

THEORETICAL AND EXPERIMENTAL PERFORMANCE OF COMPOUND PARABOLIC CONCENTRATORS

By

Mohamed Hossam Mohamed Shehata Eldakamawy

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE
in
MECHANICAL POWER ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2015

THEORETICAL AND EXPERIMENTAL PERFORMANCE OF COMPOUND PARABOLIC CONCENTRATORS

By

Mohamed Hossam Mohamed Eldakamawy

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE
in
MECHANICAL POWER ENGINEERING

Under Supervision of

Abdalla Sayed Ahmed Hanafi

Professor
Mechanical Power Engineering
Department
Faculty of Engineering,
Cairo University

Mahmoud Abdel-Wahab
Kassem

Associate Professor
Mechanical Power Engineering
Department
Faculty of Engineering,
Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2015

THEORETICAL AND EXPERIMENTAL PERFORMANCE OF COMPOUND PARABOLIC CONCENTRATORS

By

Mohamed Hossam Mohamed Eldakamawy

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE
in
MECHANICAL POWER ENGINEERING

Approved by the
Examining Committee:

Prof. Dr. Mahmoud Abdel-Fatah El-Kady,	External Examiner
---	-------------------

Prof. Dr. Abdel-Wahed El-Dib,	Internal Examiner
--------------------------------------	-------------------

Prof. Dr. Abdalla Sayed Ahmed Hanafi,	Thesis main Advisor
--	---------------------

Dr. Mahmoud Abdel-Wahab Kassem,	Thesis Advisor
--	----------------

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

Engineer: Mohamed Hossam Mohamed Shehata
Eldakamawy
Date of Birth: 14/11/1990
Nationality: Egyptian
E-mail: m_eldakamawy@eng.cu.edu.eg
Phone: 00201285240291
Address: 19, Shawky st, sheikh rihan, talbia faisal,
Giza
Registration Date: 01/10/2012
Awarding Date: / /
Degree: Master of Science
Department: Mechanical Power Engineering



Supervisors: Prof. Dr. Abdalla Sayed Ahmed Hanafi
Dr. Mahmoud Abdel-Wahab Kassem

Examiners: Prof. Dr. Mahmoud Elkady (El Azhar University)
Prof. Dr. Abdel-Wahed El-Dib
Prof. Dr. Abdalla Sayed Ahmed Hanafi
Dr. Mahmoud Abdel-Wahab Kassem

Title of Thesis: THEORETICAL AND EXPERIMENTAL PERFORMANCE
OF COMPOUND PARABOLIC CONCENTRATORS

Keywords: Compound parabolic concentrator, Twisted tape inserts, Bare
tubular absorber, Experimental, Swimming pool heating

Summary:

The compound parabolic concentrators (CPC) are promising low concentration non imaging solar collectors, with intermediate indicative working temperature range (60 - 300 °C), that can operate monthly, seasonally or annually without the need of continuous tracking. They show competitive performance with flat plate collectors when used in applications of temperatures slightly above the ambient. Likely, the CPC collectors have lower cost and smaller pumping power consumption. Thereby, the present work presents a rigorous study of the optical, geometrical and thermal characteristics of CPCs with bare tubular absorbers. This investigation covered also the effect of truncation, number of frequent tilt adjustments and usage of heat transfer enhancement (HTE) techniques like twisted tape insertion on the performance of CPC. In all cases, the CPCs are oriented as usual in an East-West direction and facing south. Moreover, a CPC test rig was set up at the Faculty of Engineering campus, Cairo University, which helped to validate the transient model and gave a clear indication for the CPC performance under Egypt's environmental working conditions. The designed CPC performed well as a solar water heater with a measured efficiency of around 46.7% during winter.

ACKNOWLEDGMENT

Firstly, I would like to thank Almighty ALLAH, whom I firstly owe everything, for his generousness and support through all my life. In our life, we rarely meet some respectful people doing their best, exerting great efforts to share their experience, knowledge and lead us to the right way. I'd like to thank ALLAH for helping me to meet such great professors: Prof. Abdalla Hanafi and Assoc. Prof. Mahmoud Abdel-Wahab, who guided me to finish this work in the most suitable form.

Further thanks go to Prof. Adel Khalil, Prof. Elgamil, Dr. Essam Elhanoony, Eng. Ahmad Abo-Elmagd, Eng. Ahmad Elmelih and Eng. Mostafa Gamal for helping and supporting me with very useful experimental instrumentation and measured data.

Special thanks and gratitude are for my father Eng. Hossam Eldakamawy for his great technical support, and my family for their patience to provide me with the most suitable conditions to finish my work.

Finally, I'd like to thank my colleagues, Eng. Ahmad Hamed, Eng. Mohamad Zidan, Eng. Mohamad Mortada, Eng. Osama Selim and Eng. Ahmad Ibrahim, also technicians in the Mechanical Power Department who encouraged and helped me to finish this work in an appropriate form.

Table of Contents

ACKNOWLEDGMENT.....	i
Table of Contents.....	ii
List of Tables	iv
List of Figures	v
List of Symbols	xi
List of Abbreviations	xiii
ABSTRACT.....	xiv
CHAPTER 1: INTRODUCTION	1
1.1. History of CPC	1
1.2. CPC Principle of operation	1
1.3. Thesis Outlines and Present Study Main Objectives	6
CHAPTER 2: LITERATURE REVIEW	8
2.1. Numerical Investigation on Optical and Geometrical Properties of CPC.....	11
2.2. Numerical Investigation on Thermal Performance of CPC	16
2.3. Previous experimental work done on CPC	22
2.4. Previous Work Done on Heat Transfer Enhancement Techniques Using Twisted Tape Inserts.....	27
2.5. Scope of the Present Work	31
CHAPTER 3: MODELING OF THE COMPOUND PARABOLIC CONCENTRATOR	32
3.1. Selecting of the appropriate solar insolation model	32
3.2. Geometrical properties of CPC with tubular absorber	37
3.3. Optical properties of CPC with tubular absorber	40
3.4. Thermal Analysis of CPC with tubular absorber	44
3.5. Validation of the 1-D model.....	53
3.6. Two dimensional model	58
3.7. Validation of the 2-D model.....	58
3.8. Comparison between 1-D and 2-D models	59
CHAPTER 4: EXPERIMENTAL SETUP	65
4.1. CPC collector	68
4.2. Tanks and Piping System	72

4.3. Measuring Instrumentation	73
4.4. Different Processes.....	75
4.5. Experimental Results and Validation.....	79
CHAPTER 5: RESULTS AND DISCUSSION.....	82
5.1. Effect of Number of Tilt Adjustments	82
5.2. Effect of Truncation Ratio.....	85
5.3. Effect of using swirlers	89
5.3.1. Laminar flow regime.....	89
5.3.2. Transition and turbulent flow regimes	95
5.4. Case studies: Swimming pool heating	99
CHAPTER 6: CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS	103
6.1. Conclusions	103
6.2. Recommendations for future work.....	104
References.....	105
Appendix A: Comparison between different solar insolation models	108
Appendix B: Optical equations for a CPC with flat absorber.....	112
Appendix C: Meteorological data for Egypt.....	113
Appendix D: Monthly and seasonal heat gained versus various tilt angles.....	114

List of Tables

Table 1.1: Comparison between different solar energy collectors [5].	4
Table 1.2: Tilt requirements of CPCs during the year at Different acceptance angles [3].	4
Table 2.1: Summary of selected literatures concerned with numerical investigation on optical performance and geometrical properties of CPCs.	8
Table 2.2: Summary of selected literatures concerned with numerical investigation on thermal performance of CPCs.	8
Table 2.3: Summary of selected literatures concerned with experimental investigation on CPCs	9
Table 2.4: Summary of selected literatures concerned with HTE mechanisms.	10
Table 3.1: Correction Factors for Climate Types [24].	33
Table 3.2: ASHRAE model constants for U.S.A. and for Egypt [24].	34
Table 3.3: Optical properties of truncated CPC with $\theta_c=35^\circ$ [8].	40
Table 3.4: CPC collector sample parameters	59
Table 3.5: Computational time versus segment size.	64
Table 4.1: Calibration data for the 7 thermocouple utilized	74
Table 4.2: Various valves settings versus each process. V stands for valve, 1 for opened and 0 for closed.	76
Table 5.1: Recommended tilt angles versus number of yearly tilt adjustments	83
Table 5.2: Design features and estimated cost of the two proposed CPC designs.	100
Table C.1: Average wind speed, average water temperature of the Nile, maximum and minimum air temperatures in all months through the year as recorded by the New and Renewable Energy Authority (NREA) [30].	113
Table C.2: Daily range values.	113

List of Figures

Figure 1.1: Construction of a light funnel with a half acceptance angle of 16° [2].	1
Figure 1.2: Cross section of a symmetrical untruncated CPC [1].	2
Figure 1.3: Ray tracing for a single light ray in a CPC collector [3].	3
Figure 1.4: Four configurations of CPC receivers, all having same perimeter and acceptance half-angle [6].	5
Figure 1.5: Fraction of radiation incident on the aperture of a CPC at angle θ which reaches the absorber surface if the reflectivity is unity. (____) Full CPC with no surface errors; (----) truncated CPC with no surface errors; (.....) full CPC with surface errors [4].	6
Figure 2.1: Four types of CPC solar collectors with diminished absorbers surrounded by glass tubes [6].	12
Figure 2.2: Four types of CPC with truncated reflectors to create a gap between the reflector and the receiver [6].	12
Figure 2.3: Four types of CPC with receiver modified to form a radiation cavity [6].	13
Figure 2.4: A CPC with flat receiver and mirrors M_1 and M_2 spread apart to maintain their foci, F_1 and F_2 respectively, at the edges of the absorber [6].	13
Figure 2.5: Full and truncated cusp concentrators with $\theta_c = 40^\circ, 35^\circ$, and 30° respectively (Left). The corresponding reflector arc length to entrance aperture ratio plotted against the concentration ratio (Right) [7].	14
Figure 2.6: Fraction of beam radiation available to CPC with $\theta_c = 35^\circ$ as a function of extreme edge ray angle, θ_D [8].	15
Figure 2.7: Average number of reflections for CPC with tubular absorber as a function of concentration ratio, for $\theta_c = 20^\circ, 30^\circ, 35^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ$ and 80° [8].	16
Figure 2.8: Calculated performance of CPC collector with flat absorber subjected to solar insolation of 1000 W/m^2 for concentration values of 1.6, 4 and 8 [4].	17
Figure 2.9: Predicted variations of the CPC collector's performance [10].	19
Figure 2.10: Variation of Nusselt number with Grashof number for different truncation ratios [11].	20
Figure 2.11: Thermal boundary conditions at the reflector [12].	20
Figure 2.12: Predicted variation of CPC efficiency with angular inclination for concentrations of 1.5, 3 and 5 [14].	22
Figure 2.13: Summary of the performance curves for the non-evacuated CPC collectors designed by Rabl et al [15].	23
Figure 2.14: The CPC tested by Collares-Pereira [16].	24

Figure 2.15: The CPC tested by Santos-González et al. [18]	25
Figure 2.16: The CPC cavity investigated by Singh and Eames [19].....	26
Figure 2.17: Schematic diagram of the SPETC with a symmetric CPC: (a) sketch diagram and (b) real photo of the system [20]	27
Figure 2.18: HTE ratio using different types of tube inserts, having various helix angles, with low and high viscosity fluids, for both laminar and turbulent flows [21].	28
Figure 2.19: Overall enhancement ratio using different types of tube inserts, having various helix angles, with low and high viscosity fluids, for both laminar and turbulent flows [21].	28
Figure 2.20: Variation of Nusselt number with Reynolds number at different twist ratios [23].....	30
Figure 2.21: Variation of friction factor with Reynolds number at different twist ratios [23].....	30
Figure 3.1: Comparison between different solar radiation models for Egypt in March.	35
Figure 3.2: Comparison between different solar radiation models for Egypt in June.	36
Figure 3.3: Comparison between different solar radiation models for Egypt in September.	36
Figure 3.4: Comparison between different solar radiation models for Egypt in December.	37
Figure 3.5: Full (untruncated) CPC with tubular absorber and half-acceptance angle = 40° [7].....	38
Figure 3.6: Generating the profile of CPC reflector [7].....	39
Figure 3.7: The extreme edge ray angle (θ_D) of a truncated CPC [8]	39
Figure 3.8: Ray-trace diagrams for a 30° acceptance half-angle tubular absorber CPC, rays incident at 0° , 29° , and 31° with the normal to the aperture cover [12].....	41
Figure 3.9: A CPC with tube receiver with radius r which has been displaced from its designed position (dashed circle) to another (solid circle) by a distance g [6].....	42
Figure 3.10: Truncated reflector to create a gap (g) between the reflector and the receiver [6].....	42
Figure 3.11: gap optical losses with different values of g and R_r , first alternative is expressed as solid line while the dashed line is for the second alternative.....	43
Figure 3.12: Reflector edge modification [16]	43
Figure 3.13: CPC collector with non-evacuated tubular absorber [10]	45
Figure 3.14: Heat fluxes and exchange rates between collector components [10]	45

Figure 3.15: Projection on a north-south plane of CPC acceptance angles and slope for a CPC on an east-west axis [1]	46
Figure 3.16: Electric analog circuit for the CPC collector [10].	48
Figure 3.17: Cross section of the CPC trough [16].	53
Figure 3.18: Numerical versus experimental thermal efficiency	54
Figure 3.19: The experimental setup by Santos-González et al. [18].	55
Figure 3.20: Numerical and experimental instantaneous thermal efficiency with a mass flow rate of 0.25 kg/s	56
Figure 3.21: Numerical and experimental results for the working fluid temperature rise.	56
Figure 3.22: Numerical and experimental results for the useful heat gain at different inlet temperatures	57
Figure 3.23: Numerical and experimental results for the CPC outlet temperature.	57
Figure 3.24: Working fluid temperature rise versus mass flow rate	58
Figure 3.25: Numerical and experimental temperature profile along the tube receiver	59
Figure 3.26: Effect of collector length on the difference between 1-D and 2-D model results of fluid outlet temperature; at 1 kg/s, $T_i = 20\text{ }^{\circ}\text{C}$ and $C = 4.6821$	60
Figure 3.27: Effect of concentration ratio on the difference between 1-D and 2-D model results' of fluid outlet temperature; at 1 kg/s, $T_i = 20\text{ }^{\circ}\text{C}$ and $L = 500\text{ m}$	61
Figure 3.28: Effect of concentration ratio on the difference between 1-D and 2-D models results' of fluid outlet temperature; at 1 kg/s, $T_i = 40\text{ }^{\circ}\text{C}$ and $L = 500\text{ m}$	61
Figure 3.29: Effect of mass flow rate on the difference between 1-D and 2-D models results' of fluid outlet temperature; at $C = 1.6082$, $T_i = 20\text{ }^{\circ}\text{C}$ and $L = 500\text{ m}$	62
Figure 3.30: Effect of mass flow rate on the difference between 1-D and 2-D models results' of fluid outlet temperature; at $C = 4.6821$, $T_i = 20\text{ }^{\circ}\text{C}$ and $L = 300\text{ m}$	62
Figure 3.31: Effect of mass flow rate on the difference between 1-D and 2-D models results' of fluid outlet temperature; at $C = 1.6082$, $T_i = 80\text{ }^{\circ}\text{C}$ and $L = 250\text{ m}$	63
Figure 4.1: Flow diagram of the test rig.	65
Figure 4.2: Real photo of the test rig (View 1).	66
Figure 4.3: Real photo of the test rig (View 2).	66
Figure 4.4: Real photo of the test rig (View 3).	67
Figure 4.5: Real photo of the test rig (View 4).	67
Figure 4.6: CPC collector box.	68
Figure 4.7: CPC from inside.	68

Figure 4.8: Velocity magnitudes through the absorber tube at $Re = 32834$	69
Figure 4.9: Gap between the absorber and the reflector	70
Figure 4.10: CPC profile along with the line of truncation (in blue).....	71
Figure 4.11: Concentrating light rays onto the absorber.....	71
Figure 4.12: Tanks and piping system	72
Figure 4.13: NI cDAQ-9174 (Left) and NI 9213 thermocouple module (Right)	73
Figure 4.14: LabVIEW program.....	74
Figure 4.15: Rotameter calibration curve	75
Figure 4.16: Filling the system with water	76
Figure 4.17: Preheating (heaters are switched on).....	77
Figure 4.18: Instantaneous test	77
Figure 4.19: Transient test	78
Figure 4.20: Discharging Tank 1 and filling Tank 2	78
Figure 4.21: Transient test on 22/12/2014.	80
Figure 4.22: Transient test on 1/1/2015.	80
Figure 4.23: Transient test on 14/1/2015.	81
Figure 5.1: Monthly useful energy gained in June.	83
Figure 5.2: Monthly useful energy gained in December.	84
Figure 5.3: Yearly useful energy gained.....	84
Figure 5.4: Effect of truncation on CPC efficiency.	85
Figure 5.5: Effect of truncation on optical, thermal and overall CPC efficiencies.....	86
Figure 5.6: Effect of truncation on the overall heat loss coefficient.....	87
Figure 5.7: Effect of truncation on the useful heat gained.....	88
Figure 5.8: The optimum range of truncation ratios.....	88
Figure 5.9: Twisted tape with alternate axis versus typical twisted tape [23]	89
Figure 5.10: CPC thermal efficiency versus inlet temperature using different twisted tape configurations (laminar regime)	91
Figure 5.11: Pumping power versus inlet temperature using different twisted tape configurations (laminar regime)	91
Figure 5.12: Thermal performance factor versus inlet temperature using different twisted tape configurations (laminar regime).....	92

Figure 5.13: CPC thermal efficiency versus mass flow rate using different twisted tape configurations (laminar regime)	93
Figure 5.14: Pumping power versus mass flow rate using different twisted tape configurations (laminar regime)	94
Figure 5.15: Thermal performance factor versus mass flow rate using different twisted tape configurations (laminar regime).....	94
Figure 5.16: Serrated twisted tape [22].....	95
Figure 5.17: CPC thermal efficiency versus inlet temperature using different twisted tape configurations (transition + turbulent regimes)	96
Figure 5.18: CPC thermal efficiency versus inlet temperature using different twisted tape configurations (turbulent regime)	96
Figure 5.19: Pumping power versus inlet temperature using different twisted tape configurations (transition + turbulent regimes)	97
Figure 5.20: Pumping power versus inlet temperature using different twisted tape configurations (turbulent regime)	98
Figure 5.21: Thermal performance factor versus inlet temperature using different twisted tape configurations (transition + turbulent regimes).....	98
Figure 5.22: Thermal performance factor versus inlet temperature using different twisted tape configurations (turbulent regime).....	99
Figure 5.23: Second design CPC profile along with the line of truncation (in blue).	101
Figure 5.24: Instantaneous CPC efficiency during the day	102
Figure 5.25: Outlet water and swimming pool temperatures during the day.....	102
Figure A.1: Comparison between different solar radiation models for Egypt in January.	108
Figure A.2: Comparison between different solar radiation models for Egypt in February.	108
Figure A.3: Comparison between different solar radiation models for Egypt in April. ..	109
Figure A.4: Comparison between different solar radiation models for Egypt in May. ...	109
Figure A.5: Comparison between different solar radiation models for Egypt in July.	110
Figure A.6: Comparison between different solar radiation models for Egypt in August.	110
Figure A.7: Comparison between different solar radiation models for Egypt in October.	111
Figure A.8: Comparison between different solar radiation models for Egypt in November.	111

Figure D.1: Monthly useful energy gained in January.	114
Figure D.2: Monthly useful energy gained in February.	114
Figure D.3: Monthly useful energy gained in March.	115
Figure D.4: Monthly useful energy gained in April.	115
Figure D.5: Monthly useful energy gained in May.....	116
Figure D.6: Monthly useful energy gained in July.	116
Figure D.7: Monthly useful energy gained in August.	117
Figure D.8: Monthly useful energy gained in September.....	117
Figure D.9: Monthly useful energy gained in October.	118
Figure D.10: Monthly useful energy gained in November.	118
Figure D.11: Seasonal useful energy gained in January, February and March.	119
Figure D.12: Seasonal useful energy gained in April, May and June.....	119
Figure D.13: Seasonal useful energy gained in July, August and September.	120
Figure D.14: Seasonal useful energy gained in October, November and December.	120
Figure D.15: Seasonal useful energy gained in April, May, June, July, August and September.	121
Figure D.16: Seasonal useful energy gained in October, November, December, January, February and March.....	121

List of Symbols

A	Area, m^2
\bar{A}	Altitude, km
α	Absorptivity
a_0, a_1 and k	Constants for standard atmospheric conditions
a_0^*, a_1^* and k^*	Corrected constants for Hottel model
β	Tilt angle, degrees
C	Concentration ratio
δ	Declination angle, degrees
ϵ	Emissivity
f_{end}	End losses factor
f	Friction factor
f_{rat}	Ratio between heat transfer coefficients
F	Control function
F'	Ratio between thermal resistances
g	Gap distance between reflector and absorber, m
γ_s	Solar azimuth angle, degrees
Gr	Grashof number
H	Full collector height, m
H_t	Truncated collector height, m
h	Heat transfer coefficient, $W/m^2.K$
H^*	Characteristic length, m
h_{tot}	Overall heat loss coefficient, $W/m^2.K$
η_o	Optical efficiency
η	Instantaneous efficiency
I_b	Normal beam radiation, W/m^2
I_d	Diffuse radiation on horizontal surface, W/m^2
I_o	Normal extraterrestrial radiation, W/m^2
I_{sc}	Solar constant, W/m^2
I_{tot}	Total incident radiation, W/m^2
I_u	Useful gained radiation, W/m^2
k	Thermal conductivity, $W/m.K$
L	Collector length, m
m	Air mass
m^*	Corrected air mass
\dot{m}	Mass flow rate, kg/s
M	Arc length, m
\bar{n}_i	Average number of internal reflections within θ_c
\bar{n}_o	Average number of internal reflections outside θ_c
n	Day number
Nu	Nusselt number
ν	Kinematic viscosity, m^2/s