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Performance analysis of a gas turbine unit combined with MED-TVC and RO desalination systems

Abdulaziz Alzahrani, Jamel Orfi*, Zeyad Alsuhaibani

Department of Mechanical Engineering, College of Engineering, King Saud University, P.O. Box 800, 11421 Riyadh, Kingdom of Saudi Arabia, Tel. +966 1 467 9798; Fax: +966 1 467 6652; email: orfij@ksu.edu.sa (J. Orfi)

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ABSTRACT

The present work deals with a theoretical study on the performance of a combined power and desalination plant. The power is a simple gas turbine unit (GT) while the desalination is composed of thermal and membrane systems. The thermal desalination consists of a multiple effect distillation (MED) with thermal vapor compression (TVC), and the membrane plant is a reverse osmosis (RO) with an energy recovery device (pressure exchanger system). The modeling is based on appropriate evaluation of the sea water properties including that of flow exergy and the solution of mass, energy, and exergy balances for the main components of the power and desalination plant. The simulations include typical data on actual GT units. The effect of the main controlling parameters of the GT plant mainly the pressure ratio and the turbine inlet temperature on the total production rates of fresh water is presented and discussed. An exergy analysis showing the destruction rates of the overall system as well as its main components is also presented. Besides, equations describing the variations of the power output with the air and the distillate mass flow rates are given.

Keywords: Multiple effect distillation; Reverse osmosis; Gas turbine; Waste heat; Exergy

1. Introduction

The electricity and water consumptions are continuously increasing due to the rapid growth in the population worldwide and the resulting increase of the standard of living. Therefore, power generation and fresh water production plants are needed to satisfy the corresponding demand of electricity and potable water. A better utilization of fuel energy supplied to these power and desalination plants is needed not only to reduce the cost of kWh of electricity and m^3 of potable water produced but also for environmental considerations.

Cogeneration, integration of systems, and hybridization are concepts that are being implemented more frequently. The cogeneration of electricity and pure water improves the utilization of supplied energy and minimizes the release of high temperature effluents to the environment. Hybrid desalination systems integrating thermal and membrane desalination processes with power generation in the same site appear to be suitable for cogeneration plants.

*Corresponding author.

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Modern gas turbine (GT) power plants are used to produce electrical power in inland and coastal regions in particular to cover peak load demand. These power plant units are used single or integrated with steam power plants to form combined cycle plants. The major advantages of GTs are their high power output for a relatively small size and weight, low initial cost, high reliability, and full flexibility [1]. However, their major disadvantage concerns low thermal efficiency compared to other internal combustion engines and steam power plants. In fact, about 70% of the fuel energy supplied to a typical simple GT unit is rejected to the environment as waste heat. Recovering such waste energy has several positive impacts in increasing the rate of fuel utilization and reducing the emissions of pollutants.

A good number of studies have focused on coupling GT plants with desalination units. Such a coupling can have several configurations. Darwish et al. [2] analyzed the performance of reverse osmosis (RO) desalting plants operated by GTs in Kuwait. The authors also studied the effect of compressor inlet air cooling using various methods such as direct evaporation as well as single- and multi-stage vapor compression refrigeration systems.

Vlachos and Kaldellis [3] presented a techno-economic study on the application of GT exhaust gases for brackish water desalination in the island of Crete. The existing LM6000 gas turbine has an installed capacity of 43.3 MWe and a mass flow rate of hot out gases (at 456°C) of 123.7 kg/s. It was proposed to couple such a power plant with a multiple effect distillation accompanied with thermal vapor compression (MED-TVC) giving a rated capacity of 460 m^3/h of potable water and gained output ratio (kg of distilled per kg of steam used) of 8:1.

El Nashar [4] reviewed the technical and economic characteristics of cogeneration plants commercially available as well as the cost parameters for both cogeneration and desalination plants. The author observed, in particular, that the power to water ratio has a strong influence on the optimum selection of a cogeneration plant. This optimum generation option depends strongly on the load variation throughout the year.

Wang and Lior [5] conducted a theoretical study using energy and exergy analysis of a coupled plant of a steam injected gas turbine (STIG) and multi-effect thermal vapor compression system (MEE-TVC). The thermal desalination unit which includes a steam jet ejector was compared to the multiple effect evaporation (MEE) process and was selected for producing fresh water and for humidification when moderate pressure (around 3 bar or higher) steam is available. The authors concluded, in particular, that the steam injection rate in the STIG cycle has a strong effect on water and power production which offers good flexibility for design and operation. Drovnikov [6] presented the results of a feasibility study on a combined GT multi-effect distiller plant. The MED evaporators are of a horizontal falling film type, and combustion turbines are with steam injection (STIG).

Several recent studies have been conducted on the analysis and optimization of integrated desalination and low temperature thermal energy systems [7–9]. Shakib et al. [9] took into account in their optimization study of a cogeneration plant for water and power production the thermo-economic considerations. The optimal design and configuration have been found using a multi-objective genetic algorithm.

Deng et al. [10] proposed a road map for the integration of low temperature MED and power plants and analyzed the performance of several cogeneration plants under operation in China.

Other recent studies on combined GT and desalination plants have integrated the economic and environmental aspects to the technical ones [11–13].

The present work presents results on the performance of GTs coupled with MED–TVC and RO units. The effect of the main parameters of the power plant on the fresh water production and exergy destruction rates is investigated.

2. Description and modeling of the system

2.1. System description

The present system, described schematically in Fig. 1, combines a basic GT using Brayton cycle, a thermal desalination unit based on MED-TVC process, and a reverse osmosis unit with a pressure exchanger system (RO-PES). The GT is composed of a compressor, a combustion chamber and a turbine. The configuration chosen for the thermal desalination unit is the forward feed MEE. It has six evaporators, a condenser, and an ejector connected to the sixth effect. The hot exhaust gases leaving the GT are used as heat supply to the desalination unit. A heat recovery steam generator (HRSG) links the power plant to the thermal desalination unit.

2.2. System modeling

The modeling of the considered system is based on the application of mass, energy, and exergy balances to the whole combined power and desalination plant as well as to its components.

The accurate evaluation of sea water properties particularly the flow exergy received a special

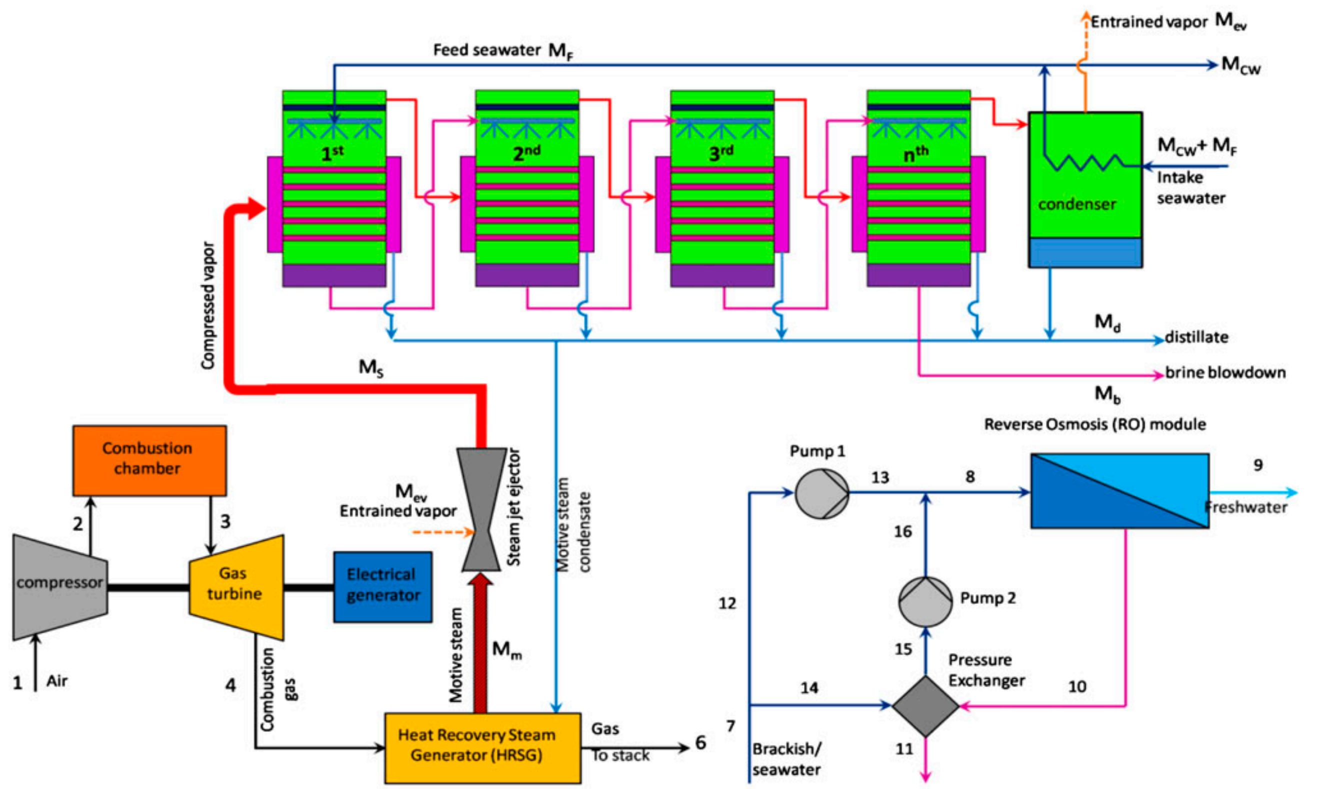

Fig. 1. Schematic diagram of GT–MED-TVC–RO.

attention in this work. Correlations for sea water properties recently verified and updated by Sharqawy et al. have been used [14]. The modeling of the MED–TVC process is based on the formulation presented in [15]. One can find more details on those governing equations corresponding to GT, thermal desalination, and RO units in references [16,17]. The Engineering Equations Solver tool [18] was used to solve the governing equations and perform several simulations. This software is known to be appropriate to solve these kinds of problems and was used in several similar applications.

Exergy analysis combines the first and the second law of thermodynamics. It permits to evaluate quantitatively and qualitatively the effect of the various thermodynamic irreversibility sources on the degree of energy degradation.

For control volume or any plant component at steady state conditions, the general exergy balance can be expressed in the rate form as:

$$\sum \dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}} - \sum \dot{\mathrm{E}}\mathrm{x}_{\mathrm{out}} = \sum \dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest}} \tag{1}$$

A general equation expressing the exergy destruction rate derived from the exergy balance can be given as [1]:

$$\mathrm{Ex}_{\mathrm{dest}} = \sum \left(1 - \frac{T_0}{T_{\mathrm{k}}}\right) Q_{\mathrm{k}} - W + \sum m_{\mathrm{in}}\,\mathrm{ex}_{\mathrm{in}} - \sum m_{\mathrm{out}}\,\mathrm{ex}_{\mathrm{out}} \tag{2}$$

where the first term of right hand side represents the exergy related to heat transfer by heat. T_0 is the environment temperature of the surroundings of the system and Q_{k} refers to the heat transfer rate across the boundary of the system at a constant temperature T_{k}. The second term corresponds to the work transfer rate to the control volume. The third and fourth terms represent exergy streams entering and leaving the control volume.

Total exergy destruction rate in the plant can be determined as the sum of exergy destruction rates of components:

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest}} = \sum_{\mathrm{i}} \dot{\mathrm{E}}\mathrm{x}_{\mathrm{desti}} \tag{3}$$

Different ways of formulating the exergy efficiency are proposed in the literature [19].

The exergy efficiency relates all exergy inputs and exergy outputs of a system. The exergetic efficiency of a component i can be expressed by:

$$\eta_{ex\,i} = \frac{\dot{E}x_{out_i}}{\dot{E}x_{in_i}} = 1 - \frac{\dot{E}x_{dest_i}}{\dot{E}x_{in_i}} \quad (4)$$

For the whole plant, one can have:

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \quad (5)$$

The flow exergy of a saltwater mixture including the mechanical exergy and chemical exergy contributions can be calculated as given by [17,20–22].

3. Results and discussion

Several simulations have been performed in order to analyze the effect of the main variables controlling the cogeneration GT desalination plant on its performance. These main variables include the pressure ratio of the GT, the inlet air temperature entering the compressor, and the maximum temperature at the turbine intake. The results of simulations are expressed in terms of tables and curves giving in particular the exergy destruction rates and the exergy efficiency of each sub-component as well as of the whole cogeneration plant.

In these simulations, the following parameters were maintained constant:

- The temperature of the gas leaving to the stack equals to 150°C.
- The compressor and turbine isentropic efficiencies η_c and η_t are taken equal to 80% and 85%, respectively.
- The cooling seawater temperature and salinity are taken as 25°C and 42 g/kg.
- The feed seawater temperature T_f is fixed to 35°C.
- The motive steam pressure P_m is equal to 250 kPa.
- The dead state properties are as follows:
  - The temperature of the hot source T_H (combustion chamber) is equal to 2,780 K [23]
  - The seawater dead state references are 25°C, 101.3 kPa and 1.55 g/kg.
  - The air dead state references are 25°C and 101.3 kPa.

In the following two Sections 3.1 and 3.2, a configuration coupling GT with thermal desalination units (see Fig. 2) is analyzed while Section 3.3 is devoted to the presentation and analysis of results on the performance of GT with MED–TVC and RO units.

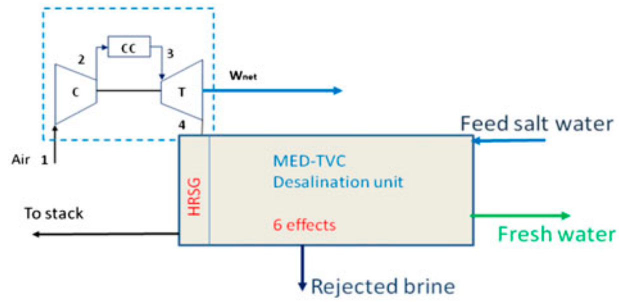

Fig. 2. Schematic diagram for the cogeneration gas turbine and thermal desalination unit.

3.1. Case of a typical GT unit

The following results concern those of thermal desalination unit coupled with a typical GT located at Riyadh.

The parameters related to the desalination part, such as the cooling water temperature and salinity, the motive pressure, and the steam temperature, have the same values as specified previously. The main inputs used in the simulations correspond to real data obtained from the field. They are as follows (see Fig. 2): $T_1 = 25.4$°C; $P_1 = 96.4$ kPa; $T_3 = 1{,}105$°C, $r_p = 10.83$; $T_6 = 150$°C; $m_a = 180$ kg/s; $\eta_c = 84\%$; $\eta_t = 94\%$; where r_p refers to the gas turbine pressure ratio.

The results computed by the program developed in this work using these inputs are given here and discussed. The net power and turbine power produced are $W_{net} = 58.1$ MW and $W_t = 120.64$ MW, respectively. The mass flow rates of produced water M_d, steam required M_s, feed sea water M_f, and cooling water M_{cw} are respectively $M_d = 271.828$ kg/s, $M_s = 34.94$ kg/s, $M_f = 679.57$ kg/s, and $M_{cw} = 1{,}660.3$ kg/s.

Thus, the performance and the recovery ratios of the desalination plant are $PR = M_d/M_s = 7.78$ and $RR = M_d/M_f = 0.4$, respectively. The specific cooling water mass flow rate, M_{cw}/M_d, is 6.11.

Table 1 and Fig. 3 give a summary of the rates of exergy destroyed within each component of the cogeneration plant. The worst situation corresponds to the heat exchanger (combustion chamber) with 45% of the total exergy destruction within the whole plant. The HRSG is the second with 17.422 MW representing 26% of the total exergy destroyed. The entropy generation rates in the desalination plant are about 17.8% of the total exergy destroyed in the system. These rates are due to the heat transfer associated with the

Table 1
Exergy destruction rates for the cogeneration gas turbine/MED-TVC plant

Component	Exergy destruction (kW)	Exergy destruction (kW)	%
Compressor	4,888.8	38,280.6	7
Heat exchanger	30,438		45
Turbine	2,953.8		4
HRSG	17,442	17,442	26
Effect 1	2,439	12,077.8	4
Effect 2	1,652		2
Effect 3	1,417		2
Effect 4	1,169		2
Effect 5	909.8		1
Effect 6	1,321		2
Condenser	2,015		3
TVC	1,155		2
Total	67,800.4	67,800.4	

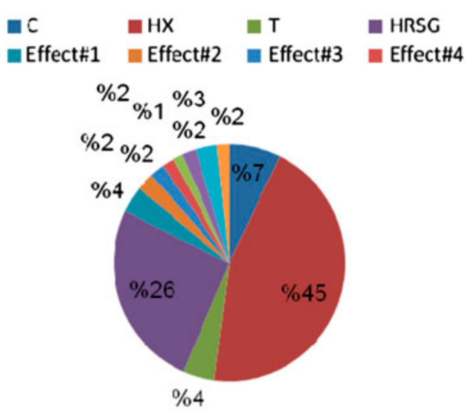

Fig. 3. Distribution of the exergy destruction rates within the cogeneration plant.

temperature differences and phase change heat within each system. The combustion chamber exhibits a large variation of temperature between the source and the working fluid (air). The same case applies for the steam generator where the hot gases with high temperature levels reaching 524˚C at its inlet leave their heat to the steam at lower temperature ($T_s = 80$˚C). The temperature differences in the desalination components are quite smaller.

It is of interest to note that using an overall exergy balance on the whole cogeneration plant, we found a total exergy destruction rates of 70.224 MW. The relative difference between 67.8 and 70.22 MW is 3.57%. This difference which remains small can be attributed to several factors including the evaluations of the fluid properties.

3.2. Sensitivity analysis

In the following section, the influence of the main GT parameters on the exergy efficiency and the overall performance of the cogeneration plant is analyzed and discussed. The main fixed inputs used in the simulations are the following (see Figs. 1 and 2):

$T_6 = 150$˚C, $W_{net} = 50$ MW, $T_s = 80$˚C, Feed salinity = 4.2%, $P_m = 250$ kPa, $T_{cw} = 25$˚C, $T_f = 35$˚C, $\eta_c = 80\%$ and $\eta_t = 0.85\%$.

The effect of the pressure ratio is studied here while the inlet turbine temperature and the maximum temperature are fixed at 25 and 1,000˚C.

Figs. 4 and 5 depict the variation of the various mass flow rates with the pressure ratio of the GT. The distillate mass flow rate, M_d, is high at lower values of the pressure ratio, $r_{p,}$ reaching more than 400 kg/s and decreases slightly as r_p increases. This trend can be attributed to the increase of the power plant efficiency with r_p. Therefore, the energy contained in the exhaust gases is reduced. The air mass flow increases slightly with r_p while the required steam mass flow rate, M_s, is constant. For a fixed pressure ratio, increasing the maximum temperature from 1,000 to 1,200˚C induces a decrease in the distillate mass flow rate, the air mass flow rate, and the steam mass flow

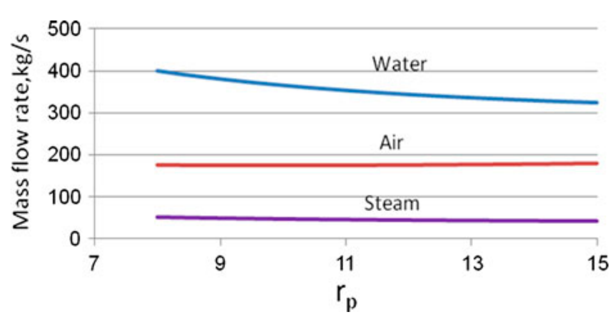

Fig. 4. Effect of the pressure ratio of the gas turbine on the distillate, air, and steam mass flow rates for two values of T_3 = 1,200˚C.

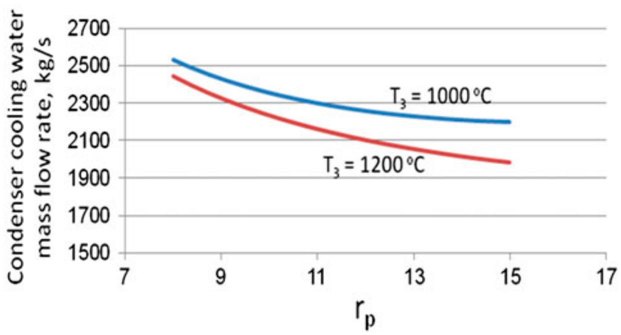

Fig. 5. Effect of the pressure ratio on the condenser cooling water mass flow rate for T_3 = 1,000 and 1,200˚C.

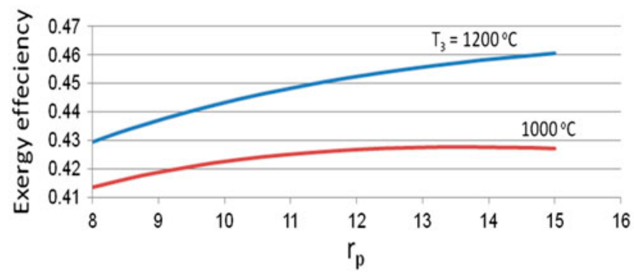

Fig. 7. Effect of the pressure ratio on the exergy efficiency of the cogeneration plant for T_3 = 1,000 and 1,200˚C.

rate. This behavior is also related to the increase of the thermal efficiency of the power plant when the inlet turbine temperature increases, which reduces the amount of energy rejected at turbine exit.

On the other hand, the increase of the r_p for a fixed T_3 reduces the cooling water mass flow. This reduction is seen to be more important for higher values of r_p. The behavior of the cooling water mass flow rate is directly related to that of the distillate mass flow rate.

Regarding the exergy analysis, Fig. 6 presents the variation of the exergy destructions rates with the pressure ratio r_p for T_3 = 1,000˚C and 1,200˚C. These rates include the total available energy destroyed in the whole cogeneration GT and desalination plant. It is shown that the system is more effective at higher T_3 and higher r_p where the entropy generation rates are the lowest approaching 80 MW. For T_3 = 1,000˚C, the total exergy destroyed is almost constant when r_p is higher than 12. The same behaviors on the performance of the cogeneration plant can be observed in the Fig. 7 in which the exergy efficiency variation is shown. A better performance is observed for higher pressure ratio and higher inlet turbine temperature. When r_p changes from 8 to 15, the exergy efficiency increases from 43 to about 46%.

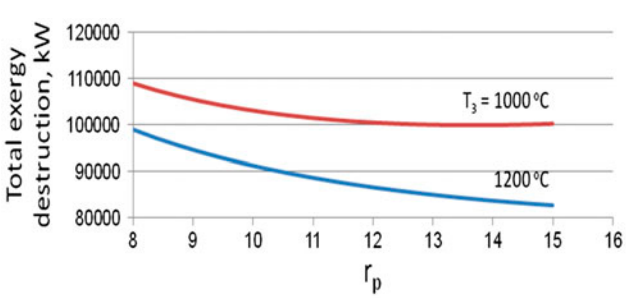

Fig. 6. Effect of the pressure ratio on the total exergy destruction of the cogeneration plant for T_3 = 1,000 and 1,200˚C.

Fig. 8 depicts the distribution of the various mass flow rates with the maximum temperature T_3. It can be seen that the fresh water production rate decreases slightly while the air mass flow rate variation is significant when T_3 increases. The distillate mass flow rate to the air mass flow rate ratio varies approximately from 0.86 to 1.95 when T_3 increases from 800 to 1,200˚C. In addition, the cooling water mass flow rate is reduced from about 2,800 to 2,100 kg/s (Fig. 9).

Fig. 10 depicts the variation of the power output with the distillate mass flow and air flow rates. As the air mass flow rate increases more power is generated and also more distillate is obtained. The power to water ratio is about 7.7. For the specified reference values, the following equations describe the linear variations of the power output with the air and the distillate mass flow rates:

$$W_{net} = 5.09 m_a + 0.0169 \quad (6)$$

$$W_{net} = 7.705 m_d + 0.0014 \quad (7)$$

Thus, the relationship between the air mass low rate and the produced fresh water can be derived as:

$$m_d = 0.661 m_a + 0.002 \quad (8)$$

3.3. General estimations of water production rates using a gas turbine connected to RO and MED-TVC units.

The gas turbine units are in general used in the peak load period. Assuming that this period starts at 10:00 am and ends at 17:00 pm as reported by AlYousef and Abu-Ebid [24]. During this period, the power outlet of the gas turbines should be fully supplied to the grid while the rest of the day, the power

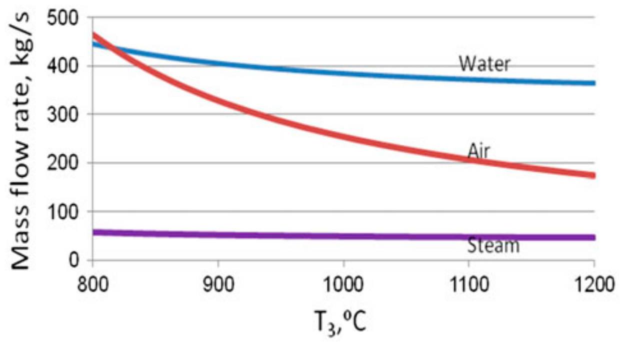

Fig. 8. Effect of the inlet turbine temperature on distillate, steam, and air mass flow rates.

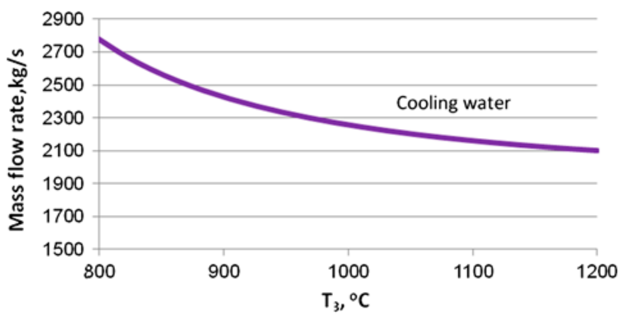

Fig. 9. Effect of the inlet turbine temperature on cooling water mass flow rate.

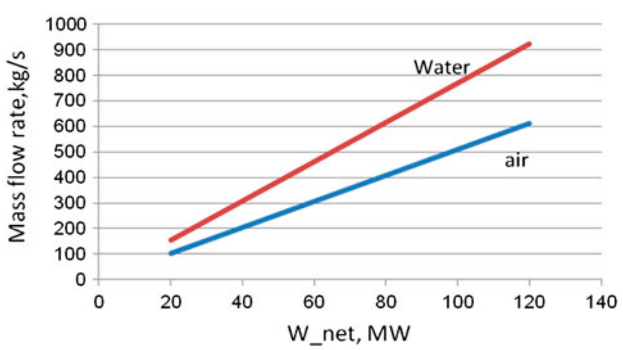

Fig. 10. Variation of the power output with the mass flow rates of air and distillate ($T_1 = 25$°C, $r_p = 10$, $T_3 = 1{,}000$°C, $T_6 = 150$°C, $T_H = 2{,}780$ K, $T_s = 80$°C, $X_f = 4.2\%$, $P_m = 250$ kPa, $T_{cw} = 25$°C, $T_f = 35$°C, $\eta_c = 0.8$, $\eta_t = 0.85$).

units can be partially employed to produce water using reverse osmosis units.

Based on the previous calculations on cogeneration gas turbine and thermal desalination plants as well as on separate calculations performed on RO unit [17], one can notice:

Table 2
Fresh water production rates by the dual purpose and desalination plant (nonpeak period)

α	0.1	0.2	0.5
W_{RO} (kW)	5,000	10,000	25,000
$M_{d\ RO}$ (kg/s)	396.82	793.65	1,984.13
$M_{d\ total}$ (kg/s)	760.75	1,157.5	2,348.10
$M_{d\ total}$ (m^3/d)	55,729	80,015	152,872

- A typical gas turbine unit can produce 363.93 kg/s of fresh water using a thermad desalination unit based on MED-TVC with six effects under the conditions specified previously. The gas turbine power output is fixed at 50 MW and the inlet air temperature is 15°C.
- The specific energy consumed to produce fresh water using RO depends on several factors such as the feed salinity and temperature and the product quality [17]. Consider that 3.5 kWh/m^3 can represent a good estimate of the specific energy required to produce fresh water uisng RO-PES (pressure exchanger system).
- During the nonpeak period, assuming that only a part of the total power generated by the gas turbine is used to produce potable water using RO unit. Let us denote this part by α.

Based on the above assumptions and data, some calculations for the estimations of the production of fresh water were performed for both the peak and nonpeak periods. For the peak period, the production rate of fresh water is found to be 363.93 kg/s or 31,443 m^3/d.

For the nonpeak period, Table 2 summarizes the total production rates for several values of α. It is shown for example $\alpha = 10\%$ (just 10% of the power output is directed to the RO unit while the remaining 90% is connected to the grid), the total fresh water production can be around 55,729 m^3/d.

4. Conclusion

In this paper, results on the performance of combined power and desalination units are presented and analyzed. The power plant consists of a simple gas turbine unit while the desalination plant is composed of a thermal desalination unit based on MED-TVC and a RO with a pressure exchanger system. The modeling is based on the solution of mass, energy, and exergy balances equations for the components of the combined plant. Data corresponding to a typical gas turbine unit located in Riyadh have been used in the simulations. The exergy destruction rates are given for the main systems of the plant. The fresh water production is estimated for several conditions including various pressure ratios and firing temperature values of the gas turbine.

For the combined GT and MED-TVC plant, the major irreversibility losses occur in the combustion chamber and in the HRSG. The exergy destruction rates in the MED-TVC can represent about 18% of the total exergy destroyed in the cogeneration plant. Increasing the pressure ratio of the gas turbine decreases slightly the produced water flow rate and increases the exergy efficiency of the cogeneration plant. The amount of fresh water produced using RO unit during the (nonpeak period) can be considerable.

This work consists of a contribution to know more about the active field of dual purpose power and desalination plants. More efforts are still needed. Examples of studies that could be conducted are deeper analysis using appropriate optimization techniques of the performance of such systems and cost analysis.

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