

**ANKARA YILDIRIM BEYAZIT UNIVERSITY**

**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**



**THERMOECONOMIC OPTIMIZATION FOR A SOLAR ASSISTED  
ABSORPTION COOLING SYSTEM**

**M.Sc. Thesis by**

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**July, 2019**

**ANKARA**

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**by**

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## M.Sc. THESIS EXAMINATION RESULT FORM

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**2019, 25 July**

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# THERMOECONOMIC OPTIMIZATION FOR A SOLAR ASSISTED ABSORPTION COOLING SYSTEM

## ABSTRACT

Turkey receives more solar energy than many countries in the world due to the geographical location. The Mediterranean and South East of the Turkey has the most solar energy potential region. So, cooling is a serious need in these regions for ventilating conditions in many residences. Also, cooling is required for industrial and commerce purposes in other industrial regions. The use of solar energy in cooling systems provides to reduce the energy costs and emission of greenhouse gases which are produced by use of fossil fuels. In these reasons, *solar assisted absorption cooling systems* have become quite attractive in recent.

In this thesis, thermoeconomic optimization for a *solar assisted single effect LiBr/water absorption cooling system* is carried out. The temperature, pressure and mass flow rate of the fluids of the system are taken from the study in the literature. For this purpose, the thermodynamics methods depending on economic bases called *thermoeconomic analysis* are used. Thermoeconomic analysis combines *second law of thermodynamics* with economic aspects. It causes us to save energy and evaluates the cost of the system.

In this thesis, energy and exergy balances for the system components are firstly calculated by *EES program*. Also, the costs of the inlet and the outlet streams are calculated by *Matlab Program*. Then, the optimum design temperatures are found in order to maximizing some system parameters. Then, the total product cost rate for the system is also calculated. Also, the total product cost rate for base case and optimum case are compared. Also, the optimum exergetic efficiency and exergoeconomic factor are determined for base and optimum case. At the end of the thesis, the base case's and optimum case's some parameters are compared. Comparison results are also given by using literatures.

**Keywords:** Solar, solar assisted, absorption cooling, optimization, thermoeconomic optimization, cooling, cost

# GÜNEŞ DESTEKLİ BİR ABSORBSİYONLU SOĞUTMA SİSTEMİ İÇİN TERMOEKONOMİK OPTİMİZASYON

## ÖZ

Türkiye coğrafi konumu nedeniyle dünyadaki birçok ülkeden daha fazla güneş enerjisine sahiptir. Akdeniz ve Güneydoğu Anadolu bölgesi Türkiye'nin en fazla güneş enerji potansiyeline sahip olan bölgeleridir. Dolayısıyla bu bölgelerde soğutma ciddi bir ihtiyaçtır. Ayrıca, ülkemizin diğer birçok bölgesinde sanayi ve ticaret amaçlı olarak da soğutma gereklidir. Soğutma sistemlerinde güneş enerjisinin kullanılması, enerji maliyetlerinin düşürülmesine ve fosil yakıtlar kullanılarak üretilen sera gazı emisyonunun azaltılmasına olanak sağlar. Bu nedenlerle, güneş enerjili absorbsiyon sistemleri son yıllarda soğutma sistemlerinde oldukça cazip hale gelmiştir.

Bu tezde, güneş enerjisi destekli tek etkili LiBr / H<sub>2</sub>O akışkanlı absorbsiyonlu soğutma sistemi için termoeconomik optimizasyon çalışması yapılmıştır. Sistemin sıcaklık, basınç, kütleli debi değerleri literatürden alınmıştır. Termoeconomik analiz, termodinamiğin ikinci yasasını ekonominin yasalarıyla birleştirir. Bu analiz aynı zamanda enerji tasarrufunu ve sistemin maliyetinin değerlendirilmesine olanak sağlar.

Bu tezde, ilk olarak enerji ve ekserji analizleri EES programı tarafından hesaplanmıştır. Ayrıca, her bir bileşenin giriş ve çıkış akış maliyeti, Matlab programından yararlanarak hesaplanmıştır. Ürün maliyeti hesaplandıktan sonra, sistemin maliyetini en aza indirmek amacıyla optimum çalışma sıcaklıkları elde edilmiştir. Daha sonra sistemin normal durum maliyeti ile optimum maliyeti karşılaştırılmıştır. Ayrıca sistemin optimum ekserji verimi ve ekserji ekonomik faktörü de sistemin durumu ve optimum durumu için hesaplanmıştır. Çalışmanın sonunda da sistemin durumunun ve optimum durumunun karşılaştırması yapılarak, sonuçları verilmiştir.

**Anahtar Kelimeler:** Güneş, güneş destekli, absorbsiyonlu soğutma, optimizasyon, termoeconomik optimizasyon, soğutma, maliyet

## CONTENTS

M.Sc. THESIS EXAMINATION RESULT FORM.....	ii
ETHICAL DECLARATION .....	iii
ACKNOWLEDGMENTS .....	iv
ABSTRACT.....	v
ÖZ .....	vi
NOMENCLATURE .....	ix
LIST OF TABLES.....	xi
LIST OF FIGURES .....	xii
<b>CHAPTER 1- INTRODUCTION.....</b>	<b>1</b>
1.1 Review of Related Works .....	2
1.2 Aim of the Study .....	5
1.3 Original Contribution .....	5
<b>CHAPTER 2 - BASICS OF THE ABSORPTION COOLING SYSTEM .....</b>	<b>6</b>
2.1 Classification Of Absorption Cooling System .....	6
2.1.1 Single Effect Absorption Cooling Systems.....	6
2.2 Comparison between LiBr/ water and NH <sub>3</sub> /water Refrigerants .....	8
2.3 Crystallization Limit For LiBr/water Solutions.....	9
2.4 Absorption Cooling System Components .....	10
2.4.1 Generator .....	11
2.4.2 Condenser.....	12
2.4.3 Expansion valve .....	12
2.4.4 Evaporator .....	13
2.4.5 Absorber .....	13
2.4.6 Pump.....	14
2.4.7 Heat Exchanger .....	14
<b>CHAPTER 3 - SUN COLLECTORS .....</b>	<b>15</b>
3.1 Flat Plate Collectors.....	16
3.1.1 Collector Overall Heat Loss Coefficient.....	17
3.1.2 Standard Fin Efficiency and Collector Efficiency Factor .....	19
3.1.3 Collector Heat Removal Factor And Flow Factor .....	20
3.1.4 The Collector Efficiency and Required Collector Numbers.....	21



<b>CHAPTER 4 - THERMODYNAMIC ANALYSIS OF THE SYSTEM.....</b>	<b>23</b>
4 .1 Coefficient of Performance (COP) .....	25
<b>CHAPTER 5 - EXERGY ANALYSIS .....</b>	<b>26</b>
5 .1 Exergy Calculations .....	27
<b>CHAPTER 6- COST ANALYSIS AND EXERGY COSTING .....</b>	<b>29</b>
6 .1 Thermoeconomic Expressions .....	32
<b>CHAPTER 7 - THERMOECONOMIC ANALYSIS AND OPTIMIZATION..</b>	<b>34</b>
7 .1 Obtain of $a_k, b_k, y_k$ Constants .....	39
7.1.1 Generator .....	39
7.1.2 Heat Exchanger Effectiveness.....	40
7.1.3 Evaporator Assembly .....	42
7.2 Thermoeconomic Optimization of the System .....	43
<b>CHAPTER 8 - DEFINING OPTIMAL DESIGN TEMPERATURES .....</b>	<b>45</b>
<b>CHAPTER 9 - OPTIMIZATION RESULTS.....</b>	<b>52</b>
9.1 Exergy and Cost Results of the System.....	53
9.2 Comparison of the Results with Other Studies.....	55
9.3 Optimization Results .....	56
<b>CHAPTER 10- DISCUSSION AND CONCLUSION.....</b>	<b>61</b>
<b>REFERENCES.....</b>	<b>63</b>
<b>APPENDICES .....</b>	<b>66</b>
<b>CURRICULUM VITAE .....</b>	<b>80</b>

## NOMENCLATURE

A	Heat transfer surface area ( $\text{m}^2$ )
a	Constant used in cost equation
b	Constant used in cost equation
B	Stefan Boltzmann constant ( $5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}$ )
C	Cost flow rate ( $\$/\text{h}$ )
COP	Coefficient of performance (%)
D	Tube diameter (mm)
ex	Specific exergy rate ( $\text{kJ/kg}$ )
Ex	Exergy flow rate (kW)
f	Exergoeconomic factor (%)
F	Fin efficiency (%)
h	Specific enthalpy ( $\text{kJ/kg}$ )
k	Thermal conductivity coefficient ( $\text{W/mK}$ )
L	Thickness (mm)
$\dot{m}$	Mass flow rate ( $\text{kg/s}$ )
N	Number
Q	Heat transfer rate (kW)
R	Other O&M cost ( $\$$ )
s	Specific entropy ( $\text{kJ/kgK}$ )
T	Temperature
U	Overall heat transfer coefficient ( $\text{W/m}^2\text{K}$ )
$\omega$	Variable operation and maintenance cost ( $\$$ )
W	Wide (mm)
X	Heat exchanger effectiveness (%)
$\dot{Z}$	Total levelized cost ( $\$/\text{h}$ )

### Greek letters

$\alpha$	Indirect investment cost constant
$\beta$	Fixed O&M costs ( $\$$ )
$\delta$	Thickness (mm)
$\Delta T$	Temperature difference ( $^{\circ}\text{C}$ )
$\epsilon$	Exergetic efficiency (%)

$\eta$	Efficiency (%)
$\Delta C$	Cooling water cost (\$/hr)
$\xi$	Capital recovery factor
$\tau$	Operation hour per year (hr)

### Superscripts

Ph	Physical
Ch	Chemical
CI	Capital investment
OM	Operation and Maintenance

### Subscripts

1,2..	Stream points
a	Environment
abs	Absorber
cond	Condenser
con	Water concentration (%)
D	Destruction
e	exit
E	Evaporator
EE	Electrical energy
F	Fuel
g	Generator
H <sub>2</sub> O	Water
i	Inlet
k	kth component
L	Losses
out	Outlet
p	Product
P	Plate
r	Removal
ref	Reference
w	wind
y	Year

## LIST OF TABLES

<b>Table 3.1</b>	The properties of solar collector material.....	22
<b>Table 4.1</b>	The overall heat transfer coefficient and logarithmic mean temperature difference.....	24
<b>Table 5.1</b>	Fuel, product, loss of exergy formula of the absorption cooling system ..	28
<b>Table 6.1</b>	Exergy costing equations.....	30
<b>Table 7.1</b>	The $Z/E_P^{0.66}$ and $E_P/E_D$ results for different generator temperature .....	40
<b>Table 7.2</b>	The $Z/E_P^{0.16}$ and $E_P/E_D$ results for different heat exchanger effectiveness	41
<b>Table 7.3</b>	The $Z/E_P^{0.66}$ and $E_P/E_D$ results for evaporator assembly .....	42
<b>Table 9.1</b>	Exergy and cost results.....	53
<b>Table 9.2</b>	Exergy analysis results .....	54
<b>Table 9.3</b>	Thermoeconomic analyzing results.....	55
<b>Table 9.4</b>	Solar collector results .....	55
<b>Table 9.5</b>	COP comparison results .....	56
<b>Table 9.6</b>	Exergy comparison results in system .....	56
<b>Table 9.7</b>	Base and optimum case temperature comparison results.....	57
<b>Table 9.8</b>	Base and optimum case comparison results .....	58
<b>Table 9.9</b>	$\Delta E$ and $\Delta f$ results for the base case .....	59
<b>Table 9.10</b>	$\Delta E$ and $\Delta f$ results for the optimum case .....	60

## LIST OF FIGURES

<b>Figure 2.1</b>	Schematic view of a solar assisted an absorption cooling system .....	7
<b>Figure 2.2</b>	Evaporator assembly scheme.....	7
<b>Figure 2.3</b>	The crystallization limit for LiBr/water solution .....	10
<b>Figure 2.4</b>	A solar assisted absorption cooling system scheme .....	11
<b>Figure 2.5</b>	Schematic view of the generator with solar energy .....	12
<b>Figure 2.6</b>	Schematic view of the condenser .....	12
<b>Figure 2.7</b>	Schematic view of the expansion valve .....	13
<b>Figure 2.8</b>	Schematic view of the evaporator .....	13
<b>Figure 2.9</b>	Schematic view of the absorber .....	14
<b>Figure 2.10</b>	Schematic view of the pump.....	14
<b>Figure 2.11</b>	Schematic view of the heat exchanger.....	14
<b>Figure 3.1</b>	The stationary solar collector (Evacuated tube type) .....	15
<b>Figure 3.2</b>	Concentrating solar collectors (Parabolic trough collector type) .....	16
<b>Figure 3.3</b>	Flat plate collectors .....	16
<b>Figure 3.4</b>	Flat plate collector components .....	17
<b>Figure 3.5</b>	Sheet and tube configuration .....	19
<b>Figure 7.1</b>	Plot of $Z/ E_P^{0.66}$ versus $E_P/ E_D$ graph for the generator .....	40
<b>Figure 7.2</b>	Plot of $Z/ E_P^{0.16}$ versus $E_P/ E_D$ graph for the heat exchanger .....	41
<b>Figure 7.3</b>	Plot of $Z/ E_P^{0.66}$ versus $E_P/ E_D$ graph for the evaporator assembly .....	43
<b>Figure 7.4</b>	Thermoeconomic optimization flow chart of the system .....	43
<b>Figure 8.1</b>	Variation of COP for different evaporator temperature .....	45
<b>Figure 8.2</b>	Variation of exergetic efficiency for different evaporator temperature ..	46
<b>Figure 8.3</b>	Variation of exergoeconomic factor for different evaporator temperature .....	46
<b>Figure 8.4</b>	Variation of $C_D+C_L$ factor for different condenser temperature .....	47
<b>Figure 8.5</b>	Variation of exergetic efficiency for different condenser temperature ...	47
<b>Figure 8.6</b>	Variation of exergoeconomic factor for different condenser temperature .....	48
<b>Figure 8.7</b>	Variation of COP for different condenser temperature .....	48
<b>Figure 8.8</b>	Variation of exergetic efficiency for different generator temperature ....	49

<b>Figure 8.9</b> Alteration of exergoeconomic factor for different generator temperature .....	49
<b>Figure 8.10</b> Alteration of COP for different generator temperature .....	50
<b>Figure 8.11</b> Alteration of $C_D+C_L$ for different generator temperature .....	50
<b>Figure 8.12</b> Alteration of exergoeconomic factor for different absorber temperature .....	51



# CHAPTER 1

## INTRODUCTION

Fossil fuels cause the some environmental problems such as air and water pollution, greenhouse gases release and global warming. However, the renewable energy sources such as sun, wind, geothermal can be used in terms of fossil fuels in many application areas. Also, solar energy could be used in many application areas because of easy access, cheap, abundant, clean and environmental friendly. Solar energy can be used in heating, cooling and generating electricity in many places.

Solar energy can be supplied a large ratio of the energy consumption used in the world. The amount of the solar energy arriving the Earth in a year is 160 times that of fossil fuel sources known in the world. It is also 15,000 times more than the power plants which are working by using fossil fuels and nuclear fuels and hydroelectric plants on the world. Also, it is an abundant, continuous, renewable and free energy source. So, it is an alternative to fossil fuels [1].

Solar energy can be used for cooling purposes such as food protection or providing in cooling comfort conditions in the buildings of commercial and residences. Accordingly, the solar energy is used in an absorption cooling systems with many advantages. Energy consumptions of these systems are lower than the other cooling systems. Also, small numbers of the moving parts of the system, the low maintenance costs, refrigerants that do not damage the ozone layer make the absorption systems quite attractive. Additionally, the absorption system can also use the other cheap energy sources such as geothermal, waste heat energy coming from industrial plants [2, 3].

Absorption cooling system was first invented by French scientist Ferdinand Carre in 1860. In the early years of the twentieth century, the absorption cooling system was become very popular. The first invention of absorption cooling machine was designed in U.K. After 1920s, advanced studies of the absorption cooling system were continued especially in USA, Germany, Italy, England and Russia. The production of largest

absorption cooling plant had 4190 kW as a cooling capacity about 1920s. In the 1950s, LiBr/water working fluid systems were used commercially in the air conditioning of large buildings. Those days, required heat energy of the absorption cooling system was supplied from steam or hot water which was obtained from boilers by using natural gas or fuel oil. In the 1970s, different methods were searched for providing the cheap energy. In this respect, the solar energy and waste heat energy from industrial plants has been started to use for the absorption cooling systems. This system is still used for cooling in many places such as large building, hotel, university and ice rink [2, 3].

### **1.1 Review of Related Works**

The performance of the absorption cooling systems has been extensively investigated in terms of both first and second law of thermodynamics. Thermo-economic analysis with optimization of the system is also studied by many researchers in recent years. It has been used analytically, numerically and experimentally. Some of the studies in the literature are given below [4].

Firstly, an experimental study has been established by Daşkın and Aksoy. This study is about simulation of a solar assisted absorption cooling system design for an air conditioning in İnönü University Engineering building. In this study, HAP (Hourly Analysis Program) is used for calculation of cooling capacity of a building. Working liquids are LiBr/ water. The angle of inclination of the collector was found to benefit the maximum amount of the sunlight. The solar utilization rates depending on the variable parameters are calculated according to the months in this research [4, 5].

Kent and Kaptan studied the solar assisted absorption heating and cooling systems for a hotel in İzmir. The solar energy was used to provide both heating and cooling needs. Total cost of the system and payback period was calculated in this study [4, 6].

In another study, ice rink cooling by using a solar assisted absorption system is analyzed. The consumption of the energy for the system was supplied by using solar collectors. The total energy requirement was supplied for working of the system at design temperatures in a steady state. The impact of the design parameters on performance of the system was examined [4, 7].



Özkan investigated the efficiency of an absorption cooling system theoretically and practically in a hotel in İzmir. Heating and cooling were supplied by using absorption heat pumps and chillers. Theoretical and practical examination of COP results was compared [3, 4].

Kaya analyzed a single effect absorption cooling systems based on the exergetic performance criterion (EPC). Two different working fluids (LiBr/H<sub>2</sub>O and NH<sub>3</sub>/H<sub>2</sub>O) are used. The exergetic performance coefficient (EPC) results are compared for two systems. Also, the effects of parameters on COP and EPC are found [4, 8].

Rameshkumar investigated the simulation of a solar assisted absorption cooling system for heating and cooling system needs. The coefficient of performance (COP) at various temperatures was also investigated. It was obtained that since the generator temperature decreases, COP increases [4, 9].

Shirazi et al. investigated the optimization of the solar assisted triple-effect LiBr/H<sub>2</sub>O absorption system. System was used to provide both cooling and heating requirements. The multi-objective optimization of the system was implemented by using genetic algorithm method in order to minimizing the total cost of the system [4, 10].

Şencan investigated the design and construction of the absorption cooling systems. LiBr/water used as a working fluid. Artificial Neural Network (ANN) method was used for determination of thermodynamic properties of the LiBr/water solution. The system parameters effect on the COP was investigated. Also, for determining the optimal design parameters of the absorption system for cooling and heating applications, Genetic Algorithm method (GA) was carried out [4, 11].

Solum et al. performed a study on double effect LiBr/water absorption cooling system. The effects of the system parameters on the COP were investigated [4, 12].

Florides et al. carried out a study on the simulation for a solar assisted absorption cooling system. Trnsys simulation program was used in this study. System optimization was performed in order to select the most appropriate collector, storage tank, generator and other parts of system [4, 13].

Birinci performed a study on the efficiency of an evacuated tube collector in a single effect absorption cooling system. The evacuated tube collector efficiencies were compared to other type collectors. Visual FORTRAN 6 program was used for the simulation. It was found that, maximum efficiency obtained from evacuated – tube collectors while the minimum system efficiency obtained from double – glazed collectors [4, 14].

Kodal et al. performed the thermoeconomic optimization for the absorption cooling systems and heat pumps. The optimal design parameters were investigated. Economical parameters and the system temperatures on the optimal performances were discussed [4, 15].

Mashayekh et al. carried out thermoeconomic optimization of the absorption cooling systems. In this study, optimal working conditions were obtained. Effect of the thermoeconomic parameters on the objective function, COP and refrigeration load was investigated [4, 16].

Misra et al. carried out the optimization for a single effect absorption cooling system. Study aimed the minimizing overall product cost rate. Simplified cost minimization methodology was applied. Optimum design conditions were obtained by using sequential optimization method. The results were compared for base and optimum case [4, 17]

Kızılkın et al. performed a study on an absorption cooling systems. The optimum heat exchanger areas in the system with corresponding operating temperatures were obtained this study [4, 18]

Yıldırım et al. carried out thermoeconomic analyze of an absorption system. In this study, it was accomplished by using "Structural Bond Coefficients Method". The optimum heat transfer areas were calculated. Internal irreversibility was reduced. Also, payback period was calculated [4, 19].

## **1.2 Aim of the Study**

The purpose of this thesis is the minimizing the total product cost rate with optimum design temperatures for a solar assisted absorption cooling system. Firstly, the exergy

analysis is carried out by using the EES program. Then, the cost analysis is made by using Matlab Computer Program. Also, thermoeconomic analysis is made which includes investment, operation and maintenance and fuel cost rate of the system. The analyzed system is considered as *base case* while the optimum design temperatures considered as *optimum case*. The optimum design temperatures are found in order to obtain optimum case parameters which are COP, cost rate of exergy destruction, cost rate of exergy loss, exergetic efficiency, exergoeconomic factor and total product cost rate. So, optimum case parameters are found and it can work more effective with these optimum parameters. Also, thermoeconomic optimization method is used because of the computing optimum exergetic efficiency, optimum exergoeconomic factor of the components and minimizing the total product cost rate of the system. Finally, the base case and optimum case results are compared.

### **1.3 Original Contribution**

The investment cost rate includes the fixed capital investment and other outlays costs. The fixed capital investment cost includes direct and indirect investment costs. Unlike other studies, this thesis considers the investment costs both fixed capital investment and other outlays costs. This approach results in obtaining more real investment cost for the system.

# CHAPTER 2

## BASICS OF THE ABSORPTION COOLING SYSTEM

### 2.1 Classification of Absorption Cooling System

Absorption cooling systems can be categorized as a half, single and multiple (double, triple, quadruple) effect. This categorization is performed according to the generator number and generators connections to each other.

A half effect absorption cooling system can be used relatively lower heat source temperature than heat sources temperatures of the other types. It has a condenser, an evaporator, two generators, two absorbers and two pumps, and three expansion valves. It has lower COP than single effect systems.

A single effect of an absorption cooling systems can be used relatively high temperature heat source than a half effect absorption cooling system. It has one generator with a condenser, an evaporator, a pump, a heat exchanger and two expansion valves. The single effect absorption cooling system working mechanism is explained with detail in below. It has higher COP than a half effect absorption cooling system.

A multiple effect system is used for higher temperature heat sources than other types. It has higher COP than others. But, investment costs are higher than other types [20].

#### 2.1.1 A Solar Assisted Single Effect Absorption Cooling Systems

The schematic view of a solar assisted single effect LiBr/water absorption cooling system is given in Figures 2.1 and 2.2. Water is used as a refrigerant while LiBr is used as absorbent [17]. The working mechanism is explained with detail in below [11]. The condenser, evaporator, absorber, and expansion valve and throttling valve are considered as *an evaporator assembly* in order to analyze the system more easily.

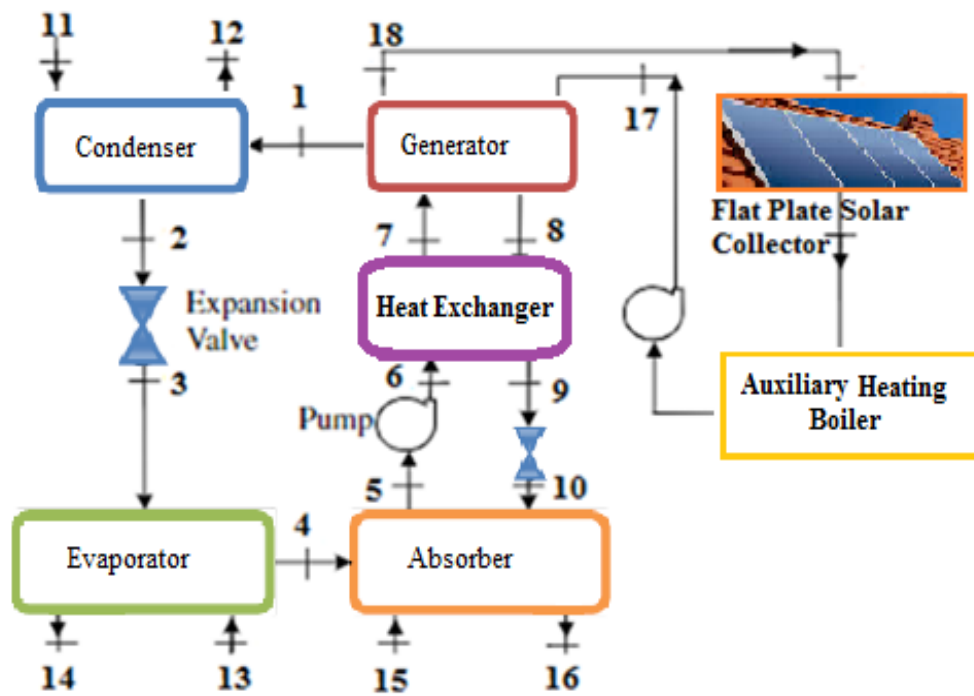


Figure 2.1 Schematic view of a solar assisted an absorption cooling system [21]

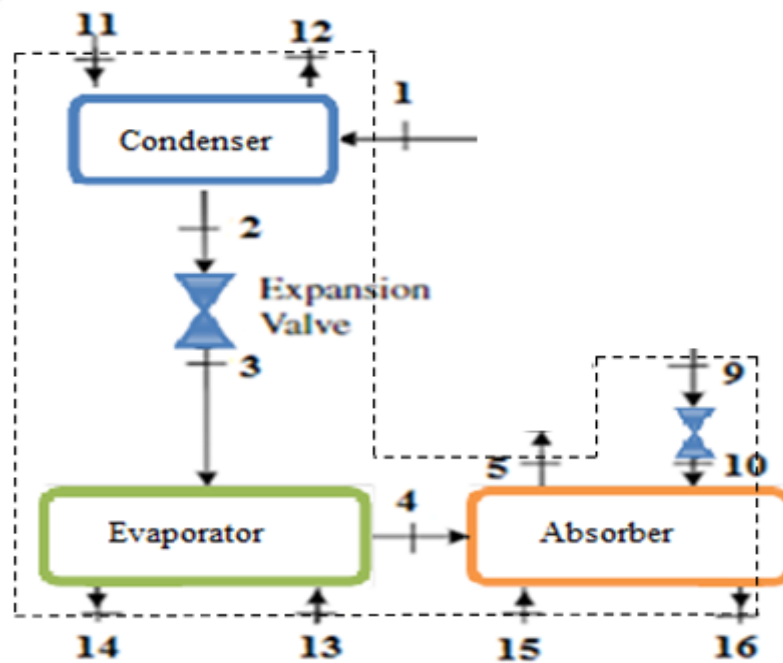


Figure 2.2 Evaporator assembly scheme [17]

Solar collectors are used for supplying steam to the generator as seen in Figure 2.1. In this system, superheated steam leaves the generator and enters to the condenser. In the condenser; the vaporized refrigerant becomes liquid by transferring heat to the cooling water. Then, it enters the expansion the valve where the refrigerant pressure is lowered at exit of the valve. The lower pressure refrigerant enters the evaporator and evaporates where heat is absorbed from the cooled space by water. The refrigerant vapor enters the absorber and is mixed with a weak solution. After the mixing, the solution is becoming a strong solution. Then, the strong solution is pumped to the generator by passing the heat exchanger. The water is separated from the absorbent by using the heat provided in the generator. The fluid which turns back to the absorber is becoming as a weak solution. This weak solution is used to heat strong solution in the heat exchanger. Then, weak solution pressure is lowered in the expansion valve and enters the absorber [4].

The meaning of the cooling water and the generator steam used in the system as seen in Figure 2.1 are given as below:

- 11 → 12 : Condenser cooling water flows
- 13 → 14 : Evaporator chilled water flows
- 15 → 16 : Absorber cooling water flows
- 17 → 18 : Generator steam flows

## 2.2 Comparison between LiBr/ water and NH<sub>3</sub>/water refrigerants

There are many absorbent and refrigerant fluid types for the absorption cooling systems. However, LiBr/water and NH<sub>3</sub>/ water are most widely used as the fluid couples in nowadays [22].

LiBr/water systems use water as a refrigerant and LiBr as an absorbent fluid while NH<sub>3</sub>/water systems use water as an absorbent and ammonia as a refrigerant fluid [22].

LiBr/water can't be used in the cooling spaces where the cooling temperature is below  $0^{\circ}\text{C}$ . However,  $\text{NH}_3/\text{water}$  systems can be used in the cooling spaces where the cooling temperature is below  $0^{\circ}\text{C}$ . So, LiBr/water systems are more used for air conditioning application in many large buildings which are hotels, universities etc. Also, ammonia  $\text{NH}_3/\text{water}$  systems are used in deep cooling applications such as ice rink [22].

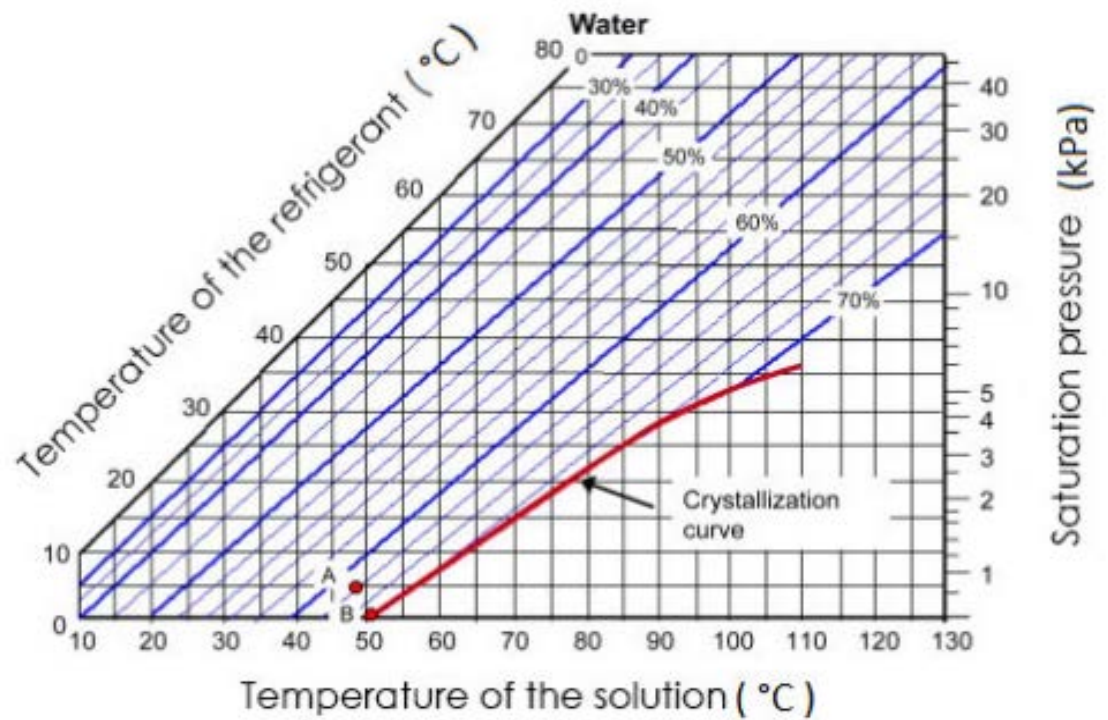
LiBr/water systems have also used due to that water has a high evaporation temperature, low cost, easy to find, and not toxic. But, LiBr/water systems have crystallization problem unlike  $\text{NH}_3/\text{water}$  systems. If the LiBr/water solution exceeds the crystallization limit, the flow may be blocked by the solid particles which were existed from the solid crystals. So, crystallization temperature should be considered in design of the absorption cooling systems [22, 23].

$\text{NH}_3/\text{water}$  systems haven't any crystallization problems. However, there are many problems coming from the practical applications in using of these systems. So, they can be used in many applications with some limitations. Ammonia reacts with copper and copper alloy materials. Hence, steel material should be used in these systems however it also increases the cost. The saturation pressure of ammonia is very high when it is compared to LiBr/water systems. So, these systems should need more thickness of the wall for the components used in the systems. Also, there is a risk that some water vapor can be transported from the generator to the condenser in these systems. In order to prevent it, rectifier must be placed in the system [22].

### **2.3 Crystallization Limit for LiBr/Water Solutions**

The solubility limit for LiBr/water solutions is very important issue for the system continuity. If the mass fraction of salt exceeds the solubility limit, the salt components will be precipitated and blocked the pipe. The solubility limit depends on the mass fraction and temperature. Mass fraction and temperature of the solution is more effect than the pressure of the solution on the solubility limit.

The crystallization limit for the LiBr/water is given in Figure 2.3 [24].



**Figure 2.3** The crystallization limit for LiBr/water solution [22]

The LiBr concentration used in the system is calculated by using some formulas given in Equation 2.1 and Equation 2.2. The range of concentration is also given in Equation (2.3). The system is properly worked only in the range of the concentration [25].

$$X_5 = \frac{49.04 + 1.125T_{abs} - T_{ev}}{134.65 + 0.47T_{abs}} \quad (2.1)$$

$$X_8 = \frac{49.04 + 1.125T_{gen} - T_{cond}}{134.65 + 0.47T_{gen}} \quad (2.2)$$

$$0.5 < X_5 \text{ or } X_8 < 0.65 \quad (2.3)$$

## 2.4 Absorption cooling system components

An absorption cooling system has main seven components which are generator, condenser, heat exchanger, pump, expansion valve, evaporator and absorber. The specific mission of the components is explained in detail as follows. The general scheme of the absorption cooling system is given in Figure 2.4.



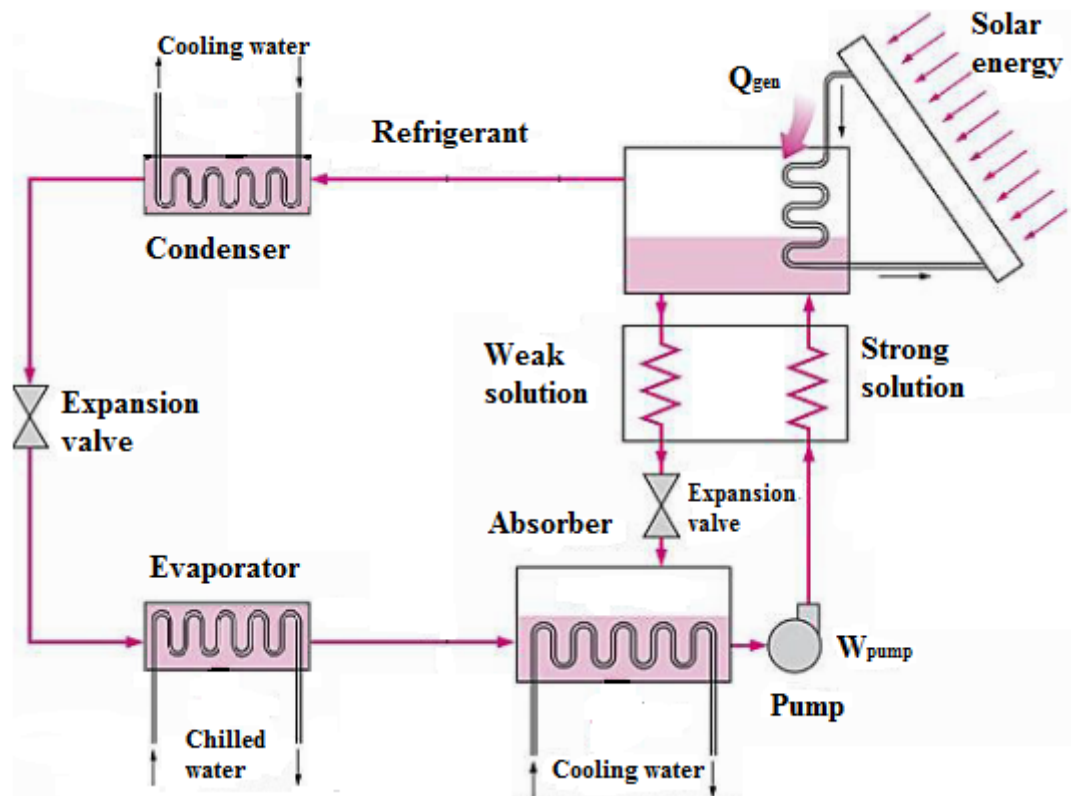
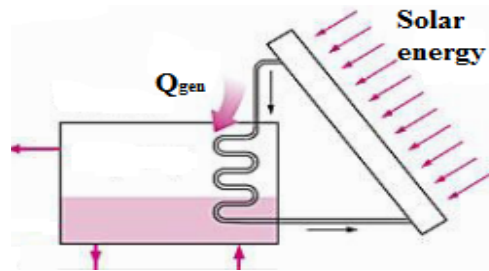


Figure 2.4 A solar assisted absorption cooling system scheme [26]

### 2.4.1 Generator

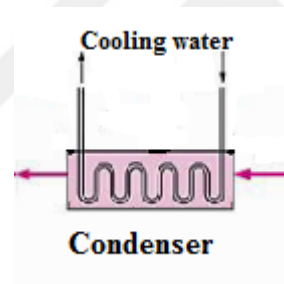
Generator is a component of the system which has one inlet and two outlets. The strong solution (coming from the absorber) enters the generator. Then, temperature of the LiBr/water strong solution is increased. While the strong solution boils, the refrigerant leaves the generator as a vapor form by using heat source. Then, the refrigerant goes to the condenser and weak solution returns back to the absorber. The generator is a 1 or 2 pass shell and tube type heat exchanger [20, 27]. The schematic view of the generator with solar collector is given as Figure 2.5 [26].



**Figure 2.5** Schematic view of the generator with solar energy [26]

### 2.4.2 Condenser

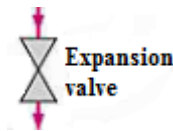
Condenser is a component of the system which purpose is cooling the refrigerant. The refrigerant leaves the condenser as a liquid form, and then enters the expansion valve. Condenser is used in absorption cooling systems which is generally 1 or 2 pass shell and tube type heat exchanger [20]. The schematic view of the condenser is given as Figure 2.6 [26].



**Figure 2.6** Schematic view of the condenser [26]

### 2.4.3 Expansion Valve

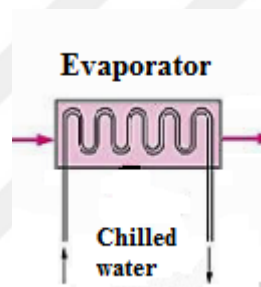
Two expansion valves are needed for the single effect absorption cooling systems. One of them is needed for the decreasing pressure of weak solution. Other one is needed to drop the pressure of the refrigerant suddenly. It also increases vapor content of the refrigerant [20]. The schematic view of the expansion valve is given as Figure 2.7 [26].



**Figure 2.7** Schematic view of the expansion valve [26]

#### 2.4.4 Evaporator

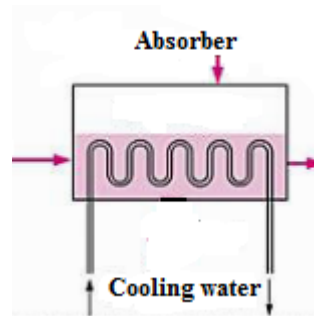
After the sudden pressure drop of the refrigerant in the expansion valve, the saturated high vapor content of the refrigerant enters the evaporator. The heat is absorbed from the cooled space and the refrigerant is vaporized. Then, vapor of the refrigerant leaves the evaporator and enters the absorber [20]. The schematic view of the evaporator is given as Figure 2.8 [26].



**Figure 2.8** Schematic view of the evaporator [26]

#### 2.4.5 Absorber

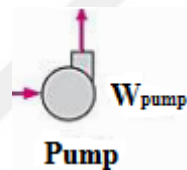
The Refrigerant coming from the evaporator and weak solution coming from the generator are mixed together and leaves the absorber as one fluid and strong solution. In this process, some heat is transferred to cooling water. The general scheme of the absorber is given as below Figure 2.4 [20]. The schematic view of the absorber is given as Figure 2.9 [26].



**Figure 2.9** Schematic view of the absorber [26]

#### 2.4.6 Pump

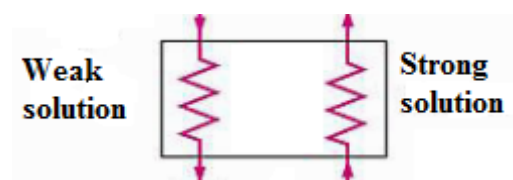
Pump is placed between the absorber and heat exchanger. The aim of the pump is to increase pressure of the strong solution [20]. The schematic view of the pump is given as Figure 2.10 [26].



**Figure 2.10** Schematic view of the pump [26]

#### 2.4.7 Heat Exchanger

Heat exchanger aim is the heat transfer from weak solution to strong solution. Double pipe heat exchanger can be used in the absorption cooling systems [20]. The schematic view of the heat exchanger is given as Figure 2.11 [26].



**Figure 2.11** Schematic view of the heat exchanger [26]

# CHAPTER 3

## SOLAR COLLECTOR

Solar collector is a heat exchanger which converts the solar energy to internal energy. Solar radiation is absorbed by the collectors, and it converted into heat. This heat is transferred to a fluid which flows through the collector. It can be used in order to heat the water directly or indirectly (by storing) [28].

The solar collector has two types which are stationary (non-concentrating) and concentrating. Stationary solar collector does not change its position according to the Sun movement. It has also three categories which are flat plate collector (FPC), stationary compound parabolic collector (CPC) and evacuated tube collector (ETC) Concentrating solar collector can change their position with the sun movement. It has also four categories which are parabolic trough collector, linear Fresnel reflector, parabolic dish, central receiver [27, 28]. The stationary and concentrating solar collector is shown in Figures3.1 and 3.2 [29].

The flat plate type of the collector (FPC) is used in this thesis. So, it is explained in detail below.



**Figure 3.1**The stationary solar collector (Evacuated tube type) [29]



**Figure 3.2** Concentrating solar collectors (Parabolic trough collector type) [30]

### 3.1 Flat plate collector

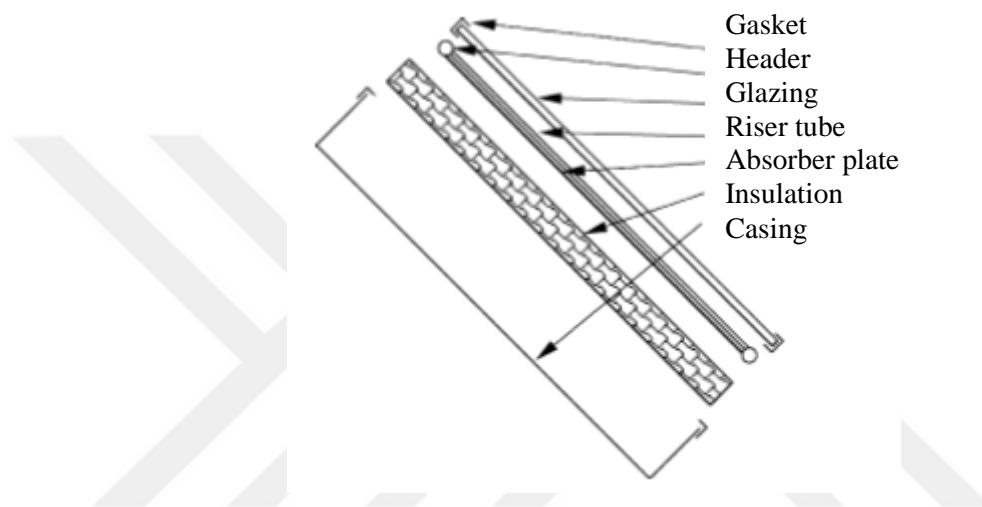
When the sunlight reaches the transparent cover and impinges the absorber surface, a large portion of this energy is absorbed by the plate. Then, this energy is transferred to the fluid in the tubes [28].

A flat plate solar collector is shown in Figure 3.3 [31]



**Figure 3.3** Flat plate collectors [31]

The bottom of the absorber plate and side of the casing should be well insulated in order to decrease the heat conduction losses. The liquid tubes can be welded or they can be a supplement part of the plate. The transparent cover is placed due to decreasing the heat losses. The flat plate collector is generally fixed and has not any tracking systems. It is advised that the collector is directed towards the Equator. The components of the flat plate consist of a gasket, header, glazing, riser tube, absorber plate, insulating and casing as shown in Figure 3.4 [32].



**Figure 3.4** Flat plate collector components [30]

### 3.1.1 Collector Overall Heat Loss Coefficient

Collector overall heat loss coefficient depends on some variables such as environment temperature, velocity of wind, collector construction and installation, transparent cover properties, absorber plate properties, insulation material type [32].

The collector overall heat loss coefficient can be expressed as follows [32, 33].

$$U_{Loss} = U_{Bottom} + U_{Top} + U_{Edge} \quad (3.1)$$

$U_{Back}$  = Back loss overall heat transfer coefficient ( $W/m^2\text{°C}$ )

$U_{Top}$  = Top loss overall heat transfer coefficient ( $W/m^2\text{°C}$ )

$U_{Edge}$  = Edge loss overall heat transfer coefficient ( $W/m^2\text{°C}$ )

The back loss overall heat transfer coefficient ( $U_{\text{Back}}$ ) can be calculated by assuming that the bottom surface of the temperature equals to the environment temperature. So,  $U_{\text{Back}}$  equation can be expressed as follows [32].

$$U_{\text{Back}} = \frac{k_y}{L_y} \quad (3.2)$$

Where  $k_y$  is heat conduction coefficient of insulation (W/m °C),  $L_y$  is insulation material thickness (mm).

The top loss overall heat transfer coefficient ( $U_{\text{Top}}$ ) can be expressed as following equation [32, 34].

$$U_{\text{Top}} = \left( \frac{N}{\frac{c}{T_{pm}} \left( \frac{T_{pm} - T_a}{N+f} \right)^e + \frac{1}{h_w}} \right)^{-1} + \frac{a(T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{(E_p + 0.00591 N h_w)^{-1} + \left( \frac{2N+f-1+0.133E_p}{E_g} \right)^{-N}} \quad (3.3)$$

Where

$$f = (1 + 0.089 h_w - 0.1166 h_w E_p) (1 + 0.07866N) \quad (3.4)$$

$$C = 520(1 - 0.000051\beta^2) \text{ for } 0^\circ < \beta^2 < 70^\circ, \text{ use } \beta = 70. \quad (3.5)$$

$$e = 0.430(1 - 100/T_{pm}) \quad (3.6)$$

$\beta$  = Collector tilt degree (°)

$N$  = Number of glass covers

$E_p$  = Emittance of plate

$E_g$  = Emittance of glass (0.88)

$T_{pm}$  = Mean plate temperature, (°C)

$T_a$  = Ambient temperature, (°C)

$h_w$  = wind heat transfer coefficient (W/m<sup>2</sup> °C)

Edge loss overall heat transfer coefficient ( $U_{\text{Edge}}$ ) can be expressed as following equation [32, 34].



$$U_{\text{Edge}} = \frac{k(L_1 + L_2)L_3}{L_1 L_2 L} \quad (3.7)$$

Where  $L_1$ ,  $L_2$ ,  $L_3$  is length, width and depth of the collector plate (mm), respectively.

### 3.1.2 Standard Fin Efficiency and Collector Efficiency Factor

The sheet-tube configuration is shown in Figure 3.5. The distance between the tubes is  $W$ , the tube diameter is  $D$ , and the sheet is thin with a thickness  $\delta$ . The temperature gradient through the sheet is negligible because that the sheet material is a good conductor. The sheet above the bond is assumed as at some local base temperature  $T_b$ . The region between the centerline separating the tubes and the tube base can be considered as a classical fin problem due to calculation of useful heat transfer rate [32].

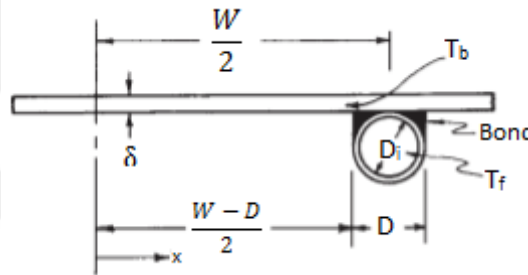


Figure 3.5 Sheet and tube configuration [32]

Hence, the straight fin efficiency for straight fins with rectangular profile and the collector efficiency factor can be calculated by using the equations as follows.

The standard fin efficiency for straight fins with rectangular profile ( $F$ ) can be expressed as follows [32].

$$F = \frac{\tanh\left(\frac{m(W-D)}{2}\right)}{\left(\frac{m(W-D)}{2}\right)} \quad (3.8)$$

The collector efficiency factor ( $F'$ ) can be written as follows [32, 34].

$$F' = \frac{1/U_L}{W\left(\frac{1}{U_L(D+(W-D)F)} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right)} \quad (3.9)$$

Where  $C_b$  is the bond conductance ( $\infty$  W/ m $^\circ$  C),  $D_i$  is the inside tube diameter (mm),  $h_{fi}$  is the heat transfer coefficient between the fluid and the tube wall (W/ m $^2$ °C). The bond conductance ( $c_b$ ) can be written as follows [32].

$$c_b = \frac{k_b b}{\gamma} \quad (3.10)$$

Where  $k_b$  is bond thermal conductivity (W/ m °C),  $\gamma$  is the average bond thickness (mm),  $b$  is the bond width (mm).

### 3.1.3 Collector Heat Removal Factor and Flow factor

Collector heat removal factor ( $F_R$ ) can be explained as the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. It can be written as follows [32].

$$F_R = \frac{\dot{m} C_p (T_0 - T_i)}{A_c (S - U_L (T_i - T_a))} = \frac{\dot{m} C_p}{A_c U_L} (1 - \exp(-\frac{A_c U_L F'}{\dot{m} C_p})) = F' F'' \quad (3.11)$$

Where  $m = \sqrt{\frac{U_L}{k\delta}}$ ,  $k$  is absorber plate thermal conductivity (W/ m °C)

The collector flow factor ( $F''$ ) is the ratio of the collector heat removal factor to the collector efficiency factor. It can be written as follows [32].

$$F'' = \frac{F_R}{F'} = \frac{\dot{m} C_p}{A_c U_L F'} (1 - \exp(-\frac{A_c U_L F'}{\dot{m} C_p})) \quad (3.12)$$

Also, useful ideal energy gain formula is given as below [32].

$$\dot{Q}_{u,ideal} = A_c (S - U_L (T_i - T_a)) \quad (3.13)$$

Where,  $T_i$  is water inlet temperature (°C),  $T_a$  is environment temperature (°C).

The collector heat removal factor times this maximum possible useful energy gain is equal to the actual useful energy gain. It is given as below [32].

$$\dot{Q}_{u,real} = A_c F_R (S - U_L (T_i - T_a)) \quad (3.14)$$

Where,  $A_c$  is the collector heat transfer area (m $^2$ ),  $I_t$  is solar radiation (W/m $^2$ ).

### 3.1.4 The Collector Efficiency and the Required Collector Numbers

The collector efficiency can be written as follows [34].

$$\eta = \frac{Q_{u,real}}{A_{collector} I_t} \quad (3.15)$$

Where,  $A_{collector}$  is the heat transfer area of the required collectors ( $m^2$ ),  $I_t$  is solar radiation ( $W/m^2$ ).

The heat transfer area of the required collectors can be written as follows [34].

$$A_{collector} = \frac{Q_{gen}}{\eta I_t} \quad (3.16)$$

Where,  $Q_{gen}$  is the heat transfer rate in the generator (kW),  $\eta$  is collector efficiency.

The required collector numbers can be written as follows [34].

$$\text{Number of collector} = \frac{A_{collector}}{A_c} \quad (3.17)$$

The properties of the solar collector are given in Table 3.1 [34].

**Table 3.1** The properties of the solar collector material [34]

The properties of the solar collector material	Species and values
The insulation material type	Glass wool
The insulation material thickness	40 mm
The thermal conductivity of the of the insulation material	0.045 W/mK
The glass covers number	1
The horizontal inclination of the collector	30°C
The absorber surface temperature	110°C
The environment temperature	30°C
Emittance of absorber plate	0.95
Velocity of wind	3 m/s
The dimension of the collector	2x1x 0.045 m
The absorber material	Copper
The absorber thermal conductivity	385 W/mK
The solar radiation	600 W/m <sup>2</sup>
The efficiency of solar collector	40%

# CHAPTER 4

## THERMODYNAMIC ANALYSIS OF THE SYSTEM

Energy can be transformed from one form to another by work and heat transfer. The total amount of energy is conserved in all transformations and transfers. The main aim of the realizing energy analysis is to determine the used and lost energies [35].

The general mass and energy balance equations of the components are given as Equation 4.1 and 4.2. The equations regarding with thermodynamic analysis of the system for all components are given in Equations 4.3-4.19 [5].

$$\sum m_{in} = \sum m_{out} \quad (4.1)$$

$$\sum (mh)_{in} + \sum Q_{in} = \sum (mh)_{out} + \sum Q_{out} \quad (4.2)$$

The equations for mass and energy balance of the *generator, condenser, evaporator, absorber and heat exchanger* are given as follows respectively [5].

$$\dot{m}_7 = \dot{m}_8 + \dot{m}_1 \quad (4.3)$$

$$\dot{m}_1 = \dot{m}_2 \quad (4.4)$$

$$\dot{m}_3 = \dot{m}_4 \quad (4.5)$$

$$\dot{m}_5 = \dot{m}_{10} + \dot{m}_4 \quad (4.6)$$

$$\dot{m}_6 = \dot{m}_7 \quad (4.7)$$

$$\dot{m}_8 = \dot{m}_9 \quad (4.8)$$

$$\dot{Q}_{gen} = (\dot{m}_7 h_7) + (\dot{m}_1 h_1) + (\dot{m}_8 h_8) \quad (4.9)$$

$$\dot{Q}_{cond} = (\dot{m}_1 h_1) - (\dot{m}_2 h_2) \quad (4.10)$$

$$\dot{Q}_{evap} = (\dot{m}_4 h_4) - (\dot{m}_3 h_3) \quad (4.11)$$

$$Q_{\text{abs}} = (\dot{m}_4 h_4) + (\dot{m}_{10} h_{10}) - (\dot{m}_5 h_5) \quad (4.12)$$

$$Q_{\text{hex}} = (\dot{m}_6 h_6) + (\dot{m}_8 h_8) = (\dot{m}_7 h_7) + (\dot{m}_9 h_9) \quad (4.13)$$

The mass and work equations of the pump are given as follows [5].

$$\dot{m}_5 = \dot{m}_6 \quad (4.14)$$

$$\dot{W}_p = \frac{v (P_{\text{out}} - P_{\text{in}})}{\eta_p} \quad (4.15)$$

$$\dot{W}_p = \dot{m}_p \dot{w}_p \quad (4.16)$$

The mass balance of the expansion valve is given as follows [5].

$$\dot{m}_9 = \dot{m}_{10} \quad (4.17)$$

$$\dot{m}_2 = \dot{m}_3 \quad (4.18)$$

$$h_2 = h_3 \quad (4.19)$$

The overall heat transfer coefficient (U) and logarithmic mean temperature difference ( $\Delta T_m$ ) of the components are given in Table 4.1. The required heat transfer area for the components can be calculated from the below equation [4, 36].

$$A = \frac{\dot{Q}}{U F \Delta T_m} \quad (4.20)$$

Where F is correction factor,  $\Delta T_m$  is logarithmic mean temperature difference.

**Table 4.1** The overall heat transfer coefficient and logarithmic mean temperature difference [36].

Components	U(W/m <sup>2</sup> K)	$\Delta T_m$
<b>Generator</b>	2300	$((T_{17}-T_8)-(T_{17}-T_7)) / \ln((T_{17}-T_8)/(T_{17}-T_7))$
<b>Condenser</b>	3265	$((T_1-T_{12})-(T_2-T_{11})) / \ln((T_1-T_{12})/(T_2-T_{11}))$
<b>Evaporator</b>	2200	$((T_{13}-T_3)-(T_{14}-T_4)) / \ln((T_{13}-T_3)/(T_{14}-T_4))$
<b>Absorber</b>	2000	$((T_{10}-T_{16})-(T_5-T_{15})) / \ln((T_{10}-T_{16})/(T_5-T_{15}))$

## 4.1 Coefficient of Performance (COP)

Coefficient of Performance (COP) is important for evaluation of the system. COP is given as follows [17].

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_P} \quad (4.21)$$

Where  $\dot{Q}_E$  is the heat transfer rate at the evaporator,  $\dot{Q}_G$  is the heat transfer rate at the generator,  $\dot{W}_P$  is the work of the pump.

The assumptions used in the absorption cooling system calculation are given as below [17].

- 1) The system is working in a steady state.
- 2) The refrigerant existing the condenser and evaporator is in a saturated liquid and a steam respectively.
- 3) The strong solution of the refrigerant leaving the absorber is saturated.
- 4) The weak solution of the refrigerant leaving the generator is saturated.
- 5) LiBr/water solutions in the generator and absorber are assumed in equilibrium at their respective temperatures and pressures.
- 6) Pressure losses in pipelines are neglected.
- 7) The reference state for the system is water at 25°C and 1 atm. pressure.

# CHAPTER 5

## EXERGY ANALYSIS

Exergy is shortly defined as an available energy to be used. If the nuclear, magnetic, electrical energy is absent in the system, the only physical and chemical exergy can be considered. So, only physical and chemical exergy in the absorption cooling system are considered. The total exergy (Ex) equation is given as below [4, 17, 37].

$$Ex = Ex^{Ph} + Ex^{Ch} \quad (5.1)$$

Where  $Ex^{Ph}$  (kW) is physical exergy and  $Ex^{Ch}$  (kW) is chemical exergy [4].

The obtainable work from initial state to thermal and mechanical equilibrium state with the environment is associated with the *physical exergy*. Its formula is given as below [4, 17].

$$Ex^{Ph} = \dot{m}((h - h_0) - T_0(s - s_0)) \quad (5.2)$$

Where  $\dot{m}$ (kg/s) is mass flow rate of a fluid,  $h$  (kJ/kg) and  $s$  (kJ/kgK) are enthalpy and entropy values at given points respectively,  $h_0$  and  $s_0$  are enthalpy and entropy values at reference points respectively [17].

The obtainable work from thermal and mechanical equilibrium with the environment to most stable configuration equilibrium with environment is associated with the *chemical exergy* [4, 17].

Since the chemical state of the absorbent remains same throughout the absorber circuit, the LiBr chemical exergy is neglected. The change of the chemical exergy of water can be calculated from below equation [17, 37].

$$Ex_{H_2O}^{Ch} = \dot{m} \left( \frac{con_{H_2O}}{M_{W_{H_2O}}} \right) e_{Ch, H_2O}^0 \quad (5.3)$$

Where  $con$  is water concentration,  $M_w$  is molecular weight,  $e_{Ch, H_2O}^0$  is water chemical exergy [17].



## 5.1 Exergy Calculations

Thermal systems include some important exergies regarding with fuel, product, destruction and loss. The exergy analysis is achieved in order to evaluate a system in terms of quality.

The product exergy ( $Ex_P$ ) can be defined as a desired result produced by the system. Also, the fuel exergy ( $Ex_F$ ) can be defined as a resource expended to generate the product [17, 37]. Exergy destruction ( $Ex_D$ ) is loss exergy from the system to the environment. It cannot be used anywhere. Loss exergy ( $Ex_L$ ) represents an amount of exergy is transferred from the system to the some other systems [17, 37].

The exergy balance is given as follows [17].

$$\sum Ex_{in} - \sum Ex_{out} - Q \left(1 - \frac{T_0}{T}\right) - W - Ex_D = 0 \quad (5.4)$$

Exergy destruction can be calculated from the below formula [4, 17].

$$Ex_{D,k} = Ex_{F,k} - Ex_{P,k} - Ex_{L,k} \quad (5.5)$$

Exergetic efficiency is ratio of product exergy to fuel exergy. It is defined as follows [17].

$$\mathcal{E} = \frac{Ex_{P,k}}{Ex_{F,k}} = 1 - \left(\frac{Ex_{D,k} + Ex_{L,k}}{Ex_{F,k}}\right) \quad (5.6)$$

The ratio of the exergy destruction to the exergy of the fuel for the components in the system is called as exergy destruction ratio ( $Y_{D,k}$ ). It is expressed as follows [17].

$$Y_{D,k} = \frac{Ex_{D,k}}{Ex_{F,total}} \quad (5.7)$$

The ratio of exergy loss to the exergy of the fuel for the components in the system is called as exergy loss ratio. It is expressed as follows [4, 17].

$$Y_{L,k} = \frac{Ex_{L,k}}{Ex_{F,total}} \quad (5.8)$$

The exergies for the components in order to analyze the system are computed by using

equations which are given in Table 5.1[4].

**Table 5.1** Fuel, product, loss of exergy formulas for the absorption cooling system [4, 17]

Components	Fuels (kW)	Products (kW)	Losses (kW)
<b>Generator</b>	$Ex_{17} - Ex_{18}$	$Ex_1 + Ex_8 - Ex_7$	-
<b>Evaporator Assembly</b>	$Ex_1 + Ex_9 - Ex_5$	$Ex_{14} - Ex_{13}$	$(Ex_{12} - Ex_{11}) +$ $(Ex_{16} - Ex_{15})$
<b>Pump</b>	$W_E$	$Ex_6 - Ex_5$	-
<b>Heat Exchanger</b>	$Ex_8 - Ex_9$	$Ex_7 - Ex_6$	-
<b>Overall System</b>	$Ex_{17} - Ex_{18}$	$Ex_{14} - Ex_{13}$	$(Ex_{12} - Ex_{11}) +$ $(Ex_{16} - Ex_{15})$

# CHAPTER 6

## COST ANALYSIS AND EXERGY COSTING

Exergy costing analysis evaluates the cost associated with the exergy stream for the each component. The general exergy costing formula is given as follows [37].

$$\sum_{out} C_{e,k} + C_{W,k} = \sum_{in} C_{i,k} + C_{Q,k} + Z_{Tot,k} \quad (6.1)$$

Where  $C_{e,k}$ (\$/h) and  $C_{i,k}$ (\$/h) are the costs for entering and exiting streams of the component,  $C_{W,k}$ (\$/h), and  $C_{Q,k}$ (\$/h), are the costs of the power component (compressor, pump etc.) and heat transfer component (boiler, generator etc.), respectively.

The inlet ( $C_i$ ) and exit ( $C_e$ ) costs flow rates of the components can be expressed as follows.

$$C_i = c_i EX_i = c_i (m_i ex_i) \quad (6.2)$$

$$C_e = c_e EX_e = c_e (m_e ex_e) \quad (6.3)$$

Where  $C_i$  and  $C_e$  are the inlet and exit cost flow rates (\$/h),  $c_i$  and  $c_e$  are the cost per exergy units (\$/GJ),  $EX_i$  and  $EX_e$  are the exergy flow rates (kW) and  $ex_i$  and  $ex_e$  are the specific exergy values (kJ/kg). It has multiplied unit conversion factor [17].

The general exergy costing formula is applied to the each component of the system by using the Equation 6.1. Then, the all equations obtained for all the components are shown in Table 6.1 [4, 17].

**Table 6.1** Exergy costing equations [17]

Components	Cost Equations
<b>Generator</b>	$C_g + C_7 + Z_{gen} = C_8 + C_1$ $C_1 + Z_{cond} = C_2 + \Delta C_{cond}$ $C_g + C_E = \Delta C_{cond} + \Delta C_{abs} + \dot{C}_P + \dot{Z}_k$ $\frac{m_1(c_1 e_{x1} - c_7 e_{x7})}{m_1(e_{x1} - e_{x7})} - \frac{m_8(c_8 e_{x8} - c_7 e_{x7})}{m_8(e_{x8} - e_{x7})}$ $\frac{c_1}{m_1(e_{x1} - e_{x7})} - \frac{c_7(e_{x8} - e_{x1})}{m_7(e_{x1} - e_{x7})(e_{x8} - e_{x7})} - \frac{c_8}{m_8(e_{x8} - e_{x7})} = 0 \quad (*1)$ $\frac{c_1}{Ex_1} = \frac{c_2}{Ex_2} \quad (*2)$
<b>Condenser</b>	$C_1 + Z_c = C_2 + \Delta C_{cond}$ $\frac{c_2}{Ex_2} = \frac{c_3}{Ex_3} \quad (*3)$
<b>Evaporator</b>	$\frac{c_3}{Ex_3} = \frac{c_4}{Ex_4} \quad (*4)$
<b>Absorber</b>	$\frac{c_4 + c_{10}}{Ex_4 + Ex_{10}} - \frac{c_5}{E_5} = 0 \quad (*5)$ $C_4 + C_{10} + Z_{abs} = C_5 + \Delta C_{abs}$
<b>Pump</b>	$C_E + C_5 + Z_{pu} + Z_{mot} = C_6$
<b>Heat Exchanger</b>	$C_6 + C_8 + Z_{hex} = C_7 + C_9$ $\frac{c_8}{Ex_8} = \frac{c_9}{Ex_9} \quad (*6)$
<b>Expansion valve</b>	$\frac{c_9}{Ex_9} = \frac{c_{10}}{Ex_{10}} \quad (*7)$
<b><math>c_p</math> (\$/h)</b>	$c_{p,tot} = \frac{C_{p,tot}}{E_{p,tot}} = \frac{c_{14} - c_{13}}{Ex_{14} - Ex_{13}}$

Note:

(\*1): The auxiliary relation for the generator is given as Equations 6.4-6.5 [17, 37].

$$\frac{C_1 - C_7}{Ex_1 - Ex_7} = \frac{C_8 - C_7}{Ex_8 - Ex_7} \quad (6.4)$$

$$\frac{m_1 c_1 ex_1 - m_7 c_7 ex_7}{m_1 ex_1 - m_7 ex_7} = \frac{m_8 c_8 ex_8 - m_7 c_7 ex_7}{m_8 ex_8 - m_7 ex_7} \text{ and write } m_7 = m_1 + m_8 \quad (6.5)$$

If the cross multiplication is made in Equation 6.5, four expressions  $((m_8 c_7 ex_7) (m_1 ex_7) = (m_8 ex_7) (m_1 c_7 ex_7))$  will be disappeared. Then, the rest of the equations and the simplifications are given below Equations 6.6-6.10.

$$\frac{m_1 (c_1 ex_1 - c_7 ex_7)}{m_1 (ex_1 - ex_7)} = \frac{m_8 (c_8 ex_8 - c_7 ex_7)}{m_8 (ex_8 - ex_7)} \quad (6.6)$$

$$\frac{m_1 c_1 ex_1}{m_1 (ex_1 - ex_7)} - \frac{m_1 c_7 ex_7}{m_1 (ex_1 - ex_7)} - \frac{m_8 c_8 ex_8}{m_8 (ex_8 - ex_7)} + \frac{m_8 c_7 ex_7}{m_8 (ex_8 - ex_7)} = 0 \quad (6.7)$$

$$\frac{C_1}{m_1 (ex_1 - ex_7)} - \left( \frac{C_7}{m_7 (ex_1 - ex_7)} + \frac{C_7}{m_7 (ex_8 - ex_7)} \right) - \frac{C_8}{m_8 (ex_8 - ex_7)} = 0 \quad (6.8)$$

$$\frac{C_1}{m_1 (ex_1 - ex_7)} - \left( \frac{C_7 (-ex_8 + ex_7 + ex_1 - ex_7)}{m_7 (ex_1 - ex_7)} \right) - \frac{C_8}{m_8 (ex_8 - ex_7)} = 0 \quad (6.9)$$

$$\frac{C_1}{m_1 (ex_1 - ex_7)} - \left( \frac{C_7 (-ex_8 + ex_1)}{m_7 (ex_1 - ex_7)} \right) - \frac{C_8}{m_8 (ex_8 - ex_7)} = 0 \quad (6.10)$$

(\*2): The other auxiliary relation for the generator is given as follows [17, 37].

$$\frac{C_1}{Ex_1} = \frac{C_2}{Ex_2} \quad (\text{when } c_1 = c_2) \quad (6.11)$$

(\*3): The auxiliary relation for the condenser is given as follows [17, 37].

$$\frac{C_2}{Ex_2} = \frac{C_3}{Ex_3} \quad (\text{when } c_2 = c_3) \quad (6.12)$$

(\*4): The auxiliary relation for the evaporator is given as follows [17, 37].

$$\frac{C_3}{Ex_3} = \frac{C_4}{Ex_4} \quad (\text{when } c_3 = c_4) \quad (6.13)$$

(\*5): The auxiliary relation for the absorber is given as follows [17, 37].

$$\frac{c_4+c_{10}}{Ex_4+Ex_{10}} - \frac{c_5}{E_5} = 0 \quad (6.14)$$

(\*6): The auxiliary relation for the heat exchanger is given as follows [17, 37].

$$\frac{c_8}{Ex_8} = \frac{c_9}{Ex_9} \quad (\text{when } c_8 = c_9) \quad (6.15)$$

(\*7): The auxiliary relation for the expansion valve is given as follows [17, 37].

$$\frac{c_9}{Ex_9} = \frac{c_{10}}{Ex_{10}} \quad (\text{when } c_9 = c_{10}) \quad (6.16)$$

The capital cost rate of the each component by giving  $Z_k$  symbol, which is shown in Table 6.1 can be calculated based on the heat transfer area for the generator, condenser, evaporator and absorber.  $Z_{pu}$  can also be calculated by using the work and pump efficiency.  $Z_{mot}$  can also be calculated by using the work and motor efficiency. The equations are given as below [4, 17].

$$Z_k = Z_{ref,k} \left( \frac{A_c}{A_{ref}} \right)^{0.6} = Z_{ref,k} \left( \frac{\frac{\dot{Q}}{UF\Delta T_m}}{A_{ref}} \right)^{0.6} \quad (6.17)$$

$$Z_p = Z_{ref} \left( \frac{W_p}{W_{ref,p}} \right)^{0.26} \left( \frac{1-\eta_p}{\eta_p} \right)^{0.5} \quad (6.18)$$

$$Z_{mot} = Z_{ref} \left( \frac{W_m}{W_{ref,m}} \right)^{0.87} \left( \frac{1-\eta_p}{\eta_p} \right) \quad (6.19)$$

Where  $Z_{ref}$  (\$) is the reference capital cost of the component,  $A_c$  is the heat transfer area of the component ( $m^2$ ),  $A_r$  is the reference heat transfer area ( $m^2$ ),  $W_p$  is the pump work (kW),  $W_{ref,p}$  is the reference pump work (kW),  $\eta$  is the pump efficiency [17].

The reference capital investment costs are considered for the generator, condenser, evaporator, absorber and heat exchanger as; 15750\$, 7150\$, 14300\$, 15000\$, 10700\$, respectively. The reference of the heat transfer area ( $A_r$ ) is assumed as 100  $m^2$ . The reference of the pump work is assumed as 10 kW.

## 6.1 Thermoeconomic expressions

In thermoeconomic evaluation of thermal systems, certain quantities, known as thermoeconomic variables, play so important role. These are: cost per exergy unit of the fuel ( $c_{F,k}$ ), the cost per exergy unit of the product ( $c_{P,k}$ ), the cost rate of the exergy destruction ( $C_{D,k}$ ) and the cost rate of the exergy loss ( $C_{L,k}$ ) and exergoeconomic factor ( $f$ ). The exergoeconomic factor is the ratio of the non exergy related costs to the total cost of the component. The formula of the cost rate of the exergy destruction ( $C_{D,k}$ ), the cost rate of the exergy loss ( $C_{L,k}$ ) and the exergoeconomic factor ( $f$ ) are given below [4, 17].

$$c_{F,k} = \frac{C_{F,k}}{E_{F,k}} \quad (6.20)$$

$$c_{P,k} = \frac{C_{P,k}}{E_{P,k}} \quad (6.21)$$

$$C_{D,k} = c_{F,k} \dot{E}_{X_{D,k}} \quad (\dot{E}_{X_{P,k}} \text{ is constant}) \quad (6.22)$$

$$C_{L,k} = c_{F,k} \dot{E}_{X_{L,k}} \quad (\dot{E}_{X_{P,k}} \text{ is constant}) \quad (6.23)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + (C_{D,k} + C_{L,k})} \quad (6.24)$$

# CHAPTER 7

## THERMOECONOMIC ANALYSIS AND OPTIMIZATION

Thermoeconomics is the branch of the engineering which combines the exergy analysis with economic principle, which is not giving directly information about the conventional energy analysis and economic evaluations. It can be considered as exergy-aided the cost minimization method [37].

The objectives of the thermoeconomic analysis can be given as follows [27, 37]:

- 1) Calculation of the cost for the each product separately.
- 2) To understand the cost formation process and the flow of the costs in the system.
- 3) To optimize specific variables in a single component or the overall system.

The objective of the thermoeconomic optimization is minimizing the total product cost rate of the system. The objective function (total product cost rate of the system) is given as below [27, 37].

$$\text{Minimize (objective function) } C_{P,Tot} = C_{F,Tot} + \dot{Z}_{Tot} = C_{F,Tot} + \dot{Z}_{Tot}^{CI} + \dot{Z}_{Tot}^{OM} \quad (7.1)$$

With the LiBr concentration boundaries are  $0.5 < X_5$  or  $X_8 < 0.65$  for the system.

Where  $C_{P,Tot}$  is the total product cost rate (\$/h),  $C_{F,Tot}$  is the total fuel cost rate (\$/h),  $\dot{Z}_{Tot}$  (\$/h) is the sum of the capital investment operation and maintenance costs rates,  $\dot{Z}_{Tot}^{CI}$  and  $\dot{Z}_{Tot}^{OM}$  (\$/h) are the capital investment, operation and maintenance costs rates of the system [4, 37].

The total product cost rate ( $C_{P,Tot}$ ) is associated with the product of the system. The total fuel cost rate ( $C_{F,Tot}$ ) is the total rate of the expenditures made to generate the product. It is calculated from the solar collector, storage tank and auxiliary heater costs.



The investment cost rate ( $\dot{Z}_{Tot}^{CI}$ ) includes the fixed capital investment and other outlays costs. The fixed capital investment has include the costs of the purchased equipment and installation, piping, instrumentation control, electrical equipment and material, all engineering and supervision, construction and contingencies. The other layouts are the startup, working capital, licensing costs and allowance for funds used during construction. Also, the operation and maintenance costs rate ( $\dot{Z}_{Tot}^{OM}$ ) include the fixed, variable and other operation and maintenance costs [4, 37].

The capital investment cost rate is given as below [17].

$$Z_{Tot}^{CI} = \xi Z_k + \alpha Z_k \quad (7.2)$$

Where,  $\xi$ ,  $Z_k$  (\$) and  $\alpha$  are the capital recovery factor, fixed capital investment and other layouts investment cost coefficient, respectively.  $\alpha$  coefficient is assumed to be 1% of the fixed capital investment cost of the each component.

The capital recovery factor can be calculated from below formula [4, 17].

$$\xi = \left( \frac{i(1+i)^{N_y}}{i(1+i)^{N_y} - 1} \right) \quad (7.3)$$

Where  $i$  is interest rate (%),  $N_y$  is the years of the life span [17].  $i$  and  $N_y$  are considered as 10% and 15 years of the system, respectively.

It is expected that the fixed capital investment cost increases with the increasing capacity and increasing exergetic efficiency of the component in the literature. The fixed capital investment of the each component can be expressed as follows [37].

$$Z_k = a_k \left( \frac{\varepsilon_k}{1 - \varepsilon_k} \right)^{b,k} EX_{p,k}^{y,k} \quad (7.4)$$

The operation and maintenance costs rate is depending on the fixed capital investment and the fixed, variable, other operation and maintenance costs. It is expressed as follows.

$$Z_{Tot}^{OM} = \beta Z_k + w_k \tau EX_{p,k} + R_k \quad (7.5)$$

Where,  $\beta$  and  $w$  are the coefficients of the fixed and variable operation and

maintenance costs, respectively.  $Z_k(\$)$  is the fixed capital investment cost,  $\tau(h)$  is hours of the operation per year and  $R$  (\$) is the all other operation and maintenance costs [4, 17]. The  $\beta$  coefficient is assumed to be 0.45% of the investment cost of the each component. Also, the  $w$  coefficient is assumed to be 1% of the investment cost of the each component.

The sum of the total investment and operation and maintenance costs rates of the system are denoted as  $\dot{Z}_{Tot}$ . It is given below.

$$\dot{Z}_{Tot} = \dot{Z}_{Tot}^{CI} + \dot{Z}_{Tot}^{OM} = (Z_{Tot}^{CI} + Z_{Tot}^{OM}) / \tau \quad (7.6)$$

The  $\dot{Z}_{Tot}$  of the system is obtained by using the some operations. First,  $Z_{Tot}^{CI}$  in Equation 7.2 and  $Z_{Tot}^{OM}$  in Equation 7.5 are summed and then is substituted in Equation 7.4. Then, it is divided to the annual operation hours per year and given as below [27].

$$\dot{Z}_{Tot} = (a_k \left(\frac{\varepsilon_k}{1-\varepsilon_k}\right)^{b,k} \text{Exp}_{p,k}^{y,k}) \frac{(\xi + \alpha + \beta)}{\tau} + w_k \text{Exp}_{p,k} + \left(\frac{R_k}{\tau}\right) \quad (7.7)$$

Where  $a$ ,  $b$ ,  $y$  are the constants,  $\varepsilon$  is the exergetic efficiency and  $\text{Exp}$  is the product exergy.

The total product cost rate ( $C_{P,Tot}$ ) can be written again as substituting the Equation 7.7 into 7.1 which is given as below.

$$C_{P,Tot} = C_{F,Tot} + \dot{Z}_{Tot} = C_{F,Tot} + (a_k \left(\frac{\varepsilon_k}{1-\varepsilon_k}\right)^{b,k} \text{Exp}_{p,k}^{y,k}) \frac{(\xi + \alpha + \beta)}{\tau} + w_k \text{Exp}_{p,k} + \left(\frac{R_k}{\tau}\right) \quad (7.8)$$

The objective function for the  $k$  th component is defined to minimize the cost per exergy unit of the product ( $c_{p,k}$ ). It is expressed as follows by using the Equation 7.1 and 7.7 [17].

$$c_{p,k} = \frac{c_{f,k} \text{Exp}_{f,k} + \dot{Z}_{Tot}}{\text{Exp}_{p,k}} = c_{f,k} \left(\frac{1}{\varepsilon_k}\right) + \frac{a \left(\frac{\varepsilon_k}{1-\varepsilon_k}\right)^{b,k} (\xi + \alpha + \beta)}{\tau \text{Exp}_{p,k}^{1-y,k}} + w_k + \left(\frac{R_k}{\tau \text{Exp}_{p,k}}\right) \quad (7.9)$$

The parameters in Equation 7.9 which are  $a$ ,  $b$ ,  $\xi$ ,  $\alpha$ ,  $\beta$ ,  $\tau$ ,  $w$ ,  $R$  remain constant during the optimization process. So, the cost per exergy unit of the product ( $c_{p,k}$ ) is the function of the exergetic efficiency ( $\varepsilon_k$ ) as a variable. The others are constants. The differential

of the Equation 7.9 with respect to the exergetic efficiency and equate it to the zero, gives the minimum cost per exergy unit of the product ( $c_{p,k}$ ). It is given below.

$$\frac{dc_{p,k}}{d\varepsilon} = 0 = -c_{f,k} \left( \frac{1}{\varepsilon^2} \right) + \frac{(\xi + \alpha + \beta)}{\tau E_{p,k}^{1-y,k}} \left( a_k \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^{b,k-1} \right) b_k \left( \frac{1}{(1-\varepsilon_k)^2} \right) \quad (7.10)$$

The equation more arranged is given as below.

$$c_{f,k} \left( \frac{1}{\varepsilon^2} \right) = \frac{(\xi + \alpha + \beta)}{\tau E_{p,k}^{1-y,k}} \left( a_k \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^{b,k-1} \right) b_k \left( \frac{1}{(1-\varepsilon_k)^2} \right) \quad (7.11)$$

If the both sides multiply with  $\left( \frac{\varepsilon_k^2}{c_{f,k}} \right)^2$  and it is simplified, the following equations are obtained.

$$1 = \frac{(\xi + \alpha + \beta)}{c_{f,k} \tau E_{p,k}^{1-y,k}} \left( a_k \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^{b,k-1} \right) b_k \left( \frac{1}{(1-\varepsilon_k)^2} \right) (\varepsilon_k^2) \quad (7.12)$$

$$1 = \frac{(\xi + \alpha + \beta)}{c_{f,k} \tau E_{p,k}^{1-y,k}} a_k b_k \left( \frac{\varepsilon_k^2}{(1-\varepsilon_k)^2} \right) \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^{b,k-1} \quad (7.13)$$

$$1 = \frac{(\xi + \alpha + \beta)}{c_{f,k} \tau E_{p,k}^{1-y,k}} a_k b_k \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^2 \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^{b,k-1} \quad (7.14)$$

$$1 = \frac{(\xi + \alpha + \beta)}{c_{f,k} \tau E_{p,k}^{1-y,k}} a_k b_k \left( \frac{\varepsilon_k}{1-\varepsilon_k} \right)^{b,k+1} \quad (7.15)$$

$$\left( \frac{1-\varepsilon_k}{\varepsilon_k} \right)^{b,k+1} = \frac{(\xi + \alpha + \beta)}{c_{f,k} \tau E_{p,k}^{1-y,k}} a_k b_k \quad (7.16)$$

$$\left( \frac{1-\varepsilon_k}{\varepsilon_k} \right) = \left( \frac{(\xi + \alpha + \beta)}{c_{f,k} \tau E_{p,k}^{1-y,k}} a_k b_k \right)^{1/b,k+1} = A \quad (7.17)$$

The optimum exergetic efficiency  $(\varepsilon_k)_{opt}$  is given as follows.

$$\left( \frac{1-\varepsilon_k}{\varepsilon_k} \right) = c^d = A \quad \left( \text{where, } \frac{a_k b_k (\xi + \alpha + \beta)}{(c_{f,k} \tau E_{p,k}^{1-y,k})} = c \text{ and } \frac{1}{x,k+1} = d \right) \quad (7.18)$$

$$(1 - \varepsilon_k) = \varepsilon_k c^d \quad (7.19)$$

$$\varepsilon_{k,opt} = \frac{1}{1+c^d} = \frac{1}{1+A} \quad (7.20)$$

$b_k = \frac{(C_{D,k} + C_{L,k})_{opt}}{\dot{Z}_{k,opt}}$ : represents the ratio of optimum of total of exergy destruction and optimum exergy loss cost rates to the optimum total cost rate [27]. So, the optimum exergoeconomic factor  $(f_k)_{opt}$  can be written in terms of  $b_k$  as follows.

$$f_{k,opt} = \frac{\dot{Z}_{k,opt}}{\dot{Z}_{k,opt} + (C_{D,k} + C_{L,k})_{opt}} = \frac{\dot{Z}_k}{\dot{Z}_k + b_k \dot{Z}_k} = \frac{1}{1 + b_k} \quad (7.21)$$

The optimization problem is minimizing the total product cost rate  $(C_{P,Tot})$  as an objective function given in Equation 7.8. Also, the optimum exergetic efficiency  $(\varepsilon_{k,opt})$  and optimum exergoeconomic factor  $(f_{k,opt})$  are obtained by using the Equations 7.20 and 7.21.

To solve this objective function,  $a_k$ ,  $b_k$  and  $y_k$  constants should be defined. These constants are defined from the curve fitting technique with power equation which is explained below.

$$Z_k = a_k \left( \frac{\varepsilon_k}{1 - \varepsilon_k} \right)^{b,k} Ex_{p,k}^{y,k} \quad (\text{As given Equation 7.4})$$

The  $\left( \frac{\varepsilon_k}{1 - \varepsilon_k} \right)$  equation equals to  $\left( \frac{E_{P,k}}{E_{D,k}} \right)$  (It is obtained by using the Equations 5.5 and 5.6).

Also,  $\left( \frac{E_{P,k}}{E_{D,k}} \right)$  equation can be denoted as  $x$ . So, the following equation is obtained.

$$\frac{Z_k}{Ex_{p,k}^{y,k}} = a_k \left( \frac{\varepsilon_k}{1 - \varepsilon_k} \right)^{b,k} = a_k \left( \frac{E_{P,k}}{E_{D,k}} \right)^{b,k} = a_k x^{b,k} = f(x) \quad (7.22)$$

$a_k$  and  $b_k$  constants are found by using the following operations.

$Z_k/Ex_{p,k}^{y,k}$  and  $E_{P,k}/E_{D,k}$  should be calculated for the each component's decision variable. First,  $Z_k$  can also be calculated from the Equation 6.17 depending on the heat transfer area.  $E_{P,k}$  and  $E_{D,k}$  can be calculated from the Table 5.1 and Equation 5.5, respectively. Then,  $E_{P,k}/E_{D,k}$  (x axis) versus  $Z_k/Ex_{p,k}^{y,k}$  (y axis) should be drawn from the curve fitting technique by using Matlab program. The power function  $(f(x) = a_k x^{b,k})$  should be defined from  $f(x)$  curve drawn by using curve fitting technique (as explained in Equation 7.22) in Matlab program. So,  $a_k$  and  $b_k$  constants can be obtained after these operations. Also, the  $y_k$  constant can be assumed according to the heat exchanger type

from the literature [27, 37].

After calculating  $a_k$  and  $b_k$  constants, the minimum objective function ( $C_{P, Tot}$ ), the optimum exergetic efficiency ( $\varepsilon_{k, opt}$ ) and optimum exergoeconomic factor ( $f_{k, opt}$ ) can be calculated by using Equations 7.8, 7.20 and 7.21 respectively [27, 37].

The difference between the exergetic efficiency of the system and optimum exergetic efficiency of the system is denoted as  $\Delta\varepsilon_k$ . Also, the difference between exergoeconomic factor of the system and optimum exergoeconomic factor of the system is denoted as  $\Delta f_k$ . They are given as follows [17].

$$\Delta\varepsilon_k = \frac{(\varepsilon_k - \varepsilon_{k, opt})}{\varepsilon_{k, opt}} \times 100 \quad (7.22)$$

$$\Delta f_k = \frac{(f_k - f_{k, opt})}{f_{k, opt}} \times 100 \quad (7.23)$$

## 7.1 Obtain of $a_k$ , $b_k$ and $y_k$ Constants

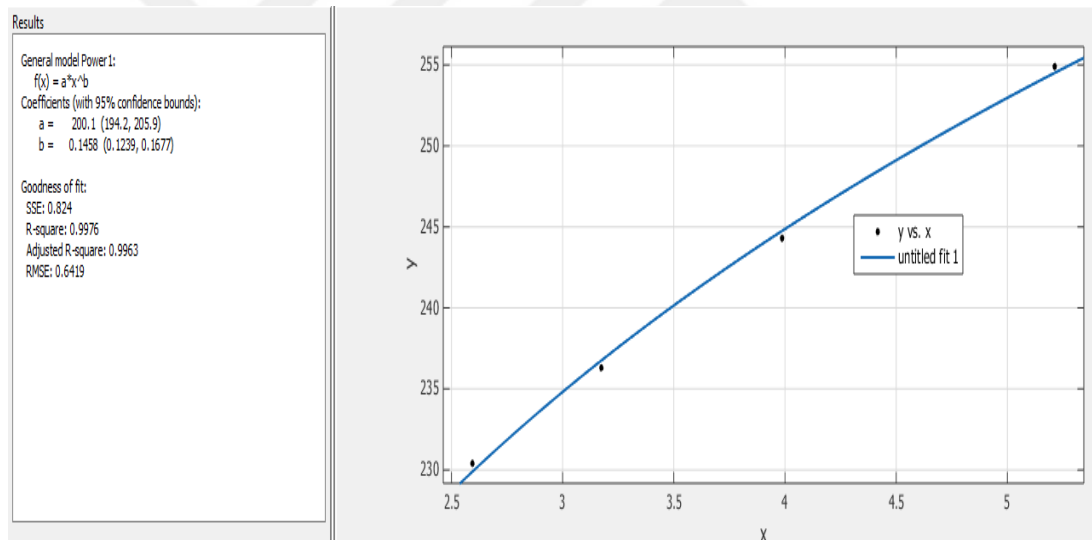
In order to compute the optimum exergetic efficiency ( $\varepsilon_{k, opt}$ ), optimum exergoeconomic factor ( $f_{k, opt}$ ) and the total product cost rate of the system ( $\dot{C}_P$ ),  $a_k$ ,  $b_k$  and  $y_k$  should be obtained by using the curve fitting technique. This technique is explained in the following.

### 7.1.1 Generator

Generator temperature is considered as a decision variable. Generator temperature interval is chosen between 100-103 °C. Also,  $y_k$  is considered as 0.66 for the generator suggested as a shell and tube type heat exchangers.  $Z_k/E_{P,k}^{0.66}$  and  $E_{P,k}/E_{D,k}$  should be calculated for the each generator temperature (100-103 °C) as given Table 7.1.  $Z_k/E_{P,k}^{0.66}$  versus  $E_{P,k}/E_{D,k}$  is plotted by using the Table 7.1. According to the curve fitting results  $a_k$  and  $b_k$  equal to 200.1 and 0.1458, respectively as shown in Figure 7.1 [27, 37].

**Table 7.1** The  $Z_k/E_{P,k}^{0.66}$  and  $E_{P,k}/E_{D,k}$  results for different generator temperature

Generator Temperature (°C)	$E_{P,k}$ (kW)	$E_{D,k}$ (kW)	$Z_k/E_{P,k}^{0.66}$	$E_{P,k}/E_{D,k}$
100	43.42	16.74	230.4	2.594
101	45.46	14.32	236.3	3.174
102	47.49	11.91	244.3	3.987
103	49.53	9.503	254.9	5.213

**Figure 7.1** Plot of  $Z_k/E_{P,k}^{0.66}$  versus  $E_{P,k}/E_{D,k}$  for the generator

### 7.1.2 Heat Exchanger Effectiveness

Heat exchanger effectiveness is considered as a decision variable. The  $y_k$  is considered as 0.16 for the heat exchanger suggested as a double pipe heat exchanger.  $Z_k/E_{P,k}^{0.16}$  and  $E_{P,k}/E_{D,k}$  are calculated for the each heat exchanger effectiveness.  $Z_k/E_{P,k}^{0.16}$  and  $E_{P,k}/E_{D,k}$  should be calculated for the each heat exchanger effectiveness as given Table 7.2.  $Z_k/E_{P,k}^{0.16}$  versus  $E_{P,k}/E_{D,k}$  is plotted by using the Table 7.2 [27, 37]. According to

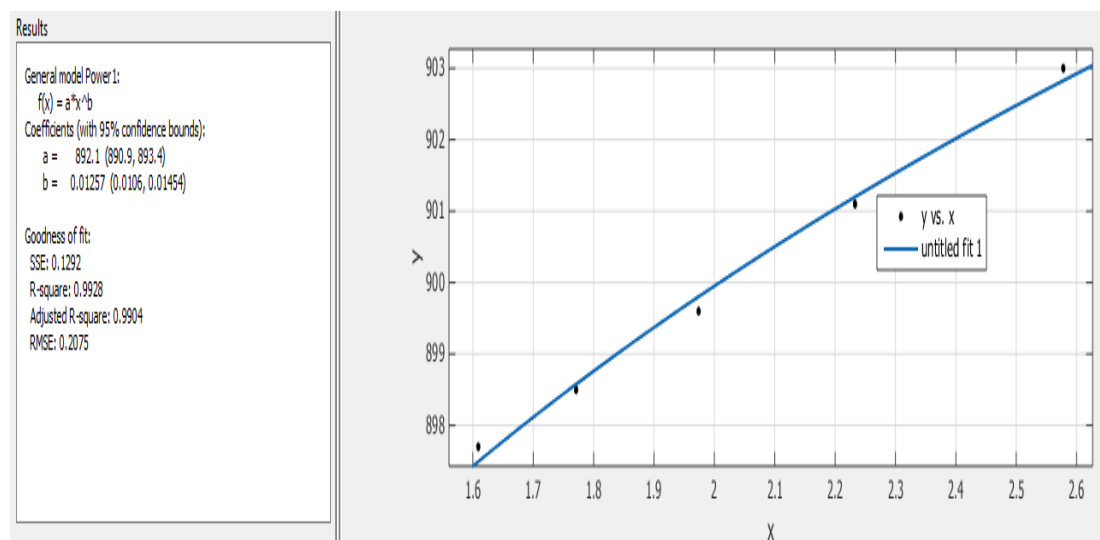
the curve fitting results (from power function),  $a_k$  and  $b_k$  equal to 892.1 and 0.01257, respectively as shown in Figure 7.2 [27, 37].

The heat exchanger effectiveness formula is calculated from below equation.

$$X = \frac{Q_{real}}{Q_{max}} = \frac{C_{min}(T_8 - T_9)}{C_{min}(T_8 - T_6)} = \frac{T_8 - T_9}{T_8 - T_6} \quad (7.24)$$

**Table 7.2** The  $Z_k/E_{P,k}^{0.16}$  and  $E_{P,k}/E_{D,k}$  results for different heat exchanger effectiveness

Effectiveness (X)	$E_{P,k}$ (kW)	$E_{D,k}$ (kW)	$Z_k/E_{P,k}^{0.16}$	$E_{P,k}/E_{D,k}$
0.815	6.634	2.574	903	2.578
0.820	6.815	3.052	901.1	2.233
0.830	6.999	3.546	899.6	1.974
0.835	7.184	4.056	898.5	1.771
0.840	7.371	4.582	897.7	1.609



**Figure 7.2** Plot of  $Z_k/E_{P,k}^{0.16}$  versus  $E_{P,k}/E_{D,k}$  for the heat exchanger

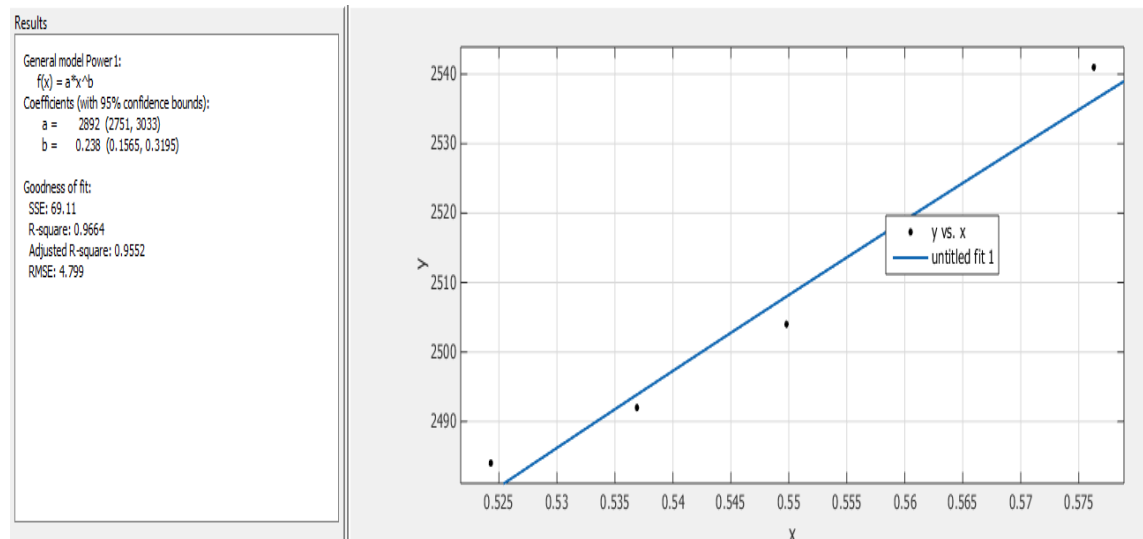
### 7.1.3 Evaporator Assembly

Evaporator assembly is considered as a decision variable. The Table 7.3 has five sets of operation conditions which have three data. The three data in each set shows the condenser-evaporator-absorber temperature, respectively. Also,  $y_k$  constant is considered as 0.66 for the evaporator assembly suggested as a shell and tube type heat exchangers.  $Z_k/E_{P,k}^{0.66}$  and  $E_{P,k}/E_{D,k}$  should be calculated for the each set as given in Table 7.3. According to the curve fitting results  $a_k$  and  $b_k$  equal to 2892 and 0.2380, respectively as shown in Figure 7.3 [27, 37].

**Table 7.3** The  $Z_k/E_{P,k}^{0.66}$  and  $E_{P,k}/E_{D,k}$  results for evaporator assembly

Temperature ( $T_{\text{cond}}-T_{\text{evap}}-T_{\text{abs}}$ ) ( $^{\circ}\text{C}$ )	$E_{P,k}$ (kW)	$E_{D,k}$ (kW)	$Z_k/E_{P,k}^{0.66}$	$E_{P,k}/E_{D,k}$
<b>43.8-6-38</b>	10.45	18.14	2541	0.5763
<b>44.8-6-39</b>	10.32	18.33	2519	0.5629
<b>45.8-6-40</b>	10.18	18.52	2504	0.5498
<b>46.8-6-41</b>	10.04	18.7	2492	0.5369
<b>47.8-6-42</b>	9.903	18.89	2484	0.5243

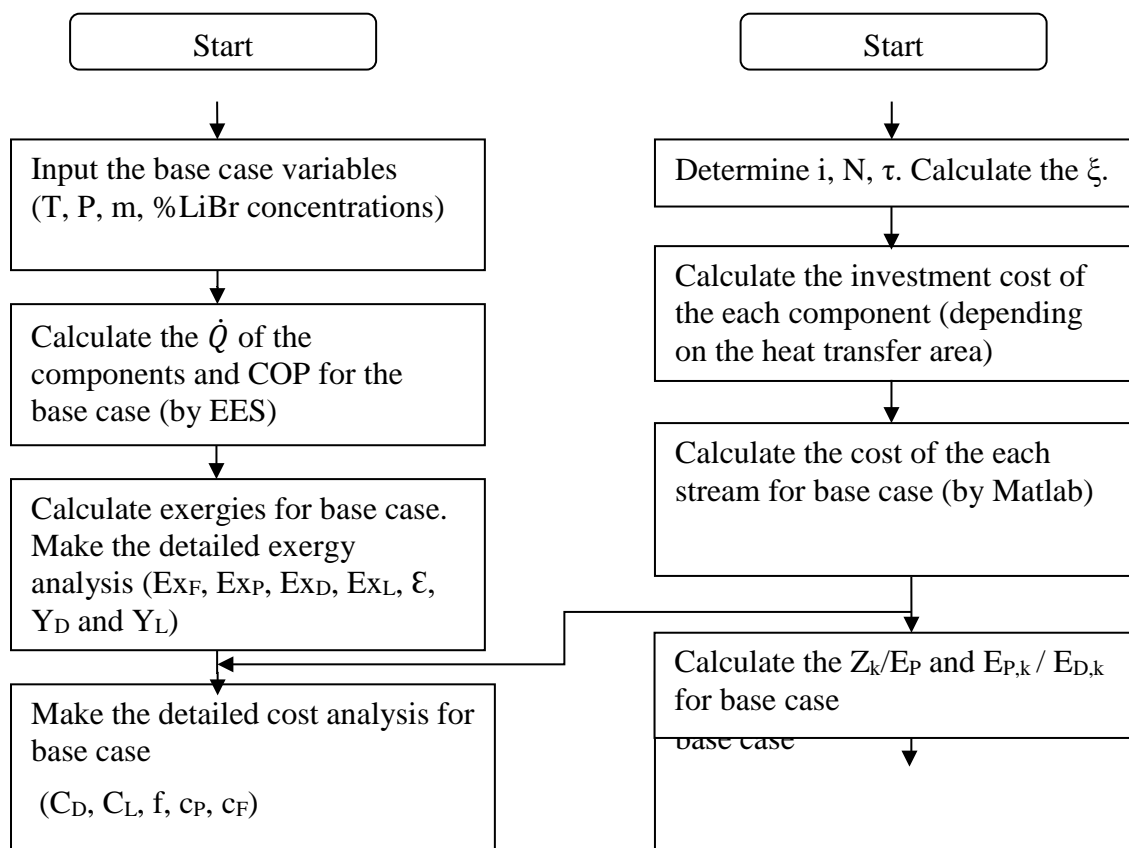


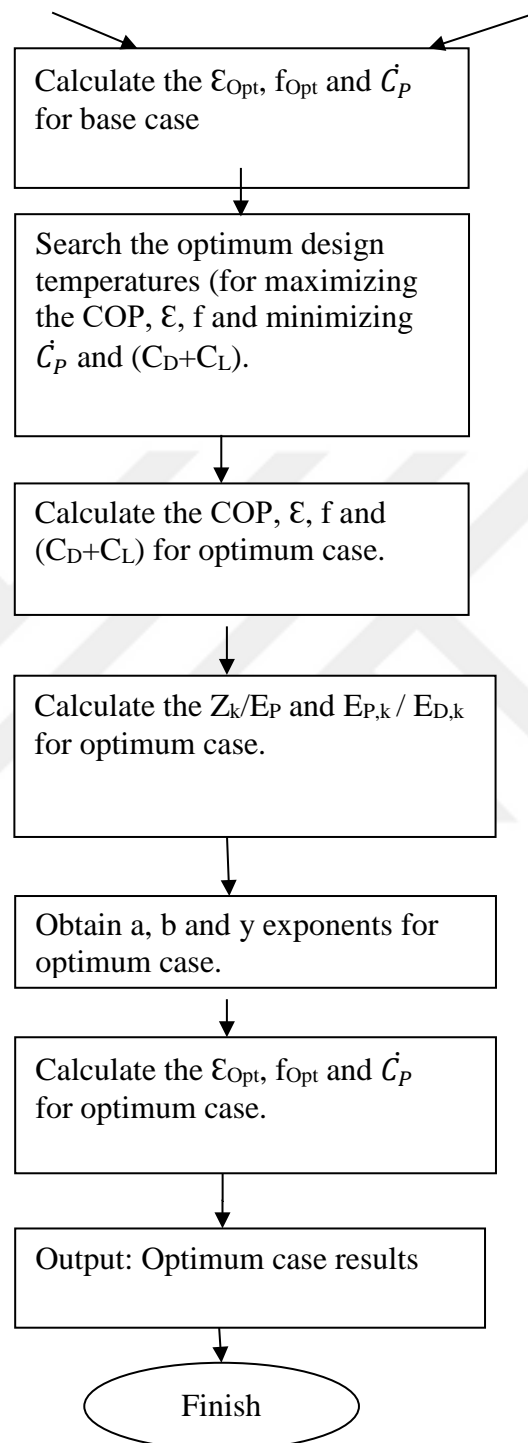


**Figure 7.3** Plot of  $Z_k / E_{P,k}^{0.66}$  versus  $E_{P,k} / E_{D,k}$  for the evaporator assembly

## 7.2 Thermo-economic Optimization of the System

The objective of a thermo-economic optimization is to minimize of total exergetic cost flow including investment, operation and maintenance costs [25]. The optimization flow chart for computing of exergy analysis, cost analysis, thermo-economic analysis and optimization of the system used in this thesis are given in Figure 7.4.





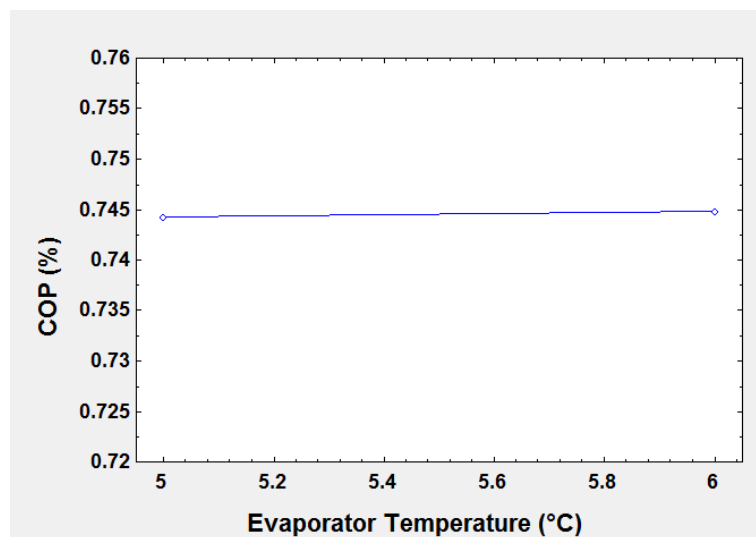
**Figure 7.4** The optimization flow chart of the system

# CHAPTER 8

## DEFINING OPTIMAL DESIGN TEMPERATURES

Optimal design temperatures are regarding to *maximizing of* COP, exergetic efficiency ( $\epsilon$ ) and exergoeconomic factor ( $f$ ) and *minimizing of* cost rate of exergy destruction and cost rate of exergy loss ( $C_D+C_L$ ). The change of the design temperature on the COP, exergetic efficiency ( $\epsilon$ ), exergoeconomic factor ( $f$ ) and cost rate of exergy destruction and cost rate of exergy loss ( $C_D+C_L$ ) are investigated in order to obtain the optimum design temperature. So, COP, exergetic efficiency ( $\epsilon$ ), exergoeconomic factor ( $f$ ) and cost rate of exergy destruction and cost rate of exergy loss ( $C_D+C_L$ ) are calculated from the Equations 4.21, 5.6, 6.23, 6.21 and 6.22, respectively. Then, some parameters versus temperature of evaporator condenser, generator and absorber are drawn. The graphs are given in Figures 8.1-16.

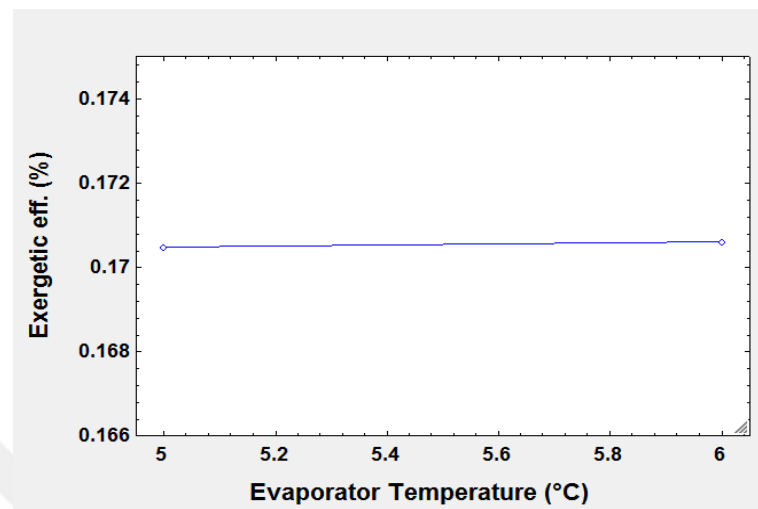
Figure 8.1 presents the variation of COP versus the different evaporator temperatures. It shows that the COP is increasing slightly with the increasing evaporator temperature.



**Figure 8.1** Variation of COP for different evaporator temperature

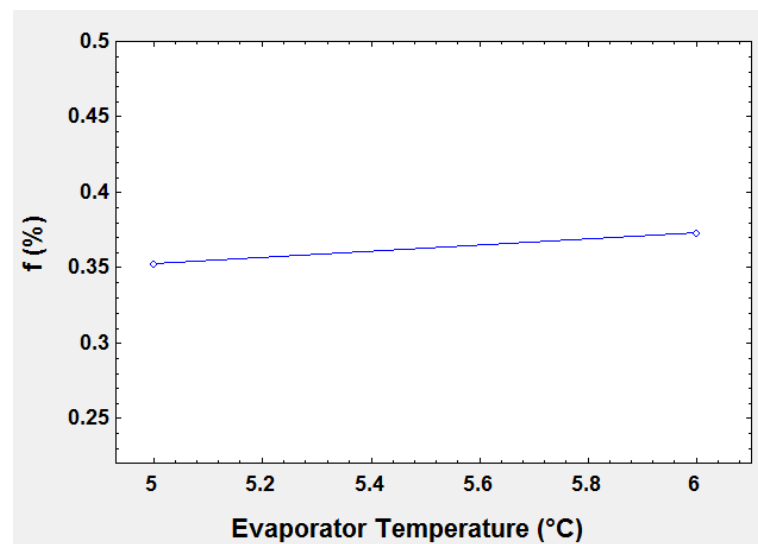
Figure 8.2 presents the variation of exergetic efficiency ( $\epsilon$ ) versus the different

evaporator temperatures. It shows that the exergetic efficiency ( $\epsilon$ ) is increasing slightly with the increasing evaporator temperature.



**Figure 8.2** Variation of exergetic efficiency for different evaporator temperature

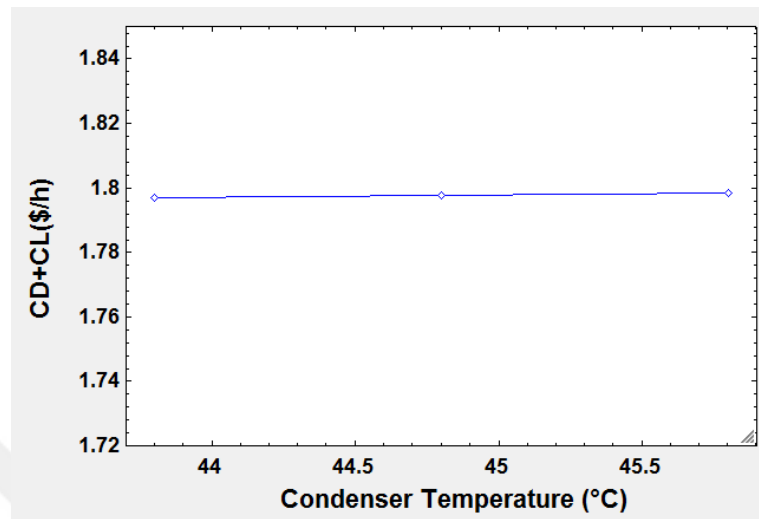
Figure 8.3 presents the variation of exergoeconomic factor ( $f$ ) versus the different evaporator temperatures. It shows that the exergoeconomic factor ( $f$ ) value is increasing slightly with the increasing evaporator temperature.



**Figure 8.3** Variation of exergoeconomic factor for different evaporator temperature

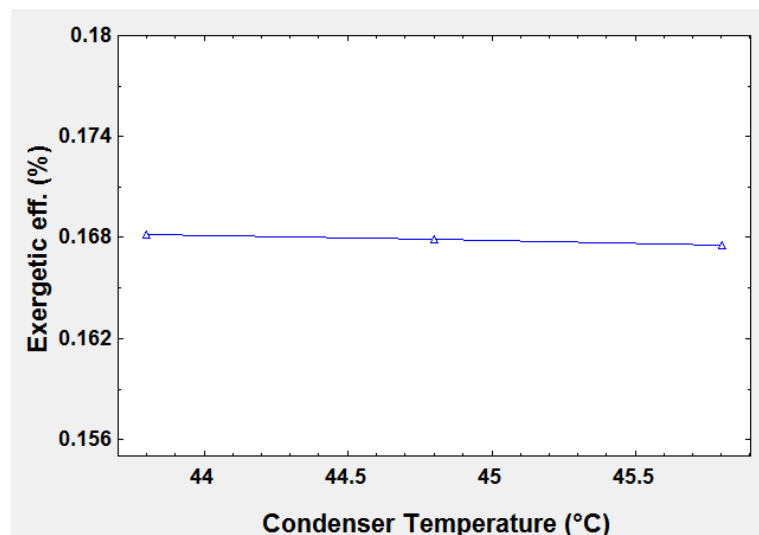
Figure 8.4 presents the variation of  $(C_D + C_L)$  versus the different condenser

temperatures. It shows that the  $(C_D+C_L)$  is decreasing slightly with the decreasing condenser temperature.



**Figure 8.4** Variation of  $(C_D+C_L)$  factor for different condenser temperature

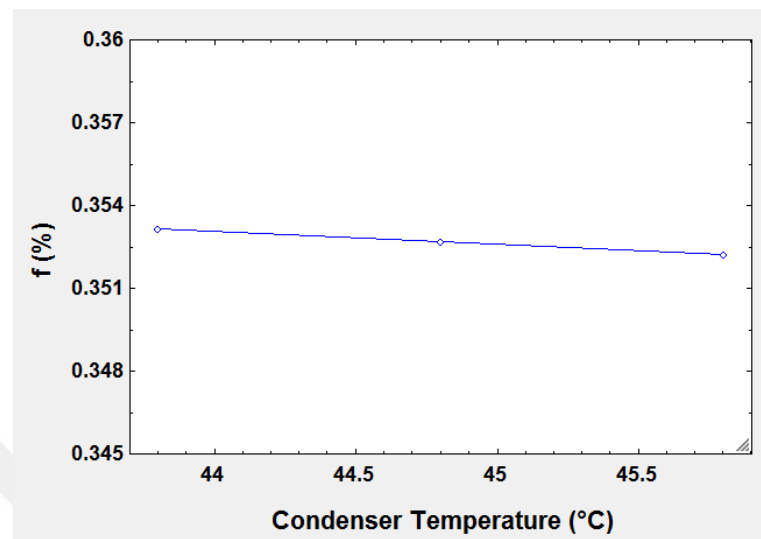
Figure 8.5 presents the variation of exergetic efficiency ( $\epsilon$ ) versus the different condenser temperatures. It shows that the exergetic efficiency ( $\epsilon$ ) is increasing slightly with the decreasing the condenser temperature.



**Figure 8.5** Variation of exergetic efficiency for different condenser temperature

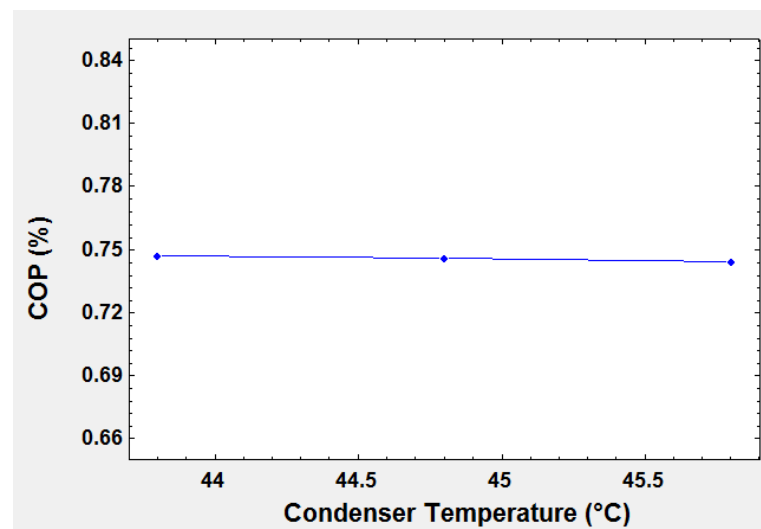
Figure 8.6 presents the variation of exergoeconomic factor ( $f$ ) versus the different

condenser temperatures. It shows that the exergoeconomic factor ( $f$ ) is increasing slightly with the decreasing condenser temperature.



**Figure 8.6** Variation of exergoeconomic factor for different condenser temperature

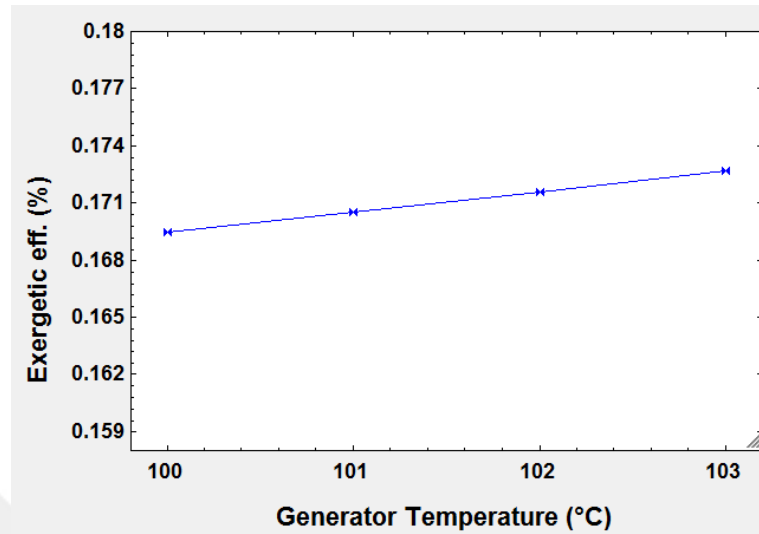
Figure 8.7 presents the variation of COP versus the different condenser temperatures. It shows that the COP is increasing slightly with the decreasing condenser temperature



**Figure 8.7** Variation of COP for different condenser temperature

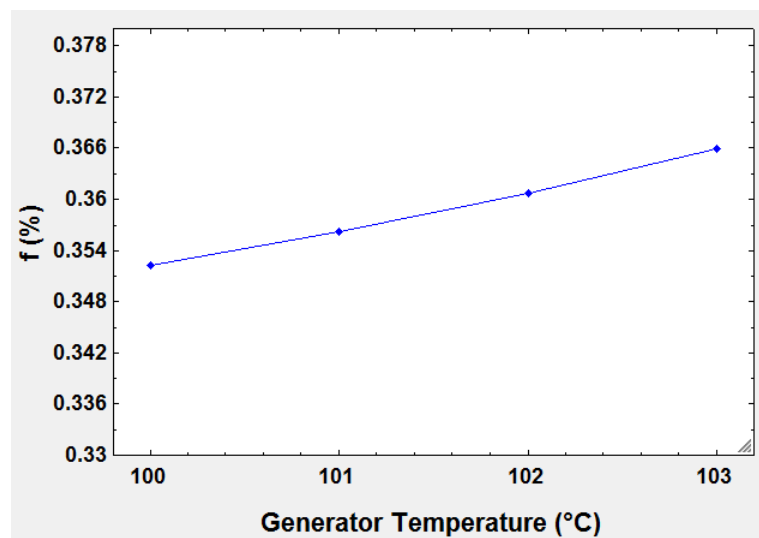
Figure 8.8 presents the variation of exergetic efficiency ( $\epsilon$ ) versus the different generator temperatures. It shows that the exergetic efficiency ( $\epsilon$ ) is increasing with the

increasing generator temperature.



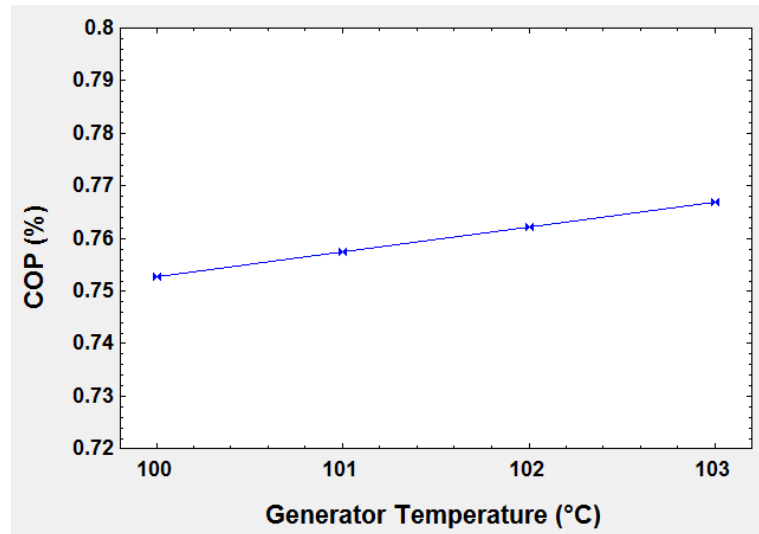
**Figure 8.8** Variation of exergetic efficiency for different generator temperature

Figure 8.9 presents the variation of exergoeconomic factor ( $f$ ) versus the different generator temperatures. It shows that the exergoeconomic factor ( $f$ ) is increasing with the increasing generator temperature.



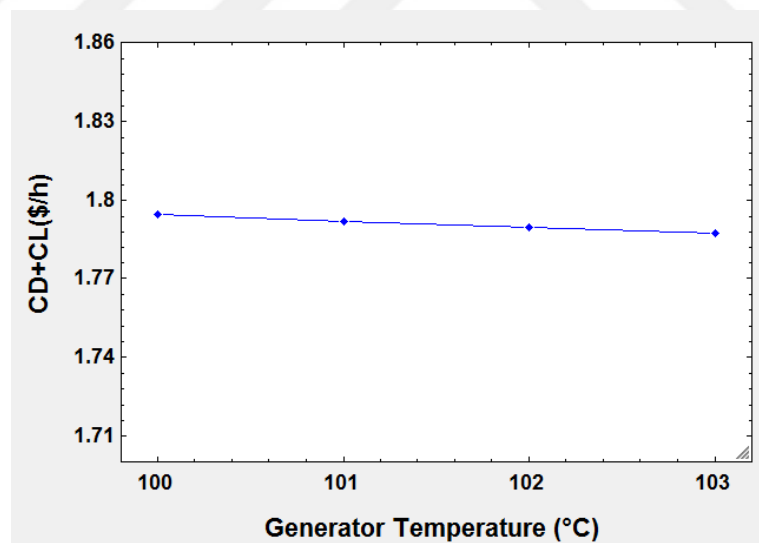
**Figure 8.9** Variation of exergoeconomic factor for different generator temperature

Figure 8.10 presents the variation of COP versus the different generator temperatures. It shows that the COP is increasing with the increasing generator temperature.



**Figure 8.10** Variation of COP for different generator temperature

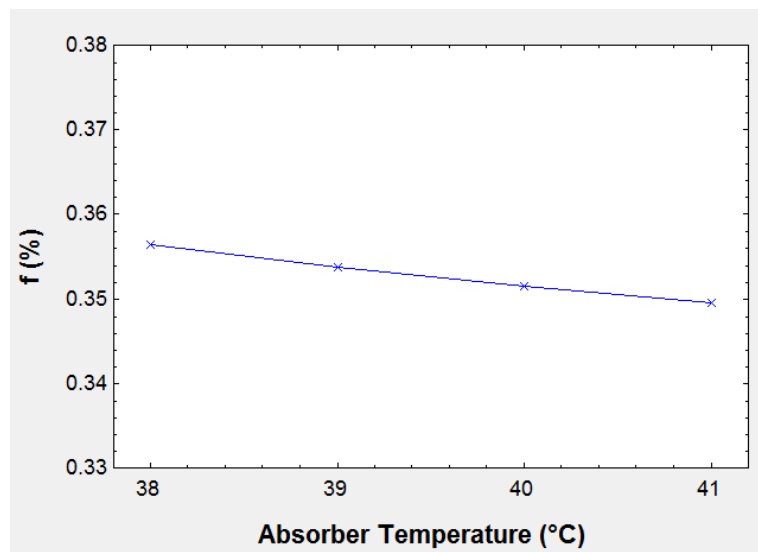
Figure 8.11 presents the variation of  $(C_D+C_L)$  versus the different generator temperatures. It shows that the  $(C_D+C_L)$  is decreasing with the increasing generator temperature.



**Figure 8.11** Variation of  $(C_D+C_L)$  for different generator temperature

Figure 8.12 presents the variation of exergoeconomic factor ( $f$ ) versus the different absorber temperatures. It shows that the exergoeconomic factor ( $f$ ) is increasing slightly with the decreasing absorber temperature.





**Figure 8.12** Variation of exergoeconomic factor for different absorber temperature

# CHAPTER 9

## OPTIMIZATION RESULTS

### 9.1 Exergy and Cost Results of the System

Table 9.1 shows exergy and cost results of the components of the base case depending on the thermodynamic properties. The temperature, pressure and mass flow rate of the system are taken from Yilmazoğlu [36]. The temperature difference of the pump is neglected.

The physical, chemical, and total exergy are calculated according to Equations 5.1-5.3 by using the EES program as codes given in Appendix A.

The cost balance equations as given in Table 6.1 are used for calculating the cost of the each stream of the system. The 15 variables of the system are  $[X] = \{C_1, C_2, C_3, \dots, C_{10}, \Delta C_{\text{cond}}, \Delta C_{\text{abs}}, \dot{C}_p, C_g \text{ and } C_E\}$ .  $C_1, C_2, C_3, \dots, C_{10}$  are the unknown costs of the streams in the system.  $\Delta C_{\text{cond}}$  and  $\Delta C_{\text{abs}}$  are the condenser and absorber cooling water unknown costs, respectively.  $\dot{C}_p$  is the unknown total product cost rate of the system.  $C_g$  and  $C_E$  are the generator costs (solar collector, storage tank and auxiliary heater costs) and electrical energy cost required for the pump, respectively.  $C_g$  is calculated as 2.16 \$/h by using the Equations 3.1-3.16.  $C_E$  is assumed as 10 \$/GJ. So, 13 variables ( $C_1, C_2, C_3, \dots, C_{10}, \Delta C_{\text{cond}}, \Delta C_{\text{abs}}, \dot{C}_p$ ) are calculated from linear system equations ( $[M][X] = [Y]$ ) by using Matlab computer program as codes given in Appendix B [4, 17].

**Table 9.1** Exergy and cost results [36]

No	T (°C)	P (kPa)	m (kg/s)	Chemical Composition	LiBr Con. (%)	Ex <sup>Ph</sup> (kW)	Ex <sup>Ch</sup> (kW)	Ex (kW)	C (\$/h)
1	100	10	0.08	Superheated Steam	-	13.85	0.20	14.05	0.786
2	45.8	10	0.08	Water	-	0.232	0.20	0.432	0.024
3	5	0.872	0.08	Water	-	-0.747	0.20	-0.547	-0.031
4	5	0.872	0.08	Water Vapor	-	-14.08	0.20	-13.88	-0.777
5	40	0.800	0.81	Water/ LiBr	58	34.94	0.85	35.79	2.139
6	40.003	10	0.81	Water/ LiBr	58	34.94	0.85	35.79	2.156
7	80	10	0.81	Water/ LiBr	58	41.58	0.85	42.43	2.777
8	100	10	0.73	Water/ LiBr	64	72.97	0.66	73.63	4.340
9	51	10	0.73	Water/ LiBr	64	63.77	0.66	64.42	3.797
10	49	0.800	0.73	Water/ LiBr	64	63.58	0.66	64.23	3.786
12- 11	35/37.5	101.325	19.10	Water	-	7.54	0.00	7.54	0.829
14- 13	12/7	101.325	8.87	Water	-	10.20	0.00	10.20	0.768
16- 15	32/35	101.325	17.84	Water	-	6.44	0.00	6.44	1.118
17- 18	111.37	149	0.11	Steam	-	60.84	0.00	60.84	2.160

The fuel exergy ( $E_F$ ), product exergy ( $E_P$ ) and loss exergy ( $E_L$ ) of the base case are calculated by using the Table 5.1. The destruction exergy ( $E_D$ ), exergetic efficiency ( $\epsilon$ ), exergy destruction ratio ( $Y_{D,k}$ ) and exergy loss ratio ( $Y_{L,k}$ ) are calculated by using the Equations 5.5-5.8. The maximum exergetic efficiency is calculated from the generator as expected (74.39%). The second most exergetic efficiency is calculated

from the heat exchanger as 72.05 %.

The maximum exergy destruction occurs in the evaporator assembly (18.50kW and  $Y_D = 43.36\%$ ). Also, the exergy loss is considered only for the evaporator assembly. So, the exergetic efficiency 23.88% is found too low to compare the others. The overall exergetic efficiency is found 16.75%. The results of the exergy analysis are given Table 9.2 [4].

**Table 9.2** Exergy analysis results

Components	$E_{XF}$ (kW)	$E_{XP}$ (kW)	$E_{XD}$ (kW)	$E_{XL}$ (kW)	Ex.D. Ratio $Y_D$ (%)	Ex.L. Ratio $Y_L$ (%)	Ex. eff. $\epsilon$ (%)
<b>Generator</b>	60.84	45.25	15.58	0.00	25.61	0.00	74.39
<b>Evaporator Assembly</b>	42.68	10.19	18.50	13.98	43.36	32.76	23.88
<b>Heat Exchanger</b>	9.21	6.63	2.57	0.000	27.95	0.000	72.05
<b>Overall System</b>	60.84	10.19	36.67	13.98	60.27	22.98	16.75

The cost of fuel per exergy unit ( $c_{F,k}$ ), cost of product per exergy unit ( $c_{P,k}$ ), cost rate of exergy destruction ( $C_{D,k}$ ), cost rate of exergy loss ( $C_{L,k}$ ) and exergoeconomic factor ( $f$ ) of the base case are calculated from the Equations 6.19-6.23. The capital cost rate ( $\dot{Z}_k$ ) is calculated by using the Equation 6.17. The maximum exergoeconomic factor is calculated from the solution heat exchanger (33.92 %). The evaporator assembly has second most exergoeconomic factor (27.33 %). It has high cost rate of exergy destruction ( $C_D$ ) and cost rate of exergy loss ( $C_L$ ). So, it has lower exergoeconomic factor ( $f$ ) than heat exchanger. The exergoeconomic factor ( $f$ ) of the evaporator assembly can be increased with lowering the cost rate of exergy destruction ( $C_D$ ) and cost rate of exergy loss ( $C_L$ ). The lowest exergoeconomic factor is calculated from the generator (25.46 %). The exergoeconomic factor of the generator can be increased with lowering cost rate of exergy destruction ( $C_D$ ). Table 9.3 shows the thermoeconomic analysis results of the system for the base case [4, 17].

**Table 9.3** Thermo-economic analysis results

Components	$c_F$ (\$/GJ)	$c_p$ (\$/GJ)	$C_D$ (\$/h)	$C_L$ (\$/h)	$\dot{Z}_C$ (\$/h)	$C_d+C_l+Z$ (\$/h)	$f$ (%)
<b>Generator</b>	9.863	14.420	0.553	0	0.189	0.742	25.46
<b>Evaporator Assembly</b>	15.910	20.93	1.06	0.801	0.779	2.597	27.33
<b>Solution Heat Exc.</b>	16.38	26	0.152	0	0.078	0.230	33.92
<b>Overall System</b>	9.863	20.93	1.302	0.496	1.060	2.858	35.28

The required solar collector numbers are calculated for base case by using the Equation 3.1-3.16. Also, the results about the solar collectors for base case are given in Table 9.4.

**Table 9.4** Solar collector results

Results	The solar collector results
$U_{Bottom}$ (W/m <sup>2</sup> K)	1.125
$U_{Top}$ (W/m <sup>2</sup> K)	8.159
$U_{Edge}$ (W/m <sup>2</sup> K)	0.135
$F'$ ( the collector efficiency factor)	0.989
$F_R$ (Heat removal factor)	0.969
$Q_u$ (useful energy gain) (kW)	1447.2
$n$ (the required number of collector)	402
The collector dimension (m)	2x1x0.08
The each solar collector costs (\$/h)	1.94
Generator steam water flows (\$/h)	0.22
$C_g$ (\$/h)	2.16

## 9.2 Comparison of the Results with Other Studies

The COP and exergy analysis comparison results of this thesis are compared to other studies. The comparison results are given below in Table 9.5 and 9.6.

**Table 9.5** COP comparison results

COP	Panah izadeh [38]	Misra et al [17]	Mohtaram et al [39]	Kaya [8]	Şencan [11]	Erden [30]	Daşkın [5]	This study
<b>COP</b> (%)	71.17	71.63	70.00	66.16	74.30	84.00	75.80	74.43

**Table 9.6** Exergy comparison results

Exergy Analysis	Panahizadeh [38]	Misra et al. [17]	Mohtaram et al [39]	Kaya [8]	Şencan [11]	This study
<b>Y<sub>D</sub></b> (%)	77.19	76.35	57.42	75.95	88.13	60.27
<b>Y<sub>L</sub></b> (%)	8.19	12.52	25.74	9.87	2.40	22.98
<b>ε</b> (%)	14.62	11.13	16.83	14.19	9.47	16.75

### 9.3 Optimization Results

It is obtained that the generator temperature should be increased and condenser, evaporator, and absorber temperatures should be decreased in order to increase the COP, exergetic efficiency ( $\epsilon$ ), exergoeconomic factor ( $f$ ) and decrease the cost rate of exergy destruction and cost rate of exergy loss ( $C_D+C_L$ ).

Above the 102°C of the generator temperature, condenser temperature should be above

the 45.8 °C in order to prevent the crystallization (Equations 2.1-2.3 are considered). However, when the generator temperature is 102°C, the condenser temperature can be lowered as 45.3°C. Also, the evaporator temperature should be higher than the 5°C as seen in Figures 8.1-8.3. However, it should be lower than 7°C which is the evaporator water flow temperature. So, it is chosen as 6°C. Also the absorber temperature is chosen as 39 °C with considering in Figure 8.12 and crystallization problem (Equations 2.1-2.3 are considered).

The analyzed system is considered as *base case* while the optimum design temperature of the system is considered as *optimum case*. So, the results are given in this explanation. The base case and optimum case results are given in Table 9.7.

**Table 9.7** Base case and optimum case temperature comparison results

Temperature (°C)	Base case	Optimum Case
Generator Temperature (°C)	100	102
Condenser Temperature (°C)	45.8	45.3
Evaporator Temperature (°C)	5	6
Absorber Temperature (°C)	40	39

Table 9.8 shows the comparison of the cost rate of exergy destruction ( $C_D$ ) and cost rate of exergy loss ( $C_L$ ), COP, exergetic efficiency ( $\epsilon$ ), exergoeconomic factor ( $f$ ) and total product cost rate ( $\dot{C}_p$ ) for base case and optimum case.

**Table 9.8** Base case and optimum case comparison results

Results	Base Case	Optimum Case
<b>COP (%)</b>	74.43	75.18
<b>Cost rate of exergy destruction (\$/h)</b>	1.302	1.197
<b>Cost rate of exergy loss (\$/h)</b>	0.496	0.465
<b><math>\epsilon</math> (%)</b>	16.75	16.92
<b>f (%)</b>	35.28	41.32
<b>Total product cost rate (\$/h)</b>	2.784	2.700

The optimum exergetic efficiency ( $\epsilon_{k,opt}$ ) and optimum exergoeconomic factor ( $f_{k,opt}$ ) are calculated by using the Equations 7.20-7.21. The difference between the exergetic efficiency ( $\epsilon$ ) and optimum exergetic efficiency ( $\epsilon_{k,opt}$ ) of the *base case* are calculated by using the Equation 7.22. The difference between the exergoeconomic factor (f) and optimum exergetic exergoeconomic factor ( $f_{k,opt}$ ) of the *base case* is calculated by using the Equation 7.23. The results are given in Table 9.9.



**Table 9.9**  $\Delta\mathcal{E}$  and  $\Delta f$  results for base case

Components		Results	
Components	$\Delta\mathcal{E}$ (%)	$\Delta f$ (%)	
<b>Generator</b>	-11.76	-70.83	
<b>Evaporator Assembly</b>	-9.85	-66.17	
<b>Heat Exchanger</b>	-26.05	-65.65	

The optimum exergetic efficiency ( $\mathcal{E}_{k,opt}$ ) and optimum exergoeconomic factor ( $f_{k,opt}$ ) is calculated by using the Equations 7.20-7.21. The difference between the exergetic efficiency ( $\mathcal{E}$ ) and optimum exergetic efficiency ( $\mathcal{E}_{k,opt}$ ) of the *optimum case* is calculated by using the Equation 7.22. The difference between the exergoeconomic factor ( $f$ ) and optimum exergoeconomic factor ( $f_{k,opt}$ ) of the *optimum case* is calculated by using the Equation 7.23. The results are given in Table 9.10.

**Table 9.10**  $\Delta E$  and  $\Delta f$  results for optimum case

Components		Results	
Components	$\Delta E$ (%)	$\Delta f$ (%)	
<b>Generator</b>	-43.48	-46.61	
<b>Evaporator Assembly</b>	-12.65	-63.50	
<b>Heat Exchanger</b>	-2.71	-30.15	

# CHAPTER 10

## DISCUSSION AND CONCLUSION

In this thesis, thermoeconomic analysis and thermoeconomic optimization for a solar assisted single effect absorption cooling system are carried out.

*The total product cost rate* of the system is taken into consideration as sum of *the total fuel cost rate*, *investment cost* and *operation and maintenance costs* for thermoeconomic analysis. Unlike other studies, this study considers the investment cost in terms of fixed capital investment and other outlays. This approach causes to obtain more real investment cost for the system.

The thermoeconomic optimization involves the maximizing thermodynamic performance and minimizing of *the total product cost rate* system. Thermoeconomics combines them and improves the system. It aims to design which has higher efficiency and lower cost simultaneously for a system. In this thesis, *the total product cost rate* is minimized with maximizing thermodynamic performance of the system. Also, the optimum exergetic efficiency and exergoeconomic factor are calculated by using the original approach to investment cost.

The thermoeconomic analysis and thermoeconomic optimization combine a detailed exergy and cost analyses. Calculations of exergy and some cost analyses are obtained by using EES and Matlab Computer Programs respectively.

The exergy analysis results show that *the evaporator assembly* has highest exergy destruction and exergy loss. So, it has the minimum exergetic efficiency as 23.88% in the system. Also, maximum exergetic efficiency occurs in the generator as 74.39%. The overall exergetic efficiency of the system is obtained as 16.75%.

Exergy costing analyses results show that the minimum *exergoeconomic factor* is occurred in the generator as 25.46% due to low investment cost and low exergetic efficiency.

The second minimum *exergoeconomic factor* is occurred in the evaporator assembly as 27.33% because the highest exergy destruction and exergy loss occur. Also, the overall exergoeconomic factor of the system is obtained as 35.28%.

In this thesis, the change of the design temperature on the COP, exergetic efficiency ( $\epsilon$ ), exergoeconomic factor ( $f$ ) and cost rate of exergy destruction and cost rate of exergy loss ( $C_D+C_L$ ) are also investigated in order to obtain the optimum design temperature. The optimum design temperature results show that the generator temperature should be increased while condenser, evaporator and absorber temperature should be decreased in the system. Hence, the optimum design temperatures which are generator temperature of 102°C, condenser temperature of 45.3°C, evaporator temperature of 6°C, absorber temperature of 39°C are chosen according to these criteria with considering the crystallization limit.

Consequently, the thermoeconomic results of the optimum case show that the minimum *total product cost rate* and COP are obtained as 2.700 (\$/h) and 75.18 (%) respectively. Also, the optimum exergetic efficiency 16.92 (%) and optimum exergoeconomic factor are determined as 41.32(%).

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# APPENDICES

**Appendix A:** EES Codes

**Appendix B:** Matlab Codes





## Appendix A- EES Codes

T[1]=100

P[1]=10

h[1]=ENTHALPY(Water,T=T[1],P=P[1])

s[1]=ENTROPY(Water,T=T[1],P=P[1])

m[1]=0.08

Ph[1]=m[1]\*((h[1]-104.83)-(298.15\*(s[1]-0.3672)))

CH[1]=m[1]\*(45/18.015)

T[2]=45.8

P[2]=11.5

h[2]=ENTHALPY(Water,T=T[2],P=P[2])

s[2]=ENTROPY(Water,T=T[2],P=P[2])

m[2]=0.08

Ph[2]=m[2]\*((h[2]-104.83)-(298.15\*(s[2]-0.3672)))

CH[2]=m[2]\*(45/18.015)

T[3]=5

h[2]=h[3]

DELTAh\_vap[3]=Enthalpy\_vaporization(Water,T=T[3])

x[3]=Quality(Water,T=T[3],h=h[2])

s[3]=Entropy(Water,T=T[3],x=x[3])

m[3]=0.08

Ph[3]=m[3]\*((h[3]-104.83)-(298.15\*(s[3]-0.3672)))

CH[3]=m[3]\*(45/18.015)

T[4]=5

h[4]=ENTHALPY(Water,T=T[4],x=1)

s[4]=ENTROPY(Water,T=T[4],x=1)

$$m[4]=0.08$$

$$Ph[4]=m[4]*((h[4]-104.83)-(298.15*(s[4]-0.3672)))$$

$$CH[4]=m[4]*(45/18.015)$$

$$P[5]=0.8$$

$$T[5]=40$$

$$LiBrH2O[1]=0.58$$

$$m[5]=0.81$$

$$v[5]=1/(\rho_{LiBrH2O}(T[5],LiBrH2O[1]))$$

$$h[5]=h_{LiBrH2O}(T[5],LiBrH2O[1])$$

$$s[5]=s_{LiBrH2O}(T[5],LiBrH2O[1])$$

$$Ph[5]=m[5]*((h[5]-104.83)-(298.15*(s[5]-0.3672)))$$

$$CH[5]=m[5]*(45/18.015)*((100-(LiBrH2O[1]*100))/100)$$

$$P[6]=10$$

$$T[6]=40.003$$

$$m[6]=0.81$$

$$h[6]=h_{LiBrH2O}(T[6],LiBrH2O[1])$$

$$s[6]=s_{LiBrH2O}(T[6],LiBrH2O[1])$$

$$Ph[6]=m[6]*((h[6]-104.83)-(298.15*(s[6]-0.3672)))$$

$$CH[6]=m[6]*(45/18.015)*((100-(LiBrH2O[1]*100))/100)$$

$$T[7]=80$$

$$m[7]=0.81$$

$$h[7]=h_{LiBrH2O}(T[7],LiBrH2O[1])$$

$$s[7]=s_{LiBrH2O}(T[7],LiBrH2O[1])$$

$$Ph[7]=m[7]*((h[7]-104.83)-(298.15*(s[7]-0.3672)))$$

$$CH[7]=m[7]*(45/18.015)*((100-(LiBrH2O[1]*100))/100)$$

$$T[8]=100$$

$$m[8]=0.73$$

$$\text{LiBrH}_2\text{O}[2]=0.64$$

$$h[8]=h_{\text{LiBrH}_2\text{O}}(T[8],\text{LiBrH}_2\text{O}[2])$$

$$s[8]=s_{\text{LiBrH}_2\text{O}}(T[8],\text{LiBrH}_2\text{O}[2])$$

$$\text{Ph}[8]=m[8]*((h[8]-104.83)-(298.15*(s[8]-0.3672)))$$

$$\text{CH}[8]=m[8]*(45/18.015)*((100-(\text{LiBrH}_2\text{O}[2]*100))/100)$$

$$T[9]=51$$

$$m[9]=0.73$$

$$h[9]=h_{\text{LiBrH}_2\text{O}}(T[9],\text{LiBrH}_2\text{O}[2])$$

$$s[9]=s_{\text{LiBrH}_2\text{O}}(T[9],\text{LiBrH}_2\text{O}[2])$$

$$\text{Ph}[9]=m[9]*((h[9]-104.83)-(298.15*(s[9]-0.3672)))$$

$$\text{CH}[9]=m[9]*(45/18.015)*((100-(\text{LiBrH}_2\text{O}[2]*100))/100)$$

$$T[10]=49$$

$$m[10]=0.73$$

$$h[10]=h_{\text{LiBrH}_2\text{O}}(T[10],\text{LiBrH}_2\text{O}[2])$$

$$s[10]=s_{\text{LiBrH}_2\text{O}}(T[10],\text{LiBrH}_2\text{O}[2])$$

$$\text{Ph}[10]=m[10]*((h[10]-104.83)-(298.15*(s[10]-0.3672)))$$

$$\text{CH}[10]=m[10]*(45/18.015)*((100-(\text{LiBrH}_2\text{O}[2]*100))/100)$$

$$T[11]=35$$

$$h[11]=\text{ENTHALPY}(\text{Water},T=T[11],x=0)$$

$$s[11]=\text{ENTROPY}(\text{Water},T=T[11],x=0)$$

$$m[11]=Q[2]/(4.18*2.5)$$

$$\text{Ph}[11]=m[11]*((h[11]-104.83)-(298.15*(s[11]-0.3672)))$$

$$T[12]=37.5$$

$$h[12]=\text{ENTHALPY}(\text{Water}, T=T[12], x=0)$$

$$s[12]=\text{ENTROPY}(\text{Water}, T=T[12], x=0)$$

$$m[12]=19.35$$

$$Ph[12]=m[12]*((h[12]-104.83)-(298.15*(s[12]-0.3672)))$$

$$A[1]=(Q[1]/(2300*TM[1]))*1000$$

$$A[2]=(Q[2]/(3265*TM[2]))*1000$$

$$A[3]=(Q[3]/(2200*TM[3]))*1000$$

$$A[4]=(Q[4]/(2000*TM[4]))*1000$$

$$A[5]=(Q[5]/(1800*TM[5]))*1000$$

$$Q[1]=-(m[7]*h[7])+(m[1]*h[1])+(m[8]*h[8])$$

$$Q[2]=(m[1]*h[1])-(m[2]*h[2])$$

$$Q[3]=(m[4]*h[4])-(m[3]*h[3])$$

$$Q[4]=(m[4]*h[4])+(m[10]*h[10])-(m[5]*h[5])$$

$$Q[5]=(m[8]*h[8])-(m[9]*h[9])$$

$$Q[6]=((m[7]*h[7])-(m[6]*h[6]))$$

$$\text{DELTA}h_{\text{vap}}[2]=\text{Enthalpy\_vaporization}(\text{Steam}, T=T[17])$$

$$Q[7]=\text{DELTA}h_{\text{vap}}[2]*m[17]$$

$$\text{COP}[1]=Q[3]/(Q[1]+PU[1])$$

$$T[13]=12$$

$$h[13]=\text{ENTHALPY}(\text{Water}, T=T[13], x=0)$$

$$s[13]=\text{ENTROPY}(\text{Water}, T=T[13], x=0)$$

$$m[13]=Q[3]/(4.18*5)$$

$$Ph[13]=m[13]*((h[13]-104.83)-(298.15*(s[13]-0.3672)))$$

$$T[14]=7$$

$$h[14]=\text{ENTHALPY}(\text{Water}, T=T[14], x=0)$$

$$s[14]=\text{ENTROPY}(\text{Water}, T=T[14], x=0)$$

$$m[14]=m[13]$$

$$\text{Ph}[14]=m[14]*((h[14]-104.83)-(298.15*(s[14]-0.3672)))$$

$$T[15]=32$$

$$h[15]=\text{ENTHALPY}(\text{Water}, T=T[15], x=0)$$

$$s[15]=\text{ENTROPY}(\text{Water}, T=T[15], x=0)$$

$$m[15]=Q[4]/(4.18*3)$$

$$\text{Ph}[15]=m[15]*((h[15]-104.83)-(298.15*(s[15]-0.3672)))$$

$$T[16]=35$$

$$h[16]=\text{ENTHALPY}(\text{Water}, T=T[16], x=0)$$

$$s[16]=\text{ENTROPY}(\text{Water}, T=T[16], x=0)$$

$$m[16]=m[15]$$

$$\text{Ph}[16]=m[16]*((h[16]-104.83)-(298.15*(s[16]-0.3672)))$$

$$T[17]=111.37$$

$$P[17]=149$$

$$h[17]=\text{ENTHALPY}(\text{Water}, T=T[17], P=P[17])$$

$$s[17]=\text{ENTROPY}(\text{Water}, T=T[17], P=P[17])$$

$$m[17]=Q[1]/2226$$

$$\text{Ph}[17]=m[17]*((h[17]-104.83)-(298.15*(s[17]-0.3672)))$$

$$E[1]=\text{Ph}[1]+\text{CH}[1]$$

$$E[2]=\text{Ph}[2]+\text{CH}[2]$$

$$E[3]=\text{Ph}[3]+\text{CH}[3]$$

$$E[4]=\text{Ph}[4]+\text{CH}[4]$$

$$E[5]=Ph[5]+CH[5]$$

$$E[6]=Ph[6]+CH[6]$$

$$E[7]=Ph[7]+CH[7]$$

$$E[8]=Ph[8]+CH[8]$$

$$E[9]=Ph[9]+CH[9]$$

$$E[10]=Ph[10]+CH[10]$$

$$E[11]=Ph[11]$$

$$E[12]=Ph[12]$$

$$E[13]=Ph[13]$$

$$E[14]=Ph[14]$$

$$E[15]=Ph[15]$$

$$E[16]=Ph[16]$$

$$E[17]=Ph[17]$$

$$C[1]=0.786$$

$$C[2]=0.024$$

$$C[3]=-0.031$$

$$C[4]=-0.777$$

$$C[5]=2.139$$

$$C[6]=2.156$$

$$C[7]=2.777$$

$$C[8]=4.340$$

$$C[9]= 3.797$$

$$C[10]=3.786$$

$$C[11]=2.16$$

$$C[12]= 0.829$$

$$C[13]= 1.118$$

$$C[14]=0.768$$

$$cp[1]=(ALL[8]*ALL[1]*(3600/(10^6)))+(N[4]/37500)$$

$$TM[1]=((T[17]-T[8])-(T[17]-T[7]))/\ln((T[17]-T[8])/(T[17]-T[7]))$$

$$TM[2]=(((T[1]-T[12])-(T[2]-T[11]))/\ln((T[1]-T[12])/(T[2]-T[11]))) * 0.57$$

$$TM[3]=(((T[13]-T[3])-(T[14]-T[4]))/\ln((T[13]-T[3])/(T[14]-T[4])))$$

$$TM[4]=(((T[10]-T[16])-(T[5]-T[15]))/\ln((T[10]-T[16])/(T[5]-T[15]))) * 1.073$$

$$TM[5]=((T[8]-T[7])-(T[9]-T[6]))/\ln((T[8]-T[7])/(T[9]-T[6]))$$

$$Z[1]=15750 * (((Q[1]*1000)/(2300*TM[1]*100))^0.6) * (0.171/2500)$$

$$Z[2]=(2100*(PU[1]/10)^0.26) * (((1-PU[13])/(PU[13]))^0.5) * (0.171/2500)$$

$$Z[3]=(10700 * (((Q[5]*1000)/(1800*TM[5]*100))^0.6)) * (0.171/2500)$$

$$Z[4]=(14300 * (((Q[3]*1000)/(2200*TM[3]*100))^0.6) + 7150 * (((Q[2]*1000)/(3265*TM[2]*100))^0.6) + 15000 * (((Q[4]*1000)/(2150*TM[4]*100))^0.6)) * (0.171/2500)$$

$$Z[5]=(14300 * (((Q[3]*1000)/(2200*TM[3]*100))^0.6) + 7150 * (((Q[2]*1000)/(3265*TM[2]*100))^0.6) + 15000 * (((Q[4]*1000)/(2150*TM[4]*100))^0.6)) * (0.171/2500)$$

$$Z[7]=14300 * (((Q[3]*1000)/(2200*TM[3]*100))^0.6) * (0.171/2500)$$

$$Z[8]=15000 * (((Q[4]*1000)/(2150*TM[4]*100))^0.6) * (0.171/2500)$$

$$Z[9]=7150 * (((Q[2]*1000)/(3265*TM[2]*100))^0.6) * (0.171/2500)$$

$$J[1]=18700 * (((Q[1]*1000)/(2300*TM[1]*100))^0.6)$$

$$J[2]=15000 * (((Q[5]*1000)/(1800*TM[5]*100))^0.6)$$

$$J[3]=20000 * (((Q[3]*1000)/(2200*TM[3]*100))^0.6)$$

$$J[4]=12500 * (((Q[2]*1000)/(3265*TM[2]*100))^0.6)$$

$$J[5]=26000 * (((Q[4]*1000)/(2150*TM[4]*100))^0.6)$$

$$J[6]=(20000 * (((Q[3]*1000)/(2200*TM[3]*100))^0.6) + 12500 * (((Q[2]*1000)/(3265*TM[2]*100))^0.6) + 26000 * (((Q[4]*1000)/(2150*TM[4]*100))^0.6))$$

$$N[1]=(J[1]*1.45)+GENEF[2]+70$$

$$N[2]=(J[2]*1.45)+HE[2]+70$$

$$N[3]=(J[6]*1.45)+EV[2]+70$$

$$N[4]=N[1]+N[2]+N[3]$$

$$EPS[1]=(T[8]-T[9])/(T[8]-T[6])$$

$$GENEF[1]=E[17]$$

$$GENEF[2]=E[1]+E[8]-E[7]$$

$$GENEF[3]=GENEF[1]-GENEF[2]$$

$$GENEF[4]=0$$

$$GENEF[5]=GENEF[3]/GENEF[1]$$

$$GENEF[6]=GENEF[4]/GENEF[1]$$

$$GENEF[7]=GENEF[2]/GENEF[1]$$

$$GENEF[8]=(C[11]*10^6)/(E[17]*3600)$$

$$GENEF[9]=((C[1]+C[8]-C[7])*(10^6))/((E[1]+E[8]-E[7])*3600)$$

$$GENEF[10]=GENEF[8]*GENEF[3]*(3600/(10^6))$$

$$GENEF[11]=GENEF[4]*GENEF[8]*(3600/(10^6))$$

$$GENEF[12]=Z[1]/(Z[1]+GENEF[10]+GENEF[11])$$

$$GENEF[14]=GENEF[2]/GENEF[3]$$

$$GENEF[15]=(15750*(((Q[1]*1000)/(2300*TM[1]*100))^0.6))/(GENEF[2]^0.66)$$

$$EV[1]=E[1]+E[9]-E[5]$$

$$EV[2]=E[14]-E[13]$$

$$EV[3]=EV[1]-EV[2]-(((E[12]-E[11])+E[16]-E[15]))$$

$$EV[4]=((E[12]-E[11])+E[16]-E[15])$$

$$EV[5]=EV[3]/EV[1]$$

$$EV[6]=EV[4]/EV[1]$$

$$EV[7]=EV[2]/EV[1]$$

$$EV[8]=((C[1]+C[9]-C[5])*(10^6))/((E[1]+E[9]-E[5])*3600)$$

$$EV[9]=((C[14])*(10^6))/((E[14]-E[13])*3600)$$



$$EV[10]=EV[8]*EV[3]*(3600/(10^6))$$

$$EV[11]=EV[4]*EV[8]*(3600/(10^6))$$

$$EV[12]=Z[4]/(Z[4]+EV[10]+EV[11])$$

$$EV[14]=EV[2]/EV[3]$$

$$EV[15]=\frac{14300*\left(\frac{Q[3]*1000}{2200*TM[3]*100}\right)^{0.6}+7150*\left(\frac{Q[2]*1000}{3265*TM[2]*100}\right)^{0.6}+15000*\left(\frac{Q[4]*1000}{2150*TM[4]*100}\right)^{0.6}}{(EV[2]^{0.66})}$$

$$PU[13]=0.7$$

$$PU[1]=\frac{(P[6]-P[5])*m[5]*v[5]}{PU[13]}$$

$$PU[2]=E[6]-E[5]$$

$$PU[3]=PU[1]-PU[2]$$

$$PU[4]=0$$

$$PU[5]=PU[3]/PU[1]$$

$$PU[6]=PU[4]/PU[1]$$

$$PU[7]=PU[2]/PU[1]$$

$$PU[8]=10$$

$$PU[9]=\frac{(C[6]-C[5])*(10^6)}{(E[6]-E[5])*3600}$$

$$PU[10]=PU[8]*PU[3]*(3600/(10^6))$$

$$PU[11]=PU[4]*PU[8]*(3600/(10^6))$$

$$PU[12]=Z[2]/(Z[2]+PU[10]+PU[11])$$

$$PU[14]=PU[2]/PU[3]$$

$$Z[6]=2100*\left(\frac{PU[1]}{10}\right)^{0.26}*\left(\frac{1-PU[13]}{PU[13]}\right)^{0.5}*(0.199/2500)$$

$$PU[16]=\frac{2100*\left(\frac{PU[1]}{10}\right)^{0.26}*\left(\frac{1-PU[13]}{PU[13]}\right)^{0.5}}{(PU[2]^{0.48})}$$

$$HE[1]=E[8]-E[9]$$

$$HE[2]=E[7]-E[6]$$

$$HE[3]=HE[1]-HE[2]$$

$$HE[4]=0$$

$$HE[5]=HE[3]/HE[1]$$

$$HE[6]=HE[4]/HE[1]$$

$$HE[7]=HE[2]/HE[1]$$

$$HE[8]=((C[8]-C[9])*(10^6))/((E[8]-E[9])*3600)$$

$$HE[9]=((C[7]-C[6])*(10^6))/((E[7]-E[6])*3600)$$

$$HE[10]=HE[8]*HE[3]*(3600/(10^6))$$

$$HE[11]=HE[4]*HE[8]*(3600/(10^6))$$

$$HE[12]=Z[3]/(Z[3]+HE[10]+HE[11])$$

$$HE[14]=HE[2]/HE[3]$$

$$HE[15]=(10700*(((Q[5]*1000)/(1600*TM[5]*100))^0.6))/(HE[2]^0.16)$$

$$ALL[0]=(ALL[8]*E[17]*3600)/(10^6)$$

$$ALL[1]=E[17]+PU[1]$$

$$ALL[2]=E[14]-E[13]$$

$$ALL[3]=GENEF[3]+EV[3]+PU[3]+HE[3]$$

$$ALL[4]=EV[4]$$

$$ALL[5]=ALL[3]/ALL[1]$$

$$ALL[6]=ALL[4]/ALL[1]$$

$$ALL[7]=(ALL[2]/ALL[1])$$

$$ALL[8]=(C[11]/3600)/(E[17]/(10^6))$$

$$ALL[9]=EV[9]$$

$$ALL[10]=ALL[8]*ALL[3]*(3600/(10^6))$$

$$ALL[11]=ALL[4]*ALL[8]*(3600/(10^6))$$

$$ALL[12]=(Z[1]+Z[2]+Z[3]+Z[4])/(ALL[10]+ALL[11]+Z[1]+Z[2]+Z[3]+Z[4])$$

$$ALL[13]=ALL[10]+ALL[11]$$

## Appendix B- Matlab Codes

```
syms C1 C2 C3 C4 C5 C6 C7 C8 C9 C10 CP CC CA;
```

```
syms CH CE E1 E2 E3 E4 E5 E7 E8 E9 E10 e1 e2 e3 e4 e7 e8 e9 e10 m1 m2 m3 m4  
m7 m8 m9 m10 ZG ZHE ZP ZM ZC ZA ZEA
```

```
CH=2.16;
```

```
CE = 2.304*10(-4);
```

```
ZG=0.189;
```

```
ZP=0.014;
```

```
ZHE=0.078;
```

```
ZEA=0.6995;
```

```
ZM=3.00*10(-3);
```

```
ZC=0.067;
```

```
ZA=0.248;
```

```
E1=14.05;
```

```
E2=0.432;
```

```
E3=-0.547;
```

```
E4=-13.88;
```

```
E5=35.79;
```

```
E8=73.63;
```

```
E9=64.42;
```

```
E10=64.23;
```

```
e1=175.625;
```

```
e7=52.383;
```

```
e8=100.863;
```

```
m1=0.08;
```

```
m7=0.81;
```

```

m8=0.73;
% C1 C2 C3 C4 C5 C6 C7 C8 C9 C10 CP CC CA
% denklem1
% -C1+C7-C8+=-ZG-CH
%denklem2
% (C1*(m7*m8*(e8-e7)))-(C7*((e8-e1)*(m1*m8)))+(C8*((e7-e1)*m1*m7)) =0
% denklem3
% C6-C7+C8-C9=-ZHE
%denklem4
% (C8-((E8/E9)*C9))=0
%denklem5
% C6-C5=CE+ZP+ZM
%denklem6
% C1-C2-CC=-ZC
%denklem7
% C4-C5+C10-CA=-ZA
%denklem8
% C1-((E1/E2)*C2)=0
%denklem9
% C2-((E2/E3)*C3)=0
%denklem10
% C9-((E9/E10)*C10)=0
%denklem11
% C4*E5-C5*(E4+E10)+C10*E5=0
%denklem12
% (C3-((E3/E4)*C4))=0

```

```

%denklem13
% CC+CP+CA=CH+CE-(ZG+ZP+ZHE+ZEA)
a=[ -1, 0, 0, 0, 0, 0, 1, -1, 0, 0, 0, 0, 0;           %denklem1
(m7*m8*(e8-e7)), 0, 0, 0, 0, 0, ((e1-e8)*(m1*m8)), ((e7-e1)*m1*m7), 0, 0,0,0,0;
                                                                %denklem2
0, 0, 0, 0, 0, 1, -1, 1, -1, 0, 0, 0, 0;           %denklem3
0, 0, 0, 0, 0, 0, 0, 1, -(E8/E9)), 0, 0, 0, 0;     %denklem4
0, 0, 0, 0, -1, 1, 0, 0, 0, 0, 0, 0, 0;          %denklem5
1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0;         %denklem6
0, 0, 0, 1, -1, 0, 0, 0, 0, 1, 0, 0, -1;         %denklem7
1, -(E1/E2)), 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0;    %denklem8
0, 1, -(E2/E3)), 0, 0, 0, 0, 0, 0, 0, 0, 0, 0;    %denklem9
0, 0, 0, 0, 0, 0, 0, 0, 1, -(E9/E10)), 0, 0, 0;   %denklem10
0, 0, 0, E5, -(E4+E10)), 0, 0, 0, 0, E5, 0, 0, 0; %denklem11
0, 0, 1, -(E3/E4)), 0, 0, 0, 0, 0, 0, 0, 0, 0;   %denklem12
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1           %denklem13
];
a_inv=inv(a);
res=[
(-ZG-CH);           %denklem1
0;                  %denklem2
(-ZHE);            %denklem3
0;                  %denklem4
(CE+ZP+ZM)         %denklem5
(-ZC)              %denklem6
(-ZA)              %denklem7

```

```
0; %denklem8
0; %denklem9
0; %denklem10
0; %denklem11
0; %denklem12
(CH+CE-(ZG+ZP+ZHE+ZEA)) %denklem13
];
fin=a_inv*res;
disp(['C1: ',sprintf('% .9f',fin(1))])
disp(['C2: ',sprintf('% .9f',fin(2))])
disp(['C3: ',sprintf('% .9f',fin(3))])
disp(['C4: ',sprintf('% .9f',fin(4))])
disp(['C5: ',sprintf('% .9f',fin(5))])
disp(['C6: ',sprintf('% .9f',fin(6))])
disp(['C7: ',sprintf('% .9f',fin(7))])
disp(['C8: ',sprintf('% .9f',fin(8))])
disp(['C9: ',sprintf('% .9f',fin(9))])
disp(['C10: ',sprintf('% .9f',fin(10))])
disp(['CP: ',sprintf('% .9f',fin(11))])
disp(['CC: ',sprintf('% .9f',fin(12))])
disp(['CA: ',sprintf('% .9f',fin(13))])
```

## CURRICULUM VITAE

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-Cooling Technique  
- Fluid Mechanics  
- Solar Energy

### RESEARCHES

Akkaya, M. and Camdali U. Solar Assisted Absorption Cooling System Thermoeconomic Analysis and Evaluation, International Scientific Research Congress. 2019

