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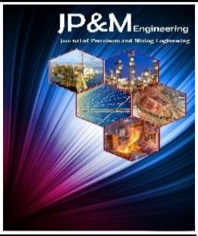

Mitigation of BTEX Emissions through Optimization of Natural Gas Dew Point Control Unit

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Abstract

Dehydration is a key process in the natural gas industry for minimizing water content, ensures safe processing and transmission, and prevent operational issues like equipment corrosion and hydrate formation. During dehydration process, the glycol solvent not only absorbs water, it also catches some volatile organic compounds (VOC) in addition to aromatic compounds like benzene, toluene, ethylbenzene, and xylene (BTEX). These substances are emitted into the atmosphere during glycol regeneration, leading to environmental pollution and severe health issues.

Natural gas dehydration could be achieved through alternative methods other than absorption such as adsorption, and direct cooling of wet gas. This study focuses on using direct cooling through JT Valve technology expansion, with MEG injection as a hydrate inhibitor for dehydration .Its goal is to enhance the natural gas dew point and reduce (BTEX) emissions by optimizing operational parameters and examining how these parameters affect BTEX emissions, as well as the water and hydrocarbon content in natural gas. Simulation results demonstrate that JT inlet & outlet pressure, MEG injection rate, inlet gas temperature & MEG regeneration temperature have a significant impact on sales water gas dew point. It also cleared that using that proposed technique resulted in the elimination of BTEX emissions from the dehydration unit, indicating that direct cooling technology by JT Valve and monoethylene glycol as a drying agent effectively mitigate BTEX emissions.

This study considers developing of two quadratic correlations using regression analysis to efficiently calculate the produced gas water content and hydrocarbon dew point at various operational variables.

Introduction

Natural gas that comes out of the wellhead of the reservoir is referred to as 'wet gas., which condenses and transforms into solid gas hydrates if the gas temperature declines below water dew point temperature. These solids can clump together and obstruct pipelines, interrupting gas production and potentially leading to pipeline blockages, corrosion, or ruptures [1,2]. Engineering research and industrial practices concluded that controlling and reducing natural gas impurity content is crucial for safe processing and transmission [3,4]. Pipeline specifications dictate water content limits for United States, Canadian, and Alaskan pipeline systems to 7, 4 and 1-2 lb/MMscf, respectively [1] .

Gas dehydration involves the removal of moisture from natural gas flow to comply with sales specifications and prevent hydrate formation and occurrence of corrosion in shipping lines.[5-9]

Gas dehydration could be accomplished by various techniques such as absorption, adsorption, and direct cooling of wet gas.

Direct cooling methods, such as expansion or refrigeration with hydrate inhibitor injection, are commonly used for Further decrease in dew point in pipeline gas production in cold weather regions, while supersonic and membranes processes provide compact design benefits ideal for offshore process [1]. Controlling the dew point of natural gas can also be accomplished through refrigeration. The most common refrigeration methods include Joule-Thomson (JT) valve refrigeration, mechanical refrigeration, and cryogenic refrigeration utilizing a turbo expander [10]. The JT valve method serves as an uncomplicated technique to enhance hydrocarbon dew point this system utilized in gas production facilities, particularly when there's a substantial pressure drop and low gas temperatures is not essential. The decrease in pressure through the valve leads to gas expansion and cooling, which in turn separates heavy hydrocarbons, and water in a cold separator. Gas dehydration process can effectively manage water and hydrocarbon dew point within a unique unit [11].

Using JT for liquid recovery is a favorable option in various scenarios; it offers several benefits compared to turbo expanders and other refrigeration methods. With JT, it is possible to use low gas rates while still achieving decent ethane recovery. Additionally, the process could be set up without any rotating equipment, making it simple to design and operate. Moreover, JT systems have the advantage of having the lowest capital costs among similar processes. However, it is important to note that they may not recover as much NGLs as other systems [12,13].

Throughout process of dehydration, glycol absorbs VOC and BTEX compounds found in saturated gas, which are then released into the environment throughout regeneration of glycol . Although BTEX and VOC amounts of in the natural gas stream are relatively small, they can lead to the emission of significant high concentrations of these compounds in the vented stream [14 -17]. The Environmental Protection Agency (EPA) classifies BTEX components and VOCs as Air pollution substance due to their irritating and carcinogenic properties. Such emissions may lead to blood disorders and adversely impact the central nervous system, reproductive system, respiratory system, and neurological system. Additionally, they can cause various industrial issues, including excessive foaming, flooding, increased glycol loss, reduced efficacy, and Increased servicing expenditures for absorbers in dehydration operations [18,19].

Garg et al [20] Cleared that Benzene, toluene, ethylbenzene, and xylene (BTEX) are hazardous compounds that pose serious health risks. As volatile substances, they contribute to air pollution by reacting with nitrogen dioxide to form harmful secondary pollutants, including ozone..

The cancer risks associated with benzene emissions exceed the safety limits set by the World Health Organization, posing a significant threat to public health..

The short-term adverse effects include nose and throat discomfort, sleeplessness, impaired short-term memory, tremors, headache, skin problems, fatigue, and dizziness .While the long-term exposure to benzene can lead to more adverse effects like genotoxicity, haematotoxicity, reproductive effects with various cancer, loss of coordination, lung cancer, anemia, leukemia, and damage to the liver, kidney and central nervous system . These compounds also has a tendency to from secondary aerosol including ozone hence possessing the ozone formation potential.

Das et al [21]Stated that During Natural gas processing a mix of light and heavy hydrocarbons, including hazardous volatile organic compounds (VOCs) like BTEX (benzene, toluene, ethylbenzene, and xylene) released to atmosphere , These chemicals pose serious health risks:

Benzene known carcinogen causing dizziness, headaches, and rapid heart rate, with chronic exposure linked to anemia and leukemia. Toluene causes acute symptoms like light-headedness and confusion, with chronic exposure potentially leading to unconsciousness or death.

Ethylbenzene inhalation can cause irritates eyes, nose, and throat, with long-term exposure harming liver, kidneys, and central nervous system.

Xylene causes respiratory irritation, with chronic exposure affecting nervous and respiratory systems.

Numerous countries enforce stringent monitoring of BTEX compounds. In the United States, they are categorized among the 189 Hazardous Air Pollutants as per the Clean Air Act Amendments of 1990. Various approaches can be taken to reduce emissions of BTEX , including Burning released gases, incorporating a condensation package, process optimization, and utilizing glycol with lower absorption capabilities as a solvent [18,22,23]. The burning process is considered the most applied method to eliminate BTEX emissions [15,23-25].

Recent initiatives are now centered on creating new processes, enhancing current ones, and utilizing solvents that absorb less BTEX or alternative solvents instead of treating water effluent containing BTEX compounds, which can be costly [18,22,24,26-29]. Selecting the right dehydrating agent can help reduce BTEX emissions. Studies have shown that BTEX compounds have lower solubility in diethylene glycol (DEG) compared to triethylene glycol (TEG), and even lower solubility in ethylene glycol (EG) [30]. Recently, Tazang et al. [31] developed a method to precisely model solubility of BTEX in triethylene glycol (TEG).

Numerous research investigations have been conducted on gas drying units, with Past investigations primarily concentrating on either enhancing process efficiency or minimizing emissions. In a study conducted by Isa et al. [32], three natural gas drying processes were simulated in an industrial facility in the UAE. The researchers suggested the addition of potassium formate to the TEG solution as a novel approach to enhance TEG-water absorption efficiency. However, this led to an increase BTEX absorption rate and raised operational costs due to the need for external introduction of chemicals. Abdulrahman and Sebastine [33] examined the utilization of various glycols for the dehydration of natural gas; they discovered that TEG is highly effective in removing water and absorbing a greater amount of hydrocarbons. Their research emphasized the significance of managing BTEX emissions in natural gas drying units because of their adverse impact on People health, however, they were unable to concurrently address both objectives. The efficiency of wet natural gas drying through absorption with liquid drying agent has been studied in different research work [34-35], however the incorporation of minimizing water content as well as BTEX and VOCs emissions is not achieved in their work.

The study by Zong et al. [36] indicates that different recycling setups for natural gas drying units fail to Considerably lower water dew point or BTEX emissions, despite incurring substantial capital and operational expenses. Additionally, they discovered that even slight reductions in total BTEX emissions consistently result in increased water dew point of dry product gas. A sensitivity analysis was carried out by Braek et al. [18] on five operating parameters of an NGDP in Abu Dhabi, UAE. Their results showed that the optimum values aiming to minimize emissions resulted in a reduction of 48-45% in BTEX and VOC emissions. Nevertheless, there is still a need for more significant reduction of these dangerous pollutants.

Nemati Rouzbahani et al. [37] discovered that BTEX emissions from natural gas dehydration plants are sensitive to the purity of lean DEG. On the other hand, Darwish and Hilal [38] found that BTEX emissions are Considerably effected by the lean TEG temperature and injection rate and, while the stripping gas flow rate greatly affects VOC emissions. Torkmahalleh et al. [39] investigated the impacts of drying agent circulation rate, reboiler duty, stripping gas flow rate, and pure TEG temperature on BTEX, VOC, and CO2 emissions. They found that increasing the drying agent circulation rate decreases water content of dry gas, whereas higher flow rates up to 9.25 GPM increase water content. Darwish and Hilal [38] also established that an increase in glycol flow rate can reduce glycol purity due to chemical dissolution, thereby decreasing water content.

Numerous researches have concentrated on the operating conditions of dehydrating natural gas [18, 39-41]. Siti et al. [42] optimized operating conditions using symmetry process simulation software to evaluate their impact on performance. Renanto et al. [43] introduced a Novel configuration for natural gas drying using TEG, while Chong et al. [44] Recommended a model for glycol dehydration units to lower total annual cost (TAC). Kharisma et al. [45] optimized the TEG dehydration System to reduce TAC and enhance efficiency, and Mukherjee et al. [46] identified optimal operational conditions to minimize BTEX emissions.

Various equilibrium correlations [47-53] are available in the literature for estimating the equilibrium water dew point of natural gas in a TEG dehydration process. While the correlations by Worley [50], Rosman [51], and Parrish et al. [47] are typically effective for most TEG system designs, they are not accurate in estimating the equilibrium water concentration above TEG solutions in the vapor phase, as reported in the literature [54]

Parrish et al. [47] and Won [53] developed correlations to ascertain water equilibrium concentrations in the vapor phase at 100% TEG (unlimited dilution). Other methods implement data extrapolations at lower concentrations to predict equilibrium in the unlimited dilution area [53]. Bahadori and Vuthaluru [55] Suggested a correlation to predict the equilibrium water dew point of a natural gas flow with a TEG solution, based on TEG concentrations and absorber temperatures. Twu et al. [56] used the Twu-Sim-Tassone (TST) equation of state (EOS) [57] to define water-TEG system phase behavior and determined water content and dew point Through natural gas systems. Although these Techniques have good predictive capability, their applications are generally limited to the specific systems for which they were designed.

It is important to mention that all the previous calculations were performed on the process of drying natural gas through absorption by TEG. So far, no research has been conducted on plants using the direct cooling method by expanding the technology using a JT valve with MEG injection as a hydrate inhibitor, which has succeeded in reducing hazardous emissions and achieving the allowed water content ratio efficiently.

In the present work, the operational parameters which impact water content together with BTEX emissions have been outlined and studied. The present study will be conducted at the DPCU in the western desert, where the JT valve refrigeration technique will be utilized. It is addressed to study and analyze the impact of operating variables on water content besides BTEX emissions, in addition to optimizing the operating conditions of the JT Plant in the Egyptian western desert for efficient dew point control with BTEX mitigation. Furthermore, a new optimization model is employed to optimize NGDU operational variables by LINGO software V-18. The variables under investigation include JT upstream pressure, JT downstream pressure, MEG injection rate, main inlet gas temperature, and MEG reboiler temperature. In addition, two innovative correlations have been established through regression analysis; the first correlation attributed the water content in the outlet gas to the operational conditions being studied, while the second correlation connects the hydrocarbon dew point in the outlet gas to the operational conditions under examination.

The optimal conditions are determined to minimize emissions while keeping the sales gas water dew point within the required specifications. Lingo software version 18 is utilized for this optimization. Lingo is a powerful tool for building and solving linear and nonlinear mathematical models, making it well-suited for a wide range of optimization tasks.

Methodology

The current study examines an NGDU situated in the western desert. This unit employs refrigeration technology with a JT valve to optimize operating conditions, focusing on reduce BTEX emissions and keep sales gas dew point within specifications. Data logs summarizing various operating variables of the NGDU during both winter and summer seasons are collected to gain a comprehensive understanding of all operating conditions.

The research approach of the present work could be summarized as follows:

Step 1: Operating data are gathered from the current NGDU located in the western desert regarding operational factors, water content of natural gas, and hydrocarbon dew point.

Step 2: The current study was simulated using HYSYS simulation software (version 11) and sensitivity analysis was conducted to study the impact of different operating conditions on BTEX emissions, water content in sales gas, and dew point of hydrocarbons.

Step 3: The constructed model's simulation results are validated through comparison with actual results obtained from the field (Simulation Results Validation).

Step 4: A study is conducted to investigate the influence of operating variables on BTEX emissions and water content. The studied variables are gas inlet temperature, JT valve pressure, MEG circulation rate, and MEG reboiler temperature.

Step 5: Optimal operating conditions have been achieved to reduce BTEX emissions and maintain the water content and hydrocarbon dew point of sales gas within the specified range.

Step 6: The simulation results are used also to extract two correlations aiming to estimate the water content in sales gas and the hydrocarbon dew point based on the operational conditions. Regression analysis with Excel is used to extract these correlations.

Step 7: The developed correlations are introduced as a part of a developed mathematical optimization model aiming to get the optimal conditions which minimize the water content in sales gas, while ensuring that the hydrocarbon dew point remains within the range of specifications. The optimization in this step is performed using Lingo software version 18, which is a comprehensive tool for efficient linear and nonlinear mathematical optimization. LINGO is an advanced programming language that utilizes both gradient-based and derivative-free optimization methods .[56,57].

Case Study

This research paper applies a case study to NGDU in the Egyptian western desert, focusing on operating conditions such as JT upstream pressure, downstream pressure, MEG injection rate, main inlet gas temperature, and MEG Regenerator temperature, which are supposed to be varied within the range of 1100-1240 (PSIG), 730-830 (PSIG), 1-8 (GPM), 25-45 ^{o}C, and 120-145 ^{o}C. respectively. These data have been published by Shoaib et.al.[58]

Table 1 :illustrates wet gas composition of the entering the DPCP. A segment of the incoming gas is cooled in a gas/gas exchanger, while the remainder is cooled in gas/liquid exchangers arranged in parallel.

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Table 1 Wet gas compositions used as a feed of the DPCP.

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

Figure 1: illustrates the process flow diagram of the NGDU under study. As depicted, the liquid hydrocarbon are Pre-chilled using the low-pressure separator, while the feel gas is Pre-chilled through exchange with cold residue gas from the second stage cold separator. Following the cooling, these gases coming from the gas/liquid and gas/gas exchangers are combined and undergo Joule Thomson (JT) expansion, resulting in a temperature drop that significantly lowers water and hydrocarbon dew point. This dew point reduction occurs due to condensation of heavy hydrocarbons and water from the gas phase into liquid form..

The incoming gas stream flow is controlled by a hot gas bypass on the JT unit. This bypass allows for fine-tuning the temperature of the cold separator by directing intake gas to gas/gas exchangers, enabling some of the incoming gases to warm the cold separator. This process can impact the gas flow, temperature, or pressure of the inlet gas

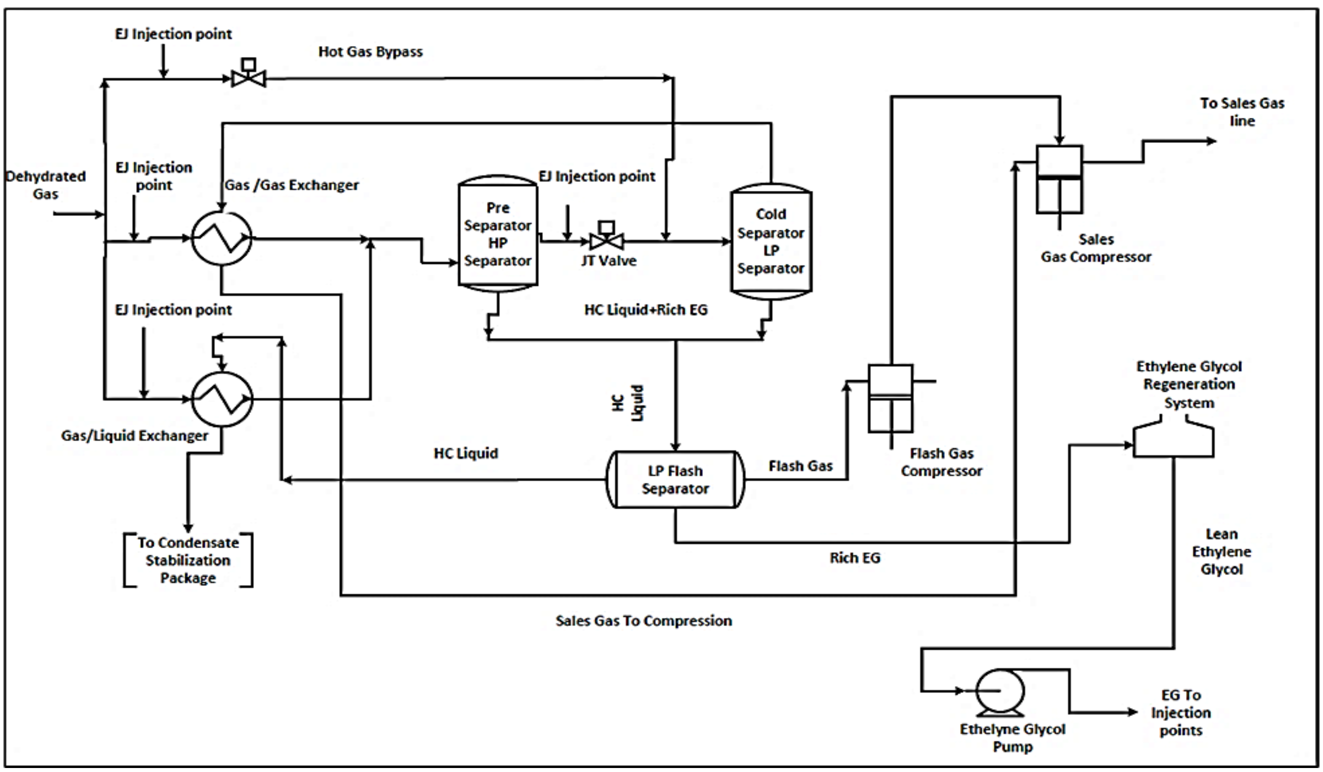

Figure 1 Process flow diagram of DPCP by Refrigeration using JT valve.

The low pressure (LP) separator uses a liquid-liquid plate to separate the condensate of hydrocarbons and wet ethylene glycol, effectively isolating the relatively viscous glycol from liquid hydrocarbon. The liquid hydrocarbon flows over an inner barrier into the flash section, while the wet glycol go out through the glycol boot, is reconcentrated , and then injected back to injection points distributed over the plant. Approximately 80 wt% of ethylene glycol is pumped at the gas/gas exchangers, followed by the gas/liquid exchangers, and finally to JT Valve to prevent the formation of gas hydrate deposits during gas cooling.

Before undergoing JT expansion, any liquids formed during Preliminary cooling are removed in the Primary separator. This vertical two-phase separator efficiently separates liquids and gases. The liquids are discharged by level control to the LP separator, while the gas is directed to JT valve. At the JT valve, the gas undergoes expansion, and any resulting liquids are extracted in the Low-temperature separator. The gas from Low-temperature separator is then returned to the gas/gas exchanger, where it exchanges heat with the incoming gas before being sent to the export gas compressors. These compressors increase the residual gas pressure to 1350 Psig.

The LP separator is a horizontal vessel designed to degas hydrocarbon liquids before they reach the stabilizer tower. It receives liquid coming from both the Primary separator and the Low-temperature separator. The gas exits through a flash gas compressor and is then drawn in by export gas compressors. The liquid hydrocarbons from the LP separator are heated in a gas/liquid exchanger and then diverted to condensate stabilization package. In the stabilization package, the liquids are reheated and stabilized to meet specifications by separation of butanes and lighter components

Validation of Simulation

To assure the reliability and accuracy of the simulated case study, it is crucial to conduct comparison between simulation results and experimental findings. This validation offers valuable insights into the effects of operating parameters on water dew point ,BTEX emissions, and hydrocarbon dew point in the DPCP

Figure 2 displays a comparison between the simulated outcomes and the actual field data for sales gas dew points under the designated operating conditions. It is obvious from Figure 2 that the simulation model accurately predicted export gas dew points, highlighting a close match between the experimental and simulated temperatures. The equation of the fitting line (x ≈ y) had a high R-squared value (0.9996), demonstrating the effectiveness of Aspen HYSYS (version 11) simulation software in estimating gas dew points. This tool is essential for evaluating BTEX emissions from the regeneration unit, ensuring they stay within the allowable operational margins .

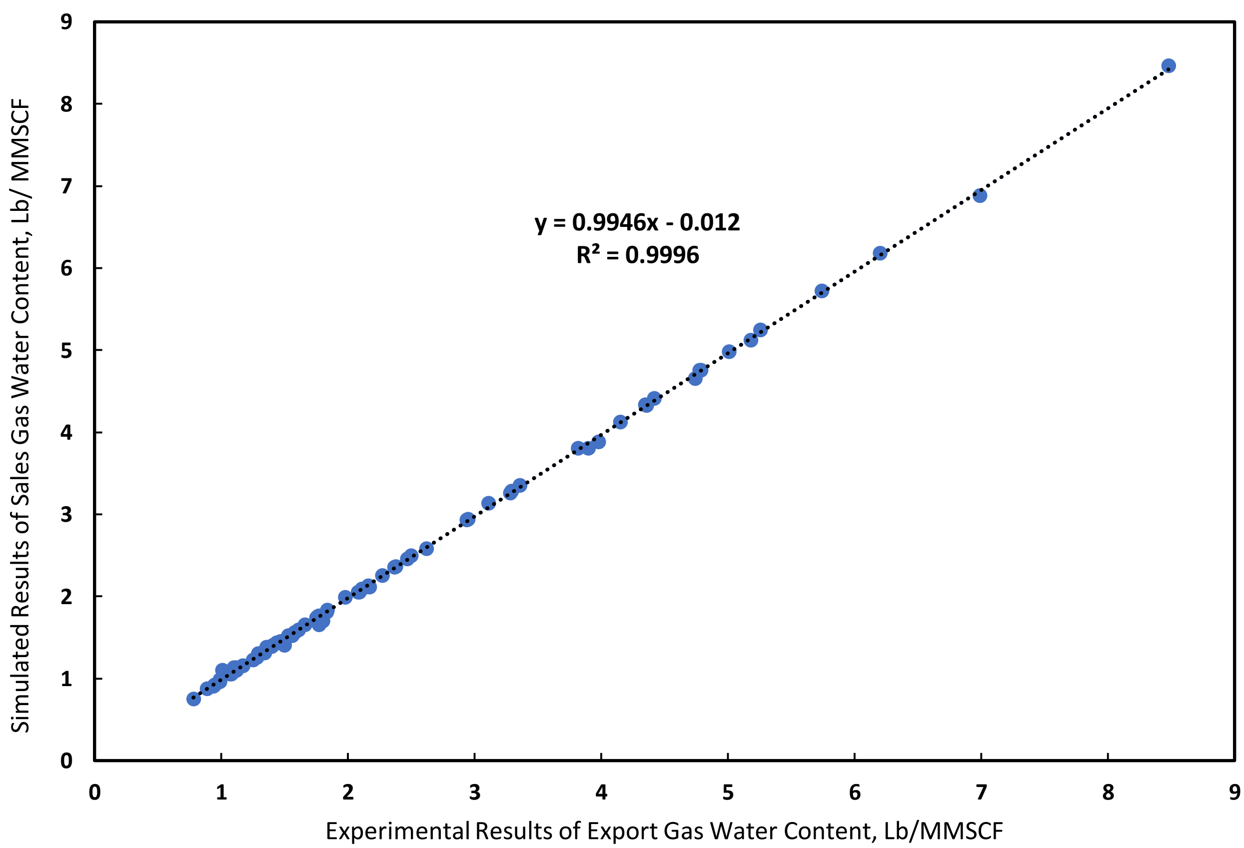

Figure 2 Comparison of experimental data with simulation results for sales gas water content assessed at different operating parameters of the natural gas dehydration unit under study

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Results and Discussions

The objective of the present study is to examine the influence of operating parameters of the considered drying unit for reducing BTEX emissions and maintaining the sales gas within specifications. This can be accomplished using the HYSYS simulation program (V11).for identifying The effect of operating parameters on the sales gas water content, hydrocarbons dew points, and BTEX emissions. Sensitivity analysis was utilized to pinpoint the key operating parameters that significantly impact these factors. Subsequently, optimization of these parameters was carried out to reduce BTEX emissions from the DPCP regeneration unit, while ensuring that the processed gas meets the required Sales gas requirements.

Utilizing LINGO optimization software (version 18) is useful to identify the best operating conditions. The main objective of this research is to investigate how plant operating conditions affect water dew point & BTEX emissions of natural gas. Additionally, this study introduces two correlations to predict BTEX emissions & natural gas dew point under various different operational parameters within the Simulation scope.

Effect of Operating Parameters

To determine the best Operational parameters for the investigated NGDU, it is necessary to analyze how different operating parameters affect water dew point and BTEX emissions of the processed gas. The operational variables include the JT inlet pressure, JT outlet pressure, MEG injection rate, main inlet gas temperature, and MEG regeneration temperature. For the present case study, the impact of these operating parameters on BTEX emissions & sales gas water content was investigated by using HYSYS (V11) as a simulation program. The JT upstream pressure varied from 1100 to 1240 PSIG, with specific values of 1100, 1120, 1140, 1160, 1180, 1200, 1220, and 1240 psig. The JT downstream pressure ranged from 730 to 830 psig, with selected values of 730, 750, 770, 790, 810, and 830 psig. The inlet feed gas temperature was set at 25, 30, 35, 40, and 45 ^{o}C. The MEG reboiler temperature was adjusted from 120 to 145 ^{o}C, with specific values of 120, 125, 130, 135, 140, and 145 ^{o}C, while the MEG circulation rate was varied from 1 to 8 GPM, with selected values of 1, 2, 3, 4, 5, 6, 7, and 8 GPM.

Effect of JT Upstream pressure

The simulation Outcomes of studying effect of JT upstream pressure on sales gas water content & BTEX emissions show that by applying JT refrigeration technology by JT valve in natural gas dehydration, no emissions evolved from the unit. This can be attributed to two reasons, the first is because BTEX Emissions is less soluble in MEG, the second is because BTEX compounds condensed through gas cooling process through JT valve.

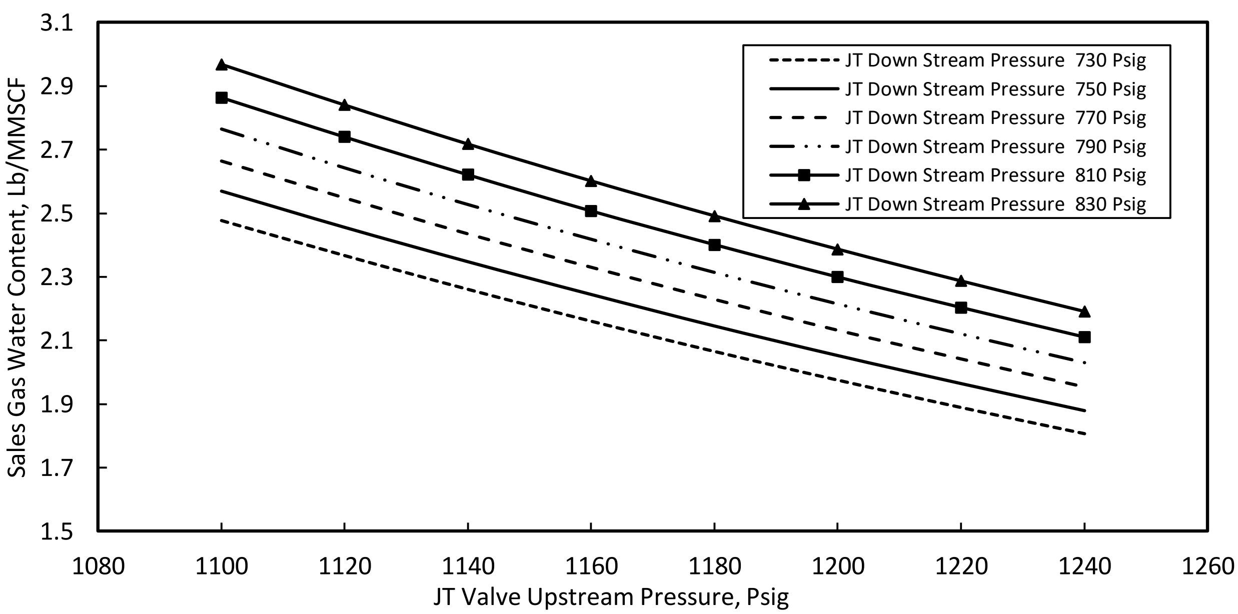


Figure 3 Impact of JT inlet pressure on Water content in sales gas at various downstream pressures, with a MEG injection rate of 2 GPM, a inlet gas temperature of 30°C, and a reboiler temperature as 120°C.

Increasing the upstream pressure of the JT system has a considerable effect on the water content of the obtained sales gas

Figure 3 illustrates the influence of upstream pressure on the sales gas water content at various downstream pressure values, with a constant MEG injection rate of 2 GPM, main inlet gas temperature of 30 ^oC, and MEG reboiler temperature of 120 ^oC. The obtained results show that as the upstream pressure increases, the sales gas water content decreases. The rising in upstream pressure leads to an increase in the pressure drop through the JT valve, resulting in a decrease in gas temperature. This consequently causes more water and heavier hydrocarbons to condense, consequently the gas produced with low dew point.

We can explain the behavior of JT valve as When a gas undergoes an adiabatic expansion, meaning it doesn't exchange heat with its surroundings, its temperature drops. This cooling effect is known as the Joule-Thomson effect. In essence, when a gas is forced through a valve or narrow passage while insulated, its temperature changes due to the expansion. As the gas expands, its molecules gain more space to move, using some of their internal energy to overcome the attractive forces between them. Since no heat is exchanged and no external work is done, the energy used to overcome these forces comes from the gas's internal energy, causing its temperature to decrease.

The mathematical description of the effect as follow The temperature change in the Joule-Thomson effect is quantified by the Joule-Thomson coefficient (μ), which can be defined as: $\mu=(\partial T/\partial P)_H$

Where $\partial T/\partial P$ is the rate of change of temperature T with respect to pressure P at constant enthalpy H. The sign and magnitude of μ indicate how the temperature will change at a given pressure.

If $\mu>0$, the gas cools upon expansion (positive Joule-Thomson coefficient).

If $\mu<0$, the gas heats up during expansion (negative Joule-Thomson coefficient).The inversion temperature is a unique property of each gas and determines whether the Joule-Thomson effect will result in heating or cooling. It represents the temperature above which the Joule-Thomson coefficient becomes negative (the gas warms when expanded) and below which it becomes positive (the gas cools when expanded)

Figure 4 illustrates how JT upstream pressure affects sales gas water content at various MEG circulation rate values when JT downstream pressure is 810 psig, main feed gas temperature is 35 ^oC and MEG reboiler temperature is 135 ^oC. It is clear that by increasing JT inlet pressure, the sales gas water content will decrease and increasing MEG circulation rate sales gas consequently consequently decrease water content.

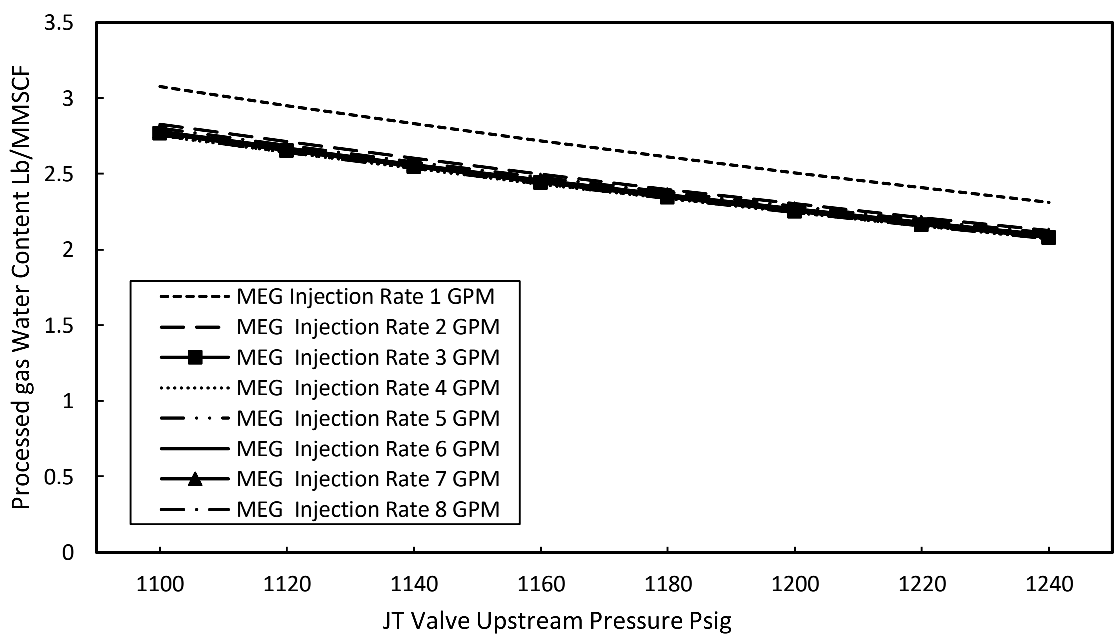


Figure 4 Impact of JT inlet pressure on Water content in sales gas at various MEG circulation rates,with JT downstream pressure of 810 Psig, inlet gas temperature of 35 ^oC, and a reboiler temperature as 135 ^oC

However, the sales gas water content remains constant at MEG circulation rate more than 3 GPM. The impact of JT upstream pressure on the water content of sales gas was investigated at various inlet feed gas temperatures. The simulation Outcomes shown in Figure 5, indicate that rising of either JT upstream pressure or the inlet feed gas temperature led to a decrease in sales gas water content. The influence of JT upstream pressure at different values of MEG reboiler temperature are presented in Figure 6. The obtained simulation results illustrate that by rising JT inlet pressure, the sales gas water content decreases and the same behavior of water content reduction is accomplished by increasing MEG reboiler temperature. This can be interpreted as the concentration of MEG is decreased by increasing of MEG reboiler temperature, and this consequently allows the absorption of the largest amount of water associated with the gas leading to a reduction of sales gas water content .

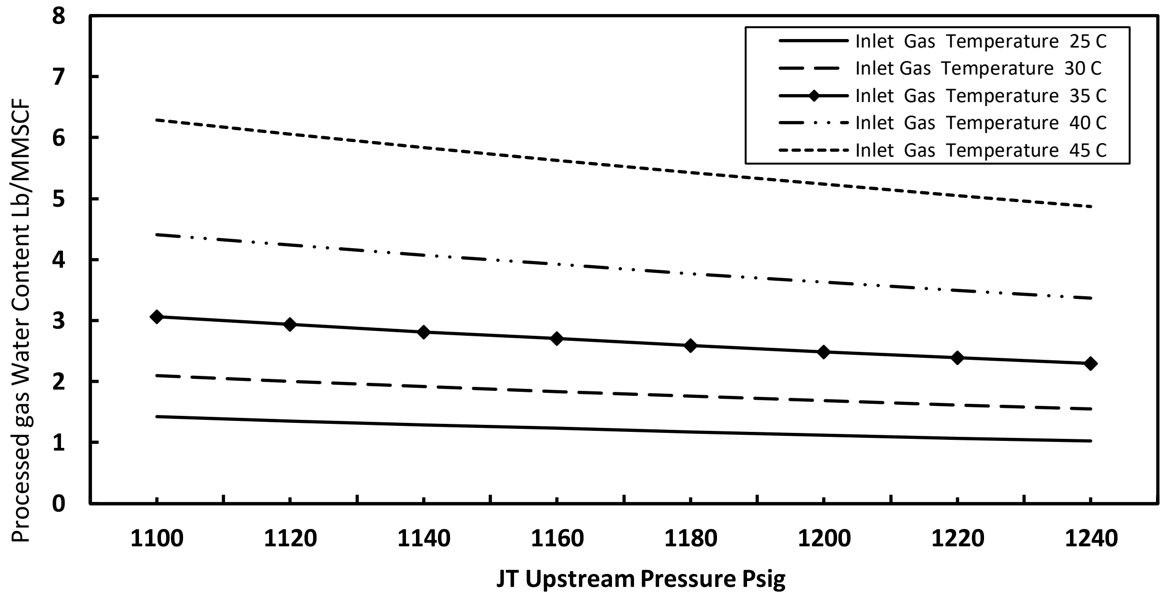


Figure 5 Impact of JT inlet pressure on sales gas water content at various inlet gas temperatures, with JT downstream pressure of 790 Psig, MEG injection rate of 4 GPM and a reboiler temperature as 130 °C.

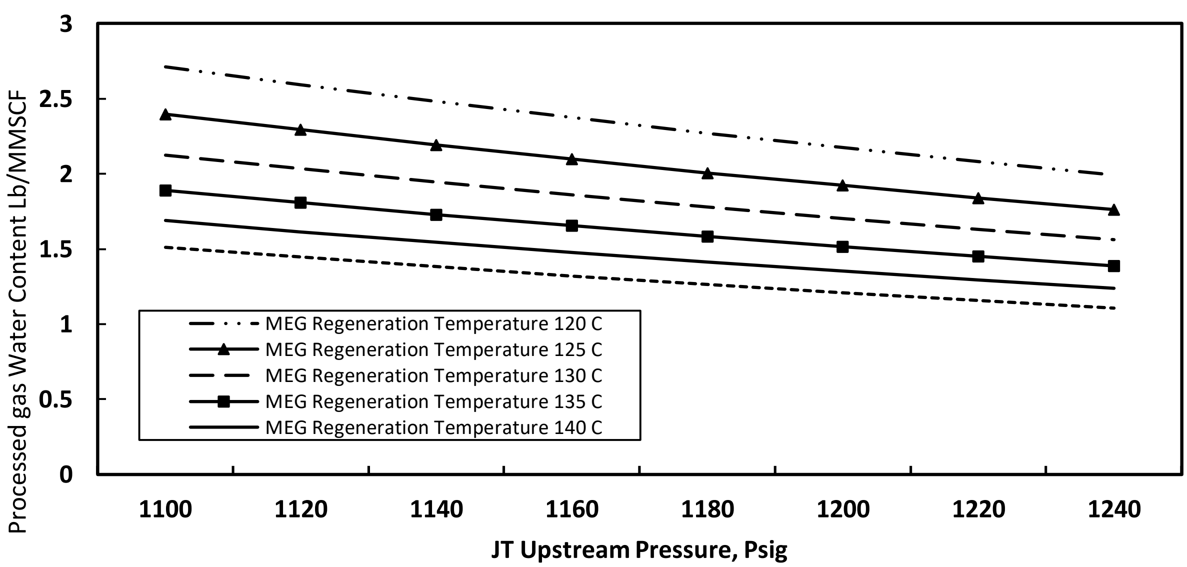


Figure 6 Effect of JT inlet pressure on sales gas water content at various MEG reboiler temperatures with JT downstream pressure of 770 Psig, MEG circulation rate of 1 GPM, and at feed gas temperatures 30 °C.

Effect of JT Downstream pressure

The abovementioned results regarding studying the effect of JT Downstream pressure on sales gas water content and BTEX emissions indicate that implementing JT refrigeration technology by installing a JT valve in natural gas dehydration prevents emissions from the unit. Additionally, JT downstream pressure significantly affects sales gas water content making it a critical parameter. A sensitivity analysis of the effect of JT inlet pressure on sales gas water content was conducted using HYSYS simulation software. Furthermore, the effect of JT inlet pressure on sales gas water content was analyzed through sensitivity studies at varying JT upstream pressure levels, MEG regenerator temperatures, feed gas temperatures, and MEG circulation rates.

The results presented in Figure 7 demonstrate the significant effect of JT outlet pressure on the water content of processed gas under specific process conditions, including a fixed MEG injection rate (4 GPM), inlet gas temperature (25°C), and MEG reboiler temperature (140°C).
The observed trend indicates that increasing the JT downstream pressure consequently increase water content in the sales gas. This behavior is due to the decrease in differential pressure across the JT valve, which consequently reduces the Joule-Thomson cooling effect. With a smaller temperature drop, less water and heavier hydrocarbons condense out, resulting in a higher dew point of the produced gas. Conversely, increasing JT upstream pressure results in a reduction in sales gas water content. This occurs because a higher upstream pressure enhances the pressure differential across the JT valve, thereby promoting a greater cooling effect. As a result, more water and heavier hydrocarbons separate from the gaseous phase, lowering processed gas water content. These findings highlight that JT upstream and downstream pressures plays critical role in controlling the dehydration efficiency of natural gas. Proper optimization of these parameters is essential to achieving the desired water content in sales gas while minimizing emissions and ensuring operational efficiency.

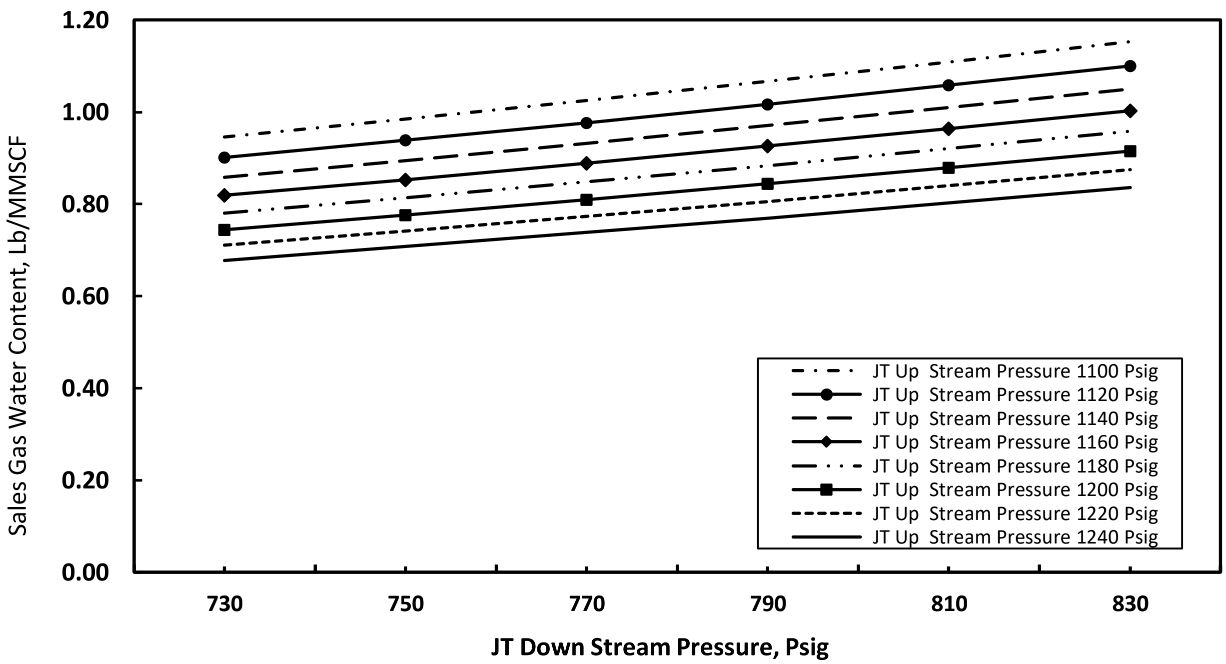


Figure 7 Effect of JT outlet pressure on sales gas water content at various JT upstream pressures with MEG injection rate of 4 GPM, inlet gas temperature of 25°C, and reboiler temperature as140°C.

The simulation results presented in Figures 8 and 9 highlight the impact of JT outlet pressure on the water content of sales gas under different operating conditions. In Figure 8, the analysis was conducted at varying MEG circulation rates, with a fixed JT upstream pressure of 1180 Psig, a main inlet gas temperature of 40°C, and MEG reboiler temperature as 120°C. The Outcomes demonstrate that increasing the JT downstream pressure consequently increase water content in the sales gas across all examined MEG circulation rates. This trend is consistent with the fact that a higher JT outlet pressure reduces pressure drop Throughout the joule Thomson valve, thereby limiting Joule-Thomson cooling effect. As a result, less water condenses out, resulting in a higher moisture content in processed gas . Additionally, while increasing MEG circulation rate generally enhances dehydration efficiency, the effect of JT downstream pressure remains a dominant factor influencing water content.

In Figure 9, the impact of JT downstream pressure on sales gas water content was studied at different inlet feed gas temperatures, with a constant JT upstream pressure of 1140 Psig, an MEG circulation rate of 3 GPM, and an MEG reboiler temperature of 145°C. The results indicate that as JT downstream pressure increases, the sales gas water content also rises, further reinforcing the role of differential pressure across the JT valve in the dehydration process. Additionally, the data reveals that increasing in inlet feed gas temperature resulting in increasing the sales gas dew point. This occurs because higher feed gas temperatures reduce the extent of cooling after expansion, thereby limiting the condensation of water and heavier hydrocarbons. Factors such as MEG circulation rate and inlet feed gas temperature play significant roles in determining dehydration efficiency. Optimizing these parameters is essential for achieving the desired water content while maintaining efficient natural gas processing operations.

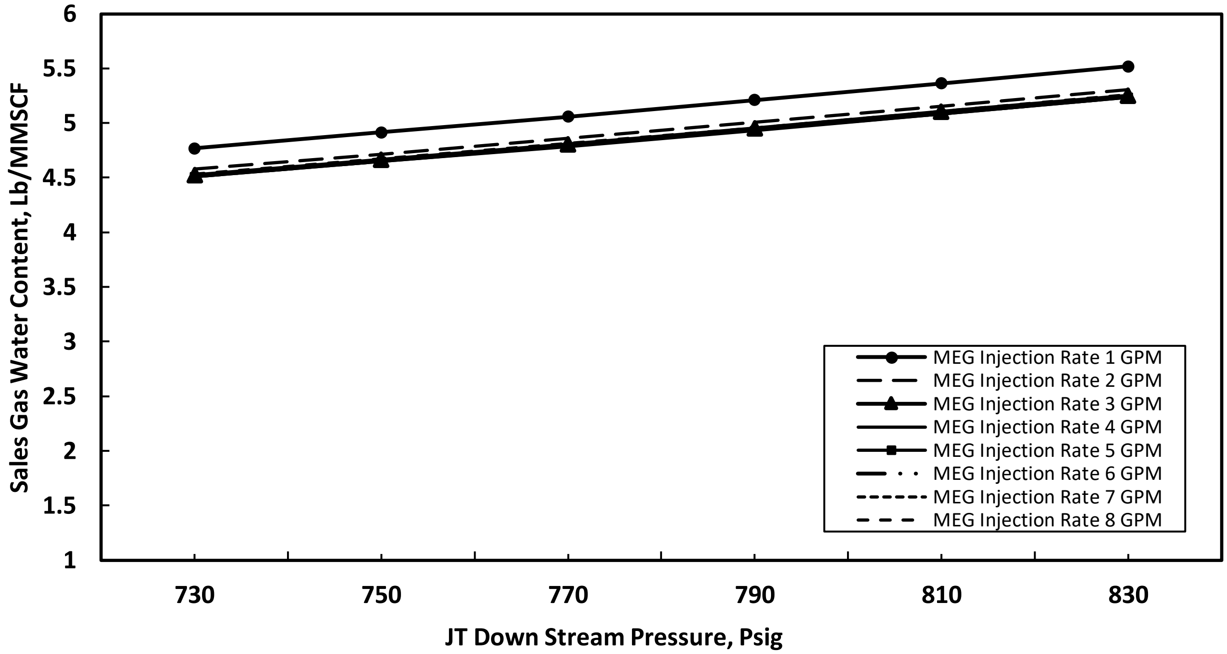


Figure 8 Impact of JT outlet pressure on water content of processed gas at different values of MEG circulation rates , JT upstream Pressure is1180 Psig, feed gas temperature 40 is ^{o}C, reboiler temperature is 120 ^{o}C.

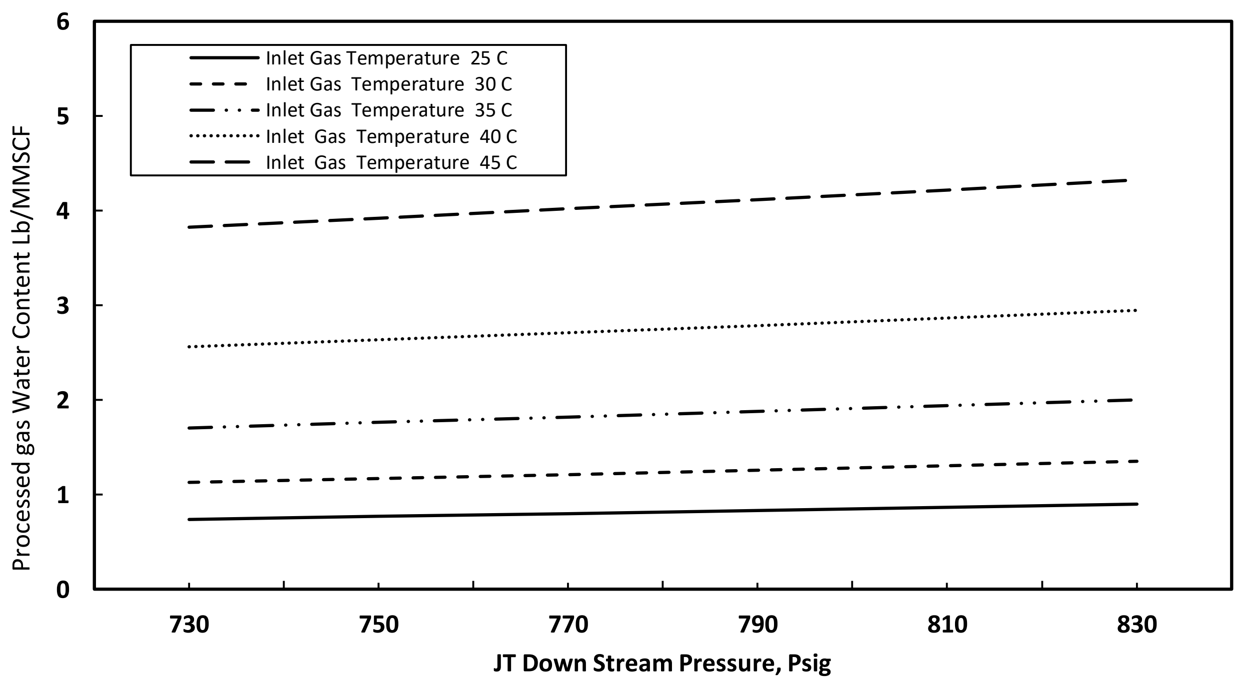


Figure 9 Impact of JT outlet pressure on water content of processed gas at different values of feed gas temperatures JT upstream pressure is 1140 Psig, circulation rate is 3 GPM, reboiler temperature is 145 ^{o}C

The simulation results presented in Figure 10 present the influence of JT downstream pressure and MEG regenerator temperature on the water content of sales gas under specific operating conditions, including a JT upstream pressure of 1200 PSIG, an MEG injection rate of 2 GPM, and inlet gas temperature of 30°C. The results indicate that as JT downstream pressure increases, water vapor content in the sales gas also rises. With less cooling, there is a reduced condensation of water and heavier hydrocarbons, resulting in high moisture content in Export gas stream. Additionally, the results demonstrate that increasing the MEG reboiler temperature resulting in decrease in water content of the sales gas. This occurs because a higher regenerator temperature enhances the regeneration efficiency of MEG by driving off more absorbed water, thereby improving its dehydration capacity. Consequently, the dried MEG is more effective at removing moisture from processed gas, resulting in lower water content in export gas. This results emphasize the dual impact of JT downstream pressure and MEG reboiler temperature on gas dehydration performance. While controlling JT downstream pressure is crucial for optimizing condensation and separation, maintaining an adequate MEG reboiler temperature ensures efficient water removal, both of which are essential for achieving the desired gas quality.

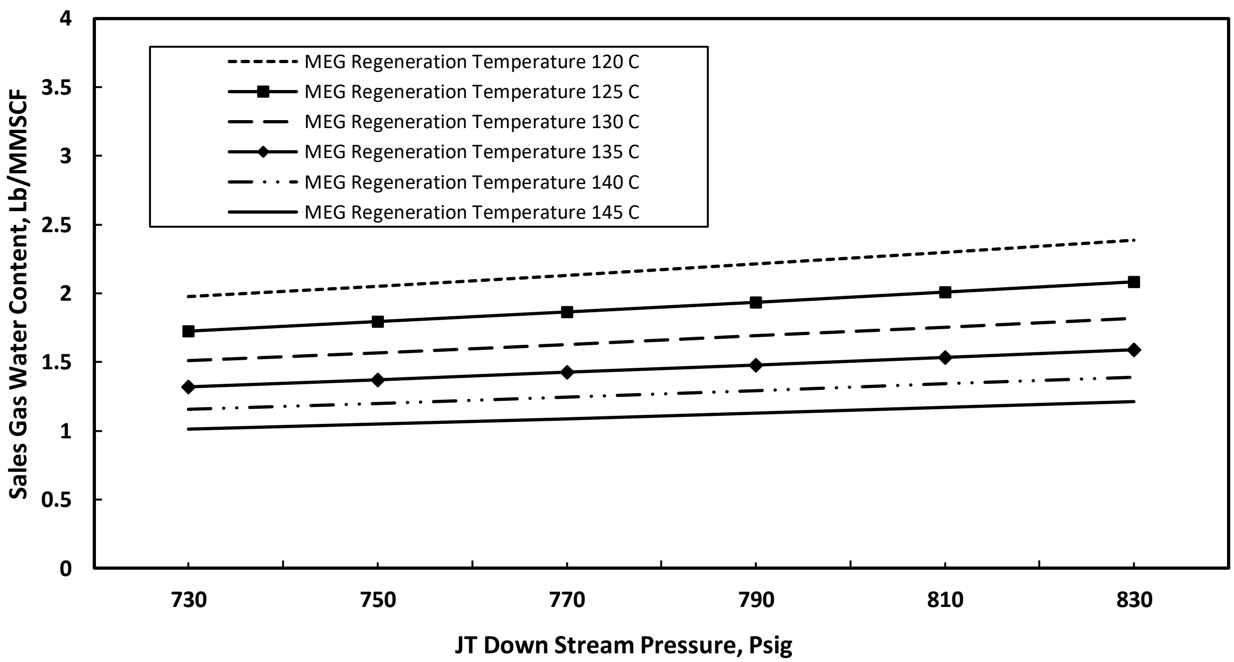


Figure 10 Impact of JT outlet pressure on sales gas water content at different values of reboiler temperatures: JT upstream pressure of 1200 Psig, MEG injection rate of 2 GPM, feed gas temp. as 30 ^{o}C

Effect of MEG circulation rate

The simulation results examining the effect of MEG circulation rate on sales gas water content and BTEX emissions clearly indicate that implementing JT refrigeration technology through a JT valve in natural gas dehydration prevents emissions from the unit. MEG circulation rate has been identified as a key parameter influencing the water content of sales gas. A sensitivity analysis was implemented to evaluate the impact of MEG circulation rate on sales gas water content at various values of JT inlet pressure, JT outlet pressure, inlet gas temperature, and MEG regeneration temperature.

Figure 11 presents The outcomes of the simulation for the impact of MEG circulation rate on sales gas water content at different JT upstream pressure values, with a constant JT downstream pressure of 830 Psig, a main inlet gas temperature as 35°C, and an MEG reboiler temperature as 135°C. The results indicate that

increasing the MEG injection rate initially results in a slight decrease in sales gas water content, up to a circulation rate of 3 GPM. Beyond this point, further increases in MEG circulation rate have a minimal impact, as the water content remains nearly constant. Additionally, as shown in Figure 11, an rising JT inlet pressure lead to a reduction in sales gas water content. These results highlight the importance of optimizing MEG injection rate and JT upstream pressure to enhance dehydration efficiency while maintaining process stability.

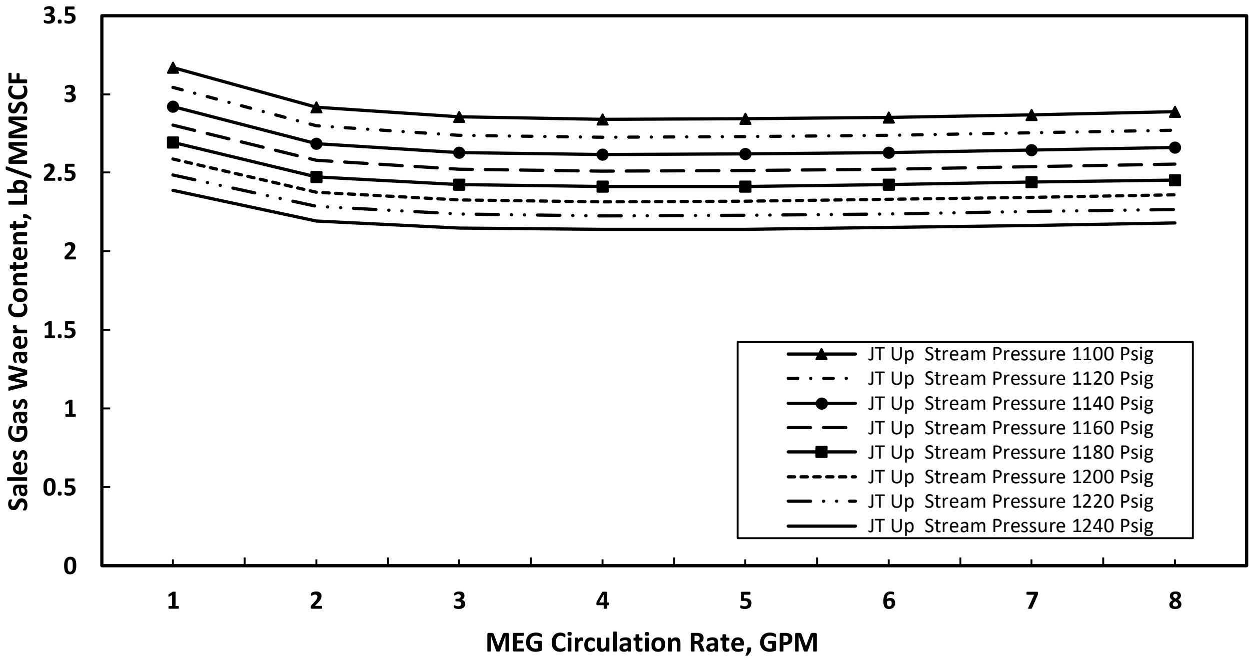


Figure 11 Effect of MEG circulation rate on sales gas water content at different JT upstream pressures, JT downstream pressure of 830 Psig, inlet gas temperature of 35 ^{o}C, reboiler temperature of 135 ^{o}C.

Figure 12 presents the influence of MEG circulation rate on sales gas water content at different JT downstream pressure values, with a JT upstream pressure of 1160 PSIG, a inlet gas temperature of 40°C, and an MEG reboiler temperature of 130°C. The outcomes of the simulator suggest that increasing the MEG circulation rate initially causes a slight decrease in sales gas water content up to a circulation rate of 3 GPM. Beyond this point, further increases in circulation rate have little to no impact, as the water content remains nearly constant. Additionally, as shown in Figure 12, an increase in JT downstream pressure leads to higher sales gas water content.

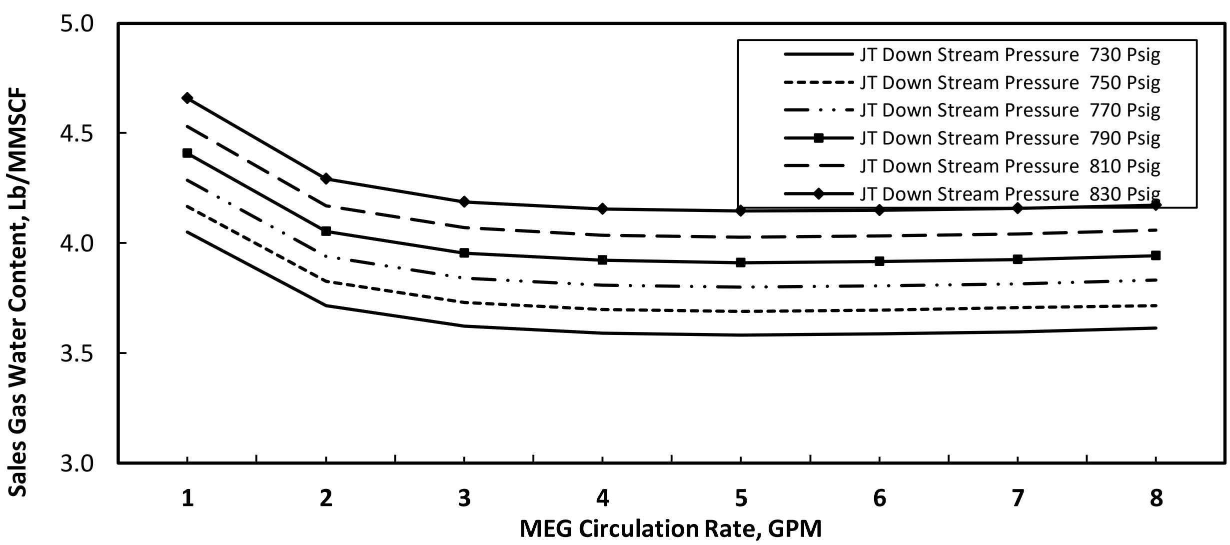


Figure 12 Effect of MEG circulation rate on sales gas water content at various JT downstream pressures with JT upstream pressure of 1160 Psig, inlet gas temperature of 40 oC, reboiler temperature is 130 oC.

Figure 13 illustrates the effect of MEG circulation rate on sales gas water content at different inlet feed gas temperatures, with a JT downstream pressure of 830 Psig, a JT upstream pressure of 1180 Psig, and an MEG reboiler temperature of 120°C. The simulation output cleared that increasing MEG circulation rate has only a slight impact on sales gas moisture content. However, the outputs also clearly indicate that inlet feed gas temperature has a significant impact. As the inlet gas temperature increases, the sales gas water content rises accordingly. A sensitivity analysis was conducted to evaluate the impact of MEG injection rate on moisture content of sales gas at various MEG evaporator temperatures. Figure 14 presents the simulation results for this analysis, with a JT downstream pressure of 770 Psig, a JT upstream pressure of 1200 Psig, and a main feed gas temperature of 35°C. The findings indicate that increasing the MEG circulation rate has only a minor effect on water content of sales gas.

Overall, these results highlight that while MEG circulation rate plays a role in gas dehydration, its impact is limited beyond a certain threshold. Meanwhile, factors such as JT downstream pressure and inlet feed gas temperature have a more pronounced influence on sales gas water content, emphasizing the need for optimized process conditions to achieve effective dehydration.

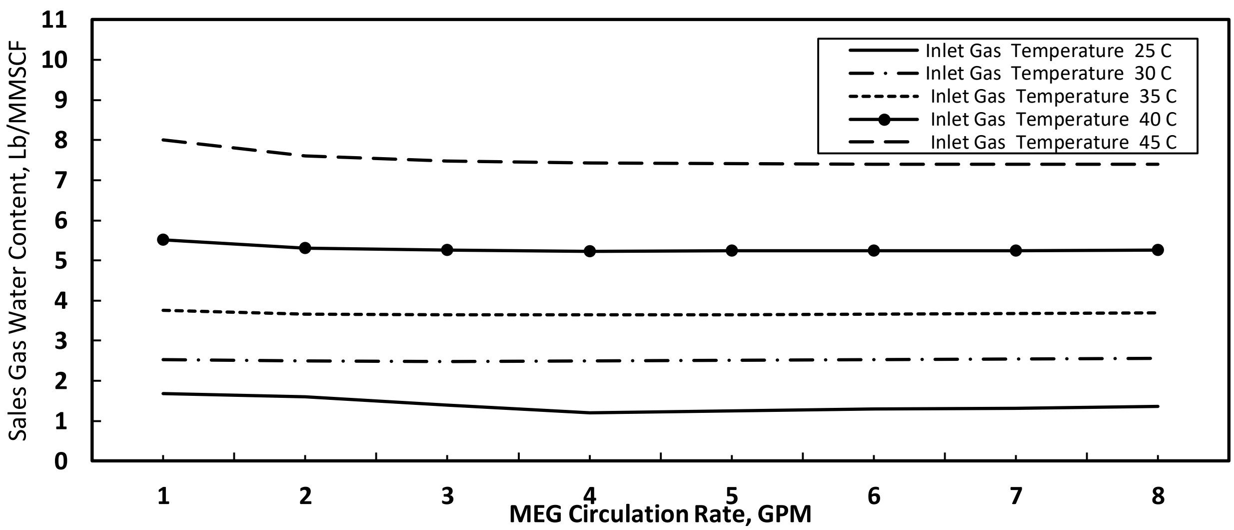


Figure 13 Impact of MEG injection rate on sales gas moisture content at various inlet gas temperatures with JT downstream pressure of 830 Psig, JT upstream pressure of 1180 Psig, and at reboiler temp. of 120 ^{o}C.

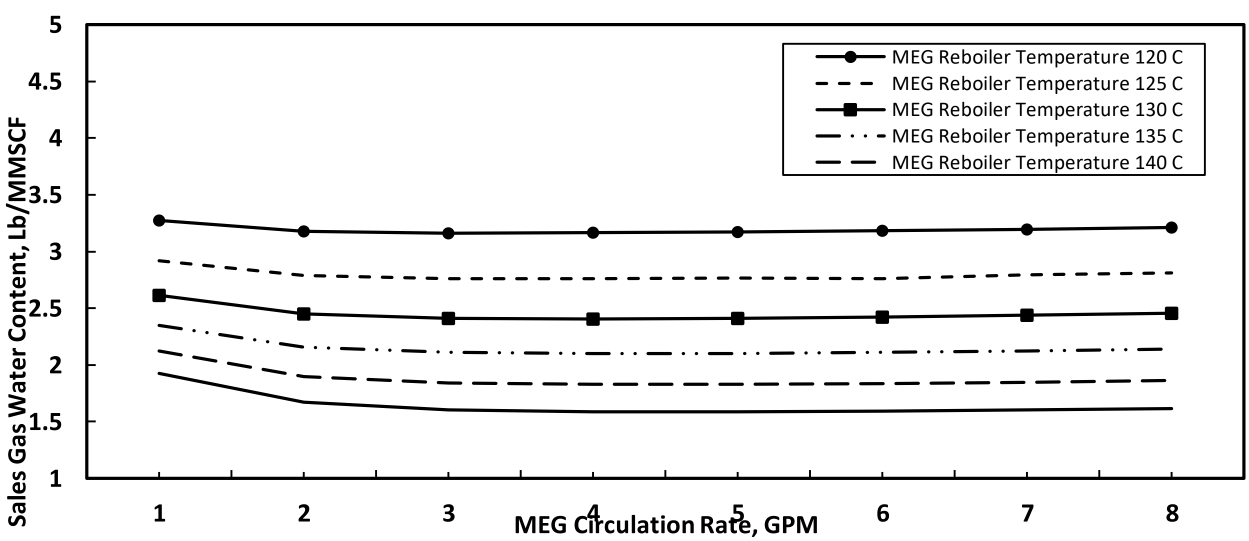


Figure 14 Effect of MEG circulation rate on sales gas water content at different reboiler temperatures: JT downstream pressure is 770 Psig, JT upstream pressure is 1200 Psig, and feed gas temperature is 35 ^{o}C.

Effect of Inlet Feed Gas Temperature

Inlet gas temperature is one of the key parameters affecting sales gas water content. Conducted sensitivity analysis to assess the effect of MEG circulation rate on sales gas water content under different JT upstream pressure, JT downstream pressure, MEG circulation rate and MEG reboiler temperature conditions. Figure 15 illustrates the results of simulation for the impact of inlet gas temperature on sales gas water content at various JT inlet pressure values, with a JT outlet pressure of 790 Psig, MEG circulation rate as 4 GPM, and an MEG reboiler temperature as 130°C. The outputs indicate by increasing the inlet feed gas temperature results in a rise in sales gas water content, whereas an increase in JT outlet pressure leads to a decrease in sales gas moisture content.

Figure 16 presents the Impact of feed gas temperature on sales gas water content at different JT downstream pressure values, with a JT upstream pressure of 1220 Psig, an MEG circulation rate of 5 GPM, and an MEG reboiler temperature of 140°C. The simulation results confirm that as the inlet gas temperature increases, sales gas water content also rises. Additionally, this increase in water content is further amplified by higher JT downstream pressure.

These results highlight the critical role of inlet feed gas temperature in Defining final water content of processed gas, with JT upstream and downstream pressures also playing significant roles in the dehydration process.

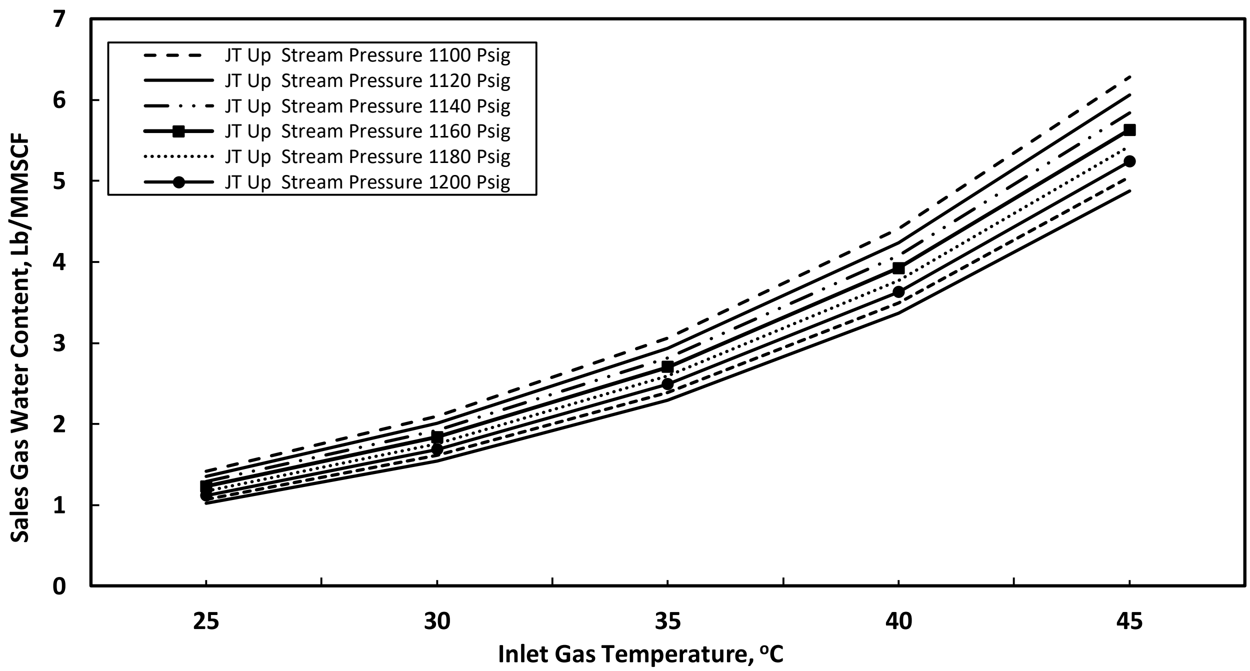


Figure 15 Impact of feed gas temperature on sales gas water content at different JT upstream pressures with a JT downstream pressure of 790 Psig, circulation rate of 4 GPM, and reboiler temp. of 130 °C.

Increasing JT downstream pressure while maintaining constant JT upstream pressure reduces the pressure differential across the JT valve. As a result, the temperature drop across the valve decreases, leading to reduced condensation of liquids, including water and hydrocarbons. Consequently, this results in higher water content in the sales gas. Figure 17 presents The outcomes of the simulation concerning the impact of inlet feed gas temperature on sales gas water content at different MEG reboiler temperature values, with a JT downstream pressure of 730 Psig, an MEG circulation rate of 3 GPM, and a JT upstream pressure of 1160 Psig. The results clearly indicate that by increasing the feed gas temperature results in increasing sales gas water content. Conversely, increasing MEG regeneration temperature results in a reduction in sales gas moisture content. This may be attributed to the fact that a higher MEG reboiler temperature enhances MEG regeneration, increasing its concentration and improving its ability to absorb water from the treated gas, thereby lowering the final water content in the sales gas.

A sensitivity analysis was conducted to examine the impact of inlet gas temperature on export gas water content at various MEG circulation rates. Figure 18 illustrates the simulation results for this analysis, with a JT downstream pressure of 790 Psig, a JT upstream pressure of 1240 Psig, and an MEG reboiler temperature of 130°C. The results indicate that by increasing the feed gas temperature consistently results in higher sales gas water content. However, increasing the MEG circulation rate helps reduce sales gas water content, particularly when the inlet feed gas temperature reaches 45°C.

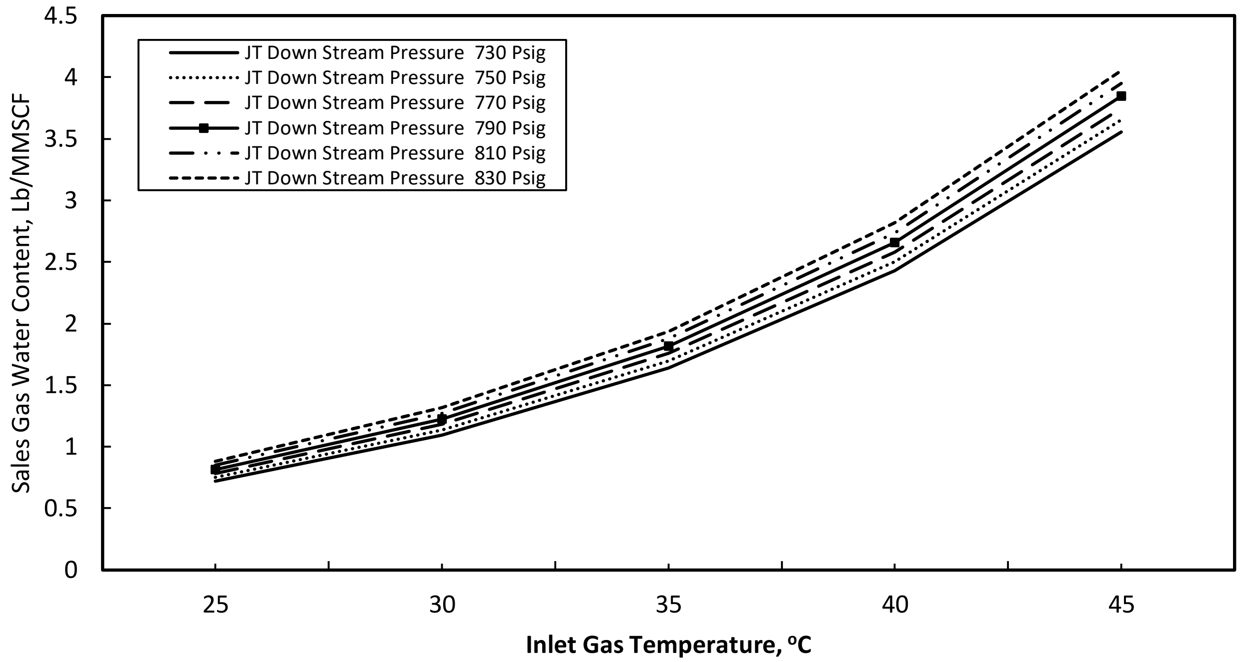


Figure 16 impact of feed gas temperature on sales gas water content at different JT downstream Pressures: JT upstream pressure is 1220 Psig, MEG circulation rate is 5 GPM, and reboiler temp. is 140 °C.

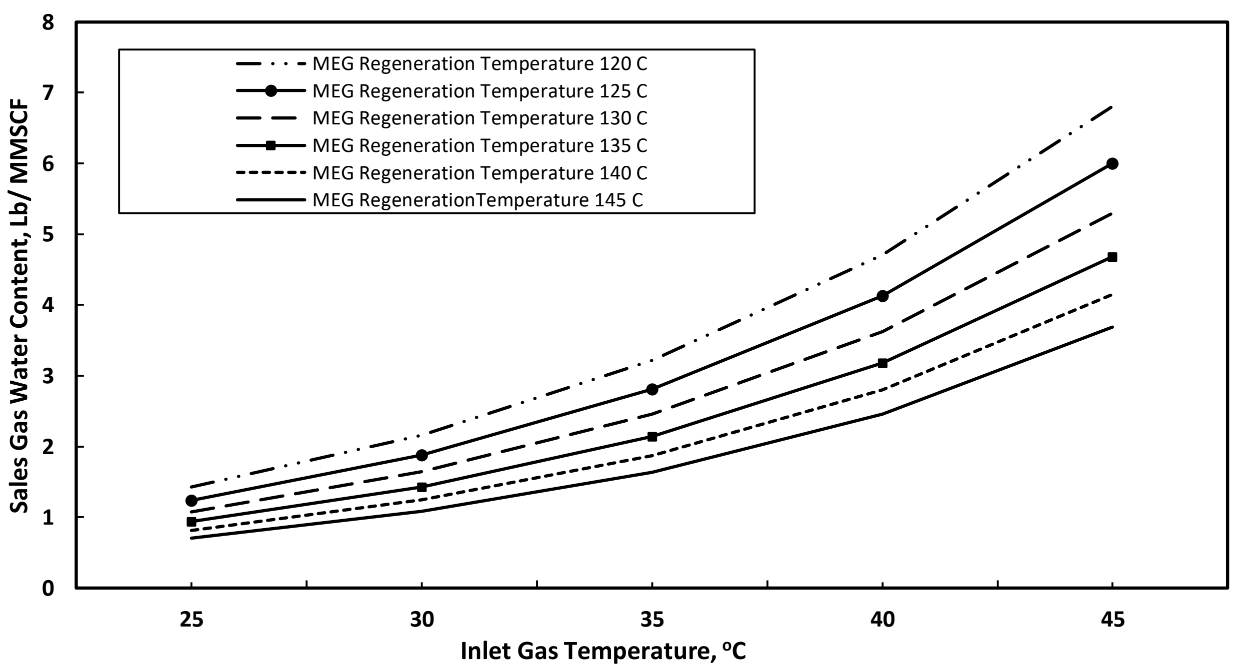


Figure 17 Impact of feed gas temperature on sales gas water content at various reboiler temperatures, JT downstream pressure of 730 Psig, MEG circulation rate of 3 GPM, and JT upstream pressure of 1160 Psig.

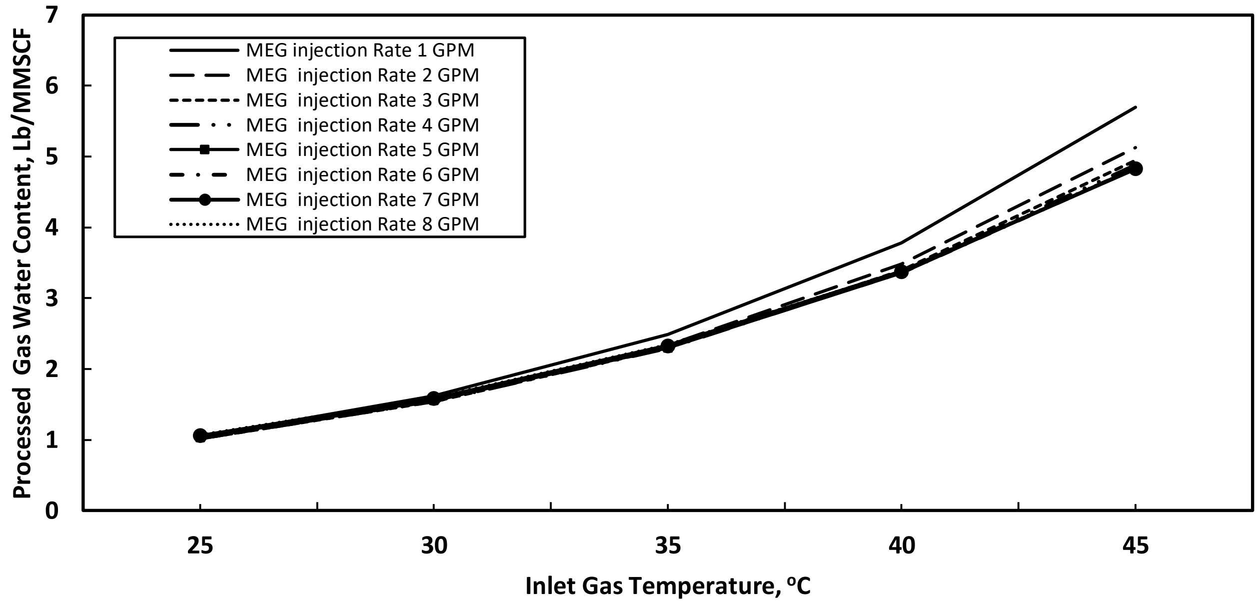


Figure 18 Impact of feed gas temperature on sales gas water content at different MEG circulation rates, JT downstream pressure of 730 Psig, reboiler temp. of 130 °C, and JT upstream pressure of 1240 Psig.

Effect of MEG Reboiler Temperature

The MEG reboiler temperature is one of studied parameters that have effect on sales gas water content. The sensitivity analysis was studied at different values of JT inlet pressure, JT outlet pressure, inlet gas temperature and MEG circulation rate. Figure 19 shows the simulation outputs for the impact of MEG reboiler temperature on sales gas moisture content at different values of JT inlet pressure with a JT outlet pressure of 770 Psig ,inlet gas temperature of 35 oC ,MEG injection of 4 GPM.

It is Noticeable that increasing of MEG reboiler temperature leads to a decrease in sales gas water content and this can be understood as increasing MEG reboiler temperature results in decreasing MEG concentration which positively has an effect on absorption efficiency of MEG and consequently decreasing sales gas water content.

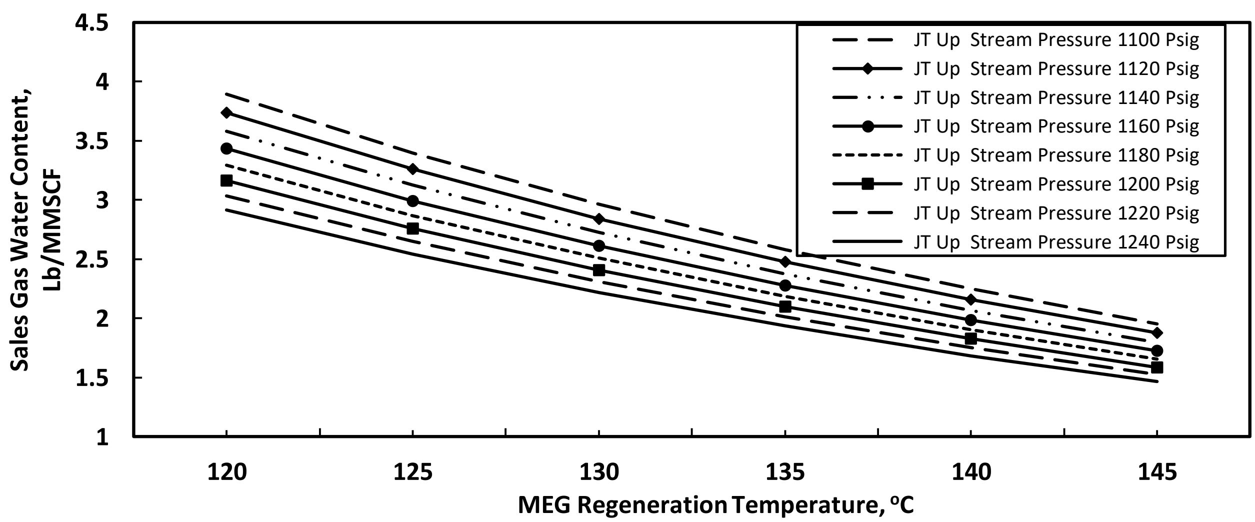
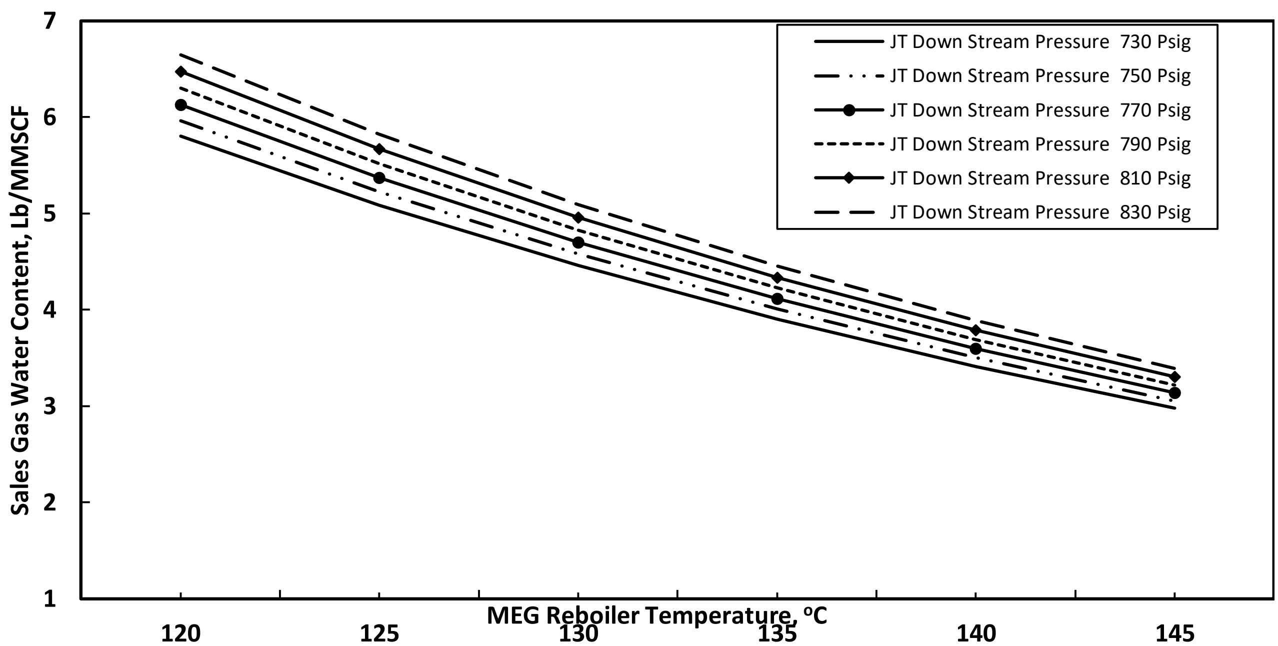


Figure 19 Effect of regeneration temperature on sales gas moisture content at different JT upstream pressure at JT downstream pressure of 770 Psig, MEG injection rate of 4 GPM, feed gas temp. of 35 Psig

The impact of MEG regeneration temperature on sales gas moisture content was studied at various values of JT outlet pressure, with a constant JT upstream pressure of 1240 Psig, MEG circulation rate of 7 GPM, and main feed gas temperature 45°C. Based on the simulation results Presented in Figure 20, it is observed that as the MEG reboiler temperature increased, the sales gas water content decreased. Conversely, increasing JT downstream pressure results an increase in sales gas moisture content.

Additionally, the effect of MEG reboiler temperature on sales gas water content was investigated at various values of inlet gas temperature, with JT upstream pressure set at 1140 Psig, MEG circulation rate of 3 GPM, and JT downstream pressure of 810 Psig. As shown in the results Displayed in Figure 21, increasing MEG reboiler temperature resulted in a decrease in sales gas moisture content. On the contrary, increasing the inlet feed gas temperature results in increasing sales gas moisture content.

Lastly, the effect of MEG reboiler temperature on sales gas moisture content was investigated at different values of MEG circulation rate, with JT upstream pressure of 1140 Psig, inlet gas temperature of 30°C, and JT downstream pressure of 830 Psig. The simulation outputs presented in Figure 22, show that increasing MEG reboiler temperature resulted in decreasing in sales gas moisture content, while the MEG injection rate has a minimal impact on the sales gas moisture content.



is 45 ºC.

Figure 20: Impact of reboiler temperature on sales gas water content at different JT downstream Pressures: JT upstream pressure is1240 Psig, MEG injection rate is 7 GPM, feed gas temp

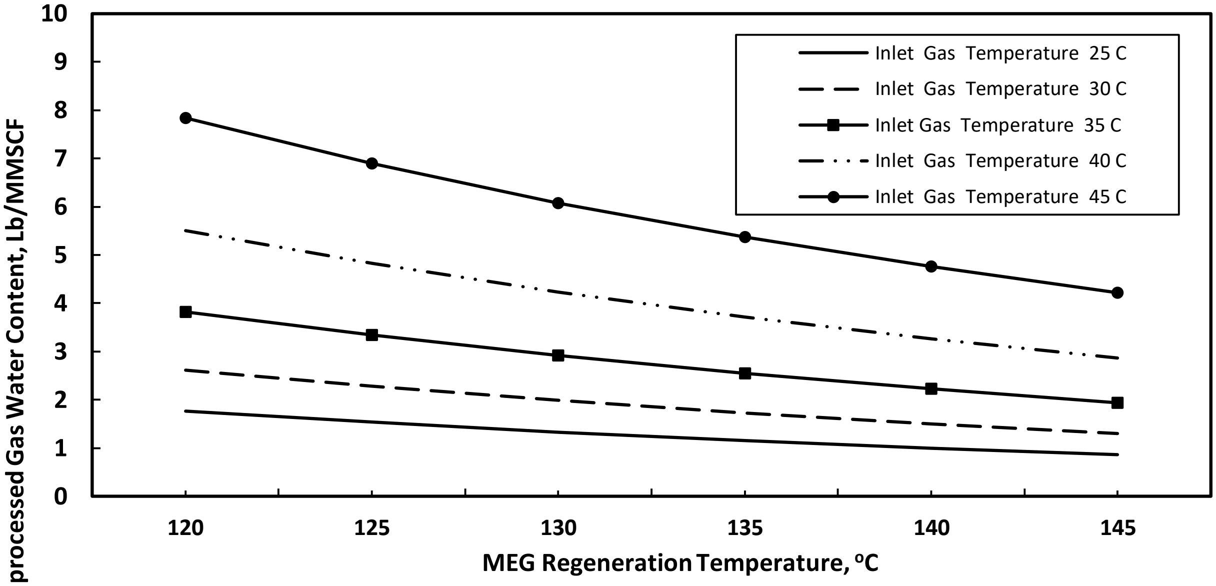


Figure 21 Effect of Regeneration temperature on sales gas moisture content at various feed gas temperatures while JT upstream pressure is 1140 Psig, MEG circulation rate is 3 GPM, and JT downstream pressure is 810 Psig.

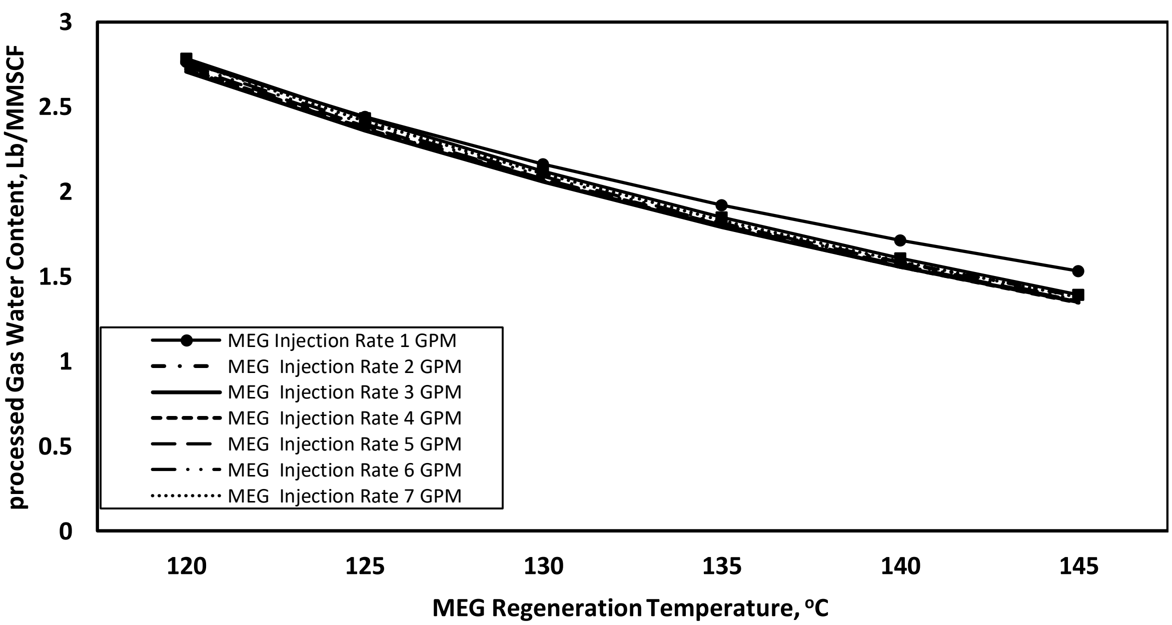


Figure 22 Effect of MEG reboiler temp. on sales gas water content at different MEG circulation

Innovating two correlations to calculate sales gas moisture content and hydrocarbon dew point

One aim of this study is to Initiate two correlations can utilized to depict the impact of the independent operational parameters . (JT inlet pressure, JT outlet pressure, inlet gas temperature, MEG reboiler temperature, MEG circulation rate) on both hydrocarbon dew point temperature and processed gas moisture content. Regression analysis is statistical technique used to identify and measure the connections between operational parameters , using real-world informations collected from experiments. The significance of these relationships is determined using the analysis of variance (ANOVA) test. The two derived correlations for estimating sales gas water content (in Lb/MMSCF) and hydrocarbon dew point temperature (in ^oC) are presented in Equations 1 and 2.

Sales gas water content $= 13.5652-0.00497A+0.0039B-0.7172C+0.162\ C^2-0.01132\ C^3-0.20795F+0.0059\ F^2-0.0553H$ *(1)*

Hydrocarbon dew point $= -46.800-0.029A+0.046B+0.191C-0.025C^2+0.002C^3+1.019F+0.00044F^2+0.049H$ *(2)*

Where A is JT inlet pressure in Psig, B is JT outlet pressure in Psig, C is MEG injection rate in GPM, F is inlet gas temperature in ^oC, H is MEG reboiler temperature in ^oC. The R^2 test, a statistical method, was employed to evaluate the alignment between experimental data and correlations. This test yields a number ranging from 0 to 1, indicating the model's predictive power as described by Lazic [61]. A higher R^2 value signifies a stronger representation of the experimental data, as illustrated by Mapiour et al. [62]. For the first correlation, the R^2 value is 0.93, and for the second correlation, it is 0.99. These values reflect a strong concordance between the experimental data and the correlations, thereby confirming the validity of the two equations within the studied operating variables.

These two correlations, which are simple and easy to use, can be utilized by process engineers or other workers to forecast the moisture content and hydrocarbon dew point temperature of natural gas. Obtaining correlations to calculate natural gas water content and natural gas hydrocarbon dew point temperature to plant that use refrigeration by JT valve technology as dehydration method is not addressed in previous research works. Many correlations are introduced to calculate sales gas water content and sales gas hydrocarbon dew point are conducted to plants that use absorption by TEG. The correlation extracted from the present study can be utilized to determine the sales gas water and hydrocarbon dew point using a basic calculator under any operating conditions of the NGDU plant.

Optimization of operational parameters

Enhancing natural gas dehydration process using the cooling technique by JT valve can be achieved by optimizing the system, which includes adapting the operating parameters. Regarding the previous discussion, it is discovered a significant impact of the operating parameters on the dew point of the outgoing processed gas. It is good mentioned that by applying cooling technique by JT valve in dehydration process the levels of BTEX emissions reach ZERO emissions. One of the main goals of this research paper is to optimize the natural gas dehydration plant to determine the best operating parameters that will accomplish the following two objectives:

1- Reduce sales gas moisture content to meet pipeline specifications.
2- Reduction of sales gas dew point temperature to be in the acceptable range of sales gas specification.

LINGO optimization software (version 18) is applied to obtain the optimal operating parameters for achieving the lowest moisture content in sales gas while maintaining the dew point of hydrocarbons in sales gas within an acceptable range of 0 ^oC to -5 ^oC at 700 Psig. By utilizing this optimization program, it becomes possible to predict and estimate the best operating parameters for the inlet gas temperature, JT valve inlet pressure, JT valve outlet pressure, MEG reboiler temperature, MEG circulation rate. The program's solution for the JT unit provides the optimal operating conditions to reduce sales gas water content while ensuring that the hydrocarbon dew point remains within the range of 0 ^oC to -5 ^oC at 700 Psig.

The optimization problem is defined by the Subsequent equations and constraints: the Purpose function aims to minimize the moisture content in sales gas while ensuring that the hydrocarbon dew point remains within the required range. The model formulation employed in Lingo optimization software to ascertain the optimal conditions of the natural gas dehydration unit can be summarized by equations (3-12). The main objective of this optimization is to minimize the moisture content in the sales gas.

min = Processed gas water content.(3)

Processed gas water content $= 13.5652-0.00497A+0.0039B-0.7172C+0.162\ C^2-0.01132\ C^3-0.20795F+0.0059\ F^2-0.0553H$ (4)

Subject to the following constraints:

Hydrocarbon dew point temperature >=0 (5)

Hydrocarbon dew point temperature <=-5 (6)

Hydrocarbon dew point $= -46.800-0.029A+0.046B+0.191C-0.025C^2+0.002C^3+1.019F+0.00044F^2+0.049H$ *(7)*

JT Upstream pressure constraint:

1100 ≤ **A** ≤ 1240; (8)

JT down Stream Pressure constraint:

730 ≤ **B** ≤ 830; (9)

MEG Circulation Rate constraint:

1 ≤ **C** ≤ 8; (10)

Main Feed Gas Temperature constraint:

25 ≤ **F** ≤ 45; (11)

MEG Reboiler Temperature constraint:

120 ≤ **H** ≤ 145; (12)

The constraints' upper and lower limits are established by analyzing experimental data from an existing unit located in western desert, as well as adhering to maximum operational parameters of the process equipment. The global optimal solution indicates that the minimum sales gas water content level while keeping sales gas hydrocarbon dew point in the acceptable temperature range of 0 ^oC to -5 ^oC at 700 Psig can be achieved at JT upstream pressure of 1150 Psig , JT downstream pressure of 830 Psig, MEG injection rate of 8 GPM, inlet gas temperature of 33 ^oC ,MEG reboiler temperature of 145 ^oC. By implementing the obtained optimum variables in the mentioned plant, the sales gas water content of 1.4 Lb/MMSCF, hydrocarbon dew point of 0 ^oC, and zero BTEX emissions can be obtained for the investigated the plant.

Conclusion

This study on gas dehydration using a JT plant has provided valuable insights into optimizing operating parameters to achieve both efficient water removal and minimal BTEX emissions. The primary goal of eliminating water vapour from natural gas to meet sales requirements and inhibit issues like hydrate formation ,corrosion was effectively addressed, with a focus on reducing BTEX emissions. Notably, the study demonstrated that no emissions were released from the MEG reboiler or flash separator during the regeneration process when utilizing this cooling technology.

Using HYSIS simulation software, the study highlighted the significant influence of operating variables such as JT inlet pressure, JT outlet pressure, inlet gas temperature, and MEG reboiler temperature on sales gas water content, while MEG circulation rate has a negligible effect. The strong correlation between experimental and simulated data (R^2 = 0.99) confirmed the accuracy of the simulation results. Furthermore, optimization of these operating parameters using LINGO software leads to the identification of optimal conditions for minimizing water content in sales gas while maintaining an acceptable hydrocarbon dew point temperature. The results obtained suggest that the minimum level of sales gas water content while keeping sales gas hydrocarbon dew point in the acceptable range of sales gas specifications can be achieved at JT upstream pressure of 1150 Psig, JT downstream pressure of 830 Psig, MEG injection rate of 8 GPM, inlet gas temperature of 33 ^oC, MEG reboiler temperature as 145 ^oC.

Additionally, two new correlations were developed through regression analysis, offering practical tools for accurately calculating sales gas water content and hydrocarbon dew point. These correlations are innovative and fill a gap in existing research. The findings of this study can be implemented to other natural gas dehydration processes, contributing to enhanced operational efficiency, improved profitability, and compliance with environmental regulations related to BTEX emissions. This study can be implemented in other natural gas dehydration plants to enhance profitability and ensure emissions are within acceptable limits as per environmental regulations.

Funding Sources

This research received no external funding

Conflicts of Interest

There are no conflicts to declare

Nomenclature

BTEX = Benzene, Toluene, Ethylbenzene, and Xylene

VOCs = Volatile Organic Compounds

NGDU = Natural Gas Dehydration Unit

TEG = Triethylene Glycol

EPA = Environmental Protection Agency

HYSYS = A software tool for processsimulation and optimization

Lingo = A software tool for linear and nonlinear mathematical optimization models

MMSCF =Million standard cubic feet

DPCU = Dew Point Control Unit

Funding Sources

This research received no external funding.

Conflicts of Interest

There are no conflicts to declare.

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