Thermodynamic evaluation of a combined-cycle power plant with MSF and MED desalination

M. H. Khoshgoftar Manesh, S. Kabiri, M. Yazdi and F. Petrakopoulou

ABSTRACT

Rising water scarcity and abundant brine water resources, especially in desert locations, call for the wider adoption of desalination techniques. Furthermore, the interdependency of water and energy has gained more attention in recent years and it is expected to play an important role in the near future. The present study deals with both topics in that it presents the coupling of a power plant with desalination units for the simultaneous generation of energy and water in Iran. The power plant used in the analysis is the Qom combined-cycle power plant. The plant is integrated, first, with a multi-stage flash (MSF) unit and, then, with a multi-effect desalination (MED) unit, and it is evaluated using energy and exergy analyses. We find that the generated power of the integrated systems is decreased by 9.7% and 8.5% with the MED and the MSF units, respectively. Lastly, the freshwater production in the plant using MED is significantly higher than in the plant with MSF (1,000 versus 1,521 kg/s).

Key words | combined-cycle power plant, exergy analysis, multi-effect desalination, multi-stage flash desalination, water scarcity

NOMENCLATURE

Abbreviations

AC air compressor
CC combustion chamber
e exergy rate per mass (MW/kg)
E exergy (MW)
h specific enthalpy (kJ/kg)
H enthalpy (kJ)
m mass flow rate (kg/s)
p pressure (bar)
s entropy (MW/K)
T temperature (°C)
W shaft work rate (MW)

Greek symbol

η Carnot factor

Subscript

00 without considering capital investment
0 ambient condition
ac air compressor
D destruction
d distillate
dis discharge
e exit
F fuel
GT gas turbine
i inlet
k kth component
L loss
n year
Over the past few decades, due to global warming, growth of population, limitations in fuel and freshwater resources, the demand for power and water has increased. This is particularly true in the Persian Gulf. For this reason, the cogeneration of water and power in combined power and water plants becomes a promising scenario for the future.

Published papers in the literature have studied combined-cycle power plants and presented results of exergy analyses of water plants becomes a promising scenario for the future. Cogeneration and organic cycles, as well as recuperated gas turbines have also been the subjects of relevant studies. (Kehlhofer et al. 2009; Godoy et al. 2010; Ahmadi et al. 2011; Ibrahim & Mohammed 2015; AlRafea et al. 2016; Sabouhi et al. 2016; Sahin et al. 2016; Blumberg et al. 2017; Mohammed et al. 2017; Ng et al. 2017; Ameri & Mohammadzadeh 2018; Calise et al. 2018; Ibrahim et al. 2018; Khan & Tlili 2018; Kotowicz et al. 2018; Martin-Gamboa et al. 2018; Shahzad et al. 2018a, 2018b; Xiang et al. 2018).

Salimi & Amidpour (2017) proposed the developed graphical methodology called R-curve to integrate desalination plants with cogeneration systems. The R-curve tool based on cogeneration efficiency was extended for the coupling of multi-effect desalination (MED) and reverse osmosis (RO) desalination systems with cogeneration units to efficiently reduce the operating cost. Coupling a gas turbine with MED and RO for the region of Bashagard in southern Iran, and the generation of power generation and freshwater production is presented in Rahimi et al. (2017).

Other studies have involved the combination of power plants with solid oxide fuel cells (SOFC) and water generation units. Gholamian et al. (2018) proposed the optimal exergoeconomic design of a hybrid gas turbine–SOFC-MED plant (GT-SOFC-MED) using a genetic algorithm. It was concluded that the simultaneous production of water and electricity reduced the energy consumption and pollution of the power generation cycle (Gholamian et al. 2018). In another study, a plant with a SOFC with a micro-gas turbine was integrated into a MED unit (Hosseini et al. 2013). This study showed that the fuel cell stack pressure had a significant effect on the capacity of the dual-purpose plant and increased the energy efficiency of the cycle. In addition, an increase in the steam pressure resulted in a lower steam mass flow rate and an increased capacity of the desalination unit. Najafi et al. (2014) focused on the optimal integration of a multi-stage flash (MSF) unit with a gas turbine power plant coupled with a SOFC. Their results indicated an optimum exergetic efficiency of about 46.7% and a total annual cost of 3.76 million $/year.

Cogeneration and organic cycles, as well as recuperated gas turbines have also been the subjects of relevant studies. Chacartegui et al. (2009) evaluated the integration of a MED desalination system in a combined-cycle cogeneration plant. Different qualitative and numerical results were obtained from the analysis using the stationary lumped volume method for the combination of the combined cycle with freshwater production. Li et al. (2012) proposed a new combined power and desalination system. The properties of inlet air to the compressor has many effects on the performance of the cycle. Deymi-Dashtebayaz & Kazemiani-Najafabad (2018) focused on analyzing these properties through energy, exergy, economic, and environmental evaluations. Absorption chillers can be used to cool down the inlet air and increase the thermal and exergy efficiency.

In their study, Shahzad et al. (2017) investigated the link between energy and water consumption and environmental protection in water desalination units. The results revealed that energy efficiency can be strongly improved by using water desalination technology and that the environment could be protected by keeping the temperature of the brine discharged to the environment constant. The simultaneous use of RO water desalination units and evaporation-based desalination can greatly reduce energy consumption in a power generation unit. Shahzad et al. (2018a, 2018b) reviewed this triple unit and showed that the lowest reported
energy consumption rate was reached based on the amount of the produced desalinated water. The amount of energy was 1.76 kWh per cubic meter of freshwater production. To obtain better energy consumption, sustainability, and efficiency, it is possible to use the water evaporation method developed by Shahzad et al. (2018a, 2018b). Using a desalination method along with power generation can increase the efficiency of a plant.

Shahzad et al. (2016) attempted to select a suitable water desalination capacity for an electric power unit. Several developments have been made in desalination methods in recent years, particularly in the combination of MED and AD methods (Shahzad et al. 2014; Ng et al. 2015). Ng et al. (2014) showed that adsorption and evaporation were important processes in the desalination of water in thermal methods. These methods had a high temperature during the desalination process. Shahzad et al.'s (2019) proposed approach circumvents the deficiency of derived energy units (kWh), as these energy units omit the quality of the supplied energy. This approach analyzed the amount of energy that has been consumed per each level of desalination production. The specific primary energy (SPE) approach considers meaningful temperature ratios to complete a thermodynamic cycle from the adiabatic flame temperature to the ambient reservoir.

This work investigates the coupling of MED and MSF desalination units with a combined-cycle power plant. These cogeneration plants have been considered to produce power and freshwater. Detailed analyses on the thermodynamic performance of the two cogeneration plants have been realized and the results of exergy analyses are further discussed and evaluated.

**CASE STUDY**

**The reference power plant**

The reference plant examined in this paper is the Qom combined-cycle power plant. The plant consists of four gas turbines and two steam turbines with a total power output of 714 MW. Figure 1 shows a simplified flow diagram of the plant.

Air is introduced into the compressors of the gas turbine package. The air is compressed and sent to the combustion chamber, where combustion takes place with methane. The combustion gases are sent to the expanders of the gas turbines generating power and are then passed to the heat recovery steam generator (HRSG) of the plant. In the HRSG, water is converted to superheated steam that is then directed to the steam turbine of the plant, where additional power is produced. The expanded steam exits the steam turbine and is passed to the air condenser of the plant, where it is condensed. The pressure of the liquid water exiting the condenser is then increased in a pump and is sent to the HRSG to complete the cycle. The compressors consume part of the power produced in the expanders of the gas turbines and the pump consumes part of the power generated by the steam turbine.

**MSF desalination unit**

The Qom reference plant is coupled, first, with an MSF desalination unit. MSF water desalination is a multi-stage evaporation process and it is a very common technology in the Middle East. Heated water is directed to tanks with decreasing pressure, where the water reaches a point of low pressure that causes its sudden evaporation. Figure 2 shows the combined-cycle plant coupled with the MSF desalination unit.

The energy consumption of this desalination method is high and the high operating temperature leads to an increase in sedimentation issues in these devices. Nevertheless, because of its relatively high-capacity operation, this method has a relatively high-water production, when compared to other methods. Since this process operates at low temperature and pressure, it is possible for a desalination plant to use heat from a power plant. This desalination technique is commonly combined with combined-cycle power plants to provide high-volume freshwater (Warsinger et al. 2015). Basic equations used to calculate thermodynamic properties in each stage of the MSF desalination unit can be found in the section ‘Energy analysis of the desalination units’ of the paper (Najafi et al. 2014).

**MED desalination unit**

At present, 5% of the world’s water production capacity uses this technology. A simple flow diagram of the coupled
reference Qom plant with a MED desalination unit is shown in Figure 3.

The process of MED is based on a multi-effect distillation desalting system with steam vaporization. Each distillation unit has several effects and a condenser. Effects are shell-tube transducers with a horizontal arrangement (Warsinger et al. 2015). Water enters the first stage; it is sprayed onto the evaporator pipes in which the initial steam is flowing and part of the evaporative feed water enters the second stage. The initial steam inside the evaporator pipes is also condensed due to loss of heat and it is returned to the boiler. The above process is repeated in all steps of the process, collecting the condensed vapor as freshwater, and further purifying the water (to bring the pH of water to an acceptable level).

The minimum number of steps designed in a MED unit depends on the feeding temperature. Thus, the higher the temperature of the inlet water and the lower the difference between the water and the steam, the less process steps are required. Increasing the number of steps causes an increase in the ratio of freshwater produced to steam consumption, increasing the thermal efficiency of the design.
METHODOLOGY

Energy analysis

In this paper, we study the integration of a reference combined-cycle power plant in Qom (Iran) with MSF and MED units for the simultaneous generation of electricity and water. The coupled plants are then compared to the reference combined-cycle power plant using energy and exergy analyses.

The energy analysis of the plants has been realized with the equations shown below (Bejan et al. 1996).
Compressor:
\[ S_{\text{inlet, air}} = S_{\text{outlet, air}} \]
\[ \eta_{\text{isentropic, compressor}} = \frac{h_{\text{outlet, isentropic}} - h_{\text{inlet}}}{h_{\text{outlet}} - h_{\text{inlet}}} \]
\[ W_{\text{compressor}} = m_{\text{air}} \times [h_{\text{outlet}} - h_{\text{inlet}}] \]

Combustion chamber:
\[ Q_{\text{combustion}} = m_{\text{combustion product}} \times [h_{\text{inlet, gas turbine}} - h_{\text{outlet, gas turbine}}] \]

Gas and steam turbine:
\[ S_{\text{inlet}} = S_{\text{outlet}} \]
\[ \eta_{\text{isentropic, turbine}} = \frac{h_{\text{inlet}} - h_{\text{outlet}}}{h_{\text{inlet}} - h_{\text{outlet, isentropic}}} \]  \hspace{1cm} (6)

\[ W_{\text{turbine}} = \dot{m}_{\text{gas}} \times [h_{\text{inlet}} - h_{\text{outlet}}] \]  \hspace{1cm} (7)

**HRSG:**

\[ \dot{Q}_{\text{HRSG}} = \dot{m}_{\text{stack gas}} \times [h_{\text{inlet, stack gas}} - h_{\text{outlet, stack gas}}] \]  \hspace{1cm} (8)

**Pump:**

\[ S_{\text{inlet}} = S_{\text{outlet}} \]  \hspace{1cm} (9)

\[ \eta_{\text{isentropic, pump}} = \frac{h_{\text{outlet, isentropic}} - h_{\text{inlet}}}{h_{\text{outlet}} - h_{\text{inlet}}} \]  \hspace{1cm} (10)

\[ W_{\text{pump}} = \dot{m}_{\text{water}} \times [h_{\text{inlet}} - h_{\text{outlet}}] \]  \hspace{1cm} (11)

**Condenser:**

\[ \dot{Q}_{\text{condenser}} = \dot{m}_{\text{air}} \times [h_{\text{outlet}} - h_{\text{inlet}}] \]  \hspace{1cm} (12)

**Combined-cycle calculations:**

\[ W_{\text{net, total}} = W_{\text{gas turbine}} + W_{\text{steam turbine}} - W_{\text{compressor}} \]  \hspace{1cm} (13)

\[ \eta_{\text{combined cycle}} = \frac{W_{\text{net, total}}}{Q_{\text{combustion}}} \]  \hspace{1cm} (14)

With the above equation, we can calculate the temperature at each stage:

\[ T_1 = T_{BT} - \Delta T \]

\[ T_{i+1} = T_i - \Delta T \]  \hspace{1cm} (16)

The mass flow rate of desalinated water at each stage can be obtained with the equation below:

\[ \dot{m}_{d,i} = y \times \dot{m}_r \times (1 - y)^{i-1} \]  \hspace{1cm} (17)

where, \( \dot{m}_r \) is the recoverable brine water that comes back to the MSF unit, and the \( y \) parameter is the amount of specific sensible and latent heat and can be obtained with the equation:

\[ y = \frac{c_p \times \Delta T}{\lambda_{\text{av}}} \]  \hspace{1cm} (18)

where, \( c_p \) is the specific heat and \( \lambda_{\text{av}} \) can be calculated with the equation:

\[ \lambda_{\text{av}} = (0.00158927 \times (T^2)) - (2.36418 \times T) + 2500.7 \]  \hspace{1cm} (19)

The salt concentration of the recoverable salt steam (\( x_r \)) is calculated as follows:

\[ x_r = \frac{(x_f - x_b) \times \dot{m}_f + (x_b \times \dot{m}_r)}{\dot{m}_r} \]  \hspace{1cm} (20)

The mass flow rates of the required motive steam (\( \dot{m}_s \)) is obtained as follows:

\[ \dot{m}_s = \dot{m}_r \times c_p \times (T_{BT} - T_{r,1}) \frac{1}{\lambda_{\text{av}}} \]  \hspace{1cm} (21)

The performance ratio of desalination units is very important for comparing different technologies and it is defined as follows:

\[ PR = \frac{\dot{m}_d}{\dot{m}_s} \]  \hspace{1cm} (22)

The next equation is used to calculate the mass flow rate of desalinated water:

\[ \dot{m}_f = \dot{m}_d + \dot{m}_b \]  \hspace{1cm} (23)
where, $m_f$ is mass flow rate of supplied seawater, $m_b$ is mass flow rate of brine discharge and $m_d$ is mass flow rate of desalinated water.

The mass flow rate of brine discharge is then calculated as:

$$m_fX_f = m_bX_b$$  \hspace{1cm} (24)

where, $X_f$ shows the water salinity of the source ($X_f = 0.035$) and $X_b$ shows the salinity of the brine.

The heat transfer and the reversible work in each stage are obtained as follows:

$$\dot{Q} = m_s(h_i - h_{i+1})$$  \hspace{1cm} (25)

$$W = m_s(h_i - h_{i+1}) - T_{ambient}(s_i - s_{i+1})$$  \hspace{1cm} (26)

where, $i$ is the number of the stage.

**Exergy analysis**

Exergy analysis is based on the second law of thermodynamics and enables us to estimate the efficiency of different processes and quantify the exergy destruction within individual plant components. Exergy analysis reveals the location and type of real thermodynamic inefficiencies, an insight that is very useful, especially for the design of new systems.

In all power equipment, all material flows can be divided into two categories: flows that carry energy to the component and can be considered as the fuel of the equipment (exergy of the fuel, $E_{F,k}$), and flows related to the desired output of the process or component, i.e., the exergy of the product ($E_{P,k}$). The difference between these two values corresponds to the exergy destruction in a component $k$:

$$E_{D,k} = E_{F,k} - E_{P,k}$$  \hspace{1cm} (27)

The ratio between the exergy of the product and the fuel of component $k$ is its exergetic efficiency:

$$\varepsilon = \frac{E_{P,k}}{E_{F,k}}$$  \hspace{1cm} (28)
RESULTS AND DISCUSSION

Energy evaluation

The Qom power plant and the desalination units have been simulated using the ThermoFlex software and computer code in MATLAB. The results for the combined-cycle power plant are compared with the real data from the operation of the plant. All thermodynamic output of all simulations of the Qom plant are shown in Table 1. As can be seen, the differences between real plant data and the two simulations with ThermoFlex and the computer code are small. The thermodynamic properties of the combined cycle coupled with the MED and MSF units are shown in Table 2.

Due to the use of steam from the power plant to generate freshwater in the desalination systems, the power production of the integrated systems is decreased relative to standalone operation. This reduction is found to be 9.7% (69.36 MW) in the simulation with the MED system and 8.5% (60.64 MW) in the simulation with the MSF.

Exergy evaluation

The stream exergeries of the combined-cycle plant and the coupled simulations (combined cycle with MED and combined cycle with MSF) are shown in Table 3. By calculating the exergy of each material stream and defining exergy balances for each plant component, the exergy destruction for each component is obtained (Table 4).

From the results shown in Tables 3 and 4, we can conclude that the differences between using MED or MSF are rather small. The exergy destruction in the plant with the MED unit is found to be 5.77 MW lower than in the plant with the MSF unit. We further find that the plant with MSF results in a reduced exergy destruction in the steam turbine and the condenser. The exergy destruction in the compressors, combustion chamber, and expanders is similar.
in all cases. When compared to the reference combined-cycle plant, the exergy destruction of the condenser in the integrated plants has been decreased by 75% and 91% in the MED and MSF integrated cycles, respectively. On the other hand, the total absolute exergy destruction of the plant with MED is found to be less than that of the plant with MSF. The highest exergy destruction is found to be in all cases in the gas turbine of the plants.

### Comparison with published studies

In a similar work by Hanafi et al. (2015), a few specific parameters such as turbine efficiency, desalination efficiency, and desalination rates are investigated using...
various graphs under various design conditions. However, in the presented analysis here, all the thermodynamic properties of the cycle are obtained at various points along with the water desalination system using coding and simulation.

Almutairi et al. (2016) focused on a MED integrated with a combined cycle, and analyzed this cycle using energy and exergy analyses. The exergy efficiency of this unit has been obtained under different conditions, including the ratio of pressure and number of desalination units and power plant performance. Our work investigates the energy and exergy analyses of the currents, the amount of exergy destruction, and the level of exergy destruction in all of the plant components. Also, this analysis includes the study of the combined cycle with both MED and MSF desalination units.

CONCLUSION

Desalination of seawater is aimed at supplying fresh, potable water for domestic, industrial, and agricultural uses. The process of seawater salt separation requires energy that can be supplied by thermal, mechanical, or electrical energy. The addition of products in power plants can lead to more efficient, reliable, and economical solutions. The cogeneration of energy and water generation in the same facility can play a very important role in the mitigation of water crisis, especially in arid regions. In this work, we simulate and evaluate the coupling of an existing combined-cycle power plant with two desalination units: first, with a multi-stage flash desalination and second, with a multi-effect desalination unit. In order to select the most viable desalination method for the Qom combined-cycle power plant, the system is evaluated using exergy analysis. We find that the generated power of the integrated systems is decreased by 9.7% and 8.5% with the MED and the MSF units, respectively. The results show that the exergy destruction of the multi-effect and multi-stage flash desalination units are 30.75 MW and 36.52 MW, respectively. The total exergy destruction of the combined-cycle power plant integrated with the multi-stage flash desalination is found to be higher than that of the combined cycle with the multi-effect desalination unit.

ACKNOWLEDGEMENTS

Fontina Petrakopoulou would like to thank the Universidad Carlos III de Madrid and the Ministerio de Economía, Industria y Competitividad (Ramón y Cajal Programme RYC-2016-20971) for their financial support of this study.

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First received 24 March 2019; accepted in revised form 7 October 2019. Available online 28 February 2020.