Open Access
Volume 3 Issue 1
Review Article

Journal of Physics and Chemistry Research
ISSN: 2582-3361

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Thermo-Economic Analysis of Gas Turbine Combined With Inverse Gas Turbine Integrated With Multi Effect Desalination (MED) Plant

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Article Info

Article History:
Received: 05 April 2021
Accepted: 09 April 2021
Published: 12 April 2021

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Abstract

Limited access to freshwater with an increased demand for water and power has raised concerns about energy and water production advancements. Multi-effect desalination (MED) integrated with a suitable power cycle is highly desirable for waste heat recovery this paper examines a thermodynamic model for a gas turbine combined with an inverse gas turbine integrated with MED. The gas turbine's exhaust gas heat is used as a heat source in a heat exchanger to preheat the seawater, furthermore, the desalination plant's pumps consume part of the power generated by the gas turbine. In this work, we calculate the cycle performance with a variety of ambient temperatures using the IPSEpro software. The results showed significant improvement when using the combined cycle over the simple cycle, we also found that the temperature of the exhaust gas from the gas turbine is significantly reduced. By increasing the ambient temperature from 15 to 45 ^{0}C, the multi effect desilation (MED) plant water production has increased from 20,326 cubic meters per day to 21,120 cubic meters per day. Economic analyses of the MED plant integrated with the gas turbine and inverse gas turbine were performed based on the Annualized Cost of System method. This study shows that this integrated system is economical as the electric and steam costs are saved. The price for freshwater has been determined at 0.94 US$ per cubic meter.

Keywords: Multi-effect desalination; Gas turbine; Inverse gas turbine; Cost; Energy; Exergy analyses; IPSEpro

Introduction

Water occupies a large area of the earth, though only a small fraction has a low enough salinity for drinkable and irrigation. The need for power generation and water production led to continuous development in power plants and freshwater production. Many studies have performed new modeling of power and desalination systems. Baccioli et al [1]. have illustrated the thermodynamic and economic analysis of integrating the Organic Rankine cycle and multi-effect desalination with a waste-heat recovery system to produce electricity and distillate water at two different configurations, they were carried out by at steady-state conditions. The work aimed to define the most viable MED-ORC coupling in a medium temperature waste heat recovery.

A tri-generation system based on organic Rankine cycle, multi-effect desalination, and absorption cooling have been evaluated by Maraver et al [2], they showed that restricting the use of waste heat for multi-effect desalination and cooling.

Al-Zahrani et al [3]. have theoretically studied a hybrid system consisting of a gas turbine unit and a membrane with a thermal desalination unit. They have proposed a modeling approach for a MED-RO system coupled to a gas turbine cycle by considering energy and exergy efficiencies for different equipment in the integrated cycle. This study also investigated the effects of the gas turbine's main parameters, such as inlet temperature and pressure rate, on freshwater production. They have also evaluated the amount of exergy destruction for the components of the system.

In this work, a dual-purpose plant is designed to reduce the cost of freshwater production. Combined gas and inverse gas turbine integrated with multi-effect desalination plant that converts seawater to high purity water for several uses. Because of exergy destruction in fuel energy conversion in the combustion chamber, a high percentage of fuel energy is discharged to the environment in the form of exhaust gases, furthermore, the thermal energy needed for seawater desalination is intensive and costly, for these reasons, we use the gas turbine's exhaust gas to provide heat input to the desalination plant. This paper presents a Thermo-economic analysis of a combined gas and inverse gas turbine with multi-effect desalination based on energy and exergy analysis. The results showed that the production of freshwater by waste heat has a high economic advantage and is attractive due to reducing the cost of steam and electricity required to operate the pumps. In this study, more 149 MW power output of the gas and inverse gas turbine has been generated.

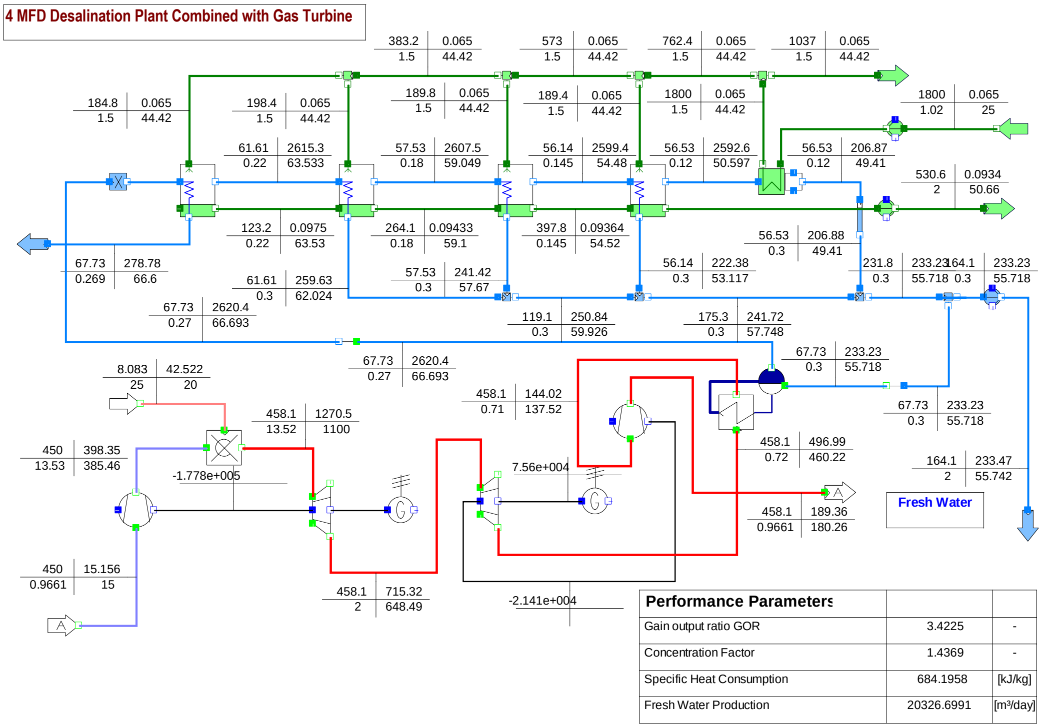
NOMENCLATURE:

Ca	*The cost of the known plant (Reference) ($),*	*GOR*	*Gain Output Ratio,*
$C_{a/y}$	*The annual capital cost ($/ year),*	*h*	*Specific enthalpy (kJ/kg),*
C_b	*is the cost of the new plant ($),*	*i*	*discount rate,*
C_{fix}	*Fixed cost ($/ year),*	*I*	*Irreversibility,*
C_{op}	*Operating cost ($/ year),*	*m*	*mass flow rate (kg/s),*
C_{pa}	*Air specific heat (kJ/kg.K)*	m_a	*Air mass flow rate (kg/s),*
C_W	*The cost of desalinating water ((\$/m^3),*	m_f	*fuel mass flow rate (kg/s),*
f	*The plant capacity scaling factor,*	*n*	*The plant life (number of years),*
R_a	*Air (gas constant) (kJ/kg.K),*	S_{gen}	*Entropy generation (kJ/K),*
S	*Specific Entropy (kJ/kg.K),*	T_o	*Ambient Temperature. (°C),*
S_a	*The capacity of the known plant mgal/ day,*	*TBT*	*Top Brine Temperature (°C),*
S_b	*The capacity of new plant mgal/ day,*	φ	*Excergy (kW).*

System Specification

We examined integrating a simple gas turbine combined with an inverse gas turbine and multi-effect distillation plant (MED). In multi effect plant, each effect is maintained at a decreasing level of pressure and temperature. Each effect has a horizontal tube bundle where the seawater is sprayed in the top of the bundle effect desalination and utilizes gravity to flow downward. Heating Steam is pushed through the tube bundle and cooled and condensed by the seawater introduced; this warms the seawater and partially evaporates it, creating a higher saline solution at the bottom of the effect, or brine. The seawater vapor has a lower temperature than the heating steam, but the vapor can still be used as a heating medium due to pressure changes between effects. The steam condenses via the heat exchanger as the distillate is collected in the last effect, and it has proven itself in large-scale drinking water production [4]. Figure 1 presents a schematic of the 4 effect desalination plant and gas turbine combined with an inverse gas turbine cycle for simultaneous generation of electric power and freshwater.

Figure 1: *4MFD Desalination plant combined with gas turbine.*



Performance Parameters		
Gain output ratio GOR	3.4225	-
Concentration Factor	1.4369	-
Specific Heat Consumption	684.1958	[kJ/kg]
Fresh Water Production	20326.6991	[m³/day]

The power generation cycle includes a compressor, combustion chamber, and gas turbine, also a heat recovery steam boiler is used to produce saturated steam for the distillation unit. The input parameters of the proposed gas engine are demonstrated in Table 1. Figure 1 presents a schematic of a desalination plant which consists of 4 parallel series of effects and a condenser. As shown in figure 1, the process involves heated seawater leaving the condenser at a high temperature after recovering the energy associated with the vapor formed in the last effect then passing it through a series of effects, and it is distributed evenly in all the effects. The brine is collected from every stream and is rejected back to the sea in a common line. The vapor released is condensed and collected as distilled water.

Table 1: *Specifications of the gas turbine and inverse gas turbine cycle.*

Parameter	Value
Ambient air temperature	15 °C
Relative Air humidity	60%
Isentropic efficiency of the compressor	87%
Compression ratio	14
Pressure loss in the combustion chamber	1%
Inlet turbine temp.	1100 °C
Isentropic efficiency of turbines	90%

IPSEpro software is used to analyze the MFD process. This powerful software solve equations and generates much information on system variables and properties. The following analysis is adopted to calculate large-scale MFD systems' main design features, including the brine recycling flow rate, the flow rate of cooling seawater, and the distillate water flow rate, also including the electricity consumption and steam consumption. The governing equations for thermodynamic modeling of the desalination plant are given by [16-22]. Technical characteristics of the proposed MFD desalination plant are listed in Table 2.

Table 2: *MED system specification Design and input data of the MED distillation unit.*

MED	Value
Number of effects	4 Effects
Fresh Water Production	20326.7 m3/day
Specific Heat Consumption	699.35 kJ/kg
Electric Power Consumption	kWh/m3
Gain output ratio GOR	3.3
Inlet seawater salinity (ppm)	45,000
Outlet brine salinity (ppm)	64,700

Thermodynamic Analysis

Exergy analysis is a useful method to evaluate the gas turbine and evaluateing multi-flash desalination (MED) performance to determine the thermodynamics inefficiencies in the system, which are calculated by applying the first and second thermodynamics laws. The exergy method are used for evaluating energy resource utilization in the environment and economics and its use has expanded drastically. The governing equations for various parts of the gas turbine and the MED are illustrated below. The exergy method presents in equation 1

$$Q\left(1-\frac{T_0}{T}\right) - \dot{W} + \sum_{in} m_{in}\, e_{in} - \sum_{out} m_{out} e_{out} = \dot{E_D} \quad (1)$$

Exergy analysis has been used to estimate the energy system performance and system components efficiency by defining the components entropy generation. The exergy analysis also provides the optimal design and operation of complex thermal systems. The exergy and exergy destruction (irreversibility) equations for each component are written as follows:

Compressor

Exergy analysis has been applied to the compressor. Flow exergy is a thermodynamic property that measures the maximum work extracted from a flow at equilibrium with the reference state. The exergy and irreversibility in the compressor are given by

$$\varphi = m_a * (h_1 - h_2) - T_\circ m_a (S_1 - S_2) \quad (2)$$

$$I_c = T_\circ m_a (S_1 - S_2) \quad (3)$$

Where

$$s_1 - s_2 = c_{pa} \ln\frac{T_2}{T_1} - R_a \ln\frac{P_2}{P_1} \text{ and } R_a = C_{pa}\frac{(\gamma-1)}{\gamma} \quad (4)$$

Combustion Chamber

The purpose of combustion in the gas turbine is to convert chemical energy into thermal energy. It is necessary to have a workable method to calculate the heat available from a combustion process. Exergy can measure the useful work that extracted from the combustion chamber rather than properties such as its internal energy or enthalpy.

The combustion chamber has the major exergy destruction and is given by

$$\varphi_{c.c} = Q_{in} + T_\circ S_{gen} \quad (5)$$

$$I_{c.c} = T_\circ S_{gen} \quad (6)$$

Where,

$$S_{gen} = \left(\dot{m}_a + \dot{m}_f\right)\left(c_p \ln\frac{T_5}{T_4}\right) - \frac{\dot{Q}_{in}}{T_{av}} \quad (7)$$

$$\text{And } T_{av} = \text{average } (T_4, T_5)$$

Turbines

The exergy equation calculates the useful energy in the turbine, which can provide a guidance for optimizing operation and conserving energy. The exergy loss due to irreversibility in the gas turbine is given by

$$\varphi_T = m_a * (h_4 - h_5) - T_\circ m_a (s_4 - s_5) \quad (8)$$

$$I_{GT} = T_\circ m_g (S_5 - S_4) \quad (9)$$

Where

$$s_5 - s_4 = c_{pg} \ln\frac{T_5}{T_4} - R_g \ln\frac{P_5}{P_4} \text{ and } R_g = C_{pa}\frac{(\gamma-1)}{\gamma} \quad (10)$$

Heat Exchanger

The hot fluid transfers the exergy to the cold fluid, but some of the exergy will be destroyed due to the fluid temperature difference. The flow of the fluids along the ducts of the exchanger requires some degree of exergy destruction.

$$\Delta s_{hot} = (s_{hot-ex} - s_{hot-in}) \quad (11)$$

$$\varphi_{hot} = m_{hot} * [(s_{hot-in} - s_{hot-ex}) - T_{\circ}(s_{hot-in} - s_{hot-ex})] \quad (12)$$

$$\varphi_{cold} = m_{cold} * [(s_{cold-ex} - s_{cold-in}) - T_{\circ}(s_{cold-ex} - s_{cold-in})] \quad (13)$$

The main reasons for irreversibility in a heat exchanger are heat transfer between the hot and cold fluids. The energy transfer between the heat exchanger and the surroundings is usually neglected, [5] the exergy loss due to irreversibility in the heat exchanger is given by

$$I_{EX} = T_{\circ} * \Delta\dot{S}_{\circ} = T_{\circ}[m_{hot}(s_6 - s_7) - m_{cold}(s_{ex} - s_{in})] \quad (14)$$

Where,

$$s_7 - s_6 = C_{pg} \ln\frac{T_7}{T_6} - R_g \ln\frac{P_7}{P_6} \quad (15)$$

Energy Balance Equations in the MED Plant:

The specific entropy and enthalpy of a component per kg in an ideal solution at a specified temperature T and pressure P are [6].

$$h = mf_s * h_s + mf_w * h_w \quad (16)$$

$$s = mf_s * s_s + mf_w * s_w \quad (17)$$

The seawater inlet for desalination is given to be at 298 K, 1 atm, and salinity of 0.065%. This condition is assumed to be the conditions of the environment. The specific heat, enthalpy and entropy of the salt at T_0= 298 K is taken to be cp_s= 0.8368 kJ/kg.K, h_{s0}= 20.92 kJ/kg and s_{s0}= 0.0732978 kJ/kg.K. Hence, we can determine the enthalpy and entropy of the salt at the temperature T from the following equation [6].

$$\boldsymbol{h_s} = h_{s0} + cp_s(T - T_0) \quad (18)$$

$$\boldsymbol{s_s} = s_{s0} + cp_s \ln\left[\frac{T}{T_0}\right] \quad (19)$$

Exergy is the maximum useful work obtainable from a system when this reachs equilibrium with the environmental (dead) state. At a steady-state, the total exergy transported into the system equals the system's total exergy. The total specific exergy consists of,

$$\varphi_{total} = \varphi_{th} + \varphi_{ch} + \varphi_{po} + \varphi_{k.e} \quad (20)$$

the E_{ch} , E_{po} , $E_{k.e}$ can be ignored, so the total exergy can be expressed as the exergy inflow and outflow associated with the streams entering and leaving the control volume and is defined in the following equation,

$$\varphi_{total} = \varphi_{th} = m * [(h - h_0) - T_0(s - s_0)] \quad (21)$$

$$I = \varphi_{in} - \varphi_{out} \quad (22)$$

Gained Output Ratio (GOR) is a measure of how much thermal energy is consumed in a desalination process, typically defined as the number of kilograms of distilled water produced per kilogram of steam consumed. Lower values are typical of applications with high availability of low-value thermal energy [7].

$$GOR = \frac{desalate\ flow\ rate}{steam\ flow\ rate} \quad (23)$$

Economic Analysis of MED Plant

We should consider the two objective functions where the water production should be increased while simultaneously the total cost should be minimized to optimize the desalination plant. For this purpose, the economic analysis of the MED distillation driven by exhaust gases from gas turbines has been examined in this work. The capital, operating, and maintenance costs must be considered to perform the cost analysis. For conventional MED distillation plants, the capital cost is approximated based on the cost function illustrated in table 3 [8,9]. Annual operating and maintenance expenses were assumed to consist of electrical, labor and chemical costs. The economic analysis is performed based on relations that are listed in Table 4. Amortization factor (i) accounts for annual interest payments for direct costs, and n is the plant life (in years). Table 3 summarizes the plant and operating cost formulas used for each process in addition to the water production cost.

Table 3: *Equations of the economic model for the MED process [8,9].*

Direct capital cost $	DC = 3018.8 *ψ^ 0.9795
Amortization factor, 1/y	A_f = (i* $(1+i)^n$)/ ($(1+i)^n$ -1)
Annual fixed charges, $/y	AFC =Af * DC
Annual heating steam costs, $/y	AHSC =(SHC *λ *LF *Md *365)/(1000*GOR)
Annual electric power cost, $/y	AEPC = SEC * SPC* LF* Md * 365
Annual chemical cost, $/y	ACC = SCC* LF* Md* 365
Annual labor cost, $/y	ALC = SLC *LF * Md* 365
The total annual cost, $/y	TAC_{MED}= AFC + AHSC+ AEPC + ACC+ ALC
Operating and maintenance costs, $	OMC_{MED} = 0:02 * DC
Hourly operating & maintenance cost in $/h	$Z^{ICOM\ MEX-VC}$ =(OMC_{MED}* Af + AFC) /8760
The water product cost, $/m³	TAC_{MED} /(f * m * 365)
The unit product cost $/m3/day.	TAC_{MED} / m

Table 4: *Parameters used in the economic model of MED.*

Parameter	Value
ψ is the total production rate	20326.7 m³/day
Interest rate	5%
SHC Specific heating steam cost	1:466 $/MJ
SEC Specific electric steam cost	0:06 $/kWh
SCC Specific chemical cost	0:025 $/m3
SLC Specific labor cost	0:025 $/m3

Results and Discussion

In this paper, the MED desalination plant model integrated with a gas and inverse gas turbine cycle is studied with detailed cost analysis for the multi effect deslination processes to estimate the freshwater cost. IPSEpro software has been used to analyze the present model. The cost evaluation of the multi effect distillation (MED) analysis was obtained and shown in table 5.

Table 5: *Summary of annual cost data of the MSF process.*

Direct capital cost $	50,070,951.90
Electric Power $/y	164543.022
Steam $/y	2055856.405
Chemicals $/y	166933.0238
Operating Labor $/y	667732.095
product cost $/m³	0.945327006

Figures 2 and 3 show an improvement in the combined gas turbine and inverse gas turbine cycle performance, where the power output and efficiency both increase by 4 % and both decrease as the ambient temperature increases.

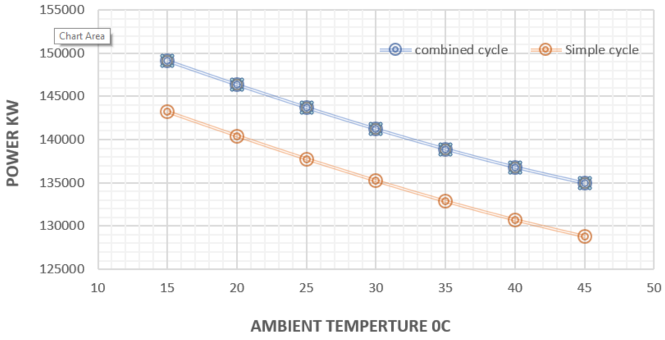


Figure 2: *Power Output as a function of Ambient Temperature.*

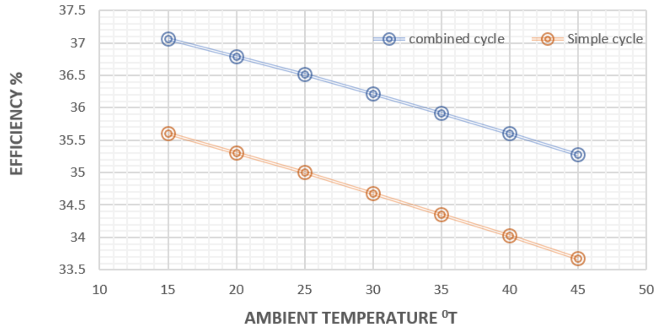


Figure 3: *Efficiency as a function of Ambient Temperature.*

The energy destruction rate for gas turbine equipment generated in the energy conversion processes, including the compressor, combustion chamber, and turbine is shown in Figure. 4. It is observed that the combustion chamber has the highest value of the energy destruction out of all the other components of the gas turbine.

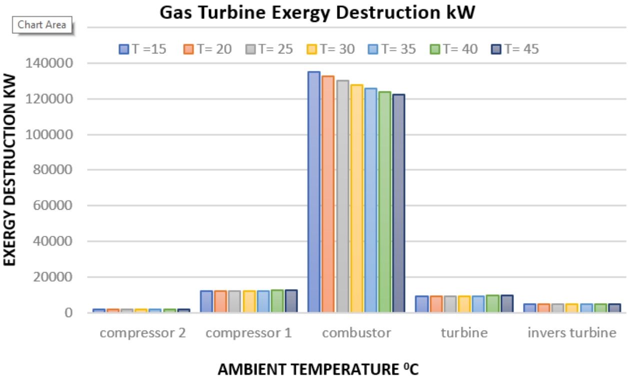


Figure 4: *Exergy Destruction in the Gas Turbine combined with inverse turbine Components.*

Exergy destruction of the MED plant versus ambient temperature is shown in Figure 5. The exergy destruction increases due to an increase in the ambient temperature, furthermore, with the rise in the seawater condenser's different temperatures, the exergy destruction increase.

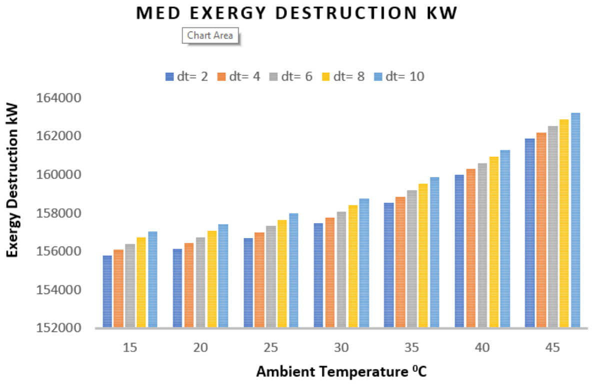


Figure 5: *Exergy Destruction in Multi Effect Deselanation Plant.*

Figure 6 shows the variation of gas turbine exhaust gases temperature versus the ambient temperature (15-45^{0}C). It shows a significant improvement using the combined gas turbine and inverse gas turbine cycle, where the exhaust temperature is reduced by 65 %.

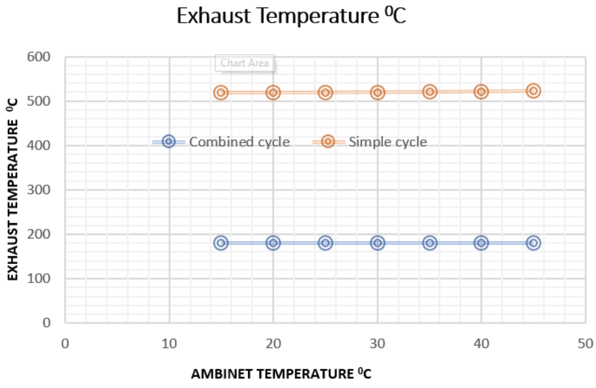


Figure 6: *Exhaust Temperature versus Ambient Temperature.*

The freshwater production increases from 20,326.5 m^3/day to 21,121.9 m^3/day when the ambient temperature rises, as shown in figure 7.

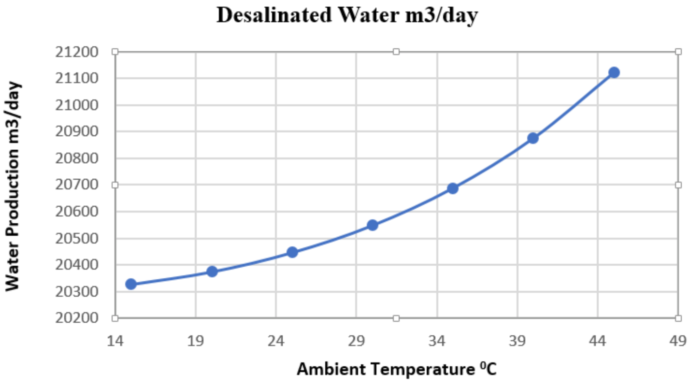


Figure 7: *Deslanted water production with the Ambient temperature.*

Figures 8 and 9 show a linear relationship between the freshwater production with cooling stream different temperature in the first effect and inlet seawater salinity. Both figures show a minor drop in freshwater production as the different temperatures and water salinity increases.

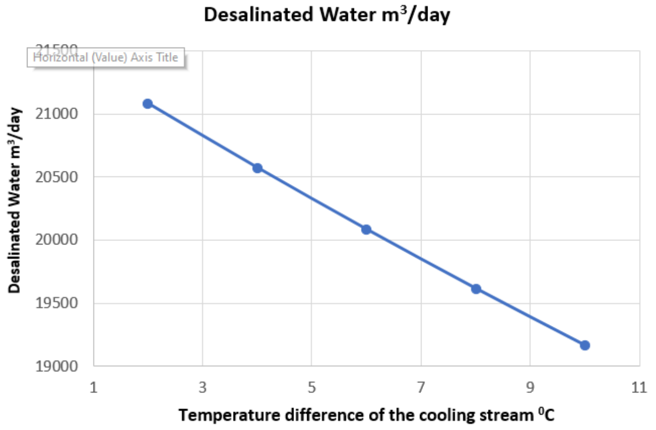


Figure 8: *Desalinted Water production with ΔT.*

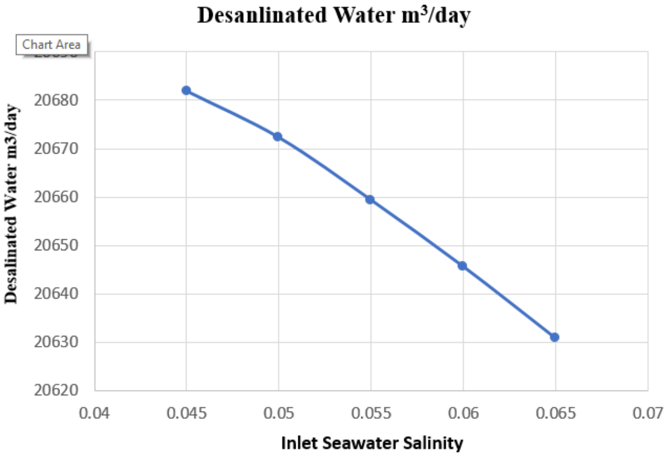


Figure 9: *Desalinted Water Production with Seawater Salinity.*

The following figure demonstrates the desalinated water cost $/m3 with the MED capacity. As shown in the figure, when the plant freshwater production increases, the cost of the desalinated water decreases.

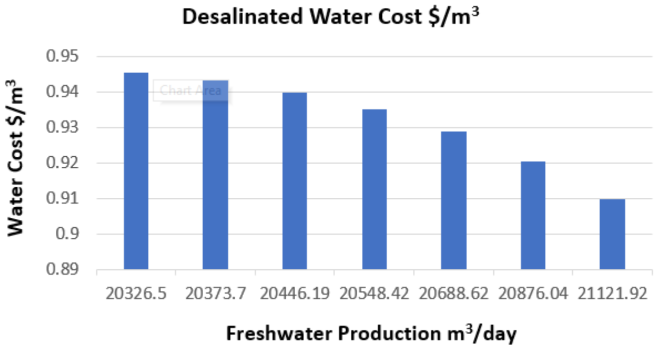


Figure 10: *Freshwater Cost versus the Plant Capacity.*

Conclusion

In the present study, we perform a thermo-economic evaluation of a MED integrated with the gas and inverse gas turbine to obtain a model of power produced and waste heat utilized to prduce freshwater. The waste heat of the gas and inverse gas turbine cycle is used in the first effect stage as a heat source for the desalination unit. The exergy analysis is applied to the gas turbine components and MED plant to give a performance evaluation and enhance understanding of the system behavior. In this study the integrated system was used for desalinated water production and power generation.

The annualized cost method is used cost is used to study the economic feasibility of the desalination system. The results demonstrated that this integration will increase the system's feasibility. The results show;

- An improvement in the combined cycle (gas turbine and inverse gas turbine) efficiency and power output.
- The exhaust temperature was reduced by 65% by using the combined cycle (gas turbine and inverse gas turbine).
- The increase in ambient temperature iincreases the desalinated water production.
- The cost of the desalinated water decreases as the plant capacity increases.

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