

Thermodynamic simulation and economic modeling and optimization of a multi generation system partially fed with synthetic gas from gasification plant

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Abstract

This paper presents thermodynamic simulation, economic modeling and annual profit optimization of a multi generation system which produces both power and fresh water. The fuel of the combined system is natural gas plus synthesis gas which is produced in biomass gasification reactor. In order to evaluate thermodynamic performance of the biomass gasification reactor, visual simulation software was developed in C# programming language. The multi generation system is analyzed both with inlet air cooling and without inlet air cooling. The final results show that the total cost of produced power is 0.0286 \$/kWh and total cost of produced water is 0.7408286 \$/m³. Also the total annual profit which comes from selling power and water to the market is 35.103 M\$ and the CHP efficiency is 67.08. Optimization of the configuration is carried out once the simulation phase is finished. The optimization results in 10.5% increase in total annual profit and 6.6% increase in CHP efficiency.

Keywords

Synthetic gas; Desalination system; Power and water cost; Net annual profit; Gasification; Genetic Algorithm

1. Introduction

Multi generation thermal systems have drawn great attention nowadays. Multi generation means the combined production of heat, power, water, cooling, liquid fuel, etc., for consumption within a site. Heat can have several uses. For example, it can be used as the motive steam for thermal desalination systems (MSF or MED) or as the source of heat for absorption chiller. Whilst power and heat are provided by the turbine and the exhaust gases refrigeration could be obtained in two different ways, either by using an absorption system in combination with low grade heat or by using an electrically driven compression system. The use of one or another will depend on the process heat/power ratio needs and specific site characteristics. Thermal desalination is among the most useful applications of multi generation. Many researchers have studied thermal desalination from thermodynamic and economic points of

view. Sayyaddi et al. (Sayyaadi&Ghorbani, 2018) introduced a systematic approach for the design of Stirling-desalination system which was found to be a reliable option for the small-scale power-water production. The proposed system could deliver 2.58 kW of the electric power as well as 23.3 m³ of the fresh water per day with a production cost of 0.25 \$ kWh⁻¹ and 0.66 \$ m⁻³, respectively, Salimi et al. (Salimi&Amidpour, 2017) evaluated several scenarios for integration of RO and MED into cogeneration systems. They used the R-curve concept to identify effective ways to decrease the operating costs, Alhazmy (Alhazmy, 2014) analyzed thermal and economic aspects of installing a feed cooler at the plant intake and concluded that the profit of selling the additionally produced water covers the cost of the cooling system, Nisan and Dardour (Nisan & Dardour, 2007) studied power and water costs of several nuclear reactors operating in a cogeneration and coupled to two main desalination processes, e.g. multiple effect

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distillation (MED) and reverse osmosis (RO), Al-Hengari et al. (Al-Hengari, El-Bousiffi, & El-Mudir, 2005) reviewed and evaluated the important design factors and operating conditions and the plant operating data to a desalination unit performance, Alasfour et al. (Alasfour, Darwish, & Bin Amer, 2005) presented thermal analysis of three different configurations of a multi-effect thermal vapor compression desalting system based on the first and second laws of thermodynamics, Kahraman and Cengel (Kahraman&Cengel, 2005) considered a large MSF distillation plant in the gulf area and analyzed it thermodynamically using actual plant operation data, the plant was determined to have a second law efficiency of just 4.2%, which was very low, Kafi et al. (Kafi, Renaudin, Alonso, & Hornut, 2004) innovate a new multi-effect plate evaporator, EasyMED and obtained experimental results from the hydrodynamics and thermal performances, Shih (Shih, 2005) evaluated the technologies of thermal desalination using low-grade heat present in a sulfuric acid plant, Mabrouk (Mabrouk, 2013) explored a techno-economic comparison between long tube (LT) and cross tube (CT) bundles of MSF evaporator for a unit production of equal and greater than 20 MIGD, Fiorini and Sciubba (Fiorini&Sciubba, 2005) adapted a modular simulation code, CAMEL™, developed by the University of Roma1, to include the capability to perform a thermo economic analysis of a MSF desalination plant

(in addition to the thermodynamic and exergetic analyses) and Nafey et al. (Nafey, Fath, & Mabrouk, 2006) did a number of comparisons for Multi Effect Evaporation (MEE) and hybrid Multi Effect Evaporation-Multi Stage Flash (MEE-MSF) systems using the exergy and thermo economic analysis.

Recently, some studies have been performed to produce fresh water with the use of renewable energy resources. Mentis et al. (Mentis et al., 2016) developed a tool for designing and optimally sizing desalination and renewable energy units. Ghaffour et al. (Ghaffour et al., 2014) worked on developing new desalination processes, adsorption desalination (AD) and membrane distillation (MD), which can be driven by waste heat, geothermal or solar energy. They constructed a demonstration solar-powered AD facility. A life cycle assessment showed that its specific energy consumption is less than 1.5 kWh per cubic meter of desalinated water, which is far less than the energy consumption of conventional desalination methods.

On the other hand, in the field of desalination system's parameter and configuration optimization, some research activities have been done. Kwon et al. (Kwon, Won, & Kim, 2016) developed a superstructure model using Mixed Integer Linear Programming to determine the optimal configuration of a renewable-based power supply.

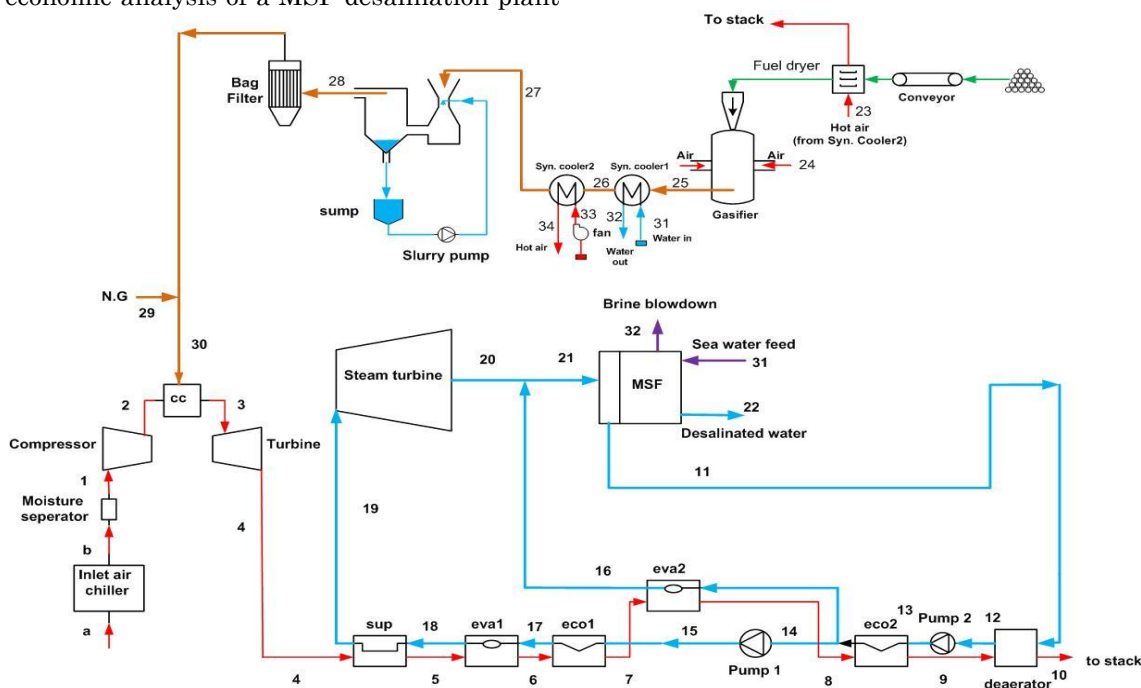


Figure 1. The schematic diagram of the multi generation system

Diverse economic factors such as transmission and reclamation costs were considered to ensure minimal cost while satisfying electricity demands, Ansari et al. (Ansari, Sayyaadi, & Amidpour, 2011) considered a typical 1000 MW Pressurized Water Reactor (PWR) nuclear power plant coupled to a multi effect distillation desalination system with a thermo-vapor compressor (MED-TVC) for optimization. Shakib et al. (Shakib, Amidpour, & Aghanajafi, 2012) did an optimization study for a combined system of gas turbine, Heat Recovery Steam Generator and MED desalination unit in view of three approaches, Kamali et al. (Kamali, Abbassi, SadoughVanini, & SaffarAvval, 2008; Kamali&Mohebinia, 2008), did a parametric optimization analysis of a multiple effect desalination system with thermal vapor compression (MED-TVC) process to increase gain output ratio (GOR), Ameri et al. (Ameri, Mohammadi, Hosseini, & Seifi, 2009) studied the effects of different design parameters such as number of evaporation effects, inlet steam pressure, temperature difference of the effects, etc. on MED system specifications, Mehrpooya et al. (Mehrpooya, Ghorbani, Jafari, Aghbashlo, & Pouriman, 2018) investigated a novel hybrid model based on neural network. The proposed model was a combination of Group Method of Data Handling type neural networks and Genetic Algorithm. The Genetic algorithm was used to optimize the correlation parameters to improve the accuracy of model, Agashichev and El-Nashar (Agashichev& El-Nashar, 2005) developed a system of models for the techno-economic evaluation of a triple hybrid, reverse osmosis (RO), multistage flash (MSF) and power generation process.

Researchers, nowadays, have been doing extensive studies about the systems that can produce more than two or even three forms of useful products. In fact, the trend is also accelerating toward using renewable forms of input energy. Malik et al. (Malik, Dincer, & Rosen, 2015) developed a renewable energy-based multi-generation system and studied it both energetically and exergetically. They employed Two renewable sources of energy, biomass and geothermal, to deliver five useful outputs. They found that the energy and exergy efficiency of the entire system is 56.5% and 20.3% respectively. Shariatinasar et al. (Shariatinasar et al., 2017) studied a cogeneration system of four useful outputs including power, heating, cooling and liquid fuels with the use of gasification of coal. Ghorbani et al. evaluated an integrated system for co-production of LNG and NGL, based on

MFC and absorption refrigeration systems. They found the highest and the lowest exergy destruction parts of the system and concluded that the forth compressor has the highest exergy destruction cost. Salehi et al. did an optimization on an integrated heat and power system which were part of a distillation column sequence. The results showed that a large amount of power can be produced between the columns due to having high flow rate flows between the columns. Huang et al. (Huang et al., 2013) did a simulation and techno-economic analysis of small scale biomass trigeneration system. The study investigates the impact of different biomass feedstock on the performance of trigeneration plant. The results specified the maximum efficiencies and the best breakeven electricity selling prices.

This paper presents a new evaluation system for the comparison of different configurations of combined cycles of power, cooling and desalinated water production. A complete thermodynamic and economic modeling and optimization procedure is used for this purpose.

2. Process Description and System Configuration

The multi generation system is composed of a gas turbine which is a Siemens V94.2 (with nominal power output of 148.8 Mw in 15 °C inlet air temperature) and the desalination system which is chosen to be MSF (Multi Stage Flash) system. The high pressure steam produced in HRSG is used for power production in the back pressure steam turbine, but the low pressure steam, which is saturated, is mixed with the low pressure steam exiting the back pressure steam turbine to feed the brine heater of MSF system. The schematic of the system and main inputs are shown in figure 1 and table 1 respectively. Simulation is done both with inlet air cooling and without inlet air cooling.

3. Modeling

3.1. Thermodynamic Modeling

In this section the thermodynamic modeling of the above mentioned configuration is outlined. The first stage in every modeling process is to identify the inputs and the outputs of the problem. Generally speaking, the inputs fall into two categories: system parameters (which are considered fixed values during modeling and simulation) and decision variables (which

Table 1. Input parameters of the multi generation system

Input parameters	Unit	Without inlet air cooling	With inlet air cooling
Motive steam temperature to MSF	C°	120	120
Motive steam pres. to MSF	Bar	2	2
Ambient air temperature (design)	C°	35	35
Inlet air temperature to compressor	C°	35	10
HP steam temperature (of HRSG)	C°	490	490
HP steam pressure (of HRSG)	Bar	75	75
LP steam temperature (of HRSG)	C°	133.5	133.5
LP steam pressure (of HRSG)	Bar	3	3
Pinch temperature of 1 st evaporator	C°	5	5
Pinch temperature of 2 nd evaporator	C°	5	5
Approach temperature of 1 st evaporator	C°	15	15
Approach temperature of 2 nd evaporator	C°	15	15
Top Brine Temperature (TBT of MSF)	C°	110	110
Terminal Temperature Difference (TTD of MSF)	C°	7.5	7.5

Table 2. Major system parameters

Name of parameter	value	unit
Ambient air temperature (design)	35	C°
Ambient air relative humidity	75	percent
Ambient air composition		
N2-Ar	75.95	percent
CO2	0.03	percent
H2O	3.88	percent
O2	20.14	percent
Temperature of inlet air to compressor (after cooling)	10	C°
Pressure drop of water side of super heater	3.5	percent
Pressure drop of water side of economizer	3	percent
Isentropic efficiency of steam turbine	85	percent
Mechanical efficiency of steam turbine	95.8	percent
Isentropic efficiency of pumps	75	percent
Mechanical efficiency of pumps	97	percent
The total stages of MSF	21	18 stage in heat recovery section and 3 stage in heat regenerative section
Feed sea water temperature	30	C°
Feed sea water salinity	3.44	percent

are changeable within a certain limit).

The outputs are actually the results obtained from inputs, using the fundamental laws (in this paper, the first and the second laws of thermodynamics).

System parameters as the major assumptions that are considered for modeling of the system are mentioned in table 2. For example, in this work, a Siemens V94.2 gas turbine was chosen and the ambient design temperature decided to be 35 C°.

Other inputs necessary for carrying out the modeling of the configuration were presented

in the previous sections, among them the pressure and temperature of High Pressure (HP) and Low Pressure (LP) steam of HRSG and the approach and pinch temperature are of great importance.

Dependent variables are those variables that will be obtained after running the simulation code. They are actually the outputs of the system and their values are dependent on the values of parameters and decision variables of the system. Major dependent variables are as follows:

1- Power produced by the gas turbine

- 2- Power produced by the steam turbine
- 3- The net power output of the cycle
- 4- The mass flow rate of the fuel
- 5- The volume flow rate of desalinated water
- 6- Total capital investment of power production
- 7- Total capital investment of water production
- 8- The net annual profit of the plant

3.1.1. Gasification Modeling

In order to evaluate thermodynamic performance of the biomass gasification reactor, visual simulation software was developed in C# programming language. The software is composed of different tabs which have specific purposes and perform required calculations.

Two modes of simulations are available for both fixed and fluidized bed reactors; both of them solve a set of non-linear equations to get the desired outputs. In the first mode, the reaction temperature is given and the program will calculate the required amount of air to satisfy energy balance in the reactor. In the second mode, the amount of air injected to the gasifier is given and the program uses an iterative approach to calculate final reaction temperature. In this mode, giving an initial reaction temperature is necessary for starting the calculations.

The software uses extended Newton-Raphson approach to solve the set non-linear equations and obtain the producer gas composition. First, the biomass inlet characteristics (atomic composition, LHV, moisture, biomass flow, etc.), environmental conditions (temperature

and pressure), gasifier parameters (gasifier temperature or mole of injected air) and other parameters (gasifier operating pressure, heat loss) are introduced into the program. In second stage, the product gas composition is calculated by stoichiometric equilibrium model. Flowchart of the calculation approach in the first and second mode of computation can be observed in figure 2 and 3.

Procedure of formulation for the second mode of simulation (air injected to the gasifier given) with the use of stoichiometric method is as follows, it should be noted that formulation of the first mode of simulation (reaction temperature given) is quite similar with marginal changes:

First off, starting from the mass fractions of carbon, hydrogen, oxygen, nitrogen and sulfur (CHONS) in the biomass and the relative mass of the moisture, the substitution fuel and the molar water content can be evaluated. In the second stage, the composition of the producer gas is estimated, using the initial value of reaction temperature and calculation of the equilibrium constants. Then the reaction temperature corresponding to the actual producer gas composition is calculated, equating the enthalpy of the entering biomass and moisture and the enthalpy of the producer gas. Using the calculated reaction temperature, the input of the next composition calculation is formed, iterating the process until chemical and thermodynamic equilibrium have been reached.

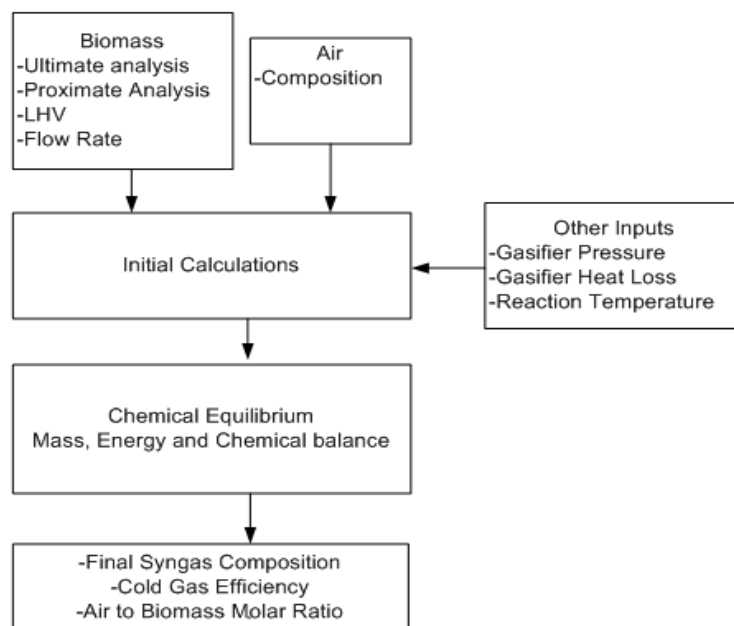


Figure.2. Flowchart of the calculation approach in the first mode of computation

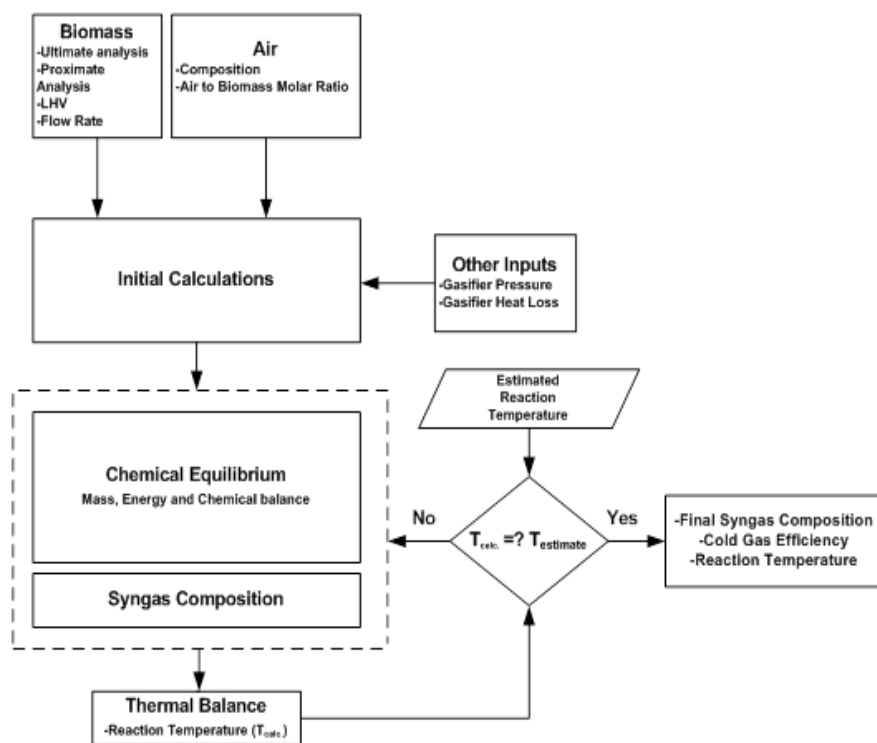
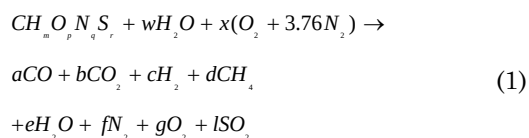


Figure 3. Flowchart of the calculation approach in the second mode of computation

Once the final producer gas composition and its corresponding reaction temperature are obtained, other outputs of the gasification process including the heating value of the producer gas, Cold Gas Efficiency, etc. can be derived.

Estimating the composition of producer gas is based on chemical equilibrium between different species, neglecting tar content in the producer gas. The reaction, in its general form, can be written as (Melgar, Pérez, Laget, & Horillo, 2007):



The variable x corresponds to the molar quantity of air used during the gasifying process and is one of the inputs of the simulation. The value of m , p , q , and r can be calculated from weight percent of Hydrogen, Carbon, Oxygen, Nitrogen, Sulfur and their molecular weights. Also, from molecular weight of biomass and water and the relative moisture of biomass, the value of w can be calculated.

Writing the atomic balance for C, H, O, N and S, respectively and assuming that no oxygen will be present in the producer gas, following six equations are derived (Melgar et al., 2007).

$$1 = a + b + d \quad (2)$$

$$m + 2w = 2c + 4d + 2e \quad (3)$$

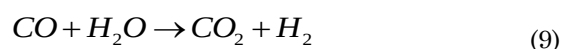
$$q + 3.76 \times 2x = 2f \quad (4)$$

$$p + w + 2x = a + 2b + e + 2g + 2l \quad (5)$$

$$r = l \quad (6)$$

$$g = 0 \quad (7)$$

In order to solve the above system of equations, to find out eight unknown variables, two more equations are needed. The first one is reduction of hydrogen to methane in reduction zone. The second one is known as the water gas shift reaction, which is the equilibrium between CO and H₂ in the presence of water.



The corresponding equilibrium constants of the above mentioned equations can be obtained from either the molar composition of

syngas or Gibbs free energy. If the second is substituted form of equilibrium constant equation (Gibbs free energy) into the first one (molar composition), the complementary equations will be found (Melgar et al., 2007):

$$K_1 = \frac{dn_r}{c^2} = \exp(-(G_{T,CH_4}^0 - 2G_{T,H_2}^0) / R_u T) \quad (10)$$

$$K_2 = \frac{bc}{ae} = \quad (11)$$

$$\exp(-(G_{T,H_2}^0 + G_{T,CO}^0 - G_{T,CO}^0 - G_{T,H_2O}^0) / R_u T)$$

In which Gibbs free energy can be calculated from (Melgar et al., 2007):

$$G_{T,i}^0 = \Delta \tilde{h}_{f,298}^0 + \int_{298}^T C_p dT - Ts^0 \quad (12)$$

Thermodynamic properties are extracted from NIST-JANAF thermochemical tables (Chase, 1998). Two of the mentioned system of equations has non-linear structure, so an extended Newton- Raphson scheme is employed in order to solve the system of equations. Once the above mentioned system of equations is solved, the syngas composition will be determined at initial reaction temperature. Knowing the syngas composition, corresponding reaction temperature can be computed, which is, in turn, the initial reaction temperature of next iteration. The reaction temperature of next iteration can be estimated using the first law of thermodynamic according to the following equations (Melgar et al., 2007):

$$H_{prod}(T_k) = H_{reac} + Q_{in} + Q_{out} \quad (13)$$

$$T_{k+1} = T_k + \frac{H_{reac} + Q_{in} + Q_{out} - H_{prod}(T_k)}{C_{pprod}(T_k)} \quad (14)$$

3.1.2. Gas Turbine Modeling

There are two approaches for Gas Turbine modeling. The first one is using classical thermodynamics laws, namely the first and second laws of thermodynamics and utilizing the concepts of isentropic efficiency, etc.(Bejan A, 1996).

In this way, some assumptions are needed. For the sake of simplicity, the fuel is considered Methane, physical properties of all streams are calculated in mean inlet and outlet temperature and the air and combustion products are treated as ideal gases.

Referring to figure 2, the temperature of air leaving the compressor in ideal condition would be (Bejan A, 1996):

$$T_{2s} = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k} \quad (15)$$

In which, K is the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume. Specific heat capacity of every component of air (or any other ideal gas mixture) can be calculated according to the following equation in which a, b, c and d are constant coefficients for each component (Bejan A, 1996).

$$C_p = a + by + cy^2 + dy^3 \quad (16)$$

Actual air temperature leaving the compressor can be calculated utilizing compressor isentropic efficiency (Sonntag, Borgnakke, Van Wylen, & Van Wyk, 1998):

$$T_2 = T_1 + (T_{2s} - T_1) / \eta_{ic} \quad (17)$$

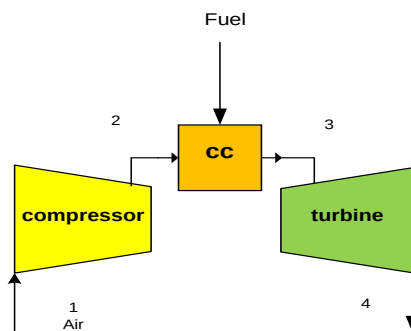


Figure 4. The schematic diagram of the gas turbine

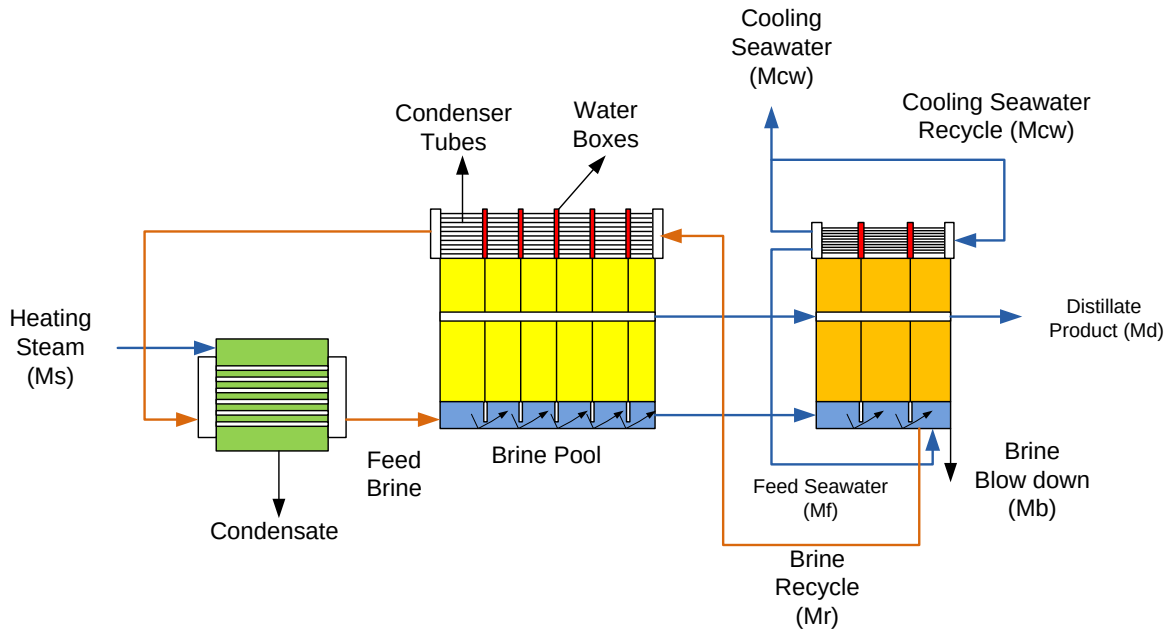


Figure 5. Multistage flash desalination with brine circulation

In a similar way, the ideal and actual temperature of combustion products leaving the turbine can be computed (Sonntag et al., 1998):

$$T_{4s} = \frac{T_3}{\left(\frac{P_3}{P_4}\right)^{(k-1)/k}} \quad (18)$$

$$T_4 = T_3 - (T_3 - T_{4s}) / \eta_{it} \quad (19)$$

Knowing the composition of ambient air (mentioned in table 5) and for complete combustion of methane, the chemical equation takes the form (Bejan A, 1996):

$$\bar{\lambda} CH_4 + [0.7595N_2 + 0.0003CO_2 + 0.0388H_2O + 0.2014O_2] \rightarrow (1 + \bar{\lambda})(x_{N_2}N_2 + x_{CO_2}CO_2 + x_{H_2O}H_2O + x_{O_2}O_2) \quad (20)$$

In which is fuel to air mole fraction. By balancing the two sides of equation, the mole fraction of the products components will be obtained (Bejan A, 1996).

$$x_{N_2} = \frac{0.7595}{1 + \bar{\lambda}} \quad (21)$$

$$x_{O_2} = \frac{0.2014 - 2\bar{\lambda}}{1 + \bar{\lambda}} \quad (22)$$

$$x_{CO_2} = \frac{0.0003 + \bar{\lambda}}{1 + \bar{\lambda}} \quad (23)$$

$$x_{H_2O} = \frac{0.0388 + 2\bar{\lambda}}{1 + \bar{\lambda}} \quad (24)$$

So the molar analysis of combustion products is fixed once the fuel to air ratio ($\bar{\lambda}$) has been determined.

The fuel to air ratio ($\bar{\lambda}$) can be obtained from an energy rate balance around combustion chamber (Bejan A, 1996):

$$\begin{aligned} \dot{Q} - \dot{W} &= \dot{n}_p \bar{h}_p - \dot{n}_f \bar{h}_f - \dot{n}_a \bar{h}_a \\ \rightarrow 0 &= (1 + \bar{\lambda}) \bar{h}_p - \bar{\lambda} \bar{h}_f - \bar{h}_a \end{aligned} \quad (25)$$

Since $\dot{n}_f = \bar{\lambda} \dot{n}_a$, the fuel and air mass flow rates are related by:

$$\dot{m}_f = \bar{\lambda} \left(\frac{M_f}{M_a} \right) \dot{m}_a \quad (26)$$

This approach, for modeling a certain type of gas turbine, like V94.2, will lead to small deviation from the actual performance of the gas turbine, since the manufacturer has probably used special assumptions for modeling and constructing the gas turbine.

The second approach which is more accurate than the first is to use the manufacturer's graphs and tables and use regression if required to get our desired outputs.

After finding the temperature, flow rate and composition of the flue gas leaving the gas turbine, the next step is finding the enthalpy and entropy of the water streams. But first it is needed to do the pressure analysis of the water side of the cycle.

Table 3. Purchase equipment costs of the plant components

Equipment	Capital cost formula	reference
Gasifier (including its auxiliaries)	$3.82 \times Q_{dry}^{0.6983} \times \frac{190}{140}$	(Bridgwater, Toft, & Brammer, 2002; Yassin, Lettieri, Simons, & Germanà, 2009)
Syngas cooler and fuel drier	$8500 + 409 \times A_{HX}^{0.85}$	(Sayyaadi & Mehrabipour, 2012)
Gas Turbine		("Thermoflow (GTpro module),")
Steam compressor (with motor)	$98400 \times \left(\frac{\dot{W}}{\dot{W}_{base}}\right)^{0.46}$	(Smith, 2005)
Heat recovery steam generator	$8500 + 409 \times A_{HRS}^{0.85}$	(Sayyaadi & Mehrabipour, 2012)
MSF desalination	$430 \times 1.6 \times Q \times \Delta T_n^{-0.75} \times \Delta T_t^{-0.5} \times dp_t^{-0.1}$	(El-Sayed, 2013)
Pump (with motor)	$1146 \times \dot{W}_p^{0.71} \left(1 + \frac{0.2}{1 - \eta_p}\right)$	(Carapellucci & Giordano, 2013)
Wet scrubber	$4920 \times \left(\frac{Vol}{Vol_{base}}\right)^{0.53}$	(Smith, 2005)
Bag filter	$83600 \times \left(\frac{FA}{FA_{base}}\right)^{0.49}$	(Smith, 2005)

Table 4. Major economic data

Parameter	Symbol -unit	Value
Interest rate	i	0.15
Utilization years	n	15
Capital Recovery Factor	CRF	0.1710
Working hours (per year)	hour	8117
availability	ava	0.9265
Fuel Low heating value	LHV(kJ/kg)	50046.7
Fuel price	\$/GJ	3
Power sale price	\$/kWh	0.05
Water sale price	\$/m ³	1.111

3.1.3. Water and Steam Cycle Modeling

3.1.3.1. Pressure Analysis

According to the assumptions for the values of pressure drop in various portions of HRSG and the known pressures of the cycle, which were mentioned before, the pressure of every single stream can be found (Sonntag et al., 1998).

$$P_{17} = P_{HP} \quad (27)$$

$$P_{16} = 1.035 \times P_{17} \quad (28)$$

$$P_{15} = P_{16} \quad (29)$$

$$P_{13} = 1.030 \times P_{15} \quad (30)$$

$$P_{12} = P_{14} = P_{18} = P_{19} = P_{LP} \quad (31)$$

$$P_{11} = 1.03 \times P_{12} \quad (32)$$

$$P_{10} = XSteam('psat - t', T_0 + TTD_h) \quad (33)$$

It should be noted that for finding steam properties, XSteam code, which is available at (Holmgren, 2006), has been used.

3.1.3.2. Finding HP and LP Mass Flow Rates

Having completed the pressures analysis and before finding the mass flow rates, the enthalpies and entropies of the all streams were found. For some streams, it is completely straightforward, since the pressure and temperature of that stream is known. Using XSteam code, it is easy to find the enthalpy and entropy of all streams.

$$h_{17} = XSteam('h - pt', P_{17}, T_{17}) \quad (34)$$

$$s_{17} = XSteam('s - pt', P_{17}, T_{17}) \quad (35)$$

For some other streams, for example the exit of pumps or steam turbine it is necessary to use the isentropic efficiency formula. For pump1 it is as follows (Sonntag et al., 1998):

$$\eta_{sp} = \frac{h_{13s} - h_{12}}{h_{13} - h_{12}} \quad (36)$$

Table 5. Thermodynamic and economic results

name	unit	value
Net gas turbine Power output	MW	148.778
Net increased power output due to inlet air cooling	MW	14.461
Net steam turbine Power output	MW	44.042
Net total power output	MW	172.497
Desalinated water produced per day	MIGD	9.33
Fuel mass flow rate	Kg/s	8.999
Net heat rate	MJ/kWh	5.3663404
Specialized equipments cost	M\$	44.658
Other equipments cost	M\$	2.584
Civil works cost	M\$	2.86
Mechanical works cost	M\$	6.681
Electrical and wiring works cost	M\$	2.373
Structural works cost	M\$	2.85
Startup and engineering cost	M\$	4.476
Total capital cost of power generation	M\$	66.482
Power cost due to the capital investment	\$/kWh	0.0081202
Fixed O&M cost	\$/kW-year	20
Power cost due to Fixed O&M	\$/kWh	0.002464
Variable O&M cost	\$/kWh	0.002
Power cost due to variable O&M	\$/kWh	0.002
Fuel price	\$/MJ	0.003
Power cost due to the consumed fuel	\$/kWh	0.016099
Total cost of produced power	\$/kWh	0.0286832
Total capital investment of MSF system	M\$	45.387
Water cost due to the capital investment	\$/m ³	0.5466286
Water cost due to Fixed O&M	\$/m ³	0.1159
Water cost due to variable O&M	\$/m ³	0.0783
Total cost of produced water	\$/m ³	0.7408286
Annual profit	M\$	35.103105
CHP efficiency	%	67.084824

Table 6. The comparison between thermodynamic and economic performance of two conditions

	Total net power output	Total capital cost of power generation	Total cost of produced power	Total water production	Total capital cost of water generation	Total cost of produced water	CHP efficiency	Total annual profit
units	Mw	M\$	\$/kWh	MIGD	M\$	\$/m ³	%	M\$
Configuration without inlet air cooling	157.53	70.404	0.027505	11.679	54.135	0.7151	79.27	35.80
Configuration with inlet air cooling	167.9568	74.5	0.0278	12.5946	57.25	0.7135	75.8172	37.8662

Since h_{13s} , h_{12} and h_{sp} can be easily obtained, h_{12} will be found. A similar procedure is applicable for pump2.

The isentropic efficiency formula for steam turbine is (Sonntag et al., 1998):

$$\eta_{st} = \frac{h_{18} - h_{17}}{h_{18s} - h_{17}} \quad (37)$$

And by the use of the mentioned formula, the enthalpy, entropy, temperature and wetness of

the leaving streams of steam turbines can be found. Generally, to find out the steam flow rates, a proper control volume around one component or two components, depending on the configuration of the cycle should be considered. Next, by employing the laws of conservation of mass and energy and simultaneous solving of the equations, the desired mass flow rate will be obtained.

To find HP steam mass flow rate, it is needed to consider a control volume encompassing both super heater and evaporator1. Writing the conservation of energy for this control volume will lead to:

$$\dot{m}_{HP} \times (h_{17} - h_{15}) = \dot{m}_p \times C_p \times (T_4 - T_6) \quad (38)$$

T_6 will be found by adding pinch temperature difference of evaporator1 to T_{16} . Solving the above equation for $\dot{m}_{HP}$ will result in finding HP steam mass flow rate. To find the temperature of the flue gas leaving economizer1, it is required to write the conversation of energy and solve it to find T_7 .

For finding LP mass flow rate, a control volume around evaporator1 would be adequate.

3.1.3.3. Finding Steam Turbine Power Output and Pumps Power Input

In order to find the power output (for steam turbine) or power input (for pumps), the steam (or water) flow rates and enthalpies upstream and downstream of the component as well as the mechanical efficiencies are needed. The former was calculated in the previous sections. The latter is considered a fixed parameter and was mentioned in table1 for each part. With reference to figure1, employing two equations as follows will lead to the power output of the steam turbine and power input of water pump:

$$\dot{W}_{st} = \dot{m}_{HP} \times (h_{17} - h_{18}) \times \eta_{mst} \quad (39)$$

$$\dot{W}_p = \dot{m}_{HP} \times (h_{13} - h_{12}) \times \eta_{mp} \quad (40)$$

$$+(\dot{m}_{HP} + \dot{m}_{LP} \times (h_{11} - h_{10}) \times \eta_{mst}$$

3.1.4.Desalination System Modeling

For evaluation of thermal performance, a mathematical model is developed by applying mass and energy conservation laws to the flashing stages and condenser (Hisham T. El-Dessouky, 2002). The final objective is to obtain the total produced desalinated water per day. For this purpose the mass flow rate and the temperature and pressure of the motive steam is needed. These values were found in the previous section. In this study, brine circulation MSF process has been chosen. The following assumptions are

considered in this regard: Distillate product is salt free, Specific heat at constant pressure, C_p , for all liquid streams, brine, distillate and seawater is constant and equal to 4.18 kJ/kg C, Sub cooling of condensate or superheating of heating steam has negligible effect on the system energy balance and The heat losses to the surroundings are negligible because the flashing stages and the brine heater are usually well insulated.

Schematic of the brine circulation MSF process is shown in Figure 3 below.

In addition to the above mentioned assumptions, some key parameters of the MSF system should be known which were indicated in table 2.

The procedure of modeling is as follows:The overall material balance equation of the system can be arranged to obtain the expression for the total feed flow rate in terms of the distillate flow rate which is given by equation 41 (Hisham T. El-Dessouky, 2002):

$$M_f = \frac{X_b}{X_b - X_f} M_d \quad (41)$$

Where M is the mass flow rate and the subscript b, d and f defines the brine, distillate, and feed and X is the salt concentration. This equation assumes that the distillate is salt free.

The temperature distribution in the MSF system is defined in terms of four temperatures; these are the temperature of the steam, T_s , the brine leaving the preheater (top brine temperature), T_o , the brine leaving the last stage, T_n and the intake seawater, T_{cw} .

A linear profile for the temperature is assumed in the stages and the condensers, the temperature drop per stage, ΔT , is $\Delta T = (T_o - T_n)/n$, where n is the number of recovery and rejection stages. Therefore, a general expression is developed for the temperature of ith stage, $T_i = T_o - i \Delta T$

By performing an energy balance on stage i, Assuming the temperature difference, $T_i - T_{vi}$, is small and has a negligible effect on the stage energy balance, it is derived that: $\Delta T_{ji} = (T_n - T_{cw})/j$

This gives the general relation for the seawater temperature in the rejection section $T_{ji} = T_{cw} + (n-i+1)(\Delta T_{ji})$

Using the conservation of energy within each stage and some mathematical work, the total distillate flow rate is obtained by summing the values of D_i for all stages (Hisham T. El-Dessouky, 2002). (D_i is the amount of flashing vapor formed in each stage)

$$M_d = M_r [1 - (1 - y)^n] \quad (42)$$

$$M_f = \frac{X_b}{X_b - X_f} M_d \quad (43)$$

In which M_r is brine recycle flow rate and y is the specific ratio of sensible heat and latent heat and are equal to (Hisham T. El-Dessouky, 2002):

$$M_r = \frac{M_s \lambda_s}{C_p (T_0 - T_{r1})}, \quad T_{r1} = T_n + (n - j) \Delta T \quad (44)$$

$$y = \frac{C_p \Delta T}{\lambda_{ave}} \quad (45)$$

Where C_p is the specific heat capacity and λ_{ave} is the average latent heat calculated at the average temperature $T_{av} = (T_0 + T_n)/2$ (Hisham T. El-Dessouky, 2002)

The Gain Output Ratio (GOR) is a measure of water produced relative to steam consumed. Specifically, Gain Output Ratio (GOR) is defined as: (kilograms desalinated water produced) / (kilograms steam condensed)

$$GOR = \frac{\dot{m}_d}{\dot{m}_s} \quad (46)$$

3.2. Economic Modeling

The main objective of economic modeling is to calculate the cost of produced power and desalinated water as well as the total annual profit of the plant. Cost of produced power and water is a function of the net power and water output, capital investment of the plant, fixed and variable operating and maintenance cost, fuel price, etc. since each system is different from other systems from several aspects, its cost of power and water would be different. Below, the process of calculating the two is outlined.

3.2.1. Cost of Produced Power

The cost of produced power is primarily composed of four parts. All of which would be in \$/kWh.

3.2.1.1. Capital Investment

Capital investment of a thermal system is composed of several parts, including purchase equipment costs of specialized equipments (gas turbine, steam turbine, HRSG, condenser, gasifier, etc.), purchase equipment costs of other equipments (pumps, tanks, cooling tower, etc.), civil and structural works, mechanical works (equipment erection and piping), electrical and wiring works and plant startup and engineering services. Purchase equipment costs of the plant components are listed in table 3.

Cost data are often presented as cost versus capacity charts, or expressed as a power law of capacity (Smith, 2005).

$$C_E = C_B \times \left(\frac{Q}{Q_{base}} \right)^M \quad (47)$$

Where C_E is equipment cost with capacity Q , C_B is known base cost for equipment with capacity Q_B and M is constant depending on equipment type.

Such data can be brought up-to-date and put on a common basis using cost indexes. Commonly used indices are Marshall and Swift, published in Chemical Engineering magazine. The cost concerning capital investment is calculated according to the following formula (Smith, 2005):

$$\text{cost}_{capital} = \frac{CAP \times 10^6 \times CRF}{P \times 365 \times 24000 \times av} \quad (48)$$

In which CAP is the total money invested for power generation components in million dollars, CRF is the Capital Recovery Factor and is obtained by the following formula (Smith, 2005):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (49)$$

Table 7. Range of decision variables

Decision variable	Upper bound	Lower bound
HP steam pressure (bar)	88	50
HP steam temperature(C)	510	450
LP steam pressure (bar)	4	1.5
Evaporator1 pinch temperature(C)	20	5
Evaporator 1 approach temperature(C)	20	3
Evaporator 2 pinch temperature(C)	20	5

Evaporator 2 approach temperature(C)		20	3
Table 8. Comparison between the base case and optimum case			
inputs	unit	Base case	Optimum Case
HP steam pressure	Bar	75	80.8001
HP steam temperature	C	490	485.9629
LP steam pressure	Bar	3	1.7824
Evaporator1 pinch temperature	C	5	8.69
Evaporator 1 approach temperature	C	5	19.25
Evaporator 2 pinch temperature	C	15	5.68
Evaporator 2 approach temperature	C	15	4.37
outputs			
Total annual profit	M\$	37.8662	41.8567
CHP efficiency	%	75.8172	80.8580
Net power output	MW	167.9568	171.4950
water production	MIGD	12.5946	13.9841
Total power cost	\$/kWh	0.0278	0.0260
Total water cost	\$/m ³	0.7135	0.7116

“*n*” and “*i*” are respectively the number of years that the plant is in operation and interest rate. *P* is the net power output of the plant in Mw and *avai* is the availability of the power generation plan which is defined as the ratio of the total days in year which the plant is in operation and produce power to the total days of a year. Refer to table 7 for the detail results.

3.2.1.2. Fixed Operating and Maintenance Cost

Fixed operating and maintenance cost of different power generation plants usually ranges from 10 to 40 \$/KW-year. For the configuration presented in this paper, this cost is as follows ("Thermo flow (GTpro module)":

$$FOM = 20 \frac{\$}{KW - year} \quad (50)$$

Since all the costs should be congruent (\$/kWh) the following formula is used:

$$cost_{FOM} = \frac{FOM}{3600 \times 24 \times avai} \frac{\$}{kWh} \quad (51)$$

3.2.1.3. Variable Operating and Maintenance Cost

This cost is usually expressed in \$/kWh. For a combined cycle power plant, similar to the herein scenario, a reasonable value is 0.002 \$/kWh according to the information of the plants currently in operation in Iran.

3.2.1.4. Fuel Cost

Considering the price of the fuel (methane) to be 0.003 \$/MJ LHV and using the following formula, the power cost, resulted from fuel price, can be calculated (Smith, 2005):

$$cost_{fuel} = 0.003 \times HR \quad (52)$$

HR is the Heat Rate in MJ/kWh and is calculated according to the following formula (Sonntag et al., 1998):

$$HR = \frac{0.0036 \times \dot{m} \times LHV}{P} \quad (53)$$

$\dot{m}$ is the fuel mass flow rate in Kg/s and LHV is the fuel Low Heating Value in KJ/Kg and *P* is the net power output in MW.

Thus the total cost of produced power in \$/kWh is the sum of the four parts mentioned above.

3.2.2. Cost of Produced Water

The cost of produced water is composed of three parts. All parts should be in \$/m³.

3.2.2.1. Capital Investment

Capital investment of a desalination system, like power generation system, is composed of several parts, the most important of which are brine heater, flashing stages, transferring pumps and related piping and civil and structural works.

Knowing the total capital investment of the desalination system in M\$, the following formula is used to find the corresponding cost term:

$$\text{cost } t_{\text{capital}_d} = \frac{\text{capital}_d \times \emptyset \times 10^6}{V \times 4500 \times 365 \times \text{avai}} \quad (54)$$

The fixed operating cost of a desalination system, according to the technical reports, is 0.1159 \$/m³ and the variable operating cost is 0.0783 \$/m³.

The total cost of produced water is the sum of the three parts mentioned above.

3.3. Results of Thermodynamic and Economic Modeling

Having finished the process of thermodynamic and economic modeling, the final results can be presented. In the table 3, the major data for economic calculations are mentioned. In table 4, the detailed results of thermodynamic and economic modeling are shown.

As it can be seen from table 4, the total cost of produced power is 0.0286 \$/kWh and total cost of produced water is 0.7408286 \$/m³. Also the total annual profit which comes from selling power and water to the market is 35.103 M\$ and the CHP efficiency is 67.08.

In table 5, a precise comparison between the outputs of the combined system, with and without inlet air cooling is shown. CHP efficiency, Total annual profit and the total cost of produced power and water are among the comparison parameters.

Table 5 shows that the configuration with inlet air cooling, in which the low pressure steam generated in HRSG, plus the low pressure steam leaving the back pressure steam turbine is used to feed the brine heater, has the higher total annual profit. This configuration is

optimized in the next section. The details of the optimization process are given in the next section.

4. Optimization

In order to achieve the optimal value of decision variables, an optimization algorithm should be employed. Although gradient descent methods are the most elegant and precise numerical methods to solve optimization problems, however, they have the possibility of being trapped at local optimum points depending on the initial guess of solution. Stochastic optimization methods such as genetic algorithm (GA) and Particle Swarm Optimization (PSO) seem to be promising alternatives for optimization problems similar to this paper's configuration. In general, they are robust search and optimization techniques, able to cope with ill-defined problem domain such as multimodality, discontinuity and time-variance (Shakib et al., 2012). GA is a population based optimization technique that searches the best solution of a given problem based on the concepts of natural selection, genetics and evolution (Holland, 1992). PSO is a heuristic population based optimization algorithm simulating the movement and flocking of birds (Modares & Naghibi Sistani, 2011).

In this work, genetic algorithm has been chosen as the optimization method with an economic objective function, namely the total annual profit.

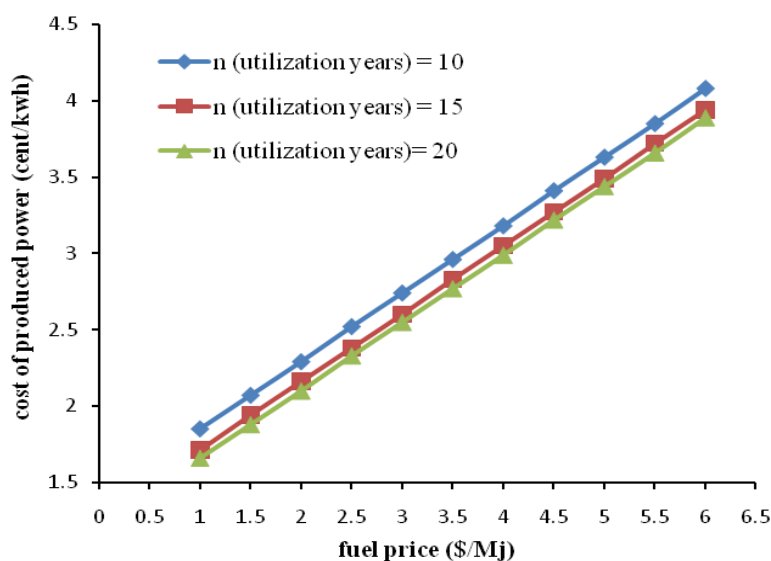


Figure 6. Cost of produced power as a function of fuel price

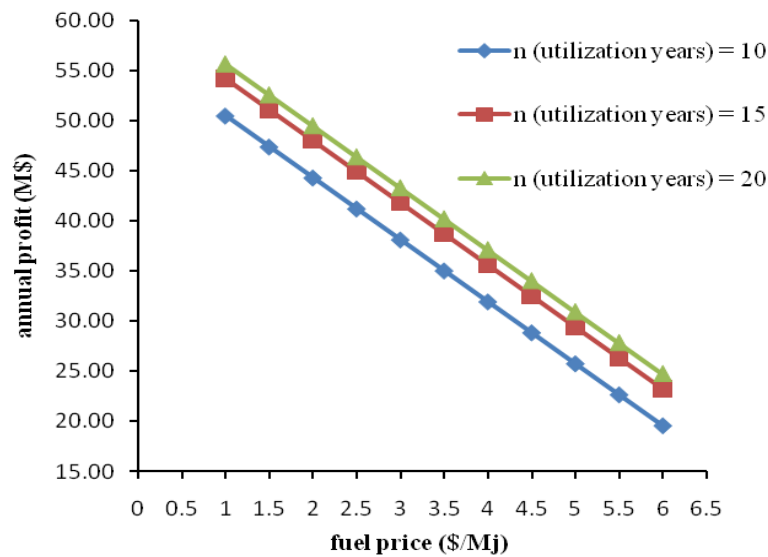


Figure 7. Annual profit as a function of fuel price

4.1. Optimization Approach

The first stage in an optimization problem is to fully specify system parameters (which are considered fixed values during optimization), decision variables (which are changeable within a certain limit) and dependent variables (which are actually the outputs of the problem). During the optimization process, objective function, that is the most important dependent variable, should be maximized (or minimized, depending on its nature) with changing the decision variables within their limits. These limits are dependent on the physical, mechanical and thermodynamic constraints. In the optimization phase, the best values of these variables for satisfying the objective function will be chosen by the optimizer. In this paper, in order to optimize the configuration, the following variables are chosen as decision variables:

- 1- The pressure of High Pressure (HP) steam of HRSG
- 2- The temperature of High Pressure (HP) steam of HRSG
- 3- The pressure of Low Pressure (LP) steam of HRSG
- 4- Pinch temperature difference of the first evaporator
- 5- Approach temperature of the first evaporator
- 6- Pinch temperature difference of the second evaporator
- 7- Approach temperature of the second evaporator

In table 6, the range of change of decision variables is shown. The major system parameters and dependent variables of this configuration were mentioned in previous sections.

4.2. Optimization Results

Once the thermodynamic and economic model of the combined system is built, the corresponding code (in MATLAB programming language) is created, the decision variables are decided and the physical constraints are exerted, the optimization process starts using the genetic algorithm toolbox of MATLAB. The optimum condition, in which the annual net profit is maximized, is achieved after several iterations. Table 8 presents the values of decision variables as well as dependent variables in the base case and optimum case. The table shows that the optimization, results in 10.5% increase in total annual profit and 6.6% increase in CHP efficiency.

4.3. Impact of the Economic and Thermodynamic Parameters on Objective Function and Cost of Produced Power

Economic parameters (for example fuel price, power sale price, water sale price, utilization years, etc.) have a great impact on the final results, including the net annual profit. In the modeling phase as well as the optimization phase, specific values for economic parameters are chosen, for example, the fuel price considered to be 3 \$/GJ (LHV), Interest rate to be 15% and so on (refer to table 6). Furthermore, thermodynamic variables (for example pressure of HP and LP steam) have the similar effects on final results and are of great importance. In this section, the impact of important economic and thermodynamic parameters on the cost of produced power and the net annual profit of the optimum case is evaluated. In the figure 6 and figure 7, the cost of produced power and the net annual profit as a function of fuel price and utilization years

are shown respectively. The range of change of fuel price is from 1 \$/GJ (LHV) to 6 \$/GJ (LHV). As it can be seen, for fuel price of 1 \$/GJ (LHV) and utilization years of 10, 15 and 20, the cost of produced power are 1.85, 1.71 and 1.66 cent/kWh respectively. It is predictable that by increasing the years of utilization of the combined system, the cost of produced power will decrease. It is also observable that the annual profits, for fuel price of 1 \$/GJ (LHV) and utilization years of 10, 15 and 20, are 50.55, 54.25 and 55.72 M\$ respectively. These figures also show that, for utilization years of $n = 15$, increasing the fuel price to 6 \$/GJ (LHV) will increase the cost of

produced power to 3.94 Cent/kWh and decrease the net annual profit to 23.26 M\$.

Figure 8 shows the annual profit as a function of PSP (power sale price) and WSP (water sale price). Apparently, increasing the two will increase annual profit with a trend shown in the figure. As it is shown in the figure 8, for power sale price of 3.5 cent/kWh, and water sale price of 0.5, 0.8, 1.11 and 1.5 $\text{\$/m}^3$, the annual profits will be 7.97, 14.35, 20.95 and 29.25 M\$ which is almost a linear trend. It is evident that power sale price effect is dominant in annual profit of the system as a larger portion of the total profit is related to power selling.

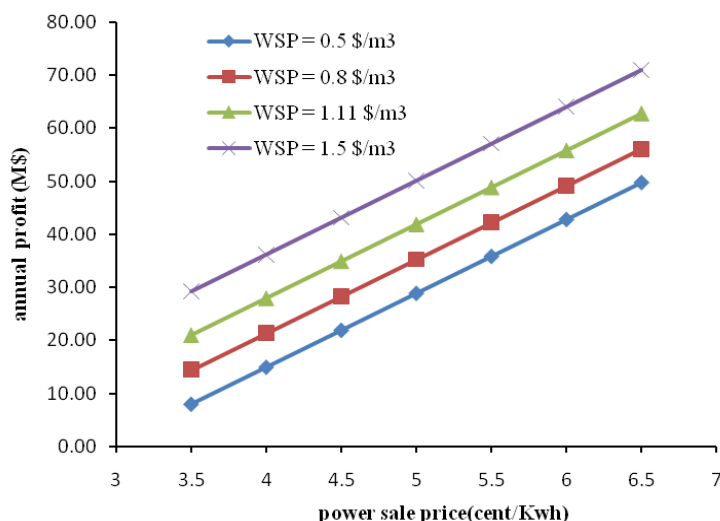


Figure 8. Annual profit as a function of power sale price

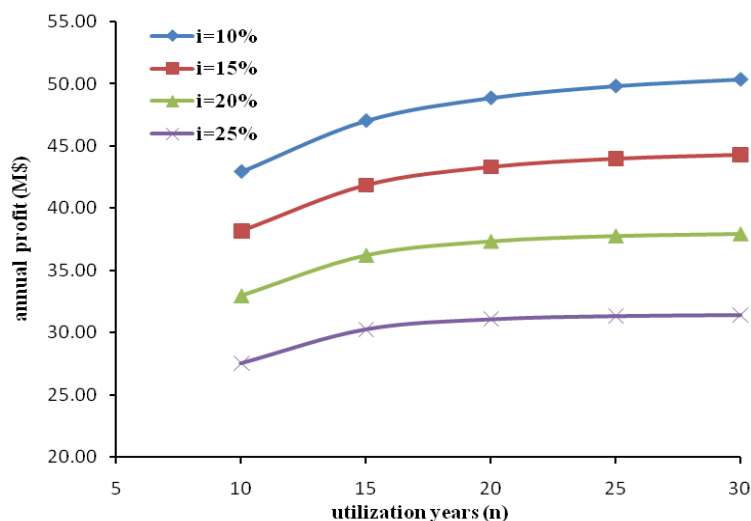


Figure 9. Annual profit as a function of utilization years

Next figure, figure 9, shows the annual profit as a function of utilization years and interest rate. It is observed that increasing the interest rate will highly decrease the total annual

profit but increasing the utilization years, especially from 20 to 30, will have a marginal increase effect on annual profit. In fact, for 10 years of utilization, increasing the interest

rate from 10% to 25% will decrease the annual profit from 42.92 M\$ to 27.51M\$, but increasing the years of utilization from 20 to 30 will increase the annual profit from 48.87 M\$ to 50.36 M\$ (for fixed interest rate of 10%). In figure 10, the annual profit as a function of pressure and temperature of HP steam is shown. As it can be seen, increasing the steam pressure initially increases the annual profit, but further increase in steam pressure will no longer increase the annual profit, but instead, marginally decrease it. In fact, figure 10 shows that increasing the high pressure steam pressure from 50 bar to 75 bar (for high pressure steam temperature of 450 °C) will increase the annual profit for 135000 \$, but increasing this pressure from 75 bar to 100 (again for high pressure steam temperature of 450 °C) will conversely decrease the annual profit for 4000\$. On the other hand, increasing

the high pressure steam from 450 °C to 510 °C will increase the annual profit on almost a regular basis.

Figure 11 demonstrates the effect of LP steam pressure on the annual profit for three HP steam temperatures. It is observed that as a result of increasing LP steam pressure, the annual profit will decrease for all three HP steam temperatures. It is observed in figure 11 that the rate of decrease is quite the same for all three HP steam temperatures. It is observable that by increasing the LP steam pressure from 2 bar to 4 bar (for high pressure steam temperature of 450 °C), there would be a decrease of 2,274,000 \$ in annual profit which a considerable value. On the other hand, for fixed LP pressure of 2 bar, increasing the HP steam temperature from 450 °C to 510 °C will only increase the annual profit for 275,500 \$.

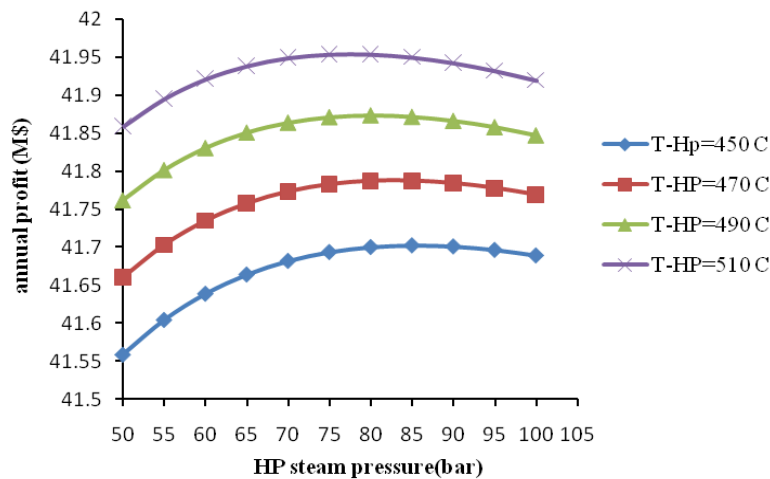


Figure 10. Annual profit as a function of HP steam pressure

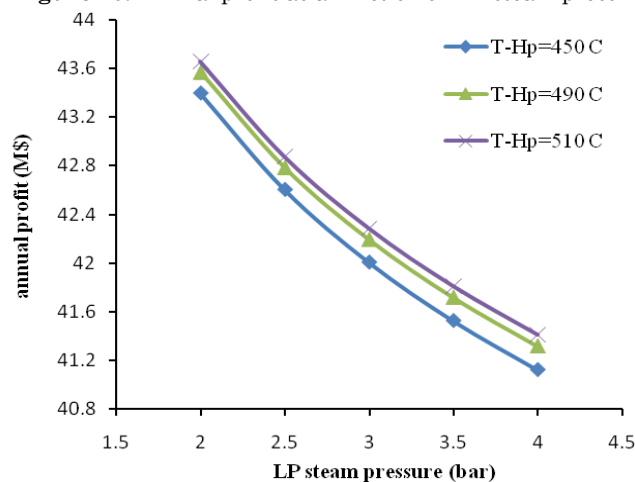


Figure 11. Annual profit as a function of LP steam pressure

5. Conclusion

In this paper, a novel thermal system for combined production of power and desalinated water was modeled and analyzed from both

thermodynamic and economic points of view. The impact of inlet air cooling on thermodynamic and economic performance of the configuration was also investigated. Optimization of the configuration was carried out next. The most

important outputs of the modeling were the net power output, total desalinated water produced, CHP efficiency, total power cost, total water cost and finally net annual profit. The results of modeling showed that the configuration had a relatively high total annual profit and the CHP efficiency. In the next section, the configuration was optimized through genetic algorithm method. Total annual profit of the combined system was chosen as objective function. The optimization process resulted in 10.5% increase in total annual profit and 6.6% increase in CHP efficiency. Evaluation of the impact of important economic and thermodynamic parameters on objective function was done in the last section. It showed the effects of fuel price, power sale price, water sale price, utilization years, interest rate and HP and LP conditions on net annual profit and cost of produced power.

Nomenclature

a	mole of CO per mole of biomass
A_{HRSG}	Heat Recovery Steam Generator Area (m^2) adjacent fins of exchanger
A_{hx}	Heat exchanger area (m^2)
$avai$	Availability
b	mole of CO ₂ per mole of biomass
c	mole of H ₂ per mole of biomass
CAP	Total Capital Cost (M\$)
$Capital_d$	Capital cost of desalination system (M\$)
C_B	equipment cost with capacity Q_B (Base capacity)
C_E	equipment cost with capacity Q
C_p	Specific heat capacity at constant pressure (KJ/Kg)
d	mole of CH ₄ per mole of biomass
e	mole of H ₂ O per mole of biomass
E	energy (KJ)
f	mole of N ₂ per mole of biomass
FA	Filter Area (m^2)
g	mole of O ₂ per mole of biomass
GOR	Gain Output Ratio (Kg desalinated water produced / Kg steam condensed)
$G_{T,i}^0$	Gibbs free energy (KJ/Kmol)
h	Enthalpy (KJ/Kg)
h	enthalpy (KJ/Kmol)
HP	High pressure
HR	Heat Rate (MJ/kWh)
$\bar{h}$	Molar enthalpy (KJ/Kmol)
h_f^0	enthalpy of formation (KJ/Kmol)
i	mole of SO ₂ per mole of biomass
i	Interest rate
K	Ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume
K	equilibrium constant

M	Flow rate (in desalination system analysis only)
M_a	Molecular weight of air (Kg/Kmol)
M_f	Molecular weight of fuel (Kg/Kmol)
M_r	brine recycle flow rate (Kg/s)
$\dot{m}$	Mass flow rate (Kg/s)
n	The number of recovery and rejection stages of MSF
n	Utilization years
n_i	mole of i^{th} component of producer gas
n_T	total mole of producer gas
P	Pressure (bar)
Q_{in}	heat input to gasifying process (preheating)
Q_{out}	heat output of gasifying process (heat loss)
$\dot{Q}$	Time rate of heat (KJ/s)
$react$	reaction reactants
R_u	universal constant
T	Temperature (C)
TBT	Top Brine Temperature (C)
TTD	Terminal Temperature difference (C)
V	Desalinated water production per day (m^3/day)
w	H ₂ O molar fraction in biomass
$\dot{W}$	Time rate of work (KJ/s)
x	Ambient air molar composition
X	salt concentration
y	the specific ratio of sensible heat and latent heat
Subscript	
a	air
av	average
b	brine
$base$	Base case
cw	Cooling water
d	distillate
db	dry base
f	feed
f	Fuel
i	Stage of desalination system
m	H atoms substitution formula
p	product
p	O atoms substitution formula
pg	producer gas
q	N atoms substitution formula
r	S atoms substitution formula
Greek letters	
η_{st}	Isentropic efficiency of turbine
η_{sc}	Isentropic efficiency of compressor
η_{sp}	Isentropic efficiency of pump
η_{mt}	Mechanical efficiency of turbine
η_{mc}	Mechanical efficiency of compressor
η_{mp}	Mechanical efficiency of pump
λ	latent heat
ΔT	the temperature drop per stage

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