

Technical, Economical, and Environmental Performance Assessment of an Improved Triethylene Glycol Dehydration Process for Shale Gas

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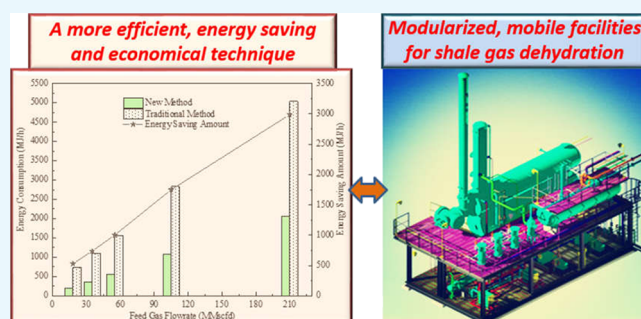
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ABSTRACT: We proposed an optimized triethylene glycol (TEG) dehydration approach in this work, with the aim of overcoming the drawbacks of traditional TEG dehydration method for shale gas processing and providing a more efficient, simplified, energy-saving, economical, and environmentally friendly technology dedicated for shale gas exploration. The proposed improved TEG dehydration method has less equipment and is convenient for modularization, which is of great significance and convenience to applications in the shale gas dehydration station. Additionally, it has some remarkable improvements on process optimization as well as the rational utilization of utilities. To evaluate the performance of this improved method, thermodynamics and economy were assessed in this study. The results proved that the new proposed method was an applicable and efficient technology. Moreover, in comparison to the conventional TEG dehydration method, the new method is more energy saving and economical. The energy-saving amount is especially high with a large feed capacity, and it reaches up to about 3000 MJ/h when the feed gas flowrate is 210 MMscfd. The capital cost (CapEx) and operation cost (OpEx) of the new proposed dehydration method are significantly lower, which represent only 56.9 and 47.8% those of the conventional method, respectively. Besides, sensitive analysis of the key parameters influencing system performance was performed to explore the energy-saving potential and to maximize the economic benefit. Additionally, an environmental assessment through a field-emission test was conducted, and the results showed that the new method exhibited superior environmental performance.



1. INTRODUCTION

As a type of clean energy with abundant reserves, shale gas is regarded as one of the most promising replacements for conventional energy in the future.¹ According to the report from Energy Information Administration (EIA), global shale gas production has reached $7688 \times 10^8 \text{ m}^3$, for which America made the main contribution and it projects that the majority of U.S. dry natural gas production through 2050 will be from shale and tight gas resources.² As the second largest reservoir all over the world, China is accelerating the shale gas exploration and utilization to meet the increasing energy requirement, and the annual production of shale gas has increased by 10 times from year 2014 to 2020.³ Shale gas production is expected to account for more than 30% of the total natural gas supply in China by 2040.⁴

Different from conventional natural gas field, shale gas wells are numerous and widely distributed, meanwhile the production along with the well head pressure decline rapidly. Therefore, the modularized and transportable processing plants, which can be relocated within the field to combat the uncertainty in production that comes along with the development of a shale

gas field, become meaningful and necessary.⁵ What is more, most of the shale gas fields in China are located close to densely populated areas which may pose environmental and health risks.⁶ Hence, for shale gas exploration, it is imperative to minimize the occupied area and achieve the facility relocation and reutilization, as well as quickly put the facilities into operation and in the meantime reduce the environmental pollution.

Shale gas in most areas presents as sweet gas which contains no acid components. However, it is generally saturated with water, which leads to several drawbacks including hydrate formation, corrosion of pipelines, and reduction in the heat capacity.^{7,8} Thus, to ensure safe processing and transportation, it is necessary to remove water vapors from shale gas before its

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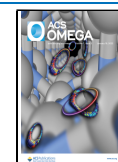


Table 1. Pros and Cons of Different Dehydration Methods

items	refrigeration-based method	solid desiccant adsorption	liquid desiccant absorption
advantages	①water dew point of dry gas could meet transportation requirements ②simple process	①water dew point of dry gas could reached $<-50\text{ }^{\circ}\text{C}$ ②less influenced by feed gas conditions	①water dew point of dry gas could meet transportation requirements ②mature process, widely utilized ③low CapEx and OpEx ④low energy consumption
disadvantages	①formation of natural gas hydrates which requires hydrate inhibitors ②high energy consumption	①high CapEx and OpEx ②high energy consumption in solid desiccant regeneration	①the solvent foams easily when heavy hydrocarbon content in the feed gas is high

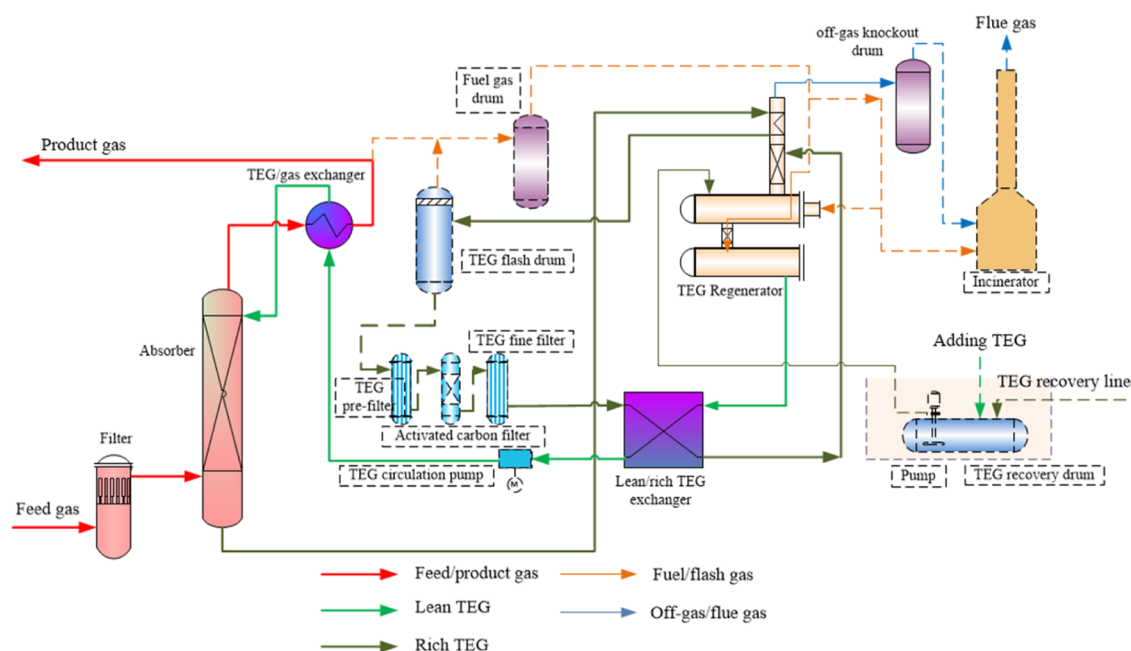


Figure 1. Traditional TEG dehydration process flow diagram.

transmission and combustion. Extensive research has been conducted on different natural gas dehydration methods, including solid/liquid desiccant and refrigeration-based approaches.^{9–11} Among these methods, a refrigeration-based method which involves condensation by cooling is simplest. However, this method is seldom utilized due to the drawbacks of the formation of natural gas hydrates which requires hydrate inhibitors.¹² What is more, the consumption for gas cooling is significant unless the pressure of the feed gas is high enough.¹³ Solid desiccant adsorption can achieve a very low water concentration in the dry gas with a water dew point as low as $<-50\text{ }^{\circ}\text{C}$.^{14,15} However, the adsorption method offers high capital cost (CapEx) and operating cost (OpEx) compared to other natural gas dehydration technologies. It is claimed that CapEx for solid desiccant adsorption can be 2–3 times higher than that of the liquid absorption method.¹⁴ Thus, the absorption via a solvent is the most commonly adopted method because of its economic and technical benefits.^{14,16} The comparisons between absorption and other dehydration methods are depicted in Table 1. In terms of liquid desiccant absorption technologies, several glycols have been found to be suitable for commercial applications, such as ethylene glycol, diethylene glycol, tetraethylene glycol, and triethylene glycol (TEG). Among different kinds of liquid desiccants, TEG is the most widely used solvent for absorption, owing to its low volatility, high hygroscopicity, and high thermal stability.^{17,18} Due to the perfect performance

of TEG application in the natural gas dehydration field, numerous research focuses on the TEG dehydration process to improve the dehydrating performances, such as predicting water removal efficiency,^{19,20} estimating TEG purity with a new method,²¹ equipment sizing and type selection,^{22,23} studies on the influence of solvent purity,^{24,25} the equilibrium model optimization,²⁶ the stripping gas injection,^{27–29} and so forth. Although extensive literature studies are available on the process simulation and parameter optimization of the natural gas dehydration process, none of the researchers focuses on the process optimization aiming at adaption to the rolling exploration of the shale gas field, for which device modularization and relocation as well as environmental performance are the major concerns. With the development of shale gas field exploration in recent years in China, some limitations have been found for the traditional TEG process utilized for shale gas dehydration. Here are some points that need to be improved for the traditional TEG dehydration process used in shale gas processing as follows:

- (1) Because off-gas from the top of the regenerator is often vented to the atmosphere after combustion, it will lead to serious environment pollution and also energy waste.³⁰
- (2) The traditional process is complicated with many various equipment; thus, it is unsuitable for a highly integrated requirement of the mobile modularized unit in the shale gas dehydration station.

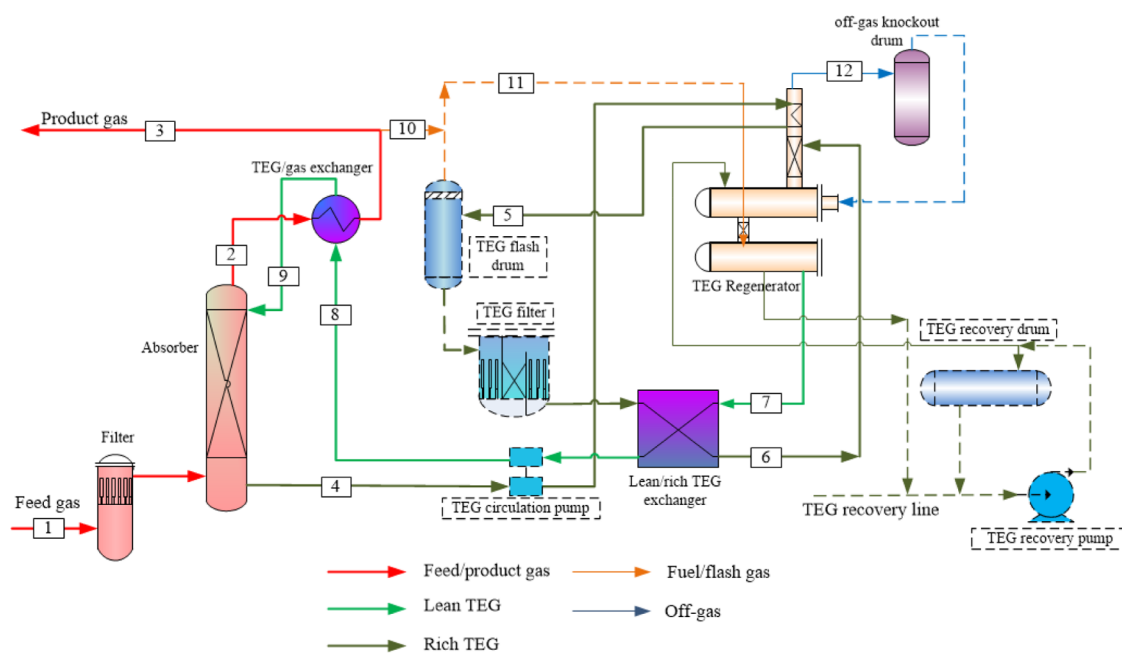


Figure 2. New improved process flow diagram.

- (3) For waste TEG generated during maintenance, it is always collected by gravity and thus the TEG collection drum needs to be located underground, which adversely affects modularization and relocation.
- (4) The complicated process and high energy consumption will definitely result in negative impacts on the economic performance, which is undesirable in shale gas exploration.

To make up these shortages of the traditional TEG dehydration process for shale gas processing, an improved TEG dehydration approach dedicated for shale gas exploration has been proposed and studied in this article. The performance of this proposed improved method was elaborated from aspects of energy efficiency, energy saving rate, economic, environment influence, and so forth. Additionally, sensitive analysis of the key parameters influencing system performance was performed to explore the energy-saving potential and to maximize the economic benefit. It is encouraging that the benefits from this improved process have been proved in industrial shale gas plants and it is generally accepted as an applicable and reliable method for shale gas dehydration.

2. PROCESS INTRODUCTION AND IMPROVEMENTS

2.1. Traditional TEG Dehydration Process. Figure 1 illustrates the schematic flow chart of the conventional TEG dehydration process. The typical TEG dehydration process consists of four major sections, and the detailed description is presented as the following section.

2.1.1. Raw Gas Treatment. The raw gas feed is first introduced to the feed gas filter to remove the impurities and the free liquid. Then, the raw gas enters from the bottom of the absorber and the lean TEG feed enters from the top. The solvent flowing downward absorbs water from the wet gas. After absorption, the dry gas leaves from the top of the absorber and rich TEG leaves from the bottom. The dry gas then passes through the dry gas/lean TEG solvent heat exchanger for heat exchange before being delivered to downstream processes or pipelines.

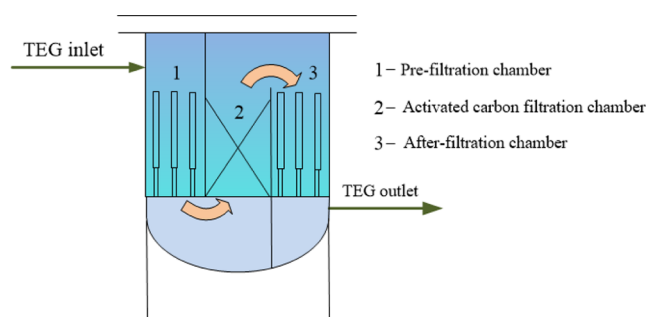


Figure 3. Schematic diagram of three-in-one integrated filter configuration.

2.1.2. TEG Solvent Circulation. Rich TEG from the bottom of the absorber arrives the TEG coil condenser to be preheated through exchanging heat with the hot vapor in the TEG regeneration column. Afterward, this rich TEG stream enters the flash drum, which removes any trapped gases and volatile components. Later, the rich TEG solvent goes into the three filters successively to remove the impurities and degradation products. Following the rich solvent goes into a lean/rich TEG exchanger by exchanging heat with a lean solvent and then is delivered to the TEG reboiler, to regenerate the TEG solvent by heating it to approximately 202 °C, which is regarded as approaching the upper limit for TEG processing because of thermal degradation at higher levels.³¹ In an effort to acquire glycol with a high purity, the stripping gas is injected from the reboiler that flows upward in the column, which can greatly enhance the solvent regeneration.²⁹ After regeneration, the lean solvent flows to the TEG buffer drum and the lean/rich TEG exchanger sequentially for heat recovery and is subsequently pumped to the dry gas/lean TEG solvent heat exchanger before being recycled back to the absorber.

2.1.3. Flash Gas/Off-Gas/Stripping Gas/Fuel Gas Process. Flash gas from top of the TEG flash drum enters the fuel gas drum for fuel gas use and in the meantime, part of the dry gas split from the dry gas pipeline is supplemented as fuel gas by

means of decreasing pressure by a pressure control valve. In terms of off-gas evacuation, as the operating pressure range of most still columns is between 1.7 and 5.2 kPa,^{32,33} and pressure more than 7 kPa could lead to glycol loss from the still column and reduction of both lean glycol concentration and dehydration efficiency,³⁴ off-gas from top of the TEG still column is often sent to an independent incinerator instead of the flare system. Stripping gas for the still column, and fuel gas for a reboiler and off-gas incinerator are all supplied from the fuel gas drum.

2.1.4. Waste TEG Solvent Collection and Recycle. A waste solvent collection drum equipped with a pump is always considered for collecting the residual TEG solvent in the system during maintenance and pumping the collected solvent back to the system once the unit starts working. The common practice is located the drum in an underground pit.

2.2. New Improved TEG Process. As mentioned above, for a traditional TEG dehydration process, there are many equipment, which is adversely beneficial for a modularized and mobile facility design. With the development of shale gas exploration and urgent demands of simple and mobile facilities for the shale gas gathering station or trial-produced well,^{35,36} efforts on simplifying and optimizing the TEG dehydration process to enhance the facilities' integration level as well as environmental performance and, in the meantime, decrease the energy demand and cost have become meaningful. For this reason, we developed the new improved process with some improvements on equipment selection, process optimization, and so forth.

Figure 2 illustrates the new improved process flow diagram. The beginning part of the new approach, as the raw gas treatment section, is consistent with the traditional process and the outstanding difference highlighted in a dashed line of Figures 1 and 2 mainly concentrates on part 2–part 4 described in Sections 2.1.2–2.1.4 of the traditional process. In comparison to the conventional process, several improvements and advantages can be expected for this new process:

- (1) The first optimization is about flash gas/off-gas/stripping gas/fuel gas disposal process. A fuel gas drum is removed, with a TEG flash drum employed as a fuel gas drum concurrently. The supplementary gas pipeline is connected directly to a TEG flash drum. The flash gas is introduced to the regenerator as stripping gas, and the off-gas is delivered to a TEG reboiler for combustion instead of fuel gas. Consequently, an off-gas incinerator is unnecessary, which makes the process simplified and thus potential benefits to reduce energy consumption as well as capital investment can be expected. Moreover, the emissions generated from off-gas combustion could be avoided and it is more environmentally friendly than the traditional method.
- (2) The second optimization is on TEG filters. For the conventional process, three-stage filters as pre-filter, activated carbon filter, and fine filter are often considered to achieve thorough filtration. A new type of filter, namely, three-in-one filter which integrates the three filters into one multifunction equipment is utilized in the newly design approach. Figure 3 presents the configuration of the three-in-one filter. There are three chambers in this filter, namely, pre-filtration chamber, activated carbon filtration chamber, and after-filtration chamber. The three chambers are connected successively to achieve the internal flow of the TEG solvent. The newly designed

filter combines the function of mechanical pre-filtration, degradation product filtration, and mechanical fine-filtration, which greatly reduces the cost of the equipment and requires a smaller occupied area in comparison to the conventional practice. This configuration is greatly beneficial for modularization.

- (3) The third optimization involves lean TEG circulation pump selection and energy utilization. It is common to utilize a motor-drive pump as the TEG circulation pump for conventional process. A kind of energy-recycle pump is employed in this new dehydration technology, which can transfer the energy from high-pressure rich TEG to low-pressure lean TEG. A small amount of the high-pressure wet gas is introduced to provide the motivation energy for the pump, as well as to compensate the energy loss due to the system frictional resistance. Through the energy exchange, lean TEG becomes a high-pressure stream, while rich TEG becomes a low-pressure stream. The detailed structure and working principle of the energy-recycle pump have been elaborated elsewhere.³⁷ The wet gas carried into the pump is finally sent to the TEG flash drum and used as fuel gas after flashing out. This energy-recycle pump consumes neither electric energy nor other external energy, which is more energy efficient and carries lower OpEx in comparison to a traditional motor pump.
- (4) The last one refers to waste TEG collection system optimization. A common practice for waste solvent collection and recycle is shown in Figure 1. The collection drum is needed to be located in a pit to achieve the solvent collection by gravity. This way is against the modular design and facility relocation as well as convenient operation, thus an improvement is made in this research with locating the collection drum above the ground and a dedicated bidirectional material transfer process of the pump is considered to achieve the solvent collection and the recycle.

All these optimizations make the improved dehydration process more simplified, convenient for modularization, environmentally friendly, energy saving, and economical. To sum, it is a reliable and optimal process for shale gas exploration.

3. METHODOLOGY AND KEY PARAMETER SETTINGS

3.1. Methodology. The performance of the new method was evaluated by simulation. The simulation model is established using industrial software Aspen HYSYS (v11), which is widely used in the oil and natural gas processing field.

Table 2. Parameters of Feed Gas and Specification of Sales Gas

parameters	units	value
volume flowrate	MMscfd	18/35/55/105/210
pressure	MPa	5.4
temperature	°C	35
composition	CH ₄	98.55%
	C ₂ H ₆	0.6%
	C ₃ H ₈	0.03%
	CO ₂	0.4%
	N ₂	0.32%
	H ₂ O	0.1%
sales gas specification	water dew point	≤−5 °C

Table 3. Key Parameters of Each Stream Shown in Figure 2 for Simulation

stream no.	pressure MPa	temperature °C	molar flowrate kmol/h
1	5.4	35	897
2	5.35	35.7	895.8
3	5.32	37	895.8
4	5.37	35.5	4.2
5	0.4	63.8	4.2
6	0.22	150	4.1
7	0.02	175	3.2
8	6.5	91	3.2
9	6.2	45	3.2
10	5.32	37	0.25
11	0.4	63.8	0.3
12	0.01	99.2	1.2

The fluid package selected for simulation by Aspen HYSYS is the Glycol package, which is specially used for glycol dehydration. This thermodynamic package uses the Two-Sim-Tassone (TST) EoS combined with a NRTL activity coefficient model through advanced mixing rules. It represents the compressibility more accurately than other methods like the Redlich–Kwong equation of states, including the Soave modified version, and the Peng and Robinson equation of state. Moreover, the glycol package has the essential pure and binary interaction parameters for components usually used in the dehydration process. Salman et al.³⁸ conducted the comparison between glycol package and GPSA-recommended model for TEG dehydration in predicting the water content. The results evinced the validity of the TST–NRTL model used in the glycol package, which demonstrated that the glycol package could predict accurate results and could be used for developing a TEG dehydration model. The required feed data and sales gas specification to develop the simulation are listed in Table 2, which are determined based on the information of the shale gas field in the Changning district, Sichuan basin in China.³⁹

3.2. Key Parameter Settings. A feed gas capacity of 18 MMscfd was taken as an example, the detailed parameters

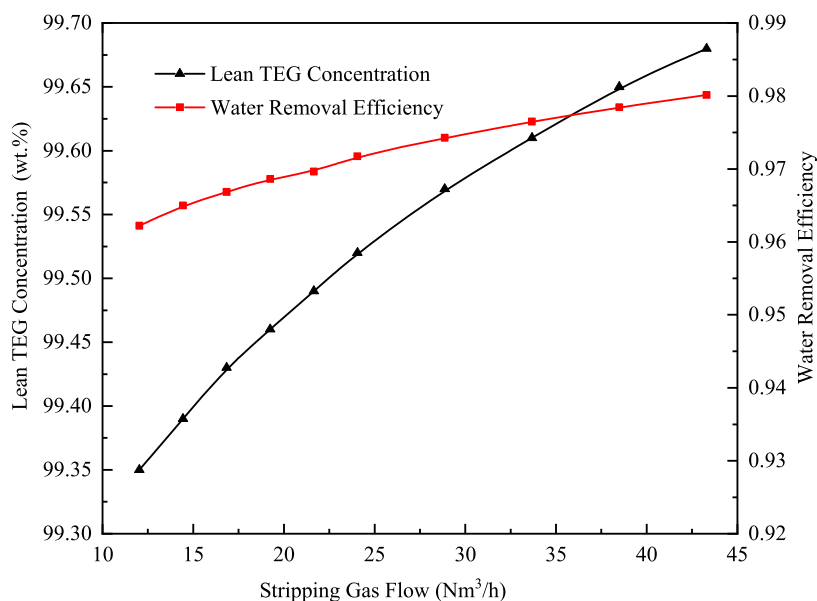
(pressure, temperature and flowrate) of each stream in Figure 2 are shown in Table 3. Notably, for the sake of meeting sales gas specification (Table 2), the water dew point is controlled to about $-9\text{ }^{\circ}\text{C}$ with a $4\text{ }^{\circ}\text{C}$ design margin considered. Regarding the solvent regeneration section, it is reported that the TEG decomposition temperature should be approximately $205\text{ }^{\circ}\text{C}$.⁴⁰ According to Gironi et al. and Piemonte et al.,²⁴ the limit of the regeneration temperature is $204\text{ }^{\circ}\text{C}$ for TEG. Thus, the reboiler temperature is fixed at $202\text{ }^{\circ}\text{C}$ to avoid the thermal decomposition of glycol. In our work, the pressure in the regenerator is kept constant and slightly above atmospheric (see Table 3).

The key parameters for TEG dehydration technology are related to TEG absorption and solvent regeneration. From the comparison of the traditional process and the new method through Figures 1 and 2, it can be seen that in terms of the absorber and regenerator, the two approaches are essentially consistent. The sensitive analyses in the aspects of feed gas pressure, temperature, and number of column trays for the traditional TEG dehydration process have been reported in many literature studies;^{11,28,41,42} thus, they are not included in our work. The numbers of trays for the absorber and regenerator are 5 and 3, respectively, as these values are found to be most feasible for the gas dehydration process.³⁸

In simulations performed for the new dehydration method, all parameters from Table 3 are kept unchanged, except the stripping gas flowrate, which will be chosen after process simulation and sensitive analysis.

4. RESULTS AND DISCUSSION

4.1. Key Parameter Optimization. To enhance the performance and maximize the potential benefits of this improved dehydration method for shale gas, the intrinsic correlation of dehydration performance with key parameters, such as the lean solvent concentration, stripping gas consumption, and TEG circulation rate, is investigated through simulation. First, the sensitivities of the water removal efficiency and lean TEG concentration against the stripping gas flow have been analyzed. In this simulation, the TEG feed and the TEG

**Figure 4.** Variation of the lean TEG concentration and water removal efficiency at different stripping gas flows.

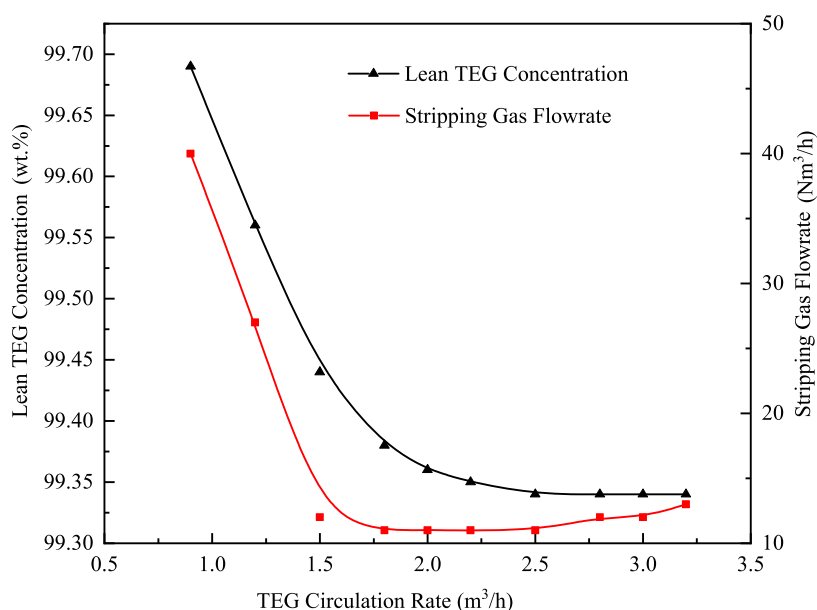


Figure 5. Variation of the lean TEG concentration and stripping gas at different TEG circulation flowrates.

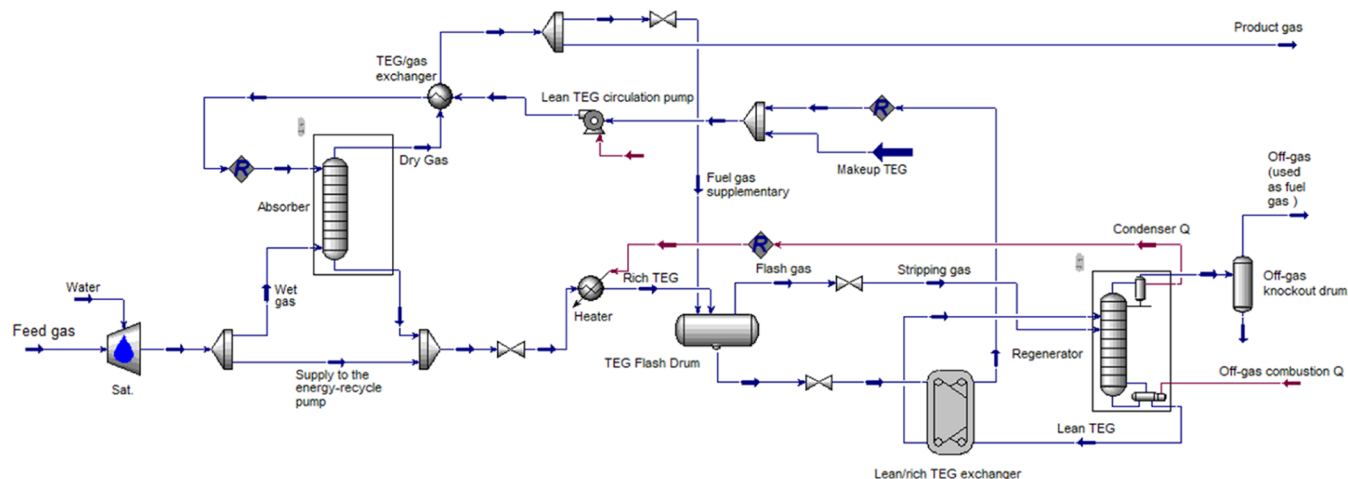


Figure 6. Aspen HYSYS process flow diagram of the new TEG dehydration method.

Table 4. Simulation Results of the New Dehydration Method

feed gas flowrate MMscfd	TEG circulation rate (m ³ /h)	lean TEG concentration (wt %)	water dew point (°C)	heating duty of the regenerator (kW)
18	0.4	99.35	−9.1	37
35	0.8	99.34	−8.9	72
55	1.2	99.31	−8.9	108
105	2.5	99.33	−9.0	220
210	4.5	99.32	−9.1	415

circulation rate are fixed at 105 MMscfd and 2.5 m³/h, respectively. The water removal efficiency is calculated by the following eq 1.

$$R = \frac{W_{in} - W_{out}}{W_{in}} \quad (1)$$

where R denotes the water removal efficiency; W_{in} denotes the mass flowrate of water in wet gas, kg/h; and W_{out} denotes the mass flowrate of water in dry gas, kg/h.

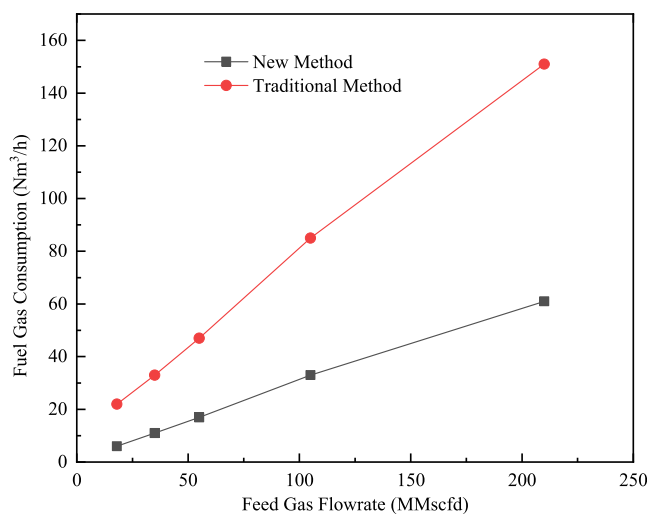


Figure 7. Fuel gas consumption comparison at different feed gas flowrates.

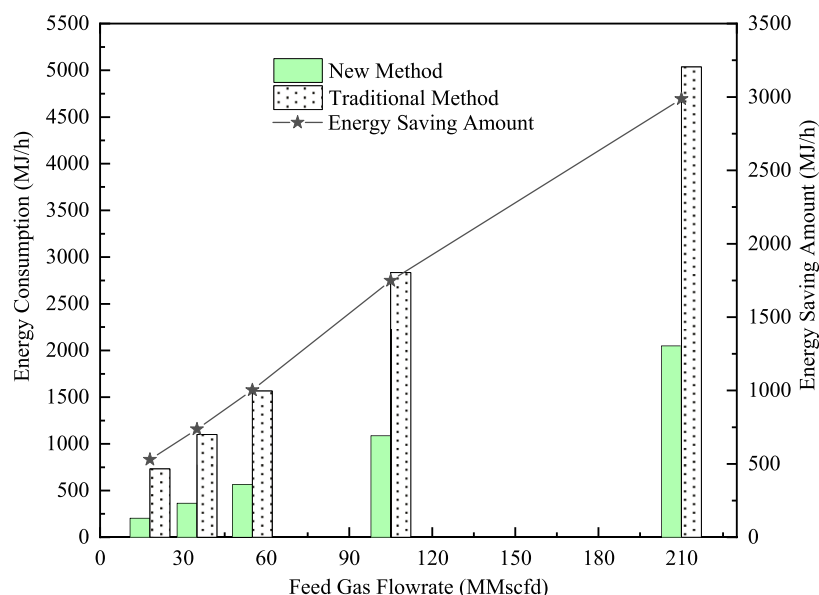


Figure 8. Energy consumption comparison at different feed gas flowrates.

Table 5. Chang Ning Raw Gas Conditions and Compositions

property	units	value
normal flow	MMscfd	18
pressure	MPa	5.0–5.4
temperature	°C	~30
composition	CH ₄	98.76 (v) %
	C ₂ H ₆	0.39 (v) %
	C ₃ H ₈	0.03 (v) %
	CO ₂	0.35 (v) %
	N ₂	0.32 (v) %
	He	0.07 (v) %
	H ₂ O	0.08 (v) %

Figure 4 depicts the variation trend of the lean TEG concentration and water removal efficiency at different stripping gas flows. As shown, the lean TEG concentration and the water removal efficiency both increase linearly with the increase of the

stripping gas flowrate. It can be concluded that once the reboiler temperature is fixed, the stripping gas flow is a key factor influencing water removal efficiency. However, it is evident that for a still and stripping regeneration approach, high TEG purity is at the cost of a considerable increase of stripping gas consumption. Thus, a balance should be struck between lean TEG concentration and stripping gas flowrate in actual applications.

Figure 5 presents the variation trend of the lean TEG concentration and stripping gas flow at different lean solvent circulation rates on the basis of maintaining the water dew point at about $-9\text{ }^{\circ}\text{C}$ when the feed gas capacity is 105 MMscfd. As shown, with the TEG circulation rate increasing from 1.0 to 2.0 m^3/h , the required lean TEG concentration drops dramatically from 99.7% to about 99.35%. Meanwhile, the stripping gas consumption declines fast correspondingly from 40 to 11 Nm^3/h . When the solvent circulation rate is higher than 2.5 m^3/h , the lean TEG concentration almost remains unchanged and the

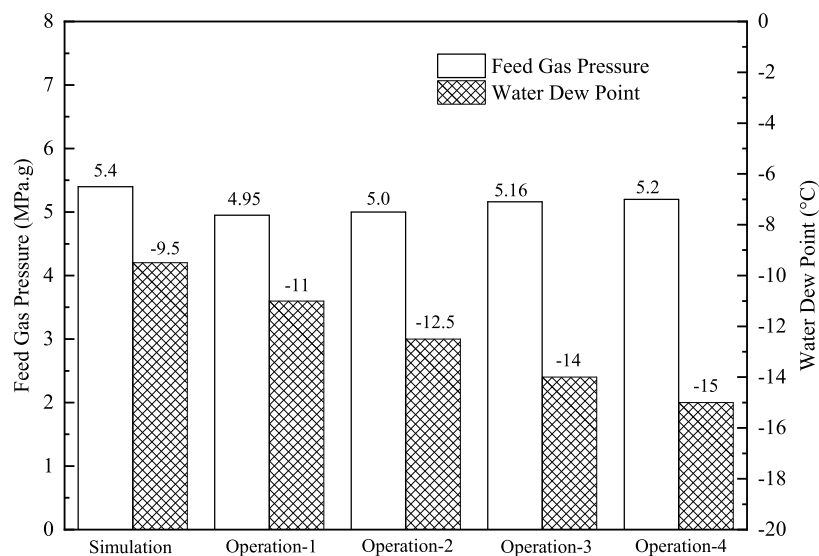


Figure 9. Comparison of the feed gas pressure and water dew point.

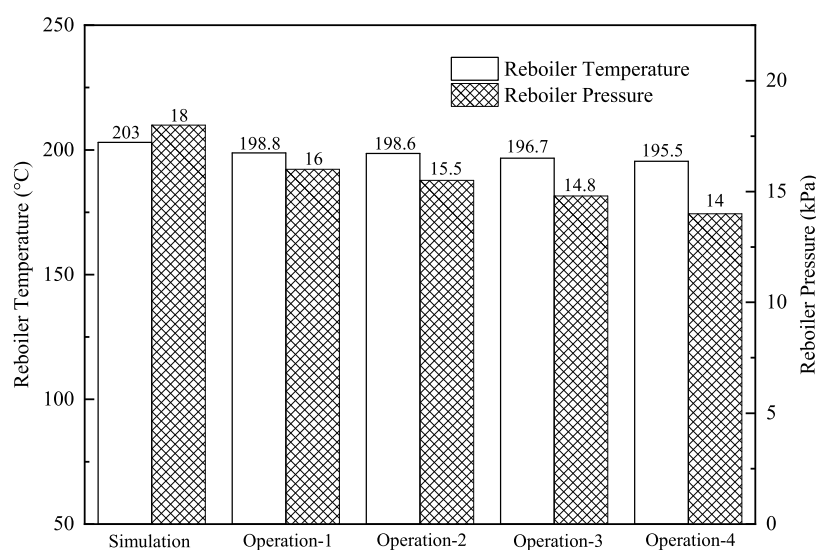


Figure 10. Comparison of the reboiler temperature and reboiler pressure.

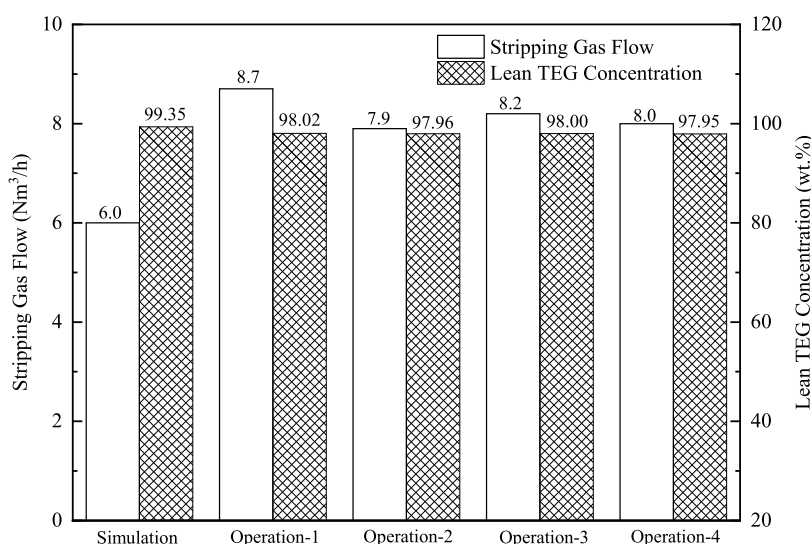


Figure 11. Comparison of the stripping gas flow and lean TEG concentration.

stripping gas flow slowly increases. It demonstrates that it is more economical to keep the lean solvent concentration within a range of 99.30–99.35%.

4.2. Simulation Results of the New Method. To further investigate the performance of the new dehydration method, five series of shale gas with different feed gas capacities were selected to carry out the simulation. The simulation was performed by software Aspen HYSYS. The simulation diagram is given in Figure 6.

The simulation results of the new dehydration method are summarized in Table 4. From the simulation results, both the TEG circulation rate and heating duty of the reboiler increase with adding of the feed gas flowrate, which is consistent with the fundamental principal. Basically, the simulation results show that when the feed shale gas flowrate varies from 18 to 210 MMscfd, the sales gas specification could be well met and the key parameters are favorable. It demonstrates that the new method has no restriction to the unit capacity, and it has a good performance within a wide range of the feed gas flowrate.

4.3. Utility and Energy Consumption Analysis. Generally, one of the key points to evaluate the performance of a

technology is the energy consumption. The main utility for the TEG dehydration process is fuel gas. Figure 7 presents the comparative results of the fuel gas consumption for the conventional method and new improved method. When the feed gas flowrate increases from 18 to 210 MMscfd, the fuel gas consumption increases linearly, for both conventional method and new method. However, the fuel gas consumption of the traditional method is obviously higher than that of the new improved method and the difference becomes more and more significant with the increase of the feed gas flowrate. It indicates that the new improved method can remarkably reduce the fuel gas consumption. It is attributed to the optimization on the flash gas/off-gas/stripping gas/fuel gas disposal process. For this new improved process, the flash gas is used as the stripping gas and the off-gas is delivered to a TEG reboiler for combustion as fuel gas. As a result, the fuel gas consumption could be greatly reduced.

Figure 8 illustrates the comparative results of energy consumption for the two methods. There is no doubt that with increasing the feed gas flowrate, the energy consumption increases correspondingly owing to that more feed needs to be

Table 6. Process Equipment Size and Cost of the Two Methods

type	equipment	conventional method			new method		
		no.	size, m	total price, \$	no.	size, m	total price, \$
vessel	feed gas filter	1	DN 0.6 × 3	27 463	1	DN 0.6 × 3	27,463
	TEG contactor	1	DN 0.75 × 10	69 247	1	DN 0.75 × 10	69,247
	TEG flash drum	1	DN 0.6 × 1.8	5253	1	DN 0.8 × 2.2	6420
	fuel gas drum	1	DN 0.4 × 1.0	3441	none		
	TEG filter	1	DN 0.5 × 0.8	14 122	1	DN 0.8 × 1.2	26,775
	pre-filter activated carbon filter	1	DN 0.8 × 1	15 967			
	trim filter	1	DN 0.5 × 0.8	14 387			
	TEG regenerator (TEG still column/TEG stripping column/TEG buffer drum)	1	DN 0.3 × 3.2/DN 0.3 × 1/DN 0.7 × 2.9	36 446	1	DN 0.3 × 3.2/DN 0.3 × 1/DN 0.7 × 2.9	36,446
	off-gas knockout drum	1	DN 0.4 × 1	2389	1	DN 0.4 × 1	2389
	TEG recovery drum	1	DN 1.4 × 4.6	14 845	1	DN 1.4 × 4.6	14,845
heat exchanger	lean TEG/gas exchanger	1	fixed tube-sheet exchanger	10 465	1	fixed tube-sheet exchanger	10,465
	lean/rich TEG exchanger	1	plate exchanger	20 388	1	plate exchanger	20,388
	TEG coil condenser	1	shell and tube exchanger	5802	1	shell and tube exchanger	5802
pump	TEG reboiler	1	fire tube exchanger	20 301	1	fire tube exchanger	20,301
	lean TEG circulation pump	2	0.4 m ³ /h, motor drive, reciprocating pump	52 880	2	0.4 m ³ /h, pneumatic pump	42,178
	TEG recovery pump	1	2 m ³ /h, motor drive, centrifugal pump	6623	1	2 m ³ /h, motor drive, centrifugal pump	6623
miscellaneous	incinerator	1	DN 0.65 × 13.6	124 018	none		
	drain drum pit	1	2.4 (L) × 6 (W) × 2 (H)	64 675	none		
	sum			508,712			289,342

Table 7. CapEx of the Two Methods

items	cost for the conventional method \$ (2021)	cost for the new method \$ (2021)
process equipment and installation	569,757	324,063
valves, piping, and installation	398,827	226,833
instrumentation and installation	341,852	194,435
electricity and installation	22,790	12,962
total CapEx	1333,226	758,293
annual CapEx	213,316	121,326

processed. Obviously, when the feed gas flowrate varies from 18 to 210 MMscfd, the new dehydration method consumes much less energy than the traditional method. Meanwhile, the energy-saving amount increases sharply with the increasing the feed gas flowrate, which means that the energy consumption decrease is more significant with a higher feed gas flowrate. When the feed gas flowrate is 210 MMscfd, the energy-saving amount is about 3000 MJ/h, which is almost 6 times that of the corresponding value (530 MJ/h) when the feed gas flowrate is 18 MMscfd.

4.4. Practical Operation Performance. A set of modularized dehydration facilities with a capacity of 18 MMscfd was founded and commissioned in 2019, in the Chang Ning 216 shale gas trial-produce well, southwest of China. This dehydration unit employed the new improved TEG dehydration process. The actual characters of the feed gas are shown in Table 5. The comparisons between the simulation results and the practical operating data are shown in Figures 9–11, respectively. For operation-1 to operation-4, it represents the operation data for the same feed at different times.

According to the operation data from Figure 9, with the feed gas pressure fluctuating in the range of 4.95–5.4 MPa, the water dew point varies in the range of –15 to –9.5 °C. This result is much better than our required target value, demonstrating the good performance of the new improved method in actual operation. From Figures 10 and 11, it is evident that the actual operating pressure and operating temperature of the regenerator are both a bit lower than the simulation values, which may be attributed to the fact that the pressure drop from the regenerator to the incinerator is lower. It is favorable for TEG regeneration. The actual stripping gas consumption is slightly higher compared to the simulation results, and the lean TEG concentration can be maintained at a high level (98% wt), which is almost close to the simulation data. Thus, although a little difference is observed between the simulation results and practical data in terms of stripping gas flow and lean TEG concentration, other outcomes are almost close to the real ones, and it is remarkable that the actual dehydration performances are even better than the simulation results.

Table 8. OpEx of the Two Methods

items	unit price	traditional method		new method	
		quantity	annual cost (\$)	quantity	annual cost (\$)
fuel gas	0.22 (\$/m ³)	528 (Nm ³ /day)	38,768	44 (Nm ³ /day)	3230
electricity	0.12 (\$/kW h)	336 (kW h/day)	14,112	180 (kW-h/day)	7560
water	0.8 (\$/m ³)	100 (m ³ /per annum)	80	80 (m ³ /per annum)	64
depreciation		10% (based on 10 years)	133,323	10% (based on 10 years)	75,829
maintenance		2% of CapEx	26,665	2% of CapEx	15,166
sum			212,948		101,849

4.5. Economic Assessment. To fully assess the economic benefits from this new dehydration method, the economic evaluation for the two processes from the perspectives of fixed CapEx (FCC), OpEx, and total annual cost is conducted.

The calculation method of CapEx were taken from literature,²⁵ where an approach has been utilized to calculate the price of the equipment according to its type and its size parameter.⁴³ For example, the price of a heat exchanger can be known from the type and the area of heat-transfer value. The FCC is based on an estimate of the cost of the major equipment items, bulk materials, civil and structural work, piping (including insulation and painting), electrical, and instrumentation. After obtaining total CapEx, the annualized CapEx (ACC) can be obtained, which is the price per year that must be spent on the equipment used.

The annual CapEx is calculated from eq 2.

$$ACC = FCC \times \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

where i denotes the interest rate and n denotes the project lifetime. The plant lifetime is assumed to be 20 years and interest rate is about 15%. For this interest rate and recovery period, the annual capital charge ratio is 0.160.

The OpEx including the utility cost, depreciation cost, and maintenance cost. The depreciation cost is considered as 10% of FCC. Furthermore, the maintenance cost is considered as 2% of FCC. Notably, the cost for natural gas is not considered due to the fixed natural gas feed rate for the conventional method and new method. The cost for fuel gas and other consumptions are taken from other previous work.³⁸

Total annual CapEx can be calculated from eq 3.

$$\begin{aligned} \text{Total annual cost} \\ = \text{annual capital cost} + \text{annual operating cost} \end{aligned} \quad (3)$$

Process equipment parameters and cost are shown in Table 6. For the two processes, the major differences are TEG filters, TEG circulation pumps, incinerators and fuel gas drums. Based on the total equipment costs, the CapExs and the OpExs of the two processes are calculated and presented in Tables 7 and 8, respectively. It is evident from the table that the difference on CapEx and OpEx between the two methods is outstanding. Compared with the conventional method, the CapEx and OpEx of the new dehydration method are significantly lower, which are only, respectively, 56.9 and 47.8% those of the conventional method. Based on the results from Tables 7 and 8, the total annual cost for the two processes are calculated by eq 3, about 426,264\$ for the conventional process and 223,175\$ for the new process.

4.6. Environmental Evaluation. As is often the case, the economic and environmental performances are contradictory.

Table 9. Off-Gas Emission Testing Results^a

items	sample	emission concentration (mg/m ³)	emission rate (kg/h)	maximum allowable emission concentration (mg/m ³)	maximum allowable emission rate (kg/h)
particulate	sample no. 1	7.3	1.16 × 10 ⁻³	120	1.6
	sample no. 2	7.6	1.22 × 10 ⁻³		
	sample no. 3	7.0	1.08 × 10 ⁻³		
	sample no. 4	8.0	1.21 × 10 ⁻³		
	sample no. 5	7.4	1.17 × 10 ⁻³		
NO _x	sample no. 1	53	8.42 × 10 ⁻³	240	0.36
	sample no. 2	56	9.21 × 10 ⁻³		
	sample no. 3	52	8.03 × 10 ⁻³		
	sample no. 4	57	9.54 × 10 ⁻³		
	sample no. 5	56	9.25 × 10 ⁻³		
VOCs	sample no. 1	3.0	4.77 × 10 ⁻⁴	60	1.6
	sample no. 2	3.8	6.37 × 10 ⁻⁴		
	sample no. 3	3.0	4.54 × 10 ⁻⁴		
	sample no. 4	3.9	6.47 × 10 ⁻⁴		
	sample no. 5	3.8	6.40 × 10 ⁻⁴		

^aMaximum allowable emission concentration and maximum allowable emission rate refer to local standards (GB 16297-1996 and DB51/2377-2017).

However, for this new improved process for shale gas dehydration, the off-gas, which is often sent to the incinerator for burning and emission in the traditional method, is utilized as fuel gas, consequently, the emission and resulting pollution could be greatly reduced. In order to assess the environmental performance, the actual emissions such as NO_x, VOC_s, and particulate in Chang Ning 216 trial-produce well are investigated. Five series of samples at different days are taken and tested. The relevant data are presented in Table 9. The emission concentration of particulate, NO_x, and VOC_s are, respectively, 7.3–8.0, 53–57, and 3.0–3.9 mg/m³, which are far below the corresponding maximum allowable values, 120, 240, and 60 mg/m³, separately. Particulate, NO_x, and VOC_s emission rates are 1.08 × 10⁻³ to 1.22 × 10⁻³ kg/h, 8.03 × 10⁻³ to 9.54 × 10⁻³ kg/h, and 4.77 × 10⁻⁴ to 6.47 × 10⁻⁴ kg/h, respectively. While the corresponding maximum allowable emission rates are 1.6, 0.36, and 1.6 kg/h, separately, which are much higher than the actual testing data. The emission results show that the new TEG dehydration method has superior environmental performance in shale gas processing.

5. CONCLUSIONS

To adapt to the shale gas field exploration and development, an improved TEG dehydration approach is proposed and thoroughly investigated from the aspects of process improvements, performance evaluation, as well as comparisons between simulation results and practical operating data. Additionally, economic analysis based on comparisons of CapEx and OpEx between the two methods and the environmental performance assessment based on actual operation data were also conducted.

The conclusions can be drawn out and summarized below:

- (1) From process flow analysis, compared with the conventional TEG dehydration method, the new proposed improved TEG dehydration method is simplified with less equipment, which is beneficial for modularization and is of great significance and convenience to the dehydration device in a trial-produce well and shale gas dehydration station. What is more, in comparison to the traditional TEG dehydration method, the new improved method consumes much less energy

and the energy saving amount is more significant with a higher feed gas flowrate.

- (2) According to the process simulation results, the stripping gas flow is the key factor influencing the water removal efficiency. When the lean TEG concentration is within the range of 99.30–99.35%, the dehydration performance is superior and the stripping gas flow is relatively low. Moreover, the new method has no restriction to the unit capacity because when the feed gas flowrate varies from 18 to 210 MMscfd, it is applicable and shows good performance for shale gas dehydration.
- (3) In view of the economic assessment, the CapEx and OpEx of this new dehydration method are significantly lower, which are only 56.9 and 47.8% those of the conventional method, respectively. This is attributed to the concise process flow and the low energy consumption. Additionally, the superior environmental performances of this new technology have been verified through actual operation data of shale gas-processing plants. The field-testing results for the emission rate and emission concentration of the particulate, NO_x, and VOC_s are far below the maximum allowable value in local standards.

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Notes

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