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Process simulation, optimization, and cost analysis of a proposed sulfur recovery unit by applying modified Claus technology

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Abstract

Removing sour gas from any suitable gas sweetening technology in a cost-effective and environmentally responsible manner is a major challenge. This paper discusses how to safely and economically dispose of small amounts of acid gases resulting from the amine sweetening process. A two-stage Claus desulfurization unit was studied and simulated to treat acid gases resulting from natural gas sweetening operations in Ras Gharib oil fields (Egypt). These acid gases are used as feedstock for the proposed plant to produce a valuable product, such as elemental sulfur, which is used as a raw material in many industries. Although many sulfur recovery techniques are available for various conditions and applications, the Claus process is a critical and widely used method for recovering elemental sulfur from gaseous hydrogen sulfide. This work represents the potential benefits of treating acid gases with high hydrogen sulfide content. In addition, operational variables that could affect sulfur production and sulfur recovery efficiency of the studied Claus unit were studied and optimized. Aspen HYSYS simulation software (version 9) was used to evaluate the economic aspects and optimize the operational parameters of the unit for producing sulfur from acid background gases. The results showed that the maximum sulfur production was achieved at a catalytic converter reactor temperature of 270 °C and 210 °C for the first and second catalytic reactor, respectively, with an air flow rate of 933.3 kg mol/h. The economic study of the proposed desulfurization unit showed that the Claus unit would be economically acceptable with an expected return on investment of approximately 10% and an average payback period of 10 years. Moreover, the introduced plant has a positive impact on the environment by reducing the concentration of hydrogen sulfide in the gas from 69.58 to 0.16%.

Keywords: Sweetening, Hydrogen sulfide, Sulfur recovery, Claus process, Sour gas

Introduction

A valuable raw material, sulfur, is found in other fossil fuels as sulfur-containing elements that are converted to hydrogen sulfide during various processes, while hydrogen sulfide (H_2S) is the main form of sulfur in the natural gas industry. The increased sulfur volumes in waste gases and the increasing environmental regulations drive demand for recovered sulfur processes. The Environmental Protection Agency (EPA) has observed

that the environment is harmed by rising levels of SO_2 and CO_2 in the atmosphere. In crude oil, sulfur typically has an elemental level of 0.1–6 wt%; however, for some crude oils and asphalts, the number could be as high as 14%. It results in SO_2 and CO_2 gases, which damage the environment and atmosphere of the earth, called primary pollutants. When SO_2 gas reacts with water in the atmosphere, it causes sulfur and nitric acid, called a secondary pollutant [1].

In natural gas, the H_2S and some of the carbon dioxide (CO_2) are removed from the sour gases through different sweetening processes. The sweetening unit's resulting acid gas stream is flared, burned, or fed to a sulfur recovery unit [2, 3].

Numerous sulfur recovery systems, including the Claus process, direct oxidation, liquid redox, and H_2S scavengers, are available for diverse conditions and purposes. The H_2S proportion in the incoming acid gas significantly determines the best sulfur extraction technique [4]. In 1883, the Claus process was introduced by a German scientist called Carl Friedrich Claus. The early Claus process was very simple and consisted of only one simple step in which H_2S was reacted over a catalyst with oxygen in a single reactor to produce elemental sulfur beside the water [5]. The sulfur recovery efficiency in the early Claus process was low, and it was difficult to control the exothermic reaction. A modification that divided the overall process into multiple steps was later developed to solve the previous issues [6]. Two main processes comprise the modified Claus technology: the combustion reaction section in the furnace and the catalytic reaction section in catalytic reactors [7]. The chemical combustion section and catalytic stage reactions of the process are shown in Eqs. 1 and 2, respectively. Claus reactions are highly exothermic and reversible, and the conversions are highly dependent on temperature and sulfur content.

$$H_2S + 3/2O_2 \rightarrow SO_2 + H_2O \tag{1}$$

$$SO_2 + 2H_2S \rightarrow 3S + 2H_2O \tag{2}$$

The first step in the Claus process is the combustion operation which is carried out in the furnace to oxidize one-third of the H_2S to sulfur dioxide (SO_2) at a pressure of 3–14 psig, besides burning any mercaptans and hydrocarbons in the inlet stream. In the majority of refinery Claus units, ammonia and cyanides are also oxidized in the input stream via the combustion process [8]. In most cases, the thermal section produces 60 to 70% of the total elemental sulfur produced in the process [9, 10]. In addition, some side reactions can be formed in the furnace which results in the formation of H_2, CS_2, CO, and COS [11].

The second step in the Claus cycle is the catalytic conversion stage. The main objective of this procedure is to encourage the remaining H_2S and SO_2 to react, allowing elemental sulfur to be recovered through several reactors. In most cases, the Claus process usually contains a series of two or three reactors [12]. All catalytic reactors must contain a catalyst; the common catalyst used in catalytic reactors is made of activated alumina with the chemical formula of Al_2O_3. However, activated titania is also employed as a catalyst to improve sulfur recovery more than regular alumina. However, titania is a very expensive material that can cost up to 10–15 times as much as activated alumina [12, 13]. Other catalysts that can be utilized within the Claus process include activated

bauxite and cobalt-molybdenum hydrogenation catalysts. In the catalytic reactors, the generated CS_2 and COS in the previous combustion section are hydrolyzed. The following major and side reactions occur on the catalyst surface:

$$2H_2S + SO_2 \leftrightarrow 1/2S_6 + 2H_2O \tag{3}$$

$$COS + H_2O \rightarrow H_2S + CO_2 \tag{4}$$

$$CS_2 + 2H_2O \rightarrow 2H_2S + CO_2 \tag{5}$$

$$CO_2 + H_2 \rightarrow H_2O + CO \tag{6}$$

The reaction in Eq. 3 is reversible and exothermic, while the reactions in Eqs. 4 and 5 are irreversible and endothermic. Generally, the process is exothermic, and temperature increases along the reactor.

Other operations in the Claus cycle include sulfur condenser and preheating operations. Following each catalytic converter, sulfur condensers are used to condense sulfur vapors in order to promote the Claus reaction [13]. These condensers are typically designed for outlet temperatures of 165–185 °C to produce condensed liquid sulfur at a temperature above the dew point of sulfuric acid, with a reasonably low viscosity. The final sulfur condenser outlet can be as low as 130 °C. The preheating operation is required to keep the process gas temperature at each catalytic converter's inlet higher than the anticipated outlet sulfur dew point while keeping the temperature as low as possible to maximize H_2S conversion. The temperature should also be high enough for complete hydrolysis of COS and CS_2 to H_2S and CO_2 as shown by reaction Eqs. 4 and 5 [6, 10].

Claus process can reach almost complete conversion of the H_2S with suitable operation conditions. However, due to the thermodynamic limitations of the Claus reaction, the sulfur conversion efficiency for three-stage Claus reactors typically does not exceed 95–97%. Researchers worked on the sulfur recovery Claus process to improve the sulfur recovery rate. The recent research focuses on the reaction mechanism taking place in sulfur recovery cycles, the reaction between H_2S, SO_2, and CO2, and side reactions, such as hydrolysis of COS and CS_2, and sulfation of catalyst. The general trend is how to treat small amounts of acid gases economically using small-scale Claus units [6, 14].

Desulfurization of acid gases in low size is very challenging. Many previous papers studied Stretford process; however, problems associated with the disposal of toxic vanadium-containing wastes produced by this process made the process not commercially applicable. Other alternative processes, such as Lo-Cat and SulFerox processes, can be used to recover sulfur. But due to sulfur plugging and foaming problems which lead to extremely high maintenance cost, the utilization of these processes is very limited.

The novelty of this study lies in the potential benefits of treating small amounts of acid gases with a high hydrogen sulfide content. This study paves the way for optimal exploitation of the small quantities of gases that are constantly burned without any economic benefit, in addition to its negative effects to the environment because of its severe pollution effects. The current work can be used as a guideline for any similar cases in other plants which already need to treat small amounts of sour gases.

Regarding the Zero Routine Flare initiative by 2030, the present study introduces a cost-effective and environmentally responsible manner to dispose small amount of H_2S instead of burning or flaring. Treating these gases can help reduce their overall emissions and minimize their impact on the environment as hydrogen sulfide which is a highly flammable, explosive gas, and can cause possible life-threatening situations if not properly handled. This study presents an idea for treating acid gases produced by the natural gas amine sweetening unit of Ras Gharib oil fields (the Eastern Desert, Egypt), as it focus on how to determine ways to economically utilize the small volume 111.9 kgmole/h (2.2 MMSCFD) of gases rich in acid gases rather than sending them to the flare, which would have an adverse effect on the environment. Thus, the aim of the present study is to introduce a low-scale two-stage Claus process to recover sulfur from the investigated acid gases. Furthermore, the economic analysis, profitability, and environmental impact as well as the operational factors optimization of the proposed acid gas treating process were also studied in the present research paper by using Aspen HYSYS (version 9) with Sulsim Sulfur Recovery model as a simulation fluid package.

Methods

This paper describes how to securely and economically dispose of the modest amounts of acid gases created by the amine sweetening process. The methodology applied in this paper depends on determining the flow rate and the operating conditions of the acid gases besides measuring the H_2S content of these gases. The selection of the optimum sulfur recovery process relies on many parameters that include the type of acid gas, volume of gas, temperature, pressure, sulfur recovery level, the impurities present, and environmental laws to be met, besides the economic reasons [10]. However, the H_2S fraction in the inlet acid gas is the primary screening parameter for selecting the most cost-effective desulfurization method.

Regarding the H_2S content in the considered acid gas stream to be treated, the optimal process selection is the Claus desulfurization process. The suggested Claus process for the proposed sulfur recovery unit will then be simulated using simulation software; Aspen HYSYS (version 9) is a trustworthy and widely used software that can give acceptable results with a high level of satisfaction and validity. This simulation program is also beneficial for determining the optimal operational conditions at which the investigated desulfurization plant can be operated with higher efficiency and lower cost.

Case study

This study discusses the utilization of the acid gases resulting from the amine sweetening unit used to treat 15 MMSCFD of the sour gases produced from El-Hamd, Gharib, and Fanar fields in the Eastern Desert (Egypt). This acid gas stream is taken as the feed for the proposed desulfurization plant applying the Claus process. The analysis of the acid gas stream made by a gas chromatograph to determine its composition is shown in Table 1.

The operating conditions of the acid gas stream were measured using local gauges and an orifice plate flow meter. The determined pressure, temperature, flow rate, and H_2S content (in mole fraction) as operating conditions of the acid gas feed are 15 psia, 41 °C, 111.9 kgmole/h (2.247 MMSCFD), and 0.6958, respectively.

Table 1 Acid gas stream composition

Component	Mol fraction
Methane	0.0011
Ethane	0.0007
Propane	0.0005
i-Butane	0.00
n-Butane	0.0001
i-Pentane	0.0306
n-Pentane	0.0361
Hexane	0.0354
Heptane	0.0439
H_2S	0.6958
H_2O	0.0759
CO_2	0.0799
Total	1.00

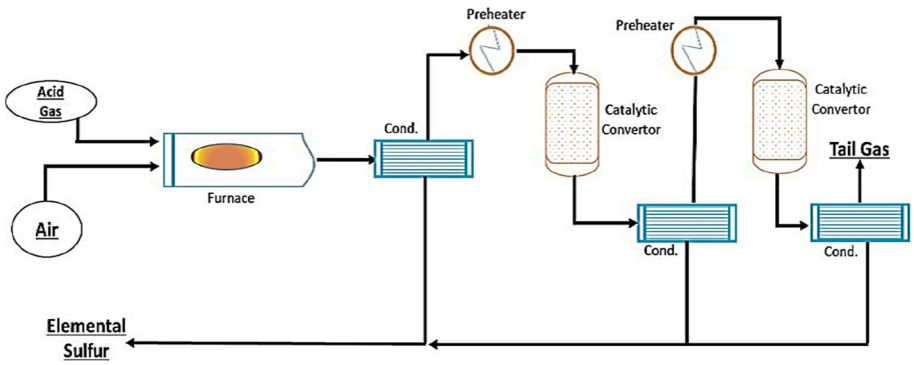

Fig. 1 Process flow diagram of the proposed desulfurization process

A two-stage Claus process was suggested in the current work as a desulfurization plant to recover sulfur from the abovementioned acid gas stream as a feed. Because of the high concentration of H_2S (69.58%) in this stream, the straight-through Claus process is the best choice to be applied for achieving the desired target of the desulfurization process [3]. The process flow diagram of this proposed desulfurization plant is shown in Fig. 1.

Results and discussion

As discussed before, the straight-through Claus process with two stages was chosen to be the desulfurization unit to be applied for the sulfur recovery of the considered acid gas stream. In the previous studies, different mathematical models based on the mass and energy conservation laws at steady state conditions were used to simulate the Claus process [15–17], an advanced approach was introduced by HYSYS software to simulate the Claus process with more accuracy to match the actual operation conditions of the process. The simulation results, operational condition influence, and the economic study of the introduced sulfur recovery unit are discussed in the following subsections.

Simulation results of the proposed desulfurization unit

The proposed two-stage Claus process was simulated using the Sulsim (sulfur recovery) package in Aspen HYSYS (version 9). The composition of the acid gas feed stream used to simulate the plant is shown in Table 1 with the operation conditions mentioned earlier. There are some assumptions taken into account when performing the simulation. The furnace is designed as a reaction furnace (single chamber) at a pressure difference of 3.5 kPa, the waste heat boiler (WHB) as a waste heat exchanger (single pass) at a pressure difference of 3.5 kPa, the reactors (CV1 and CV2) as a catalytic converter, the condensers (CD1, CD2, CD3) as a sulfur condenser with a pressure drop of 3.5 kPa, and heaters (E-100 and E-101) with a pressure drop of 3 kPa. Figure 2 shows a simulation of the proposed sulfur recovery unit.

The proposed sulfur recovery cycle includes a reaction furnace (RF), a waste heat boiler (WHB), heaters, condensers, and only two catalytic converters to control the cost. Gamma alumina or γ-Al_2O_3 (activated alumina) is the catalyst bed used in the catalytic converters to control the costs. Alumina is much less costly than titania, and satisfactory results could be achieved using the gamma alumina bed. Gamma-alumina or γ-Al2O3 is the most employed one for applications in catalysis and adsorption, because of its high surface area, catalytic activities, good adsorption performance, and good porosity parameters besides the thermal stability [18, 19].

The simulation results of the inlet temperature, outlet temperature, and operating pressure of the reaction furnace are 41 °C, 1465 °C, and 103 kPa, respectively. The temperature of the reaction furnace of 1465 °C is applied to ensure flame stability and total burning of undesirable components like heavy hydrocarbons and ammonia [20, 21]. The outlet stream of the reactor furnace with a high temperature (1465 °C) is used to produce steam through the WHB which reduces its temperature to 300 °C. The elemental sulfur produced due to the combustion reactions done in the reactor furnace is removed by condensation from the WHB outlet stream in condenser 1 which condenses 40.79 tons/day of elemental sulfur. Condenser 1 outlet stream of 135 °C [13] is indirectly heated to the optimal temperature (approximately 270 °C) for catalytic conversion reactions in the first reactor preheater by high-pressure steam coming from Claus WHB before entering the first catalytic reactor. Due to the exothermic reactions, the gas leaving this reactor has a temperature of about 300 °C. The effluent gas from the first Claus reactor is then routed to the second condenser, where 7.83 tons/day of the produced sulfur is condensed.

The process gas stream leaves the second condenser at 135 °C and is reheated in the second preheater to 210 °C by using HP steam and it is then supplied to the second catalytic reactor. It is more practical to increase the temperature to around 210 °C to keep the outlet tail gas slightly over the sulfur dew point. The operating pressures for the first and second preheaters are 93.06 kPa and 83.16 kPa, respectively. The outlet stream of the second reactor is directed to the third condenser to condense 5.03 tons/day of the produced elemental sulfur. The inlet and outlet temperatures of the third condenser are 217 °C and 135 °C, respectively. The tail gas produced from the third condenser can be safely flared or injected into an underground reservoir without posing any environmental hazards. The tail gas composition generated by the desulfurization plant under investigation is addressed in Table 2.

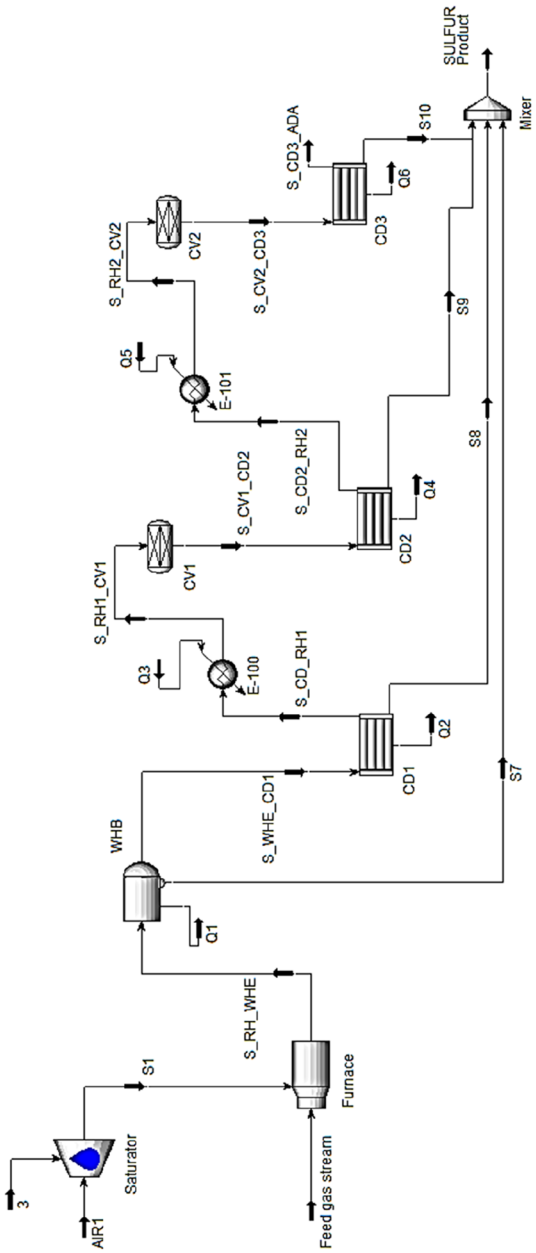

Fig. 2 Simulation of the proposed two-stage Claus sulfur recovery unit

Table 2 Composition of the tail gas stream of the investigated desulfurization plant

Component	Mole fraction
Methane	0.00
Ethane	0.00
Propane	0.00
Butane	0.00
Pentane	0.00
N_2	0.6815
H_2	0.011
H_2S	0.0016
H_2O	0.1902
$C0_2$	0.0975
CO	0.0048
SO_2	0.0043
COS	0.001
Argon	0.0081
Total	1.00

Table 3 Sulfur conversions and recoveries for different units of the proposed Claus cycle

Conversion/ recovery	Reaction furnace		Catalytic converter 1		Catalytic converter 2	
	%	Tons/day	%	Tons/day	%	Tons/day
Conversion	69.21	41.47	42.80	7.89	48.45	5.11
Cumulative conversion	69.21	41.47	82.39	49.37	90.92	54.48
Recovery	98.38	40.79	91.36	7.83	85.90	5.03
Cumulative recovery	68.09	40.79	81.15	48.62	89.54	53.65

In reference to this table, it is evident that the H_2S content decreases from 69.58 to 0.16% after the implementation of the proposed sulfur recovery process.

Table 3 shows sulfur conversion and recovery as a performance summary of the considered Claus cycle [22]. Regarding the simulation results shown in Table 3, it is noticed that about 41.47 tons/day of sulfur is converted through the reaction furnace, and 98.38% of this converted amount (40.79 tons/day) is recovered with the first condenser. The first catalytic converter can convert about 7.89 tons/day of sulfur plus the residual amount from the first condenser (0.68 tons/day), 91.36% of this amount is recovered (7.83 tons/day) through the second condenser. The second catalytic converter can convert about 5.11 tons/day of sulfur in addition to the residual sulfur from the previous stages (0.74 tons/day), 85.90% of this amount is recovered (5.03 tons/day) through the third condenser.

It is obvious that most of the sulfur produced in the whole process is recovered from the reaction furnace section which produces about 41 tons/day of sulfur with a recovery percentage of 69%. As presented in Table 3, the total sulfur produced from the introduced sulfur recovery unit is about 54 tons/day.

Operational variables affecting the desulfurization process efficiency

Many operational variables can affect the introduced desulfurization process efficiency. These variables are oxygen enrichment, inlet catalytic reactor temperature, outlet temperature of condenser, and feed gas flow rate. These operating variables are the variables that can be changed in the Claus process in order to maximize sulfur production and overall desulfurization recovery efficiency.

Effect of oxygen enrichment in inlet air flow on sulfur production rate

To increase the desulfurization process throughput, oxygen enrichment in air flow is often used. The purpose is to convert as much H_2S gas as possible into elemental sulfur during the desulfurization process. Oxygen enrichment increases flame temperature by eliminating the effect of diluent nitrogen in the air. The use of oxygen-enriched technology can reduce the size of the sulfur recovery unit, thereby reducing investment costs. Enriching the combustion air with oxygen is an effective modification of the Claus burner and is used to increase the temperature of the Claus reaction furnace. This method can partially or completely replace the nitrogen in the air with oxygen, or simply increase the inlet air flow [17]. Enriched oxygen should be used with caution. Controlling the combustion gas mixture is critical to preventing oxygen breakthrough in the catalytic converter. Free oxygen can deactivate the alumina catalyst by sulphation. In the presence of SO_2, the alumina catalyst forms a layer of SO_3, which deactivates the catalyst via two separate mechanisms [23, 24]. The first happens at temperatures ranging from 300 to 350 °C, when SO_3 interacts directly with the catalyst, forming $Al_2(SO_4)_3$, which inhibits active sites (Eq. 7).

$$2Al_2O_3 + 6SO_2 + 3O_2 \rightarrow 2Al_2(SO_4)_3 \tag{7}$$

The second method involves SO_3 chemisorption on catalytic active sites at lower temperatures, which causes geometric obstruction or changes in the structure of the catalytic surface. Additionally, SO_3 combines with water to form sulfuric acid, which corrodes steel [17, 18, 25].

In this work, oxygen enrichment is achieved by increasing the air flow rate entering the reaction furnace. Figure 3 presents the relationship between the inlet air flow rate to the reaction furnace (S1 stream) and the sulfur produced. It is noticed that the sulfur production is increased by increasing the saturated air flow until it reaches its maximum value at peaks, then falls with increased air flow. This is a logical finding because both too much and too little air will impact H_2S conversion. For the proposed sulfur recovery plant, the maximum amount of sulfur recovered can be obtained at an optimum saturated air flow rate of 933.3 kg mol/h with an increase of 12% of the normal air flow calculated from Eq. 1.

Effect of inlet catalytic reactor temperature on sulfur production rate

Most of the previous papers focused on the temperature of the furnace; however, this paper studies the effect of reactor temperature. The reactor temperature is an important operational variable in the desulfurization process and is inversely proportional to the

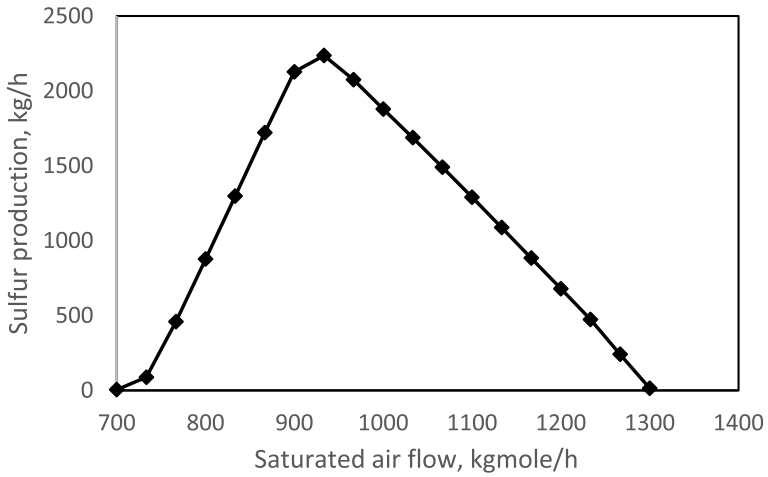

Fig. 3 Effect of oxygen flow rate on sulfur production in the first condenser

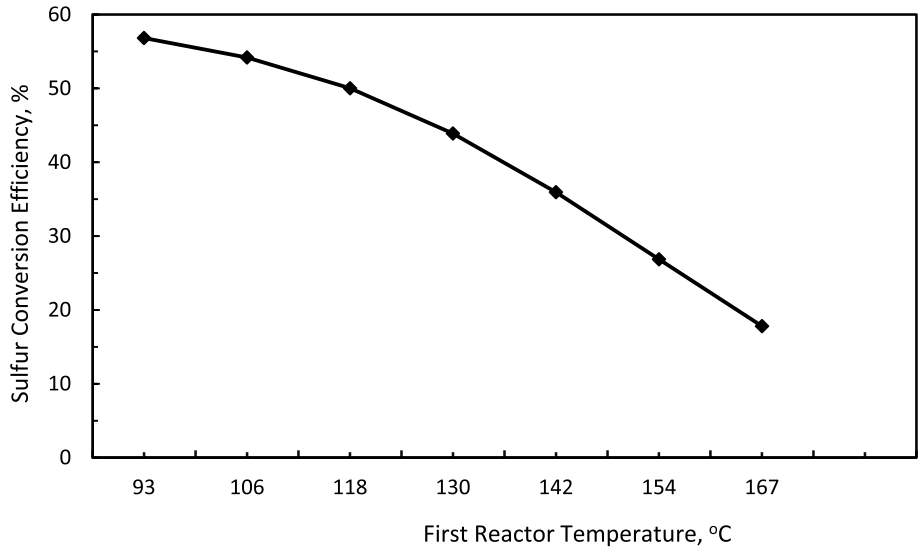

Fig. 4 Effect of the first reactor temperature on the H_2S production

H_2S conversion of the sulfur recovery reactions. The simulation results for studying the effect of the temperature on the H_2S conversion for the first and second reactors are illustrated in Figs. 4 and 5, respectively.

These results show that the conversion is increased at lower temperatures. However, the temperature should be maintained at a higher level than the anticipated outlet sulfur dew point to avoid condensation of the vapor sulfur. Additionally, the temperature within the first reactor must be high enough to promote the hydrolysis of COS and CS_2 into H_2S and CO_2 respectively since hydrolysis reactions are non-reversible. It is a practical approach to keep the outlet tail gas slightly over the sulfur dew point [8, 15].

In the current paper, the cumulative sulfur recovery increased by 5%, when the temperature of the first and second reactors was decreased from 320 °C and 260 °C to 270 °C and 210 °C, respectively. The optimum temperature for the first and second reactors are

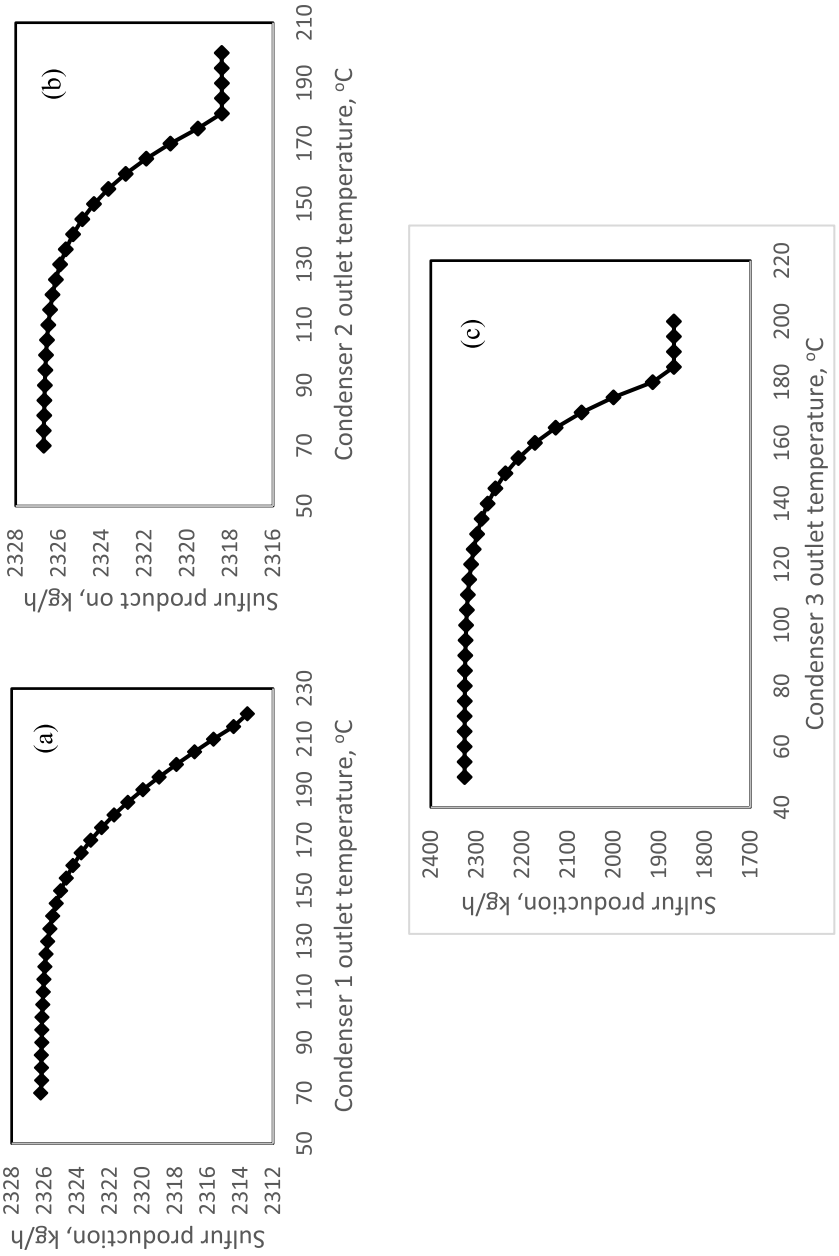

Fig. 5 Condensers outlet temperatures; **a** condenser 1 outlet temperature; **b** condenser 2 outlet temperature; **c** condenser 3 outlet temperature

270 °C and 210 °C respectively to maximize the sulfur produced without any expected condensation of the vapor sulfur.

Effect of outlet condenser temperature on sulfur production rate

The effect of the output temperature of the three condensers (CD1, CD2, and CD3) on the sulfur production rate was evaluated at a temperature of 70–200 °C. The Claus process was simulated under the optimal operating conditions defined in the previous sections. Figure 6 shows the relationship between the sulfur production rate and the outlet temperature of the different condensers.

It was found that the rate of sulfur production is inversely proportional to the temperature emerging from the condensers. As the condenser outlet temperature increased, the sulfur production rate decreased. It is also noted from the figure that the maximum sulfur production rate was achieved at the optimum outlet temperature of 135 °C for condensers 1 and 2, while the optimum outlet temperature for condenser 3 was at 70 °C [13, 16].

However, many factors limit the utilization of these optimum temperatures such as the increase in power of the condensers, the pressure drop inside the condensers, the dew point temperature of sulfuric acid, and the viscosity of the produced liquid sulfur. Besides that, the overcooling can result in another problem which is sulfur solidification [26].

Effect of feed gas flow rate on sulfur production rate

To study the effect of changing the feed gas flow rate on the sulfur production rate and the overall sulfur recovery efficiency, the Claus process was conducted at a feed gas molar flow of 80–140 kg mol/h and the air flow rate at its optimum value of 933.3 kg mol/h. The temperature of the first and second catalytic converters is at their optimum values, which are respectively 270 and 210 °C.

The simulation results are shown in Fig. 6a. It shows that the Claus process can operate very efficiently at a feed gas molar flow of 109 kgmol/h. This optimum value of feed gas flow is close to the actual molar feed flow presented in this work (111.9 kgmol/h).

Regarding the effect of the concentration of hydrogen sulfide in the feed gas, it was noted that increasing the concentration of hydrogen sulfide increases the production of sulfur, and it reached its maximum value at 0.69 mol fraction of H_2S (current value). As the hydrogen sulfide concentration increased above 0.69 mol fraction, the sulfur recovery decreased. These results are consistent with other results presented by Al Hamadi et al. [16] and Abumounshar et al. [13]. But they explained the reason for this decrease by saying that the decrease in sulfur recovery may be due to the increase in the reaction temperature in the furnace, which leads to increased formation of carbon dioxide and thus the pyrolysis of carbon dioxide to carbon monoxide.

In this work, it was found that increasing the feed gas stream or H_2S concentration in the feed without increasing the inlet air flow will reduce the temperature in the reaction section as shown in Fig. 6c and thus reduce the products of the reaction section (Fig. 6a, d). It was found that the concentration of other products SO_2, COS, CO, and CS_2 also decreased with increasing feed gas stream or H_2S concentration in feed gas.

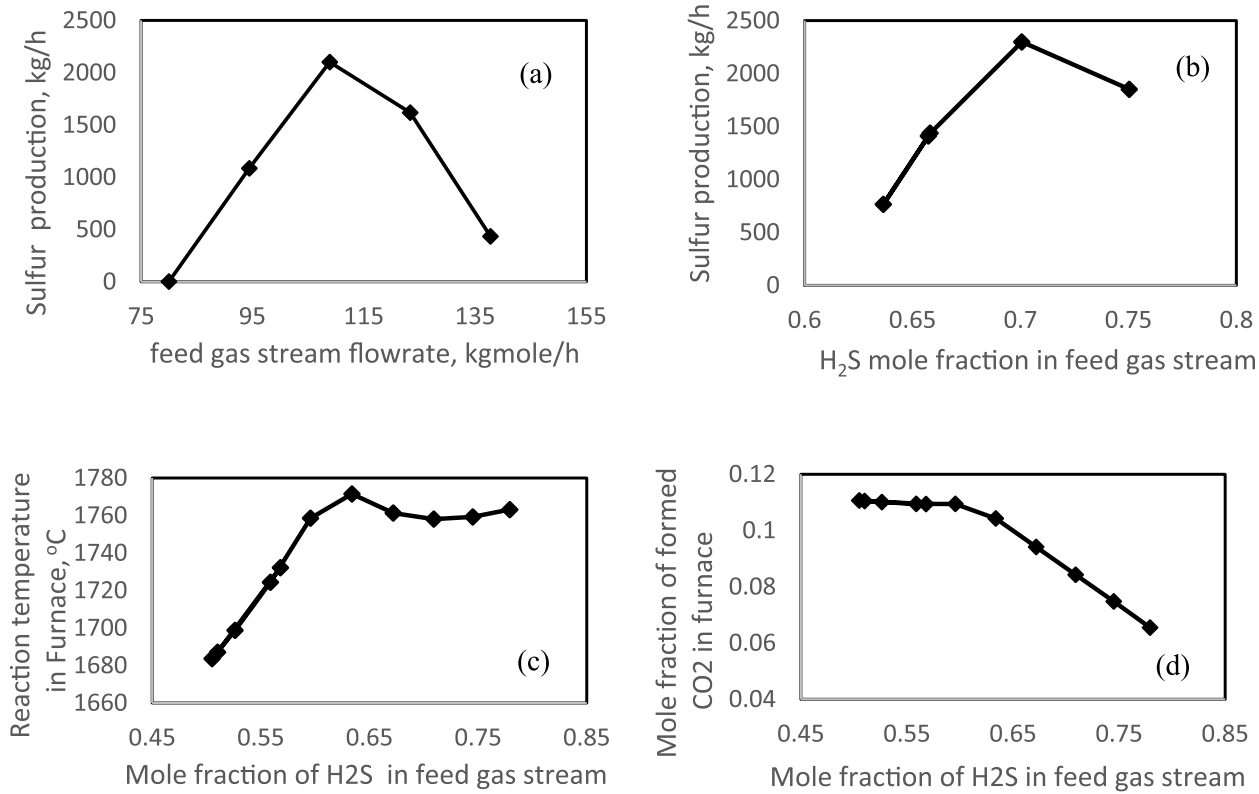

Fig. 6 Effect of feed gas flow on sulfur production (**a**), mole fraction of H_2S in feed gas stream on the sulfur production rate (**b**), reaction temperature in furnace (**c**), and CO_2 mole formed in furnace (**d**)

Economic study of the proposed desulfurization plant

As mentioned earlier, the proposed sulfur recovery unit contains reaction furnace, waste heat exchanger, heaters, condensers, and two catalytic converters in series. The company's current direction is towards renting for several reasons. These reasons include the uncertainty of reservoir life, short payback time, and reduction of investment hazards [27]. Compared to similar projects, the average estimated rental cost for the operation and maintenance of the entire sulfur recovery cycle is around 8500 $ per day with an annual cost of 3,102,500 USD. Another vital parameter that must be considered is the plant installation cost. The overall installation cost for the proposed desulfurization plant includes different items such as equipment erection, piping, instrumentation, utility cost, building, site preparation, design, and contingency costs. Because a rental unit is proposed in this study, the installation cost will depend mainly on piping, electricity, contingency, and site preparation costs. The installation costs of the investigated plant were calculated to be about 1,200,000 USD.

The operating cost of the considered plant includes mainly the raw materials and power costs. The feed to the sulfur recovery plant under investigation which can be considered raw material is 111.9 kgmole/h (2.2 MMSCFD) of acid gases that can be derived from the sweetening unit. The cost of these gases can be neglected as it is already directed to the flare without any economic benefits. Power is very vital for any project. The estimated power requirements for the proposed desulfurization unit are 1750, 1380, and 795 KW for the first, second, and third condensers, respectively.

The introduced plant's cost for the first year will include the installation cost, with an approximate value of 6,600,000 USD. The annual cost for the next years will be reduced to nearly 5,400,000 USD. The average sulfur price is about 285 USD/ton, and the annual outcome of selling 54 tons/day is about 5,503,265.60 USD. As a result, the current sulfur recovery project is predicted to generate revenue in the second year, with an ROI of about 10% and a payback time of about 10 years, which makes the introduced sulfur recovery plant commercially viable. Furthermore, the current proposal has a positive impact on the environment. This can be illustrated by the composition of the tail gas produced from the investigated Claus unit as shown in Table 2. Regarding this table, it is obvious that the H_2S content decreased from 69.58 to 0.16% after applying the proposed Claus desulfurization process. The produced tail gas can be flared or injected into an underground reservoir without any environmental hazards.

Conclusions

This paper discusses the safe removal of acid gases from the amine sweetening unit used in Ras Gharib oil fields (Western Desert, Egypt) in an economical method. The proposed sulfur recovery plant for treating the considered acid gas stream was simulated using Aspen HYSYS (version 9). All the data required to design this plant including all the operational conditions of the reactor furnace, the two catalytic converters, and the three condensers are introduced in this paper. The simulation results demonstrated that the two-stage Claus process may be utilized efficiently to remove safely the sulfur from small amounts of the acid gas stream. By applying this sulfur recovery technology, the H_2S concentration of the acid gas feed stream is decreased from 69.58 to 0.16%. The

investigated sulfur recovery unit produces approximately 54 tons/day of elemental sulfur. The produced elemental sulfur can be used in different industrial processes such as the manufacturing of fertilizers, detergents, and chemicals. Additionally, sulfur is used in the production of sulfuric acid.

The second part of the current work is directed to study the effect of some operational conditions on the efficiency of the introduced desulfurization plant. The simulation results showed that sulfur conversion is inversely proportional to the reactor temperature and positively proportional to oxygen enrichment within certain limits. Both reaction temperatures and air flow rate were optimized to increase the produced sulfur. The cumulative sulfur recovery increased by 5% when the temperature of the first and second reactors was optimized from 320 °C and 260 °C to 270 °C and 210 °C, respectively. For the oxygen flow rate, the amount of recovered sulfur can be increased from 32 to 53.65 tons/day when the air flow rate was increased to 933.3 kg mol/h by an increment of 12% of the normal air flow leading to a cumulative conversion efficiency of 91%.

The last part of this paper is focused on the economic study of the introduced desulfurization plant. According to the economic study results, the proposed two-stage Claus technique is an economical and acceptable process for sulfur recovery of a small amount of acid gas feed stream. Considering the costs of power, rental unit, and installation, the predicted annual savings for the current sulfur recovery project are estimated at 5,503,265.60 USD, with a calculated ROI of around 10% and an average payback period of 10 years, indicating the commercial viability of the introduced sulfur recovery plant. As a result, the present proposal can effectively and responsibly dispose of small amounts of acid gases with high sulfur content in a cost-efficient and environmentally conscious manner.

Abbreviations

MDEA	Methyl diethanolamine
MMSCFD	Million standard cubic feet per day
MMBTU	Million British thermal unit
H_2S	Hydrogen sulfide
COS	Carbonyl sulfide
CS_2	Carbon disulfide
kW	Kilowatt
CO_2	Carbon dioxide
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide

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Authors' contributions
Ahmed M. participated in conceptualization, methodology, software, validation, and writing—original draft. Professor Fatma K. Gad participated in supervision, conceptualization, methodology, data curation and analysis. Dr Walaa M. Shehata participated in supervision, conceptualization, methodology, data curation and analysis, optimization formulation and analysis, and editing of the current research paper. Professor Ahmed A. Bhran participated in formal analysis, investigation, visualization, data curation, and writing—review and editing of the current research paper. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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