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Energy and exergy analysis of oil-field produced water treatment process by using a closed-loop spray dryer

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ABSTRACT

Wastewater resulting from oil and gas production processes (called produced water) can cause heavy pollution of soil and water. In this study, a closed-loop and single-stage bench-scale plant equipped with a spray dryer have been designed, constructed and used for the treatment of PW. The PW from three oil reservoir fields in the southwest of Iran was used. The newly developed method captured 98.78%, 98.65%, and 98.90% of total dissolved solids of the PW, and reduced total organic carbon to zero for the three mentioned reservoirs, respectively. The hot air produced by a direct-fired heater enters the spray dryer and vaporizes the water in the feed inlet to the dryer. The outlet humid air is condensed in an air condenser and the water is separated from the air in a separator and finally, the dehumidified air is pressurized to the heater by an air blower. In the experiments, the effect of the inlet air rate and its temperature, and the concentration of dissolved solids in the feed were tested. For system components, the energy and exergy analyses were carried out and then the models of the components were coupled together and a comprehensive model was developed for the entire system. The results of the developed model were compared with obtained results from the experiments and the model was validated. The results show that the inlet air temperature has the greatest effect on the rate of desalinated water. The direct-fired heater, the spray dryer, and the air condenser are the key components that allocate up to 50% of total exergy destruction within the system. The exergy efficiency of the entire system is in the range of 3% to 13% and by appropriate selection of operational parameters and accurate selection of more suitable components instead of exergy destructive components, greater exergy efficiency can be obtained.

Keywords: Produced water treatment; Spray dryer; Closed cycle; Energy and exergy analysis

1. Introduction

Today's, reuse of the polluted water due to the scarcity of water resources alongside the increase in the growing demands for freshwater has been noticed. The issue is also envisaged as one prerequisite in the sustainable development of under developing or even developing countries. Oil and gas industries have potential capabilities in the area of reduction of freshwater consumption via reuse of the treated water. In the oil industries, produced water is the main waste from oil production processes, about 3–10 barrel of PW per barrel of oil, which up to 95% of these resources can be treated and re-injected to the oil and gas reservoirs [1]. Different methods for PW treatment and disposal were proposed by many researchers and reported in the literature. Okiel et al. [2] studied the performance of synthesized CNT/polypropylene composite membrane distillation for

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the oil field produced water desalination. The techniques for PW treatment are classified into physical, chemical, and biochemical methods, and their advantages and disadvantages were tabled [3]. The general disadvantages of physical methods are high initial capital investments and sensitivity to variation of water input, while chemical treatment methods are the formation of hazardous sludge and problems encountered consequent treatment and disposal of these sludge, high operational costs, and sensitivity to the initial concentration of wastewater. The biological treatment methods are sensitive to the variation of organic chemicals as well as the salt concentration of input waste [3]. High amounts of total dissolved solids (TDS) and total organic carbons (TOC) are the most vital challenge in the PW treatment process. The TDS causes scale formation and TOC leads to create fouling in the equipment used in the PW treatment process. These problems are even seriously considered for bio-purification methods. Therefore, for PW treatment, the use of strong and flexible systems, which are capable of confronting the difficult and variable conditions of the different percentages of the materials present in the PW, with the objective of treating them to the required standards, is deemed necessary.

According to the various uses of the treated water, the combinations of various percentages of it can be considered in this regard. For example, the use of treated water in the process of desalting crude oil necessitates the removal of materials, which increase TDS. However, for irrigation purposes, both the TDS and TOC should be decreased [3–5]. More care should be taken for the treatment of water returned to the environment because PW contains poisonous and dangerous substances, which damages human beings and the environment [6,7]. Although there are numerous methods for removing various kinds of pollutants such as dissolved solids and hydrocarbons in oil and gas industries, the application of simple, effective and methods with short-time processes can result in a cost-effective treatment technique [8–14]. Furthermore, simple technologies, which need lesser and cheaper maintenance, are more attractive for oil and gas industries. Some important issues should be considered in the development of a new method or selection of existing methods for PW treatment operation, including flexibility of the treatment method to variation of PW flow rate and specifications, using available energy sources or other utilities, waste heat recovery from existing equipment, the maturity of technology, simple operability, portability, and integration with existing units and equipment. Abdelmoez et al. [15] studied comprehensively the water desalination processes using the humidification/dehumidification technique powered by solar energy. Attia et al. [16] proposed new materials for water desalination and purification using photobiosynthesis of metal/graphene nanocomposites.

Energy consumption is one of the most primary parameters in selecting the type of treatment method [6,17]. While the study of the energy and exergy efficiency of the PW treatment processes can be very helpful, but no sufficient attention had been paid to the performance evaluation of PW treatment processes based on simultaneously energy and exergy analyses. Energy analysis expresses the quantity of energy within the system but does not provide information about the quality of energy and useful work availability, therefore it cannot fully answer our needs. The exergy analysis of systems is very important and is a suitable and powerful tool for the performance evaluation of the system. Exergy analysis uses a combination of the first and second laws of thermodynamics and is an applicable tool for analyzing the quantity and quality of energy [18]. Thermodynamic knowledge plays an important role in energy and exergy analyses of the industrial processes. The first thermodynamic law is applied in engineering for investigation and improvement of the performance of energy conversion systems. Despite the numerous advantages, the first law of thermodynamics gives no information regarding the irreversibility of thermodynamic processes and the quality of various forms of energy. Thus, it is not sufficient for designing a sustainable system and/or optimizing it. Exergy determines the energy or the acquirable work in various points of a system interacting with a reference environment and is a combination of the system properties and the peripheral environment because it is dependent on both the system and the environment in the periphery thereof [19]. Unlike energy, exergy is not conserved and can destroy or loss due to some irreversible phenomena or thermal losses within the system. Exergy analysis is a more efficient method in evaluating the effective use of energy resources because it presents a more realistic view of the process, which is even sometimes different in some cases in comparison to the standard energy analysis [20]. Therefore, the study of the energy and exergy efficiency of a PW treatment process can be very helpful in order to accurately analyze the process performance, identification of the energy consumer components and irreversibilities within the process and finally, providing a cardinal solution to increase the process productivity. Before now, a few studies have been focused on the simultaneously energy and exergy analyses of PW treatment processes and no sufficient attention had been paid to the study and evaluation of the performance of PW treatment processes based on exergy analysis. Nafey et al. [21] mathematically modeled the thermodynamics of a hybrid desalting system composed of multi-effect evaporation and mechanical vapor condensation (MEE–MVC) and investigated its performance based on an exergy analysis. Drioli et al. [22] performed energy and exergy analyses of a distillation/crystallization plant and its micro and nano filter systems and reverse osmosis (MF–NF–RO). Nematollahi et al. [23] conducted a theoretical and laboratory energy and exergy analyses for a solar water desalting system. Mabrouk et al. [24] also carried out energy and exergy analyses in a redesigned multi-stage flash system.

In the present study, a closed-loop and single-stage process have been used for PW treatment, which takes advantage of a spray dryer. The method is simple and a combination of simple types of equipment is used in it. As well as, according to customary, operations, desalting, and compression units are usually built together, this plan can be integrated with them. The presented method can be used to construct a useful plant that is flexible to PW quality. The studied PW samples are the disposal from the desalting of crude oil from three oil reservoir fields in the southwest of Iran. In addition, a comprehensive energy and exergy analyses are carried out for the entire process, and the destruction and loss portion of exergy for each component within the process are obtained.

2. Material and methods

2.1. Bench-scale PW treatment system

A schematic of the designed and constructed bench scale is shown in Fig. 1. The system was tested under different operating conditions. The method consists of a closed-loop process system wherein a spray dryer with 420 cm in height and 50 cm in diameter is used. This spray dryer has an atomizer (Fixmee 3010 Brass Fog Mist Nozzle) in its upper section applied for converting the PW flow into tiny drops with 0.03 mm in diameter and distributing them in the carrier gas inlet to the spray dryer. To supply the required pressure of the PW, a diaphragm pump (C.C.K RO-900-EZ) has been used. A flow meter (OMEGA FLMH-1401AL) measures the amount of the liquid inlet to the spray dryer. The treatment system of the PW uses a variable round blower (Nanima motor SZ-09WM/1800W CLASS F), which is installed before the fired heater to circulate carrier gas in the closed cycle. The flow rate of the circulating carrier gas is measured based on flowing cross-sectional area and using of an Anemometer (STANDARD Anemometer ST-82) [25].

The direct-fired heater, which is of cross-flow type, is equipped with a flame spreader and channels for passing the combustion gases. The temperature of the outlet carrier gas is controlled by regulating the inlet flow rate of fuel gas. The rate of the inlet fuel gas to the fired heater is monitored by a mass flow meter (S420, CSi-tec, Germany). The PW treatment system also includes a cyclone after a spray dryer to separate the tiny particles of salt from the humid air. The other part of the system is a condenser installed after the cyclone. This condenser uses cold water as the coolant to condense the vapor in the air. The flow rate of the coolant in the condenser is adjusted in such a way that the outlet humid air reaches a low saturation temperature in order to condense the maximum amount of water vapor. The system also includes a knock out drum (K.O.D) installed after the condenser. The various parts of this closed system are connected via pipes. To monitor the temperature of the circulating carrier gas, use probes and digital display screens (HANYOUNG ED6) installed in the inlet and outlet of the spray dryer and outlet of the condenser. To monitor the amount of moisture in the circulating carrier gas, a humidity meter device (BENETECH GM1362) has been used that is placed before blower.

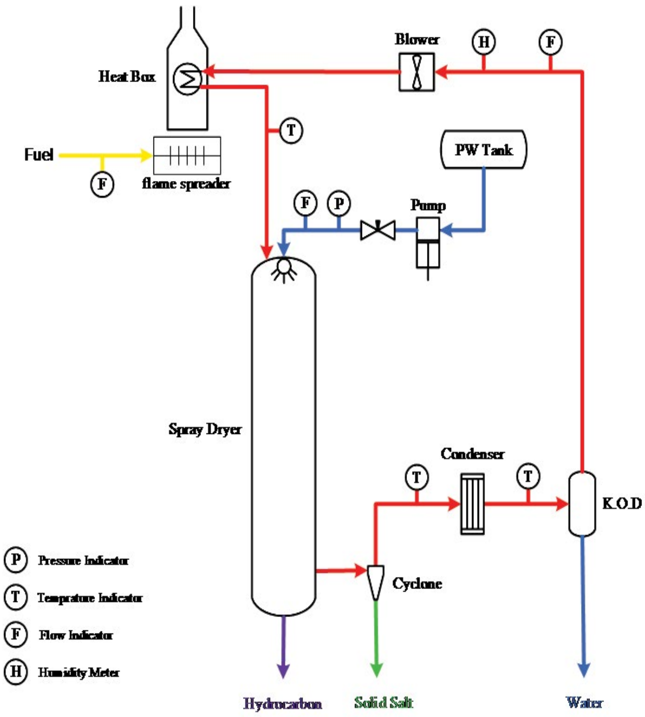

Fig. 1. Schematic of the bench-scale treatment system used in experiments.

2.2. Inlet disposal specifications and compositions

The specification and compositions of the inlet disposal samples are summarized in Table 1. The inlet disposal sample to the bench-scale process in the experiment is the disposal flowing out of Ahwaz, Marun and Mansori crude oil desalting plants. Samples were collected in containers made of polyethylene terephthalate (PET).

2.3. Experimental procedure

In this work, at first, the feasibility study of the proposed method was performed [26], to avoid lengthening the text, it will not be repeated here. The PW from the three large reservoirs of Ahwaz, Maroun, and Mansouri fields, which have different compositions but with the same TDS and TOC, are desalted using the developed bench-scale experimental plant. In the experiments, the effect of various operating parameters such as inlet feed composition and flow rate, inlet hot air temperature and flow rate on the performance of the entire system were investigated. For the start-up of the system operation, the blower is first put into service and the circulating carrier gas flow rate is controlled by regulating the blower rounds. The fired heater is then put into service and the temperature of the passing carrier gas is controlled by regulating the flow rate of the fuel gas. The temperature of the passing carrier gas is controlled at the same time by initiating the flow of the coolant in the condenser. It takes 10 min to stabilize the conditions and reach steady-state conditions. The pump tank is filled with the feed and the diaphragm pump is started. Immediately, the feed flowing into the spray dryer is monitored and regulated. The pressure of the feed pump is 10 bar. Each experiment takes 20 min to complete, after which the feed pump should be turned off and the flow of liquid entering the spray dryer should be cut. The fired heater is then switched off. After 10 min, the condenser and blower are turned off, respectively. Afterward, the drain doors of the spray dryer, cyclone and K.O.D are opened and the materials in them are collected, weighed by a digital mass balance (KERN EMB 500-1SS05) and sent to the laboratory in containers. To ensure the cleanness of the PW treatment system after each experiment, the whole system is washed by demineralized water and dried using the blower and fired heater. In this study, the effect of the flow rate of the carrier gas entering the spray dryer (run 1, 2, and 3), the temperature of the carrier gas entering the spray dryer (run 4, 5, and 6), and TDS of the used feed

Table 1
Compositions of inlet disposal samples

Parameter	Ahwaz field	Marun field	Mansori field	Unit
TDS	92,415	1,05,452	1,00,475	ppm
Total hardness	28,800	42,300	45,900	ppm
Temporary hardness	189	183	189	ppm
Permanent hardness	28,611	42,115	45,711	ppm
Turbidity	559	387	246	NTU
pH	5.71	5.31	5.18	-
Calcium (Ca^{+2})	9,720	14,400	15,840	ppm
Magnesium (Mg^{+2})	1,094	3,063	1,531	ppm
Sodium (Na^{+})	57,927	66,217	61,036	ppm
Potassium (K^{+})	590	699	586	ppm
Sulfate (SO_4^{-2})	288	40,656	37,632	ppm
Chloride (Cl^{-})	1,10,050	1,07,210	99,400	ppm
Total organic carbon (TOC)	115	250	2,000	ppm

(run 1, 4, and 7) on the energy and exergy of the PW treatment system was investigated (Table 3).

2.4. Mathematical model description

Mathematical modeling technique is a powerful tool for the parametric study of a system and can be used effectively to improve the performance of a system by investigating the influence of effective parameters. In this study, the PW treatment process using a closed-loop spray dryer for desalting water from produced water of reservoir oils has been modeled comprehensively. In the proposed model and deriving of system governing equations some assumptions are used, which are summarized as below:

- The whole system and its components are at the steady-state condition.
- The heat losses in the pipelines and a number of system components such as feed pump, condenser, K.O.D, and air blower are negligible.
- The chemical exergies of PW, treatment water, salt, and air are disregarded.
- The dead state conditions are taken as atmospheric conditions.
- The values of energy and exergy accomplished by the difference in velocity and elevation are ignored in components due to little difference in velocity and potential head.

2.4.1. Energy and exergy analysis

To investigate the performance of the developed system at different operating conditions and obtaining the energy and exergy efficiencies of each component within the system, the energy and exergy analyses are carried out for the entire system. The governing equations for describing the mass and energy balances, and also the exergy balance for the process at steady-state conditions are presented below [27]:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \tag{1}$$

$$\sum \dot{Q} + \sum \dot{m}_{\text{in}} h_{\text{in}} = \sum \dot{W} + \sum \dot{m}_{\text{out}} h_{\text{out}} \tag{2}$$

$$\sum \dot{Q}_j \left(1 - \frac{T_0}{T_j}\right) + \sum \dot{m}_{\text{in}} \text{ex}_{\text{in}} = \sum \dot{W} + \sum \dot{m}_{\text{out}} \text{ex}_{\text{out}} + \sum Ex_{\text{des}} \tag{3}$$

In the proposed system, the humid air and liquid water exist that the specific exergy of the humid air is calculated from Eq. (4) [28]:

$$\text{ex}_{\text{air}} = \left(C_{\text{pa}} + wC_{\text{pv}}\right)\left(T - T_0\right) - T_0 \left\{ \begin{matrix} \left(C_{\text{pa}} + wC_{\text{pv}}\right) \\ \ln\frac{T}{T_0} - \left(R_a + wR_v\right)\ln\frac{P}{P_0} \end{matrix} \right\} + T_0 \left\{ \left(R_a + wR_v\right)\ln\left(\frac{1+1.608w}{1+1.608w_0}\right) + 1.608wR_a \ln\left(\frac{w}{w_0}\right) \right\} \tag{4}$$

where, R_a and R_v are the specific gas constant of air and water vapor respectively. The subscript 0 indicates the dead state conditions and w is the mass fraction of the water vapor in the humid air.

The exergy of liquid flow is described as the following equation [29]:

$$\text{ex}_{\text{water}} = C_p \left\{ T - T_0 - T_0 \ln\frac{T}{T_0} \right\} + \frac{\left(P - P_0\right)}{\rho} \tag{5}$$

To evaluate the energy and exergy efficiency of any system, it is common to use other parameters such as energy efficiency, exergy efficiency, improvement potential rate, relative irreversibility, exergetic factor, and sustainability index. These parameters are considered as an exergetic performance of the systems [30].

For the system described, the relative irreversibility of the k component in the system is calculated by Eq. (6) [31,32]:

$$\mathrm{RI}_k = \frac{\mathrm{Ex}_{\mathrm{des,k}}}{\mathrm{Ex}_{\mathrm{des,total}}} \times 100 \tag{6}$$

Since the components used in the PW treatment process are coupled together in a series configuration, the total exergy efficiency of the process can be defined as the following equations:

$$\eta_{\mathrm{ex,tot}} = \prod_k \eta_{\mathrm{ex},k} \tag{7}$$

To evaluate the energy and exergy efficiencies of the studied PW treatment system, the materials and energy flows have been specified as presented in Fig. 2.

Using the mass and energy balance equations, the governing equations for the components employed in the system are summarized in Table 2. In addition, the exergy balance equations, and the exergy efficiency of each component are given in Table 3.

2.4.2. Solution procedure

To solve the derived governing equations for energy and exergy analyses of the process, at first, the energy balance equation for each component must be solved to obtain the temperature of inlet and outlet streams, and thermal losses from equipment. For this purpose, mass balance equations also are needed. Therefore, the energy and mass balance equations that are given in Table 3, are solved simultaneously, and the mass rate and temperature of all streams are found. Since the components used in the process are coupled in a series configuration, the mass and energy balance equations for one component that has zero degrees of freedom, are solved and then, they are used for the next equipment. After finding the mass rate and temperature of inlet and outlet streams, the obtained values are used in exergy balance equations for each component, and the exergy analysis of the components and the entire process is carried out.

3. Results and discussions

3.1. Model validation

In order to use the model to carry out a system parametric study and investigate the effect of various operational or even structural parameters on the performance of the whole system, the model at first must be validated that to be reliable. For the presented PW treatment process, the energy and exergy analyses were performed for each component employed in the process, and finally, the components model are coupled and developed a comprehensive model for the whole system. The results of the experiments for three different inlet feed flow rates and concentrations and three inlet air temperatures to the spray dryer are given in Table 4. Also for model validation, these criteria, the root mean square error, RMSE, coefficient of determination, R^2 and mean bias error, MBE were chosen for comparison between the results for produced water in the experiments and predicted results by the developed model. The mentioned parameters are defined as follows:

$$\mathrm{MBE} = \frac{1}{N}\sum_{j=1}^{N}\frac{b_j - o_j}{o_j} \tag{8}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{N}\left(o_j - b_j\right)^2}{N}} \tag{9}$$

$$R^2 = 1 - \frac{\sum_{j=1}^{N}\left(o_j - b_j\right)^2}{\sum_{j=1}^{N}\left(o_j - \bar{o}\right)^2} \tag{10}$$

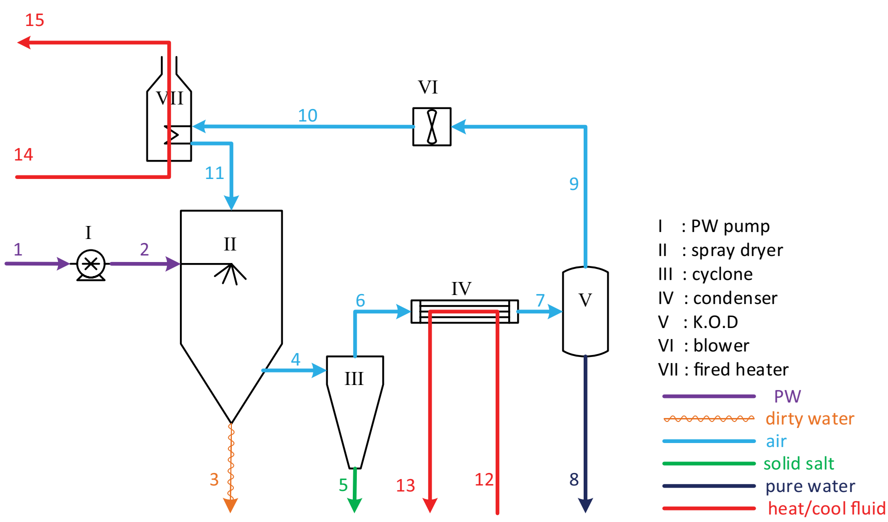

Fig. 2. Schematic diagram of the PW treatment system.

Table 2
Mass and energy balance equations for components in the PW treatment system

No.	Component	Mass balance	Energy balance
I	Feed pump	Feed: $\dot{m}_1 = \dot{m}_2$	$\dot{m}_1(h_2 - h_1) = \dot{W}_S - \dot{Q} = \dot{W}_S = \dot{m}_1 v \Delta P$
II	Spray dryer	Water: $\dot{m}_{11} w_{11,W} + \dot{m}_2 w_{2,W} = \dot{m}_3 w_{3,W} + \dot{m}_4 w_{4,W}$ Air: $\dot{m}_{11}(1 - Y_{11}) = \dot{m}_4(1 - Y_4)$ Salt: $\dot{m}_2 w_{2,S} = \dot{m}_3 w_{3,S} + \dot{m}_4 w_{4,S}$	$\dot{m}_2 C_{p,2} T_2 + \dot{m}_{11} C_{p,11} T_{11} = \dot{m}_3 C_{p,3} T_3 + \dot{m}_4 C_{p,4} T_4 + \dot{m}_v \lambda + Q_L$
III	Cyclone	Salt: $\dot{m}_4 w_{4,S} = \dot{m}_5$ Air: $\dot{m}_4(1 - Y_4) = \dot{m}_6(1 - Y_6)$ Total: $\dot{m}_4 = \dot{m}_5 + \dot{m}_6 \Rightarrow \dot{m}_4(1 - w_{4,S}) = \dot{m}_6$	$\dot{m}_4 C_{p,4} T_4 = \dot{m}_5 C_{p,5} T_5 + \dot{m}_6 C_{p,6} T_6 + Q_L$
IV	Condenser	Water: $\dot{m}_6 Y_6 = \dot{m}_7 Y_7$ Total: $\dot{m}_6 = \dot{m}_7$ $\dot{m}_{12} = \dot{m}_{13}$	$\dot{m}_{13} C_{p,13} T_{13} - \dot{m}_{12} C_{p,12} T_{12} = \dot{m}_6 C_{p,6} T_6 - \dot{m}_7 C_{p,7} T_7 + \dot{m}_8 \lambda - Q_L$ $\dot{m}_{12} C_{p,12}(T_{13} - T_{12}) - \dot{m}_6 C_{p,6}(T_6 - T_7) = 0$
V	K.O.D	$\dot{m}_8 = \dot{m}_7 - \dot{m}_9$	$\dot{m}_8 C_{p,8} T_8 = \dot{m}_7 C_{p,7} T_7 - \dot{m}_9 C_{p,9} T_9 + Q_L$
VI	Blower	$\dot{m}_9 = \dot{m}_{10}$	$\dot{m}_9(H_{10} - H_9) = \dot{W}_S - \dot{Q} = \dot{W}_S = \dot{m}_9 v \Delta P$
VII	Fired heater	$\dot{m}_{10} = \dot{m}_{11}$	$\dot{Q}_{\text{Flue}} = \dot{m}_{\text{Flue}} H_{\text{Flue}}$ $\dot{m}_{\text{Flue}} = \dot{m}_{CO_2} + \dot{m}_{H_2O} + \dot{m}_{N_2} + \dot{m}_{O_2} + \dot{m}_{SO_2}$ $\dot{Q}_L = (2-5)\%\ \dot{m}_{\text{Fuel}} \text{NCV}$ $\dot{Q}_{\text{input}} - (\dot{Q}_{\text{Flue}} - \dot{Q}_L) = \dot{Q}_u =$ Heat gained $\dot{m}_{10}(H_{11} - H_{10}) = \dot{Q}_u = \dot{m}_{\text{Fuel}} \text{NCV} + \dot{m}_{\text{Fuel}} H_{\text{Fuel}}$ $+\dot{m}_{\text{Com.Air}} H_{\text{Com.Air}} - \dot{m}_{\text{Flue}} C_{p,\text{Flue}} T_{15}$ $-(2-5)\%\ \dot{m}_{\text{Fuel}} \text{NCV}$

Table 3
Exergy balance equations for components in the PW treatment system

No.	Component	Exergy balance	Exergy efficiency
I	Feed pump	$\dot{\text{E}}\text{x}_{\text{des,pump}} + \dot{W}_S - \dot{\text{E}}\text{x}_1 - \dot{\text{E}}\text{x}_2 = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{W}_S}\right) \times 100$
II	Spray dryer	$\dot{\text{E}}\text{x}_2 + \dot{\text{E}}\text{x}_{11} - \dot{\text{E}}\text{x}_3 - \dot{\text{E}}\text{x}_4 - \dot{\text{E}}\text{x}_{\text{Loss}} - \dot{\text{E}}\text{x}_{\text{des}} = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{\text{E}}\text{x}_2 + \dot{\text{E}}\text{x}_{11}}\right) \times 100$
III	Cyclone	$\dot{\text{E}}\text{x}_4 - \dot{\text{E}}\text{x}_6 - \dot{\text{E}}\text{x}_5 - \dot{\text{E}}\text{x}_{\text{Loss}} - \dot{\text{E}}\text{x}_{\text{des}} = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{\text{E}}\text{x}_4}\right) \times 100$
IV	Condenser	$\dot{\text{E}}\text{x}_6 + \dot{\text{E}}\text{x}_{12} - \dot{\text{E}}\text{x}_7 - \dot{\text{E}}\text{x}_{13} - \dot{\text{E}}\text{x}_{\text{Loss}} - \dot{\text{E}}\text{x}_{\text{des}} = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{\text{E}}\text{x}_6 + \dot{\text{E}}\text{x}_{12}}\right) \times 100$
V	K.O.D	$\dot{\text{E}}\text{x}_7 - \dot{\text{E}}\text{x}_8 - \dot{\text{E}}\text{x}_9 - \dot{\text{E}}\text{x}_{\text{Loss}} - \dot{\text{E}}\text{x}_{\text{des}} = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{\text{E}}\text{x}_7}\right) \times 10$
VI	Blower	$\dot{\text{E}}\text{x}_9 - \dot{\text{E}}\text{x}_{10} - \dot{\text{E}}\text{x}_{\text{Loss}} + \dot{W}_S - \dot{\text{E}}\text{x}_{\text{des}} = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{\text{E}}\text{x}_9 + \dot{W}_S}\right) \times 10$
VII	Fired heater	$\dot{\text{E}}\text{x}_{14} + \dot{\text{E}}\text{x}_{10} - \dot{\text{E}}\text{x}_{11} - \dot{\text{E}}\text{x}_{15} - \dot{\text{E}}\text{x}_{\text{Loss}} - \dot{\text{E}}\text{x}_{\text{des}} = 0$	$\eta_{\text{ex}} = \left(1 - \frac{\dot{\text{E}}\text{x}_{\text{des}}}{\dot{\text{E}}\text{x}_{14} + \dot{\text{E}}\text{x}_{10}}\right) \times 100$

Table 4
Results of experiments carried out on disposal of crude oil desalting plants Ahwaz, Marun and Mansori and error analysis results

Measurement point		1	2	3	4	5	7	8	9	9	11	RMSE	R^2	MBE
Variable (unit)		TDS (ppm)	QL (gr/min)	MAT (gr)	TGOT (°C)	MAC (gr)	TGOC (°C)	MAK (gr)	QG (m^3/hr)	Humidity RH %	TGIT (°C)			
Category A	Run 1	92,415	45	5	110	82	12	813	60	35	140			
	Run 2	92,415	45	20	110	83	12	797	50	35	140	0.0023	0.9432	0.0021
	Run 3	92,415	45	80	110	82	12	738	30	35	140			
Category B	Run 4	1,05,452	45	5	110	94	12	801	60	35	140			
	Run 5	1,05,452	45	90	99	93	12	717	60	35	130	0.0123	0.9324	–0.0210
	Run 6	1,05,452	45	190	85	91	12	619	60	35	110			
Category C	Run 1	92,415	45	5	110	82	12	813	60	35	140			
	Run 7	1,00,475	45	5	110	90	12	805	60	35	140	0.0014	0.9521	0.0012
	Run 4	1,05,452	45	5	110	94	12	801	60	35	140			

QL: Flow rate of feed
QG: Flow rate of carrier gas
MAT: Accumulated mass in the tower
MAC: Accumulated mass in cyclone
MAK: Accumulated mass in K.O.D
TGOT: Carrier gas temperature outlet from the tower
TGOC: Carrier gas temperature outlet from the condenser
TGIT: Carrier gas temperature outlet into the tower

In Eqs. (8)–(10), N is the number of data, o_j and b_j are the i^{th} experimental data and corresponding model value, and $\bar{o}$ is the average value of the experimental data. The value of R^2 varies between 0 and 1, and the larger value shows a better agreement between the model results and the experimental data. Also, for RMSE and MBE, smaller values represent better matches. For the present system, the model results were compared with all experimental data and for some conditions with the greatest deviations, the results of error analysis were reported in Table 4. The results of error analysis for other operational conditions are also carried out and only the results with the greatest deviation are reported here to avoid lengthening of the text. The results of the error analysis show that the developed model has good accuracy and can be reliable. After model validation, using the validated model, the influence of some effective parameters on the system performance are discussed.

3.2. Effect of inlet airflow rate to the spray dryer

The effect of the inlet airflow rate to the spray dryer on the temperature of streams is shown in Fig. 3. The results indicate that for constant other operating parameters, when the rate of inlet air increases, the temperature of outlet humid air from dryer increases due to rising in energy content of airflow within the dryer. The temperature of outlet air from the condenser and the air blower, $\bar{T}7$ and $\bar{T}10$ respectively not change significantly. It can be explained that when the condenser capacity is high, it can reduce the outlet temperature to the lower saturation temperature, and consequently the outlet temperature does not vary meaningfully. Therefore, when the inlet temperature to the separator does not change, the outlet temperature from the separator and consequently outlet from the blower does not change meaningfully. However, when the air rate increases, the outlet temperature of coolant from the condenser, $\bar{T}13$ increases.

The effect of the inlet air rate on the relative irreversibility of the component within the system is shown in Fig. 4. According to Eq. (6), when the air rate increases, the amount of water transferred to the air inside the dryer increases due to an increase in convective mass transfer and consequently, the exergy destruction in the dryer decreases. Therefore, by increasing the inlet air rate to the dryer, the spray dryer relative irreversibility decreases. For the cyclone, when the air rate increases, the solid dust in the cyclone increases, and therefore, exergy destruction, and consequently relative irreversibility growths. According to the results in Fig. 3, since the outlet temperature of coolant increases, the exergy destruction and relative irreversibility in the condenser increase. For an air blower with constant power consumption, when the larger air rates enter the blower, the exergy destruction, and relative irreversibility decreases. Larger air rates in the direct-fired heater lead to smaller exergy destruction in the fired heater and consequently smaller relative irreversibility.

The main result obtained from the developed model is to predict the amount of desalinated water from the treatment system. The rate of desalinated water for various rates of inlet air is shown in Fig. 5. The results indicate that the rate of inlet air to the dryer has a significant effect on the final expectation of the process, which is the production of desalinated water from a disposal water source. For very small rates of inlet feed and hot air produced by the direct-fired heater, the system can produce an acceptable amount of desalinated water. For 0.00075 kg/s inlet feed and a rate of 0.03 kg/s inlet hot air, the system can produce up to 1.3 kg/h desalinated water.

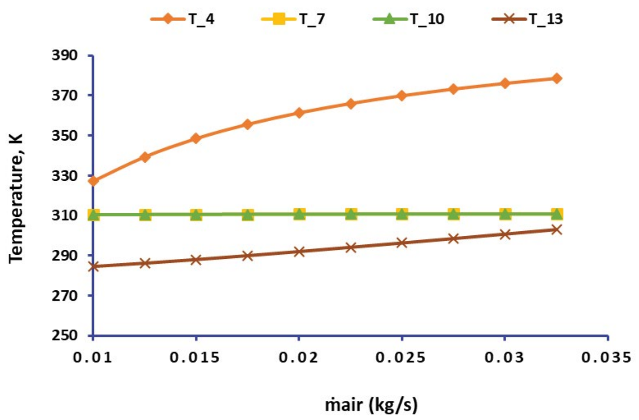

Fig. 3. Effect of inlet air rate on the spray dryer on the temperature of streams, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, T_{in} = 140°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

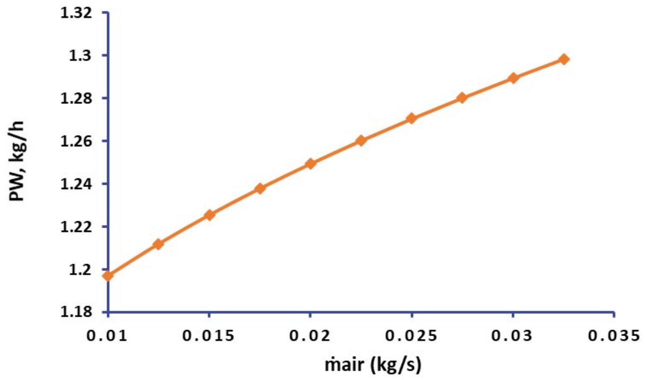

Fig. 5. Effect of inlet air rate on the amount of produced water by the treatment process, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, T_{in} = 140°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

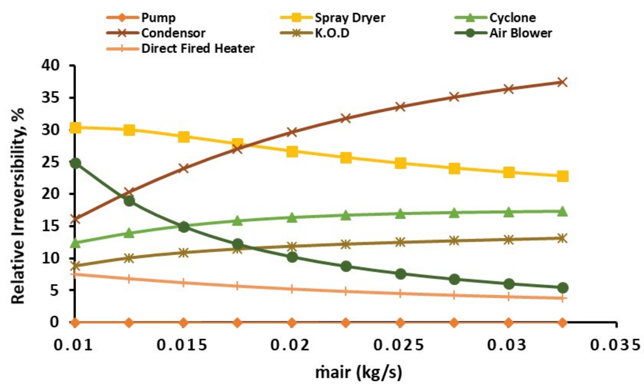

Fig. 4. Effect of inlet air rate relative irreversibility of the component in the PW treatment process, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, T_{in} = 140°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

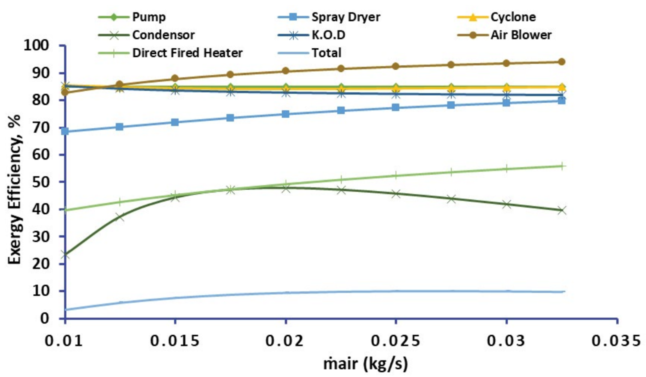

Fig. 6. Effect of inlet air rate on the exergy efficiency of the components within the system and system exergy efficiency, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, T_{in} = 140°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

The exergy efficiency of the component in the system and system exergy efficiency is shown in Fig. 6. The results illustrate that the air blower, cyclone, separator, and feed pump are the equipment with lower exergy destruction and larger exergy efficiency within the system. The results in Fig. 4 show that the portion of each mentioned equipment in the destruction of the exergy within the system is less than 20%. Therefore, the exergy efficiency of the mentioned components is higher compared to other employed components in the process such as spray dryer, condenser or direct-fired heater. The results in Fig. 6 show that when the air rate increases from 0.01 to 0.03 kg/s, the system exergy efficiency increases from 5 up to 10%. It means that the inlet air rate has a significant effect on the exergy efficiency of the whole system.

3.3. Effect of inlet air temperature

The effect of inlet air temperature on the temperature of various streams in the process is shown in Fig. 7. Results show that when the inlet air enters the dryer with higher temperatures, the temperature of outlet humid air, the temperature of outlet air from the separator and consequently air blower increases. The temperature of outlet coolant from the condenser is also increased because a hotter air enters the condenser but, the main parameter that affects the outlet temperature of coolant from the condenser is the rate of air inside the condenser and its temperature has not a great effect on the temperature of coolant for larger coolant rates.

The relative irreversibility for the various components in the process and for different inlet air temperatures is shown in Fig. 8. The results indicate that for the inlet air rate of 0.015 kg/s, the maximum relative irreversibility is for spray dryer, and the condenser and also air blower have a great portion of exergy destruction within the PW treatment process. When the hotter air enters the dryer, the exergy of outlet streams from the dryer increase but compared to the inlet air is decreased, and consequently the exergy destruction in the dryer increases. About 25% of the total exergy destruction within the process is related to the spray dryer. Since the cooling capacity of the condenser is high, when a humid air with greater temperatures enters the condenser, no significant changes are observed in the outlet exergy streams and consequently the exergy destruction within the condenser increases.

The desalinated water produced for various inlet air temperatures is shown in Fig. 9. When he hotter air enters

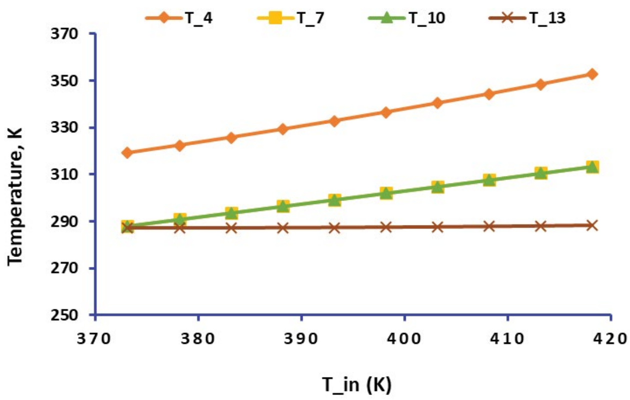

Fig. 7. Effect of the temperature of inlet air on the temperature of various streams in the PW treatment process, $\dot{m}_{air}$ = 0.015 kg/s, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

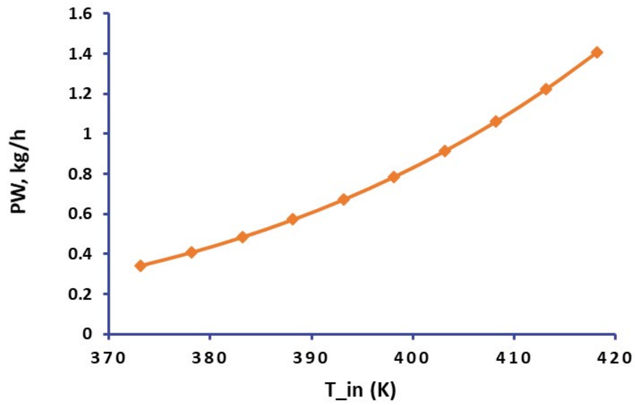

Fig. 9. Effect of inlet air temperature on the desalinated water produced in the PW treatment process, $\dot{m}_{air}$ = 0.015 kg/s, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

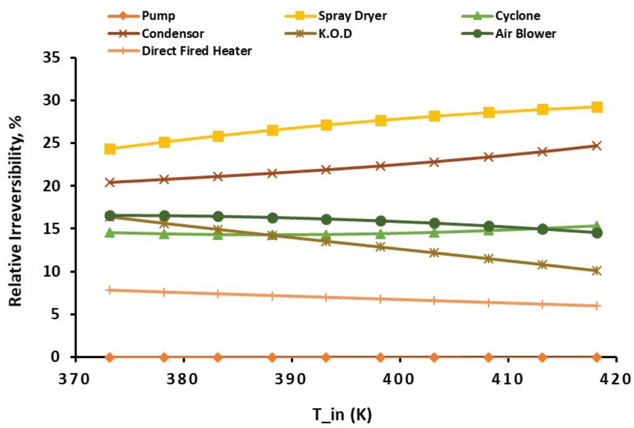

Fig. 8. Effect of inlet air temperature on the relative irreversibility for the component within the PW treatment process, $\dot{m}_{air}$ = 0.015 kg/s, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

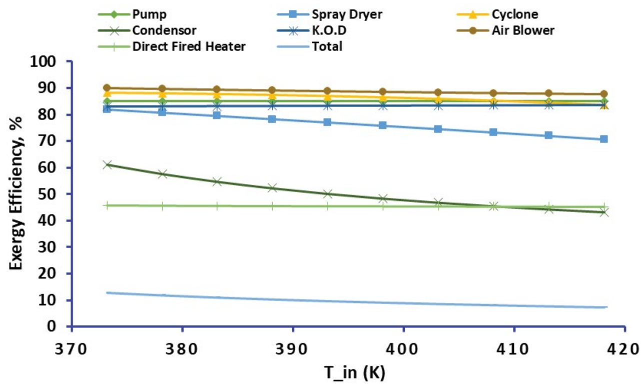

Fig. 10. Effect of inlet air temperature on the exergy efficiency of the components in the process and system exergy efficiency, $\dot{m}_{air}$ = 0.015 kg/s, $\dot{m}_{feed}$ = 0.00075 kg/s, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

the process, the heat and mass transfer inside the dryer increase and consequently the greater amounts of water removed from the disposal feed and is transferred to the air stream. The results show that when the inlet air temperature increases from 373 to 418 K, the produced desalinated water increases up to 4.5 times. By comparing the results in Fig. 5 and Fig. 9, it can be seen that the effect of inlet air temperature compared to its rate is more considerable and the slope of water production rate for inlet air temperature is increasing while for inlet air rate is decreasing.

The exergy efficiency of components employed in the process and the system exergy efficiency for various inlet air temperature is shown in Fig. 10. Results indicate that when the inlet air temperature increases, the exergy efficiency of the direct-fired heater, feed pump, air blower, feed pump, and separator does not change significantly. Since hotter air has greater exergy content, and when air with higher temperature enters the spray dryer, its exergy efficiency decreases. The air condenser also its exergy efficiency is reduced when a hotter air enters the system. When the inlet air temperature increases from 373 to 418 K, the exergy efficiency of the spray dryer and air condenser decreases about 15% and 42% respectively, and the exergy efficiency of the whole system decrease about 78% and its exergy efficiency decrease from 12.81% at 373 K to 7.2% to 418 K.

3.4. Effect of disposal feed rate

Another operating parameter that affects the system performance is the flow rate of inlet disposal. The effect of inlet feed temperature on the temperature of streams within the system is shown in Fig. 11. The results indicate that the inlet feed rate has no significant effect on the temperature of air streams and only affects the temperature of the humid air outlet from the dryer. When the rate of inlet feed increases, the larger amounts of water is removed from the feed and is transferred into the air stream, and as a result, the larger amount of heat energy from the hot air inside the dryer is transferred to the liquid feed water in opposite direction and consequently its temperature decrease.

The relative irreversibility for the components in the system for various inlet feed rates is shown in Fig. 12. It is clear that in two components inside the process, the spray

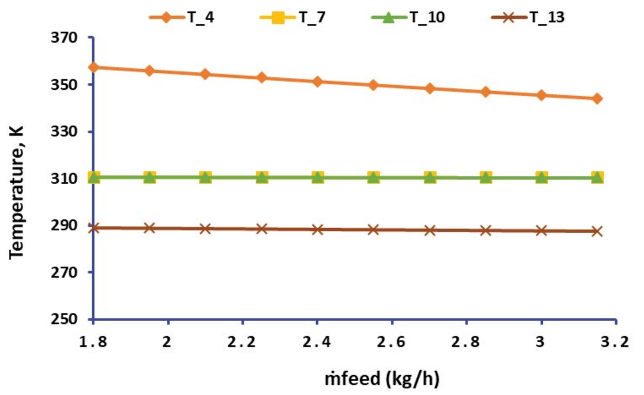

Fig. 11. Effect of inlet feed rate on the temperature of streams in the PW treatment process, $\dot{m}_{air}$ = 0.015 kg/s, T_{in} = 140°C, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

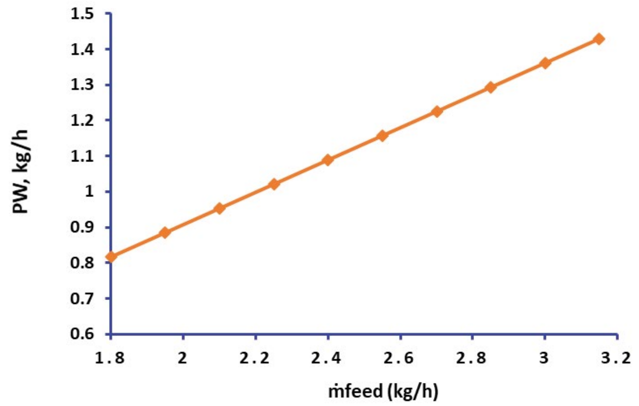

Fig. 13. Effect of inlet feed rate on the rate of desalinated water by the system, $\dot{m}_{air}$ = 0.015 kg/s, T_{in} = 140°C, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

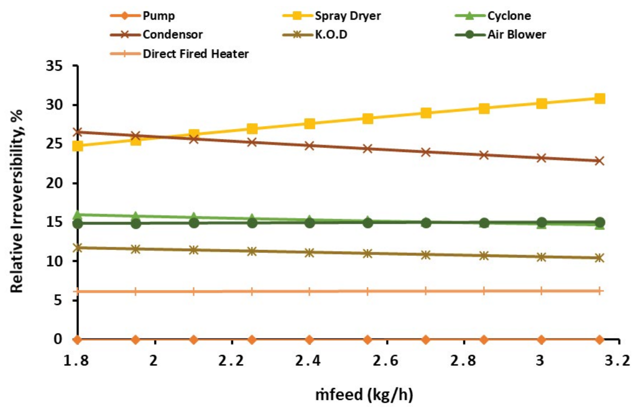

Fig. 12. Effect of inlet feed rate on the relative irreversibility for component employed in the process, $\dot{m}_{air}$ = 0.015 kg/s, T_{in} = 140°C, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

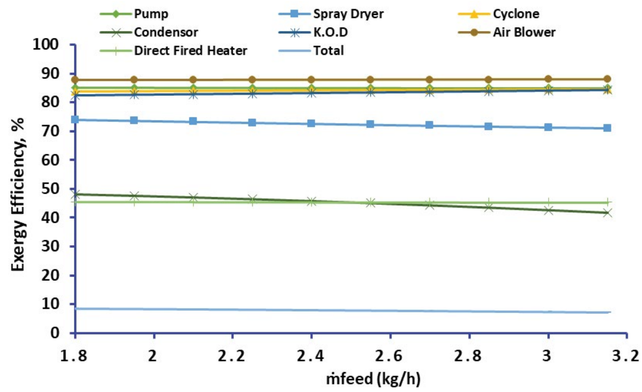

Fig. 14. Effect of inlet feed rate on the exergy efficiency of the component in the system and the entire system exergy efficiency, $\dot{m}_{air}$ = 0.015 kg/s, T_{in} = 140°C, T_{amb} = 40°C, and $\dot{m}_{cw,cond}$ = 0.027 kg/s.

dryer, and air condenser allocate up to 50% of the total exergy destruction within the system. The inlet feed rate approximately has no great effect on the other parts of the system and when the inlet feed rate increases, the outlet humid air from the spray dryer has greater water content and when enters the air condenser, the exergy destruction inside the condenser decreases and consequently the exergy destruction inside the dryer increases.

The effect of the inlet feed rate on the produced desalinated water by the system is shown in Fig. 13. It can be seen that the variation of the produced water by the system vs. the rate of inlet feed is linear and when the inlet feed increases from 1.8 to 3.2 kg/h, the produced water increase from 0.82 to 1.43 kg/h. it means that for an increase in the feed rate to the system about 77%, the produced desalinated water increases by up to 74%. The component exergy efficiency and the entire system exergy efficiency for the various rates of inlet feed are shown in Fig. 14. Results indicate that the inlet feed rate has no significant effect on the exergy efficiency of the other components in the process except the spray dryer and air condenser. When the inlet feed rate increase from 1.8 to 3.2 kg/h, the exergy efficiency of the spray dryer decreases up to 3.5% and the exergy efficiency of the condenser is reduced up to about 9%.

4. Conclusions

In this study, a PW treatment process was introduced to desalinate the disposal water of oil and gas reservoirs and produce usable water. In the process, a new type of closed-loop spray dryer was employed in the combination with an air condenser, a separator, an air blower, and a direct-fired heater. A bench-scale system was designed and manufactured and three reservoir water samples were tested. In the experiments, the effect of the inlet hot air flow rate and its temperature and inlet feed rate were tested. A mathematical model was developed for each component within the system and coupled together to propose a complete model for the entire system in order to energy and exergy analyses of the process. The results of the developed model and obtained results from the experiments were compared together and the results of the comparison showed that the model is reliable and can be used to investigate the effect of operating or even structural parameters on the performance of the system.

The results of the model parametric study show that the inlet air rate and its temperature and also inlet feed rate have a great effect on the rate of produced desalinated water by the system. When the inlet air rate increases from 0.01 to 0.0325 kg/s, the produced water increases up to 8.5%, for an increase in the inlet air temperature from 373 to 418 K, the produced desalinated water increases up to 410%, while for inlet feed rate an enhancement up to 75% can be obtained when the feed rate increases from 1.8 to 3.15 kg/h. The key components in the system that destroy the maximum amount of exergy in the system are the direct-fired heater, spray dryer, and air condenser and in some cases, these three components allocate up to 50% of total exergy destruction within the system. The exergy efficiency of the entire system is in the range of 3 to 13% and by appropriate selection of operational parameters and accurate selection of more suitable components instead of exergy destructive components, greater exergy efficiency can be obtained.

Symbols

C_p — Heat capacity
ex — Specific exergy
Ex — Exergy rate
h — Enthalpy
K.O.D — Knock out drum
$\dot{m}$ — Inlet mass flow rate
MAC — Accumulated mass in cyclone
MAT — Accumulated mass in the tower
MAK — Accumulated mass in K.O.D
MBE — Mean bias error
MEE — Multi-effect evaporation
MF — Microfilter
MVC — Mechanical vapor condensation
N — Number of data
NCV — Net Calorific Value of Fuel
NF — Nano filter
ppm — Part per million
P — Pressure
PET — Polyethylene terephthalate
PW — Produced water
$\dot{Q}$ — Heat flow rate
Q — Heat
QL — Flow rate of feed
QG — Flow rate of carrier gas
R — Specific gas constant
RI — Relative irreversibility
RMSE — Root mean square error
RO — Reverse osmosis
T — Temperature
TDS — Total dissolved solids
TGOT — Carrier gas temperature outlet from the tower
TGOC — Carrier gas temperature outlet from the condenser
TGIT — Carrier gas temperature outlet into the tower
TOC — Total organic carbon
v — Air velocity
w — Mass fraction
$\dot{W}$ — Work
Y — Mole ratio
ρ — Density
η — Efficiency

Subscripts

a — Air
amb — Ambient
cw — Cooling water
con — Condenser
des — Destruction
ex — Exergy
in — Inlet
k — Component
L — Loss
out — Outlet
S — Shaft
tot — Total
u — Gained
v — Water vapor
0 — Dead state conditions
o, b — Experimental data

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