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Exergoeconomic optimization of a double effect desalination unit used in an industrial steam power plant

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ABSTRACT

An exergoeconomic optimization of a double effect thermal vapor compression desalination system is performed. This unit is integrated in the thermal power plant of Phosphoric Acid factory owned by The Tunisian Chemical Group. The daily production of this unit is about 528 m^3 of fresh water. A mathematical model based on energy, exergy and economic balances is established using EES software. Multi-objective optimization is carried out in the purpose to obtain the maximum exergy efficiency with minimum production cost. The effects of the main operating parameters on the desalination unit performances are analyzed.

Obtained results show that, the maximum exergy efficiency is obtained for the evaporator II followed by the distillate and brine pumps. The condenser has the lowest exergy efficiency.

The thermocompressor is the major contributor in exergy destruction. The mass flow rate and the pressure of the motive steam affect positively the GOR. The SPECO method is used to perform the economic optimization. The maximum exergoeconomic factor f is obtained for the evaporator II followed by the evaporator I, the thermocompressor, the distillate pump and the condenser. The optimum operating conditions leading to suitable overall exergy efficiency with low production cost of distillate water are determined.

1. Introduction

The Tunisian Chemical Group (TCG) constitutes the most industrial pole in the country. The main activities of this group are to produce the phosphoric acid and fertilizers from crude phosphate. For this reason several chemical industrial factories are built in different regions. That represents an important factor for the Tunisian economic balance. Although the economic importance of the phosphate industry, the investment and operating costs of the different plants, remain very substantial. To overcome this problem the TCG conducts programs in the purpose to optimize the production cost and to reduce the energy consumption.

In the frame of this program, a thermoeconomic analysis of a steam turbine power plant operating in a Phosphoric Acid factory owned by TCG is performed. This paper is focused on an exergoeconomic optimization of a double effect desalination unit constituting one of the important parts of the indicated power plant. The main object of this study is to define the optimum operating conditions leading to the maximum exergy efficiency with minimum production costs.

The multi-effect thermal vapor compression (MED-TVC) is considered as one of the best technologies of desalination systems. Several works have been carried out on the MED-TVC optimization; among them we found:

Abdulrahman Almutairi et al. [1] conducted an energetic and exergetic optimization of a cogeneration combined power plant and a ME-TVC-MED desalination unit under several operating conditions. This unit is with 8 effects and has a capacity of 340.7 kg/s. The motive steam flow rate and pressure are equal to 17.5 kg/s and 2.7 bars respectively. The seawater temperature is equal to 37 °C and the GOR is of about 9.47. The developed model of the plant is performed using IPSEpro software. The obtained results showed that the higher exergy destruction rate of the considered plant occurs in the combustor. In order to improve the plant performances, authors suggest to operate in full load and with a lower ambient temperature. Moreover an increase of pressure ratio is recommended. In the desalination side, the obtained results showed that the main sources of irreversibility are located in the effects and the thermo-compressor of about 78.7%. Exergy efficiency of the desalination unit is equal to 7.685%. The increase of the effect numbers leads to an enhancement of the exergetic efficiency by about 0.7%. While the raise of the feed water temperature allows slightly increasing in the exergetic efficiency. In other hand, an entrainment ratio close to unit is recommended in the aim to obtain a higher performance and

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capacity of the cogeneration plant.

B. Ortega-Delgado et al. [2] performed a parametric study of a MED-TVC plant coupled with a Rankine cycle power unit installed in Trapani, Italy. This unit has 12 effects and a capacity of about 9000 m^3/d. A mathematical model was developed and validated for the plant using EES software. The considered motive steam pressure and temperature are equal to 45.4 bars and 257 °C respectively. The effect of operating parameters on the plant performances was established. The main results drawn from this study reveal that a higher Gain Output Ratio (GOR) was reached for a higher motive steam pressure and for a steam ejector location close to the last effect. The produced distillate decreases by reducing the pressure of motive steam and increasing the suction pressure.

K. M. Bataineh [3] investigates the overall performance of a MED-TVC plant motivated by a solar steam generation located in Aqaba, Jordan with a daily production of about 50,000 m^3. The motive steam flow rate is about 16.7 kg/s and the GOR is equal to 7.45. The mathematical model established by EES software allows determining the influence of operational and conceptual parameters on the plant performances. The results demonstrate that the system efficiency increases with augmentation of the first effect temperature. Furthermore, a collector orientation of along a north-south axis with an area around 1.080.000 m^2 and a storage size of about 75 l/m^2 lead to an optimum plant performance.

O. Samaké et al. [4] carried out a parametric study of a MED-TVC system. A mathematical model was developed using EES software. The effect of operational parameters on the plant performance is analyzed in order to determine the optimal system efficiency. The plant is considered as a black box and the developed model permits to obtain the influence of design variables on plant capacity.

An exergoeconomic analysis of an integrated multi-effect desalination unit with an organic Rankine cycle is performed by M. Ameri et al. [5]. A multi-objective optimization is conducted so as to obtain the optimum conditions leading to a maximum fresh water production with a minimum cost. Moreover, different working fluids are considered in this optimization (R123/R245fa/R134a). They found that the increase of the compressor pressure ratio permits to increase the exergy efficiency of the whole system and to decrease the production cost. In addition, R134a seems to be the best working fluid leading to higher exergy efficiency. The power generation by ORC cycle for the different studied working fluids is determined. In the other hand, the ratio of investment cost to total cost are determined for the different working fluids as follows: 82.736% for R123; 82.736% for R245fa and 84.110% for R134a.

A thermoeconomic optimization of a MED-TVC system is conducted by K. J. Gabriel et al. [6]. The considered unit has a capacity of 20,000 m^3/d with effect number ranging between 4 and 12. The motive steam pressure is equal to 2.4 bars; the temperature of seawater is 25 °C and the GOR is about 9.7. The mathematical model of the plant based on mass and thermal balances is developed. In addition, the effect of operating conditions on the system efficiency is established. The obtained results highlight a new dispersion of condensate throughout the evaporator permitting to overcome the salinity constraints. Moreover, the effect numbers depend on operating and economic conditions as well as the temperature difference between the effects.

B. Hang et al. [7] carried out an experimental study in order to improve the performance of Thermal Vapor Compressor (TVC) entrainment ratio. A parallel flow MED-TVC distillation unit was set up. This work investigates the effect of preheating and superheating entrained steam on the TVC entrainment ratio. The results prove that the heating of entrained vapor permits to increase significantly the entrainment ratio of TVC and reduces the intake motive steam. Then improve the MED-TVC performance system.

Mohammed T. Mazini et al. [8] developed a dynamic mathematical model for a MED-TVC system. A mass and energy balances are established. The dynamic and static behaviors in the different compound of the plant are modeled and simulated by MATLAB/SIMULINK software. The suggested model is validated using real operating data of Kish Island plant installed in Iran. Furthermore, this model is investigated with modifying operating conditions and applying disruption in the system behavior. The obtained results show a good performance of the proposed model.

A steady-state mathematical model of MEE-TVC plant is conducted by Ibrahim S. Al-Mutaz et al. [9]. Mass, energy and heat transfer equations governing the system behavior are established. Moreover, authors investigate the effects of conceptual and operational conditions on the plant performances. The proposed model shows excellent agreement with real data and commercial multi-effect evaporation with thermal vapor compression systems.

A comparative performance study between three desalination system configurations was carried out by Ibrahim S. Al-Mutaz et al. [10]. A mathematical model based on material and energy balances was conducted for each configuration systems. This work aims to investigate, for each configuration, the influence of design and operating parameters on the multi-effect desalination plant performances. It was found that the specific heat transfer area increases significantly with the increase of effect numbers and the decrease of temperature difference across the effects. The parallel/cross feed configurations represent the best performance comparing to the forward and backward feed configuration.

Seyed R. Hosseini et al. [11] established a multi-objective optimization in order to design a combined gas turbine cycle and a multi stage flash desalination system. The developed model based on exergetic and economic balances carried out by using a multi-objective genetic algorithm (MOGA). The exergetic, economic and environmental aspects are taking into account in the optimization. Therefore, authors define a new thermoenvironomic objective function. The obtained results show an enhancement in exergy efficiency of about 14.8% as well as a decreasing of the production cost and environmental cost of about 13.4% and 53.4%, respectively.

S. Sadri et al. [12] performed a mathematical model of MED-TVC-RO hybrid desalination plant installed in Iran. The material, energy and exergy equations governing the behavior of fluid flow in the different compound system are developed. Moreover, the thermodynamic properties of each stream are determined taking into account the boiling point elevation. That permits to determine the performances of the desalination unit. A multi-objective optimization for different configurations of hybrid system are established in the aim to select the best one leading to a higher permeate production and exergy efficiency as well as a suitable Gain Output Ratio. Obtained results show that the MED part engenders the maximum of exergy destruction rate, especially in the thermal vapor compressor followed by the first effect. In the other hand, the permeate flow production is increased by 34% in the hybrid system compared to the MED unit. Furthermore, the RO unit and MED system exergy efficiencies are increased to reach 8.63% and 12.84% respectively in the hybrid configuration.

A. Piacentino [13] conducted an advanced thermoeconomic analysis of a forward feed multi-effect distillation plant. The developed model based on energetic, exergetic and economic balances are established and simulated using EES software. The exergy analysis reveals that the thermal exergy flows have a relevant role than the chemical exergy. The developed method permits to obtain the specific cost production of distilled water in each effect. Authors found that the production cost of fresh water in last effects is more expensive.

I.B. Askari et al. [14] performed a techno-economic analysis of a multi-effect desalination system with thermal vapor compression operating by a linear Fresnel solar field. This plant located at Kish Iran, is designed to produce 9000 m^3/day. Several configurations are considered in the aims to determine the optimum tradeoff between the cost sizes of LF solar field system and the total annual storage fuel. Authors found that the obtained distillate cost of desalination system with thermal storage is higher than without thermal storage. Moreover, the