



Cairo University

# **SOLAR HETEROGENEOUS ORGANIC RANKINE CYCLE**

By

**Nora Hany Ibrahim Shaheen**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Chemical Engineering**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2018

# **SOLAR HETEROGENEOUS ORGANIC RANKINE CYCLE**

By  
**Nora Hany Ibrahim Shaheen**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Chemical Engineering**

Under the Supervision of

**Prof. Dr. Seif Eddeen Khaled  
Fateen**

.....  
Professor  
Chemical Engineering  
Faculty of Engineering, Cairo University

**Dr. Ahmed Soliman Mohamed  
Fawzy**

.....  
Associate Professor  
Chemical Engineering  
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2018

# **SOLAR HETROGENEOUS ORGANIC RANKINE CYCLE**

By  
**Nora Hany Ibrahim Shaheen**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Chemical Engineering**

Approved by the  
Examining Committee

Associate Prof. Dr. **Ahmed Soliman Mohamed Fawzy** (Thesis Main Advisor)

Associate Prof. **Dr. Ayat Ossama Mohamed Ghallab** (Internal Examiner)

Associate Prof. Dr. **Mamdouh Ayad Gadalla Ibrahim** (External Examiner)

- Head of Chemical Engineering Department, Faculty of Engineering, Port Said University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2018

**Engineer's Name:** Nora Hany Ibrahim Shaheen  
**Date of Birth:** 27/02/1991  
**Nationality:** Egyptian  
**E-mail:** [eng.nshaheen@yahoo.com](mailto:eng.nshaheen@yahoo.com)  
**Phone:** +202 010 9279 2435  
**Address:** 39 El Taif St.-El Mohandseen  
**Registration Date:** 1/10/2014  
**Awarding Date:** 2018  
**Degree:** Master of Science  
**Department:** Chemical Engineering



**Supervisors:**

Prof. Dr. Seif Eddeen Khaled Fateen  
Associate. Prof Dr. Ahmed Soliman Mohamed Fawzy

**Examiners:**

Associate Prof. Ahmed Soliman (Thesis main advisor)  
Associate Prof. Dr. Ayat Ossama (Internal examiner)  
Associate Prof. Mamdouh Ayad (External examiner)  
Head of Chemical Engineering Department, Faculty of  
Engineering, Port Said University

**Title of Thesis:**

Solar Heterogeneous Organic Rankine Cycle

**Key Words:**

Heterogeneous Binary Mixtures; Azeotropic Mixtures; Organic Rankine Cycle; Solar Energy; Hexane Water Mixtures

**Summary:**

The present thesis work studies the opportunities of performance improvement related to Solar Organic Rankine Cycle using heterogeneous organic working fluids, which are predicted to increase the thermal efficiency of the cycle from a thermodynamic point of view. This cycle is of critical importance since it can be integrated in multiple industrial plants helping in the waste heat recovery, which is a cost effective and environmentally friendly solution.

In the study, an investigation was carried out on three stages. The first stage was the selection of pure working fluids, which are suitable for cost efficient low temperature scale solar application. The second stage was a comparison between heterogeneous organic working fluid mixtures and pure working alternatives. Third, all the heterogeneous working mixture alternatives that did not achieve an increase in either thermal efficiency or savings were eliminated. Finally, the optimum alternatives of heterogeneous mixtures were indicated after multiple screening steps as water normal hexane and water cyclohexane mixtures, which showed promising results in terms of thermal efficiency increase taking into consideration cost savings and safety limitations.

## **Acknowledgments**

This work is a result of honest efforts and the support of those who stood by me in the journey.

My supervisors Dr. Ahmed Soliman and Dr. Seif El Deen Fateen who suggested this thesis topic passing on their knowledge and expertise to me, they offered me their time and efforts empowering me to move all the way until the end.

The Chemical Engineering Department with all its members especially Prof. Dr. Osama Abd El Bary, Prof. Dr. Mai Fouad, Prof. Dr. Reeem Ettouney, Eng. Nourhan Hisham and Eng. Hoda Anwar who supported me at different stages of the journey either in the pre-masters or in the thesis work stages.

Finally, my family who has always supported me in better or in worse, my mother who always pushed me to do my best, my sisters who encouraged me to pursue my dreams and my father who taught me how to leave my legacy, even though he passed away but his legacy is alive now and here on this work.

## **Dedication**

This thesis is dedicated to the soul of my beloved father, my brave mother, my kind sisters and all the people who stood by my side in the journey.

# Table of Contents

|                                                                       |            |
|-----------------------------------------------------------------------|------------|
| <b>ACKNOWLEDGMENTS .....</b>                                          | <b>I</b>   |
| <b>DEDICATION.....</b>                                                | <b>II</b>  |
| <b>TABLE OF CONTENTS.....</b>                                         | <b>III</b> |
| <b>LIST OF TABLES .....</b>                                           | <b>V</b>   |
| <b>LIST OF FIGURES .....</b>                                          | <b>VI</b>  |
| <b>NOMENCLATURE .....</b>                                             | <b>IX</b>  |
| <b>ABSTRACT .....</b>                                                 | <b>XI</b>  |
| <b>CHAPTER 1: INTRODUCTION .....</b>                                  | <b>1</b>   |
| <b>CHAPTER 2: LITERATURE REVIEW.....</b>                              | <b>2</b>   |
| 2.1 TYPES OF ENERGY RESOURCES.....                                    | 2          |
| 2.2 THE TRANSITION FROM CONVENTIONAL ENERGY TO RENEWABLE ENERGY ..... | 3          |
| 2.3 SOLAR ENERGY POTENTIAL USE IN EGYPT .....                         | 4          |
| 2.4 SOLAR POWER GENERATION.....                                       | 6          |
| 2.4.1 Photovoltaic Cells .....                                        | 6          |
| 2.4.1.1 Crystalline Silicon Photovoltaic Cells .....                  | 7          |
| 2.4.1.2 Thin Film Photovoltaic Cells .....                            | 7          |
| 2.4.1.3 Organic Material Photovoltaic Cells.....                      | 7          |
| 2.4.2 Solar Thermal Technologies .....                                | 8          |
| 2.4.2.1 Charging Cycle (Thermal Energy Storage Cycle) .....           | 9          |
| 2.4.2.2 Organic Rankine Cycle (Discharging Cycle).....                | 10         |
| 2.4.2.2.1 The ORC Basic Scheme.....                                   | 10         |
| 2.4.2.2.2 ORC modified with a recuperator .....                       | 12         |
| 2.4.2.2.3 Cascade ORC.....                                            | 13         |
| 2.4.2.2.4 Classification of the ORC .....                             | 14         |
| 2.4.2.2.5 Comparison between Steam and Organic Rankine Cycle .....    | 16         |
| 2.5 ORC APPLICATIONS .....                                            | 17         |
| 2.5.1 Solar ORC Application .....                                     | 18         |
| 2.5.2 Pure Working Fluid Selection.....                               | 21         |
| 2.5.3 Zeotropic and Azeotropic Mixtures .....                         | 24         |
| <b>CHAPTER 3: STATEMENT OF THE PROBLEM.....</b>                       | <b>27</b>  |
| <b>CHAPTER 4: SIMULATION MODEL DESIGN DEVELOPMENT .....</b>           | <b>29</b>  |
| 4.1 MAIN DESIGN EQUATIONS USED .....                                  | 29         |
| 4.1.1 Work and Heat Equations per Each Stage .....                    | 29         |
| 4.1.2 Thermal, Pump and Turbine Efficiencies .....                    | 30         |
| 4.1.3 Second Law Efficiency .....                                     | 31         |
| 4.1.4 Total Irreversibility Calculations .....                        | 32         |
| 4.1.5 Cost Saving Calculations.....                                   | 32         |
| 4.2 CALCULATION METHODOLOGY & SIMULATION ASSUMPTIONS .....            | 33         |
| 4.2.1 Simulation Solution Logic.....                                  | 33         |

|                                                                          |           |
|--------------------------------------------------------------------------|-----------|
| 4.2.2 Simulation Solution Steps followed on Aspen Plus .....             | 34        |
| 4.2.3 Process Variables.....                                             | 35        |
| 4.2.4 Simulation Assumptions .....                                       | 36        |
| 4.2.5 Selection of the Working Fluid used in the Simulation Scheme ..... | 37        |
| <b>CHAPTER 5: RESULTS AND DISCUSSION.....</b>                            | <b>39</b> |
| 5.1 RESULTS OF THE PURE WORKING FLUIDS .....                             | 39        |
| 5.1.1 Thermal Efficiency Results for Selected Pure Working Fluids.....   | 41        |
| 5.1.2 Thermal Efficiency Results for Selected Pure Working Fluids.....   | 43        |
| 5.2 SELECTION OF THE OPTIMUM HETEROGENEOUS MIXTURES .....                | 44        |
| 5.2.1 Creating Matrix of Mixtures .....                                  | 45        |
| 5.2.2 1 <sup>st</sup> Screening Step.....                                | 46        |
| 5.2.3 2 <sup>nd</sup> Screening Step.....                                | 47        |
| 5.2.4 3 <sup>rd</sup> Screening Step .....                               | 48        |
| 5.2.5 4 <sup>th</sup> Screening Step .....                               | 53        |
| 5.2.6 5 <sup>th</sup> Screening Step .....                               | 67        |
| 5.1.6.1 Water Cyclohexane Mixture .....                                  | 68        |
| 5.1.6.2 Water Normal Hexane Mixture.....                                 | 71        |
| <b>CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS .....</b>                  | <b>74</b> |
| <b>REFERENCES .....</b>                                                  | <b>75</b> |

## List of Tables

|                                                                                                                                    |    |
|------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 2.1: Comparison between Steam and Organic Rankine Cycles .....                                                               | 16 |
| Table 4.1: Comparison between Aspen HYSYS and Aspen Plus soft wares .....                                                          | 34 |
| Table 4.2: Constraints inserted in Aspen plus Software Simulation .....                                                            | 36 |
| Table 4.3: The properties of different hydro carbon categories .....                                                               | 38 |
| Table 5.1: Aliphatic hydrocarbons results from Aspen Plus software .....                                                           | 42 |
| Table 5.2: Alcohols results from Aspen Plus software .....                                                                         | 42 |
| Table 5.3: Alicyclic hydrocarbons results from Aspen Plus software .....                                                           | 42 |
| Table 5.4: The matrix of 45 created mixtures .....                                                                                 | 46 |
| Table 5.5: 13 Excluded Mixtures for $T_{\text{outlet condenser}} > 40^{\circ}\text{C}$ in the 1 <sup>st</sup> screening step ..... | 46 |
| Table 5.6: 10 Excluded Mixtures in 2 <sup>nd</sup> screening step .....                                                            | 47 |
| Table 5.7: The Details of Pressure Composition Diagram of the 10 Excluded Mixtures in 2 <sup>nd</sup> screening step .....         | 47 |
| Table 5.8: The four semi excluded mixtures .....                                                                                   | 48 |
| Table 5.9 Methanol Cyclo pentane results from Aspen Plus Simulator .....                                                           | 49 |
| Table 5.10 2,2-Dimethyl Butane/Methanol Mixture results .....                                                                      | 50 |
| Table 5.11 2-Methyl Pentane/ Methanol Mixture Results .....                                                                        | 51 |
| Table 5.12 Normal Hexane/ Methanol mixture results .....                                                                           | 51 |
| Table 5.13: Possible 18 Best Alternatives of Heterogeneous Organic Mixtures .....                                                  | 53 |
| Table 5.14 Water/Cyclohexane mixture results .....                                                                                 | 54 |
| Table 5.15 Propanol/Cyclohexane mixture results .....                                                                              | 55 |
| Table 5.16 Water/Normal Hexane Mixture results .....                                                                               | 56 |
| Table 5.17 Normal Hexane/Ethanol Mixture Results .....                                                                             | 56 |
| Table 5.18 Isopropanol/ Normal Hexane Mixture Results .....                                                                        | 57 |
| Table 5.19 Water/ 2-Methyl Pentane Mixture Results .....                                                                           | 58 |
| Table 5.20 Ethanol/ 2-Methyl Pentane Mixture Results .....                                                                         | 58 |
| Table 5.21 Cyclohexane/Isopropanol Mixture Results .....                                                                           | 59 |
| Table 5.22 Propanol/ n-Hexane Mixture Results .....                                                                                | 60 |
| Table 5.23 Ethanol/Cyclopentane Mixture Results .....                                                                              | 60 |
| Table 5.24 Isopropanol/ 2-Methyl Pentane Mixture Results .....                                                                     | 61 |
| Table 5.25 Isopropanol/ 2,2-Dimethyl Butane Mixture Results .....                                                                  | 62 |
| Table 5.26 2,2-Dimethyl Butane / Ethanol Mixture Results .....                                                                     | 62 |
| Table 5.27 Isopropanol/ Cyclopentane Mixture Results .....                                                                         | 63 |
| Table 5.28 2-Methyl hexane/ Isopropanol Mixture Results .....                                                                      | 64 |
| Table 5.29 Cyclohexane/ Ethanol mixture results .....                                                                              | 64 |
| Table 5.30 Propanol/ 2,2-Dimethyl Butane Mixture Results .....                                                                     | 65 |
| Table 5.31 Propanol/ 2, Methyl Pentane Mixture Results .....                                                                       | 66 |

## List of Figures

|                                                                                                                                            |    |
|--------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 2.1: The two main categories of energy resources.....                                                                               | 2  |
| Figure 2.2: EPO Patent Publications per different renewable energy sources (1979-2003).....                                                | 3  |
| Figure 2.3: Market size evolution comparison (1980-2005).....                                                                              | 3  |
| Figure 2.4: The components of interaction between solar radiation and atmosphere.....                                                      | 4  |
| Figure 2.5: Global annual average solar irradiance in KWh/m <sup>2</sup> .....                                                             | 5  |
| Figure 2.6: Solar power generation categories .....                                                                                        | 6  |
| Figure 2.7: Photovoltaic cell applications in Egypt.....                                                                                   | 6  |
| Figure 2.8: Mono crystalline silicon PV Cell.....                                                                                          | 7  |
| Figure 2.9: Amorphous silicon PV Cell .....                                                                                                | 7  |
| Figure 2.10: Organic PV Cell.....                                                                                                          | 7  |
| Figure 2.11: TES combined power generation plant.....                                                                                      | 8  |
| Figure 2.12: The three Categories of thermal energy storage materials.....                                                                 | 9  |
| Figure 2.13: The basic layout for ORC .....                                                                                                | 10 |
| Figure 2.14: T-S Diagram for basic layout of ORC .....                                                                                     | 11 |
| Figure 2.15: Schematic Diagram of the ORC with recuperator .....                                                                           | 12 |
| Figure 2.16: Waste heat recovery power generation plant integrated with ORC.....                                                           | 13 |
| Figure 2.17: ORC classification based on pressure level .....                                                                              | 14 |
| Figure 2.18: ORC classification based on temperature level .....                                                                           | 15 |
| Figure 2.19: ORC Applications.....                                                                                                         | 17 |
| Figure 2.20: HTF Technology Solar ORC .....                                                                                                | 18 |
| Figure 2.21: DVG Technology Solar ORC .....                                                                                                | 18 |
| Figure 2.22: Main categories of solar collectors .....                                                                                     | 19 |
| Figure 2.23: Integrated solar ORC in SWRO desalination plant .....                                                                         | 20 |
| Figure 2.24: Isentropic fluid vapor saturation dome in T-S Diagram .....                                                                   | 22 |
| Figure 2.25: Wet fluid vapor saturation dome in T-S Diagram .....                                                                          | 22 |
| Figure 2.26: Dry fluid vapor saturation dome in T-S Diagram.....                                                                           | 22 |
| Figure 2.27: NFPA Diamond .....                                                                                                            | 23 |
| Figure 2.28: Schematic T-S Diagram of ORC using zeotropic working fluids mixtures .....                                                    | 24 |
| Figure 2.29: Temp. Composition Diagram of min boiling heteroazeotrope .....                                                                | 26 |
| Figure 2.30: Temp. Composition Diagram of zeotropic mixture.....                                                                           | 26 |
| Figure 2.31: Temp. Composition Diagram of min boiling homoazeotrope .....                                                                  | 26 |
| Figure 2.32: Temp. Composition Diagram of max boiling azeotrope .....                                                                      | 26 |
| Figure 3.1 : A Scheme of the heterogeneous mixture pressure composition Diagram ..                                                         | 27 |
| Figure 3.2: A schematic comparison between a pure component and its heterogeneous mixture using pressure and temperature constraints ..... | 28 |
| Figure 4.1: The simulation solution logic.....                                                                                             | 33 |
| Figure 4.2: ORC drawn on Aspen Plus software .....                                                                                         | 34 |
| Figure 4.3: The configuration of Flat Plate Collector (FPC) (Source: [9], [40]) .....                                                      | 35 |
| Figure 4.4: Main categories of the organic fluids.....                                                                                     | 37 |
| Figure 5.1: Vapor pressure curves of alcohols .....                                                                                        | 39 |
| Figure 5.2: Vapor pressure curves of alicyclic hydrocarbons .....                                                                          | 40 |
| Figure 5.3: Vapor pressure curves of aliphatic hydrocarbons .....                                                                          | 40 |
| Figure 5.4: Vapor pressure curve of water .....                                                                                            | 41 |

|                                                                                                                                             |    |
|---------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 5.5: % $\eta$ results of pure working fluids .....                                                                                   | 41 |
| Figure 5.6: The cost of pure working fluids in (\$/kg) .....                                                                                | 43 |
| Figure 5.7: Screening Steps for optimum alternatives selection .....                                                                        | 44 |
| Figure 5.8: Schematic T-S Diagrams of the organic pure working fluids liquid-vapor zones .....                                              | 45 |
| Figure 5.9: The dry and wet working fluids .....                                                                                            | 45 |
| Figure 5.10: The % $\eta$ increase and cost savings for the 10 excluded mixtures in the 2 <sup>nd</sup> screening Step .....                | 48 |
| Figure 5.11: Pressure Composition Diagram of Methanol/Cyclopentane, 1 <sup>st</sup> mixture in the four semi excluded mixtures .....        | 49 |
| Figure 5.12: Pressure Composition Diagram of 2,2-Dimethyl Butane /Methanol, 2 <sup>nd</sup> mixture in the 4 semi excluded mixtures .....   | 50 |
| Figure 5.13: Pressure Composition Diagram of 2-Methyl Pentane/Methanol, 3 <sup>rd</sup> mixture in the 4 Semi excluded mixtures .....       | 50 |
| Figure 5.14: Pressure Composition Diagram of Normal Hexane/Methanol, 4 <sup>th</sup> mixture in the 4 semi excluded mixtures .....          | 51 |
| Figure 5.15: The % $\eta$ increase and cost Savings for component 1 in the four semi-excluded mixtures .....                                | 52 |
| Figure 5.16: The % $\eta$ increase and cost savings for component 2 in the four semi-excluded mixtures .....                                | 52 |
| Figure 5.17: Pressure Composition Diagram of Water / Cyclohexane, 1 <sup>st</sup> mixture in the 18 best alternatives .....                 | 54 |
| Figure 5.18: Pressure Composition Diagram of Propanol / Cyclohexane , 2 <sup>nd</sup> mixture in the 18 best alternatives .....             | 55 |
| Figure 5.19: Pressure Composition Diagram of Water/Normal Hexane , 3 <sup>rd</sup> mixture in the 18 best alternatives .....                | 56 |
| Figure 5.20: Pressure Composition Diagram of Normal Hexane/Ethanol, 4 <sup>th</sup> mixture in the 18 best alternatives .....               | 56 |
| Figure 5.21: Pressure Composition Diagram of Isopropanol / Normal hexane Mixture, 5 <sup>th</sup> mixture in the 18 best alternatives ..... | 57 |
| Figure 5.22: Pressure Composition Diagram of Water/2-Methyl pentane, 6 <sup>th</sup> mixture in the 18 best alternatives .....              | 57 |
| Figure 5.23: Pressure Composition Diagram of Ethanol /2-Methyl pentane, 7 <sup>th</sup> mixture in the 18 best alternatives .....           | 58 |
| Figure 5.24: Pressure Composition Diagram of Cyclohexane/Isopropanol, 8 <sup>th</sup> mixture in the 18 best alternatives .....             | 59 |
| Figure 5.25: Pressure Composition Diagram of Propanol /n-Hexane, 9 <sup>th</sup> mixture in the 18 best alternatives .....                  | 59 |
| Figure 5.26: Pressure Composition Diagram of Ethanol/Cyclopentane, 10 <sup>th</sup> mixture in the 18 best alternatives .....               | 60 |
| Figure 5.27: Pressure Composition Diagram of Isopropanol / 2-Methyl Pentane, 11 <sup>th</sup> mixture in the 18 best alternatives .....     | 61 |
| Figure 5.28: Pressure Composition Diagram of Isopropanol / 2,2-Dimethyl Butane, 12 <sup>th</sup> mixture in the 18 best alternatives .....  | 61 |
| Figure 5.29: Pressure Composition Diagram of 2,2-Dimethyl Butane/ Ethanol, 13 <sup>th</sup> mixture in the 18 best alternatives .....       | 62 |
| Figure 5.30: Pressure Composition Diagram of Isopropanol/Cyclopentane, 14 <sup>th</sup> mixture in the 18 best alternatives .....           | 63 |
| Figure 5.31: Pressure Composition Diagram of 2-Methyl hexane /Isopropanol, 15 <sup>th</sup> mixture in the 18 best alternatives .....       | 63 |

|                                                                                                                                      |    |
|--------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 5.32: Pressure Composition Diagram of Cyclohexane/Ethanol, 16 <sup>th</sup> mixture in the 18 best alternatives .....         | 64 |
| Figure 5.33: Pressure Composition Diagram of Propanol/2,2-Dimethyl Butane, 17 <sup>th</sup> mixture in the 18 best alternatives..... | 65 |
| Figure 5.34: Pressure Composition Diagram of Propanol /2, Methyl Pentane, 18 <sup>th</sup> mixture in the 18 best alternatives.....  | 65 |
| Figure 5.35: The 18 best alternatives % Cost Savings and % $\eta$ increase results .....                                             | 67 |
| Figure 5.36: The criteria of choosing the optimum alternatives .....                                                                 | 67 |
| Figure 5.37: NFPA standard of the components in the best 18 alternative mixtures.....                                                | 67 |
| Figure 5.38: Water Cyclohexane pressure composition Diagram.....                                                                     | 68 |
| Figure 5.39: Water Cyclohexane net power vs pump outlet pressure Diagram .....                                                       | 68 |
| Figure 5.40: Water Cyclohexane % $\eta$ vs. pump outlet pressure Diagram .....                                                       | 69 |
| Figure 5.41: Water Cyclohexane $\eta/\eta_{Carnot}$ vs. pump outlet pressure Diagram .....                                           | 69 |
| Figure 5.42: Water Cyclohexane $\Delta S_{total}$ vs. pump outlet pressure Diagram.....                                              | 70 |
| Figure 5.43: Water Normal hexane pressure composition Diagram .....                                                                  | 71 |
| Figure 5.44: Water Normal hexane $\dot{W}_{net}$ vs. pump outlet pressure Diagram .....                                              | 71 |
| Figure 5.45: Water Normal Hexane % $\eta$ vs pump outlet pressure Diagram.....                                                       | 72 |
| Figure 5.46: Water Normal Hexane $\eta/\eta_{Carnot}$ vs. pump outlet pressure Diagram.....                                          | 72 |
| Figure 5.47: Water Cyclohexane $\Delta S_{total}$ vs. pump outlet pressure Diagram.....                                              | 73 |

# Nomenclature

## Abbreviations

|             |                                  |
|-------------|----------------------------------|
| <i>BIPV</i> | Building Integrated Photovoltaic |
| <i>CSP</i>  | Concentrated Solar Power         |
| <i>CPC</i>  | Compound Parabolic Collector     |
| <i>CPV</i>  | Concentrated Photo Voltaic       |
| <i>CSTP</i> | Concentrated Solar Thermal Power |
| <i>DVG</i>  | Direct Vapor Generation          |
| <i>DHI</i>  | Diffusion Horizontal Irradiance  |
| <i>DNI</i>  | Direct Normal Irradiance         |
| <i>EHE</i>  | External Heat Exchanger          |
| <i>EPA</i>  | Environmental Protection Agency  |
| <i>ETC</i>  | Evacuated Trough Collector       |
| <i>FPC</i>  | Flat Plate Collector             |
| <i>GHP</i>  | Global Horizontal Irradiance     |
| <i>GWP</i>  | Global Warming Potential         |
| <i>HPP</i>  | High Pressure Pump               |
| <i>HTF</i>  | Heat Transfer Fluid              |
| <i>IHE</i>  | Internal Heat Exchangers         |
| <i>kWh</i>  | Kilo Watt Hour                   |
| <i>LFC</i>  | Linear Fresnel Collector         |
| <i>LFL</i>  | Lower Flammability Limit         |
| <i>MDM</i>  | Octamethyl trisiloxane           |
| <i>MM</i>   | Hexa methyl disiloxane           |
| <i>NBP</i>  | Normal Boiling Point             |
| <i>NFPA</i> | National Fire protection Agency  |
| <i>ODP</i>  | Ozone Depletion Potential        |
| <i>ORC</i>  | Organic Rankine Cycle            |
| <i>PCM</i>  | Phase Change Material            |
| <i>PFC</i>  | Per Fluoro Carbons               |
| <i>PR</i>   | Peng Robinson                    |
| <i>PTC</i>  | Parabolic Trough Collector       |
| <i>PV</i>   | Photovoltaic                     |
| <i>RO</i>   | Reverse Osmosis                  |
| <i>STPC</i> | Solar Thermal Power Cycle        |
| <i>SWRO</i> | Solar Water Reverse Osmosis      |
| <i>TES</i>  | Thermal Energy Storage           |

## Greek Letter Symbols

|                  |                       |           |
|------------------|-----------------------|-----------|
| $\mu$            | Viscosity             | kg/m. sec |
| $\dot{W}$        | Power Consumption     | kW        |
| $\lambda$        | Latent Heat           | kJ/kg     |
| $\eta_{Carnot}$  | Carnot Efficiency     |           |
| $\eta_{thermal}$ | Thermal Efficiency    |           |
| $\eta_{II}$      | Second law Efficiency |           |

### Letter Symbols

|                           |                                     |          |
|---------------------------|-------------------------------------|----------|
| $C_p$                     | Specific Heat                       | KJ/kg. K |
| $\dot{m}$                 | Mass flow Rate                      | kg/s     |
| $Q$                       | Energy                              | kJ       |
| $H$                       | Enthalpy                            | kJ/kg    |
| $K$                       | Thermal Conductivity                | W/mK     |
| $P$                       | Pressure                            | bar      |
| $P$                       | Pressure Ratio                      |          |
| $S$                       | Entropy                             | kJ/ K    |
| $\Delta S_{system}$       | Change of Entropy in System         | kJ/ K    |
| $\Delta S_{surroundings}$ | Change of Entropy in Surroundings   | kJ/ K    |
| $T$                       | Temperature                         | °C       |
| $T_{hot\ pp}$             | Pinch Point difference at Hot Side  | °C       |
| $T_{cold\ pp}$            | Pinch Point difference at cold Side | °C       |
| $T_H$                     | Highest Temperature in the cycle    | °C       |
| $T_L$                     | Lowest Temperature in the Cycle     | °C       |
| $T_{source}$              | Heat Source Temperature             | °C       |
| $T_{sink}$                | Heat Sink Temperature               | °C       |
| $T_o$                     | Ambient Temperature                 | °C       |

## Abstract

The current thesis is dealing with the application of solar thermal power generation that contributes to saving Earth; one of the merits of this application is its ability to be integrated within any process for variety of applications; one of which is the waste heat recovery. Generally, the solar thermal power generation plants consist of thermal energy storage (TES) systems and power generation cycles. Egypt has a high potential in solar energy utilization since it is located within the Sun Belt countries and has wide land area available for harnessing this energy resource.

The present work addresses improving the performance of Organic Rankine Cycle (ORC), this cycle can be a part of low temperature solar thermal electric generation plant. ORC produces power via the conversion of heat energy into mechanical energy. Although, heterogeneous organic working mixtures can be utilized in ORC for their potential to improve its thermal efficiency, no studies were published in this topic and that is where the novel impact of this investigation lies. Heterogeneous working fluids have higher vapor pressure at azeotropic compositions than their pure alternatives at the same working conditions, which can eventually lead to a significant improvement of the thermal efficiency of the cycle from a thermodynamic point of view using the proper temperature and pressure constraints.

The investigation to improve the ORC thermal efficiency was completed successfully in three main stages. The first stage is the development of a simulation model using Aspen plus Software in which suitable pure organic working fluids are used in ORC application using Direct Vapor Generation (DVG) Technology in low temperature scale within the temperature range between 30 °C - 200 °C. The heat collector used is of the Flat Plate Collector (FPC) type, which does not have complex tracking systems with relatively low cost. In the second stage, a comparison was performed between the thermodynamic calculations of pure and heterogeneous organic working mixtures. The third and final stage was the five steps of screening followed in order to identify the heterogeneous mixtures optimum alternatives.

The results are promising and they are covering all the stages followed in the calculations. From an engineering point of view, the two optimum heterogeneous organic mixtures are water/cyclo hexane and water/normal hexane mixtures. The Optimum mixtures are indicated based on their potential to achieve significant improvement in the performance of the ORC in terms of thermal efficiency taking into account the cost savings and safety limitations.