Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 44 No. 7
July 2023

Simulating the Combined-Cycle Model of Chabahar Port under ISO and Ambient Temperature Conditions with an Inlet Cooling System

Mohammad Bagher Karimi Shavaki[1], Seyed Amin Hosseini[2]*
[1] Mechanical Engineering Department Chabahar Maritime University,
P.O. Box 99717-56499, Chabahar, Iran
[2] Mechanical Engineering Department Chabahar Maritime University,
P.O. Box 99717-56499, Chabahar, Iran

Abstract- At first, the Chabahar combined cycle power plant was modeled in the GT PRO module of the Thermoflow software package at an ambient temperature of 15 degrees and 40 degrees, and its energy and exergy were investigated and analyzed. Subsequently, a multi-effect thermal water desalination system was coupled with the power plant at an ambient temperature of 40 degrees and its effectiveness was analyzed. The analyzes carried out in the field of energy showed that under all the modeled conditions, the most thermal energy loss among the components of the Chabahar power plant cycle occurs in the condenser and the chimney outlet, respectively, and is transferred to the environment.

Keywords- thermal water desalination, combined-cycle power plant, simulation.

Introduction

In recent years, the use of gas turbines as a reliable tool in the field of power generation has increased greatly [1]. Their design is based on optimization concepts and energy-saving principles. The sustainable supply of fresh water for the southern and port areas of Iran, such as Chabahar, has long been considered one of the critical challenges due to the climatic conditions and special commercial situations. Combining desalination technologies with power plant cycles is a special solution to solve the water shortage in these areas [2]. Each desalination method has its advantages and disadvantages. During the past years, extensive research has been done on the types of desalination systems, connecting types of water desalination with combined-cycle power plants in dual systems to produce power and water [3,4]. Most of these studies are focused on connecting thermal water desalination systems to combined-cycle power plants [5]. At the same time, few studies have been conducted in the field of using solar energy in water-desalination systems of combined-cycle power plants. Shakib and his colleagues in 2012, in the field of thermoeconomic analysis and optimization using exploratory algorithm, genetics and particle swarm for a dual and simultaneous simulated system with the aim of producing power and water and using recovery boiler for single and multi-objective approaches [6]. Esmaili et al., in 2013, conducted research in the field of energy and exergy analysis of a combined cycle power plant integrated with a multi-stage evaporative water softener with the aim of producing power and water. They modeled the use of the heat recovery boiler as an energy source for the water softener system in the power plant and separately examined parameters such as functional pressure levels, gas temperature entering the boiler, screw temperatures for the pressure level that affect the total exergy efficiency, power generation rate and the amount of fresh water produced was effective. The results of their research and investigation in the field of functional pressure levels showed that the output power of the steam turbine increases with the increase of the high-pressure steam pressure at first and after a maximum point, it decreases due to the difference in the production rate of high-pressure and low-pressure steam in the recovery boiler. And on the other hand, with the reduction of the steam pressure at the low-pressure level, the turbine power increases due to the increase in the specific enthalpy of the fluid, which is associated with the decrease in the saturation temperature in the low-pressure part of the recovery boiler [7]. Aliyar and Baghernejad analyzed the energy and exergy of the equipment of a thermal water desalination system in the Qom combined-cycle power plant and studied several parameters such as motive steam pressure, number of stages, energy and exergy efficiency, a simultaneous production rate of power and fresh water [8]. The motive steam energy received from the turbine's lower part is higher at high pressures. It also leads to an increase in the amount of freshwater produced at the same flow rate. However, increasing the pressure of the motive steam leads to a decrease in the power of the power plant. Therefore, the use of motive steam at the right temperature and pressure will lead to the production of an optimal amount of fresh water. Mehrpouya et al. developed an integrated structure for simultaneous and multiple production systems using solar collectors in the field of power generation, fresh water, and annealing [9]. Ghorbani et al. simulated and developed an integrated structure for simultaneous and multiple production systems using solar collectors to produce power, heat, and freshwater through the integration of multi-stage desalination and Kalina's power generation cycle under special weather conditions of Asalouye [10]. This study deals with the simulation of the combined-cycle model of Chabahar in ISO and ambient temperature conditions coupled with an inlet cooling system.

Governing equations

In the study of thermal systems, energy balance is similar to exergy. Energy balance and exergy balance represent energy conservation and energy quality or deviation of the system from the equilibrium state, respectively.

The balance of energy and exergy in a stable state is expressed in the form of the following relations [11].

$$\sum \dot{m}_\imath = \sum \dot{m}_e \qquad (1)$$

$$\dot{Q} + \sum \dot{m}_\imath h_i = \dot{W} + \sum \dot{m}_e h_e \qquad (2)$$

where $\dot{W}$, $\dot{Q}$, $\dot{m}$, and h are work exchange rate, heat transfer rate, mass flow rate, and specific enthalpy, respectively. Also, *i* and *e* reflect the input and output flows of the control volume, respectively.

$$\dot{E}_Q + \sum \dot{m}_\imath h_i = \dot{E}_W + \sum \dot{m}_e h_e + \dot{E}_D \qquad (3)$$

where the subscripts *i* and *e* are the input and output flows, respectively, h represents enthalpy, $\dot{E_Q}$ is exergy due to heat transfer, $\dot{E}_W$ is exergy due to doing work, and $\dot{E_D}$ indicates exergy destruction.

Energy and exergy equations for different parts of the power plant are represented separately [12].

The equation of the production power of the air compressor is compiled as follows.

$$w_C = \dot{m}_1 c_p (T_2 - T_1) \qquad (4)$$

The equation of gas turbine production power rate is expressed as follows.

$$\dot{W}_{GT} = \dot{m}_a (h_{out} - h_{in}) \qquad (5)$$

The network output of the entire gas turbine cycle is expressed as follows.

$$\dot{W}_{NET} = \dot{W}_{GT} + \dot{W}_{AC} \qquad (6)$$

The equation of steam turbine production power is represented as follows.

$$w_{ST} = m_{ST}(h_{in} - h_{out}) \qquad (7)$$

The equation of the steam flow rate entering the steam turbine is expressed as follows.

$$\dot{m_{tur}} = a \times \dot{m}_{LP} + \dot{m}_{HP} \qquad (8)$$

where, $\dot{m}$ is the steam flow rate in kilograms per second, a is the ratio of the steam flow taken from the boiler, the subscripts tur, LP, and HP indicate the input to the steam turbine, the input to the low-pressure part of the turbine, and the input to the high-pressure part of the turbine, respectively.

The working rate of the steam turbine is expressed as follows [11]

$$\dot{W}_{tur} = \dot{m}_{LP} h_{s.i.L} + \dot{m}_{HP} h_{s.i.H} - \dot{m}_t h_{s.o.a} \qquad (9)$$

where $\dot{W}$ is the work rate in kilowatts, h is the enthalpy in kilojoules per kilogram, $\dot{m}$ is the steam flow rate in kilograms per second, and the subscripts t, s.i.L, s.i.H, and s.o.a represent the whole turbine, the inlet of the low-pressure part of the turbine, and the inlet of the high-pressure part of the turbine, and the actual output of the turbine, respectively.

Subsequently, the heat transfer balance performed in the condenser is calculated based on the following equation.

$$\dot{m_{tur}}(h_{s.o.a} - h_{w.i}) = \dot{m}_c (h_{c.o} - h_{c.i}) \qquad (10)$$

where $\dot{m}$ is the output steam flow rate from the turbine, h is the enthalpy, and the subscripts tur, s.o.a, w.i, c.o, and c.i respectively indicate the turbine input, the actual output of the turbine, input to the pump, condenser water, output, and the input to the condenser.

Thermal multi-effect desalination (MED)

The temperature difference of the adjacent stages in the water desalination system is the same and can be calculated based on the following equation.

$$\Delta T = T_1 - T_2 = T_2 - T_3 = \cdots = T_{n-1} - T_n \qquad (11)$$

If the temperature of the first and last stages of water desalination is indicated by T_s and T_n respectively, the temperature difference is obtained using the following equation.

$$\Delta T = \frac{T_s - T_n}{n - 1} \qquad (12)$$

The temperature of the steam produced in the first stage is lower than the boiling and evaporation temperature of the water. On the other hand, the temperature of the resulting effluent in each stage is higher than the temperature of the saturated steam due to the presence of undissolved salts. This parameter is called boiling point elevation (BPE) and it is obtained based on the relation of El-Dessouky [13].

$$\mathrm{BPE} = \mathrm{X}_b \times [\mathrm{B} + (\mathrm{C} \times \mathrm{X}_b)] \times 10^{-3} \qquad (13)$$

The relation of calculating the amount of freshwater produced (total water produced in each stage) is expressed as follows.

$$M_d = \sum_{i=1}^{n} D_i \qquad (14)$$

The relation of calculating the performance coefficient or the efficiency ratio of the thermal water desalination system (the mass flow rate of produced fresh water to the mass flow rate of steam entering the system) is expressed as follows.

$$GOR = \frac{M_d}{M_m} \quad (15)$$

where GOR is the performance coefficient of the system, M_d represents the produced freshwater flow rate, and M_m is the steam flow rate entering the thermocompressor.

The equation of the steam ejector absorption ratio is represented below.

$$Ra = 0.235 \frac{P_s^{1/19}}{P_{ev}^{1/04}} \left(\frac{P_m}{P_{ev}}\right)^{1/05} \quad (16)$$

The suction steam by the ejector is represented by the following relation.

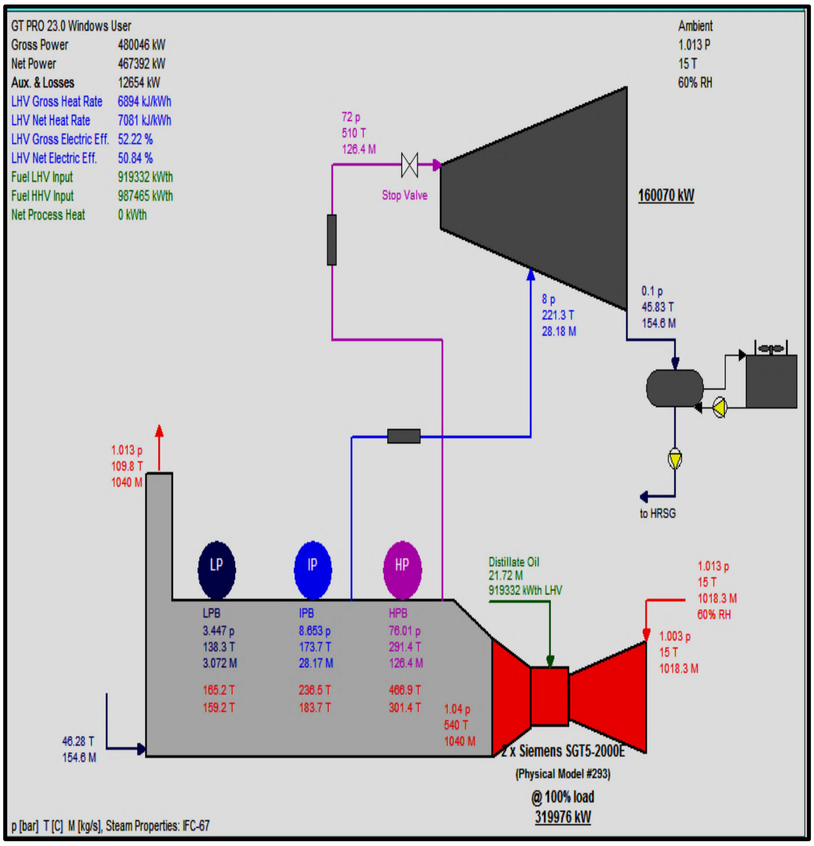
$$D_{ev} = \frac{D_m}{Ra} \quad (17)$$

Results

- **Modeling of Chabahar combined-cycle power plant at an ambient temperature of 15 degrees**

Chabahar power plant was modeled considering the conditions of power plant design, i.e., ambient temperature of 15 degrees Celsius, rated capacity of 480 MW, sea level height, and humidity of 60%.

In the research literature, the efficiency of a power plant is measured based on the high heating value (HHV) or low heating value (LHV) of the fuel and the total power or net output of the power plant. The power plant was modeled with defined conditions, the output of which is shown in Figure 1. In this situation, the rated power of the power plant is 480 MW, and the net power is about 467 MW. Also, its efficiency has been calculated based on the net output power and low heating value of the fuel, which is approximately equal to 50.84%.



```
GT PRO 23.0 Windows User
Gross Power              480046 kW
Net Power                467392 kW
Aux. & Losses            12654 kW
LHV Gross Heat Rate      6894 kJ/kWh
LHV Net Heat Rate        7081 kJ/kWh
LHV Gross Electric Eff.  52.22 %
LHV Net Electric Eff.    50.84 %
Fuel LHV Input           919332 kWth
Fuel HHV Input           987465 kWth
Net Process Heat         0 kWth
```

Figure 1: The output of the simulated power plant model at an ambient temperature of 15 degrees Celsius

Energy distribution in different parts of the power plant is shown in Figure 2. The highest thermal energy loss occurs in the condenser of the power plant and is approximately equal to 322973 KW. The wasted energy is 31.61% of the total input energy transferred to the environment by the condenser cooling tower. The highest output is related to the chimney, which is approximately equal to 19.97% of the total energy input to the system. In total, 45.75% of the total input energy is converted into net output power.

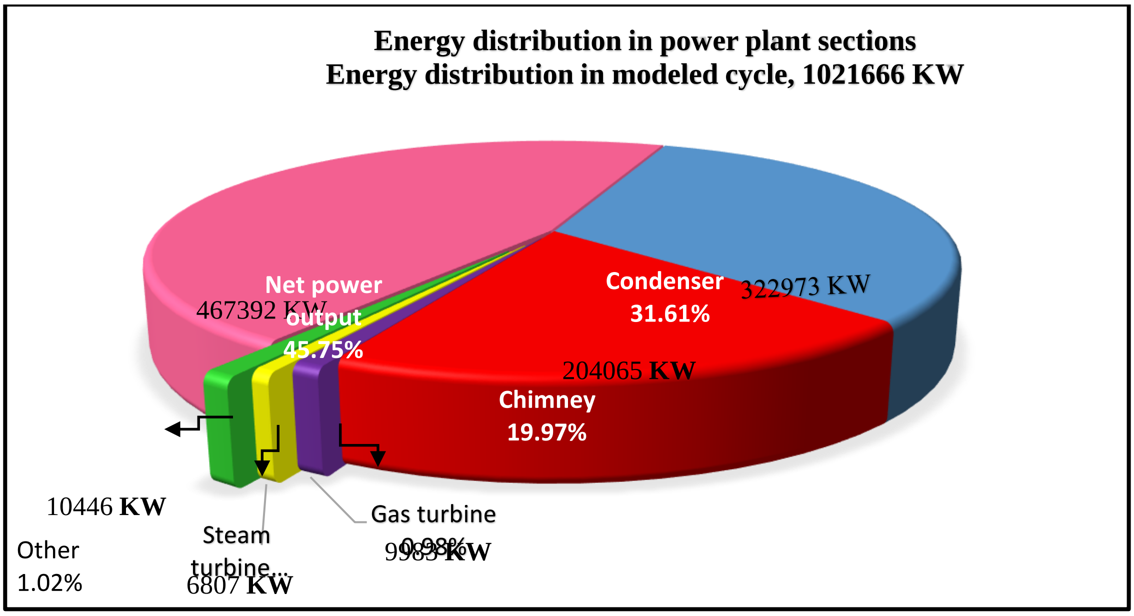
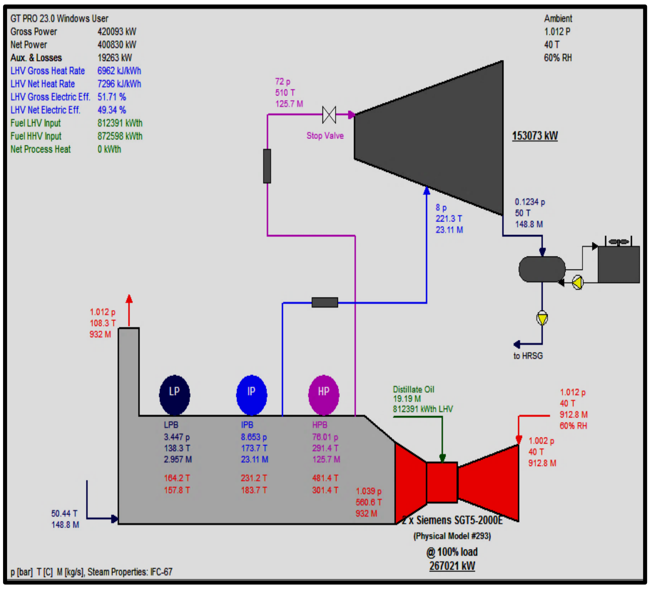


Figure 2: Energy balance and distribution in the modeled power plant at an ambient temperature of 15 degrees Celsius

Modeling of Chabahar combined-cycle power plant at an ambient temperature of 40 degrees

One of the factors influencing the operation of power plants is the temperature of the air entering the compressor. The lower the air temperature, the higher the flow rate of the incoming air and the lower the power consumption of the compressor. As a result, the efficiency and power of the power plant improves. However, in hot areas, the efficiency and power of the power plant decrease and have a negative effect on the compression ratio and compressor pressure.

Modeling has been achieved at an average temperature of 40 degrees Celsius (for the hot seasons of the year in Chabahar), an altitude of 7 meters above sea level, and a humidity of 60%, according to Figure 3. The power plant has been modeled at an ambient temperature of 40 degrees Celsius for Chabahar and the following results have been obtained. Due to the increase in the ambient temperature, the flow rate of the incoming air to the compressor has decreased and reached 456 kg/s from 509 at a temperature of 15 degrees. Also, the total power and net power of the power plant have decreased to 420 and 400 MW, respectively. The efficiency based on net output power and low heating value of the fuel is almost equal to 49.34%.



GT PRO 23.0 Windows User

Gross Power	420093 kW
Net Power	400830 kW
Aux. & Losses	19263 kW
LHV Gross Heat Rate	6962 kJ/kWh
LHV Net Heat Rate	7296 kJ/kWh
LHV Gross Electric Eff.	51.71 %
LHV Net Electric Eff.	49.34 %
Fuel LHV Input	812391 kWth
Fuel HHV Input	872598 kWth
Net Process Heat	0 kWth

Ambient
1.012 P
40 T
60% RH

Figure 3: The output of the simulated model of the power plant at an ambient temperature of 40 degrees Celsius

The energy obtained from the fuel along with the energy of the ambient air and its distribution in different parts of the power plant at an ambient temperature of 40 degrees Celsius have been modeled and represented in Figure 4. The highest thermal energy loss occurred in the condenser of the power plant, which is approximately equal to 311,381 KW and constitutes 31.92% of the total input energy. This fraction of the wasted energy is transferred to the environment by the cooling tower of the condenser. The highest output is related to the chimney, which is approximately equal to 23.69% of the total energy input to the system. In total, 41.08% of the total input energy is converted into net output power.

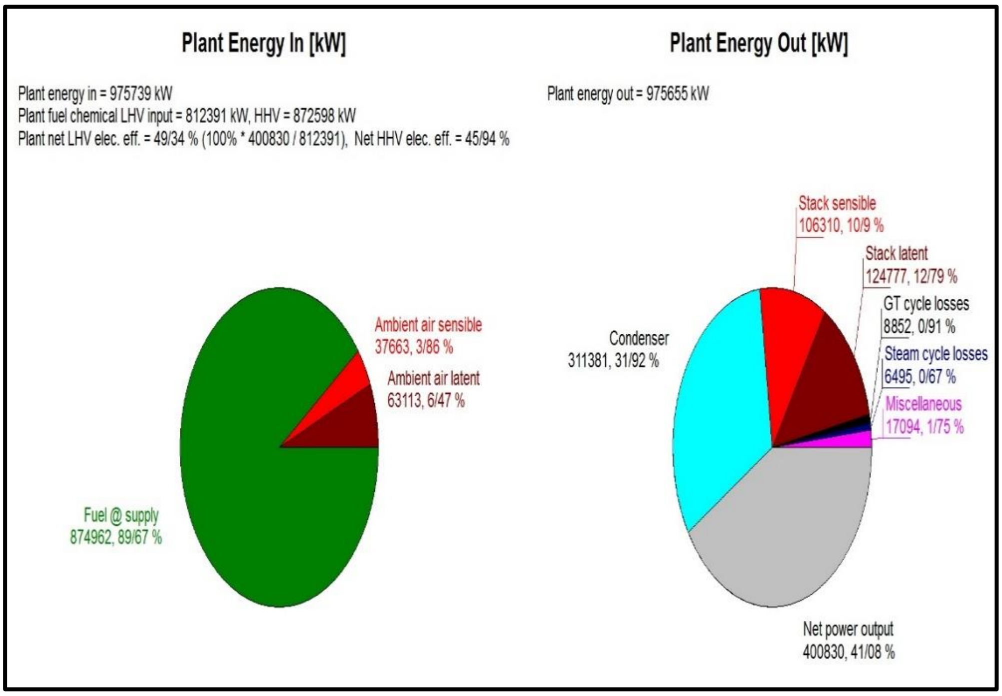


Figure 4: Energy input, balance, and its distribution in the modeled power plant at an ambient temperature of 40 degrees Celsius

The results of simulated models of the Chabahar power plant in different design conditions

Chabahar combined-cycle power plant was simulated in two different designs at ambient temperatures of 15 and 40 degrees Celsius. The results are represented and compared in Table 1.

Table 1: Comparison of the results of simulated models of the Chabahar power plant in different design conditions

Parameter	Ambient temperature of 15 degrees	Ambient temperature of 40 degrees
The total power of the power plant	480 MW	420 MW
Net power of the power plant	467 MW	400 MW
Output power of a gas turbine	159.9 MW	133.5 MW
Steam turbine output power	160 MW	153 MW
Power plant efficiency based on low heating value of fuel	60.84 %	49.34 %
Net heat rate	7081 kj/kwh	7296 kj/kwh
Energy efficiency	45.75 %	41.08 %
Exergy efficiency	48.89 %	44.7 %

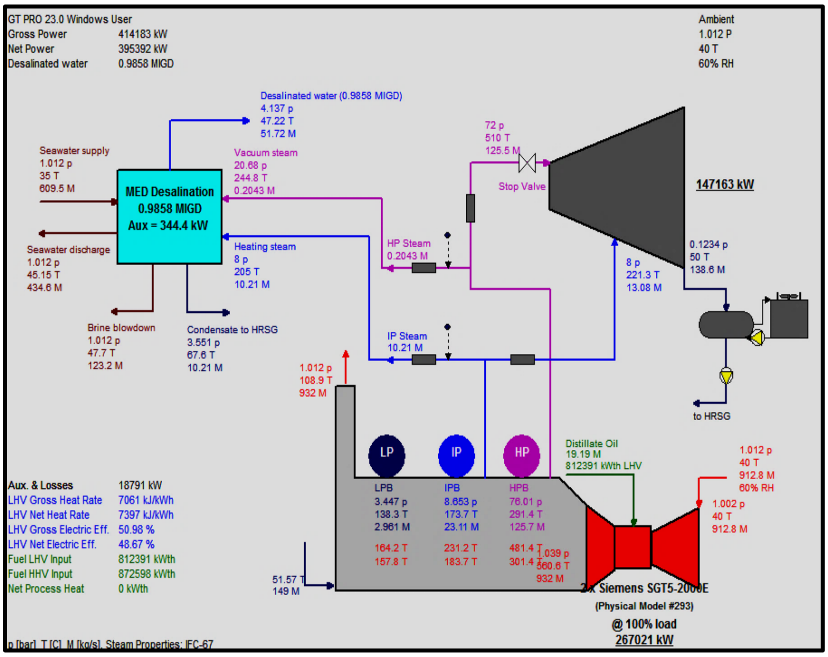
Modeling the integration of the MED desalination system with the Chabahar combined-cycle power plant

In this section, a MED water desalination system of parallel feeding type including 2 main condenser sections of several evaporators has been integrated and simulated with the Chabahar combined-cycle power plant at an ambient temperature of 40 degrees. The steam needed for this system is taken from the flow rate of the low-pressure feed line of the steam turbine. The considered parameters for the water desalination system are inspired by the data of the thermal water desalination of Qeshm Island as the only thermal water desalination system in the country, which are listed in Table 2. These parameters have been used in modeling considering the environmental conditions of Chabahar.

Table 2: Parameters considered for modeling and integration of thermal water desalination with power plant

Parameter	Value	Unit of measurement
The temperature of the seawater entering the condenser	35	C˚
Steam source for heating	Low-pressure feed line of steam turbine	-
Steam source to create a vacuum	High-pressure feed line of steam turbine	-
Heating steam temperature	205	C˚
Heating steam pressure	8	bar
The concentration or salinity percentage of the incoming feed water	35000	ppm
The concentration or salinity percentage of the effluent	49700	ppm
Salinity ratio	1.42	-
The percentage of vacuum steam to heating steam	2	%
TTD of condenser	2	C˚
Saturated steam temperature of the first stage	67.5	C˚
Evaporation temperature of the last stage	48.7	C˚
Number of MED stages	5	-
The maximum capacity considered for the MED system	4500	m^3/day

Figure 5: The output of the power plant model integrated with the MED desalination system at an ambient temperature of 40 degrees



Taking into account the mentioned parameters and the following assumptions to reduce energy consumption and increase the efficiency of the water desalination system, the best place for steam extraction for water desalination with a thermo-compressor (steam turbine low-pressure feed line) is selected. In all the modeling, this place has been used to provide thermal energy in the simulations. A MED thermal water distillation is coupled to Chabahar combined-cycle power plant at a temperature of 40 degrees Celsius. The resulting simulation model is shown in Figure 5.

- Feed water in all stages is considered in the form of a parallel feed.

- Waste heat has been ignored in each step.
- The steam produced in each stage is considered salt-free.
- The pressure drop inside the tube is ignored.
- The temperature difference ΔT in each stage is considered equal to 4.75 degrees Celsius.
- The system is considered stable.

The diagram of MED desalination integrated with the power plant is shown in Figure 6.

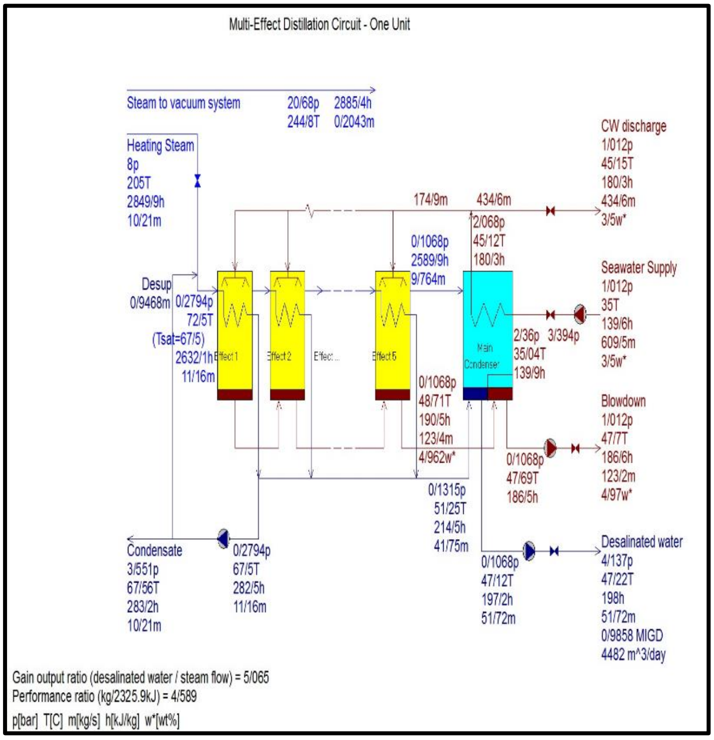


Figure 6: Diagram of the power plant integrated with the MED desalination system under the ambient temperature

Table 3: The results of the simulated model resulting from the integration of the MED desalination system with the Chabahar power plant

Parameter	Value	Unit of measurement
The total power of the power plant after integration	414	MW
The output power of a gas turbine	133.5	MW
Steam turbine output power	147.1	MW
Power plant efficiency	48.67	%
Net heat rate	7397	kj/kwh
The amount of freshwater produced	4482 (0.9858)	M^3/day (MIGD)
The efficiency ratio of desalination	5.08	-

As shown in Table 4, after the integration of the water desalination system into the combined cycle at an ambient temperature of 40 degrees, the total power of the power plant decreased from 420 to 414 MW. The drop in output power of the steam turbine is evident from 153 to 147.1 MW. Also, the efficiency of the power plant has reached 48.67% with a decrease of about 0.67%.

The quantitative performance of the desalination system (GOR) is expressed in the form of the ratio of the mass flow rate of the produced fresh water to the mass flow rate of the input motive steam. Therefore, the performance of the system according to the ratio of the amount of freshwater produced to the amount of steam received is about 5.08. The thermal diagram of the second stage of the modeled water desalination system is reflected in Figure 7.

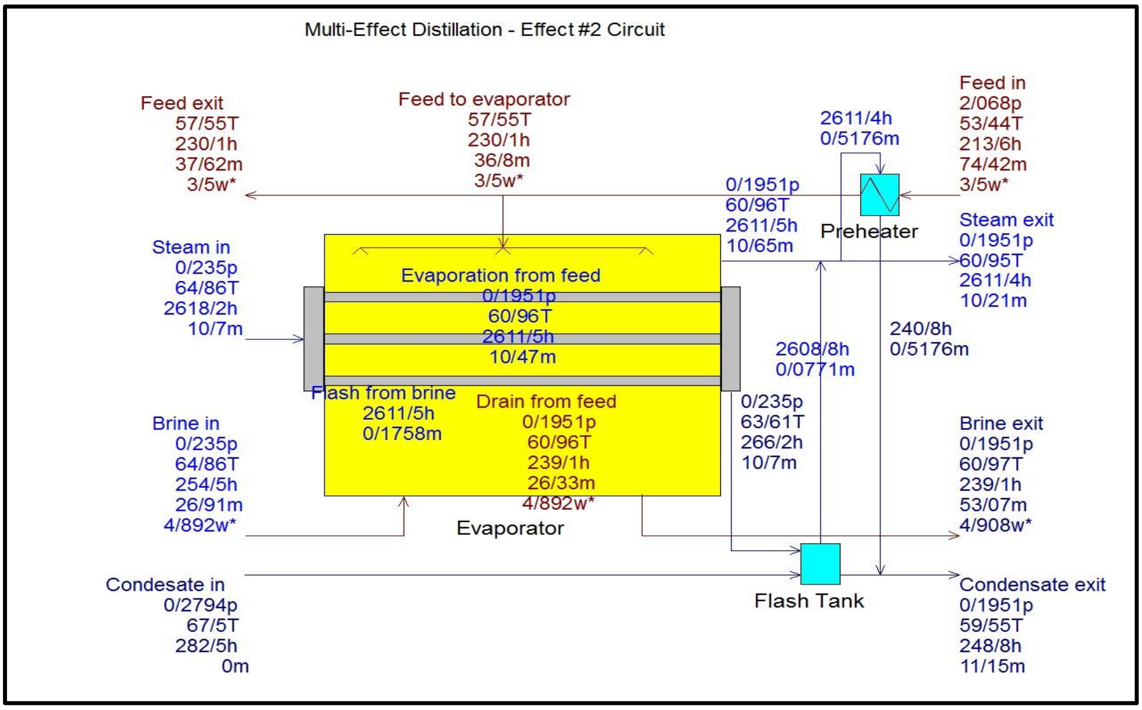


Figure 7: Diagram of the second stage of the modeled MED desalination system

Investigating the parameters affecting the performance of the water desalination system coupled with the power plant:

The parameters affecting the performance of the water desalination coupled with the combined-cycle power plant at an ambient temperature of 40 degrees Celsius were analyzed separately in the related software and the following results were obtained.

- Sea water temperature:

One of the critical parameters in the design of water desalination is the temperature set for the water entering the system. By keeping the mentioned assumptions constant, the temperature of the inlet salt water in the simulated model changes between 15 and 42 degrees Celsius. The results are represented in Figures 8 and 9.

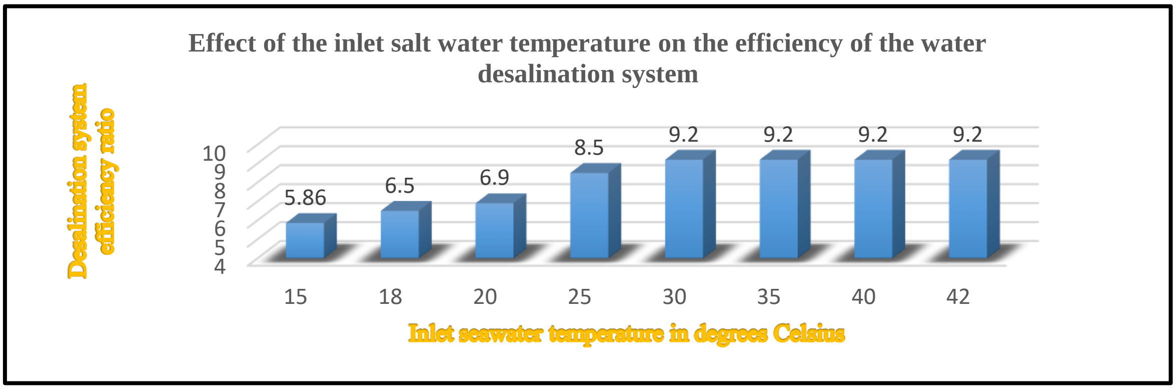


Figure 8: The effect of the inlet saltwater temperature on the efficiency of the water desalination system (n=5)

According to the obtained results, to increase the incoming water with low temperature, it needs to receive more steam. As a result, the amount of steam flow rate received increases. Subsequently, due to the constant flow rate of produced fresh water, the efficiency ratio of the water desalination also decreases. From the temperature of 30 degrees Celsius onwards, the flow rate of the steam received does not change and the performance of the water desalination is also constant.

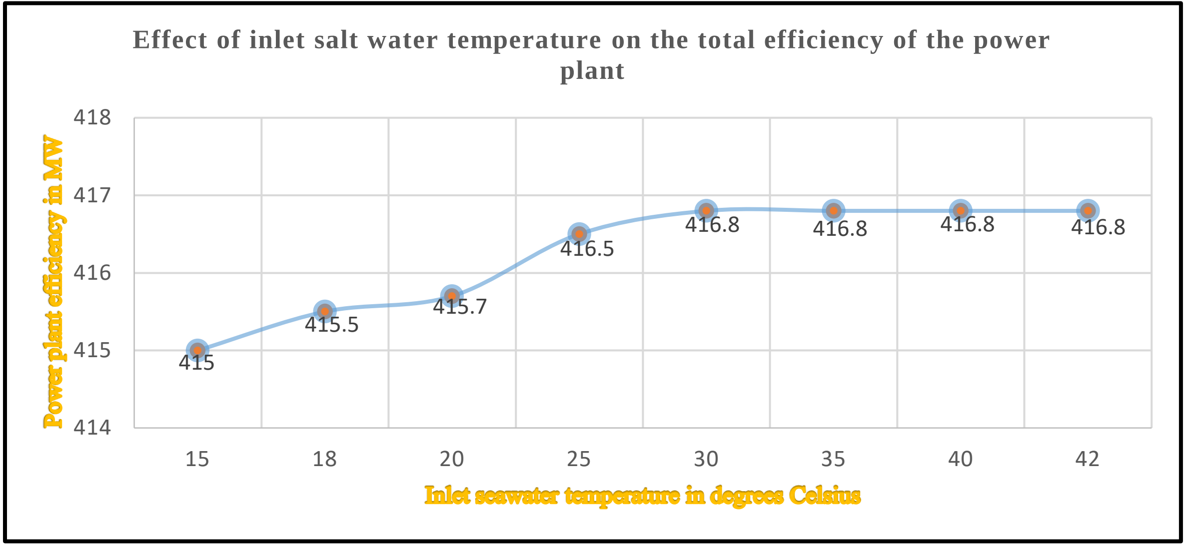


Figure 9: The effect of inlet saltwater **temperature** on the total efficiency of the power plant (n=5)

According to the graph obtained from the results of the models, the increase in the flow rate of motive steam at low temperatures leads to a decrease in the efficiency of the power plant. From the temperature of 30 degrees Celsius onwards, the flow rate of the received motive steam does not change, as a result, the efficiency of the power plant also remains constant.

- The number of effects or the number of stages of the water desalination system

Another key parameter in the design and simulation of MED systems in the software platforms is determining the number of effects or system stages. Considering the mentioned defaults, the number of MED-TVC stages in the simulated model varies from 3 to 9. The results are represented in the graph of Figure 10.

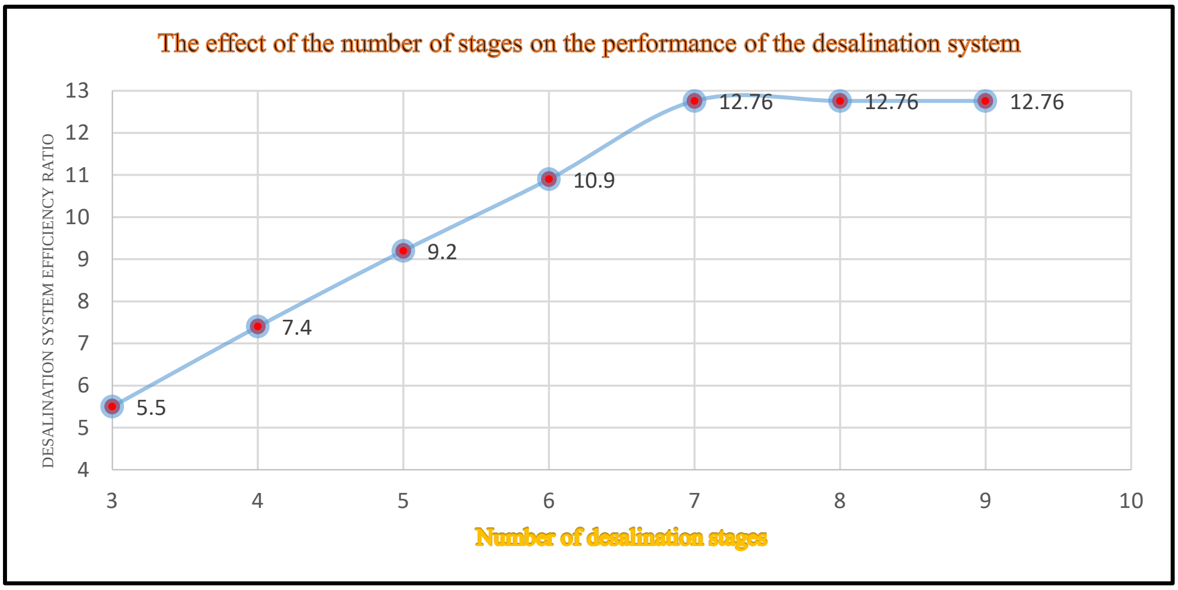


Figure 10: The effect of the number of stages on the performance of the water desalination system

According to the obtained results, increasing the number of stages leads to an increase in the efficiency ratio and performance of the water-desalination system. From the seventh stage onwards, the saturated steam temperature of the first and last stages is constant. As a result, by increasing the number of stages, the temperature drop also decreases. So, increasing the number of stages does not impose a change in the performance and efficiency of the system. In other words, increasing the number of stages does not affect the performance of the water desalination system. There is usually an optimal value for the parameter n.

- The saturated steam temperature of the first stage (first effect)

Another parameter affecting the design and simulation of the water desalination system in the software is the determination of the saturated steam temperature for the first stage. This parameter is the amount of heat given to the first stage in the form of saturated steam. According to the assumed assumptions, the saturated steam temperature for the first stage varies from 70 to 90 degrees Celsius. The results are represented in the graph of Figure 11.

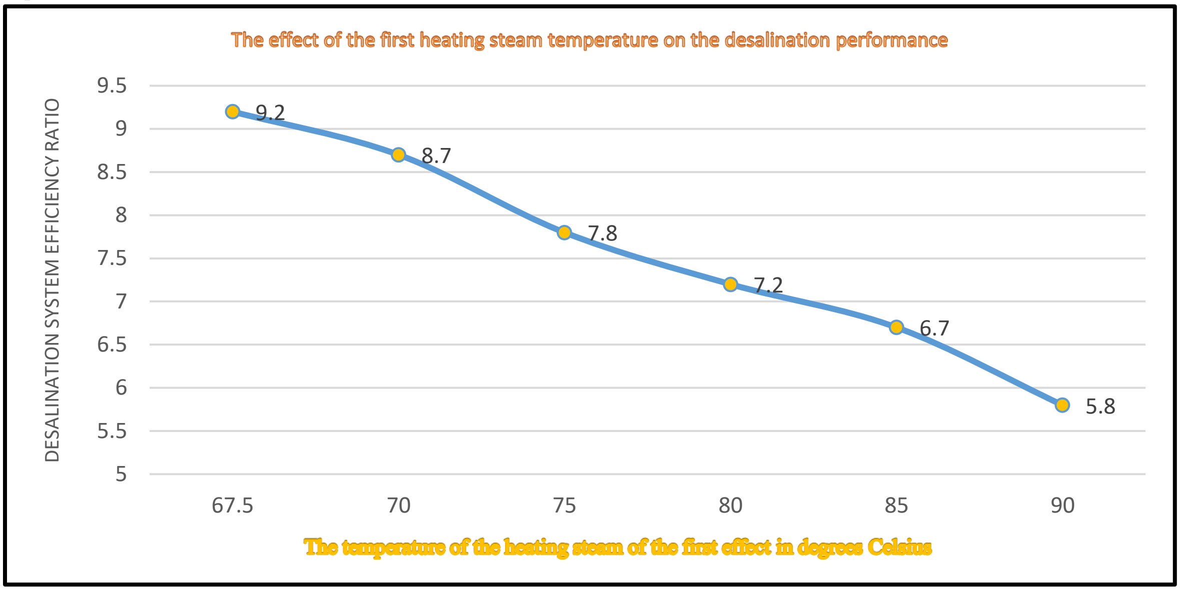


Figure 11: The effect of the heating steam temperature of the first stage on the performance of the water desalination system (n=5)

According to the obtained results, increasing the heating steam temperature while keeping the number of stages constant reduces the efficiency and performance of the water desalination. Therefore, if the temperature of the heating steam increases, the number of stages of water desalination should also increase. The reason is that by increasing the temperature of heating steam and keeping the number of stages constant, the temperature drops and subsequently the performance drop of the water desalination system is strengthened. Therefore, the higher the input value of this parameter, the greater the possibility of designing the MED system with more effects.

Conclusion

The present study analyzed the energy and exergy modeling of the Chabahar combined-cycle power plant at ambient temperatures of 15 and 40 degrees Celsius in hot seasons under temperature crisis conditions and reached the following results. The analyzes conducted on energy showed that in the cycle of the Chabahar power plant under the modeled conditions, the most thermal energy loss occurs in the condenser and chimney outlet, respectively, and is transferred to the environment. The energy efficiency of the simulated models is 45.75% and 41.08% respectively. The efficiency of the power plant based on output power and low heating value of fuel is 50.84% and 49.34%, respectively. Also, the exergy analysis showed that the amount of exergy destruction in the condenser is insignificant compared to other components of the power plant regarding thermodynamics due to the low quality of the wasted thermal energy. Therefore, the most exergy destruction is realized in the turbine combustion chamber due to the combustion process and pressure and expansion changes. At the same time, the exergy efficiency of the two models is 48.89% and 44.7%, respectively. According to the results of the conducted models and thermodynamic studies and the analysis of the extracted data, the designed system based on renewable energy sources and fossil fuels can supply urban water and electricity in Chabahar to some extent and has a favorable and effective efficiency. In case of adding a solar farm to the power plant and fully benefiting from solar energy in Chabahar, it is possible to improve the power and efficiency of the power plant while providing water for the citizens, taking into account the amount of electrical energy consumption and the weather conditions of the region.

References

[1] Askari, I. Baniasad, and Mohamad Ameri. "Thermodynamic analysis of multi effect desalination unit with thermal vapor compression feed by different motive steam pressures. " Desalination and Water treatment 184.57–71 (2020).

[2] Alipour, Mehran, Mahdi Deymi-Dashtebayaz, and Mostafa Asadi. "Investigation of energy, exergy, and economy of co-generation system of solar electricity and cooling using linear parabolic collector for a data center." Energy (2023): 128076.

[3] Cheong, So-Min, Gye-Woon Choi, and Ho-Sun Lee. "Barriers and solutions to smart water grid development." Environmental management 57 (2016): 509-515.

[4] Heck, Nadine, et al. "Coastal residents' literacy about seawater desalination and its impacts on marine ecosystems in California," *Marine Policy,* 68 (2016): 178-186.

[5] Ghaffour, Noreddine, et al. "Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems." *Desalination* 356 (2015): 94-114.

[6] Shakib, Seyed Ehsan, Majid Amidpour, and Cyrus Aghanajafi. "Simulation and optimization of multi effect desalination coupled to a gas turbine plant with HRSG consideration." Desalination 285 (2012): 366-376.

[7] Esmaieli, Alireza, et al. "Applying different optimization approaches to achieve optimal configuration of a dual pressure heat recovery steam generator." International journal of energy research 37.12 (2013): 1440-1452.

[8] Aliyar, Hadi., Baghernejad Ali., Analyzing the energy and exergy of equipping a combined-cycle power plant with thermal desalination water system, the 27th international mechanical engineering conference and the 7th thermal power plant industry conference, Tarbiat Modares University, Tehran 3180-3175. 2018.

[9] Mehrpooya, Mehdi, Bahram Ghorbani, and Seyed Sina Hosseini. "Thermodynamic and economic evaluation of a novel concentrated solar power system integrated with absorption refrigeration and desalination cycles." Energy Conversion and Management 175 (2018): 337-356.

[10] Ghorbani, Bahram, Mehdi Mehrpooya, and Milad Sadeghzadeh. "Developing a tri-generation system of power, heating, and freshwater (for an industrial town) by using solar flat plate collectors, multi-stage desalination unit, and Kalina power generation cycle." Energy Conversion and Management 165 (2018): 113-126.

[11] Cengel, Y.A., Boles, M.A., "Thermodynamics: an engineering approach", 5th ed., McGraw–Hill: New York. 2006.

[12] Baghernejad, A., and M. Yaghoubi. "Exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm." Energy conversion and Management 52.5 (2011): 2193-2203.

[13] El-Dessouky, Hisham, et al. "Evaluation of steam jet ejectors." Chemical Engineering and Processing: Process Intensification 41.6 (2002): 551-561.