTEX emissions increase almost linearly with an increase in TEG flow rate; such trend agrees with other research works in the field of natural gas dehydration [22, 24, 28] and [31]. In situations where BTEX emission becomes a significant concern, it is advisable to reduce the flow rate of TEG. This will help in ensuring compliance with environmental regulations.

Figure 11 shows the influence of TEG circulation rate on BTEX emissions at different values of TEG regenerator temperatures. The stripping gas molar flow rate is fixed at 0.1 MMSCFD, while the inlet feed temperature is fixed at 30°C. The simulation results presented in Figure 11 show that increasing the TEG circulation rate leads to an increase in BTEX emissions. However, there is an insignificant effect of TEG regenerator temperature on BTEX emissions.

The effect of the glycol circulation rate on BTEX emissions at different values of inlet feed gas temperature is investigated at stripping gas flow rate of 0.2 MMSCFD, and TEG regenerator temperature of 190°C. According to the simulation results shown in Figure 12, it is clear that increasing inlet gas temperature has a significant effect on increasing BTEX emissions at all studied TEG circulation rates.

5.1.3. Effect of Inlet Feed Gas Temperature. It is worth mentioning that the current research work is the first work that studies the effect of inlet feed gas temperature on BTEX emissions. The sensitivity analysis for the effect of inlet feed gas temperature on BTEX emissions is studied at different values of stripping gas flow rates, TEG circulation rates, and TEG reboiler temperatures. Figure 13 shows the simulation results for the effect of inlet feed gas temperature on total emissions from TEG regeneration package at different values of TEG circulation rate with a stripping gas flow rate of 0.1 MMSCFD, and TEG regenerator temperature of 205°C. Regarding these results, it is obvious that increasing inlet feed gas temperature leads to an increase of BTEX emissions; and these emissions are increased more significantly by increasing TEG circulation rate. As it is known, BTEX are volatile

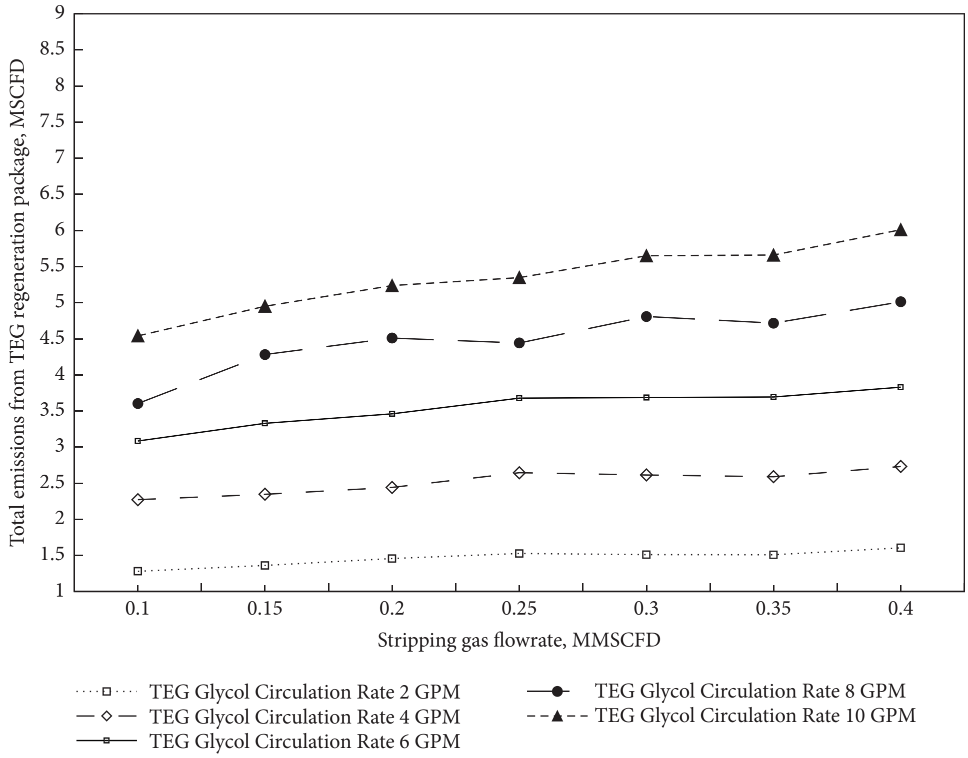

Figure 3: Effect of stripping gas rate on BTEX emissions at different values of TEG circulation rate when inlet feed temperature is 25°C and TEG regenerator temperature is 190°C.

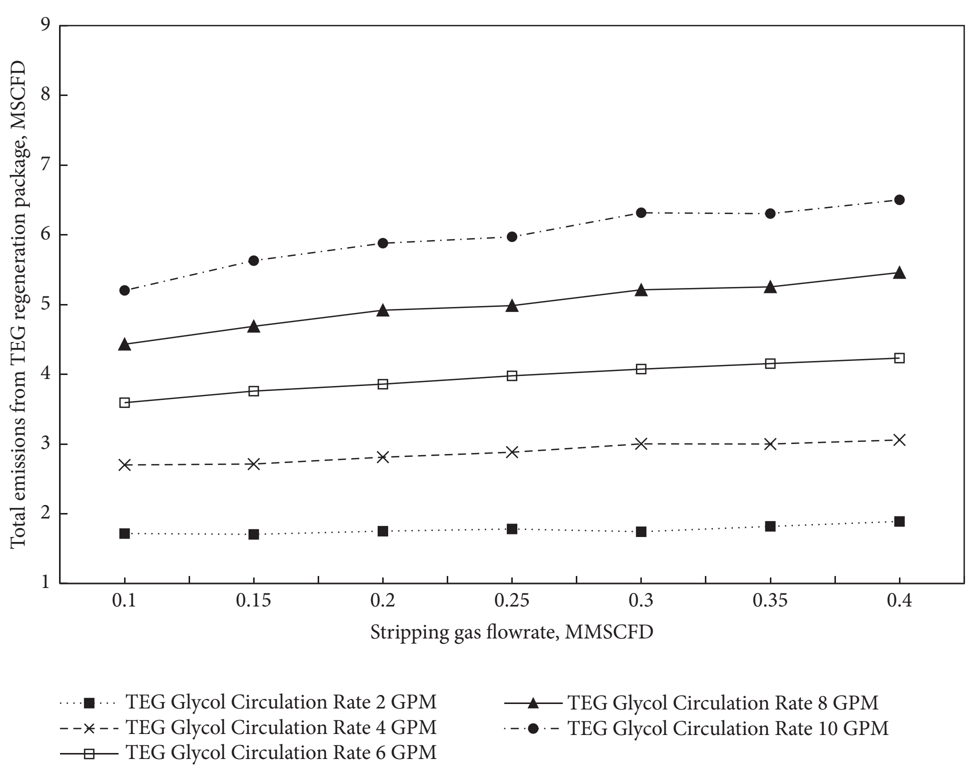

Figure 4: Effect of stripping gas flow rate on BTEX emissions at different values of TEG circulation rate when inlet feed temperature is 35°C and TEG regenerator temperature is 195°C.

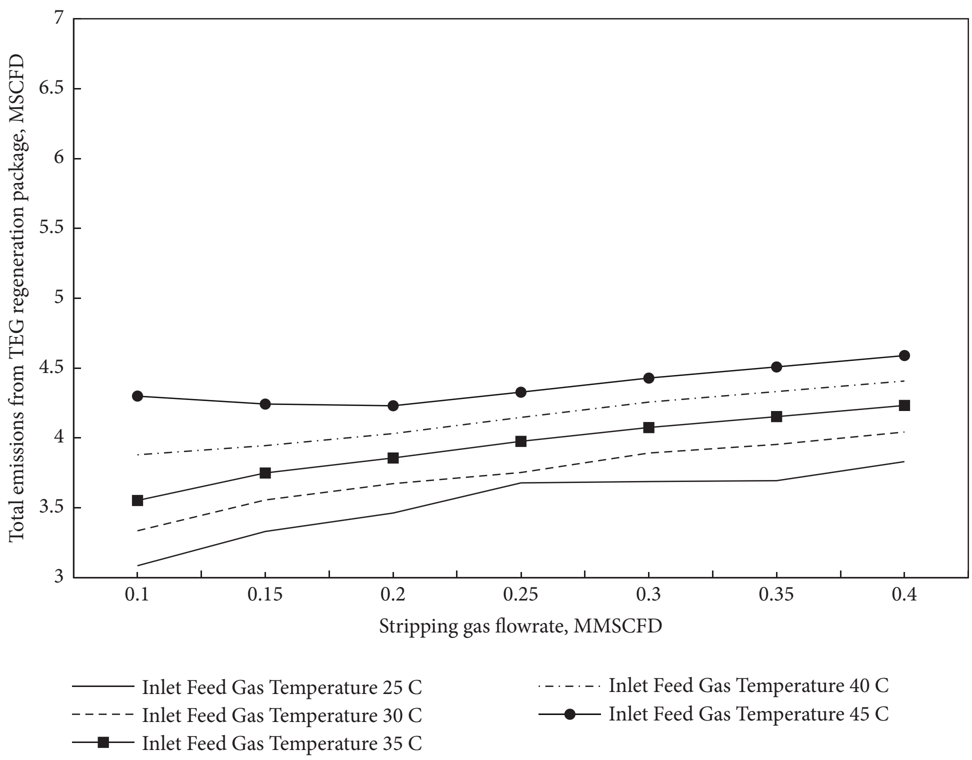

Figure 5: Effect of stripping gas flow rate on BTEX emissions at different values of inlet feed gas temperature when TEG circulation rate is 6 GPM and TEG regenerator temperature is 190°C.

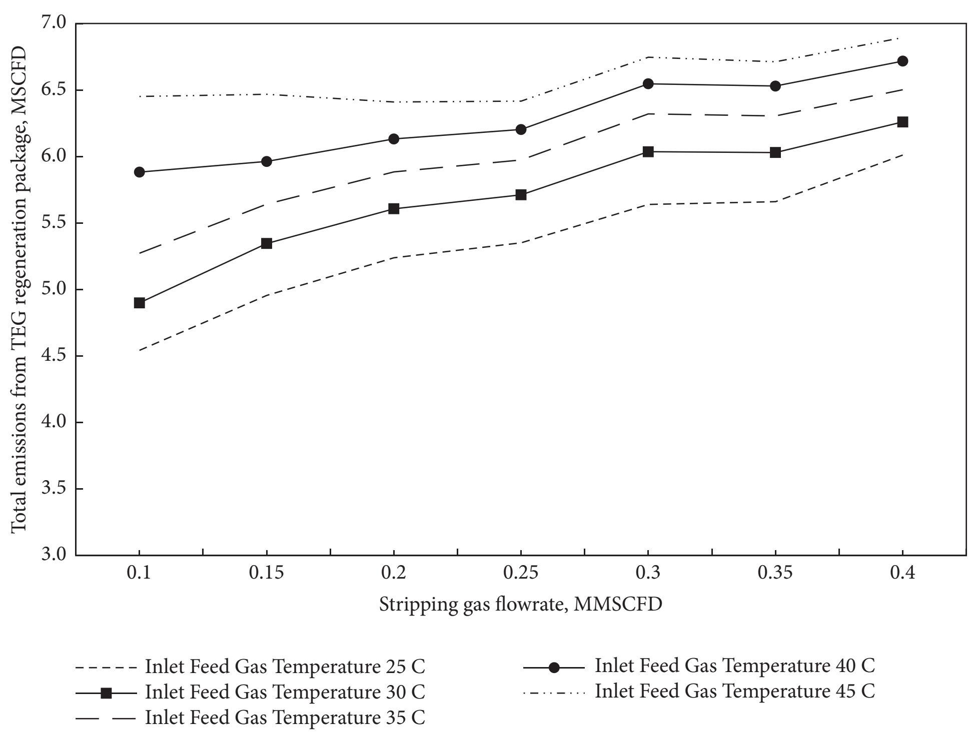

Figure 6: Effect of stripping gas flow rate on BTEX emissions at different values of inlet feed gas temperature when TEG circulation rate is 10 GPM and TEG regenerator temperature is 200°C.

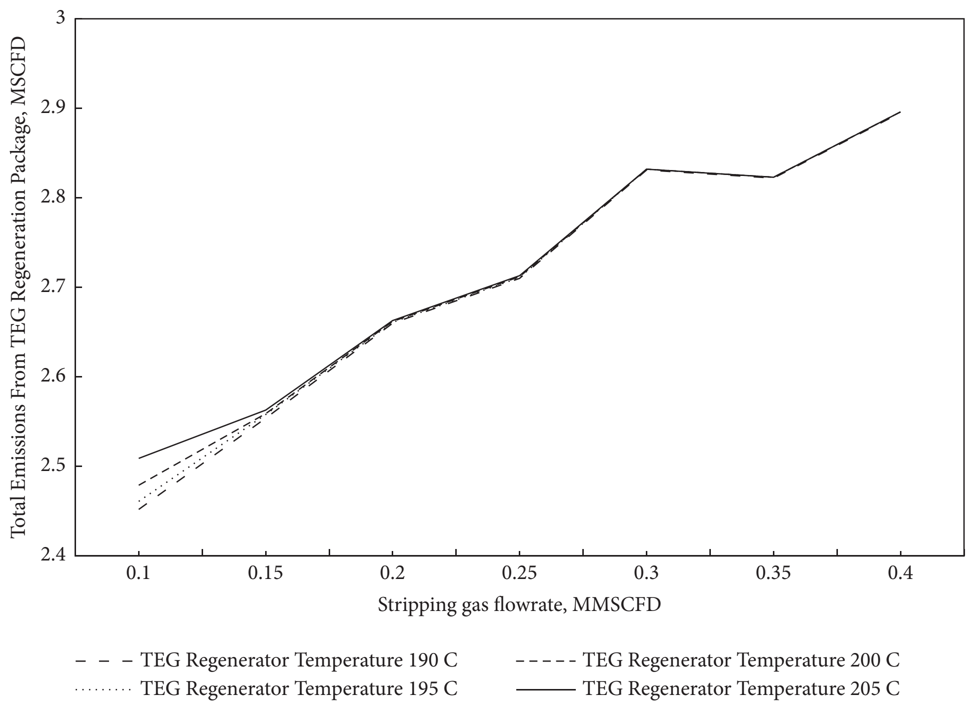

FIGURE 7: Effect of stripping gas flow rate on BTEX emissions at different values of TEG regenerator temperature when TEG circulation rate is 4 GPM and inlet feed gas temperature is 30°C.

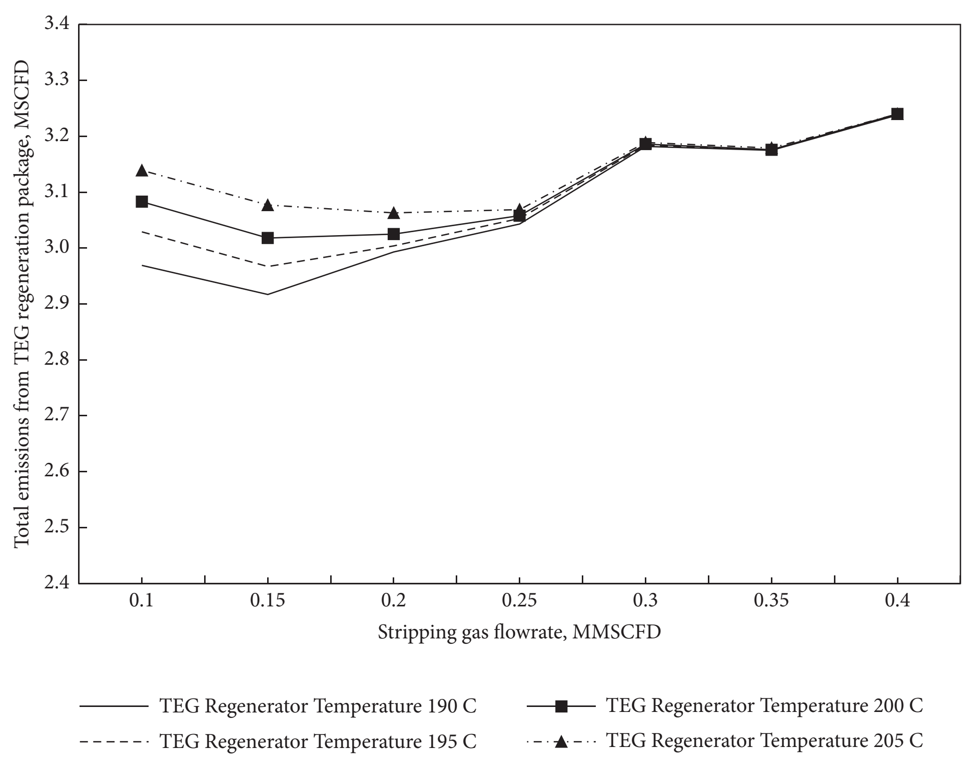

FIGURE 8: Effect of stripping gas flow rate on BTEX emissions at different values of TEG regenerator temperature when TEG circulation rate is 4 GPM and inlet feed gas temperature is 40°C.

compounds, and increasing inlet gas temperature facilitates the conversion of BTEX emissions from liquid to vapor state in which they can be easily separated in the regeneration package.

The influence of inlet feed gas temperature on total emissions at different values of TEG regenerator temperature, at stripping gas flow rate of 0.15 MMSCFD, and at TEG circulation rate of 4 GPM is presented in Figure 14. The

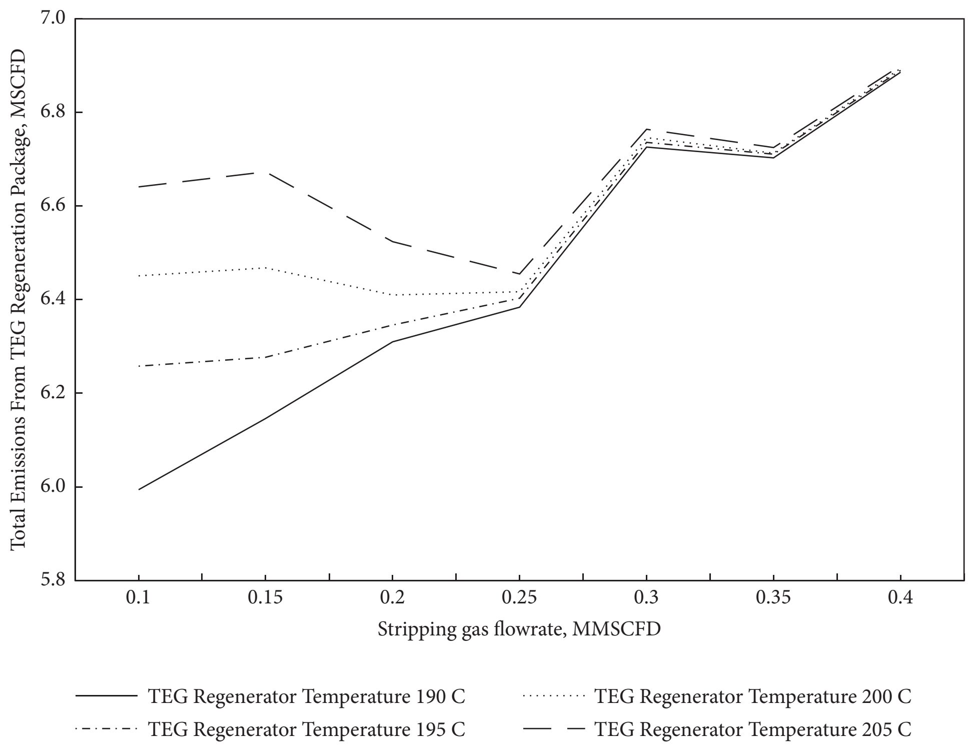

Figure 9: Effect of stripping gas flow rate on BTEX emissions at different values of TEG regenerator temperature when TEG circulation rate is 10 GPM and inlet feed gas temperature is 45°C.

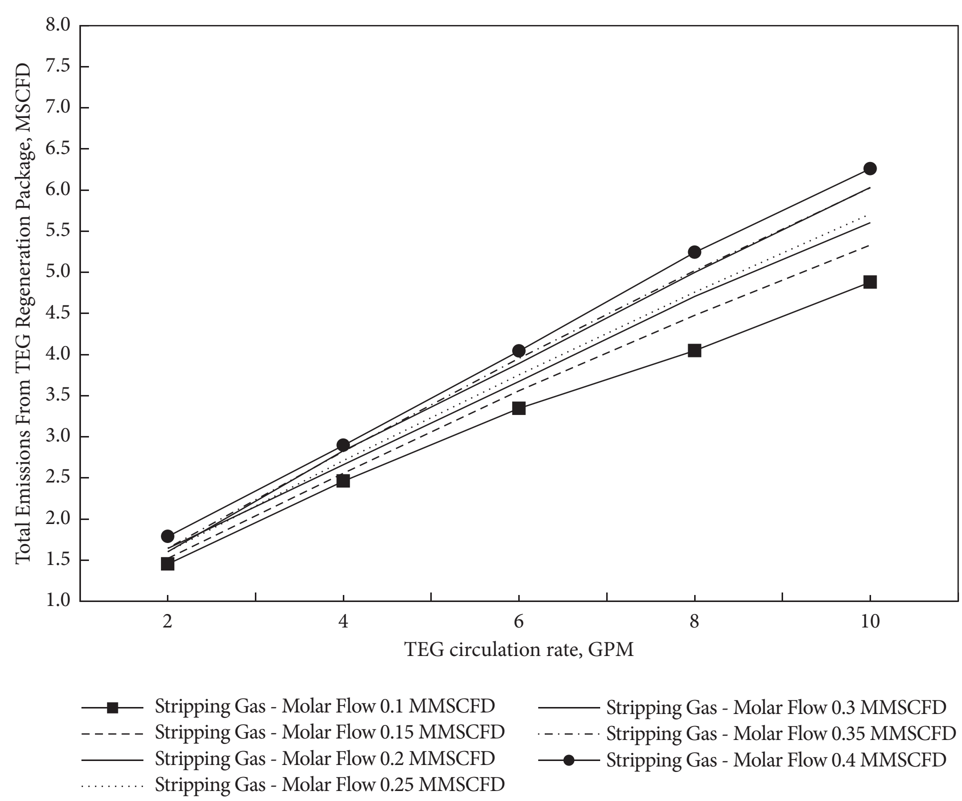

Figure 10: Effect of TEG circulation rate on BTEX emissions at different values of stripping gas flow rate, the feed gas temperature is 30°C, and regeneration temperature is fixed at 195°C.

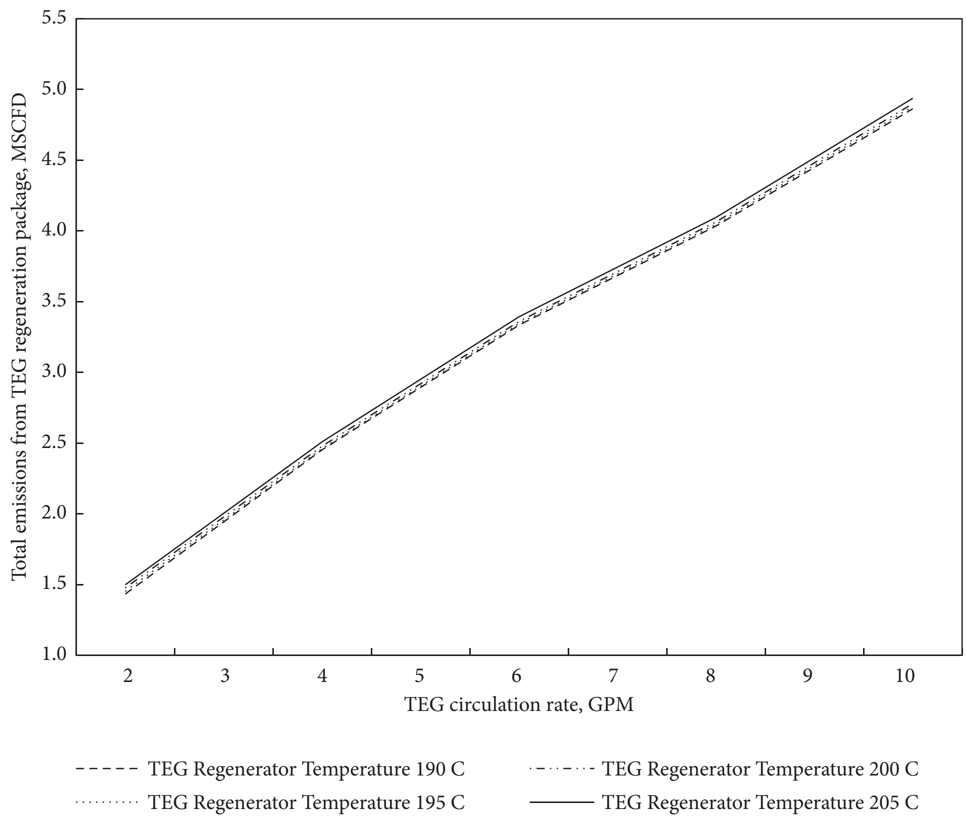

Figure 11: Influence of TEG rate on BTEX emissions at different values of regeneration temperature at stripping gas flow rate and inlet feed temperature of 0.1 MMSCFD and 30°C, respectively.

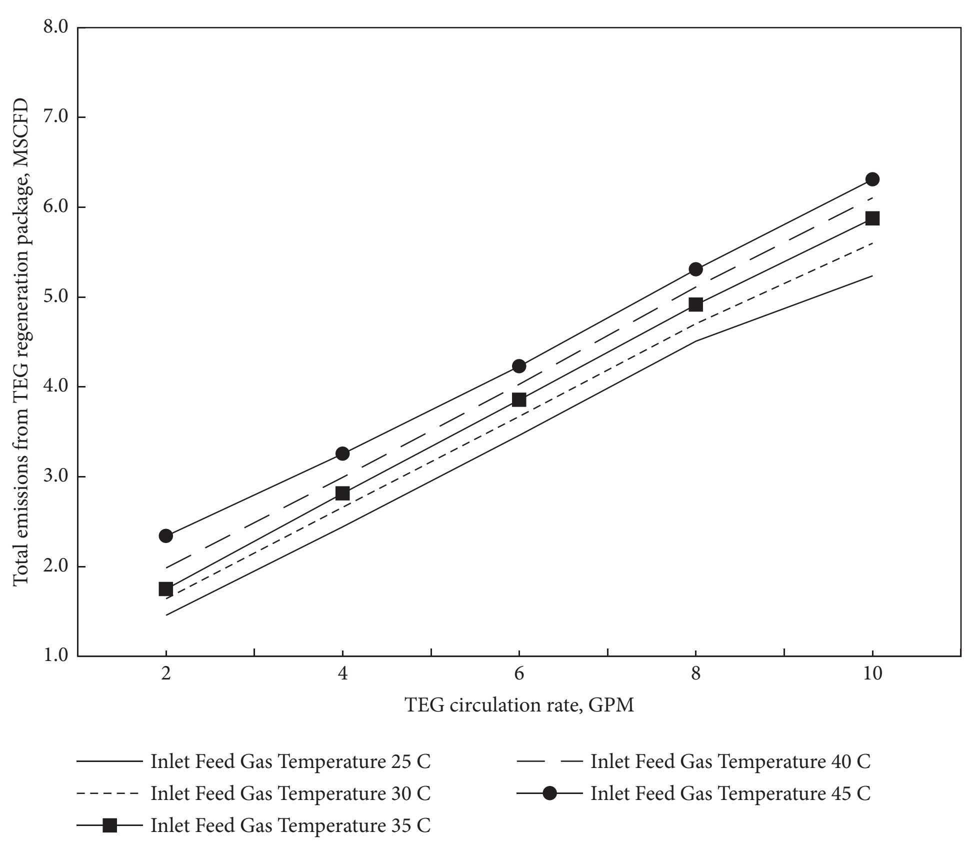

Figure 12: Effect of TEG circulation rate on BTEX emissions at different values of inlet feed gas temperature with a stripping gas flow rate of 0.2 MMSCFD, and a regenerator temperature of 190°C.

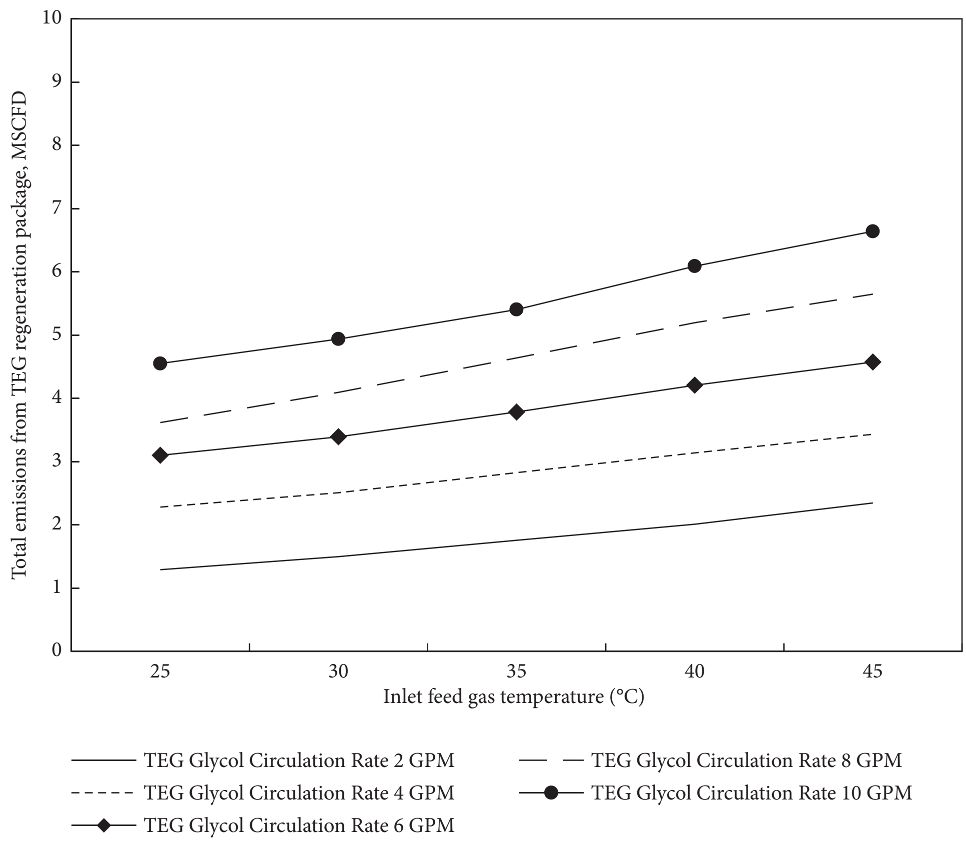

Figure 13: Effect of inlet gas temperature on regeneration package emissions at different values of TEG flow rate when stripping gas flow rate is 0.1 MMSCFD and regenerator temperature is 205°C.

simulation results of this figure show that increasing regeneration temperature has a minor effect on increasing BTEX emissions, and this effect appears only for inlet feed gas temperatures higher than 35°C. According to a study conducted by Braek et al. [22], it was found that the reboiler temperature does not have a significant impact on the emission level from the regenerator vent stream. This suggests that the performance of the regenerator is primarily determined by the stripping gas, rather than the boiling-off ratio of the reboiler. In other words, this means that BTEX emissions from the regenerator are more sensitive to stripping gas than reboiler temperature.

The effect of inlet gas temperature on total emissions at different values of stripping gas flow rate when TEG regenerator temperature is 190°C and TEG circulation rate is 8 GPM is displayed in Figure 15. The results indicate that the effect of inlet gas temperature on increasing BTEX emissions is highly influenced by the stripping gas quantity. Increasing stripping gas quantity leads to more BTEX emissions.

5.1.4. Effect of TEG Regenerator Temperature. The sensitivity analysis for the effect of TEG regenerator temperature on BTEX emissions is studied at varying values of stripping gas flow rate, TEG circulation rate, and inlet feed gas temperature.

The effect of TEG regenerator temperature on total emissions from TEG regeneration package at different values of TEG glycol circulation rate is investigated at a stripping gas molar flow rate of 0.4 MMSCFD and at an inlet feed gas temperature of 45°C as displayed in Figure 16. The simulation results show that the TEG regenerator temperature has a minor effect on BTEX emissions, while increasing TEG circulation rate has a high influence on increasing BTEX emissions, as previously discussed.

Figure 17 shows the effect of TEG regenerator temperature on total emissions at different values of inlet feed gas temperature when stripping gas molar flow rate of 0.4 MMSCFD and TEG circulation rate of 4 GPM are used. It is noticed from the results that TEG regenerator temperature still has a minor effect on BTEX emissions, but on the other hand, these emissions are increased by increasing the inlet feed gas temperature. It is also noticed that BTEX emissions are significantly affected by the TEG circulation rate compared to the effect of the inlet feed gas temperature.

At an inlet feed gas temperature of 25°C and TEG circulation rate of 8 GPM, the effect of TEG regenerator temperature on the considered emissions from the TEG regeneration package at different values of stripping gas flow rate is studied and the results are presented in Figure 18. According to these simulation results, as expected, the TEG regenerator temperature has a minor effect on the BTEX emissions, while these emissions are increased by increasing

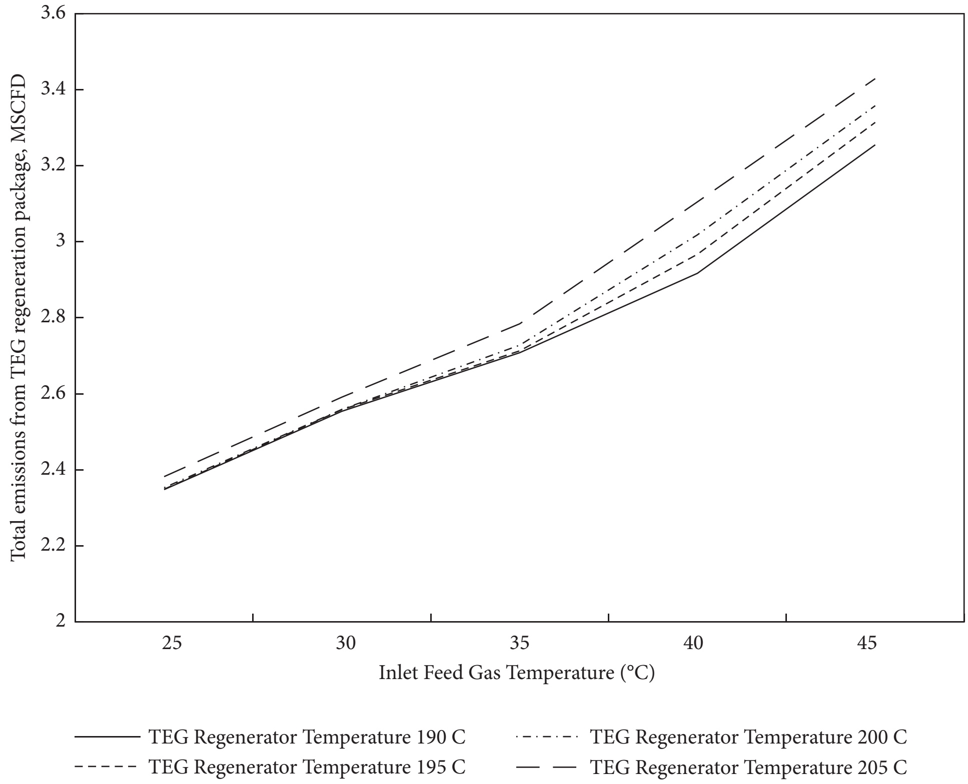

Figure 14: Influence of inlet gas temperature on regeneration package emissions at different values of regenerator temperature, at stripping gas flow rate of 0.15 MMSCFD, and at TEG flow rate of 4 GPM.

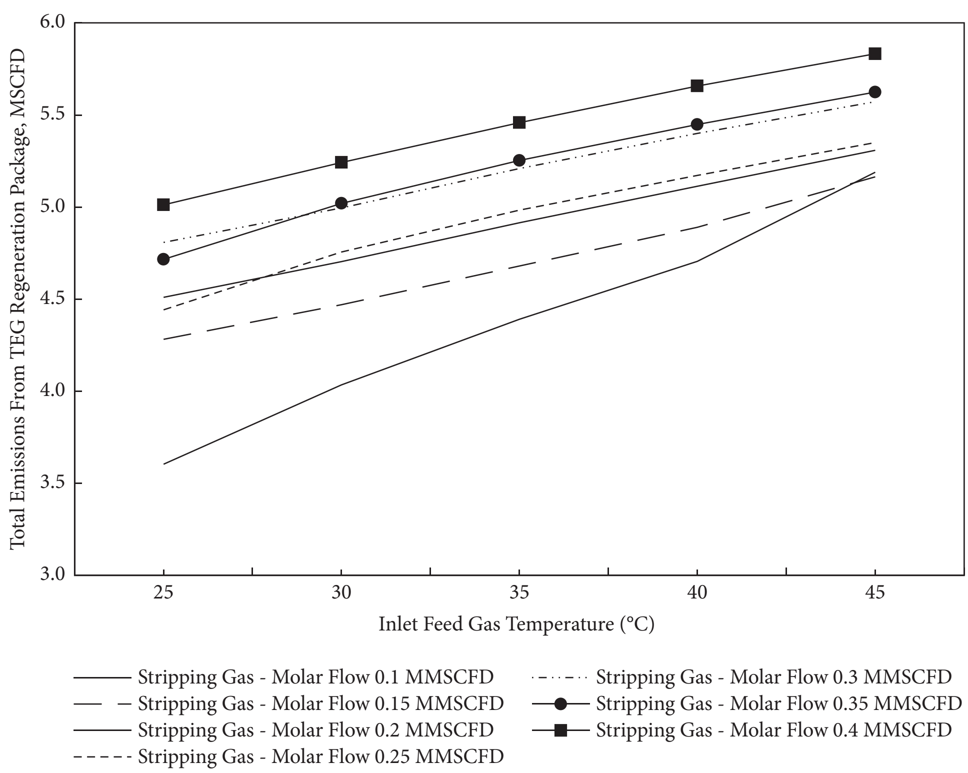

Figure 15: Influence of inlet gas temperature on regeneration package emissions at different values of stripping gas flow rate when at regenerator temperature of 190°C and TEG flow rate of 8 GPM.

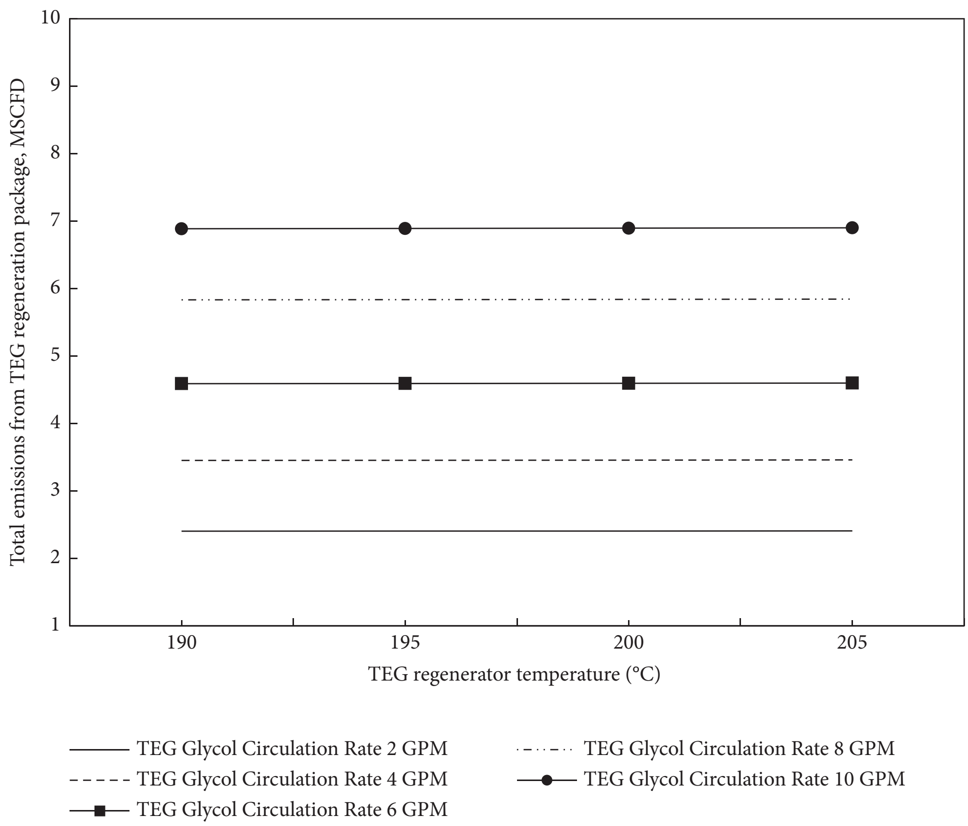

FIGURE 16: Effect of TEG regenerator temperature on total emissions at different values of TEG flow rate, at a stripping gas flow rate of 0.4 MMSCFD, and at an inlet feed gas temperature of 45°C.

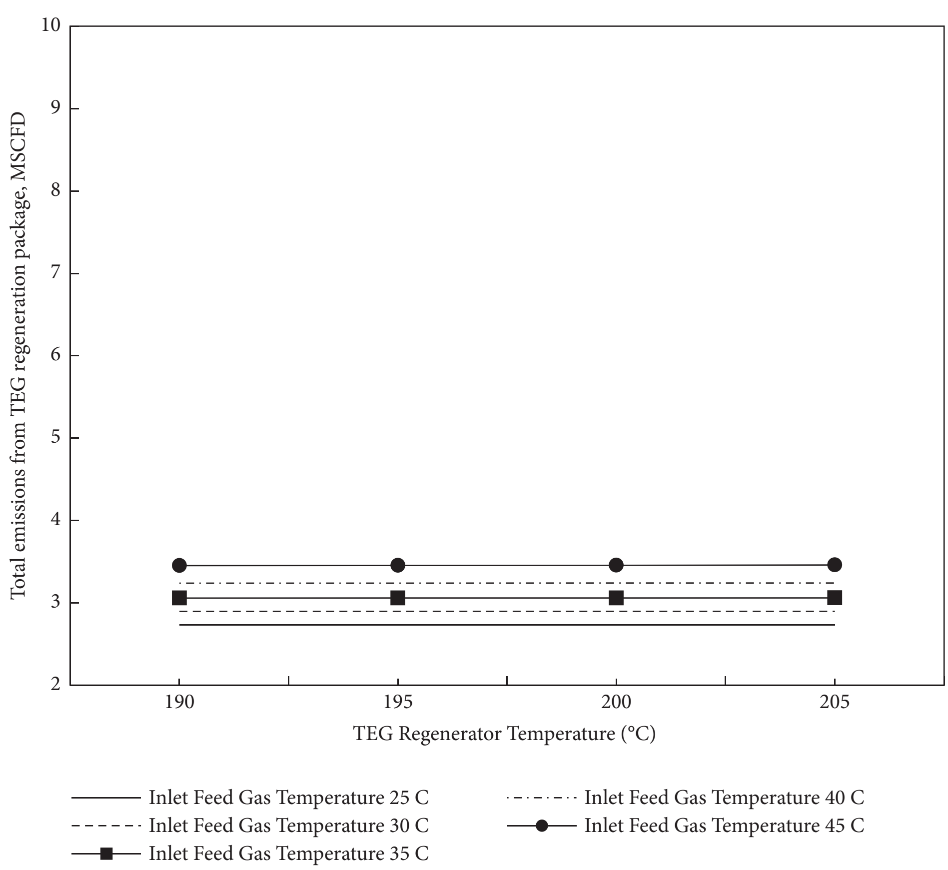

FIGURE 17: Effect of TEG regenerator temperature on total emissions at different values of inlet feed gas temperature when using a stripping gas flow rate of 0.4 MMSCFD, and a TEG flow rate of 4 GPM.

the stripping gas flow rate. Regarding the previous results, the effect of operating variables on BTEX emissions takes place in the order that TEG flow rate has the highest influence compared to the stripping gas flow rate, which in turn has a higher effect than the inlet feed gas temperature.

Amouei Torkmahalleh et al. [38] observed that the influence of the reboiler duty, which is related to the regenerator temperature, is insignificant with a slight increase in BTEX emissions observed with increasing the regeneration temperature. However, it is noted that at lower reboiler duty values, the influence of the reboiler duty on BTEX emissions is more significant. The same trend can be observed for the amount of BTEX absorbed in the solvent, which means that the amount of BTEX absorbed by the solvent is increased at lower reboiler duty. A similar pattern was observed by Darwish and Hilal [29], as well as by Braek et al. [22] research works, in which BTEX emissions are nearly insensitive to the reboiler duty changes. Thus, according to the current study and other research works, the reboiler temperature has insignificant effects on the emissions from the regenerator vent stream. This means that the performance of the regenerator is governed totally by the stripping gas flow rate rather than the boiling-off ratio of the reboiler as presented in Braek et al. [22] research work. This means that BTEX emissions from the regenerator are more sensitive to stripping gas than reboiler temperature.

5.2. Developing Correlations for Calculating BTEX Emissions and Sales Gas Water Content. One objective of the present work is to introduce two correlations, which can be used to represent the effect of the independent variables (stripping gas flow rate, TEG circulation rate, inlet feed gas temperature, and TEG regenerator temperature) on both BTEX emissions and sales gas water content. Regression analysis is a statistical method employed to determine and quantify the relationships among variables, based on empirical data obtained through experiments. The analysis of variance (ANOVA) test is utilized to ascertain the significance of these correlations. The two derived correlations for estimating BTEX emissions (in MSCFD) from TEG regeneration unit and sales gas water content (in Lb/MMSCF) are presented in the following equations:

$$\text{BTEX emissions} = -2.3594 + 2.6945\,A + 0.5176\,B + 0.0438\,C + 0.00545\,D - 1.2639\,A^2, \tag{1}$$

$$\text{Sales gas water content} = -9.1658 - 10.8903\,A - 0.1196\,B + 0.3489\,C + 0.0213D + 6.9775\,A^2, \tag{2}$$

where A is the stripping gas flow rate in MMSCFD, B is the TEG circulation rate in GPM, C is the inlet feed gas temperature in °C, and D is the TEG regenerator temperature in °C. The statistical test used to assess the match between the experimental data and correlations is the R^2 test. This test assigns a value between 0 and 1, representing the predictive power of the model Lazic [47]. A higher R^2 value indicates a stronger representation of the experimental data, as demonstrated by Mapiour et al. [48]. In this case, the first correlation has R^2 value of 0.99, while the second correlation has R^2 value of 0.90. These results indicate a high level of agreement between the experimental data and correlations. This consequently proves that the two introduced equations are valid within the limits of the studied operating conditions.

These two introduced correlations involve no complex expression, and they can be easily used by process engineers or other workers to predict the natural gas water content and the amount of BTEX emissions. Obtaining correlations to calculate BTEX emissions were not addressed in previous research works. That is why, as a novelty, the present study introduced a correlation to determine the sales gas water content. Correlations extracted by Bahadori and Vuthaluru [49] used tuned coefficients and many assumptions should be assumed to determine the natural gas dew point. However, the extracted correlations of the current study can be used to obtain the sales gas dew point by using a simple calculator at any operating parameters of the NGDU plant.

5.3. Operating Conditions Optimization. The glycol dehydration process can be enhanced through system optimization, which involves adjusting the operating parameters. This technique serves as a pollution prevention measure in the industry. One of the major objectives of this work is the optimization of the considered dehydration plant to define the optimum operating conditions that achieve the following two goals:

(1) Minimizing BTEX emissions from TEG regeneration package can be considered an environmental issue.
(2) Reduction of natural gas water content to be in the acceptable value required for the desired sales gas specifications, and this can be considered an operational issue.

In the present work, the operating parameters are optimized by using two different methods to achieve minimum BTEX emissions from NGDU regeneration package while keeping the sales gas water content at the desired value (less than 4 Lb./MMSCFD). The first method is LINGO optimization software (version 18), while the second method is using HYSYS program (version 11).

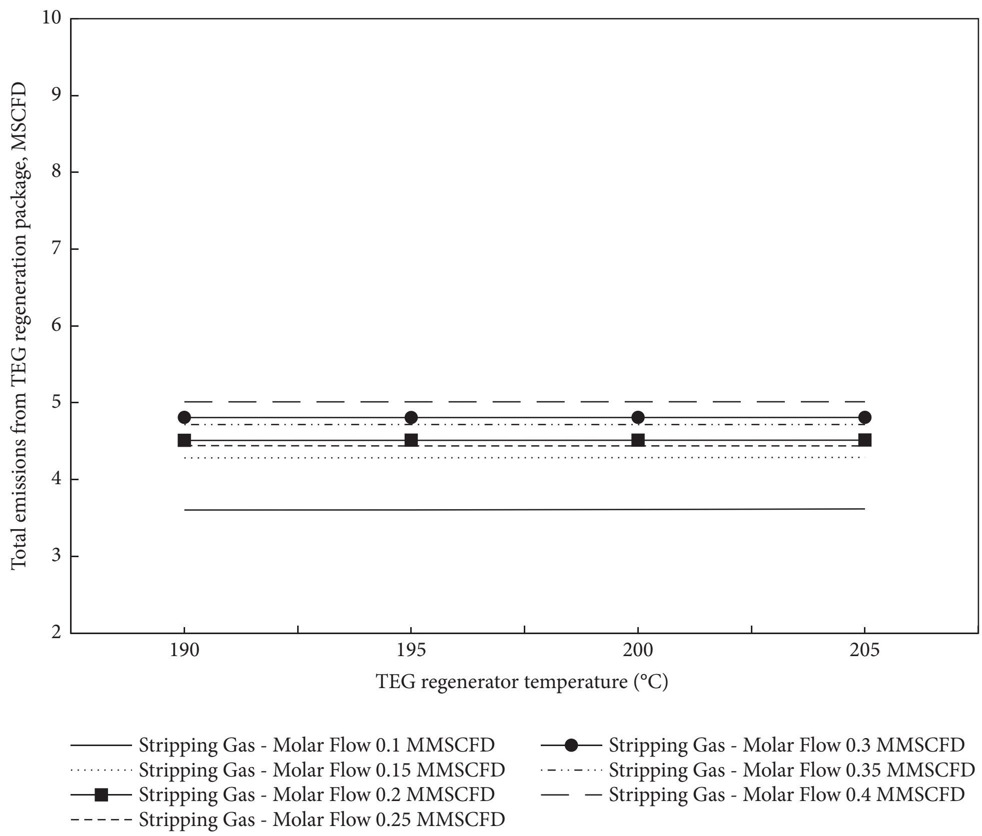

Figure 18: Effect of TEG regenerator temperature on total emissions with varying the stripping gas flow rate at an inlet feed gas temperature of 25°C and at a TEG circulation rate of 8 GPM.

Equations (3)–(10) summarize the model formulation used in LINGO optimization software to find the optimum conditions of the NG dehydration unit, where the objective function is to minimize BTEX emissions evolved from the TEG regeneration unit:

$$\min = \text{BTEX emissions}, \tag{3}$$

$$\text{BTEX emissions} = -2.3594 + 2.6945\,A + 0.5176\,B + 0.0438\,C + 0.00545\,D - 1.2639\,A^2. \tag{4}$$

Subject to the following constraints:

$$\text{Sales gas water content} <= 4, \tag{5}$$

$$\text{Sales gas water content} = -9.1658 - 10.8903\,A - 0.1196\,B + 0.3489\,C + 0.0213D + 6.9775\,A^2. \tag{6}$$

Stripping gas flow rate constraint:

$$0.1 \le \mathbf{A} \le 0.4. \tag{7}$$

TEG circulation rate constraint:

$$2 \le \mathbf{B} \le 10. \tag{8}$$

Inlet feed gas temperature constraint:

$$25 \le \mathbf{C} \le 40. \tag{9}$$

TEG regeneration temperature constraints:

$$190 \le \mathbf{D} \le 205. \tag{10}$$

The exact values of upper and lower limits of constraints are extracted from experimental data, which are collected from existing unit located on western desert and guided by maximum operating parameter values of process equipment.

The obtained results showed that the two considered techniques of optimization gave the same values for the optimum operating conditions. The global optimum solution suggests that the minimum level of BTEX emissions while keeping sales gas water content less than 4 Lb./MMSCFD can be achieved at stripping gas flow rate of 0.1 MMSCFD, TEG circulation rate of 2 GPM, inlet feed gas temperature of 25°C, and TEG regenerator temperature of 190°C. By applying the obtained optimal parameters on the considered plant, the BTEX emissions can be reduced from 6.894 MSCFD to 1.281 MSCFD with a reduction percent of 81.42%.

6. Conclusion

The gas processing industry faces a significant challenge in minimizing the emission of BTEX compounds in the natural gas dehydration unit. The current study aims to address this challenge by focusing on both minimizing BTEX emissions and achieving efficient dew point control. By combining these objectives, we can optimize the overall performance of the gas dehydration process while reducing environmental impact. Firstly, the influence of different operating variables on BTEX emissions from NGDU located in the western desert and their effects on sales gas water content is studied by using HYSYS (version 11) as a simulation tool. The simulation results showed that the stripping gas, TEG circulation rate, and inlet feed gas temperature have great influences on the BTEX emissions, while TEG regenerator temperature has an insignificant on BTEX emissions. Also, the validation of simulation results shows good agreement between experimental and simulated results with R^2 of 0.99 for the fitting line and this in turn shows the effectiveness of the HYSIS simulation program used in the current work.

This study also aims to identify the optimum operating conditions to be applied to achieve the minimum level of BTEX emissions with efficient control of sales gas water content. The process optimization is done using two different methods: LINGO software (version 18) and HYSYS (version 11). The values of the optimum operational conditions are the same by applying both of the two considered optimization techniques. The obtained results indicate that the minimum level of BTEX emissions with efficient control to natural gas water dew point can be achieved at stripping gas flow rate of 0.1 MMSCFD, TEG circulation rate of 2 GPM, inlet feed gas temperature of 25°C, and TEG regenerator temperature of 190°C. The BTEX emissions can be reduced from 6.894 to 1.281 MSCFD with 81.42% as a reduction percent when applying the obtained operational condition on the investigated dehydration plant.

Additionally, two new correlations are developed in the present work by using regression analysis. The first correlation is simple and can be used easily to calculate the water content of the outlet sales gas. The second correlation is new, and it is not addressed in previous research works. This correlation is used to determine the amount of BTEX emissions that evolved from the regenerator and flash separator. The two developed quadratic correlations can be used for calculating, with a higher degree of accuracy, the BTEX emissions, and the sales gas water content at any operational variables.

This study that aims to minimize the BTEX emissions from NGDU and at the same time to obtain a sales gas water content required for sales gas desired specification can be applied to other natural gas dehydration processes for increasing their profitability and reducing emissions to be acceptable according to the environmental regulations.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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