



Alexandria University  
**Alexandria Engineering Journal**

[www.elsevier.com/locate/aej](http://www.elsevier.com/locate/aej)  
[www.sciencedirect.com](http://www.sciencedirect.com)



# Exergy study of amine regeneration unit for diethanolamine used in refining gas sweetening: A real start-up plant

Ahmed Y. Ibrahim<sup>a,\*</sup>, Fatma H. Ashour<sup>a</sup>, Mamdouh A. Gadalla<sup>b,c</sup>, Rania Farouq<sup>d</sup>

<sup>a</sup> Department of Chemical Engineering, Cairo University, Giza 12613, Egypt

<sup>b</sup> Department of Chemical Engineering, Port Said University, 42526 Port Fouad, Egypt

<sup>c</sup> Department of Chemical Engineering, The British University in Egypt, Misr-Ismalia Road, El-Shorouk City, 11837 Cairo, Egypt

<sup>d</sup> Petrochemical engineering, faculty of engineering, Pharos university in Alexandria, Egypt

Received 28 November 2020; revised 6 April 2021; accepted 24 April 2021

Available online 10 June 2021

## KEYWORDS

Amine regeneration unit;  
 DEA;  
 Energy;  
 Exergy destruction;  
 Exergy efficiency;  
 Refining

**Abstract** Diethanolamine (DEA) solutions are used in refineries to sweeten gas. DEA is responsible for absorbing H<sub>2</sub>S from sour gas. In an Amine Regeneration Unit (ARU), the rich amine with H<sub>2</sub>S is regenerated. A refining column in the Middle East started commercial production in 2020. Using Aspen HYSYS V.11, an amine regeneration unit in the refinery that supplies lean amine to the delayed cooker unit for gas sweetening was simulated, and an exergy study was performed on various equipment. Exergy is destroyed in an irreversible process, while energy is converted from one type to another. The sum of the physical and chemical exergy is the total exergy. The chemical exergy was calculated using a series of equations embedded in Excel, while the physical exergy was calculated using HYSYS. The DEA concentration used is 25 wt%. Each equipment's exergy destruction rates, destruction efficiency, and percentage share of destruction were determined. The regenerator had the highest destruction rate of 2144.11 kW and an 80.21 percent share of total destruction. With a value of 326.00 kW and a percentage share of 12.20 percent of total destruction, the air cooler has the second-highest exergy rate. Exergy has a 99.70 percent overall efficiency. Due to system losses, the DEA concentration fell from 25% to 20% of the design value. The regenerator had the highest destruction rate of 2616.74 kW followed by the air cooler with a value of 294.61 kW. In DEA 20%, an exergy analysis was carried out. Exergy research showed the same percentage share distribution for equipment at a concentration of 20 DEA wt. percent. To find related equipment relationships, the results of the unit's exergy analysis were compared to those of another ARU exergy study at the same refinery plant. The regenerators were found to have the highest exergy destruction of the two units with a percentage share of the overall destruction reaching 80% followed by the air coolers with values reaching 9%.

© 2021 THE AUTHORS. Published by Elsevier BV on behalf of Faculty of Engineering, Alexandria University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

\* Corresponding author.

E-mail address: [yehiawe@hotmail.com](mailto:yehiawe@hotmail.com) (A.Y. Ibrahim).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

<https://doi.org/10.1016/j.aej.2021.04.085>

1110-0168 © 2021 THE AUTHORS. Published by Elsevier BV on behalf of Faculty of Engineering, Alexandria University.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

**Nomenclature**

A	Area of heat transfer
$c_p$	Sensible heat
D	Distillate rate
e	Specific exergy
E	Exergy rate
$\dot{E}_k$	Kinetic energy
$\dot{E}_p$	Potential energy
$\varepsilon$	Exergy efficiency
F	Distillation feed rate
g	Gravitational Acceleration constant
H	Enthalpy
$\dot{H}$	enthalpy rate
$\hat{H}$	Specific enthalpy
$h_d$	Specific enthalpy in distillate
$h_f$	Specific enthalpy in feed
$h_w$	Specific enthalpy in residue
L	Rate of the liquid flow return returning to the top plate
$\dot{m}$	Mass rate
P	pressure
$P_f$	pressure due to friction
$\dot{Q}$	Heat duty
$Q_c$	Condenser duty
$Q_r$	Reboiler duty
S	Entropy
R	Gas constant
T	Temperature
$T_1$	hot fluid temperature inlet
$T_2$	hot fluid temperature outlet
$t_1$	cold fluid temperature inlet
$t_2$	cold fluid temperature outlet
$T_{lm}$	log mean temperature
U	overall heat transfer coefficient
V	Rate of the vapor at the top plate
v	velocity

W	Distillation bottom rate
$\dot{W}_s$	Shaft work
$x_d$	Distillate composition in top
$x_f$	Distillate composition in feed
$x_w$	Distillate composition in bottom
z	elevation

*Greek letter*

$\Delta$	The difference between inlet and outlet
$\lambda_{mix}$	Latent heat of vaporization for overhead mixture
$\lambda_{steam}$	Latent heat of vaporization for reboiler steam
$\rho$	Liquid density

*Subscripts*

c	Condenser
che	Chemical
d	Distillate
e	Exit
f	Feed, friction
i	Inlet, specie in a mixture
k	Kinetic
lm	Log mean
p	Potential
r	Reboiler
s	Shaft
w	Residue
0	Standard conditions

*Superscripts*

ch	Chemical
ph	Physical
0	Standard conditions

**1. Introduction**

Hydrogen sulphide is a toxic, corrosive pollutant that is produced in refineries. It causes acid rain, which is harmful to equipment as well as human health [1,2]. Sulphur recovery plants (SRU) use hydrogen sulphide as a feedstock to produce elemental sulphur [3,4]. The primary goal of SRU plants is to avoid H<sub>2</sub>S emissions from violating global environmental regulations [5-8]. Sulphur is most commonly generated using the modified Claus process [9-11]. Some dangerous pollutants are present in the process sour water provided by refinery plants. In sour water, the major contaminants are hydrogen sulphide (H<sub>2</sub>S) and ammonia [12-14]. H<sub>2</sub>S and NH<sub>3</sub> are extracted from sour water using strippers [15-17]. Amine treating units are used to sweeten sour gas that contains acid gas such as H<sub>2</sub>S. H<sub>2</sub>S is removed from the gas by a lean Amine solution, which is then stripped from the rich amine in a regenerator [18,19]. This role is performed by the amines Diethanolamine (DEA) and Methyl diethanolamine (MDEA) [2,20-22]. MDEA is used when an acidic gas contains both CO<sub>2</sub> and H<sub>2</sub>S

because of its high selectivity for H<sub>2</sub>S over CO<sub>2</sub> [23-25]. An amine scrubber unit is shown in Fig. 1.

The fastest-growing population on the planet has resulted in a significant rise in energy consumption [26,27]. The value of optimum energy use for community growth cannot be overstated. Optimal energy usage is now a significant measure of a community's degree of growth from an energy standpoint. As a result, energy optimization and loss prevention in different industries are critical. Chemical processes with higher energy consumption have higher operating and production costs, as well as lower device performance [28]. Though energy is conserved in chemical reactions, exergy is irreversibly lost. Exergy is the amount of work or power we can get from a given amount of energy concerning the natural environment. Potential, kinetic, chemical, and physical exergy are all components of total exergy. Potential and kinetic exergy is often ignored because of their lower values as compared to physical and chemical exergy [11]. The chemical exergy is described as the maximum amount of work performed when a material transitions from an environmental state to a dead state. Only the environment is involved in the process of process exchange

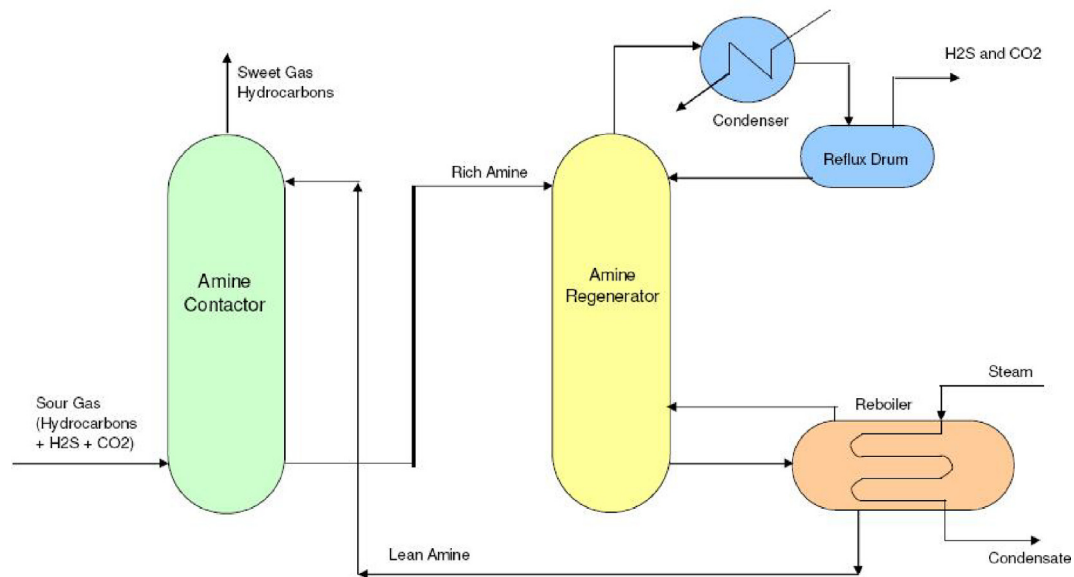


Fig. 1 Amine scrubber unit.

and heat transfer. The maximum amount of work is often considered in the concept of physical exergy, but when the material is transported from its initial state to the state of the environment, the physical exergy concept is used. Only thermal contact with the environment is involved in physical exergy [29]. Ibrahim et al. carried out an energy optimization analysis on the same refinery plant to conserve steam from the SWS1, SWS2, ARU1, and ARU2 units. The research saved 1,537,206.38 \$/year [10]. Some researchers studied the effect of using nanofluid on exergy. Sheikholeslami et al. mentioned that Hybrid nanofluid is useful to increase the exergy efficiency of solar water heaters. Sheikholeslami et al. concluded that using nanofluids can result in reduces exergy losses. Sheikholeslami et al. added hybrid nanoparticles to enhance the efficiency of solar collector. The exergy loss decreases about 8.671%. [30-32].

There was no notable examination of energy and exergy analysis of Amine scrubber units and Amine regenerator units in the literature review. (Mohamadi-Baghmolaie, et al.) performed an exergy analysis on various compositions of a mixture of DEA and MDEA, as well as the CO<sub>2</sub> emissions of the exit sweet gas from the blended mixture. There was no research on the individual DEA solution and the impact of its original concentration being reduced due to operational issues [20]. Except for an exergy analysis conducted by Ibrahim et al. for the same refinery plant [33], there were no exergy studies related to the individual DEA solution and the impact of a decrease in the original concentration due to operational problems. Aspen HYSYS V.11 was used to simulate an industrial ARU unit. Two amine regeneration units regenerate the rich amine solution to lean amine in a refinery plant in the Middle East that began official production in 2020. All refinery units are serviced by ARU1, except the Delayed Coker Unit (DCU). ARU1 unit was exergy studied by Ibrahim et al. [33]. The second unit, ARU2, is only responsible for regenerating DCU's rich amine. The research presented here is for ARU2. The study aims to calculate the exergy destruction rates for all equipment, as well as the percentage share of

equipment that is destroyed. To infer the relationships between similar equipment, the current ARU No.2 research results were compared to the results of the ARU No.1 study. These recent exergy studies will aid in the reduction of exergy losses in process systems. DEA is present in the solvent solution at a concentration of 25% by weight. Exergy analysis (chemical and physical) and local irreversibility in equipment are performed after model validation. The distribution of destroyed exergy between equipment is compared, and the exergy efficiency of different equipment is calculated. Due to system losses, the concentration of DEA fell to about 20%. The same exergy analysis is carried out on the DEA solution at a concentration of 20% to see what changes occurred in the exergy calculations.

## 2. Materials and methods

### 2.1. Simulation step

The amine regeneration unit is simulated with Aspen HYSYS software V.11, and the simulation output, which describes the plant, is shown in Fig. 2, along with the feed characteristics in Table 1.

Fig. 2 is an output from the simulation and can be considered as a PFD for the plant.

### 2.2. Simulation sections

Rich amine from other refinery process units and absorbers is regenerated to lean amine in the regenerator column, and acid gas from overhead is sent to the Sulphur Recovery Unit (SRU) for further processing. The rich amine solution is pumped to the tube side of the (lean/rich Amine heat exchanger E1) and fed to the Amine regenerator by the Rich Amine Pump (P1). The regenerator reboiler provides heat to the regenerator, which is used to remove H<sub>2</sub>S from the rich amine solution. In the regenerator overhead condenser, the vapour from the

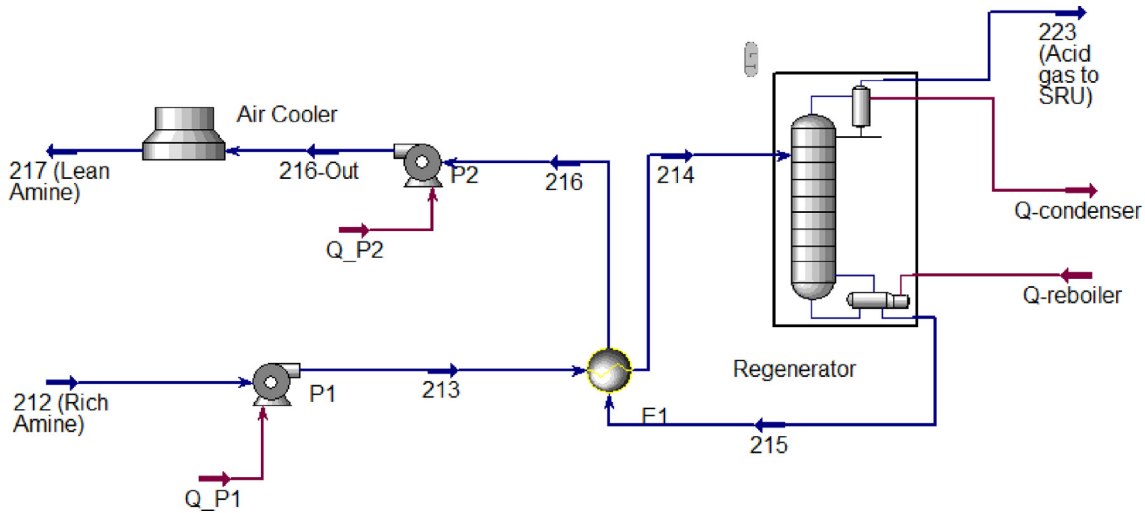


Fig. 2 Amine regeneration unit.

Stream description	Rich Amine
Temperature	103
Pressure	2
Mass flow	73176.4
<b>Total Weight Comp. Fraction</b>	
DEA	0.243
Water	0.728
H <sub>2</sub>	0.000
NH <sub>3</sub>	0.000
H <sub>2</sub> S	0.028
CO <sub>2</sub>	0.000

regenerator is cooled to 55 °C. SRU receives the acid gas from the Regenerator Reflux Drum. The lean amine solution from the Amine regenerator is transferred to E1's shell side and cooled to about 88.2 °C. After cooling at E1, the lean amine is pumped to the lean Amine Air Cooler by (Amine charge pump P2).

### 2.3. Simulation criteria

Chemical Solvent was the fluid package used in the simulation. This package was appropriate for component feeding. The results will deviate if the fluid package was selected incorrectly. The regenerator was simulated as a distillation tower, which needed some data (the number of trays, inlet and outlet stream connections, bottom pressure, top pressure, bottom temperature, and top temperature), and the column was based on flow rates or top and bottom component fractions. E1 is simulated as a standard heat exchanger. This necessitated a set of values for the cold and hot side streams, including flow rates, temperatures, and pressure drops. The pumps P1 and P2 were chosen as pumps.

### 2.4. Validation step

The simulation results were compared to the industrial data for validation. Since the unit's goal was amine regeneration, the simulation's two-stream selected were 217 (regenerated LA) and 223 (Acid gas to SRU).

### 2.5. Exergy calculations [11,20,28,29,33]

The physical and chemical exergy is determined using the following equations in a sequence:

$$\text{Physical exergy} = (H - H_0) - T_0(S - S_0) \quad (1)$$

$$\text{Chemical exergy} = \sum ex^0_{che} + RT^0 \sum x_i \ln x_i \quad (2)$$

$$\text{Destruction exergy} = \sum m_i e_i - \sum m_c e_c \quad (3)$$

$ex^0_{che}$  is the standard chemical exergy found directly from tables or calculated by methods, where  $x_i$  is the mole fraction of specie "i" in the mixture.

Enthalpy, entropy, temperature, global constant of gases, and standard condition are represented by the letters H, S, T, R, and 0. We did not disregard chemical exergy because its value is comparable to and higher than physical exergy; therefore, total exergy is calculated as the amount of physical and chemical exergy.

$$E^{ph} = \dot{m} e^{ph} \quad (4)$$

$$E^{ch} = \dot{m} e^{ch} \quad (5)$$

The sum of the physical and chemical exergy values for each stream is used to calculate the exergy of the material stream.

$$E = E^{ph} + E^{ch} \quad (6)$$

The exergy efficiency of system components is defined as the ratio of outlet exergy to inlet exergy for each component, and the exergy efficiency of the entire system is defined as the percentage of inlet exergy converted to the system's outlet.

## 2.6. Exergy destruction calculations equations of equipment

Table 2 shows exergy in, exergy out, and exergy destruction equations based on equipment types in the studied unit.

## 2.7. Material and energy balance concepts [34]

A distillation column with a condenser and reboiler (the regenerator), one heat exchanger, two pumps, and an air cooler were among the several pieces of equipment in the ARU unit. This paper tries to use a method for calculating the plant's material and energy balance that will be useful to readers.

### 2.7.1. Material balance equations

The general material balance equation is as follows:

$$\text{Input} - \text{output} + \text{generation} - \text{consumption} = \text{accumulation.} \quad (7)$$

In the case of steady-state conditions, no accumulation exists, and the equation can be written as follows:

$$\text{Input} + \text{generation} = \text{output} + \text{consumption.} \quad (8)$$

### 2.7.2. Material balance assumptions

In the case of a non-reactive system with no generation or consumption, the plant operates at steady-state conditions.

### 2.7.3. Material balance equations used in plant

Equation refers to reactive systems. The equation for the continuous nonreactive system is as follows:

$$\text{Input} = \text{output.} \quad (9)$$

Otherwise, the equation is written as follows:

$$\sum_{input} \dot{m}_i = \sum_{output} \dot{m}_i \quad (10)$$

### 2.7.4. Energy balance equations

The overall energy balance equation is as follows:

$$\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s \quad (11)$$

The enthalpy difference is calculated based on the following equation:

$$\Delta\dot{H} = \sum_{output} \dot{m}_i \hat{H}_i - \sum_{input} \dot{m}_i \hat{H}_i \quad (12)$$

The kinetic energy is calculated based on the following equation:

$$\Delta\dot{E}_k = \sum_{output} \dot{m}_i v^2 / 2 - \sum_{input} \dot{m}_i v^2 / 2 \quad (13)$$

The potential energy is calculated based on the following equation:

$$\Delta\dot{E}_p = \sum_{output} \dot{m}_i g z_j - \sum_{input} \dot{m}_i g z_j \quad (14)$$

### 2.7.5. Energy balance assumptions

Since there was so much equipment at the factory, it was important to make assumptions about each piece of machinery.

- If there was no noticeable change in pressure from the inlet to the outlet, if there was no temperature change, phase change, or chemical reaction, and  $\Delta H = 0$  (the mechanical energy balance was more useful in this case).
- If a temperature change, phase change, or chemical reaction occurred,  $\Delta\dot{H} \neq 0$ , ( $\Delta\dot{E}_k$ ,  $\Delta\dot{E}_p$ ) could be neglected.
- If there were no great vertical distances between the inlets and the outlets,  $\Delta\dot{E}_p = 0$ .
- If the system and its surroundings were at the same temperature or the system was perfectly insulated, then  $\dot{Q} = 0$  and the process was adiabatic.
- If the energy was not transmitted across the system boundary by a moving part, an electric current, or radiation,  $\dot{W}_s = 0$

### 2.7.6. Plant equipment energy balance equations

For the pumps, the following equation was used:

$$\Delta\dot{H} = \dot{W}_s \quad (15)$$

For the condenser and reboiler, the following equation was used:

$$\Delta\dot{H} = \dot{Q} \quad (16)$$

For the mixers, waste heat boilers, and adiabatic reactors, the following equation was used:

$$\Delta\dot{H} = 0 \quad (17)$$

Felder et al. provided material and energy balance equations for various processes and equipment, along with assumptions for each case [31].

**Table 2** Exergy calculations.

Equipment	Exergy in	Exergy out	Exergy destruction
P1	$E_{212} + Q_{P1}$	$E_{213}$	$E_{212} + Q_{P1} - E_{213}$
E1	$E_{213} + E_{215}$	$E_{13} + E_{14}$	$E_{213} + E_{215} - E_{13} - E_{14}$
Regenerator	$E_{214} + Q_{Reboiler}$	$E_{215} + E_{223} + Q_{Condenser}$	$E_{214} + Q_{Reboiler} - E_{215} - E_{223} - Q_{Condenser}$
P2	$E_{216} + Q_{P2}$	$E_{216\_Out}$	$E_{216} + Q_{P2} - E_{216\_Out}$
Air Cooler	$E_{216\_Out}$	$E_{217}$	$E_{216\_Out} - E_{217}$

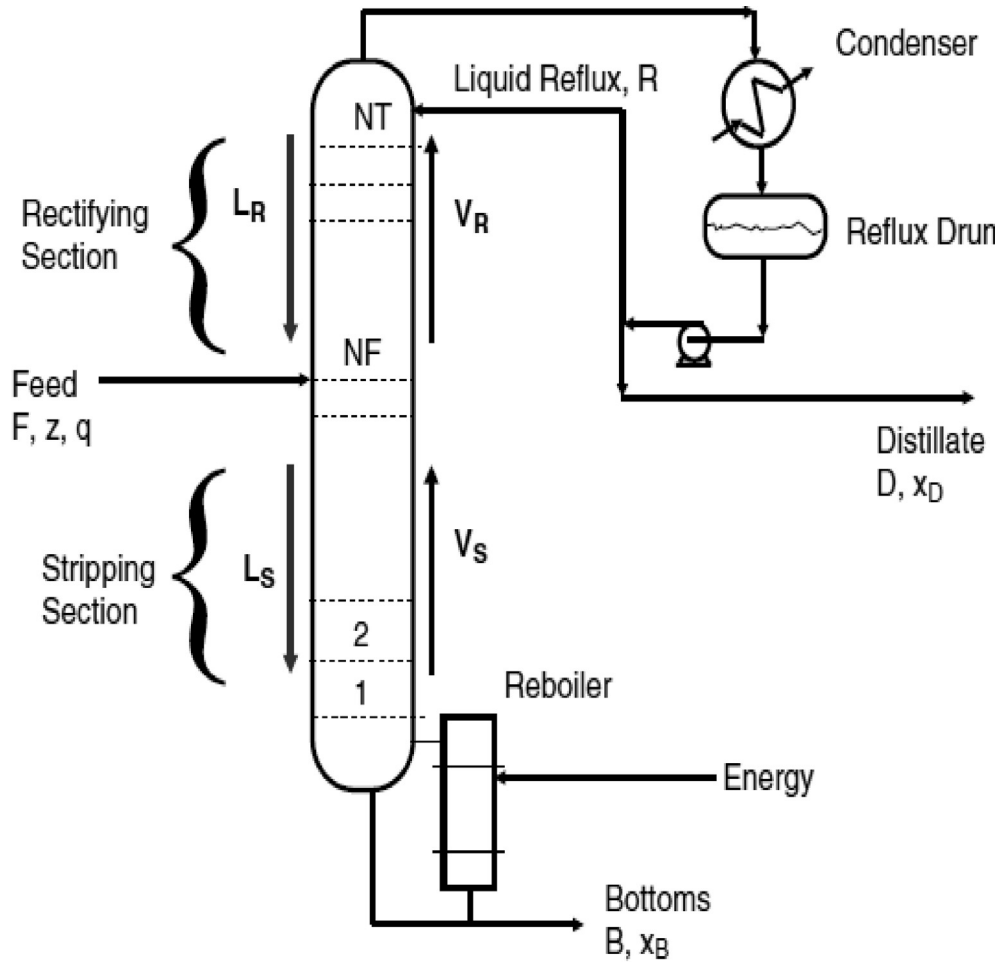


Fig. 3 Tray distillation [32].

## 2.8. Detailed equipment equations [35]

### 2.8.1. Distillation (Stripper)

A distillation column (Stripper) can be described using several material and energy balance equations. Fig. 3 shows a typical distillation column. The overall material balance can be found as follows:

$$F = D + B \quad (18)$$

where  $F$ ,  $D$ , and  $B$  are the feed, distillate, and bottom rates, respectively (kg/h). The component material balance can be found as follows:

$$Fx_f = Dx_D + Bx_B \quad (19)$$

where  $x_f$ ,  $x_D$ , and  $x_B$  are the distillate compositions in the feed, distillate, and residue, respectively.

The overall heat balance can be found as follows:

$$Fh_f + Q_r = Dh_d + Wh_B + Q_c \quad (20)$$

where  $Q_r$  and  $Q_c$  are the reboiler duty and condenser duty, respectively, and  $h_f$ ,  $h_d$ , and  $h_B$  are the specific enthalpies (J/kg) for the feed, distillate, and residue, respectively.

$$Q_c = V\lambda_{mix} = (mc_p\Delta T)_{water} \quad (21)$$

Here,  $c_p$  is the sensible heat (J/kg °C).

$$V = L + D \quad (22)$$

Here,  $V$  and  $L$  are the rates of the vapor at the top plate and liquid flow returning to the top plate (kg/h), respectively.

$$Q_r = m_{steam}\lambda_{steam} \quad (23)$$

Here,  $\lambda_{mix}$  and  $\lambda_{steam}$  are the latent heat of vaporization (J/kg) values for the overhead mixture and reboiler steam, respectively [32] (see Fig. 4)

### 2.8.2. Heat exchanger equations

The material balance equations were presented in equation (10). The general equation for the heat transfer across a surface is as follows:

$$Q = UA\Delta T_m \quad (24)$$

where  $Q$ ,  $U$ ,  $A$ , and  $\Delta T_m$  are the heat transfer per unit time (W), overall heat transfer coefficient (W/m<sup>2</sup> °C), area of heat transfer (m<sup>2</sup>), and log mean temperature difference (°C), respectively. The log mean temperature difference was calculated using the following equation:

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{(T_2 - t_1)}}, \quad (25)$$

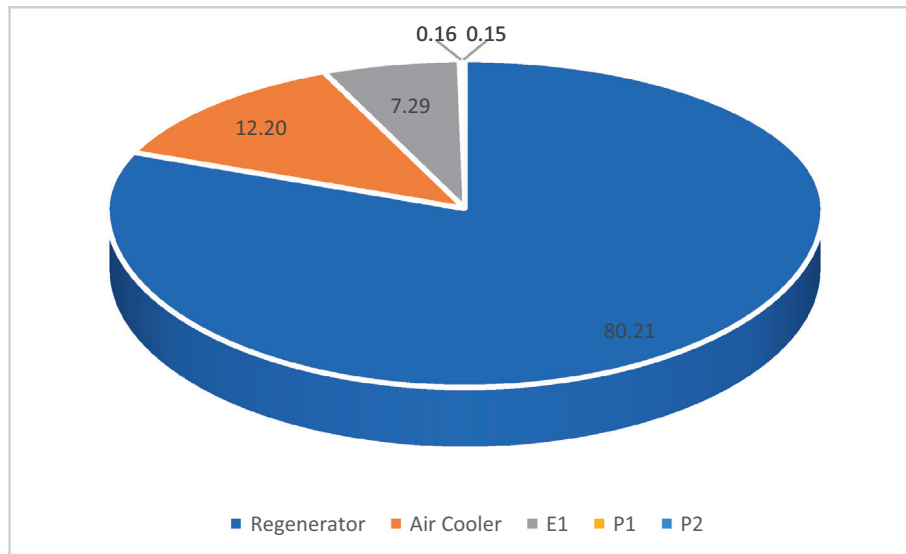


Fig. 4 Percentage share of equipment.

where  $T_1$  is the hot-fluid inlet temperature,  $T_2$  is the hot-fluid outlet temperature,  $t_1$  is the cold fluid inlet temperature, and  $t_2$  is the cold fluid outlet temperature.

### 2.8.3. Pump equation

The total energy required can be calculated from the following equation:

$$g\Delta z + \frac{\Delta P}{\rho} - \frac{\Delta P_f}{\rho} - W = 0 \quad (26)$$

where  $W$  is the work done (J/kg),  $\Delta z$  is the elevation difference between  $z_1$  and  $z_2$  (m);  $\Delta P$  is the system pressure difference between  $P_1$  and  $P_2$  (N/m<sup>2</sup>);  $\Delta P_f$  is the pressure drop due to friction, including miscellaneous losses and equipment losses (N/m<sup>2</sup>);  $\rho$  is the liquid density (kg/m<sup>3</sup>), and  $g$  is the acceleration due to gravity (m/s<sup>2</sup>) [32].

## 3. Results and discussion

### 3.1. Validation results

Table 3 shows the validation findings, which demonstrate that the industrial and simulation results are almost identical. The authors' experience with numerous simulations has shown that the most important aspect in simulation is the adequate package selection, which allows for high accuracy results. The temperature of stream 223 has the largest variance in this simulation, with a deviation of (−9.09 percent). In terms of component composition, there is almost no difference. In this case, the (chemical solvent package) was chosen.

### 3.2. Calculations for DEA concentration of 25%

#### 3.2.1. Physical and chemical exergy calculations for streams

The streams' physical and chemical exergy calculations were based on section equations (2.5 Exergy Calculations). The

molar flow rates, mass flow rates, and mass exergy for the streams were determined by HYSYS and are shown in Table 4.

The streams' physical exergy, chemical exergy, and total exergy were determined using the equations in Section 2.5 (Exergy Calculations) and are described in Table 5.

Q\_P1, Q\_P2, Q\_Reboiler, and Q\_Condenser had respective values of 13.29, 20.03, 5428.11, and 2534.72 kW. Table 2 shows the values that were used in the equipment destruction calculations. The magnitude of chemical exergy is usually greater than that of physical exergy. In all of the streams, the depletion of chemical exergy was greater than 99 percent.

#### 3.2.2. Exergy destruction and exergy efficiency of equipment

Exergy destruction calculations for equipment are computed using the equations in Table 2, and exergy efficiencies and percentage share of destruction are computed using the section (2.5 Exergy Calculations) and provided in Table 6.

Regenerator has the highest destruction rate, with a value of 2144.11 kW and an 80.21 percent share of total destruction, followed by air cooler with a value of 326 kW and a 12.2 percent share of total destruction. Fig. 4 shows the destruction percentage share. Exergy has a 99.7 percent overall efficiency.

### 3.3. Calculations for DEA concentration of 20%

#### 3.3.1. Physical and chemical exergy calculations for streams

The streams' physical and chemical exergy calculations were based on section equations (2.5 Exergy Calculations). The molar flow rates, mass flow rates, and mass exergy for the streams were determined by HYSYS and are shown in Table 7.

Q\_P1, Q\_P2, Q\_Reboiler, and Q\_Condenser had respective values of 12.77, 19.00, 5188.04, and 1718.01 kW. Table 2 shows the equations that were used in the equipment destruction calculations. The physical exergy, chemical exergy, and total exergy calculations for the streams were based on the equations in 2.5 (Exergy Calculations) and listed in Table 8.

**Table 3** Validation results.

Stream	217 (Lean Amine)			223 (Acid gas to SRU)		
	Design	Simulation	Dev	Design	Simulation	Dev
Temperature (°C)	60.00	60.00	0.00	55.00	50.00	9.09
Pressure (kg/cm <sup>2</sup> g)	8.50	8.50	0.00	0.80	0.80	0.00
Mass flow (kg/h)	71272.50	71126.93	0.20	2049.60	2049.47	0.01
<b>Component</b>	<b>Total Weight Comp. Fraction</b>					
DEA	0.250	0.250	0.00	0.000	0.000	0.00
water	0.749	0.749	0.00	0.046	0.046	0.00
H <sub>2</sub>	0.000	0.000	0.00	0.000	0.000	0.00
NH <sub>3</sub>	0.000	0.000	0.00	0.000	0.000	0.00
H <sub>2</sub> S	0.002	0.002	0.00	0.953	0.953	0.00
CO <sub>2</sub>	0.000	0.000	0.00	0.000	0.000	0.00

**Table 4** HYSYS calculations for streams.

Stream number	Molar flow (kmol/h)	Mass flow (kg/h)	mass exergy (kJ/kg)
212 (RA)	3189.51	73176.40	8.74
213	3189.51	73176.40	9.19
214	3189.51	73176.40	35.21
223	61.53	2049.47	43.01
215	3127.98	71126.93	63.03
216	3127.98	71126.93	26.40
126-Out	3127.98	71126.93	27.21
217 (LA)	3127.98	71126.93	10.71

The exergy calculations for streams with a 20% DEA concentration were identical to those for streams with a 25% DEA concentration. The chemical exergy values were higher than the physical exergy values. The percentage share of the destruction for the chemical exergy exceeded 99% in all the streams.

### 3.3.2. Exergy destruction and exergy efficiency of equipment

Exergy destruction calculations for equipment are computed using the equations in Table 2, and exergy efficiencies and percentage share of destruction are computed using Section 2.5 Exergy Calculations and provided in Table 9.

Regenerator has the highest destruction rate, with a value of 2616.74 kW and an 84.25 percent share of total destruction, followed by air cooler with a value of 294.61 kW and a 9.49 percent share of total destruction. Fig. 5 shows the destruction percentage share. Exergy has a 99.56 percent overall efficiency.

**Table 5** Stream exergies.

Stream number	E <sub>ph</sub> (kW)	E <sub>ch</sub> (kW)	E <sub>tot</sub> (kW)	Percentage share of E <sub>ph</sub> in E <sub>tot</sub>
212 (RA)	177.74	141480.75	141658.49	99.87
213	186.83	141480.75	141667.58	99.87
214	715.62	141480.75	142196.37	99.50
223	24.48	13209.95	13234.44	99.81
215	1245.35	128465.86	129711.21	99.04
216	521.63	128465.86	128987.49	99.60
126-Out	521.63	128465.86	128987.49	99.60
217 (LA)	211.68	128465.86	128677.54	99.84

**Table 6** Exergy destruction and exergy efficiency results.

Equipment	Destructed energy (KW)	Percentage share	Exergy Efficiency (%)
Regenerator	2144.11	80.21	98.55
Air Cooler	326.00	12.20	99.75
E1	194.93	7.29	99.93
P1	4.20	0.16	100.00
P2	3.98	0.15	100.00
Sum	2673.23	100.00	99.70

**Table 7** HYSYS calculations for streams.

Stream number	Molar flow (kmol/h)	Mass flow (kg/h)	mass exergy (kJ/kg)
212 (RA)	3189.51	69983.85	8.47
213	3189.51	69983.85	8.92
214	3189.51	69983.85	35.01
223	103.16	2760.81	144.77
215	3086.35	67223.04	62.56
216	3086.35	67223.04	25.39
126-Out	3086.35	67223.04	26.20
217 (LA)	3086.35	67223.04	10.43

### 3.4. Comparison of DEA concentrations of 25% and 20%

Table 10 shows a comparison of DEA concentrations of 25 and 20 percent. By 432.7 kW, the total destroyed exergy with 25% DEA was less than that with 20% DEA. From an exergy viewpoint, this indicated that working with a higher concentra-



**Table 8** Stream exergies.

Stream number	$E_{ph}$ (kW)	$E_{ch}$ (kW)	$E_{tot}$ (kW)	Percentage share of $E_{ph}$ in $E_{tot}$
212 (RA)	164.62	113677.76	113842.38	99.86
213	173.34	113677.76	113851.10	99.85
214	680.60	113677.76	114358.36	99.40
223	111.02	12742.93	12853.96	99.14
215	1168.10	101189.59	102357.70	98.86
216	474.12	101189.59	101663.71	99.53
126-Out	474.12	101189.59	101663.71	99.53
217 (LA)	194.70	101189.59	101384.30	99.81

**Table 9** Exergy destruction and exergy efficiency results.

Equipment	Destroyed energy (KW)	Percentage share	Exergy Efficiency (%)
Regenerator	2616.74	84.25	97.81
Air Cooler	294.61	9.49	99.71
E1	186.73	6.01	99.91
P1	4.05	0.13	100.00
P2	3.80	0.12	100.00
Sum	3105.93	100.00	99.56

tion would be preferable. The regenerator was the primary cause of this decline.

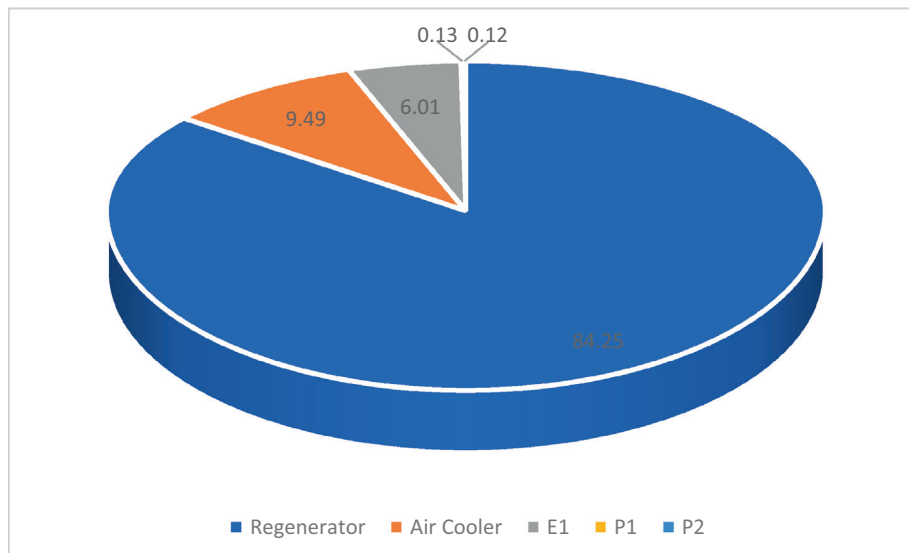
The main purpose of the difference in destructed values in the regenerator must be established. Table 2 demonstrates how to calculate the destructed exergy in the regenerator using the equation ( $E_{214} + Q_{Reboiler} - E_{215} - E_{223} - Q_{Condenser}$ ). condenser duty decreased by 816.71 kW, while the reboiler duty regenerator 25 percent exceeds 20 percent by 240.06 kW. The discrepancy between the two values is 576.65 kW, which is roughly the total destruction value surpassed in both cases (432.72 kW). Since some other small values may increase or decrease, we're just talking about the key contributor. The streams related to regenerator destruction calculations are shown in Table 11.

Table 11 shows that some exergies measured for streams with a 25 percent concentration outperformed those calculated for streams with a 20 percent concentration by large amounts. As an example, the (214) stream can be considered. The  $E_{tot}$  value of the stream, at 25%, was 27838.01 kW higher than the  $E_{tot}$  value of the stream, which was at 20 percent. The sum of physical and chemical exergy values is the overall exergy. By just 35.02 kW, the  $E_{ph}$  value of 25% was higher than the value of 20%. As a result, it wasn't the primary contributor. The  $E_{ch}$  value at the 25 percent concentration was higher than that with the 20 percent concentration by 27802.99 kW.  $E_{ch}$  was the cause of this difference. The  $E_{ch}$  value determined using the equation ( $\sum x_i ex_{che}^0 + RT_0 \sum x_i \ln x_i$ ) was primarily influenced by the component composition. The chemical standard chemical exergy of the DEA was much higher than that of water. DEA and  $H_2O_L$  have  $ex_{che}^0$  values of 2718.1 kJ/mol and 0.90 kJ/kmol, respectively. As a result, the chemical exergy at the 25% concentration was substantially higher than at the 20% concentration.

Table 12 indicates the difference in mole fractions between these compositions with with  $ex_{che}^0$

### 3.5. Exergy results comparison with ARU2 study

Ibrahim et al. performed previously an exergy study of the first ARU unit of the plant. DEA used to provide LA to all the

**Fig. 5** Percentage of destruction share of equipment.

**Table 10** Comparison between destruction values for DEA concentrations of 25% and 20%.

Concentration	25	20	Difference
Equipment	Destructed energy (KW)	Destructed energy (KW)	
P1	4.20	4.05	0.15
E1	194.93	186.73	8.20
Regenerator	2144.11	2616.74	-472.62
P2	3.98	3.80	0.18
Air Cooler	326.00	294.61	31.39
Sum	2673.23	3105.93	-432.70

plant units except the DCU is regenerated in this unit. The DEA concentration decreased from the design concentration of 25 wt% to 20% wt.% due to system losses. The design concentration value of the amine is set by the licensor of the process to guarantee that the amine will perform efficiently for H<sub>2</sub>S gas sweetening. The decrease in this concentration due to any purposes may lead also to other severe problems. System losses in general for amine may happen due to many purposes. The study was conducted on two different concentrations (25% and 20%) by weight [30]. A comparison was conducted between the similar equipment of the current study of ARU2 unit providing LA to the DCU and the previous study to conclude the similar relationships between equipment.

### 3.5.1. Columns comparison

It was observed that the main highest exergy destruction in the two units was in the columns (Regenerators). Table 13 shows the tower values in the two units and the percentage share of these values in total unit destructions.

It was observed that the columns in the two units have the highest destruction rate. All destruction rate values of the columns exceed 79% of the total destruction of the units.

### 3.5.2. Air coolers comparison

The air coolers exist in ARU and SWS. The air coolers in their units have the second-highest destruction rates and percentage shares in destruction as shown in Table 14. The destruction values exceed 9% in the two units.

### 3.5.3. Pumps comparison

The pumps in the two units have the lowest percentage share in the destruction of the units. Table 15 shows a comparison between pumps destructions in ARU1 and ARU2 units. The pumps have a contribution lower than 1% in three units.

## 4. Summary and conclusions

In 2020, a refining plant in the Middle East began commercial production. An amine regeneration unit in the refinery supplies lean amine to the delayed cooker unit for gas sweetening. HYSYS V.11 was used to simulate the unit, and an exergy study was performed on various equipment. The study aims to calculate exergy destruction rates for all equipment, as well as the percentage share of exergy destruction for each equipment and exergy efficiencies. The concentration of regenerated diethanolamine is 25% by weight. Regenerator, with a value of 2144.11 kW and a percentage share of 80.21 percent of total destruction, has the highest destruction rate, followed by air cooler, with a value of 326.00 kW and a percentage share of 12.20 percent of total destruction. Exergy has a 99.70 percent overall efficiency. The total amount of energy destroyed was 2673.23 kW. Due to start-up issues, the DEA concentration was reduced to 20% by weight. At a concentration of 20 DEA wt. percent, an exergy analysis revealed the same percentage share distribution for equipment. The regenerator, with a value of 2616.74 kW and a percentage share of 84.25 percent of total destruction, has the highest destruction rate. With a value of 294.61 kW and a percentage share of 9.49 percent of total destruction, the second-highest one was also an air cooler. The overall efficiency of the exergy is 99.56 percent. The total amount of exergy destroyed was 3105.93. At a 20

**Table 11** Regenerator streams.

Stream		Conc	Eph	Ech	Etot
Inlet	214	25	715.62	141480.75	142196.37
		20	680.60	113677.76	114358.36
Diff	Q_Reboiler	25	5428.11	27802.99	27838.01
		20	5188.04		
Diff			240.06		
Stream	Outlet	25	1245.35	128465.86	129711.21
		20	1168.10	101189.59	102357.70
Diff	223	25	77.24	27276.27	27353.51
		20	24.48	13209.95	13234.44
Diff	Q_Condenser	25	111.02	12742.93	12853.96
		20	-86.54	467.02	380.48
Diff			2534.72		
			1718.01		
Diff			816.71		

**Table 12** Standard chemical exergy values and mole fraction of DEA [26,27,30].

DEA Concentration	$ex_{che}^0$ (kJ/kmol)	25 wt%	20 wt%
Components		Mole Fr.	
DEA	2718.10	0.05	0.04
H <sub>2</sub> O <sub>L</sub>	0.90	0.93	0.94
H <sub>2</sub>	236.09	0.00	0.00
NH <sub>3</sub>	337.90	0.00	0.00
H <sub>2</sub> S	812.00	0.01	0.01
CO <sub>2</sub>	19.48	0.00	0.00

**Table 13** Comparison between regenerators destructions in ARU1 and ARU2.

Columns (Regenerators)			
Unit	Destructed energy (KW)	Total unit destruction (kW)	% share of destruction in its unit
ARU2 25%	2144.11	2673.23	80.21
ARU2 20%	2616.74	3105.93	84.25
ARU1 25%	13459.73	16907.45	79.61
ARU1 20%	15571.65	18964.53	82.11

**Table 14** Comparison between air coolers destructions in two units.

Air cooler			
Unit	Destructed energy (KW)	Total unit destruction (kW)	% share of destruction in its unit
ARU2 25%	326.00	2673.23	12.20
ARU2 20%	294.61	3105.93	9.49
ARU1 25%	2096.65	16907.45	12.40
ARU1 20%	2034.29	18964.53	10.73

percent concentration, the overall destruction increased by 16.19% in contrast to the other concentration (432.70 kW). The regenerator, which had a higher destruction value for the DEA concentration of 20% by 472.62 kW, was found to be the cause of the discrepancy. The sum of chemical and physical exergies is known as total exergy. Chemical exergy calculations of all streams in DEA concentrations of 25% and 20% revealed that a percentage share of the total exergy values of each stream exceeded 99 percent. Equipment's exergy effi-

**Table 15** Comparison between pumps destructions in two units.

pumps			
Unit	Destructed energy (KW)	Total unit destruction (kW)	% share of destruction in its unit
ARU2 25%	8.18	2673.23	0.31
ARU2 20%	7.85	3105.93	0.25
ARU1 25%	198.41	16907.45	0.59
ARU1 20%	198.95	18964.53	0.53

ciency should be compared to its destructed values. In both cases, the regenerator has the highest destruction values but also has a good exergy efficiency of over 97 percent. The findings of the ARU2 exergy study were compared to those of the ARU1 exergy study at the same refinery plant. The regenerators were found to have the highest exergy destruction of the two units. With a percentage share of the overall destruction reaching 80% the second-highest destruction rates were found in air coolers, with values reaching 9% of the overall destruction of their units. The pumps in the two units contribute the least to the destruction of the units, accounting for less than 1% of the overall destruction in the two of them.

#### 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.

#### Acknowledgments

The authors would like to thank the refinery company team for the availability of the data and information on the study, as well as the process engineering team for contributing ideas.

#### References

- [1] A. Khatami, Y. Heidari, A. Safadoost, A. Aleghafouri, M. Davoudi, The activity loss modeling of catalytic reactor of sulfur recovery unit in South Pars Gas Complex (SPGC) 3rd refinery based on percolation theory, *J. Nat. Gas Sci. Eng.* 28 (2016) 723–736.
- [2] H. Abdolahi-Mansoorkhani, S. Seddighi, H<sub>2</sub>S and CO<sub>2</sub> capture from gaseous fuels using nanoparticle membrane, *Energy* 168 (2019) 847–857.
- [3] B. Mahmoodi, S.H. Hosseini, G. Ahmadi, A. Raj, CFD simulation of reactor furnace of sulfur recovery units by considering kinetics of acid gas (H<sub>2</sub>S and CO<sub>2</sub>) destruction, *Appl. Therm. Eng.* 123 (2017) 699–710.
- [4] P. Abdoli, S.A. Hosseini, M.A. Mujeebu, Effect of preheating inlet air and acid gas on the performance of sulfur recovery unit—CFD simulation and validation, *Forschung im Ingenieurwesen* 83 (1) (2019) 81–89.

- [5] C.B. Lavery, J.J. Marrugo-Hernandez, R. Sui, N.I. Dowling, R. A. Marriott, The effect of methanol in the first catalytic converter of the Claus sulfur recovery unit, *Fuel* 238 (2019) 385–393.
- [6] R. Sui, C.B. Lavery, D. Li, C.E. Deering, N. Chou, N.I. Dowling, R.A. Marriott, Improving low-temperature CS<sub>2</sub> conversion for the Claus process by using La (III)-doped nanofibrous TiO<sub>2</sub> xerogel, *Appl. Catal. B* 241 (2019) 217–226.
- [7] S. Ibrahim, R.K. Rahman, A. Raj, Effects of H<sub>2</sub>O in the feed of sulfur recovery unit on sulfur production and aromatics emission from Claus furnace, *Ind. Eng. Chem. Res.* 56 (41) (2017) 11713–11725.
- [8] A.Y. Ibrahim, Performance assessment of a sulphur recovery unit, *Petrol. Petrochem. Eng. J.* 5 (1) (2021).
- [9] A.Y. Ibrahim, Performance monitoring of a sulphur recovery unit: a real start-up plant, *Petrol. Petrochem. Eng. J.* 5 (1) (2021).
- [10] Ahmed Y. Ibrahim, Fatma H. Ashour, Mamdouh A. Gadalla, Refining plant energy optimization, *Alexandria Eng. J.* 60 (5) (2021) 4593–4606.
- [11] Ali Rostami, Yadollah Tavan, A survey on exergy, energy and environmental analysis of sulfur recovery unit in case of five intensified configurations, *Chem. Pap.* 73 (6) (2019) 1529–1539.
- [12] J. Minier-Matar, A. Janson, A. Hussain, S. Adham, Application of membrane contactors to remove hydrogen sulfide from sour, *J. Membr. Sci.* 541 (2017) 378–385.
- [13] Hengjun Gai, Shuo Chen, Kaiqiang Lin, Xiaowei Zhang, Chun Wang, Meng Xiao, Tingting Huang, Hongbing Song, Conceptual design of energy-saving stripping process for industrial sour water, *Chin. J. Chem. Eng.* 28 (5) (2020) 1277–1284.
- [14] D. Dardor, A. Janson, E. AlShamari, S. Adham, J. Minier-Matar, The effect of Hydrogen sulfide oxidation with ultraviolet light and aeration, *Sep. Purif. Technol.* 236 (2019) 116262.
- [15] Umer Zahid, Techno-economic evaluation and design development of sour water stripping system in the refineries, *J. Cleaner Prod.* 236 (2019) 117633, <https://doi.org/10.1016/j.jclepro.2019.117633>.
- [16] Min Zhu, Li Sun, Guofu Ou, Kai Wang, Kuanxin Wang, Yanlin Sun, Erosion corrosion failure analysis of the elbow in sour water stripper overhead condensing reflux system, *Eng. Fail. Anal.* 62 (2016) 93–102.
- [17] Haitem Hassan-Beck, Tommy Firmansyah, Mabruk Issa Suleiman, Tadao Matsumoto, Mohamed AL Musharfy, Abdul Hamid Chaudry, Mohammad Abdur Rakib, Failure analysis of an oil refinery sour water stripper overhead piping loop: assessment and mitigation of erosion problems, *Eng. Fail. Anal.* 96 (2019) 88–99.
- [18] Jaber Amini, Ali Davoodi, Hamidreza Jafari, Analysis of internal cracks in Type 304 austenitic stainless steel cladding wall of regenerator column in amine treating unit, *Eng. Fail. Anal.* 90 (2018) 440–450.
- [19] M. Wang, S. Hariharan, R.A. Shaw, T.A. Hatton, Energetics of electrochemically mediated amine regeneration process for flue gas CO<sub>2</sub> capture, *Int. J. Greenhouse Gas Control* 82 (2019) 48–58.
- [20] M. Mohamadi-Baghmoleaei, A. Hajizadeh, P. Zahedizadeh, R. Azin, S. Zendejboudi, Evaluation of hybridized performance of amine scrubbing plant based on exergy energy, environmental, and economic prospects: a gas sweetening plant case study, *Energy* 31 (2020) 118715.
- [21] Hassan Pashaei, Ahad Ghaemi, CO<sub>2</sub> absorption into aqueous diethanolamine solution with nano heavy metal oxide particles using stirrer bubble column: Hydrodynamics and mass transfer, *J. Environ. Chem. Eng.* 8 (5) (2020) 104110, <https://doi.org/10.1016/j.jece.2020.104110>.
- [22] Babak Aghel, Sasan Sahraie, Ehsan Heidaryan, Carbon dioxide desorption from aqueous solutions of monoethanolamine and diethanolamine in a microchannel reactor, *Sep. Purif. Technol.* 237 (2020) 116390, <https://doi.org/10.1016/j.seppur.2019.116390>.
- [23] E.I. Concepción, A. Moreau, M.C. Martín, D. Vega-Maza, J.J. Segovia, Density and viscosity of aqueous solutions of Methyl-diethanolamine (MDEA) + Diethanolamine (DEA) at high pressures, *J. Chem. Thermodyn.* 148 (2020) 106141.
- [24] Kang Shunji, Shen Xizhou, Yang Wenze, Investigation of CO<sub>2</sub> desorption kinetics in MDEA and MDEA+DEA rich amine solutions with thermo-gravimetric analysis method, *Int. J. Greenhouse Gas Control* 95 (2020) 102947, <https://doi.org/10.1016/j.ijggc.2019.102947>.
- [25] Priyabrata Pal, Ahmad AbuKashabeh, Sameer Al-Asheh, Fawzi Banat, Role of aqueous methyl-diethanolamine (MDEA) as solvent in natural gas sweetening unit and process contaminants with probable reaction pathway, *J. Nat. Gas Sci. Eng.* 24 (2015) 124–131.
- [26] Patricia Mores, Nicolás Scenna, Sergio Mussati, CO<sub>2</sub> capture using monoethanolamine (MEA) aqueous solution: Modeling and optimization of the solvent regeneration and CO<sub>2</sub> desorption process, *Energy* 45 (1) (2012) 1042–1058.
- [27] Hongqun Yang, Zhenghe Xu, Maohong Fan, Rajender Gupta, Rachid B Slimane, Alan E Bland, Ian Wright, Progress in carbon dioxide separation and capture: a review, *J. Environ. Sci.* 20 (1) (2008) 14–27.
- [28] Meysam Hashemi, Fathollah Pourfayaz, Mehdi Mehrpooya, Energy, exergy, exergoeconomic and sensitivity analyses of modified Claus process in a gas refinery sulfur recovery unit, *J. Cleaner Prod.* 220 (2019) 1071–1087.
- [29] T.J. Kotas, *The Exergy Method of Thermal Plant Analysis*, Butterworths, 1985.
- [30] M. Sheikholeslami, Seyyed Ali Farshad, Z. Ebrahimpour, Zafar Said, Recent progress on flat plate solar collectors and photovoltaic systems in the presence of nanofluid: a review, *J. Cleaner Prod.* 293 (2021) 126119, <https://doi.org/10.1016/j.jclepro.2021.126119>.
- [31] M. Sheikholeslami, Seyyed Ali Farshad, Zafar Said, Analyzing entropy and thermal behavior of nanomaterial through solar collector involving new tapes, *Int. Commun. Heat Mass Transfer* 123 (2021) 105190, <https://doi.org/10.1016/j.icheatmasstransfer.2021.105190>.
- [32] M. Sheikholeslami, S. Farshad, Investigation of solar collector system with urbulator considering hybrid nanoparticles, *Renewable Energy* 171 (2021) 1128–1158.
- [33] Ahmed Y. Ibrahim, Fatma H. Ashour, Mamdouh A. Gadalla, Exergy study of amine regeneration unit using diethanolamine in a refinery plant: a real start-up plant, *Heliyon* 7 (2) (2021) e06241, <https://doi.org/10.1016/j.heliyon.2021.e06241>.
- [34] R. Felder, R. Rousseau, *Elementary Principles of Chemical Processes*, John Wiley, 2005.
- [35] R.K. Sinnott, Coulson & Richardson's chemical engineering design, fourth edition, volume 6, Elsevier, London, 2005.