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Feasibility analysis and process simulation of CO_2 dehydration using triethylene glycol for CO_2 pipeline transportation

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A B S T R A C T

The operation of dehydration is very important in the process of gas transportation. This study aims to evaluate the application feasibility of CO_2 dehydration using triethylene glycol, which is also called TEG for short. Aspen Plus software was used to simulate the dehydration process system of CO_2 gas transportation using TEG dehydration. Parameter analysis and process improvement were carried out for the simulation of dehydration process. At first, a sensitivity analysis was conducted to analyze and optimize operating conditions of conventional CO_2-TEG dehydration process system. Subsequently, a recycle unit was introduced into the conventional CO_2-TEG dehydration process system, it can be found that the improved process system with the recycle unit has a higher CO_2 recovery rate which was about 9.8% than the conventional one. Moreover, the improved process system showed excellent operation stability through the comparison of simulation results of several processes with various water contents in their feed gases. Although the energy consumption is increased by about 2%, the improved process was economically and technically feasible for the long-term availability of CO_2 pipeline transportation. The simulated results showed that the improved CO_2-TEG process system has promising application prospects in CO_2 dehydration of CO_2 gas transportation with high stability.

1. Introduction

Pipeline transportation of carbon dioxide (CO_2) plays an important role in the deployment of carbon dioxide capture and storage (CCS) with large transportation volume, little environmental impact, low operational costs, enclosed conveying and low product losses [1,2]. It allows only extremely low amount of water in the CO_2 fluid in case the formation of hydrate and free water, which can plug valves and fittings in the process of CO_2 pipeline transportation and also react with CO_2 to cause electrochemical corrosion. Therefore, it is urgently needed to find proper approaches to remove water from the CO_2 gas fluid to be transported.

Up to now, there is no standard criterion to accurately define the allowable water content in the CO_2 gas stream to be transported. For different application purpose, the extent of dehydration is different. For the CO_2 stream being transported from the CCS projects, the water content is usually lower than 50 $mg \cdot L^{-1}$ [3]. When the CO_2 stream is used for enhanced oil recovery (EOR), its limitation is also 50 $mg \cdot L^{-1}$ [4]. While for geological storage purpose, the range of water concentration in the transported CO_2 stream can be smoothly larger, which could be no more than 500 $mg \cdot L^{-1}$ [5]. According to the research result of Abbas *et al.* [6], a water content of 50 $mg \cdot L^{-1}$ was considered as the indication of full dehydration for the overall range of applications. And this content is also regarded as the restricted target in this study.

Up to now, there are several commonly used dehydration methods for acid gas stream, including compression and cooling, solid adsorption, absorption, and so on [7–9]. Among them, compression and cooling is one of the most widely used methods since it can compress and cool the gases at the same time. However, it is not suitable for deep dehydration [6]. Solid adsorption dehydration using adsorbent, such as silica gel, molecular sieve, activated alumina, activated carbon, *etc.*, can be applied to remove water vapor under various temperature, pressure and flow rate conditions, which is also a mature enough method. However, considering the economic and technical benefits, the absorption *via* solvent is the most commonly adopted method [10]. Up to now, it is also considered to be the most attractive method to dehydrating water deeply from almost pure gas fluid [11].

Glycol is one kind of good dehydrants for gas dehydration due to its molecular structure and physical property. The molecular

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structure of glycol contains hydroxyl and ether bond, which can form hydrogen bond with water and perform a strong affinity to water so that it has a high dehydration depth. TEG, which dehydrates water by means of its hydrophilicity, is thermal-stable and easy to regenerate, and has relatively low vapor pressure and high moisture-absorption performance [12,13]. It has been widely used for various gases dehydration, especially for natural gas (NG). Grosso [14] studied the gas dehydration process using the glycol solvent, and discovered that glycol is the good choice for gas dehydration due to its molecular structure and physical property. Gandhidasan [15] dealt with the design analysis of NG-TEG dehydration process and briefly discussed the effects of various operating parameters (such as pressure, temperature, and TEG circulation rate) on the design of this dehydration process. Piemonte *et al.* [16] studied the TEG regeneration process in NG dehydration plants to meet the regeneration level of TEG (98.5%–99.0%) through the measurements of boiling temperatures for binary mixtures of TEG and water and the simulation of a natural gas dehydration process using the fitted NRTL parameters in the Hysys process simulator. Besides, some mathematical methods, such as advanced equation of state, correlation and artificial neural network model, were developed to analyze and simulate the whole NG-TEG dehydration process or optimize the key operational parameters [13,17–19].

When it comes to CO_2 dehydration, firstly, its process is so similar with that of natural gas; secondly, impurities in the highly concentrated CO_2 gas stream from CO_2 capture unit and that in the natural gas stream are also similar; and finally, even though CO_2 is more soluble in TEG than methane (CH_4), the amount of dissolved CO_2 accounts for quite a small proportion of total CO_2. In view of the reasons mentioned above, TEG is expected to be suitable and has a great potential for CO_2 dehydration. As well known, evaluation of TEG performance in CO_2 dehydration requires comprehensive simulation at various operating conditions. Yet so far, there are only several references in the open literature about the simulation of CO_2 dehydration using TEG. Grynia *et al.* [20] have investigated, by means of two methods (*i.e.*, by compression and cooling alone and by TEG dehydration), the dehydration process of an acid gas mixture including H_2S, CO_2, and a small amounts of other components. They discussed the design considerations of application for both methods and concluded that TEG is very feasible for CO_2 dehydration. This concept was also accepted by Abbas *et al.* [6]. In their research, they mentioned that TEG can be used as dehydrant for CO_2 dehydration with a few modification in the process. Moreover, in 2014, Øi and Fazlagic [21] applied Aspen HYSYS to consider the application possibility of a traditional glycol dehydration process and more advanced CO_2 dehydration processes for CO_2 dehydration process using different equilibrium models. Their simulated results demonstrated that TEG is a reasonable alternative for CO_2 dehydration to reduce water levels lower than 5 $mg\cdot L^{-1}$.

As it is well known, the water removal efficiency of NG-TEG dehydration process is mainly influenced by absorber temperature, absorber pressure, stage number of absorber (or height of packing), TEG circulation rate, TEG purity in the lean TEG solution, *etc.* As similar with it, in this study, these parameters are also considered as the investigation objects of CO_2-TEG dehydration process to look for the optimum operation parameter values. Besides, due to the high mutual solubility of TEG and CO_2, the loss of TEG solvent and CO_2 increase, which result in larger TEG makeup rate and higher reboiler duty and costs [22]. Consider of this, the loss of TEG solvent and CO_2 also need to be analyzed, and some improvements need to be done in the CO_2-TEG dehydration process to reduce the losses and reboiler duty.

In the aspects of CO_2 transportation and dehydration, a number of process commercial software, such as Aspen Plus, Aspen HYSYS, Pro/II and PROSIM, have been applied to simulate process configurations or optimize operating conditions in the attempt to improving operating performance and minimizing energy consumption [16,19,21,23,24]. Aspen Plus has found widespread application in the simulation of absorption/regeneration process and therefore can be used for CO_2 dehydration owing to its rich database of property parameters (contains Aspen CD and DIPPR) and comprehensive unit operation modules. Moreover, Aspen Plus can be used to perform sensitivity analysis to evaluate the effects of key parameters on the CO_2 dehydration performance, and finally, to optimize operational conditions.

In view of the above mentioned issues, this paper attempts to evaluate the potential of TEG in CO_2 dehydration by simulating its performance in two process configurations, namely the conventional process and the improved process. Both process configurations were simulated using Aspen Plus simulation software. Moreover, sensitivity analysis was performed to investigate the effect of several key parameters on the CO_2 dehydration efficiency in both process configurations and finally to obtain optimized operating conditions. And then, the feed gas streams with different water content were dehydrated using the improved process to evaluate the dehydration performance of TEG solvent and to validate the stability of the improved CO_2-TEG dehydration process.

2. Process Descriptions

2.1. The dehydration mechanism of TEG solvent

Due to the existence of hydroxy and ether bond in the TEG molecular structure, water molecules can be fixed on TEG molecules through the intermolecular hydrogen bonds. TEG has a strong affinity for water, and therefore possesses a high dehydration depth. Moreover, TEG is easy to regenerate, and has a large dew point depression and relative low operation cost, which makes it widely used in the field of gas dehydration.

2.2. Feed gas and product specifications

In general, the CO_2 stream to be transported is rarely pure and always has some contaminants such as N_2, H_2O and hydrocarbons. These impurities may influence or even hinder the cost-effective transportation of CO_2 stream when their amount over a certain specification, especially the H_2O [25]. Therefore, reducing H_2O content to a certain value is the primary work for CO_2 gas purification. In this study, the specifications of various components in the CO_2 gas to be deeply dehydrated, as shown in Table 1, are based on the stream specifications of CO_2 product from post-combustion capture technologies proposed by Abbas *et al.* [6]. Post-combustion capture is an energy intensive and expensive process and it can be done using a variety of methods, including chemical solvents, sorbents, membranes and distillation. Here, CO_2 is removed from flue gases of power plants or from other fossil fuel-based large point sources [26,27]. And for the CO_2 pipeline

Table 1
The specifications of CO_2 stream compositions from post-combustion capture technologies [6]

Specifications/%	
CO_2	92–97
H_2O	2.8–7.3 [28]
N_2	0.02–0.13
Ar	0.00001–0.000025
O_2	0.001–0.03
SO_2	0.001
Gas feeding temperature/°C	40–42
Gas feeding pressure/MPa	0.1–0.285

transportation purpose, the constrained limit of H_2O in CO_2 stream is usually 50 mg·L^{-1}, therefore it is also be the dehydration criterion used in this work. This study assumes the total gas stream flow rate to be 3×10^4 kmol·h^{-1}, and the CO_2 recovery rate is great than 98%. Based on these assumptions, a series of process simulations about CO_2 gas streams with different water content, which are within the range of 2.8%–7.3%, are conducted to evaluate the dehydration efficiency of TEG solvent and to validate the stability of the improved CO_2-TEG dehydration process.

2.3. Process configuration of the CO_2-TEG dehydration process

The basic CO_2-TEG dehydration process in this work consists mainly of two sections: a dehydration unit and a regeneration unit, as shown in Fig. 1. Detailed description about the dehydration and regeneration operational unities presented as follows:

Dehydration: The feed CO_2 gas stream is introduced at the bottom of the absorber, while the TEG solvent is injected at the top of the absorber. Through the countercurrent contact of feed wet gas and TEG solvent in the absorber, water is removed from the gas stream. Then the water-rich TEG stream drains out from the bottom of absorber, and the dried CO_2 gas ejects from the top of the absorber. After that, the H_2O-rich TEG stream is introduced into a flash tank to flash off some of the dissolved CO_2 before it heated and sent to the regenerator.

Regeneration: The H_2O-rich TEG stream (from the flash tank) is preheated in a cross-flow heat exchanger by the lean TEG (returned from the bottom of the reboiler) to a desired temperature before being pumped into the top of the regenerator. In the regenerator, absorbed water is stripped out from the TEG solvent by elevating temperature under atmospheric pressure. After the H_2O stripping step, the already-regenerated lean TEG is cooled by the lean/rich heat exchanger first and a lean cooler second, and then pumped back to the absorber for recycling.

2.4. Process configuration of the improved CO_2 -TEG dehydration with the recycle unit

Since TEG is a physical solvent for CO_2 absorption, some amount of CO_2 will inevitably dissolve into the TEG during the absorption process, especially at higher pressures. It can be seen from Fig. 1 that most of the dissolved CO_2 in the H_2O-rich TEG stream is flashed out through a flash tank. Since the majority of the flash gas is CO_2, if it is emitted to the atmosphere, there will be a loss of CO_2 in the dry gas stream and the total CO_2 recovery rate would reduce. On the contrary, if the flash gas is recycled directly with the main dry gas (out of the top of the absorber), the final CO_2 dehydration efficiency will be decreased due to the relative high moisture content in the flash gas. Given this, we consider to recycle the flash gas (which contains some water) back to the dehydration process for further simulation. Fig. 2 showed the improved CO_2-TEG dehydration process with the recycle unit. As it was shown in Fig. 2, the flash gas is recycled back to the mixer, and mix with fresh feed gas to form a new gas stream (Stream 1). Then the new gas stream is introduced at the bottom of the absorber. Recycling CO_2 in the flash gas stream would results in a significant reduction of CO_2 loss, and increases the total CO_2 recovery rate as a consequence.

Table 2 shows the thermodynamic model and model setting parameters of the improved CO_2-TEG dehydration process.

3. Results and Discussion

In this work, Aspen Plus was applied to simulate the CO_2-TEG dehydration process, so as to evaluate the application feasibility of CO_2 dehydration using TEG. At first, we conducted the dehydration process simulation of one CO_2 gas stream (which is composed of 94.9% CO_2, 5 % H_2O, and 0.1% other infinitesimal impurities) using the basic CO_2-TEG dehydration process. And sensitivity analysis was performed to evaluate the effects of several key operational parameters on the dehydration performance. These operational parameters include absorber pressure, absorber temperature, stage number of absorber, TEG circulation rate and reboiler temperature. Secondly, the performance of the improved CO_2-TEG dehydration process with the recycle unit was evaluated and compared with the basic one using the same gas stream composition. Finally, a range of process simulations were done to dehydrate CO_2 gas streams with different water content, *i.e.* 3%, 4%, 5%, 6% and 7%, respectively, and to evaluate the dehydration efficiency of TEG solvent and to validate the stability of the improved CO_2-TEG dehydration process.

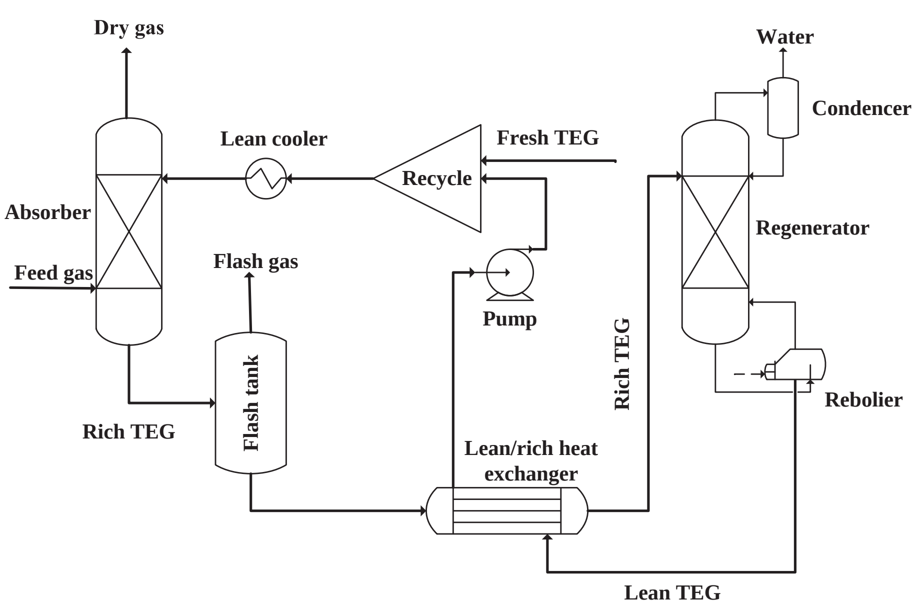

Fig. 1. Process flowsheet of the CO_2-TEG dehydration process.

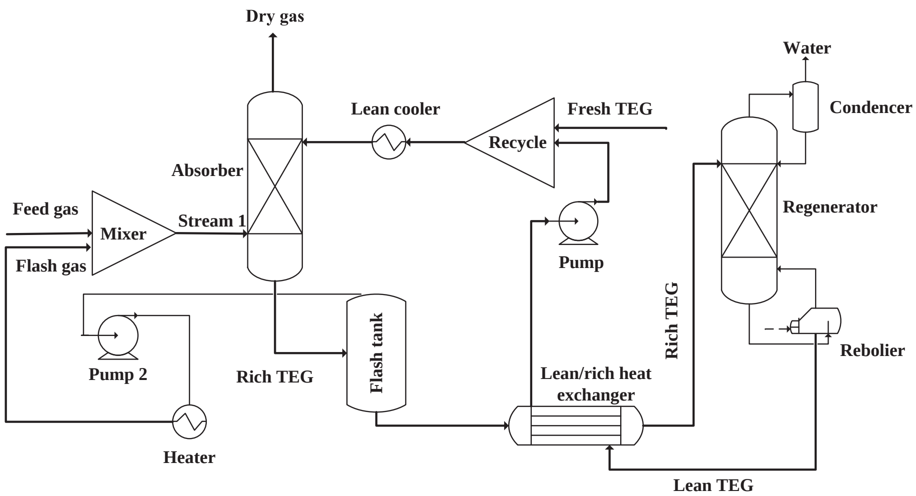

Fig. 2. Process flowsheet of the improved CO_2-TEG dehydration process with the recycle unit.

Table 2
The model setting parameters

Model name	Property method	Model	Temperature/℃	Pressure/MPa
Heater	PENG-ROB	Heater	40	2
Lean cooler	PENG-ROB	Heater	40	2
Heat exchanger	PENG-ROB	Heater	40	0.01
Pump	PENG-ROB	Pump	40	2
Pump 2	PENG-ROB	Pump	50	2
Flash tank	PENG-ROB	Flash 2	50	0.1
Model name	Property method	Model	Number of stages	Condenser pressure
Absorber	PENG-ROB	RadFrac	7	2
Regenerator	PENG-ROB	RadFrac	4	0.01

3.1. Simulation and optimization of the basic CO_2-TEG dehydration process

3.1.1. Effect of absorber pressure on the CO_2-TEG dehydration efficiency and CO_2 loss rate

Absorber pressure has significant effect on the CO_2-TEG dehydration efficiency and CO_2 loss rate. As can be seen in Fig. 3, with the increase of absorber pressure, water content in dry gas first decreases dramatically and then becomes horizontal. When the pressure is greater than 2.0 MPa, the change range of water content in dry gas becomes very small. Even though increasing the absorber pressure would improve the dehydration performance, it will increase the operational cost as well. As mentioned in Section 2.2, CO_2 can dissolve into TEG solvent, and the solubility of CO_2 in TEG at higher pressure can't be ignored. Therefore, the CO_2 loss during the absorption process needs to be discussed. It can also be seen clearly from Fig. 3 that CO_2 loss rate increases with the increase of absorption pressure, which means that a higher pressure may lead to a considerable amount of CO_2 loss. Consider of these discussion above and in order to meet the product specifications that water content in dry gas considerably below 50 $mg·L^{-1}$, the optimum pressure is recommended at 2.0 MPa.

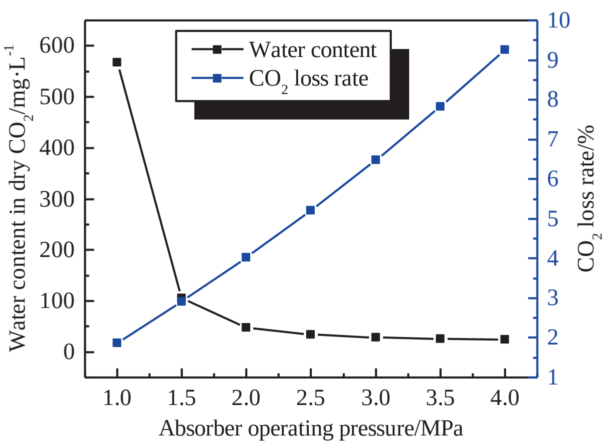

Fig. 3. Effect of absorber pressure on the dehydration efficiency and CO_2 loss rate (absorber temperature: 40 °C; TEG circulation rate: 2500 $kmol·h^{-1}$; stage number of absorber: 5).

3.1.2. Effect of absorber temperature on the CO_2-TEG dehydration efficiency and CO_2 loss rate

Absorber temperature is an important factor for the CO_2-TEG dehydration process, since it can affect the solubility of H_2O in TEG and the fluidity of TEG in the absorber (due to the change of TEG viscosity). However, the viscosity of TEG is high at low temperature, which may worsen the mobility and distribution of TEG in the absorber and even block pipelines. Therefore, it is important to select an appropriate absorber temperature.

The effects of absorber temperature on the dehydration efficiency and CO_2 loss rate are shown in Fig. 4, in which the water content in the dry gas increases monotonously with the rise of absorber temperature while the CO_2 loss rate changes slightly during this temperature range (CO_2 loss rate varied from 3.98% to 4.12%). It can be seen from Fig. 4 that water content is less than 50 $mg·L^{-1}$ at 40 °C, and CO_2 loss rate is about 4.02%; therefore, this temperature is quite reasonable for the absorption process.

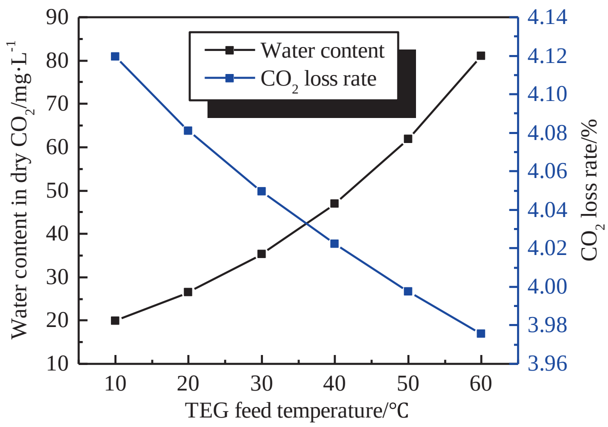

Fig. 4. Effect of absorber temperature on the dehydration efficiency and CO_2 loss rate (absorber pressure: 2.0 MPa; TEG circulation rate: 2500 kmol·h^{-1}; stage number of absorber: 5).

Besides, since the feed gas temperature after the CO_2 capture process is about 40 °C (as shown in Table 1), keep the dehydration temperature at the same level could make an energy balance and achieve a high dehydration efficiency. Based on these discussions, the optimum absorber temperature is 40 °C.

3.1.3. Effect of stage number of absorber on the CO_2-TEG dehydration efficiency and CO_2 loss rate

The stage number of absorber, which directly related to the column height, has a significant effect on the CO_2-TEG dehydration performance. Fig. 5 shows the investigation of the effect of stage number of absorber on the water content in the dry gas and CO_2 loss rate. It can be seen that the water content in dry gas decreases as the increase of absorber stage number. This is because increasing the number of stages leads to the increases of both contacting area and residence time for gas and liquid phases. Both these effects result in the full usage of the TEG solvent and thus requiring less amount of TEG solvent. With respect to the loss rate of CO_2 gas, it varies quite slight with the addition of absorber stage number (which is about 4%). However, with the increase of the stage number of absorber, the facility and operational costs increase accordingly. Therefore, the best choice is using less number of stages to achieve the desired dehydration efficiency (*i.e.* the mole fraction of water in dry gas less than 50 mg·L^{-1}). As shown in Fig. 5, water content in dry gas is less than 50 mg·L^{-1} at a seven-stage absorber. Considering above, the optimal stage number of absorber is 7 in this process.

3.1.4. Effect of TEG circulation rate on the CO_2-TEG dehydration efficiency and reboiler duty

TEG circulation rate relates closely to the dehydration degree of TEG solvent and energy consumption for heating and pumping. The increase of TEG circulation rate is beneficial to the dehydration performance. Fig. 6 exhibits the effect of TEG circulation rate on the dehydration efficiency and reboiler duty. As shown in this figure, water content in dry gas decreases with the increase of TEG circulation rate, indicating that increasing the TEG circulation rate is beneficial to the absorption of moisture and then improving the TEG dehydration efficiency; while as the TEG circulation rate exceeds 2250 kmol·h^{-1}, the change trend gradually slows down, and the amount of water be removed increases inconspicuously. However, a high TEG circulation rate requires a corresponding large energy input to heat the H_2O-rich solvent to the proper temperature for TEG regeneration, which will raise the operational cost. The required energy consumption of reboiler for each TEG circulation rate is also displayed in Fig. 6. It can be seen clearly that more energy is required to obtain a higher TEG circulation rate, and their line is linear and steep. According to the simulation results and the desired dehydration degree, the most economic TEG circulation rate is 2500 kmol·h^{-1}.

3.1.5. Effect of the temperature of reboiler on the CO_2-TEG dehydration efficiency and purity of the regenerated TEG

The temperature of reboiler has a great effect on the regeneration performance, the higher the reboiler temperature, the better the TEG regeneration efficiency, and therefore, the better the TEG-CO_2 dehydration efficiency. As it is known that TEG has a thermal decomposition temperature of 206.7 °C [29], therefore, the temperature of reboiler could not be more than 204 °C. Fig. 7 shows the changes of the water content in dry CO_2 gas and the purity of the regenerated TEG (*i.e.* the purity of lean TEG solution) with the increase of reboiler temperature. As can be seen from Fig. 7, the water content in dry CO_2 gas decreases with the increase of the temperature of reboiler, and the purity of TEG increases accordingly, which is agreement with the fact that the higher the purity of TEG lean solution lead to a higher dehydration efficiency for wet feed gas. Consider of this, in order to get a desirable TEG purity (usually 99.9%) in continuous operation process, the temperature of reboiler should be as high as possible. However, it is generally known that the higher the temperature of reboiler, the higher

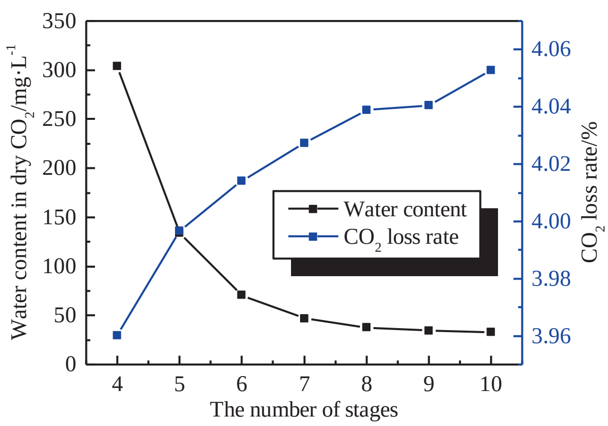

Fig. 5. Effect of stage number of absorber on the dehydration efficiency and CO_2 loss rate (absorber pressure: 2.0 MPa; absorber temperature: 40 °C; TEG circulation rate: 2500 kmol·h^{-1}).

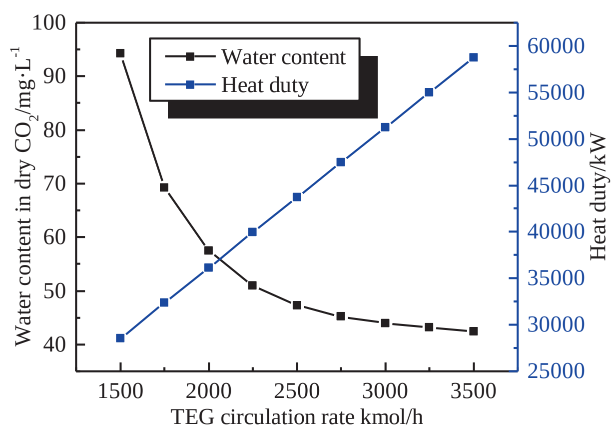

Fig. 6. Effect of TEG circulation rate on the dehydration efficiency and reboiler duty (absorber pressure: 2.0 MPa; absorber temperature: 40 °C; stage number of absorber: 7).

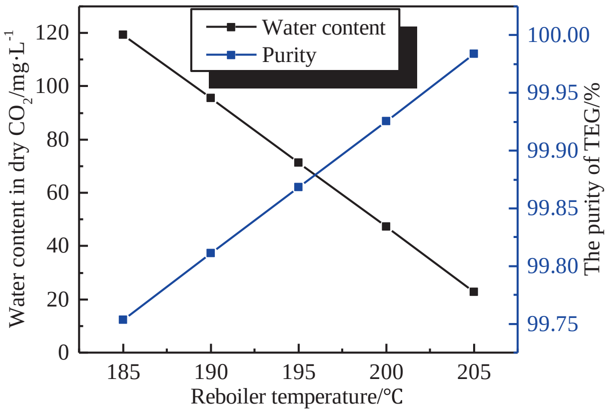

Fig. 7. Effect of the temperature of reboiler on the dehydration efficiency and purity of the regenerated TEG (absorber pressure: 2.0 MPa; absorber temperature: 40 °C; stage number of absorber: 7; TEG circulation rate: 2500 kmol·h^{-1}).

the energy consumption accordingly. Thus, it is important to select a fit temperature in order to get the optimal TEG purity and meet the requirement of low-energy. According to the specification of the purity of TEG and the desired dehydration degree, the suitable temperature of reboiler should be 200 °C.

3.1.6. Overview of the conventional CO_2-TEG dehydration process

Based on the sensitivity analysis mentioned above, the appropriate operational parameters of the conventional dehydration process are obtained. These parameters and their values are presented in Table 3. After the CO_2-TEG dehydration process, the water content in dry gas is 47.3 mg·L^{-1}, the CO_2 recovery rate and CO_2 purity in the dry gas is about 95.97% and 99.87%, respectively. And this process can achieve a very high TEG purity in the recovered lean TEG solution (which is 99.93%) with a reboiler duty of 5.53×10^4 kW. It can be seen from Table 3 that the total dehydration performance of TEG is quite good except for a little high CO_2 loss rate of 4%.

3.2. Simulation and optimization of the improved CO_2-TEG dehydration process with the recycle unit

Since the problem of low CO_2 recovery rate exists in the basic CO_2-TEG dehydration process (more than 4% of CO_2 is lost), the improved CO_2-TEG dehydration process increased the recycle unit, and the flashed gas goes into the absorber for recycling aim to increase the CO_2 recovery rate. It is generally accepted that CO_2 recovery rate should be great than 98%. Therefore, the operational parameters (*i.e.* flash pressure and flash temperature) of flash tank have great influences on the CO_2 recovery rate and CO_2 purity in the flash gas. So this part mainly discusses: (i) the effect of flash pressure and flash temperature on the CO_2 recovery rate and CO_2 purity in flash gas, and (ii) the analysis and comparison of total energy consumptions of the improved process and the basic one.

3.2.1. Effect of the flash pressure and temperature on the CO_2 recovery rate and CO_2 purity in flash gas

For flash tank, its main role is to provide a space for the high pressure fluid to rapid evaporation and realize gas–liquid separation, and this separation can be achieved by reducing the flash pressure or increasing the flash temperature. Therefore, this section is to search for the most suitable flash operation conditions to get the objective goal. The effects of the flash pressure and temperature on the CO_2 recovery rate and CO_2 purity in flash gas are shown in Fig. 8. As can be seen from it: (i) CO_2 recovery rate increases with the increase of flash temperature and the decrease of flash pressure, while the purity of CO_2 reduces as the rise of flash temperature and the decline of flash pressure, and (ii) at lower pressure (*e.g.* 0.1 MPa), with the increase of flash temperature, CO_2 recovery rate is relative large and increases gently, while the purity of CO_2 reduces largely; at larger pressure (such as 1 MPa), the results are reversed. These results are mainly because of the fact that the boiling point of a fluid is increased with the increment of pressure, when the pressure reduces, fluid evaporates rapidly with the decrease of its boiling point. At this status, the dissolved substance could transform from a saturated or unsaturated state into a super-saturation state, and then separated from the main body of fluid. For CO_2-TEG-H_2O system (*i.e.* the H_2O-rich TEG stream), that is to say, a high CO_2 recovery rate can be achieved at a low flash pressure (as shown in Fig. 8). And it can be deduced that pressure is almost no effect on the solubility of water in TEG, namely that little amount of water will go into the flash gas, which lead to the high CO_2 purity in the flash gas. On the other hand, the increase of flash temperature could enhance the evaporation of CO_2 since it offers more energy for the CO_2-TEG-H_2O fluid to form a new gas–liquid equilibrium to evaporate more CO_2. But due to the temperature dependence of solubility of H_2O in TEG, more water will go out of the rich-H_2O TEG stream to the gas phase, which makes an obvious decrease in the CO_2 purity in the flash gas. As shown in Fig. 8, at a certain flash pressure, there is a balance point between CO_2 recovery rate and CO_2 purity. After correlating the corresponding curves of each flash pressure, we can get the optimal flash operation conditions. And at a pressure of 0.1 MPa and a temperature of 13 °C, both the CO_2 recovery rate andCO_2 purity can achieve 94.5%, which is similar with the water content in

Table 3
The optimized operational parameters of the conventional CO_2-TEG dehydration process

Item	Parameter values
Pressure of absorber/MPa	2.0
Absorber temperature/°C	40
Stage number of absorber	7
TEG circulation rate/kmol·h^{-1}	2500
Reboiler temperature/°C	200
The water content in dry gas/ mg·L^{-1}	47.3
CO_2 recovery rate/%	95.97
Purity of the dry CO_2 gas/%	99.87
Purity of the lean TEG solution/%	99.93
Reboiler duty/kW	5.53×10^4

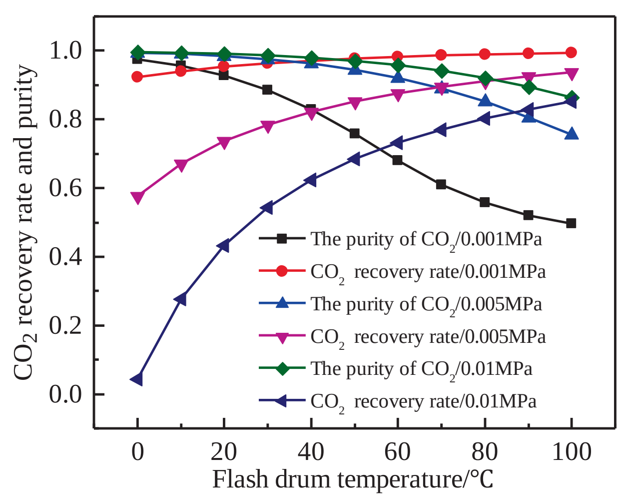

Fig. 8. Effect of the flash pressure and temperature on the CO_2 recovery rate and CO_2 purity in flash gas.

Table 4
Simulation results of the improved CO_2-TEG dehydration process at various water contents

Parameter	Water content in the feed gas/%				
	3	4	5	6	7
Water content in dry gas/mg·L^{-1}	59.2	53.2	47.3	42.4	38.4
Total CO_2 recovery rate/%	99.79	99.78	99.78	99.77	99.76
Purity of the dry CO_2 gas/%	99.88	99.88	99.87	99.87	99.87
Purity of the lean TEG solution/%	99.93	99.93	99.93%	99.93	99.93
Reboiler duty/kW	4.97×10^4	5.25×10^4	5.53×10^4	5.82×10^4	6.11×10^4
Energy consumption of the recycle unit/kW	670.7	791.3	895.4	984	1058.4

the feed gas. And the total CO_2 recovery rate in dry gas can be increased to 99.78%. Therefore, the optimal flash conditions are 0.1 MPa and 13 °C, respectively.

3.2.2. The analysis and energy consumption calculation of the improved process

It should be noted that in the improved process, the recycled CO_2 gas from the flash tank is mixed with the fresh wet gas in the mixer directly and then be injected into the absorber. For this unit, there are two questions should be pay attention to: (i) when mixing the flashed CO_2 gas with the fresh one, due to the difference in their inlet temperatures, some additional heat is needed to heating the flashed CO_2 gas to the feed gas inlet temperature (*i.e.* heated from 13 °C to 40 °C); (ii) since there is a difference of water content between the feed gas and the flashed CO_2 gas, it may have an effect on the composition of the gas enter into absorber (*i.e.* Stream 1). For the first issue, the energy consumption of the recycle unit is calculated (*i.e.* 895.4 kW), which is pretty small compared to the reboiler duty of regenerator and can be neglected. For the second question, the difference of water content in the feed gas and the flashed CO_2 gas is slight (5% and 5.5%, respectively), and the water content in the final mixing gas is 5.02% (which is almost 5%), therefore, water contents in the feed gas basically remain unchanged with or without the recycle unit, and the improved dehydration process can be considered as steady simulation.

3.2.3. Overview of the improved process

In this work, the improved CO_2-TEG dehydration process with the recycle unit is simulated. Through the sensitivity analysis, the optimal operating parameters were obtained: the temperature and pressure of flash tank are13 °C and 0.1 MPa, respectively. The simulation results showed that the final CO_2 recovery rate is 99.78%. Compared with the conventional process, the improved CO_2-TEG dehydration has a higher CO_2recovery rate (increase by 3.81%), which is beneficial for the greenhouse effect in the long run. It also should be noted that, due to the recycle of flashed CO_2 gas, some more energy is need to mixing it with the fresh feed gas. However, the energy consumption is quite small and has slight effect on the total energy consumption of the improved process. Therefore, it can be said that the improved process is better than the basic one with more CO_2 recovery rate and almost the same energy consumption.

3.3. Simulation and performance evaluation of the improved CO_2-TEG dehydration process with various water contents

It can be known from Table 1 that water contents in the captured CO_2 stream are usually vary from 2.8% to 7.3%. Therefore, in order to get a more clear understanding about the performance and stability of the improved CO_2-TEG dehydration process, a series of processes with various water content (*i.e.* 3%, 4%, 5%, 6% and 7%, respectively) were simulated and analyzed. And in order to maintain the consistency of each simulation, all the process simulations are conducted at the same operation conditions, in other words, the operating parameters of absorber, regenerator and recycle units remain unchanged at every process simulation. Based on these preconditions, the final simulation results were obtained (as shown in Table 4).

From Table 4, it can be seen that: (i) at the same operation conditions, water content in the dry gas decreases with the increase of water content in the feed gas, but all of them have relative good dehydration performances (all their dehydration efficiencies are around 50 mg·L^{-1}); (ii) all of these five processes have high CO_2 recovery rates and CO_2 gas purities near 99.8%; (iii) the purities of TEG in lean solution after regenerating are greater than 99.9%; (iv) the energy consumption (including the reboiler duty and the energy for CO_2 recycle) of each process is different with the vary of water content in the feed gas and increases with the rise of water content. All these results indicated the excellent dehydration performance of our improved process, since the final dehydration efficiency basically unchanged along with the fluctuation of water contents in the feed gas, and the increments of the total energy consumptions are not too much. Based on the process simulation and results discussion, it can be concluded that the improved process is quite suitable for the dehydration of CO_2 gas using TEG dehydration with high stability.

4. Conclusions

In this paper, Aspen plus software was used to simulate the dehydration process of CO_2 gas using TEG dehydration. Two dehydration processes were conducted for this purpose, include the conventional CO_2-TEG dehydration process and the improved CO_2-TEG dehydration with the recycle unit. Through the simulation and technical analysis of these two processes, the optimal values of several main operating parameters of the CO_2-TEG dehydration process were obtained. And it can be found that the improved process with the recycle unit has a higher CO_2 recovery rate (about 99.8%) than the conventional one. Moreover, the improved process showed excellent operation stability through the comparison of simulation results of several processes with various water contents in their feed gases. Although the energy consumption is increased (about 2%), the improved process was economically and technically feasible for the long-term availability of CO_2 pipeline transportation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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