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**UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES**

**MODELLING AND SIMULATION OF A
CENTRAL SOLAR POWER TOWER PLANT**

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**BY
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Modelling and Simulation of a Central Solar Power Tower Plant



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**Supervisor
Prof. Dr. Mehmet Sait SÖYLEMEZ**

**By
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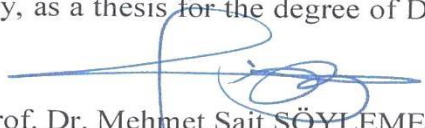
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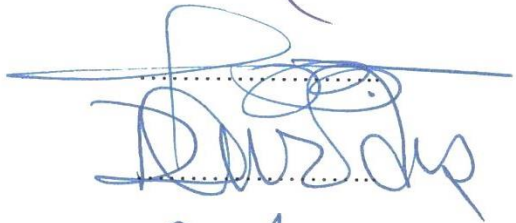
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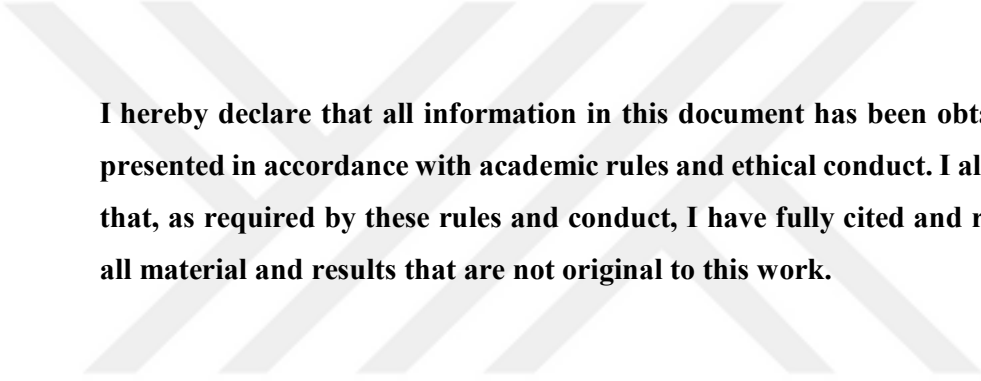
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Raad Kadhim Mohammed AL-DULAIMI

ABSTRACT

MODELING AND SIMULATION OF A CENTRAL SOLAR POWER TOWER PLANT

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Ph.D. in Mechanical Engineering

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163 page

A novel heliostat field layout is suggested by dividing specified heliostats located farthest from the tower and exhibiting low optical efficiency into strips and increasing the height for these strips with varying heights, based on the consideration of no blocking. A novel geometrical equation is presented for this purpose, and the results indicate an increase in the total annual efficiency of the field. Furthermore, shading and blocking are considered one of the main causes that result in the drop of the optical performance of the heliostat fields. In this study, we suggest through the simulation, an accurate and fast framework to enhance the optical performance of the solar field with the existence of the shading and blocking. By practicing the new style, running down the implementation time and keeping off unnecessary computations, our framework increases the speed of the computations through parallel computing architectures, then using the Artificial Neural Network (ANN) to investigate the efficiency of our proposed system. A prior study on the performance of high-efficient models for a heliostat field and solar receiver at various candidate locations (e.g., certain regions in the south of Turkey) helped determine suitable locations for installing solar tower power plant units. This study considered the fact that solar tower power plants are affected by the working conditions of a particular site, which helps realize the highest performance of the solar power tower plant. An optimized heliostat field consisting of 2650 SENER heliostats and a model of a solar receiver based on the data obtained using Gemasolar in Seville, Spain, was used as a reference in this work.

Key Words: Solar power tower plant, heliostat field, multilevel layout, artificial neural networks, shadowing and blocking, phyllotaxis, Turkey.

ÖZET

BİR MERKEZİ ALICILI GÜNEŞ GÜÇ SANTRALİNİN MODELLENMESİ VE SİMÜLASYONU

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163 sayfa

Güneş tarlalarında bloklama etkilerini azaltmak için yeni bir helyostat yerleştirme dizaynı önerilerek gerilerde kalan helyostatların düşük optik verimlilikleri artırılmıştır. Bu amaçla yeni bir geometrik formülasyon sunulmuş ve yıllık verimdeki artış gözlenmiştir. Ayrıca, helyostatlarda gölgeleme ve bloklama etkilerinin azaltılması temel problem olarak ele alınmış olup bu amaçla çalışmada hızlı ve doğru çalışan matematiksel model kullanılmıştır. Önerilen çözüm modeli sayesinde gereksiz yere uzun zamanlı bilgisayar hesaplama süresi azaltılmıştır. Paralel çalışan suni ağ kullanımı tekniği ile hesaplama verimliliği artırılmıştır. Kullanılan metod ile alınan sonuçlar literatürdeki sonuçlarla uyumluluk göstermiştir. Güneş tarlalarının Türkiye'nin değişik iklimsel bölgelerindeki verimleri anılan yeni hesaplama tekniği kullanılarak hesaplanmak suretiyle en verimli bölgeler araştırılmış ve bölgesel öneriler sunulmuştur. En iyi çalışma şartlarına göre dizayn edilmiş olan 2650 SENER helyostat kullanan İspanya Sevilla'da kurulu Gemosolar güneş tarlasının deneysel sonuçları, bu çalışmada mevcut sonuçların doğruluğunun kontrolünde kullanılmıştır. Mevcut model sayesinde optimizasyon algoritması kullanılarak daha önceki verimlilik değerlerinin artırılması iki yeni parametrenin değiştirilmesi ile sağlanmıştır. Ayrıca, örnek bir analitik ısıl model kullanılarak toplayıcıdaki ısıtım ve taşınım kayıpları hesaplanmıştır.

Anahtar Kelimeler: Güneş enerjili güç sistemi, helyostat tarlası, değişken yükseklikli yerleştirme, yapay sinir ağları, gölgeleme ve bloklama, filotaksi, Türkiye

DEDICATION

To the soul of my parents,
The reason of what I have become today,
Who made of me a fixed principles man, with a strong will to overcome difficulties,
wish you were here with me....

To Shayma Ihsan,
My wife, my love brought to me by God's beautiful grace.
Partner with me on a vibrant journey, full of life...

To my three angels,
Sara, Aaya and Dalya,
My sunshine in dark moments,
The source of hope and beauty, my smile in sad days...

To my brothers and sisters,
You are my family, my support,
Your prayers were the source of goodness in my life...

To Dr. Ihsan Altimimi and his family,
My second father,
You made me part of your family,
My source of support, attention and guidance at every step of my life...

Thanks to all of you for your great support and continuous care, my happiness on this
occasion completed by your presence with me...

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TABLE OF CONTENTS

	Page
ABSTRACT	v
ÖZET	vi
ACKNOWLEDGEMENTS.....	viii
TABLE OF CONTENTS	ix
LIST OF FIGURES	xii
LIST OF TABLES	xvi
NOMENCLATURE	xvii
CHAPTER 1.....	1
INTRODUCTION.....	1
1.1 Research Objective	1
1.2 Motivation and Scope of Work.....	3
CHAPTER 2.....	5
LITERATURE SURVEY.....	5
2.1 Central Receiver Solar Thermal Power Plants.....	5
2.2 Heliostat Fields	7
2.3 Heliostat Field Analysis	7
2.4 Field Optimization Methods	9
2.4.1 Field Growth Method	9
2.4.2 Geometrical Style Method	10
2.5 Field Optimization Considerations.....	13
2.5.1 Objective Function	13
2.5.2 Parameters and Algorithms	13
2.6 Solar Receivers	14
CHAPTER 3	16
TOOLS AND MATHEMATICAL MODEL	16
3.1 The Sun's Position	16
3.1.1 Latitude Angle (ϕ)	17

3.1.2 Declination (δ)	17
3.1.3 The Hour Angle (ω)	18
3.1.4 Solar Time(t_s)	19
3.2 Heliostat-Sun Angles	19
3.2.1 Solar Zenith, Altitude, and Azimuth Angles	19
3.3 Solar Radiations	21
3.4 Ambient Temp.	22
3.5 Sun-Tracking Formula.	22
3.6 SENER Heliostats and Receiver Model, Specifications.	26
3.7 Geometrical Style Layout for Heliostat Field.	27
3.8 The Mean Yearly Heliostat Field Efficiency.	27
3.9 Instantaneous Optical Efficiency Factors.	29
3.9.1 Descretized Heliostat Surface and Coordinate Transformation of Heliostat.	33
3.9.2 Mathematical Model for Shading and Blocking Algorithm	36
3.9.3 Parallel Computing in MATLAB.....	42
3.9.4. Artificial Neural Networks (ANNs).....	43
3.10 Mathematical Model for Multilevel Heliostat Field Layout.....	46
3.11 Thermo Economical Optimization of Number of Heliostats for Solar Fields.....	49
3.11.1 Mathematical Formulation	50
3.12 Receiver	52
3.12.1 Receiver Model Sizing and Mass Flow Rate.....	55
3.12.2 Shape Distribution of the Incident Power on an External Receiver..	56
3.11.3 Receiver Thermal Model.....	58
3.11.4 The Methodology of Total Heat Loss Calculation.....	62
3.13. Rankine Cycle for the Central Receiver Power Plant.....	63
CHAPTER 4	67
CFD: NUMERICAL SOLUTION	67
4.1 Modeling.....	67
4.1.1 Geometry.....	67
4.1.2 FLUENT Boundary Conditions and Settings	68
CHAPTER 5	71
RESULTS AND DISCUSSION	71

5.1. Optimization of the Field Layout	71
5.1.1. Computational Benchmarking for Heliostat Field Efficiency	73
5.1.2. Performance of Artificial Neural Networks (ANNs)	74
5.1.3. Analysis of Increased Height for Certain Groups of Heliostats	78
5.1.4. A Thermo Economic Optimization Analysis.	80
5.2. Solar Receiver.	82
5.2.1. Computational Benchmarking for Solar Receiver Efficiency and Performance.....	82
5.2.2. Numerical Simulation Result	82
5.3 Analysis of Simulating the (CRS) Behavior in Different Locations.....	83
CHAPTER 6	96
CONCLUSION	96
6.1. Findings	96
6.2. Recommendations for Future Work	97
REFERENCES.....	98
APPENDIX (A).....	103
APPENDIX (B).	104
APPENDIX (C).	105
APPENDIX (D).	106

LIST OF FIGURES

	Page
Figure 2.1 Schematic of a molten salt central receiver system [12]	6
Figure 2.2 Radial stagger patterns [26]	10
Figure 2.3 Photograph of the solar two plant (https://en.wikipedia.org/wiki/The_Solar_Project)	11
Figure 2.4 The scheme used in the graphical method to calculate the new row radius [29].....	12
Figure 3.1 Annual motion of the earth relative to the sun [38].....	17
Figure 3.2 Latitude angle (ϕ).....	17
Figure 3.3 The declination angle (δ). [26].....	18
Figure 3.4 The Hour Angle (ω) [26]	18
Figure 3.5 Earth Surface Coordinate System for Heliostat Point, Clarifying The Solar Azimuth Angle A_z , The Solar Altitude Angle α , and The Solar Zenith Angle θ_z for a Central Sun Ray [26].	20
Figure 3.6 Unit direction vector $\vec{S}$ as respective to their axes.	21
Figure 3.7 Movements of heliostat vectors in azimuth-elevation sun- tracking method	24
Figure 3.8 The flow chart to show the algorithm to estimate the $\eta_{year,Eb}$..	29
Figure 3.9 The cosine effect on heliostat [26]	30
Figure 3.10 Discretization of the heliostat	34
Figure 3.11 Fixed heliostats numbers that Cause shadowing and blocking for heliostat (571), with the polar coordinates(r_{sb} & θ_{sb}).....	37
Figure 3.12 Shadowing aperture	38
Figure 3.13 Shadowing test	39
Figure 3.14 Discretization area of heliostats	40
Figure 3.15 Normal distance between two centers of subdivisions	41

Figure 3.16	Running a Loop That Occurs in the Series Change to Parallel (https://computing.llnl.gov/tutorials/parallel_comp)	43
Figure 3.17	The Flow Chart to Show the Algorithm to Estimate The $\eta_{year,Eb}$ with Using ANNs	45
Figure 3.18	Properties of the network, which is used in ANNs	46
Figure 3.19	Front view of the reference and successive heliostats.	47
Figure 3.20	Increasing height of two successive strips.	49
Figure 3.21	Typical Receiver Panel Design [12]	53
Figure 3.22	Eight possible flow configurations for the external receiver. Each configuration is presented from a top-down, axial line of sight viewpoint [53].	54
Figure 3.23	Discretization of the surface of the solar receiver with present projection plane	57
Figure 3.24	Shape distribution of the incident power on the external surface at spring equinox-solar noon for Seville, Spain	58
Figure 3.25	Heat transfer in receiver	59
Figure 3.26	Receiver pipe thermal resistance model	61
Figure 3.27	Temperature-entropy diagram of the cycle configuration adapted from Solar Two power cycle	64
Figure 4.1	Sketch of the computational domain for CFD simulations[37]	68
Figure 4.2	Sketch of the mesh structure	69
Figure 5.1	Layout of the field and $\eta_{year,Eb}$ for each heliostat	73
Figure 5.2	Different between ANNs and the discretization model, for computing the field efficiency (eft) and shadow efficiency (efs) and block efficiency (efb), for day 180 and every 4 minutes	75
Figure 5.3	Field efficiency by discretization model and by ANNs	76
Figure 5.4	Different between ANNs and discretization model for computing efficiencies for heliostats (2640,3006)	77
Figure 5.5	Mean yearly heliostat field efficiency $\eta_{year,Eb}$ with increasing the heights of different numbers of strips.....	78
Figure 5.6	Eight heliostat strips encircling the center of the tower.	79

Figure 5.7	$\eta_{year,Eb}$ for the full heliostat field after increasing heights for eight strips.	80
Figure 5.8	Total Life Cycle Savings versus Number of Heliostats.....	81
Figure 5.9	Annual Average of Daily Total Solar Thermal Energy versus Number of Heliostats.....	81
Figure 5.10	Temperatures of $T_{HTF}(i, j)$ and $T_{s,i,j}$ along length of path flow L_{pf} (Analytic solution)	82
Figure 5.11	Temperatures of T_{HTF} at output of each panel for path flow (north – west - south) and for (Analytic solution and Numerical solution)	83
Figure 5.12	Accumulated solar energies transformed from the heliostat field and receiver for 12 average days in Seville, Spain.....	84
Figure 5.13	The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 202 and for Seville –Spain.....	84
Figure 5.14	The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Seville –Spain.....	85
Figure 5.15	Accumulated energies for Gaziantep, Turkey.....	85
Figure 5.16	The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 172 and for Gaziantep, Turkey...	86
Figure 5.17	The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Gaziantep, Turkey...	86
Figure 5.18	Accumulated energies for Sanliurfa, Turkey.....	87
Figure 5.19	The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 141 and for Sanliurfa, Turkey....	88
Figure 5.20	the power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Sanliurfa, Turkey.....	88
Figure 5.21	Accumulated energies for Finike, Turkey	89

Figure 5.22	the power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 172 and for Finike, Turkey.....	89
Figure 5.23	the power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Finike, Turkey.....	90
Figure 5.24	Total accumulated solar energies for all 12 days at different locations.....	95



LIST OF TABLES

	Page
Table 3.1 Gemasolar fields and receiver parameters[8, 9, 10]	27
Table 3.2 Input and output variables for ANNs	44
Table 3.3 Molten salt mixture properties [54].	55
Table 3.4 Isentropic efficiencies of turbine and pump with temperature and high-pressure turbine inlet and condensing pressure [53].....	65
Table 5.1 Yearly weighted efficiency for different design variables	74
Table 5.2 The values of efficiencies during the day 180	75
Table 5.3 The values of the implementation time (sec) for one step for the deferent technique	78
Table 5.4 Average increase in annual efficiency $\eta_{year,Eb}$ with increasing heights for successive strips	79
Table 5.5 Thermo economic performance values for solar heliostats.....	81
Table 5.6 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Seville –Spain	91
Table 5.7 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Gaziantep, Turkey.	92
Table 5.8 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Sanliurfa, Turkey	93
Table 5.9 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Finike, Turkey	94
Table 5.10 Field and receiver efficiencies for each city	94

NOMENCLATURE

A	Solar azimuth angle, (degree)
A_h	Heliostat total area, (m ²)
A_m	Heliostat mirror area, (m ²)
A_e	Area element, (m ²)
A_{sh}, A_{bl}	Areas that not effected with shadowing & blocking, (m ²)
A_{su}	The surface area of the panel block, (m ²)
b	Beam air mass exponents
C_p	Specific heat, (J/kg · K)
C_E	Cost of solar thermal energy produced, (\$/W.hr)
C_N	Area dependent first cost of the heat exchanger, (\$/m ²)
D	The distance between the heliostat Centre and the aim point in receiver, (m)
d	The square root of the whole heliostat area
d_h	Diagonal diameter of the total heliostat, (m)
d_e	Diagonal diameter of the element
d_{Md}	Market discount rate in fraction
E_h, N_h	Cartesian coordinates for heliostat position
$E_b(t)$	Beam normal radiation, (W/m ²)
E_o	Extraterrestrial normal irradiance, (W/m ²)
E_{av}	Annual average of daily total solar thermal energy collected by heliostats, (kW.hr)
$[G]$	Final three transformation matrix
Gr	Grashof number
H_r	Receiver height, (m)
h_{en}	Enthalpy, (kJ/kg)
h_r	Receiver optical height, (m)
h_h	Height of heliostat upon ground, (m)
$\bar{h}_{mix}$	Convection heat transfer coefficient, (W/m ² · K)
i	Energy price escalation rate in fraction
k	Thermal conductivity, (W/m · K)
m	Air mass
$\dot{m}$	Mass flow rate, (kg/s)
M	Technical life of cross flow heat exchanger, (yr)
M_s	Ratio of annual maintenance and operation cost into first original cost
n_d	Day of the year
n_h	Number of heliostat in the field as a sequence

N_h	Number of heliostat in the field as value
N_{crit}	Critical number of heliostats
$N_{h,opt}$	Optimum number of heliostats
ns, nb	Number of elements area for heliostat, that is not effected by shadowing and blocking
n_{bl}	Number of block elements for solar receiver
n_p	Number of panel elements for solar receiver
n_t	The number of tubes n_t in each panel
$\vec{n}$	The unit normal vector of the heliostat surface
Nu	Nusselt number
P_C	Center point of the heliostat surface
Pr	Prandtl number
$P_{i,j}$	Coordinates of the heliostat grid points
$P'_{i,j}$	Coordinates the center of the discretization area relative to the coordinate System in the heliostat field
$P'_{i,j, sb}$	The center of the subdivisions for heliostat causes for shadowing and blocking
$P'_{i,j, h}$	The center of the subdivisions of the main heliostat
P_1	Ratio of the life cycle energy cost savings to the first year energy cost savings, (yr)
P_2	Ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment,
$\dot{Q}_{inc}$	incident power on the external receiver surface, (W)
$\dot{Q}_{abs}$	The energy absorbed by the working fluid, (W)
$\dot{Q}_{conv}$	Convective losses, (W)
$\dot{Q}_{rad}$	Radiative losses, (W)
$\dot{Q}_{ref}$	Reflective losses, (W)
$\vec{R}$	The unit vector from the center of the heliostat pointing to the receiver
R_r	Receiver radius
Ra	Rayleigh number
Re	Reynold number
R_V	Ratio of resale value into the first original cost
r_P	Radius position for heliostat
S_{Lf}	Net overall life cycle savings by the help of the solar heliostats, (\$)
$\vec{s}$	The unit vector from the center of the heliostat pointing to the sun
T	Temperature degree
T_{bb}	Black body temperature, (K)
t_s	Solar time
v	Specific volume, (m ³ /kg)
W_h, H_h	Width & Height of the heliostat , (m)
W_e, H_e	Width & Height of the element

Greek symbols

η	Instantaneous optical efficiency
η_{cos}	Cosine efficiency
η_{at}	Atmospheric attenuation efficiency
η_{in}	Interception efficiency
$\eta_{s\&b}$	Shading and blocking efficiency
η_{ref}	Reflectivity
$\eta_{year,Eb}$	Yearly insolation weighted efficiency
η_{year}	Yearly unweighted efficiency
δ	Solar declination angle, (degree)
ϕ	Latitude angle
ω	Hour angle, (degree)
α	Solar altitude angle, (degree)
α_{AE}	Angular movements of the heliostat frame about the elevation axis
α_P	Solar profile angle
α_{ab}	Hemispherical absorptivity
θ	Angle of incidence
θ_z	Solar zenith angle
θ_P	Polar position Angle for heliostat in field
$\tau_b \& \tau_d$	Beam and diffuse “pseudo” optical depths
σ_{tot}	Dispersion of the reflected beam, (mrad)
σ_{sun}	Dispersion of sunlight, (mrad)
σ_{bq}	Dispersion due to mirror slope error, (mrad)
σ_s	Circular Gaussian error distribution
σ_{ast}	Dispersion due to astigmatic effect, (mrad)
σ_t	Dispersion due to tracking errors, (mrad)
ρ_{AE}	Angular movements of the heliostat frame about the azimuth axis
λ	Orientation angle of heliostat
ψ	Angle position for heliostat
μ	Dynamic viscosity, (Pa.s)
β	Volume expansion coefficient
φ	Golden ratio $(1 + \sqrt{5})/2 = 1.618$

Subscript

<i>amb, hourly</i>	Ambient temperature for each hour
<i>amb</i>	Ambient air temperature
<i>bo</i>	Boiler
<i>cond</i>	Conduction
<i>conv</i>	Convection
<i>ex</i>	Exit flow rate from the tube
<i>en</i>	Entrance flow rate to the tube
<i>i</i>	Inside from receiver pipe
<i>L</i>	Length of the receiver which equals height of the receiver
<i>l</i>	Molten salt mixture liquid
<i>ms</i>	Mean molten salt temperature
<i>o</i>	Outside from receiver pipe
<i>r</i>	Receiver
<i>sky</i>	Sky temperature
<i>s</i>	Surface
<i>st</i>	Steam
∞	Infinity

Acronyms

CRS	Central Receiver Solar Thermal Power Plants
CSP	Concentrating Solar Power
DB	Monthly Design Dry Bulb
MCDBR	Mean Coincident Dry Bulb Temp. Range, (°C)
AE	Azimuth-Elevation Sun-Tracking Method
(<i>sb</i>)	Shading and Blocking Function
PCT	Parallel Computing Toolbox
HTF	Heat Transfer Fluid
GA	Genetic Algorithm
Ebn,noon	Beam Normal at Solar Noon

CHAPTER 1

INTRODUCTION

The growth in energy demand, the run out of fossil fuels, and the awareness of public opinion of environmental problems prompt producing electrical energy towards renewable sources. The sunshine is the most plentiful source of energy on Earth and every year delivers more than 10,000 times the quantity of energy that humans currently use [1]. Of all technologies for concentrated solar power (CSP), the Central Receiver Solar Thermal Power Plants (CRS) technology viewed as more worthwhile, because of its high working temperatures, that giving rise for raising the efficiency of the power cycle. With this great feature, and the Neoteric rush of attention in decreasing the price and increasing the efficiency of (CSP), incited most researchers to work in the (CRS) technology. The main job for a plenty of reflectors that they joined and called the heliostat field, reflected and condensed sun's rays toward the main receiver. For each reflector, a computer controls the rotation around two axes to ensure a continuous, accurate orientation, with a tracking error of less than a fraction of a degree. By orientation, the intensified sunlight focused straight on the tower receiver. Where an absorber heated up to temperatures of about 1000 °C, or more [2]. Heat transfer fluid (HTF) transfers the absorbed energy to a heat exchanger connected to a gas or steam turbine, in its turn coupled to an electric generator.

1.1 Research Objective

The capital importance and the topic of many works are the ideal layouts of the reflector field. The main reason is that approach 50% of the full price of the scheme and its annual energy loss is around 47% [3]. Several codes have produced for this aim, from the 1970s, most of them recorded in Garcia et al. [4].

Thus, evaluations of the different layouts were checked through forming multiple distribution layouts. After that, an optimization study performed with a new methodology to find the best layout of the field for a 19.9 MWth (CRS) for GEMASOLAR (Seville –Spain), was used as a reference in this work and as a case study, Utilizing genetic algorithms (GA), and depending on the prophylaxis pattern proposed by Noone [5]. Then, study increasing heliostats height depended on derived geometric formulation, for selected strips of heliostat which placed at the end of the field layout, which suffer from low optical efficiency.

Any ideal layout evaluation should depend on annual energy that reaches for the receiver. Because any SPT optimization operation should depend on annual energy estimation of the different layouts checked. The annual energy is the integrated sum of the instantaneous energy that is transformed by all reflectors; after considering global efficiency for each one, over the moments of time [6].

The shading and blocking efficiency($\eta_{s\&b}$), consider one of the main ingredients which result in the run-down the optical performance of the heliostat fields. At the same time, considers is the most intensive element as estimates from others included in the equation of global efficiency, because it depends on different factors. Like, the site of sun's, and position of the reflector, and placement of the neighboring for it. Thus, during the optimization All neighbors causing shading or blocking on the analyzed reflector should evaluate individually, to estimate the ($\eta_{s\&b}$) exactly. Then the overlapping effects among multiple reflectors should remove, and the relative location of each heliostat with placement of the neighboring changed, to increase total field performance, and this needed a noticeable accounting time.

In this study, the central ray tracing and discretization technique adopted to calculate the shading and blocking efficiency($\eta_{s\&b}$), with small subdivision and high accuracy. But at the same time, ameliorate the computational period, and superfluous computations for heliostats that are not causing of shading or blocking blocked, and the process can handle the overlapping problem created by multiple heliostats through logical parameters using. Development of this technique occurred by using parallel computing architectures based on the MATLAB Parallel Computing Toolbox, and by using neural algorithms that clarify in detail later. The outcomes match with others studying and good improvement in result is found.

At the same time one of the main purpose of this work is to apply software simulations, a dynamic simulation developed in MATLAB, and consider all average days in the

year, as presented in (American Society of Heating, Refrigeration, and Air-conditioning Engineers) (ASHRAE) [7], within a specified interval time, to study the potential of SPTP technology through a hypothetical relocation of Seville, Spain's Gemasolar SPTP to regions in the south of Turkey (Gaziantep, Sanliurfa, and Finike). This study also determines where the highest energy output can be achieved by comparing the performance in terms of the accumulated energies and efficiencies of main units that are affected by special construction requirements in these border locations.

Further, the field and geometrical data receiver model for a GEMASOLAR (SPTP) (Seville–Spain), which is a modern, efficient, and highly productive energy plant, with its border location is considered as a reference in this study.

GEMASOLAR is 20 MW power plant that was established in 2011 [8]. One of the reasons of the success and possesses distinct characteristics of this plant is because of the careful selection of the site. It is situated within the city limits of Fuentes de Andalucía in the province of Seville, Spain, which is considered to be one of the most sunniest and warmest areas in the Europe.

It is considered as a reference case in several studies. For instance, in Amadei et al. [9], the author studies the hypothetical relocation of the same plant to different Chinese regions through software simulation (Solar Advisor Model, SAM). In Collado et al. [10], the author studied the optimization of the heliostat field by adopting radially staggered distribution with an implemented Campo code [6], and estimated the maximum annual energy with a new layout suggested.

Furthermore, a thermo economic optimization analysis is presented yielding simple algebraic formula for estimating the optimum number of heliostats for solar fields which are applied in industrial applications. An economic analysis method is used in the present study, together with the thermal analyses of heliostats, for thermo economic optimization. The validity of the optimization formulations was checked.

1.2 Motivation and Scope of Work

This thesis involved the development of a software tool that assists in the preliminary performance modeling of central receiver plants. The scope of this work is to study, through software simulations, the potential of (CRS) technology in Turkey, through a hypothetical relocation of GEMASOLAR in different Turkey regions, verifying where it is possible to accomplish the highest energy output solutions. Take into account heat

transfer losses from the receiver and optical efficiency of the solar field. Further optimization of field layout, performed using an available optimization algorithm with new geometric consideration to add to the body of knowledge in this research area. At the same time, speed up calculations by A new, fast algorithms with high precision for estimate optical efficiency of optimizing solar fields.

After that, this study investigates changing heliostat levels with no blocking consideration, but with variable slope, starting with the heliostat located farthest from the tower's central receiver because it has higher optical losses than the closer heliostats.



CHAPTER 2

LITERATURE SURVEY

The literature survey in this chapter contains highlights from the literature studied in this research project. It places the main target, that enhancement of performance of CRS technology, and describe some of the current studies in this field, with focusing on the heliostat field layout optimization and with different ways selected to reach this point.

2.1 Central Receiver Solar Thermal Power Plants

Concentrating solar power (CSP) is a process of utilizing the energy from the sun, which uses mirrors that are placed in such a way that they can reflect light from the sun toward a centralized area. The sun's rays, instead of being absorbed by the earth, are reflected in that particular area. The CRS that shown in Figure 2.1 is an application of CSP technology. This system involves the use of a field of mirrors called a heliostat pointed towards receiver atop a large tower. The field of heliostats acts as a large parabolic reflector broken into small segments. The receiver heats up due to the incoming solar radiation flux and transmits heat to a heat transfer fluid. This fluid is usually water, air, or molten salt. The heat transfer fluid is then utilized, directly or indirectly, to run a turbine that produces electricity through a generator. Concentration ratios (total area of the heliostats to the area of the receiver) as high as 3000 may be achieved with solar central receiver systems. The CRS can be considered as sufficiently mature after the pioneering experience of several 0.5-10MW pilot plants in the early 1980s, and the subsequent improvement of such key components as heliostats and solar receiver in many later projects emerging international collaboration during the past 20 years [11].

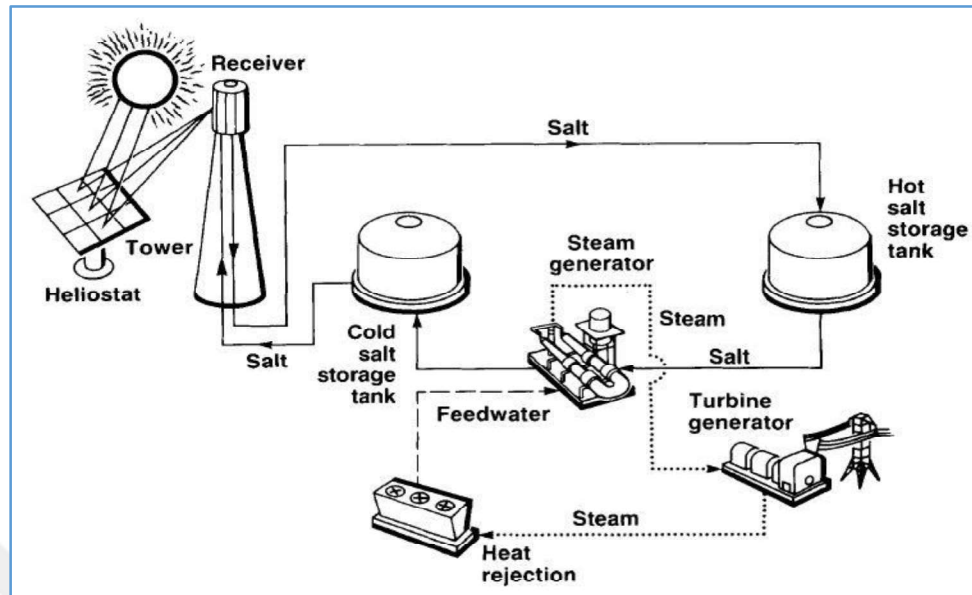


Figure 2.1 Schematic of a molten salt central receiver system [12]

An early paper on a central receiver concept by Baum (1956) outlined a design in which heliostats were to be mounted on semicircular railway tracks, with the assemblies of mirrors moved during the day to keep beam radiation focused on the central receiver [13]. On the other hand, CRS considered more significantly performing than other CSP systems, such as line-focus systems [14]. That's a result of the high energy flux densities and, then, the high temperatures that may be achieved by these systems [15]. The dual-axis tracking system that is a feature of reflectors on CRS contributed in performance progression, and more uniform optical efficiency over the duration of CRS working [16].

The beginning of the implementation of heliostats, the sun-tracking manner has been performed utilizing the Azimuth-Elevation (AE) manner [17]. Azimuth-Elevation (AE) system is among the most popular sun-tracking system utilized in various solar energy implementations [18].

In the azimuth-elevation tracking, the reflector must be free to rotate about the zenith axis and the axis parallel to the surface of the earth. The tracking angle about the zenith axis is the solar azimuth angle, and the tracking angle about the horizontal axis is the solar elevation angle [17]. Therefore, the accuracy of the azimuth-elevation tracking system highly relied on how well the azimuth axis is aligned to be parallel with the zenith axis [18]. The movements of the heliostat are implemented by two actuators: one of them for the azimuth that supplies rotational motion in the azimuth direction,

and the second rotates the heliostat in the elevation direction. Azimuth-elevation manner more widely used because of its straightforward design learned from the steering mirror used in the optical system and radar antennae.

2.2 Heliostat Fields

The heliostat field is the "largest single capital investment" in a CRS. The paramount manner for decreasing the total cost of a CRS noticeably (in terms of capital equipment cost), is by ameliorating the efficiency of the heliostat field [19]. That issue related to many factors, some of them, Optical efficiency of the heliostat field that determined by the layout of the heliostats, the surface of the reflective facet surface (the coating used) and the methods of keeping the reflective surface clean.

2.3 Heliostat Field Analysis

Garcia et al. [4], screen present codes, and tried to estimate which one should be utilized relying on the objectives of the simulation, and which outcomes can be predictable. He divided modeling tools for CRS into two main concepts, compatible to two kinds of problems, with regard to heliostat fields; two kinds of problems can be categorized. The first one is an optimization problem: “what is the best heliostat field layout to maximize the collected solar energy or to minimize the cost of that energy?”; the second one is a performance estimation: “what is the power reflected from the field and received at the receiver aperture? First Group concern with optimization codes to design, installation projects like HFLCAL, UHC-RCCELL, or (WIN) DELSOL; second Group concern with performance analysis codes to assess optical performances of a given installation like FIAT LUX, MIRVAL, UHC-NS or IH, or SOLTRACE. He refers that for research laboratories or industrial developers, it seems interesting to use one code for each category to reach the optimal heliostat field.

The most recent studies [1, 5, 10, 20], use various access for increasing the global efficiency, Which they consist from; the cosine effect efficiency(η_{cos}), the atmospheric attenuation efficiency (η_{at}), the interception efficiency(η_{in}), the shading and blocking efficiency($\eta_{s\&b}$), and the reflectivity of the heliostats (η_{ref}). To maximize the percentage of energy that transformed from the sun by the heliostat field. The ray tracing method that referred in studies [4, 21] that used for optical analysis by estimate summing number of rays from the sun that intersect with surfaces in the

system being analyzed. The surfaces include the heliostats and the receiver. Each ray carries a certain amount of energy. Further, they considered ray tracing is more computationally expensive than the approximation methods.

Leonardi et al. [2], perform complete ray tracing to estimate the shading and blocking factor of the square and circular heliostat or possibly mixed in the composing solar field with a Gaussian distribution. This method can do precise calculations for each heliostat in the field, but a massive quantity of computation is required. Further, make a comparison with optical performance for solar field, between flat ground and leaned ground, assumed an inclined ground, with a slope of 15° , in the northern quadrants, this study showed the presence of the inclined ground allows a slower increase of η_{sb} With respect to the ground.

Huang et al. [22] reported that shading and blocking are one of the primary factors that result in the drop of the optical performance of the heliostat field. He evaluates four methods for accurate and quick estimations of shading and blocking with developed two kinds of accurate models; the integration of analytical function and solar central ray tracing model. He states the central ray tracing and discretization technique consider an accurate model, but it's so time-consuming and computationally expensive.

Chiesi et al. [1] cut down the computational time by algorithms that utilize the new parallel calculating framework depended on the general objective graphic processing units and carried out on desktop workstations developed with multiple graphics processing units (GPU) using the data parallel programming pattern provided by the CUDA C implementation). Further, the algorithms of computing shading and blocking effect based on projection coordinates of the affecting heliostats onto the plane called mirror projection. Then discretized the main heliostat into a matrix of square sub-mirrors. A sub mirror counted in the shadow area if the neighbor mirrors' projection falls on it. Similar to blocking, the only difference is in the observation position, which, in this case, matches with the receiver. It's considered an accurate model if it has a high number of sub-elements.

Collado et al. [6] adopted radially staggered distribution and convert the field into several angular sections, showed seven angular sections in this study, features the relative location of the shadowing reflectors kept constant. Then pick tests of the shadowing reflectors for each angular section erected for the intensive layouts. After that, maximum three shadowing reflectors have selected for each angular section and

the same for blocking, the shading and blocking efficiency ($\eta_{s\&b}$) estimated by following Sassi procedure [23] and consider the a duration time of calculation, start from minimum sun elevation of 15° to noon. This made out precisely for PSA in Almería, Spain. Nevertheless, the hurdle of this model is that for other sites and other ends of the sun elevation.

2.4 Field Optimization Methods

In general, there are two models utilized for Heliostat field layout optimization, as described below.

2.4.1 Field Growth Method

Sa'nchez et al. [24] depended on Field Growth Method to generate the field layout for (CRS), by plan yearly normalized energy surface (YNES) or efficiency maps that based on factors of optical efficiency, which their values are a direct function of location coordinate (X, Y) of the field with respect to the tower. These factors consist of; the cosine, the atmospheric attenuation and spillage factors. After that, estimate yearly energy available from (Typical Meteorological Year (TMY)) data as the product of the three factors at every point. Despite (YNES) is not yet influenced by shadowing and blocking, it provides first- sight datum on the energy potential of the field for the specific receiver and heliostat being considered. Then the first heliostat is located on the site with the greatest energy available at the less distance from the tower. When the heliostat is assigned, yearly normalized shadowing and blocking are added to the evaluation of this heliostat. Then every point in the field is once again evaluated to estimate the best location for a second heliostat to be assigned, and a second heliostat is located in this position. This process is repeated for heliostats three and four and so on until the field size can meet the system requirements.

In spite of, each heliostat allocation is dependent on the preceding allocation. This leaves little space for parallelization of the optimization; it is not possible to place heliostats simultaneously. Parallelization can be employed during the search phase, though; that is, for a single heliostat placement, each possible location can be evaluated simultaneously through parallelization. At the same time, as shown in this search, all optical losses should consider simultaneously to get the ideal layout.

Implantation time cut down with the growth method; a reasonable field can be acquired, only once the optimization has been completed. This is different from

following methods, which can be discontinued at any time yet still deliver a feasible field.

2.4.2 Geometrical Style Method

Heliostat field layout can be planned by depending on a geometric pattern that based on specific parameters.

The radial stagger heliostat layout pattern, which heliostats are placed around a tower in rings. This model proposed by the University of Houston [25], and estimate the nominal values for radial (ΔR) and azimuthal (angular) (ΔA) spacing as shown in Figure 2.2.

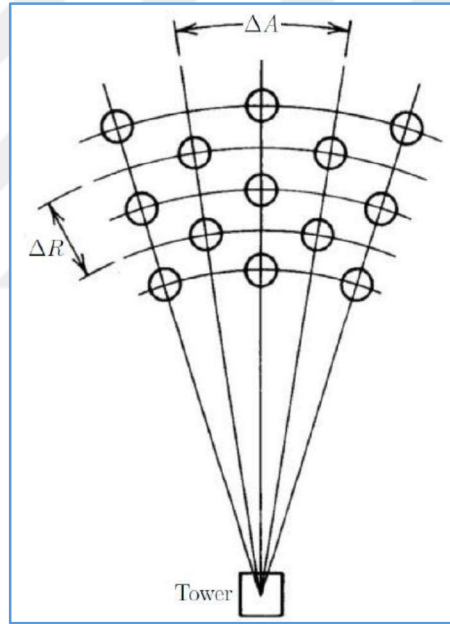


Figure 2.2 Radial stagger patterns [26].

This model developed from the DELSOL user's manual [27], the heliostat field layout in Figure 2.2 can be optimized through two parameters of the pattern which control the increase in distance between successive rows and when the rows split (i.e., when the distance between heliostats in a row is large enough that the angular separation between heliostats in the successive row can be split in half without the potential for heliostat collision or causing significant shading or blocking). The nominal values for radial and azimuthal (angular) spacing are from the DELSOL3 user's manual [26], based on previous work [25], where θ_L is the receiver aperture altitude angle with

respect to a position on the ground (function of row radius), HM is the heliostat height, WM is the heliostat width, and THT is the tower height. The radial spacing has been divided by two from the original form of the equation to represent the distance between successive rows.

$$\Delta R = HM(1.14424 \cot \theta_L - 1.0935 + 3.0684\theta_L - 1.1256\theta_L^2) \dots \dots \dots (2.1)$$

$$\Delta Az = \left(1.7491 + 0.6396\theta_L + \frac{0.02873}{\theta_L - 0.04902} \right) WM \frac{2r}{2r - HM \cdot \Delta R} \left(1 - \frac{HM \cdot \Delta R}{2r \cdot THT} \right)^{-1} \dots \dots \dots (2.2)$$

where all the dimensions have to be taken in meters, since the equation is not dimensionally consistent.

The optimized heliostat field obtained by DELSOL3, as in Solar One and Solar Two [28], has a radially staggered layout, as we see in the Figure 2.3.

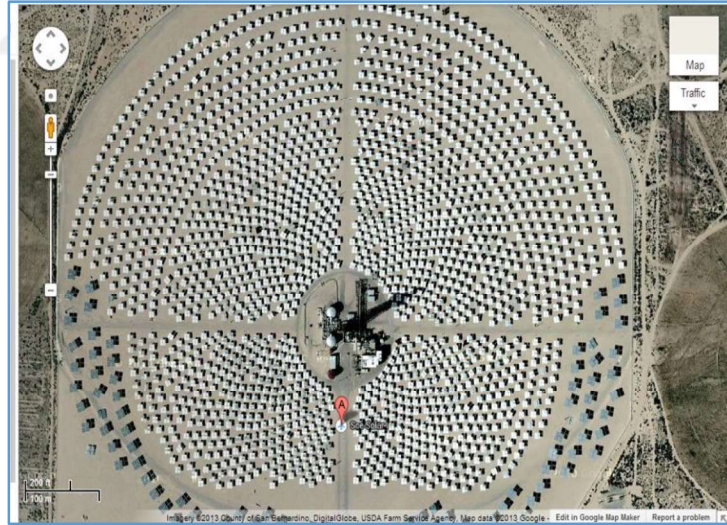
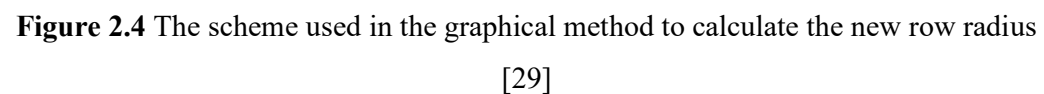


Figure 2.3 Photograph of the solar two plant;
https://en.wikipedia.org/wiki/The_Solar_Project

And adopted with another developed by [6]. The last author proposes the spacing between the rings of a zone constant. To reduce the shadowing and blocking losses, and to keep the minimum distance for mechanical constraints, the algorithm proposed a parameter 'desp' to define the minimum distance between the heliostats. For this algorithm, the first step is the estimation of the parameters that define each of the zones

Siala et al. [29], derived a graphical method to planning radial stagger arrangement of solar field layout, based on the consideration that no blocking losses over the year as shown in Figure 2.4 This method responsible for distributing reflectors in the field by specifying the placement of each one along an inclined plane, with assures that neighboring mirrors block none of the energy reflected by heliostat. Further, the sloping of the ground considers for all field area with unity angle. That lead to the process is inefficient and expensive at the same time because the balance of efficiency factors may be touched on in a negative way like shadow losses, but this method can weigh as a suitable for the preliminary design of heliostat field.



12

patterns are a style that mimics naturally existing patterns, such as the phyllotaxis disc pattern utilized by [5].

2.5 Field Optimization Considerations

Optimizing a field should depend on several points. Some of them are mentioned in the literature below.

2.5.1 Objective Function

Yearly heliostat field efficiency or the insolation-weighted ($\eta_{year, Eb}$) adopted as objective function from, [5] and [20], they refer that any heliostat field optimization operation should depend on annual energy estimation of the different layouts checked. The annual energy is the integrated sum of the instantaneous energy transformed by all reflectors, over the moments of time [10].

Pitz-Paal et al. [30] Considers the objective function of the optimization field is the average annual solar-to-chemical energy conversion efficiency.

Sa'nchez et al. [24] Depends on the high potential yearly energy to planned yearly efficiency map to specify locations of the heliostats.

2.5.2 Parameters and Algorithms

Noone et al. [5] and Besarati et al. [20] depended on two factors that responsible for the scheme of the layout of the field, handled as the design variables, where the best value of them estimated by using an optimization algorithm.

Besarati et al. [20] developed the optimization process by using genetic algorithms (GA) to find the best value for two parameters, which considered responsible for the final layouts of the field. But when fix needed heliostats (594 of 3000), depend on collecting power after considered global efficiency, without calculate($\eta_{s\&b}$). Further, estimate annual energy after fix heliostat number, because the heliostat needed, estimated at noon, March 21st.

Pitz-Paal et al. [30] Selected the primary design parameters estimating the layout of the heliostat field, the shape of the secondary concentrator, and reactor geometry to be free parameters subject to optimization. These parameters consist of; heliostat field spacing parameters, angle of sight of the secondary concentrator, the angle between the horizontal and the optical axis of the secondary concentrator receiver-reactor compound of the aperture, and aperture radius of the reactor. The Genetic algorithm,

and the Nelder–Mead algorithm, and the Powell algorithm used for the optimization of these parameters. The author found the last one, has unsatisfied performing.

Further, the author utilized the genetic algorithm to recognize the parameter extensively and search for a parameter vector close to the global maximum. The outcome is fed as a starting point to the Nelder–Mead algorithm for further improvement.

2.6 Solar Receivers

There are a lot of studies related to solar receiver, in this section mentioned some of them, as presented blow, especially which related to our research.

Yu et al. [31]. Estimated and simulated the dynamic performance of the solar cavity receiver for full range operation conditions using a combined model that mainly couples the radiation–heat conversion process and three heat transfer parameters. They also tested the effect of wind and DNI on the performance of DAHAN receiver. Their results showed that wind angle or velocity can obviously influence the thermal losses. Li et al. [32] Established an easy–to use global steady- state model, taking into account all elements that effected on the receiver performance, like receiver area, heat loss (convective, emissive, reflective and conductive), the number of tubes in the receiver panel, tube diameter and receiver surface temperature. The model was also utilized to estimate the receiver performance of the Sandia National Laboratories’ molten salt electric experiment (MSEE). Further, the thermal performance of the designed molten salt cavity receiver is presented for a fixed outlet flow rate and a fixed output temperature.

Fang et al. [33] chose an iterative method, depend on Monte–Carlo Ray Tracing technique, to estimate surface temperature and to investigate the performance of the cavity receiver under windy conditions.

The present model for solar receiver analyzed through computational fluid dynamics (CFD), which used from several authors to design or analyzed thermal performance for cylindrical receiver, for instance

Yang et al. [34] utilized the CFD, to simulate the heat transfer into the HTF within a tube, and consider the half tube was heated by an uneven radiation while the other half tube was considered an adiabatic surface, at the same time, the outcome compared with experimental result which recorded by experimental establish, and the comparison

shows that the deviation within $\pm 7.5\%$, for the values of the Nusselt number between experimental and numerical, over a Re range of 10,000-40,000

Joshua. [35] utilized the CFD, to simulate and estimate the thermal performance of the solar two power plant receiver model, a simplified trapezoidal panel with flat surfaces representing a single receiver panel, and the author adopted two boundary condition in his simulation first a uniform heat flux on the receiver and second a distributed heat flux generated from the code DELSOL, and the outcome appear the second boundary in radiative heat losses that were 14% higher than the first boundary, and in convective losses that were 5-10% higher than the first one

Garbrecht et al. [36] utilized the CFD to investigate the thermal efficiency in new design for external receiver which aimed to decrease thermal losses, by applying a new geometry based on numerous hexagonal pyramid- shaped elements, to hold radiative losses to connect with ambiance, and he utilized numerical simulated by coupled the CFD simulation with Matlab code to predictive the radiation and heat flow into the receiver.

Sanchez et al. [37] utilized the CFD to simulate the heat transfer in the external receiver by selected exemplary tube per panel and consider the outlet condition for each tube as the inlet for the successive tube of the next panel in path flow, and the outcome of this simulation compare with two thermal model, one suppose homogeneous surface boundary condition and second suppose homogeneous surface heat flux, the comparison showed that the difference in the HTF, wall temperatures and absorbed heat flux was lower than 7%.

CHAPTER 3

TOOLS AND MATHEMATICAL MODEL

So as to realize how to gather energy from the sun and convert to another kind of the energy, the first concept be able to estimate the position of the sun with respect to the energy collection system. This chapter includes the development the important equations by utilizing a unique vector approach. Further, development the mathematical model for entire heliostat field and a solar receiver was introduced.

One objective in writing this chapter has been to present adequate analytical expressions so that the solar designer can develop computer algorithms for modeling and simulating CRS, and then mimic the real plant for analysis to find the best performance of the subject of the research.

3.1 The Sun's Position

The earth completes one rotation about its axis every 24 h and makes a revolution about the sun in an interval of approximately 365.25 days. This revolution is not circular but moves an ellipse with the sun at one of the foci, as clarified in Figure 3.1. The sun-earth distance, at perihelion (shortest distance, at January 3) and aphelion (longest distance, at July 4). The worth of the longest distance equal to $152.1 \times 10^6 km$ and for the shortest distance equal to $147.1 \times 10^6 km$, as clarified in Figure 3.1.

The proportional motions of the sun and earth are not simple, but they are methodical and thus predictable. The sun's location in the sky alters from day to day and from hour to hour. It is the popular knowledge that the sun is higher in the sky in the summer than in winter. The earth rotates around the sun in an orbit that is elliptical in shape at Once a year. As the earth complete its yearly revolution around the sun, it rotates every 24 h about its axis, which is tilted at an angle of $23^\circ 27.14 \text{ min}$ (23.45°) to the plane of the elliptic, which include the earth's orbital plane and the sun's equator[13], as clarified in Figure 3.1

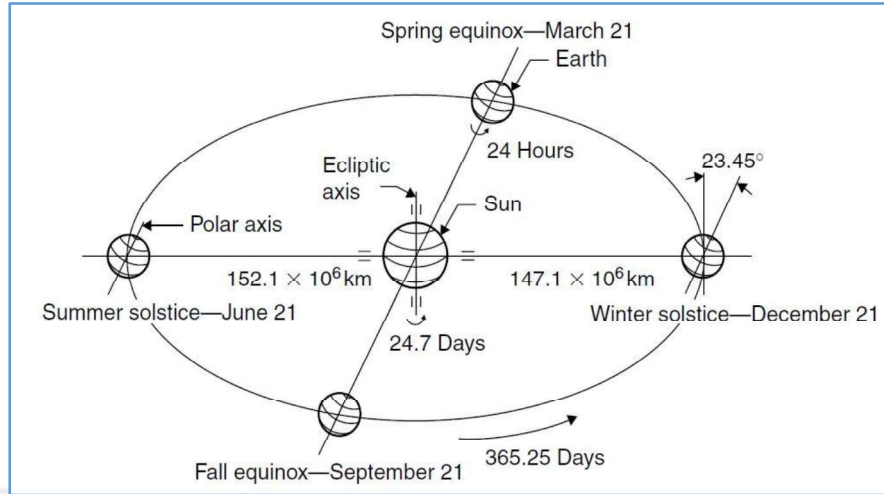


Figure 3.1 Annual motion of the earth relative to the sun [38].

3.1.1 Latitude Angle(ϕ)

The latitude angle(ϕ) , the angular location north or south of the equator, north positive;($-90 \leq \phi \leq 90^\circ$)[13], as we see from the Figure 3.2.

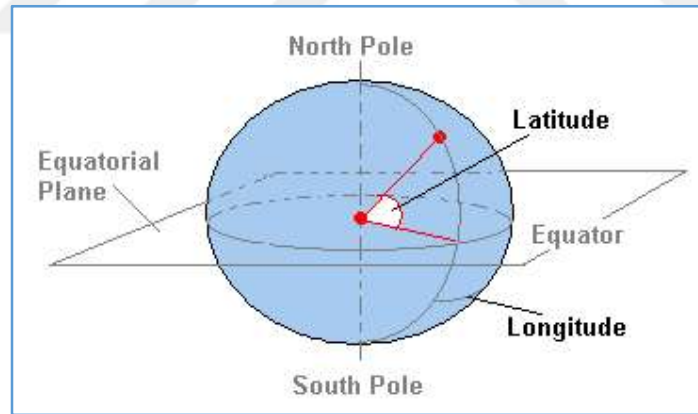


Figure 3.2 Latitude angle (ϕ)

3.1.2 Declination(δ)

The angular position of the sun at solar noon (i.e., when the sun is on the local meridian) relative to the plane of the equator, north positive; $-23.45^\circ \leq \delta \leq 23.45^\circ$ [13] as we see from the Figure 3.3.

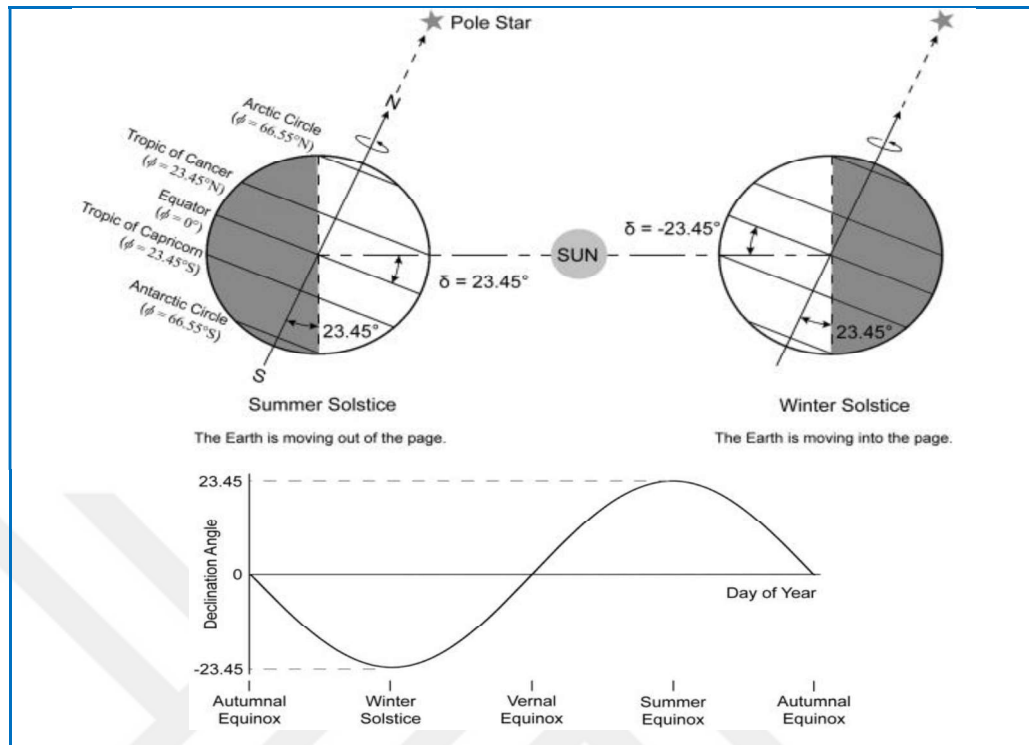


Figure 3.3 The declination angle (δ) [26].

The declination δ can be estimated from the sacrificial equation of Cooper (1969) [13].

$$\delta = 23.45 \sin \left(360 \frac{284 + n_d}{365} \right) \dots \dots \dots 3.1$$

3.1.3 The Hour Angle(ω)

The angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, as we see from the Figure 3.4, morning negative, afternoon positive.

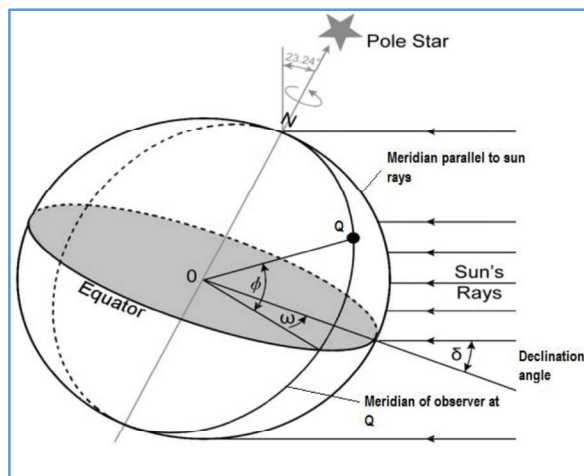


Figure 3.4 The hour angle (ω) [26]

3.1.4 Solar Time(t_s)

Time depend on the obvious angular motion of the sun across the sky, with solar noon the time the sun crosses the meridian of the observer. The notion of solar time is utilized in estimating the direction of sun rays with respect to a point on the earth. Solar time places (longitude) dependent and is generally different from local clock time, which is defined by politically defined time zones and other approximations. Solar time is utilized extensively in this text to realize the rotation of the earth with respect to the sun. An expression to estimate the hour angle from solar time [17] is

$$\omega = 15(t_s - 12) \dots \dots \dots (3.2)$$

Where (t_s) is the solar time in hours.

Hour angle (ω) for sunrise and sunset estimate from the equation [5]

$$\omega_{sunrise} = \cos^{-1}(\tan \phi \tan \delta) - \pi = -\omega_{sunset} \quad (rad) \dots \dots \dots (3.3)$$

3.2 Heliostat-Sun Angles

It is important to estimate the path of the sun ray relative to the heliostat. That helps to orientate the heliostat in a direction that maximizes gathered energy. Thus, it is interested to estimate the sun position with respect to a coordinate system based on the point of the heliostat, not at the center of the earth. The conventional earth-surface based coordinates are a vertical line (straight up) and a horizontal plane containing a north-south line and an east-west line. The location of the sun with respect to these coordinates can be characterized by two angles; the solar altitude, or zenith angle and the solar azimuth angle as defined below.

3.2.1 Solar Zenith, Altitude, and Azimuth Angles

Solar zenith (θ_z) angle; the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.

The solar altitude angle (α); the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle, as clarified in Figure 3.5.

$$\theta_z = 90^\circ - \alpha \dots \dots \dots (3.4)$$

The other angle defining the position of the sun is the **solar azimuth angle (A)**. It is the angle, measured clockwise on the horizontal plane, from the north-pointing coordinate axis to the projection of the sun's central ray.

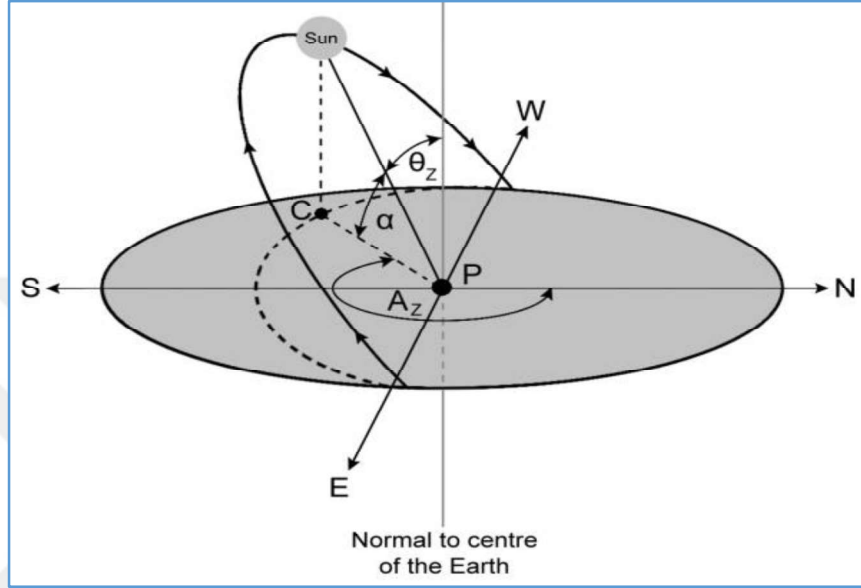


Figure 3.5 Earth surface coordinate system for heliostat point, clarifying the solar azimuth angle A , the solar altitude angle α and the solar zenith angle θ_z for a central sun ray [26].

The mathematical formulations for these angles [17], as a function of the heliostat field latitude (*location*), the hour angle (*time*), and the sun's declination (*date*), can write as.

$$\alpha = \sin^{-1}(\sin\delta \sin\phi + \cos\delta \cos\omega \cos\phi) \dots \dots \dots (3.5)$$

$$A'' = \cos^{-1}\left(\frac{\sin\delta \cos\phi - \cos\delta \cos\omega \sin\phi}{\cos\alpha}\right) \dots \dots \dots (3.6)$$

Where if: $\sin \omega > 0$ then $A = 360^\circ - A''$

Otherwise $\sin \omega \leq 0$ and $A = A''$

That's lead to estimate a unit direction vector $\vec{S}$ pointing toward the sun from the heliostat position $\mathbf{Q}$ as shown in Figure 3.6:

$$\mathbf{S} = S_z \mathbf{i} + S_e \mathbf{j} + S_n \mathbf{k} \dots \dots \dots (3.7)$$

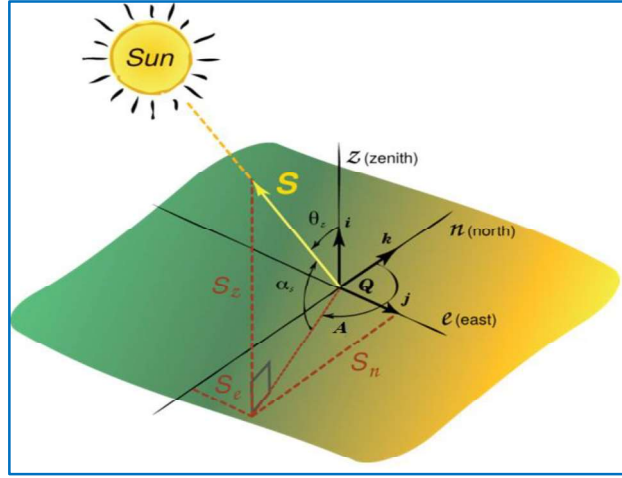


Figure 3.6 Unit direction vector $\vec{S}$ as respective to their axes.

Where i, j , and k are unit vectors along the z, e , and n axes respectively. The direction cosines of S with respect to the z, e , and n axes are S_z, S_e , and S_n , respectively. These may be written regarding solar altitude and azimuth as

$$\vec{S} = \begin{bmatrix} \sin\alpha \\ \cos\alpha \sin A \\ \cos\alpha \cos A \end{bmatrix} \dots \dots \dots (3.8)$$

In summary, we now have equations for both the sun's altitude angle and azimuth angle written regarding the latitude, declination and hour angles. This now permits us to calculate the sun's position in the sky, as a function of date, time, and location(δ, ω, ϕ).

3.3 Solar Radiations

The annual energy reaching the receiver is the total of the instantaneous energy transformed by the solid field of heliostats. After transforming it from the solar radiation, Along the moments of time sampled in atypical of the ASHRAE Clear-sky Radiation Model [7], which utilized to evaluate the solar radiation, and based on two monthly factors and the relative air mass(m). That can estimate by:

$$m = \frac{1}{\sin \alpha + 0.50572(6.07995 + \alpha)^{-1.6364}} \dots \dots \dots (3.9)$$

Where (α) expressed in degrees. The beam normal radiation (E_b) given as:

$$E_b = E_o \exp[-\tau_b m^b] \dots \dots \dots (3.10)$$

Whereas beam air mass exponents (b) equal:

$$b = 1.219 - 0.043\tau_b - 0.151\tau_d - 0.204\tau_b\tau_d \dots \dots \dots (3.11)$$

E_o is the extraterrestrial normal irradiance which can be determined by:

$$E_o = E_{sc} \left(1 + 0.033 \cos \left(360^\circ \frac{(n_d - 3)}{365} \right) \right) \dots \dots \dots (3.12)$$

Where E_{sc} is equal to 1366.1 W/m² and (n_d) is the day number. Besides, (τ_b) and (τ_d) (beam and diffuse “pseudo” optical depths) are site specific and change during the year. For (Seville –Spain) and other cities that study relocation (CRS) technology in it, they given in ASHRAE handbook as [7] and tabulated in Appendix (A) for each city and for the 21st day of each month. Values for other days of the year should be determined by interpolation.

3.4 Ambient Temperature

The procedures for generating 24-h temperature data sequences suitable as inputs to the thermal equations describing the receiver, as in [7], are based on three factors: the monthly dry bulb design temperature (DB), the mean coincident DB temperature range (MCDBR), and a fractions of the daily temperature range. Which tabulated in Appendix (A) These are included in [7] for the 21st day of each month for Seville, Spain, (Lat: 37.42) and other cities, except for the fraction because it is a function of solar time and is therefore tabulated for each 24 h of solar time. To calculate the hourly temperature T_{amb} the fraction of the DB daily range is subtracted from the dry bulb design temperature as presented in Eq. (3.13):

$$T_{amb, hourly} = (DB) - (fraction \times (MCDBR)) \quad (^\circ\text{C}) \dots \dots \dots (3.13)$$

3.5 Sun-Tracking Formula

A heliostat is a mirror that tracks the sun in order to constantly reflect the rays of sunlight onto a fixed target. In the case of a solar tower power plant, a field of heliostats concentrates the sunlight onto a central receiver a top a tower. This application requires

a high mirror reflectivity, accuracy of the tracking system, resistance to wind, and low specific costs. Current heliostats are either a single mirror facet or an assembly of several facets, mounted on a frame supported by a horizontal axis and a vertical axis [39]. The mirror facets are plane rectangular mirror with a slight convex curvature. Alternative concepts have also been proposed, such as stretched membranes over steel rings, but were abandoned because of damaged membranes after a few years only [12]. A heliostat is an off-axis sun tracker, which means that the target is fixed and the heliostat's normal vector must always bisect the angle between the sun's vector and the target's vector. As a consequence of the off-axis tracking, the size and the shape of the sun's image on the receiver strongly depends on the angle of incidence on the heliostat and canting of the mirror facets. The canting is the individual orientation of the mirror facets in order to minimize the size of the reflected sun's image and thus increase the concentration ratio of the heliostat. A fixed canting consists in the individual orientation of the mirror facets when assembling the heliostat, according to a spherical or a parabolic shape whose focus length is the distance to the target.

In CRS, sun rays that impact on a field of heliostats (each heliostat is an array of $m \times n$ facet mirrors linked to a movable mechanical frame) are reflected to a single point in space namely fixed target or central receiver. Thus, sun-tracking formulas method has to include a sun position vector (incident sun ray)(s), a receiver position vector (reflected sun ray)(R) and a heliostat normal vector(n). Since the sun is a moving object and the receiver is a fixed object, the heliostat normal must be regulated from time to time when the sun position alters with time. The sun's location with respect to any position on the earth's surface can be mathematically described as sun altitude angle (α) and sun azimuth angle(A).

As referred in chapter two. Azimuth-elevation (AE) manner more widely used in implentaion of sun tracking .For the Azimuth-Elevation (AE) sun-tracking method, the coordinate system being referred to the earth-surface reference frame where the heliostat normal vector (n) is defined as the function of the angles(α_{AE}) and (ρ_{AE}) as shown in Figure 3.7.

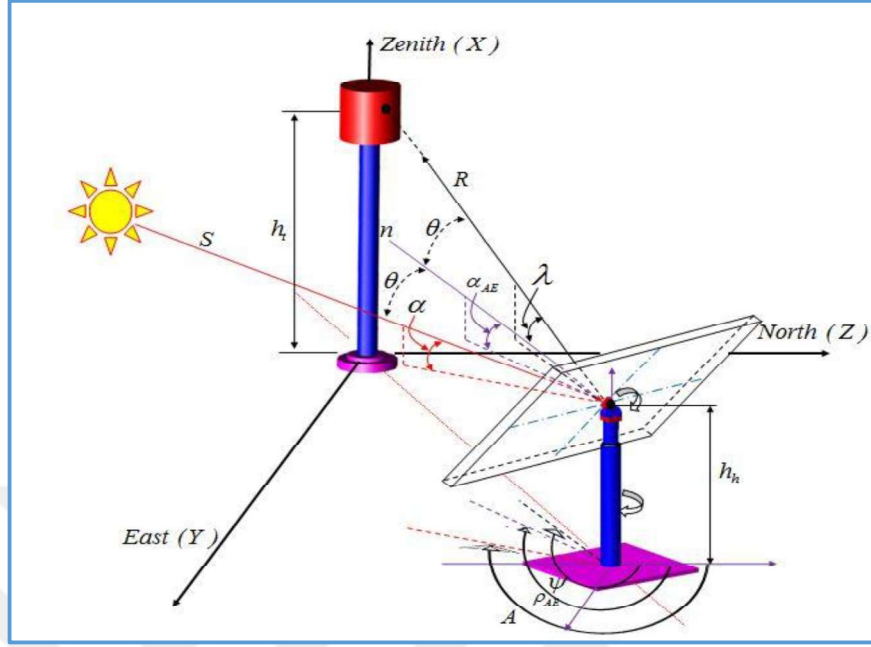


Figure 3.7 Movements of heliostat vectors in azimuth-elevation sun-tracking method

The azimuth angle (ρ_{AE}) and the elevation angle (α_{AE}) can be formulated depended on the reflection law that related with the **sun position vector**($\vec{s}$), the **receiver position vector**($\vec{R}$) and the **heliostat normal vector**($\vec{n}$) in the earth-surface coordinate system. The sun position can be describe by a unit vector that can be recalled from the equation (3.8), as follow:

$$\vec{S} = \begin{bmatrix} \sin\alpha \\ \cos\alpha \sin A \\ \cos\alpha \cos A \end{bmatrix} \dots \dots \dots (3.8)$$

The receiver position vector defined as a function of angles (λ) and (ψ), which is written as:

$$\vec{R} = \begin{bmatrix} \sin\lambda \\ \cos\lambda \sin\psi \\ \cos\lambda \cos\psi \end{bmatrix} = \begin{bmatrix} \frac{(h_r - h_h)}{\sqrt{(h_r - h_h)^2 + E_h^2 + N_h^2}} \\ \frac{-E_h}{\sqrt{(h_r - h_h)^2 + E_h^2 + N_h^2}} \\ \frac{-N_h}{\sqrt{(h_r - h_h)^2 + E_h^2 + N_h^2}} \end{bmatrix} \dots \dots \dots (3.14)$$

The heliostat normal vector defined as a function of angles (α_{AE}) and (ρ_{AE}), which is written as:

$$\vec{n} = \begin{bmatrix} \sin \alpha_{AE} \\ \cos \alpha_{AE} \sin \rho_{AE} \\ \cos \alpha_{AE} \cos \rho_{AE} \end{bmatrix} \dots \dots \dots (3.15)$$

From the reflection law [17, 40], the relationship of the three vectors is as follows:

$$\vec{n} = \frac{1}{2 \cos \theta} (\vec{S} + \vec{R}) \dots \dots \dots (3.16)$$

$$\begin{bmatrix} \sin \alpha_{AE} \\ \cos \alpha_{AE} \sin \rho_{AE} \\ \cos \alpha_{AE} \cos \rho_{AE} \end{bmatrix} = \frac{1}{2 \cos \theta} \begin{bmatrix} \sin \alpha + \sin \lambda \\ \cos \alpha \sin A + \cos \lambda \sin \psi \\ \cos \alpha \cos A + \cos \lambda \cos \psi \end{bmatrix} \dots \dots \dots (3.17)$$

where $\cos 2\theta = (\mathbf{S} \cdot \mathbf{R})$ so that the incident angle can be obtained as

$$\theta = \frac{1}{2} \cos^{-1} (\sin \alpha \sin \lambda + \cos \alpha \sin A \cos \lambda \sin \psi + \cos \alpha \cos A \cos \lambda \cos \psi) \dots \dots \dots (3.18)$$

From eqn (3.17), first row, the elevation angle(α_{AE}) can be calculated as follows:

$$\begin{aligned} \alpha_{AE} &= \sin^{-1} \left(\frac{\sin \alpha + \sin \lambda}{2 \cos \theta} \right) \\ &= \sin^{-1} \left(\frac{\frac{(h_R - h_h)}{\sqrt{(h_R - h_h)^2 + E_h^2 + N_h^2}} + \sin \alpha}{2 \cos \theta} \right) \dots \dots \dots (3.19) \end{aligned}$$

From second row

$$\begin{aligned} \sin \rho_{AE} &= \left(\frac{\cos \alpha \sin A + \cos \lambda \sin \psi}{2 \cos \theta \cos \alpha_{AE}} \right) \\ &= \left(\frac{\frac{-E_h}{\sqrt{(h_R - h_h)^2 + E_h^2 + N_h^2}} + \cos \alpha \sin A}{2 \cos \theta \cos \alpha_{AE}} \right) \dots \dots \dots (3.20) \end{aligned}$$

From third row

$$\begin{aligned} \cos \rho_{AE} &= \left(\frac{\cos \alpha \cos A + \cos \lambda \cos \psi}{2 \cos \theta \cos \alpha_{AE}} \right) \\ &= \left(\frac{-\frac{N_h}{\sqrt{(h_R - h_h)^2 + E_h^2 + N_h^2}} + \cos \alpha \cos A}{2 \cos \theta \cos \alpha_{AE}} \right) \dots \dots \dots (3.21) \end{aligned}$$

$$\text{if } \cos \rho_{AE} > 0 \rightarrow \rho_{AE} = \sin^{-1} \left(\frac{\cos \alpha \sin A + \cos \lambda \sin \psi}{2 \cos \theta \cos \alpha_{AE}} \right) \dots \dots \dots (3.22)$$

$$\text{if } \cos \rho_{AE} < 0 \rightarrow \rho_{AE} = \pi - \sin^{-1} \left(\frac{\cos \alpha \sin A + \cos \lambda \sin \psi}{2 \cos \theta \cos \alpha_{AE}} \right) \dots \dots \dots (3.22)$$

the angles ρ_{AE} and α_{AE} are exactly 0° when the elevation axis is aligned to be parallel along the east-west axis and heliostat frame facing the north.

3.6 SENER Heliostats and Receiver Model, Specifications

Gemasolar, an SPTP in Seville, Spain, is the plant used as a reference in this work. The complete dimensions of the SENER heliostats used in Gemasolar are presented in [8, 10, 9]; the field parameters used in this study are presented in Table 3.1 along with other parameters of the receiver model, which are considered similar to those of Gemasolar, because some data related to the receiver model is hard to obtain, therefore, the study depended on some parameters from the literature review of solar two [41], as the number of panels and the tube wall thickness, which considered (24, 1.25mm) respectively and the number of path flow for HTF (2), and set the number of tubes n_t in each panel which is equal to 38.

Table 3.1 Gemasolar fields and receiver parameters[8, 9, 10]			
Heliostats		Receiver	
Width W_h	12.305 m	Receiver optical height h_r	140m
Height H_h	9.752 m	Receiver radius R_r	4m
Heliostat total diagonal, d_h	15.7 m	Receiver height H_r	9m
Heliostat total area, A_h	120 m^2	Coating emittance	0.1
Heliostat mirror area, A_m	115.7 m^2	Coating absorptance	0.95
Effective reflectivity, η_{ref}	0.88×0.95	Max receiver flux (kW/m ²)	1000
Heliostat numbers	2650	Inlet Temp for HTF $T_{HTF,in}$ (°C)	290
Standard deviation surface error (σ_s)	0.94 mrad	Outlet Temp for HTF $T_{HTF,ou}$ (°C)	595
Standard deviation tracking error (σ_t)	0.63 mrad		
Standard deviation of sunshape (σ_{sun})	2.51 mrad		

3.7 Geometrical Style Layout for Heliostat Field

The main step in forming of heliostat field, that define field layout, which are based on the pattern of the MIT model [5], which is inspired by the spiral patterns of the phyllotaxis disc. The disc shown increases the overall efficiency of the proposed model. The equations needed for this layout are presented as [5]:

$$\theta_p = 2\pi\varphi^{-2}n_h \dots \dots \dots (3.23)$$

$$r_p = an_h^b \dots \dots \dots (3.24)$$

Where (θ_p) is the polar position angle for heliostat in field, (r_p) is the radius position for the heliostat, (φ) Golden ratio $(1 + \sqrt{5})/2$, and (a), and (b) are the layout constants estimated precisely by applying an optimization algorithm later.

3.8 The Mean Yearly Heliostat Field Efficiency

The capital importance and the topic of many studies are the ideal layouts of the reflector field, mainly because the approach requires 50% of the full price of the

scheme, and the annual energy loss is approximately 47% [3]. Several codes have been produced for this purpose dating from the 1970s, and most of those codes are recorded in Garcia et al. [4]. At the same time, the most recent codes [1, 5, 10, 20] mostly use various forms of access for increasing the global efficiency, which is given as:

$$\eta = \eta_{cos} \times \eta_{at} \times \eta_{in} \times \eta_{s\&b} \times \eta_{ref} \dots \dots \dots (3.25)$$

Where the parameters are the cosine effect efficiency(η_{cos}), the atmospheric attenuation efficiency (η_{at}), the interception efficiency(η_{in}), the shading and blocking efficiency($\eta_{s\&b}$), and the reflectivity of the heliostats (η_{ref}) which is referred to its value in Table 3.1 because its depended on the property of the heliostat. The mean yearly heliostat field efficiency or the insolation weighted efficiency ($\eta_{year,Eb}$) is calculated [5] and defined as:

$$\eta_{year,Eb} = \frac{\sum_{day=1}^{365} \int_{sunrise}^{sunset} E_b(t) \eta(t) dt}{\sum_{day=1}^{365} \int_{sunrise}^{sunset} E_b(t) dt} \dots \dots \dots (3.26)$$

because any (CRS) optimization operation should depend on the annual energy estimation of the different layouts studied. The annual energy is the integrated sum of the instantaneous energy transformed by all reflectors, over the moments of time [9]. The procedure of an algorithm to estimate the annual optical efficiency of the heliostat field is present in the flowchart as sketched in Figure 3.8.

To compromise between the CPU time and resolution, specify the 21st of each month during the year (average day), and carry out over all days the same eq. (3.26) with all computations that are related to the other parameters of optical efficiency [20].

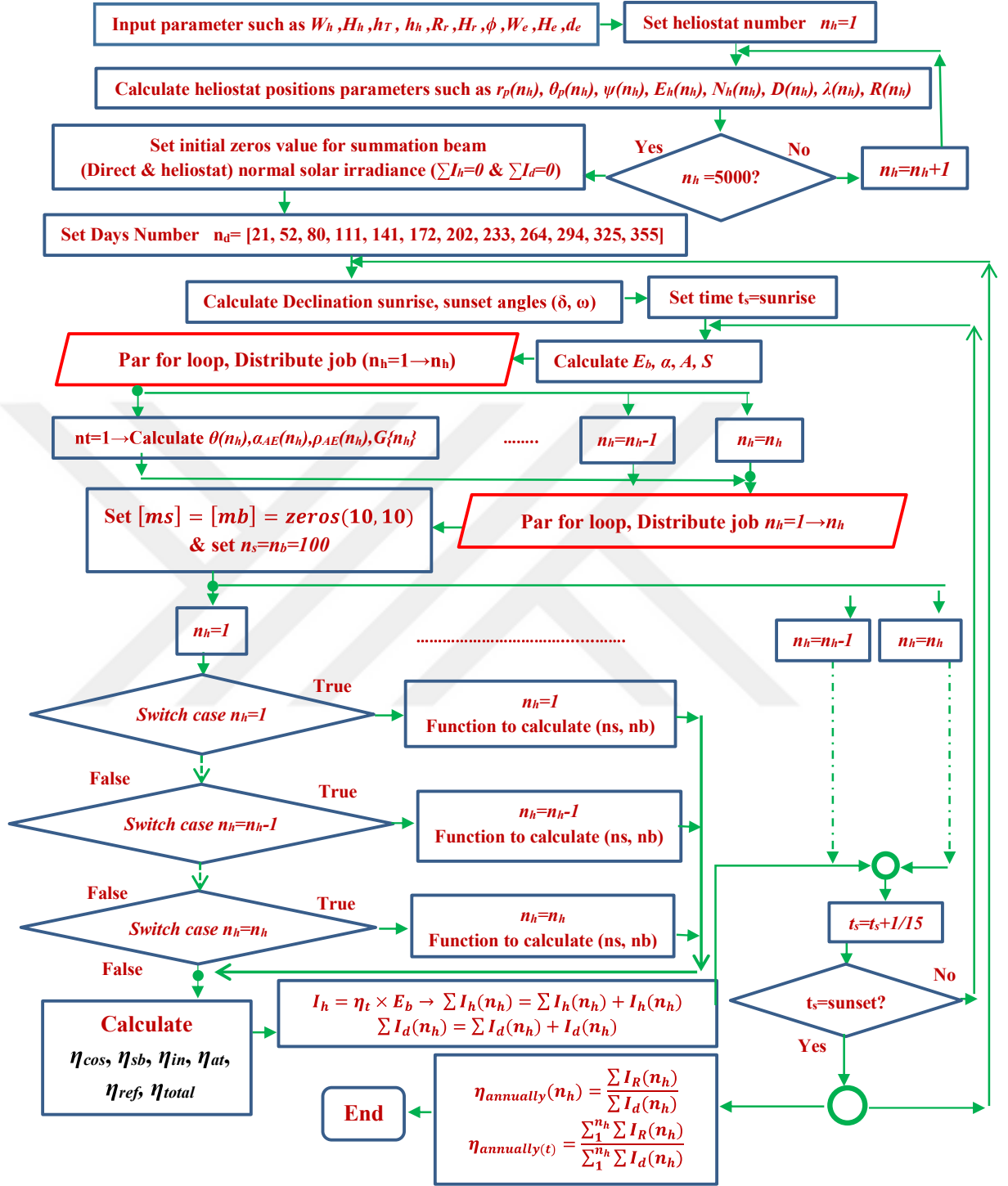


Figure 3.8 The flow chart to show the algorithm to estimate the $(\eta_{year, Eb})$

3.9. Instantaneous Optical Efficiency Factors

The factors which Eq. (3.25) consists of, and which presented energy losses associated with the heliostat field are specified as follows.

Cosine efficiency(η_{cos}); It takes into account that any radiation impacting a surface with an angle θ will produce less energy per square meter compared with the same radiation striking perpendicularly that surface as Figure 3.9 shows. Such efficiency can be easily evaluated from the dot product of the directions of the sun and heliostat (or facet) normal direction is related to the angle of incidence, (θ) [5, 10, 20, 2].

$$\eta_{cos} = \cos\theta = \vec{n} \cdot \vec{S} \dots \dots \dots (3.27)$$

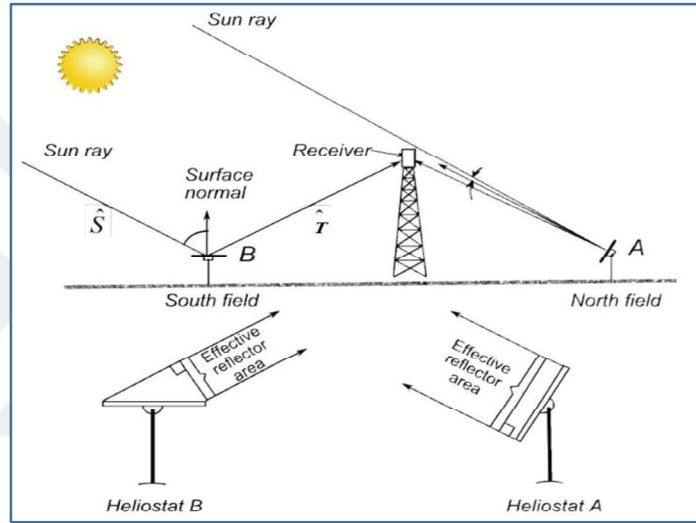


Figure 3.9 The cosine effect on heliostat [26]

Atmospheric attenuation efficiency(η_{at}); The reflected beam radiation from the surface of the heliostat may be scattered, depending on the distance between the heliostat and the receiver. This atmospheric attenuation efficiency can be estimated [42]

Where D is the distance between heliostat and receiver. This formula is approximated for a visual range of 40 km.

$$D = \sqrt{r_p^2 + (h_r - h_h)^2} \dots \dots \dots 3.28$$

$$\eta_{att} = 0.99321 - 0.000176D + 1.97 \times 10^{-8}D^2 \quad D \leq 1000m \dots \dots \dots 3.29$$

$$\eta_{att} = e^{-0.0001106D} \quad D > 1000m \dots \dots \dots 3.30$$

Interception efficiency(η_{in}); A portion of the reflected image may go away to oppose the receiver as a result of various reasons such as tracking precision, the form of the sun, and non-uniformity of mirror surface, etc. [20].

There are two general approaches to compute the interception efficiency (spillage factor), i.e. ray tracing methods and analytical integration of the image shape generated by the mirror over the recipient area.

The HFLCAL model [43], which well-known as an analytic flux density model that is applied to estimate the interception efficiency in this research, as appropriate tools, much simpler and slightly more accurate than other models [10, 20]. The HFLCAL model is integrated the flux distribution along the receiver aperture plane to get the intercepted power at a certain point in time.

The interception efficiency is then [43, 42]:

$$\eta_{in} = \frac{1}{2\pi\sigma_{tot}^2} \int_{(x')} \int_{(y')} e^{\left(-\frac{x'^2+y'^2}{2\sigma_{tot}^2}\right)} dy' dx' \dots\dots\dots (3.31)$$

Where σ_{tot} is the total standard deviation result measured on the image plane [10, 44], i.e., a plane normal to the unit vector $\vec{R}$ (the reflected vector directed at the aim point on the receiver), and with coordinates($\hat{x}, \hat{y}$).

The total deviation σ_{tot} in HFLCAL is the outcome of the convolution of the, four Gaussian error functions considered [43, 42], namely sun shape error, with standard deviation σ_{sun} , beam quality σ_{bq} associated with mirror slope errors, the astigmatic effect σ_{ast} , and, eventually, the tracking error σ_t . Then σ_{tot} is

$$\sigma_{tot} = \sqrt{D^2(\sigma_{sun}^2 + \sigma_{bq}^2 + \sigma_{ast}^2 + \sigma_t^2)} \dots\dots\dots (3.32)$$

Where D is the slant range, i.e., the distance between the heliostat Centre and the aim point in the receiver (also utilized in the former attenuation factor).

For σ_{sun} , the standard deviation of the Gaussian equivalent to the sun shape which it's values refered in Table 3.1.

The standard deviation of beam quality σ_{bq} is concerned to the slope error σ_s (deviations in the mirror curvature from the ideal shape and waviness and roughness

of the reflecting surface), which is defined with respect to the surface normal error [42, 43, 45, 46].

Therefore, Its effect is, doubled in the reflected ray and it's values also referred in Table 3.1 with an average standard deviation of the Gaussian tracking error of σ_t [10, 45].

$$\sigma_{bq}^2 = (2\sigma_s)^2 \dots \dots \dots (3.33)$$

Finally, following [42, 43], the standard deviation of the astigmatic effect is

$$\sigma_{ast} = \frac{\sqrt{0.5(H_t^2 + W_s^2)}}{4D} \dots \dots \dots (3.34)$$

where H_t and W_s are the image dimensions in the tangential and sagittal planes at a distance D from the mirror, respectively. Their values are [42, 43].

$$H_t = d \left| \frac{D}{f} - \cos\theta \right|; \quad W_s = d \left| \frac{D}{f} \cos\theta - 1 \right| \dots \dots \dots (3.35)$$

Where f is the focal distance, which is equal to D when the heliostat is focused on its slant range as usual, and d is the square root of the whole heliostat area

$$d = \sqrt{W_h \times H_h} \dots \dots \dots (3.36)$$

Concerning the integration limits in Eq. (3.31), the intercept factor will be the integral on the contours of the cylindrical receiver for a surrounding field as in GEMASOLAR [10, 45]. But here the integration is made on the image plane, normal to the unitary vector($\vec{R}$). So the cylindrical receiver is seen by the heliostat as a rectangle with a width equal to the diameter of the receiver($2 \times R_r$), and a height($H_r \times \cos \lambda$). (λ) Is the orientation angle of heliostat which estimated from.

$$\lambda = \tan^{-1} \left(\frac{h_r - h_h}{r_p} \right) \dots \dots \dots (3.37)$$

Shading and blocking efficiency; shading often takes place when a heliostat shaded from the sunlight by an adjoining heliostat or a tower, and similarly blocking occurs if a heliostat block the sun rays reflected from an adjoining to the receiver. Theoretically, high-density heliostat layouts would result in serious shading and blocking, and reduce the optical efficiency. Nevertheless, the placement of the mirrors should be equally near to the tower as much as possible to get a high intercept factor. Thus, to optimize the heliostat field layout, it should be accurately computed the effects of shading and blocking. The demand for working out $(\eta_{s\&b})$ with high precision, as time, is as a rule high. Because of depending on the site of sun, the individual position of the analyzed reflector, and the placements of the adjoining reflectors. As told previously discretization technique embraced in this study, with modified form, the implementation built quicker and able to work out the overlapping produced by multiple heliostats. Nevertheless, the computational time significantly trimmed in this inquiry; a novel approach applied To do so, which applies to both surrounding and north field designs.

The Methodology of computing $(\eta_{s\&b})$ depend on two main steps:

- a- discretized heliostat surface with Coordinate Transformation of Heliostat.
- b- Mathematical model for Shading and blocking algorithm

3.9.1 Discretized Heliostat Surface and Coordinate Transformation of Heliostat

In the selection coordinate system (referred to in the following text as “tower system of coordinates”), east is in the positive (y) direction, and north is in the positive (z) direction, while the zenith is in the (x) direction, as Figure 3.7 shows.

Given that the sun is a moving object while the receiver is a fixed object, the normal ($\vec{n}$) of the heliostat has to adjust when the sun position changes with time, to ensure that the heliostat is oriented at the necessary angles. To determine the $(\eta_{s\&b})$ of the heliostat, the heliostat position frame should be estimated. The altered orientation of the frame during the sun tracking period in three-dimensional space can modeled by applying the coordinate transformation. For the convenience of the three-dimensional coordinate transformation, an additional dimension of space is added to make all of the transformations linear. The rest position or the initial coordinate of the frame is first defined in a fixed coordinate system. When the plane of the heliostat is parallel to the x-y plane, the normal to its surface($\vec{n}$) is directed to the north direction, where the center point of the heliostat surface is given by P_C with coordinating (0, 0, 0). In this

analysis, the total heliostat surface elements in our research will be 100 because the error reduces to less than 10^{-4} using a grid of 100 points [5], which are assigned for the grid fixed on the moving frame to study the shadow and block effect, as we will see in the following section. The coordinates of the points are treated as a vector in the coordinate space and are written as:

$$[P_{i,j}] = \begin{bmatrix} P_{i,j,x} \\ P_{i,j,y} \\ P_{i,j,z} \\ 1 \end{bmatrix} \dots \dots \dots (3.38)$$

In addition, The surface of the heliostat is partitioned into (H_e) for height(H_h) and (w_e) for width (W_h) as we see in Figure 3.10, and the diagonal diameter of the element d_e which equal, $d_e = \sqrt{(W_e^2 + H_e^2)}$ is calculated.

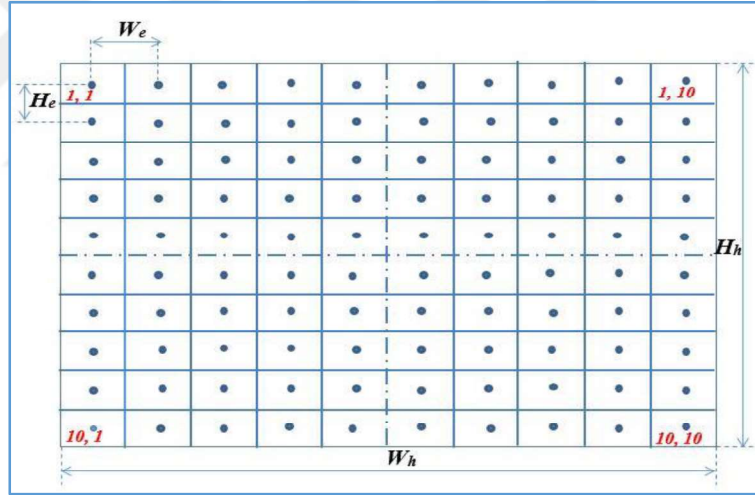


Figure 3.10 Discretization of the heliostat

To convert from P_C to the center of discretization area $[P_{i,j}]$, we should use translational transformation $[T_r, c]$, which can be written as

$$[T_r, c] = \begin{bmatrix} 1 & 0 & 0 & (H_h/2 - ((2 \times i) - 1/2) \times H_e) \\ 0 & 1 & 0 & ((-W_h/2) - ((2 \times j) - 1/2) \times W_e) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \dots \dots \dots 3.39$$

Then, the coordinates for the center of the discretization area relative to the center of the heliostat is calculated as follows:

$$[P_{i,j}] = \begin{bmatrix} P_{i,j,x} \\ P_{i,j,y} \\ P_{i,j,z} \\ 1 \end{bmatrix} = [T_r, e] \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \dots \dots \dots (3.40)$$

$$[P_{i,j}] = \begin{bmatrix} P_{i,j,x} \\ P_{i,j,y} \\ P_{i,j,z} \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & (H_h/2 - ((2 \times i) - 1/2) \times H_e) \\ 0 & 1 & 0 & ((-W_h/2) - ((2 \times j) - 1/2) \times W_e) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

The reflector is oriented using an actuator for rotation in the coordinate transformation for the Azimuth-Elevation (**AE**) sun-tracking method [40], there are two angular movements of the heliostat frame about the azimuth axis and the elevation axis. The first rotation transformation by the angle (α_{AE}) about the Y-axis will transform the point from the fixed coordinate system to an elevation-movement coordinate system. The second rotation transformation for the rotational movement by the angle (ρ_{AE}) about the X-axis will transform the point of the elevation-movement coordinate system to azimuth-movement coordinate system. As indicated by the following two rotation matrices are as follows:

$$[\alpha_{AE}] = \begin{bmatrix} \cos(\alpha_{AE}) & 0 & \sin(\alpha_{AE}) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\alpha_{AE}) & 0 & \cos(\alpha_{AE}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \dots \dots \dots (3.41)$$

$$[\rho_{AE}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\rho_{AE}) & \sin(\rho_{AE}) & 0 \\ 0 & -\sin(\rho_{AE}) & \cos(\rho_{AE}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \dots \dots \dots (3.42)$$

After all of the rotational transformation, the points will be transformed from the heliostat coordinate system to the real coordinate system in the heliostat field under a translational transformation which can be written as:

$$[T_r, p] = \begin{bmatrix} 1 & 0 & 0 & h_h \\ 0 & 1 & 0 & E_h \\ 0 & 0 & 1 & N_h \\ 0 & 0 & 0 & 1 \end{bmatrix} \dots \dots \dots (3.43)$$

The final three transformation matrices for heliostat [**G**] are presented as.

$$[G] = [T_r]([\rho_{AE}][\alpha_{AE}]) \dots \dots \dots (3.44)$$

Finally, the coordinates for the center of the discretization area after finishing the orientation and relative to the coordinate system in the heliostat field, after the transformation $[P'_{i,j}]$ written as

$$[P'_{i,j}] = \begin{bmatrix} P'_{i,j,x} \\ P'_{i,j,y} \\ P'_{i,j,z} \\ 1 \end{bmatrix} = [G][P_{i,j}] \dots \dots \dots (3.45)$$

And final matrices were stored in the cells which were set previously.

3.9.2 Mathematical Model for Shading and Blocking Algorithm

The Shading and blocking function (*sb*) calculations are estimated after preparing the final three transformation $[G]$ matrices for the heliostat.

The first step in function that set zero matrices as the value of the logic parameters in the shadow and blocking estimate for each number of the heliostat is seen in the following form.

$$[ms] = [mb] = \text{zeros}(10,10) = \begin{bmatrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{bmatrix} \dots \dots \dots (3.46)$$

This matrix is imposed to prevent recalculation of the discretization area that occurs when shadow or block conditions take place with overlapping produced by multiple heliostats. This is one of the features that are characterized by, the method of calculating the effect of shading and blocking and implemented in this research. At the same time, the set initial value for the number of discretization areas for calculating shading and blocking is ($ns = nb = 100$). In the beginning, the numbers of the heliostats causes (n_{sb}) have been fixed, which probably causes shadowing and blocking, and named it (heliostats causes) for shadowing and blocking, then finding polar coordinates (r_{sb} & θ_{sb}) of each relative to the main heliostat and studying the effect of each reflector on the main heliostat separately. As an example, we have a heliostat number (571), which is seen in Figure 3.11. This method may lead to the selection of heliostats that is more than factual. Study heliostats also might not have

an impact on the shading and blocking effect at the specified time. So, the next steps will include estimation of the possibility for each heliostat, whether the shading or blocking is affected or not before the calculation of $(\eta_{s\&b})$. if the shading or blocking has not been impacted, the heliostat should be passed and another heliostat studied. in this way, we can decrease the time for computation by decreasing a number of heliostats that will require implementation $(\eta_{s\&b})$ computations. Then, prevent any overlapping produced by multiple heliostats in the calculations, and the computation can be done with tests, which are summarized in next points.

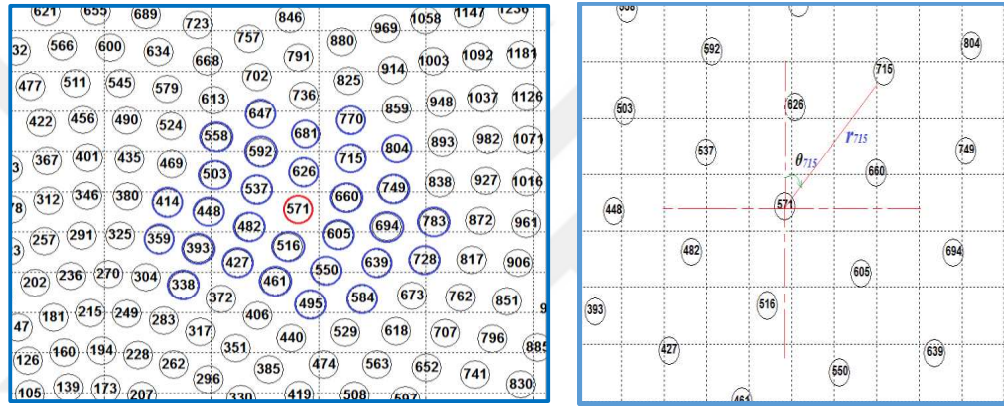


Figure 3.11 Fixed heliostats numbers that Cause shadowing and blocking for heliostat (571), with the polar coordinates(r_{sb} & θ_{sb}) .

- 1- Testing between the heliostat main and the heliostat causes if the intersection between the horizontal circles of the movement exists, and it can be done, by a comparison between diagonal diameters.
- 2- Shadowing and blocking aperture: The shadowing aperture is a window that allows the sunshine to fall on the main heliostat through it. Any obstacle (heliostat) in the place of the direction of the rays of the sun will cause shade to occur on the main heliostat. The shadowing aperture can be seen as a thick red line in Figure 3.12. The chance of an event should be checked in this case, depending on the solar azimuth angle (A), when the (θ_{sb}) value is within the possible range of angle (A), (± 90). The blocking aperture is a window that pass sunshine through, from the main heliostat toward the tower. Any obstacle (heliostat) in the direction of the rays of the sun will cause blocking to occur on the main heliostat. Check the chance of an event in this case, depending on the heliostat polar angle or facing angle $\psi(n_h)$ which is seen in

Figure 3.7, when the (θ_{sb}) value has been within the possible range of angle $\psi(n_h)$ (± 90).

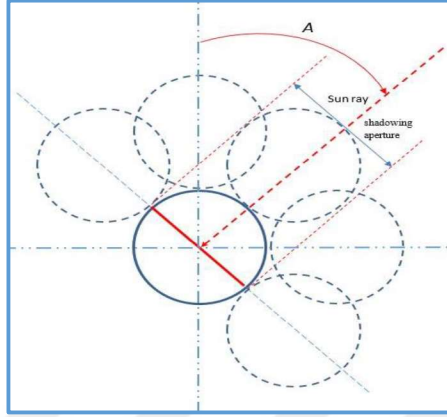


Figure 3.12 Shadowing aperture.

3- Normal distance between the two centers of circles of movement of the heliostats (main heliostat and heliostat causes), which is presented here as (P_{c1}, P_{c2}) . For shadowing, the normal distance (d_{s1}) between the center of the circle of movement for each heliostat causes and the vector of the sun that passes through the center circle of movement of the main heliostat should be calculated [47, 48] from the following equation.

$$d_{s1} = \frac{\|\overrightarrow{P_{c1}P_{c2}} \times \vec{S}\|}{\|\vec{S}\|} \dots \dots \dots (3.47)$$

Then, a comparison is made between distance (d_{s1}) and diameter of movement (d_h) for each heliostat. If the distance falls within the circle of movement of the heliostat causes, shadows occur.

For blocking; the normal distance (d_{b1}) between the center of the circle of movement for each heliostat and the vector of the receiver that passes through the center of the circle of movement of the main heliostat should be calculated [47, 48] from the following equation.

$$d_{b1} = \frac{\|\overrightarrow{P_{c1}P_{c2}} \times \vec{R}\|}{\|\vec{R}\|} \dots \dots \dots (3.48)$$

Then, a comparison is made between distance (d_{b1}) and diameter of movement (d_h) for each heliostat as the shadow case.

4- solar profile angle

This test is used to find the probability of shadowing only, by estimating a surface oriented solar angle, called the solar profile angle (α_p), given as :

$$\alpha_p = \tan^{-1} \left(\frac{\tan \alpha}{\cos(A - \rho_{AE})} \right) \dots \dots \dots (3.49)$$

At the same time, calculat of the (Labc) angle or (α_{sb}) angle as shown in Figure 3.13 for each heliostat causes yields the following equation.

$$\alpha_{sb} = \tan^{-1} \left(\frac{H_h * \cos \alpha_{AE}}{r_{sb} - (H_h * \sin \alpha_{AE})} \right) \dots \dots \dots (3.50)$$

Then, a comparison between angles is made, as shown in Figure 3.13; If $\alpha_p > \alpha_{sb}$, no shadow occur as the case (1) .If $\alpha_p < \alpha_{sb}$ shadow occurs as in the case (2)

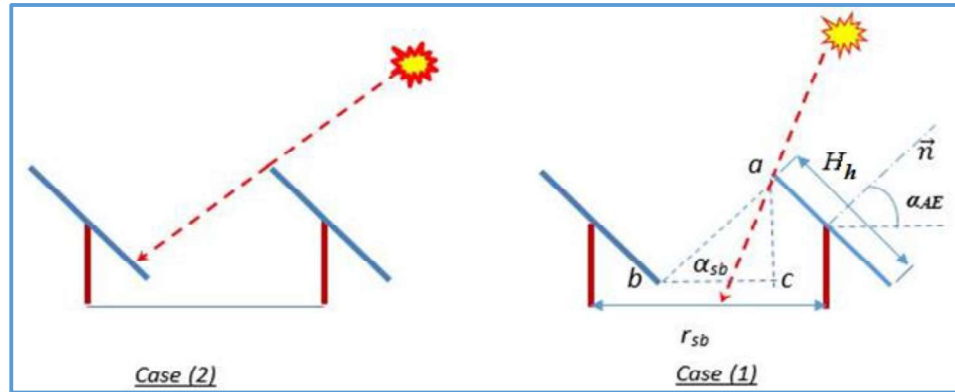


Figure 3.13 Shadowing test

After passing the likelihood test for shadowing and blocking those have been set for heliostat causes and having confirmed that heliostat causes have an impact by shadowing and blocking, then divide the heliostat causes and main surfaces into 100 elements, as shown in Figure 3.14.

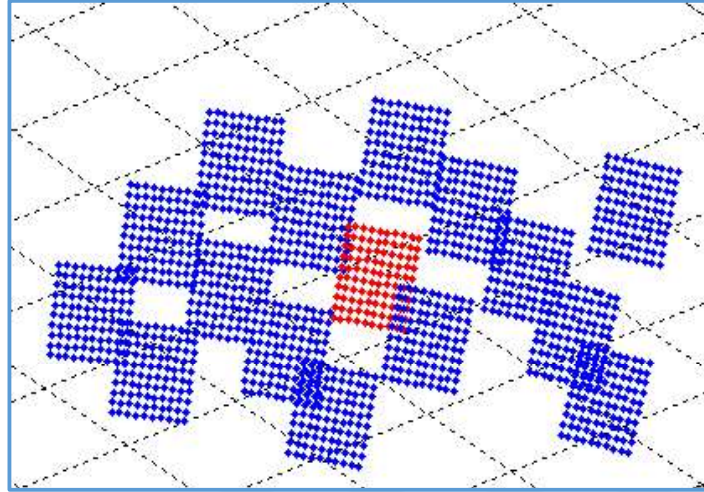


Figure 3.14 Discretization area of heliostats.

Then, find the coordinates of the center of the discretization $[P'_{i,j}]$ of heliostats (causes and main) relative to the coordinate system in the heliostat field after the transformation by using equation (3.45). After that, by using the same equation (3.47) for shadowing. The normal distance (d_{s2}) is found between the center of subdivisions ($P'_{i,j, sb}$) of each heliostat cause and the center of subdivisions ($P'_{i,j, h}$) of the main heliostat that the vector of the sun passes through. Later, a comparison is made between the distance (d_{s2}) and the diagonal diameter(d_e), of the subdivisions. If the distance falls within the diagonal diameter, shadowing occurs. Then by using the same equation (3.48), for blocking, the normal distance (d_{b2}) is found between the center of the subdivisions ($P'_{i,j, sb}$) of each heliostat cause and the center of the subdivisions ($P'_{i,j, h}$) of the main heliostat that the vector of the tower passes through. Then, same comparison is made between the distance (d_{b2}) and the diagonal diameter(d_e), of the subdivisions; as Figure 3.15 shows.

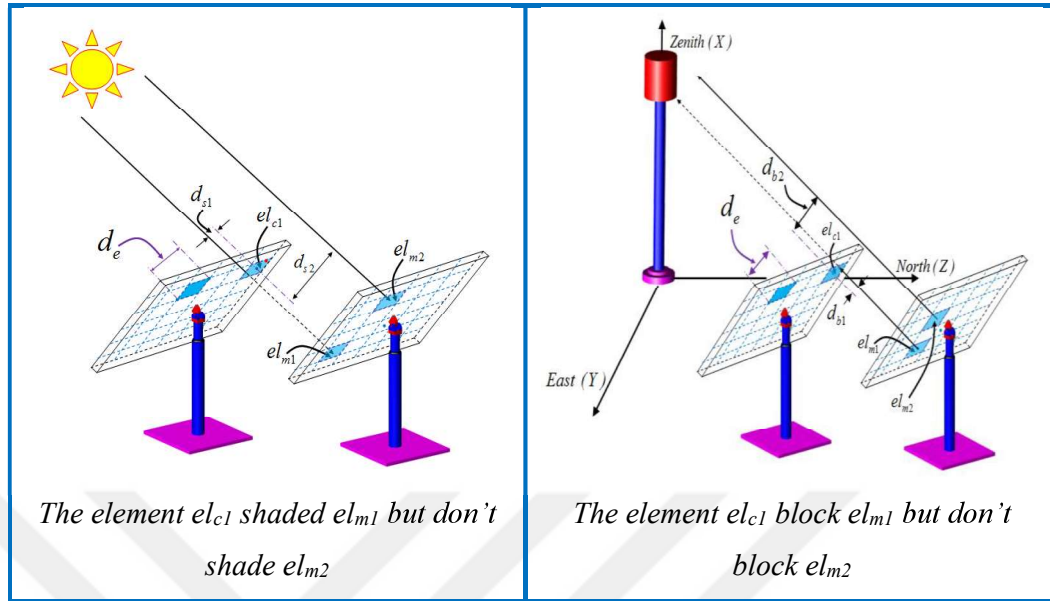


Figure 3.15 Normal distance between two centers of subdivisions

At the same time, after confirmation that the subdivision of the main heliostat is affected by shadowing or blocking, the value of the number of discretization areas is decreased one unit, and the value of the element in the zero matrices, from imposing Equation(3.46) as a logic parameter (in the case of shadowing ($ms(i,j)$) and case blocking ($mb(i,j)$) that have the same position ($P'_{i,j,h}$) in the arrangement subdivision of the main heliostat is changed to one. This method is imposed to prevent recalculation of the discretization area that is estimated within the shadow or block conditions under overlapping produced by multiple heliostats. Finally, to calculate($\eta_{s\&b}$), we should estimate the area that is not effected by shadowing and blocking, and we can do that by multiplying (ns, nb) by the area of an element as follows:

$$A_{sh} = n_s * A_e \dots \dots \dots (3.51)$$

$$A_{bl} = n_b * A_e \dots \dots \dots (3.52)$$

Then, the shadowing efficiency is calculated as follows:

$$\eta_{shadow} = \frac{A_{sh}}{A_t} \dots \dots \dots (3.53)$$

Then, the blocking efficiency as follows:

$$\eta_{block} = \frac{A_{bl}}{A_t} \dots \dots \dots (3.54)$$

3.9.3 Parallel Computing in MATLAB

This technique is characterized as an accurate model but at the same time, the slowest model, so one of the targets of this study is how to use this technique, or its accuracy calculation, with less implementation time.

The first solution to decreasing processing time is that for each step of time, parallel computing is carried out to perform all computation that is related to factors of annual efficiency.

As scientific/engineering problems grow in complexity and the need for computational and storage resources grows, MATLAB can solve “embarrassing parallel” parallel problems with minimum modification to the existing MATLAB code.

Dramatic changes have been made in hardware, and parallelism has become mainstream. We now have clusters of machines (since the late 1990’s) and multi-core processors on new machines (more recently), so The Parallel Computing Toolbox (PCT) in MATLAB is available. The PCT, which is explained in details in [49], lets you solve any data-intensive problems computationally using multi-core CPUs, GPUs (graphics processing units), and computer clusters. Thus, running a loop that occurs in the series change to parallel as we see in Figure 3.16.

Through change (for loop) to (parfor loop) and by developing the program on a multi-core desktop computer utilizing the PCT, we can then scale up to many computers by running program on a MATLAB distributed computing server. The server supports batch jobs, parallel computations, and shared large data sets, and the percentage decrease in time depends on the specification of the computers, as shown in the same reference. Parallel computing is prompted by the need to have a precise and fast simulation environment for estimating and maximizing The optical efficiency of heliostat field. The algorithm is carried out to run on desktop workstations equipped with 6/12 CPU cores, 15 M Cache, up to 3.50 GHz (Intel®I7-3970X CPU @3.5GHz), which means the computations of all numbers of heliostats(n_h), distributed on 12 working units to decrease the running time. This technique is employed in our code twice as we see from Figure 3.8. The first instance gives out computing final three

transformations $[G]$ for the heliostat with other boundaries that are needed in efficiency computing. The second instance gives out the computations carried for the shading and blocking algorithm that is based on the MATLAB type cell data framework, as shown in Figure 3.8.

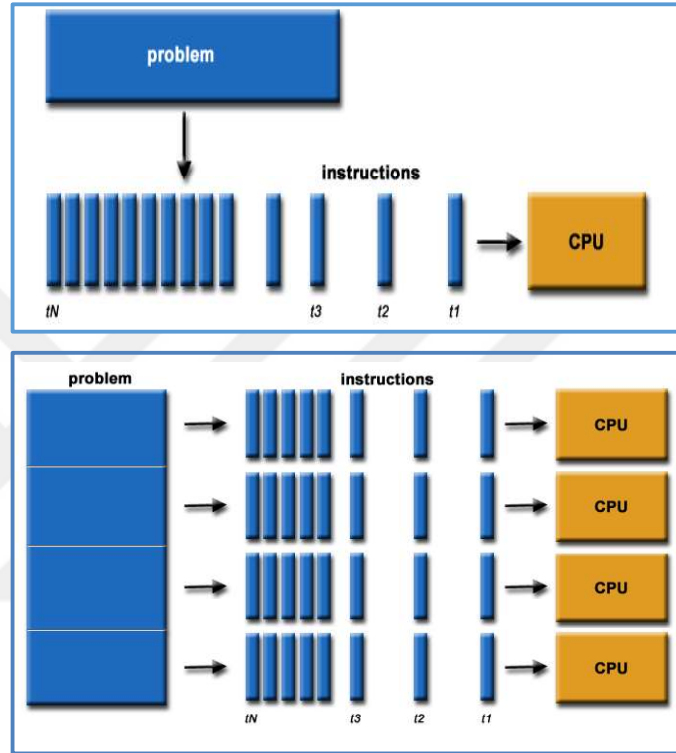


Figure 3.16 Running a loop that occurs in the series change to parallel

https://computing.llnl.gov/tutorials/parallel_comp

3.9.4. Artificial Neural Networks (ANNs)

The present code is based on a discretization model to estimate the $(\eta_{s\&b})$, which is considered an accurate model but at the same time, the slowest model. The second step to speed up operations while keeping high accuracy in calculations is the use of fast algorithms, the ANNs used. ANNs feature a relative simplification of a simulation methodology description. Neural nets are employed to find out the manner of the system and then to simulate and anticipate its manner. ANNs mimic the learning process of a human brain. ANNs, although carried out on computers, are not programmed to do specific jobs. Instead, the ANNs are trained on data sets until they learn the patterns used as inputs. Once the ANNs are trained, new patterns may be

delivered to them for prediction or classification. ANNs can automatically learn to spot patterns in data from real systems or physical examples, computer programs, or other authors. They can handle many inputs and obtain results in a shape suited for architects. A training set is a group of matched input and output patterns used for training the network, usually by suitable adjustment of the synaptic weights. The outputs are the dependent variables that the network produces for the corresponding input. It is important that all the information the network needs to learn be supplied to the network as a data set. When each pattern is read, the network uses the input data to produce an output, which is then compared to the training pattern, i.e., the correct or desired output. If there is a difference, the connection weights (usually, but not always) are altered in such a direction that the error is decreased. In this study, the task of the ANNs is to estimate ($\eta_{s\&b}$), which depends on the location of the sun and the heliostat location, after fixing the location of the neighboring heliostat when the (GA) finds the best layout from the previous step, which clarified next chapter. Therefore, in our code, the input and output variables for ANNs are presented in Table 3.2.

Table 3.2 Input and output variables for ANNs			
Input variables		Output variables	
1	Solar declination δ	1	Shadowing efficiency η_s
2	Solar altitude angle α	2	Blocking efficiency η_b
3	Solar azimuth angle A		
4	Polar angle for heliostat axis position θ		
5	Radius position for heliostat r_h		

In addition, the training set is prepared during runs of the code for each fixed time step (specific period of days during the year and specific period of minutes during the day), Increases in the steps or decrease in the duration time during training leads to higher accuracy in evaluating the($\eta_{s\&b}$) and after multi-values of the time step are evaluated, then recording the input and output variables, which are used for training the network in (for each 15 days in the year and for each 20 minutes from sunrise to sunset).

Further, we will identify the network type that was used that are presented in Figure 3.18: Generalized regression with one hidden layer and one output layer. Then, after

preparing the network of ANNs, the ANNs are joined with the main code to use the ANNs in computations of efficiency as shown in Figure 3.17.

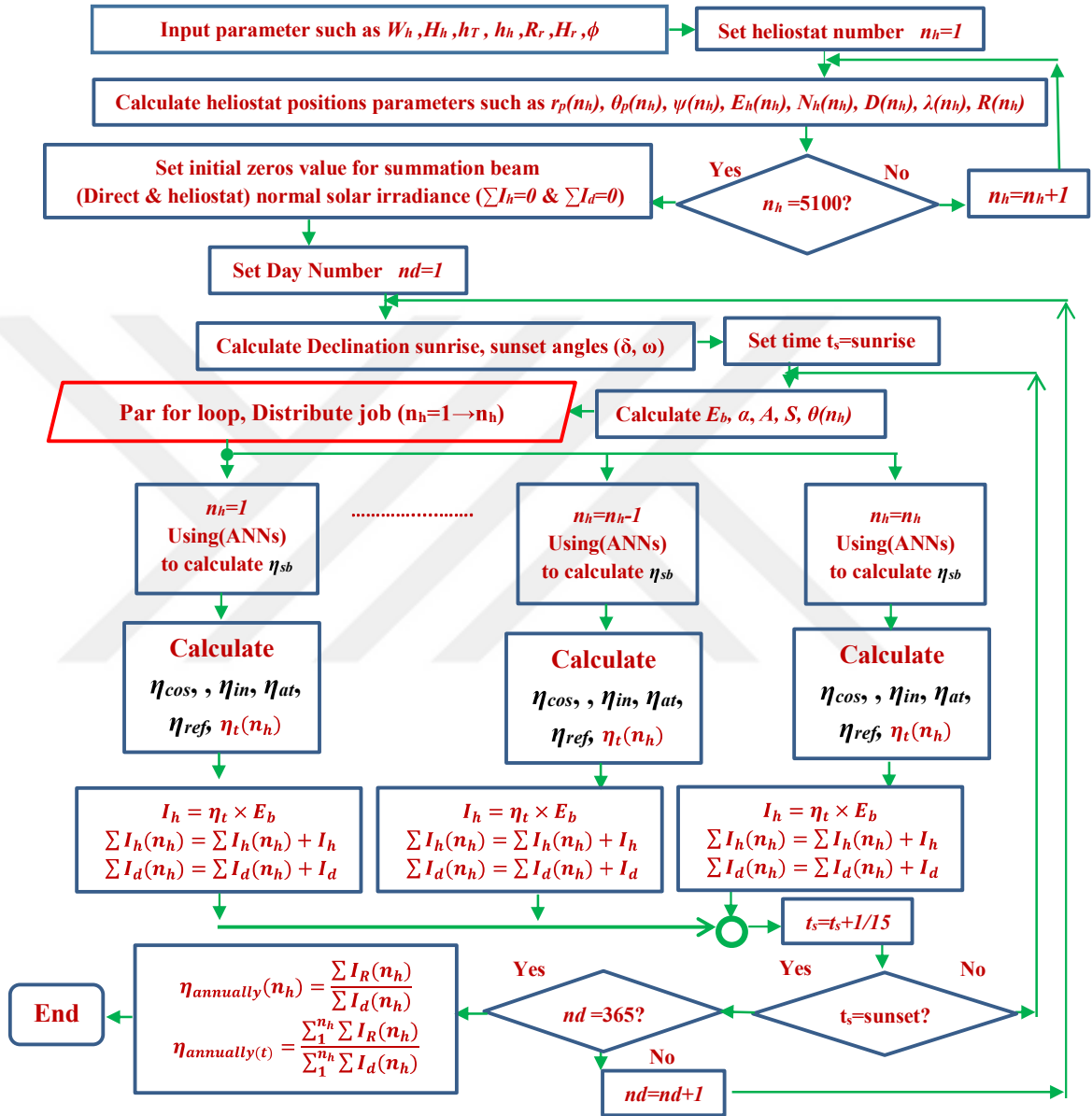


Figure 3.17 The flow chart to show the algorithm to estimate the $(\eta_{year, Eb})$ with (ANNs)

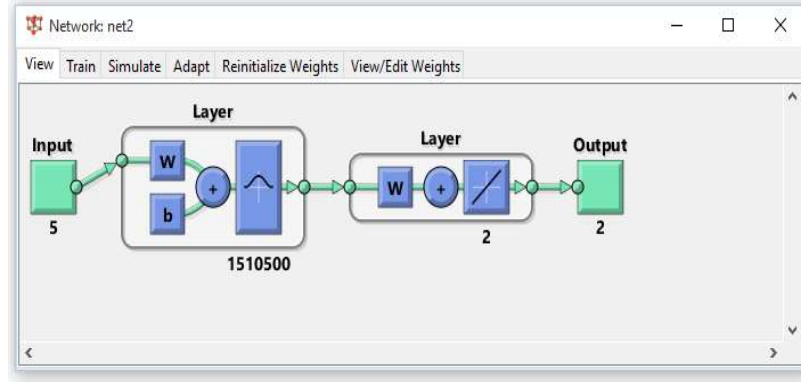


Figure 3.18 Properties of the network, which is used in ANNs

3.10 Mathematical Model for Multilevel Heliostat Field Layout

In the process of estimating the annual efficiency, several conditions become apparent: that the farthest heliostat from a tower has less optical efficiency, and heliostats closer to the tower and to the north exhibit higher cosine effect efficiency.

From these conditions, a new rear heliostat field arrangement is derived, arranging heliostats at different levels, such that no blocking losses occur throughout the year, with implementing the same layout model. To enhance the performance of these heliostats, the heliostats height is increased for selected heliostats located at the edge of the field layout, which exhibit the lowest optical efficiency. This arrangement can be formulated mathematically from purely geometrical considerations.

The farthest heliostat in the layout, which experiences the highest blocking losses, is considered as a reference to delineate heliostat strips. In addition, the numbers and radii of successive heliostats are specified in relation to this reference heliostat farthest from the tower; successive heliostats are located in the same spiral line as the reference heliostat.

The successive heliostats are numbered for reference, considering the farthest heliostat as number one, and then heliostats that have a radius value between one and two are identified. This group represents the first strip. The same operation is conducted to identify subsequent strips.

The new height for all heliostats in the first strip is determined by representing the reference heliostat with its successive heliostat in a front view as shown in Figure 3.19 by the circles (he_{c1} , he_{c2}). Subsequently, a straight tangential line (l_{ta}) is drawn from the point (T_p) on the lower edge of the receiver to the point tangent to the circle (he_{c2}), while increasing the circle's height (he_{c1}) with the same radius position until the circle

becomes tangent to line (l_{ta}) . In this configuration, (l_{ta}) represents the lowest limit of reflected rays originating behind the heliostat described by (he_{c2}) that also hit the receiver with no blocking by (he_{c1}) .

The geometrical steps to derive Eq. (3.55) described below in Figure 3.19 which is implemented to calculate the new height for all heliostats in the first strip, depending on the no blocking method illustrated in Figure 3.19.

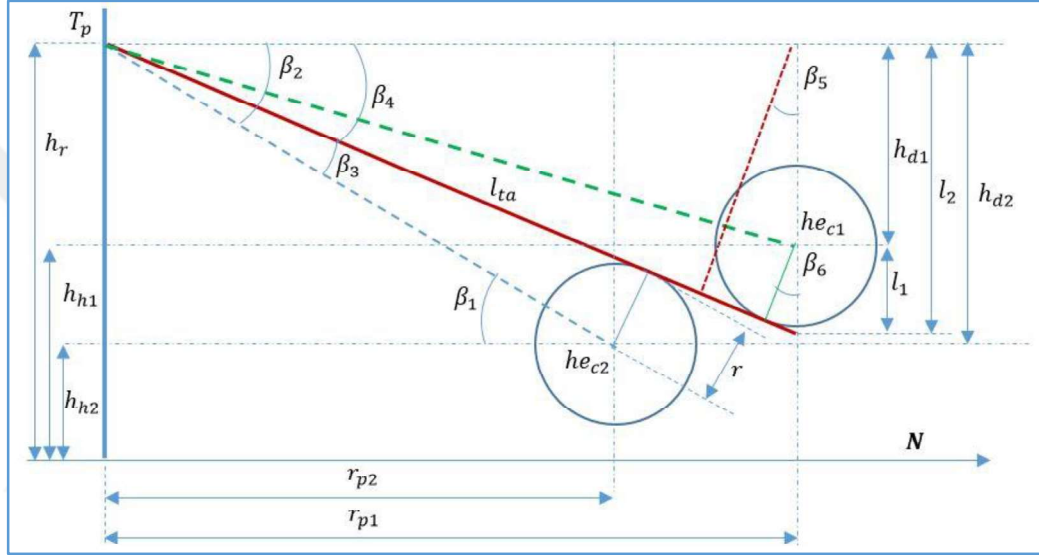


Figure 3.19 Front view of the reference and successive heliostats.

$$\beta_1 = \tan^{-1} \frac{h_{d2}}{r_{p2}}$$

$$\beta_1 = \beta_2$$

$$\overline{T_p, he_{c2}} = \sqrt{h_{d2}^2 + r_{p2}^2}$$

$$\beta_3 = \sin^{-1} \frac{r}{\overline{T_p, he_{c2}}} = \sin^{-1} \frac{r}{\sqrt{h_{d2}^2 + r_{p2}^2}}$$

$$\beta_4 = \beta_2 - \beta_3$$

$$\tan \beta_4 = \frac{\bar{l}_2}{r_{p1}}$$

$$\bar{l}_2 = \tan \beta_4 \times r_{p1}$$

$$\beta_6 = \beta_5 = \beta_4$$

$$\cos \beta_6 = \frac{r}{\bar{l}_1}$$

$$\begin{aligned}
\bar{l}_1 &= \frac{r}{\cos \beta_6} \\
h_{d1} &= \bar{l}_2 - \bar{l}_1 \\
h_{h1} &= h_t - h_{d1} \\
h_{h1} &= h_r - (\bar{l}_2 - \bar{l}_1) \\
h_{h1} &= h_r - \left((\tan \beta_4 \times r_{p1}) - \left(\frac{r}{\cos \beta_6} \right) \right) \\
h_{h1} &= h_r - \left((\tan(\beta_2 - \beta_3) \times r_{p1}) - \left(\frac{r}{\cos(\beta_2 - \beta_3)} \right) \right) \\
h_{h1} &= h_r - \left(\left(\tan \left(\left(\tan^{-1} \frac{h_{d2}}{r_{p2}} \right) - \left(\sin^{-1} \frac{r}{\sqrt{h_{d2}^2 + r_{p2}^2}} \right) \right) \times r_{p1} \right) \right. \\
&\quad \left. - \left(\frac{r}{\cos \left(\left(\tan^{-1} \frac{h_{d2}}{r_{p2}} \right) - \left(\sin^{-1} \frac{r}{\sqrt{h_{d2}^2 + r_{p2}^2}} \right) \right)} \right) \right) \dots \dots \dots (3.55)
\end{aligned}$$

Where, $r = H_h/2$ and, $h_{d2} = h_r - h_{h(old)}$

The same procedure is used to determine the height for heliostats in the second strip by considering the two strips beyond the one under investigation, again with no blocking of the heliostats in the third strip, as shown in Figure 3.20.

With the new heights (h_{h1}, h_{h2}) for the first and second strips, from Eq. (3.55), while the height of the second strip is added to the difference in elevation of the first strip, as shown in Eq. (3.56):

$$h_{h1} = (h_{h1} - h_{h(old)}) + h_{h2} \dots \dots \dots (3.56)$$

Rising to three strips, Eq. (3.56) becomes Eqs. (3.57) and (3.58):

$$h_{h1} = (h_{h1} - h_{h(old)}) + (h_{h2} - h_{h(old)}) + h_{h3} \dots \dots \dots (3.57)$$

$$h_{h2} = (h_{h2} - h_{h(old)}) + h_{h3} \dots \dots \dots (3.58)$$

In this way, Eq. (3.55) is implemented three times, and the height of each strip is added to the difference in elevation for subsequent strips, as many times as necessary.

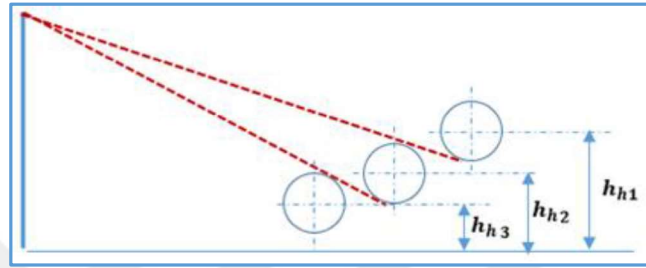


Figure 3.20 Increasing height of two successive strips.

3.11 Thermo Economical Optimization of Number of Heliostats for Solar Fields

A thermo economic optimization analysis is presented yielding simple algebraic formula for estimating the optimum number of heliostats for solar fields which are applied in industrial applications. An economic analysis method is used in the present study, together with the thermal analyses of heliostats, for thermo economic optimization.

Economics of solar energy collection is vitally significant. So, optimum operating conditions especially optimum number of heliostats for solar fields depending on thermo economic analysis is extremely important in order to have maximum overall life cycle earnings for these heliostats. The optimum values of solar collector area or number of heliostats must be calculated at which minimum cost and so maximum savings occur for solar fields that are widely used for energy generation applications for that reason. There exist many parameters for optimizing such systems in a thermo economical manner. Fixing and, so eliminating all of these thermal and economical parameters depending on the certainty of operating characteristics of applications and the most efficient operating condition of the them can determine the optimum number of heliostats for solar fields. It is known that the energy output of the solar energy system is directly related to its size which affects its initial cost. A thermo economic feasibility study is necessary before installing the solar fields. The one of the basic

topic of the present work depends upon this idea. A new thermo economic optimization technique is realized and presented for this purpose. Original formulae are developed for calculating the optimum number of heliostats for solar fields at which the maximum total life cycle savings occur. A thorough search of the current literature showed that there was no previous study on optimizing the size solar fields in detail. A well known and practical method, P₁-P₂ method, which is offered by Duffie and Beckman [1980], is used for optimizing the size and capacity of solar fields, and original interesting results are presented. Variable parameters used in formulating the optimization problem are listed as technical life of the solar field, first cost of each heliostat, annual interest rate, present net price of thermal energy, annual energy price escalation rate, annual average operating time, resale value and the ratio of annual maintenance and operation cost to the first original cost. Optimum number of heliostats and optimum value of net life cycle savings can be calculated easily in a few minutes with the help of practical formulae.

3.11.1 Mathematical Formulation

The life cycle net savings of a solar heliostat field can be calculated by using the average cost data [50, 51] as:

$$S_{Lf} = 365,25 \cdot P_1 \cdot C_E \cdot E_{av} - P_2 \cdot C_N \cdot N_h \dots \dots \dots (3.59)$$

The amount of annual average of daily thermal solar energy obtained by solar fields as a function of number of heliostats, in kW.hr, can be correlated by the following equation:

$$E_{av} = a \cdot N_h^2 + b \cdot N_h + c \dots \dots \dots (3.60)$$

Where the correlation coefficients were calculated as follows.

$$a = -0,0467; b = 781,59; c = 95 \dots \dots \dots (3.61)$$

The total net life cycle savings of the solar fields as presented in Eqn. (3.59) can be derived wrt. number of heliostats itself and setting it into zero to get optimum value of number of heliostats as in the form of the following function.

$$\frac{\partial S_{Lf}}{\partial N_h} = 365,25 \cdot P_1 \cdot C_E \cdot \frac{\partial E_{av}}{\partial N_h} - P_2 \cdot C_N = 0 \dots \dots \dots (3.62)$$

Where the derivative of the effectiveness wrt. area can be evaluated from Eqn. (3.60) as:

$$\frac{\partial E_{av}}{\partial N_h} = 2 \cdot a \cdot N_{h,opt} + b \dots \dots \dots (3.63)$$

And Eqn. (3.62) can now be rewritten as follows.

$$\frac{\partial S_{Lf}}{\partial N_h} = 365,25 \cdot P_1 \cdot C_E \cdot (2 \cdot a \cdot N_{h,opt} + b) - P_2 \cdot C_N = 0 \dots \dots \dots (3.64)$$

Then follows:

$$N_{h,opt} = \frac{\frac{P_2 \cdot C_N}{365,25 \cdot P_1 \cdot C_E} - b}{2a} \dots \dots \dots (3.65)$$

The second derivative of the net total life cycle savings function is always negative which indicates a local maximum certainly since a is always negative.

$$\frac{\partial^2 S_{Lf}}{\partial N_h^2} = 2 \cdot 365,25 \cdot a \cdot P_1 \cdot C_E < 0 \dots \dots \dots (3.66)$$

The economic parameters P_1 and P_2 are defined as in following equations [5].

If i is equal to d_{Md} :

$$P_1 = \frac{M}{1+i} \dots \dots \dots (3.67)$$

And for $i \neq d_{Md}$:

$$P_1 = \frac{1}{(d_{Md} - 1)} \cdot \left\{ 1 - \left[\frac{1+i}{1+d_{Md}} \right]^M \right\} \dots \dots \dots (3.68)$$

And

$$P_2 = 1 + P_1 \cdot M_s - R_v \cdot (1 + d_{Md})^{-M} \dots \dots \dots (3.69)$$

For solar energy generation application purpose the payback period can be estimated by setting the net savings into zero for optimal number of heliostats as:

$$S_{Lf} = 0 \Rightarrow P_1 = \frac{P_2 \cdot C_N \cdot N_{h,opt}}{365,25 \cdot C_E \cdot E_{opt}} \dots \dots \dots (3.70)$$

For $i = d_{Md}$ case:

$$N_p = \frac{P_2 \cdot C_N \cdot N_{h,opt} \cdot (1 + i)}{365,25 \cdot C_E \cdot E_{opt}} \dots \dots \dots (3.71)$$

For $i \neq d_{Md}$ case the value of payback is calculated via using the following equality.

$$N_p = \frac{\ln \left[\frac{P_2 \cdot C_N \cdot N_{h,opt} \cdot (d_{Md} - i)}{365,25 \cdot C_E \cdot E_{opt}} \right]}{\ln \left[\frac{1 + i}{1 + d_{Md}} \right]} \dots \dots \dots (3.72)$$

The critical value of the annual average of the solar thermal energy obtained from solar heliostats can be determined by setting S_{Lf} function into zero as in the following equality:

$$E_{crit} = \frac{P_2 \cdot C_N \cdot N_{crit}}{365,25 \cdot P_1 \cdot C_E} \dots \dots \dots (3.73)$$

The critical value of the number of heliostats can be found by using Eqns. (3.60) and (3.73) together as in Eqn. (3.74).

$$N_{crit} = \frac{-e - \sqrt{\Delta}}{2 \cdot a} \dots \dots \dots (3.74)$$

Where as:

$$e = b - \frac{P_2 \cdot C_N}{365,25 \cdot P_1 \cdot C_E} \dots \dots \dots (3.75)$$

And

$$\Delta = e^2 - 4 \cdot a \cdot c \dots \dots \dots (3.76)$$

3.12 Receiver

In an (CRS), the receiver is the heat exchanger that intercepts the concentrated sunlight and removes its energy to a heat transfer fluid (HTF), which may be water, molten salt, atmospheric air, or pressurized air. Radiant flux and temperature are substantially higher than in parabolic troughs, and therefore, high technology is involved in the design, and high-performance materials should be chosen. The solar receiver should mimic a blackbody by minimizing radiation losses. Receivers are positioned at the height of the tower and high above the point of the heliostats on the pinnacle in order to downplay the effect of overshadowing and blocking among neighboring heliostats.

In this method, the reflected energy from the heliostats is collected as efficiently as possible. The model presented in this thesis is based on molten salt tubular cylindrical receivers and the characteristics of this model is presented in Table 3.1, because these are in accordance with the specifications of the Gemasolar receiver and are illuminated by 360° of the surrounding field. The surface of the cylindrical receiver is formed with a number of smaller rectangular panels, each consisting of a number of vertical tubes filled with HTF that flows in parallel between a common lower and upper flow header, as shown in Figure 3.21.

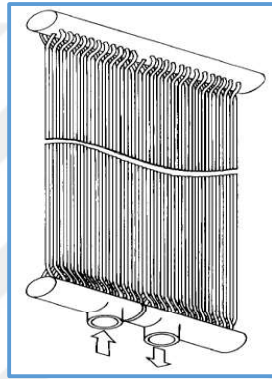


Figure 3.21 Typical receiver panel design [12]

As presented in Figure 3.21, the thin-walled vertical tubes welded between the inlet and outlet header tanks are filled with HTF that runs in parallel between a common lower and upper flow header [12]. The panel face is uncovered to the solar flux while the rear of the panel is insulated. The pipes are generally stainless-steel alloy [52]. In addition, to maximize absorption of the incident solar flux, the pipes are coated with high-absorptivity paint such as the black-matte Pyromark™ paint used for Solar II and Gemasolar. According to the Gemasolar literature [9], the average absorptivity of this particular coating is claimed to be 95% and the coating's emittance is 0.1, as presented in Table 3.1.

Heat transfer fluid flow configurations can vary from receiver design to design, depending on material thermal strain constraints, heliostat field distribution, and pumping requirements. Figure 3.22 shows plan views for eight of the many possible flow configurations for the external receiver [53].

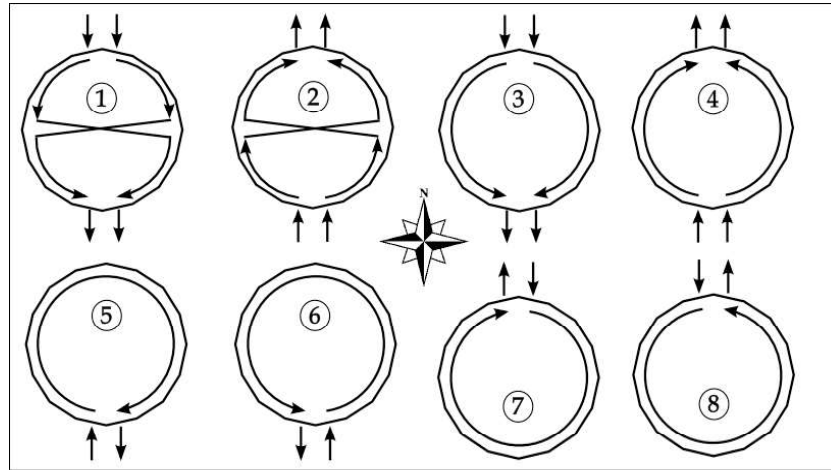


Figure 3.22 Eight possible flow configurations for the external receiver. Each configuration is presented from a top-down, axial line of sight viewpoint [53].

Referable to the large radiation flux concentration on the receiving surface, the liquidator is able to generate high heat transfer fluid temperatures.

Molten salt was successfully applied in the solar Two projects and exhibits great potential as of fluid of choice for (CRS).

Receivers that use a molten salt as the HTF benefit because there is no phase change and it is possible to heat the HTF up to 595°C. Mixtures of 60% sodium nitrate NaNO_3 and 40% potassium nitrate KNO_3 have been extensively tested with satisfactory results in France and the U.S.A. Molten nitrates provide good thermal conductivity and heat capacity as presented in Table 3.3 at relatively low prices. [54], molten nitrate salt, though an excellent thermal storage medium, can be a troublesome fluid to deal with because of its relatively high freezing point (220°C). To reserve the salt molten, a fairly complex heat trace system must be employed. (Heat tracing is composed of electric wires attached to the external surface of the tubes. Pipes are kept warm by way of resistance heating.) Problems were experienced during the start-up of Solar Two due to the improper installation of the heat trace this problem has been addressed and corrected, research is needed to reduce the reliance on heat tracing in these plants. [11]

Table 3.3 Molten salt mixture properties [54].		
	parameter	value
1	v_l liquid specific volume (m ³ /kg)	$v_l = \frac{1}{2090 - 0.636 \cdot (T - 273.15)}$
2	Liquid specific heat (J/kg · K)	$c_{p_l} = 1443 + 0.172 \cdot (T - 273.15)$
3	Liquid thermal conductivity (W/m · K)	$k_l = 0.443 + 1.9 \cdot 10^{-4} \cdot (T - 273.15)$
4	Dynamic viscosity (Pa.s)	$\mu_l = \frac{22.714 - 0.12 \cdot (T - 273.15) + 2.281 \cdot 10^{-4} \cdot (T - 273.15)^2}{1000} - \frac{1.474 \cdot 10^{-7} \cdot (T - 273.15)^3}{1000} \quad (\text{Pa.s})$
Temperature in K		

In receivers using a molten salt as the heat transfer fluid, maximum temperatures are constrained by receiver materials of construction and in some instances by the heat transfer fluid stability or boiling point. For the receiver in the Gemasolar system, is used the same heat transfer fluid [52, 54] which presented its properties in Table 3.3. The HTF is pumped from the “cold” storage tank at 290°C into the receiver, where it is heated to 595°C and pumped to the hot storage tank [9]. The mass flow rate of the HTF through the receiver is modulated to accommodate the desired outlet temperature from the tower as the incident flux varies throughout the procedure.

3.12.1 Receiver Model Sizing and Mass Flow Rate

The overall dimensions of the receiver are given by its radius R_r (or diameter) and height H_r which presented in Table 3.1.

The receiver dimensions have a strong influence on the final optical efficiency, since a significant share of reflected light may miss the target (spillage loss). In practice in the case of Solar One/Two, the original receiver at Solar One was 7 [m] wide and 13.7

[m] high, and for Solar Two it was replaced by a 5.1 [m] by 6.2 [m] receiver, which was one of the reasons for large spillage losses, close to 10% of incident rays [41]. This may happen especially when the receiver is smaller than the heliostats, which increases the need for heliostat canting.

On the other hand, when the receiver is at least as large as the heliostats, there is still always a need for focusing heliostats with curved mirrors and canting, but to a lesser extent such as in the example of the Sierra Sun Tower in Lancaster.

The HTF enters the receiver from the north side, where the concentration of solar flux is maximum, and the temperature of the HTF is the lowest, and flows through one of the two 12-panel flow circuits as a serpentine flow, as shown in Figure 3.25. The HTF then exits the system via the south side.

The total mass flow rate ($\dot{m}_{total}$) considered objective function in receiver computations because it represented the “door” for power cycle module computations and calculating energy output from the plant. The total mass flow rate is calculated from the desired inlet and exit enthalpies using the known enthalpy data or from temperatures and the mean thermal heat capacity (C_p) of the heat transfer fluid. The total mass flow rate can be calculated from the appropriate equation:

$$\dot{m}_l = \frac{\dot{Q}_{absorb}}{C_p(T_{l,ex} - T_{l,en})} \quad \dot{m}_l = \frac{\dot{Q}_{absorb}}{h_{en_{ex}} - h_{en_{en}}} \dots \dots \dots (3.77)$$

3.12.2 Shape Distribution of the Incident Power on an External Receiver

The scheme of the shape distribution of the incident power on the external receiver surface $\dot{Q}_{inc}(i, j)$ should be estimated before applying energy balance formulation, which can be done using analytic functions of the HFLCAL model (presented in section 3.9) with the adaptation projection model of Gonzalez et al. [55]. Generally, the analytic functions of the HFLCAL model are estimated on the plane normal to the central reflected ray for each heliostat. Thus, the image plane is used in the projection method. First, discretize the receiver panels into several flux points per panel in the vertical direction, approximate them as much as possible into equilateral blocks. Then, divide each panel into nine blocks of the same length, after which the center of each discretization is projected onto the image plane in the direction of the central reflected ray, as shown in Figure 3.23.

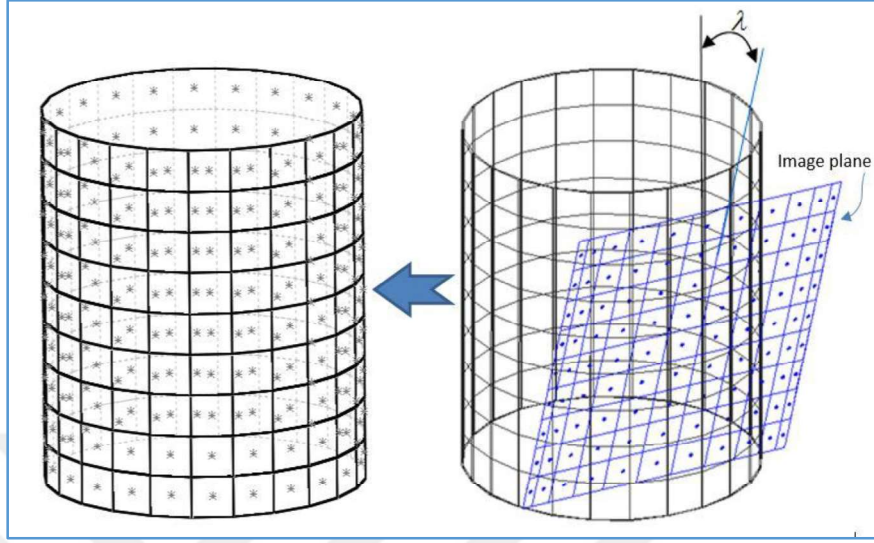


Figure 3.23 Discretization of the surface of the solar receiver with present projection plane

Generally, the scale of resolution increases when the grid is more accurate; however, the computation time also increases.

For each heliostat in the field, we applied the analytic function in Collado et al. [56], on the nodes in the image plane to estimate the shape distribution of the incident power, as given by Eq. (3.78).

$$\dot{Q}_{inc,h}(x_r, y_r) = \frac{E_b(t) \times A_m \times \eta_{ref} \times \eta_{cos} \times \eta_{at} \times \eta_{s\&b}}{2\pi\sigma_{tot}^2} e^{\left(-\frac{x_r^2 + y_r^2}{2\sigma_{tot}^2}\right)} \dots \dots \dots (3.78)$$

Next, the flux distribution is projected from the image plane to the receiver, the flux map caused by an entire field of heliostats is generated, and the shape distribution of the incident power at each center of the discretization element of the receiver $\dot{Q}_{inc}(i, j)$ is estimated, where i represent the number of panels n_p , and j represents the number of blocks n_{bl} , which means that each block has its own incident power, as shown in Figure 3.24, which clarify the $\dot{Q}_{inc}(i, j)$ at spring equinox-solar noon for Seville, Spain, that appear the close shape distribution with Gonzalez et al. [55] after comparison, and the total incident power equal at specified time, $\dot{Q}_{inc} = \sum_{i,j} \dot{Q}_{inc}(i, j)$

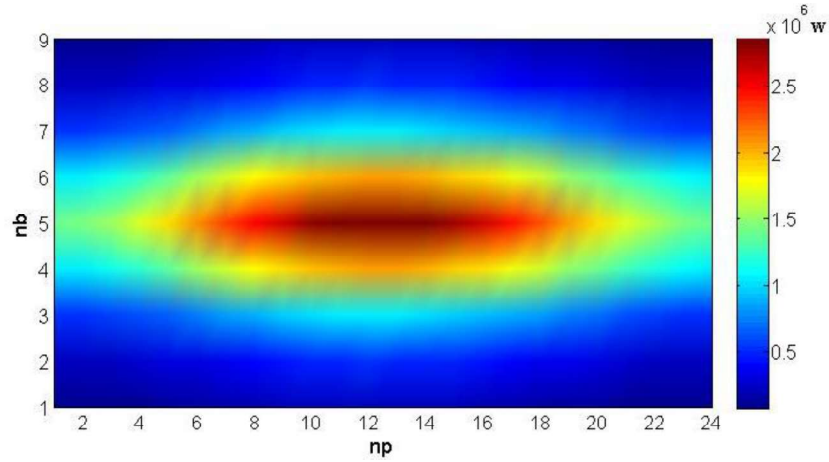


Figure 3.24 Shape distribution of the incident power on the external surface at spring equinox-solar noon for Seville, Spain

The cylindrical surface of the external receiver is mapped to a planar surface in which the progression from 0° to 360° along the horizontal axis corresponds to the progression around the circumference of the receiver.

The maximum $\dot{Q}_{inc}(i, j)$ occurs at the northernmost panels where the angular position is 180° .

3.12.3 Receiver Thermal Model

Energy balance and model formulation

The solar energy will be reflected by the heliostat field onto the receiver and absorbed by the HTF. The energy absorbed by the HTF would be the difference between the total incident energy and total losses through the receiver. These losses consist of 1) convective losses due to the air surrounding the receiver, which are directly related to local temperature and wind conditions; 2) radiative losses due to the radiations emitted from the receiver's hot surface to the environment; and 3) reflective losses due to the material's properties. These heat transfer losses are shown in Figure 3.25

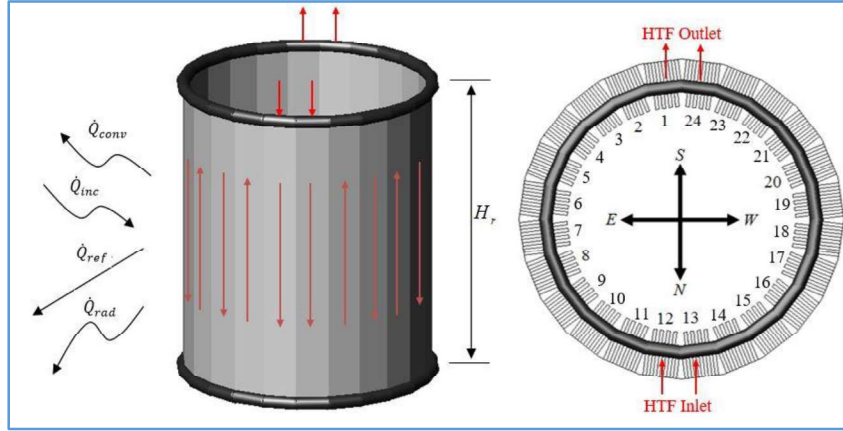


Figure 3.25 Heat transfer in receiver

The modeling tool is limited to the scheme of the $\dot{Q}_{inc}(i, j)$, which as estimated before contains one data point per panel in the circumferential direction and several flux points per panel in the vertical direction.

The proposed model considers that the inlet and outlet temperatures are fixed, that the tube-to-tube conduction and radiation exchange is negligible, and that the axial conduction is also small because the internal convection due to molten salt flowing in the tubes dominates the relatively large resistance to conduction.

The overall energy balance of the heat flow components entering and exiting each block in the receiver is expressed by Eq. (3.79) to estimate the absorbed heat $\dot{Q}_{abs}(i, j)$:

$$\dot{Q}_{abs}(i, j) = \dot{Q}_{inc}(i, j) - \left(\dot{Q}_{conv}(i, j) + \dot{Q}_{rad}(i, j) + \dot{Q}_{ref}(i, j) \right) \dots \dots \dots (3.79)$$

Radiative losses: The radiative heat transfer losses are dominant losses at high temperatures. The heat loss due to radiation is calculated using equation (3.80). as a function of both ambient air temperature and effective sky temperature [53] In this case the ambient temperature, plays a very important role and is calculated hourly by using equation (3.13), and then a simple relationship be used to estimate the apparent sky temperature equation stated as in equation (3.81) [57]. The Equations (3.82-3.83) [34] show the relationship between the sky temperature, ambient air temperature, and radiative heat transfer losses.

$$\dot{Q}_{rad} = hr_{rad,amb} \cdot A_{su} \cdot (T_{s,i,j} - T_{amb}) + hr_{rad,sky} \cdot A_{su} \cdot (T_{s,i,j} + T_{sky}) \dots (3.80)$$

$$T_{sky} = 0.0552T_{amb}^{1.5} \quad (K) \dots \dots \dots (3.81)$$

$$hr_{rad,amb} = \sigma \varepsilon F_{s,amb} (T_{s,i,j}^2 + T_{amb}^2) (T_{s,i,j} + T_{amb}) \quad (W/m^2 \cdot K) \dots \dots \dots (3.82)$$

$$hr_{rad,sky} = \sigma \varepsilon F_{s,sky} (T_{s,i,j}^2 + T_{sky}^2) (T_{s,i,j} + T_{sky}) \quad (W/m^2 \cdot K) \dots \dots \dots (3.83)$$

The Stefan-boltzmann constant is $\sigma = 5.67 \times 10^{-8} (W/m^2 K^4)$ and the surface emissivity is $\varepsilon = 0.88$. The view factors between the ground and the tower, and the sky and the tower are $F_{s,amb} = 0.5$ and $F_{s,sky} = 0.5$, respectively [53].

The surface area A_{su} of the element equals $n_t(\pi r_o L)$, where L is the length of the panel block in the vertical direction, and r_o , r_i are the absorber tube's inner and outer radii, respectively.

Convective losses: Convective losses from different blocks,

$$\dot{Q}_{conv}(i, j) = \bar{h}_{mix} \cdot A_{su} (T_{s,i,j} - T_{amb}) \dots \dots \dots (3.84)$$

The above result is obtained from forced and natural convection. The convection heat transfer coefficient can be estimated from the Eq. $\bar{h}_{mix} = (\bar{h}_{fc}^{3.2} - \bar{h}_{nc}^{3.2})^{1/3.2}$ According to the correlations of Siebers and Kraabel [58], where $\bar{h}_{nc}$ is the natural convection coefficient, which is based on the Nusselt and Grashof numbers, that are consider the receiver height as characteristic length.

$$Nu_L = \frac{hL}{k} = 0.098 \cdot Gr_L^{(1/3)} \cdot \left(\frac{T_{s,i,j}}{T_{amb}} \right)^{-0.14} \dots \dots \dots (3.85)$$

$$Gr_L = \frac{g\beta(T_{s,i,j} - T_{\infty})L_c^3}{\nu^2} \dots \dots \dots (3.86)$$

Properties at T_f

$$T_f = \frac{T_{s,i,j} + T_{\infty}}{2} \dots \dots \dots (3.87)$$

And $\bar{h}_{fc}$ represents the forced convection coefficient, which is estimated from the Nusselt and Reynold numbers that are based on the receiver diameter and wind velocity, proposed by Churchill and Bernstein [59] as shown in Eq.(3.88)

$$Nu_D = \frac{hD}{k} = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr} \right)^{2/3} \right]^{1/4}} \left[1 + \left(\frac{Re_D}{282,000} \right)^{5/8} \right]^{4/5} \dots \dots \dots (3.88)$$

Reflection losses: The energy that is initially reflected from the tower is represented by the ref $\dot{Q}_{ref}$ term. The receiver model assumes a constant, spectrally independent, hemispherical absorptivity (α_{ab}) for the tower surface. Since the tower surface is opaque, the reflectivity is $(1 - \alpha_{ab})$.

$$\dot{Q}_{ref}(i, j) = (1 - 0.95) \cdot \dot{Q}_{inc}(i, j) \dots \dots \dots (3.89)$$

Receiver surface temperature:

The first consideration in the computation of heat losses is the calculation of the average receiver surface and HTF temperatures for each block because they are required for almost all types of heat loss computations, excluding reflective heat loss. An additional energy balance is needed. This balance considers the thermal resistance between the outer surface of the tube and the HTF running through the tube, as presented in Figure 3.26

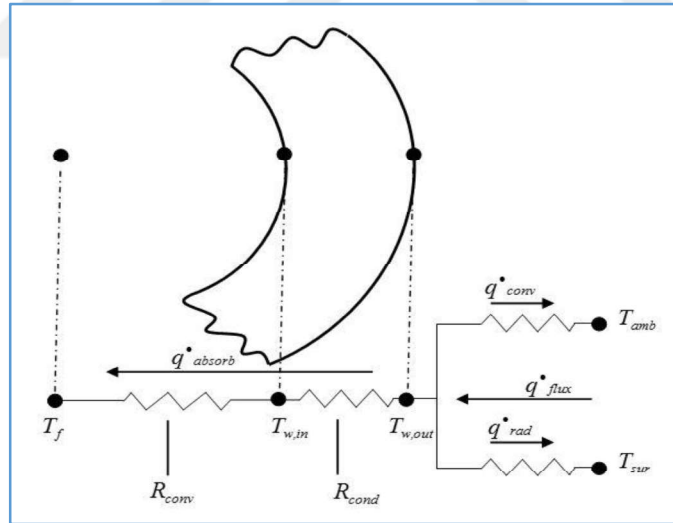


Figure 3.26 Receiver pipe thermal resistance model

To determine the temperatures of the HTF along the flow path of the HTF through the receiver tubes, as shown in equation (3.90), which depend on the accumulated heat from the entrance until the block where the temperature of the HTF is computed, that mean, as mentioned before the HTF flow in two paths in the receiver, each path flow in 12 panels and 9 blocks in each panel, each path consist of 108 blocks, then to simplified computations, defined length of path flow (L_{pf}) Which present the

sequence of the blocks with path flow, then when computed temperature for specified block, should estimate the summation heat for all heat from entrance to specify a block, as Consecutively to the fluid flow path, or in the other ward, follow the flow of the HTF as shown in Figure 3.25, that mean the sequence of the summation in Eq. (3.90) for the specified number of (L_{pf}), start from the first element in panel 12 and end at ($n=108$), for path flow (north-east- south) and the sequence of the number of the elements (i, j) That corresponding to the sequence of the length of the path flow of HTF, and for other path start from the first element in panel 13 and end at ($n=108$), for path flow (north-west south), and same procedure for sequence of blocks.

$$T_{HTF}(i, j) = T_{HTF}(L_{pf}) = 290 + \sum_{L_{pf}=1}^n \frac{\dot{Q}_{absorb}(i, j)}{\dot{m}_{HTF,p} \cdot c_{pHTF}} \dots \dots \dots (3.90)$$

$\dot{m}_{HTF,p}$ represents the mass flow rate of the HTF for each panel, and $T_{HTF}(0)$ equals 290 °C, which is the entrance temperature for the HTF

Further, an additional energy balance is required to estimate the surface temperature of the element $T_{s,i,j}$. This balance considers the thermal resistance between the outer surface of the tube and the HTF running through the tube, and can be described by Eq. (3.91):

$$T_{s,i,j} = \frac{\dot{Q}_{abs}(i, j)}{n_t} \left(\frac{\ln(r_o/r_i)}{2\pi Lk} + \frac{1}{h_{in}(2\pi r_i L)} \right) + T_{HTF}(i, j) \dots \dots \dots (3.91)$$

where $T_{HTF}(i, j)$ is the HTF temperature in the absorber tube.

In equations 3.91, h_i Is the molten salt convective heat transfer coefficient in the absorber tube. The classical Dittus-Boelter equation presented in [32] is applied as Eq. (3.92):

$$Nu_{ms} = 0.023 Re^{0.8} Pr^{0.4} \dots \dots \dots (3.92)$$

3.12.4 The Methodology of Total Heat Loss Calculation

The receiver system is the “door” for which the energy passes from the field collector to the thermal-electric cycle; it represents, therefore, the core of the CRS and its performance directly affects plant production. A special attention has to be paid to its analysis because it is a component subjected to high working temperatures. ($\dot{m}_l$)

Considered the main parameter which needed to perform the rankine cycle calculations.

This mathematical model is further refined by two more steps. First, the $T_{\text{HTF}}(i, j)$ and $T_{s,i,j}$ temperatures are calculated beginning with a set of values based on the conjecture that is then adjusted through iteration. The main assumption used to start this calculation is that $\sum_{i,j} \dot{Q}_{\text{abs}}(i, j) = \sum_{i,j} \dot{Q}_{\text{inc}}(i, j)$, after which the mass flowrate for each path flow $\dot{m}_{\text{HTF},p}$ is esimated. Then, the temperature $T_{\text{HTF}}(i, j)$ along path flow of the HTF from Eq. (3.90) with an initial estimation of the fluid property is estimated, after which $T_{s,i,j}$ is estimated from Eq. (3.91).

Second, $T_{s,i,j}$ is substituted in heat losses equations (3.80–3.89) to determine $\dot{Q}_{\text{abs}}(i, j)$ from Eq. (3.79), and then $T_{\text{HTF}}(i, j)$ and $T_{s,i,j}$ are recalculated using the new $\dot{Q}_{\text{abs}}(i, j)$ value. Subsequent $\dot{Q}_{\text{abs}}(i, j)$ values are compared, and if the difference is equal to 0.001, the last value can be considered the true value, this computation and comparison occur for each element, with consider the path of HTF flow, then the last comparison will be for the total value $\sum_{i,j} \dot{Q}_{\text{abs}}(i, j)$ with same difference and the last value can be considered the true value.

Third, then, calculate mass flow rate ($\dot{m}_{l,r}$) depending on Equation 3.93. In addition, the accumulated mass during the day for the 21st day of each month is estimated that based on dynamic simulation (for every 20 minutes), that was developed in MATLAB, to form a clear picture about the capacity of storage thermal and to estimate the mass flow rate through heat exchanger of the Rankine cycle ($\dot{m}_{l,bo}$)

$$(\dot{m}_{l,bo}) = \frac{\text{accumulated mass}}{24 \times 60 \times 60} \dots \dots \dots 3.93$$

3.13. Rankine Cycle for the Central Receiver Power Plant

The thermal power from the central receiver system is used to drive an electric power generation cycle. Therefore, the most common generation cycle for this application is the steam Rankine cycle. The cycle under consideration is intended to accommodate the conversion of heat provided by the central receiver heat transfer fluid flow to electric power in the turbines with a combined input energy from the thermal storage through fixed mass flow rate during the day so that the Rankine cycle model can apply to any size cycle.

Since GEMASOLAR is a modern project, more or less of its parameters were hard to estimate, due to the degree of confidence surrounding the scheme. When some data were not obtainable (like an electric power generation cycle), they were estimated from a literature review on solar Two (CRS) [41, 9], which consider the most similar plant that has been fully studied up-to-date.

Figure 3.27 shows a simplified scheme (temperature-entropy diagram) of the cycle configuration adapted from Solar Two power cycle schematic presented by [53, 60]. The original figure clarified in Appendix C.

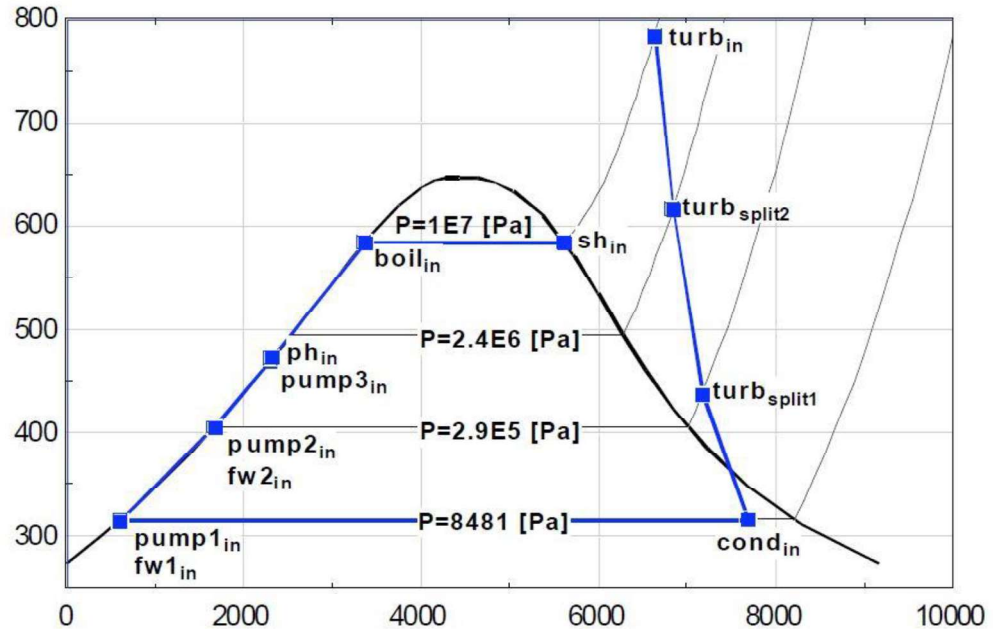


Figure 3.27 Temperature-entropy diagram of the cycle configuration adapted from Solar Two power cycle

Typical turbine and pump efficiencies are specified, with the pump efficiencies equal to the value of an isentropic efficiency calculated from the Solar II cycle analyzed by [60] that clarified with high-pressure turbine inlet with a temperature of the same point and condensing pressure in Table 3.4.

Table 3.4 Isentropic efficiencies for turbine and pump with temperature and high-pressure turbine inlet and condensing pressure[53]	
high-pressure turbine inlet	1.00E+07 (pa)
Temperature for turbine inlet	783.2 (k)
condensing pressure	8481 (pa)
Isentropic efficiency (turb1)	0.7
Isentropic efficiency (turb2)	0.7
Isentropic efficiency (turb3)	0.7
Isentropic efficiency (pump1)	0.695
Isentropic efficiency (pump2)	0.695
Isentropic efficiency (pump3)	0.695

The pressure at the turbine inlet is equal to the boiler pressure, since the pressure drop of the steam across the heat exchangers is neglected

The turbine splitter extraction phases can be fixed at a desired pressure to maximize cycle efficiency. The dependence of cycle efficiency on these pressures is relatively weak, and exact optimization is not needed. The pressure can be estimated as the saturation pressure of the temperature at the stage outlet. At this pressure, the corresponding saturation temperature is calculated, and the intermediate splitter stage pressure is calculated by evenly dividing the difference in temperature between the first turbine inlet stage and the last turbine outlet stage into even increments [61, 53]. The resulting temperature at saturation is associated with the actual saturation pressure to be used at that splitter stage. At each of the two splitter stages, a portion of the steam mass flow rate is diverted into an open feed-water heater, as shown in the cycle schematic in Figure 3.27 above. The fractions that are extracted are denoted as (x) for the higher pressure feed-water heater and (y) for the lower pressure feed-water heater. The remaining fraction passes through the subsequent turbine stage(s) and condenser, with the total remaining fraction passing through the condenser being $(1 - y)(1 - x)$. Since the power output from the turbine needed to determine , before that The mass flow rate of the steam should be calculated from the following equation

$$\dot{m}_{st} = \frac{\dot{m}_{l,bo} c_p (T_{l,ex} - T_{l,en})}{(hen_{turb,in} - hen_{bo,in})} \dots \dots \dots (3.94)$$

And power turbine from the following

$$\begin{aligned} \dot{W}_{turb,out} = \dot{m}_{st} [& (hen_{turb,in} - hen_{turb,split2}) \\ & + (1 - x)(hen_{turb,split2} - hen_{turb,split1}) \\ & + (1 - x)(1 - y)(hen_{turb,split1} - hen_{cond,in})] \dots \dots \dots (3.95) \end{aligned}$$



CHAPTER 4

CFD: NUMERICAL SOLUTION

A numerical simulation of the central receiver utilized for verification tool for the analytical solution which presented in the previous chapter and this duty implement by anticipating the commercial code, ANSYS Fluent. And the solution of the analytical model compared with three-dimensional and highly complex CFD model.

4.1 Modeling

4.1.1 Geometry

There are several models to simulate solar receiver presented in literature, and in present simulation, select the most accurate model of Sanchez et al. [37] to predict the outcome of the presented receiver geometry.

The mass, momentum and energy equations were solved, in CFD simulation by utilizing a control volume technique. A pressure correction based model was employed to solve the Naviere Stokes equations. Only one representative tube per panel was simulated, to decrease the implementation time, taking into account the impact of the adjacent tubes in the panel by consider the periodic surface for computational domain sides. Each tube was estimated separately, utilizing the conditions at the outlet of each tube as the inlet conditions for the tube of the next panel down flow. The air surrounded the tubes was simulated as an ideal gas. The computational domain utilized to simulate the flow and the radiation for each tube, occupies a rectangular cuboid of dimensions: $9m \times 0.027m \times 0.5232m$ ($H \times B \times L$), as shown in Figure 4.1, the model analyzed utilizing CFD software of Fluent 15, and the model is carried out to run on desktop workstations equipped with 6/12 CPU cores, 15 M Cache, up to 3.50 GHz (Intel®I7-3970X CPU @3.5GHz), with using parallel computing processing, which means the computations of the model, distributed on 12 working units to decrease the running time.

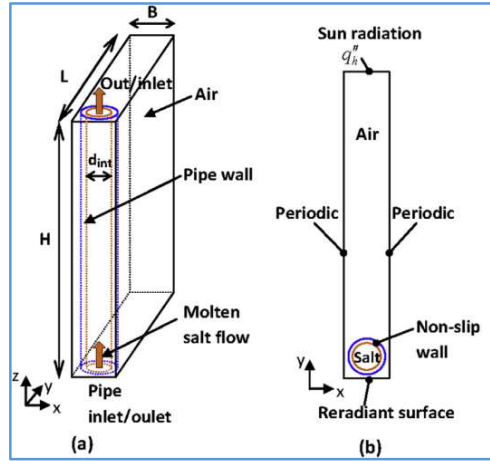


Figure 4.1 Sketch of the computational domain for CFD simulations [37]

The domain includes the tube, the reradiating wall of the tower receiver and the air surrounding the tube.

4.1.2 FLUENT Boundary Conditions and Settings

The domain was discretized using an unstructured mesh and hexahedral cells. And the physical model is generated by Gambit 2.4, Referable to the large aspect-ratio of the domain the size of the grid is of order of 10^6 cells.

A grid-refinement study was implemented on the model and appeared that 2,140,200 polyhedral elements are involved. The great number of elements results from delivering a refined boundary layer between the external air domain and the receiver to assure proper heat transfer during simulation.

To simulate the influenced of the adjacent tubes, the periodic planes arranged to the sides of the computational domain, which can implement across translationally periodic boundaries, and then can be done by Creating Conformal Periodic Zones, which can assign periodicity to domain mesh by coupling a pair of face zones, thus accurate structured mesh was built as shown in Figure 4.2 to have identical node and face distributions, then we can create conformal periodic zone.

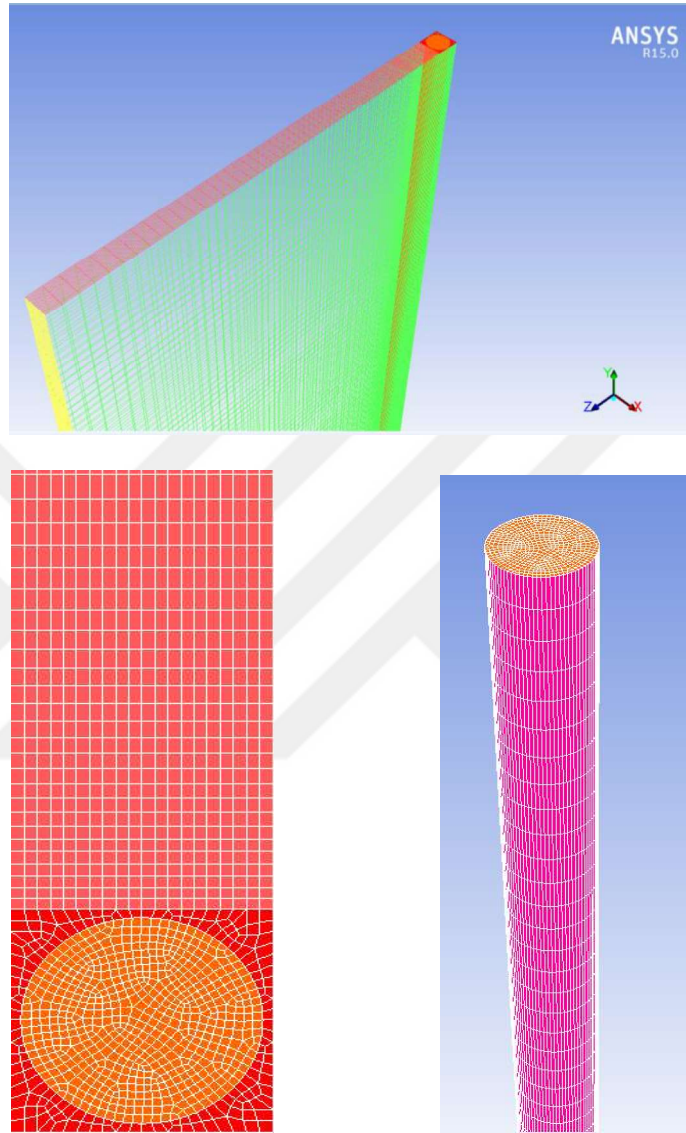


Figure 4.2 Sketch of the mesh structure

To simulate the radiation between the tube surface, the reradiating wall and the surroundings, the Discrete Ordinates model was chosen. The turbulent model used to simulate the molten salt behavior and utilize Standard realizable $k-\epsilon$ model. Enhanced Wall Treatment was used to solve the flow near the walls. An implicit method was selected to solve the Navier Stokes and the energy equations, and a second-order discretization was chosen for the convective terms. A scheme from the family of the

SIMPLE algorithms was used for the coupling of the Pressure and velocity of each fluid.

At the inlet of each tube the mass flow rate and temperature of the molten salt was imposed. No-slip condition was assumed on the walls of the tubes. Pressure-outlet at the outlet of the tube and pressure-inlet at the front side of the cuboid were imposed. To simulate the radiation received by each tube, an effective external blackbody temperature, $T_{bb}(n_{bl})$, was also assumed on nine axial blocks of the front side of the cuboid, so that $\sigma T_{bb}(n_{bl})^4$ reproduced the values of the irradiation map of Figure 3.24. That means that the temperature of the equivalent black body was a function of the height as well as the panel considered. Implicit in this equivalent blackbody temperature is the fact that the irradiation from the heliostats is much higher than from atmosphere and the land.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presented the important final optimizations to form the final layout of heliostat field. Further, find the optimal number of strips and their height, which rises to multi-level depending on the previous derivative analytical model from the previous chapter, to increase the performance of heliostat field.

Furthermore, study the performance of the new algorithm to compute the optical efficiency of the heliostat field, and present the thermo economical optimization of the number of heliostats for solar fields.

Another objective in writing this chapter has been to present adequate analysis expressions to study the potentiality of concentrating solar power by (CRS) plants in the new born Turkey green energy market, added to the original location.

5.1. Optimization of the Field Layout

Any ideal layout evaluation should depend on the annual energy that reaches the receiver. Thus, evaluations of the different layouts are checked by forming multiple distribution layouts from Equations (3.23) and (3.24), by changing the (a, b) parameters, which, depending on a Noone et al. model. [5], therefore have (a, b) considered as design variables of field layouts, where the best value of (a, b) must be estimated by using an optimization algorithm. The limits of (a, b) assume [2,8] and [0.4,0.7], respectively. A feature of the created layout, which is larger than the reflector number for the needed range uses Equations. (3.23) and (3.24). Every optimization starts with 5000 heliostats. Thus, the specific trimming of the field applies to find the best layout of 2650.

The layout is the conclusion of the needed collector field size to achieve the dedicated plant design power at the design point time. However, this code, for comparison with the case study model, selected the best 2650. The main conditions, the distance between the heliostat and its neighbors, need to be specified and be addressed before

of optical efficiency (including ($\eta_{s\&b}$)), and each 21st of the month during the year, then calculating from Equation (3.26) and for all 5000 heliostats, then selecting the 2650 heliostats with the best performance.

Today, GA is one of the most efficient methods for optimization. The first step is constructing the population based on the chromosomes, a good result obtained with a large number of chromosomes as well as 100 chromosomes used, without increasing the execution time. Each chromosome consists of two variables, and the execution time is evaluated according to the values of these variables.

The population in each generation is represented by 100 x 3 matrixes, where each row represents the variable values, and the last column (column three) represents the fitness values (F) which represent($\eta_{year, Eb}$) .

[illegible]

Random values of the design variables are created and go on until the highest value of $(\eta_{year, Eb})$ is recorded using (GA) optimization, and the optimal field layout is shown in Figure 5.1, where the corresponding a and b parameters are 3.55 and 0.675, respectively, demonstrating 2650 heliostats in this layout.

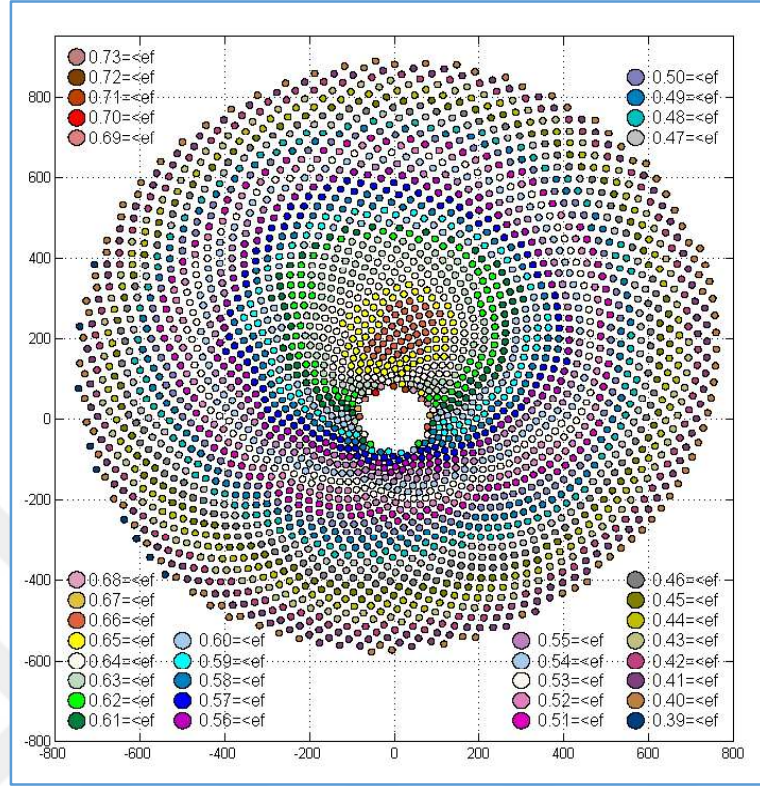


Figure 5.1 Layout of the field and $\eta_{year,Eb}$ for each heliostat

5.1.1. Computational Benchmarking for Heliostat Field Efficiency

The first comparison is targeted by computing the value of the field efficiency in GEMASOLAR with modeling results of Collado et al. [10], depending on the same reference data, and considering the same model of solar radiation, where the values of solar radiation of the Collado et al. [10] started from (15°) of sun elevations over horizontal. Even more than (15°), some values range from (17°), and end at noon, and shorthand all year by 35 steps at a time. The comparison shows that the result (57.3693%) are very close to the published data of Collado et al. [10], which equal (57.232%).

In order to increase the reliability, implement the same value of the parameters of Noone et al. [5], with same number of heliostats and locations. The results of unweighted heliostat field efficiency are obtained with the same Eq. (3.26), but without considering $E_b(t)$ in the computation; the result obtained in Noone et al. [5] is 64.3% and that obtained in the present study is 65.173%.

The new value of $(\eta_{year,Eb})$, (52.8589%) is recorded, when, this code started calculations from sunrise to sunset. Further, instant energy depended on the ASHRAE

Clear-sky Radiation Model [7] (which clarified previously in section (3.3)) for each 21st in a month during the year and from sunrise to sunset, and for step time (20 minutes), and the layout of the field is presented in Figure 5.1 where the corresponding (a, b) parameters are 3.55 and 0.675, respectively, which is explored with the design variables that are recorded by [5] and [20], which used the same heliostat area and layout, and compared to the layout suggestion in this study, as presented in the Table 5.1. The results show that a higher performance was obtained than others with new values of parameters, as shown in Table 5.1.

Table 5.1 Yearly weighted efficiency for different design variables			
	$a = 3.55$ and $b = 0.675$ present model	$a = 4.5$ and $b = 0.65$ [5]	$a = 3.935$ and $b = 0.7$ [20]
$\eta_{year, Eb}$	52.8589%	51.7604%	48.563%

5.1.2. Performance of Artificial Neural Networks (ANNs)

The second analysis targets the performance of computing $(\eta_{s\&b})$ by ANNs, and compares results with a discretization model with parallel computing. The performance of the network and the instantaneous error (that is, single time step) in calculating $(\eta_{s\&b})$ by ANNs can be seen in Figure 5.2, when several days are studied randomly during the year. Then, one day is chosen randomly, its sequence equal to 180, not within the days on which the network was trained to present the result that is based on computing $(\eta_{s\&b})$ during the day, from sunrise to sunset and every four minutes. A period is selected, different from the period fixed when the network was trained. The convergence noted between the results is shown in Figure 5.2.

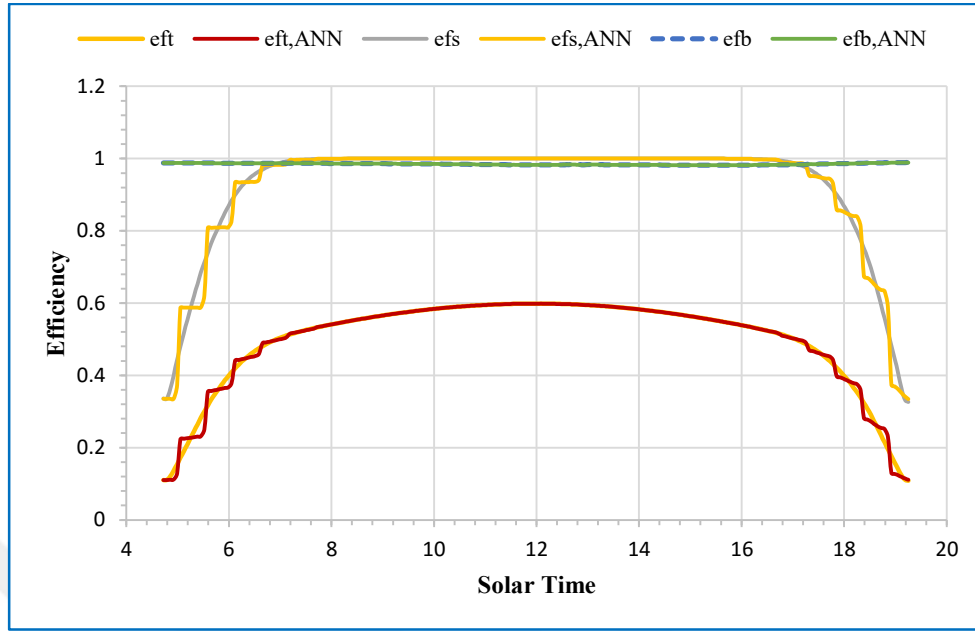
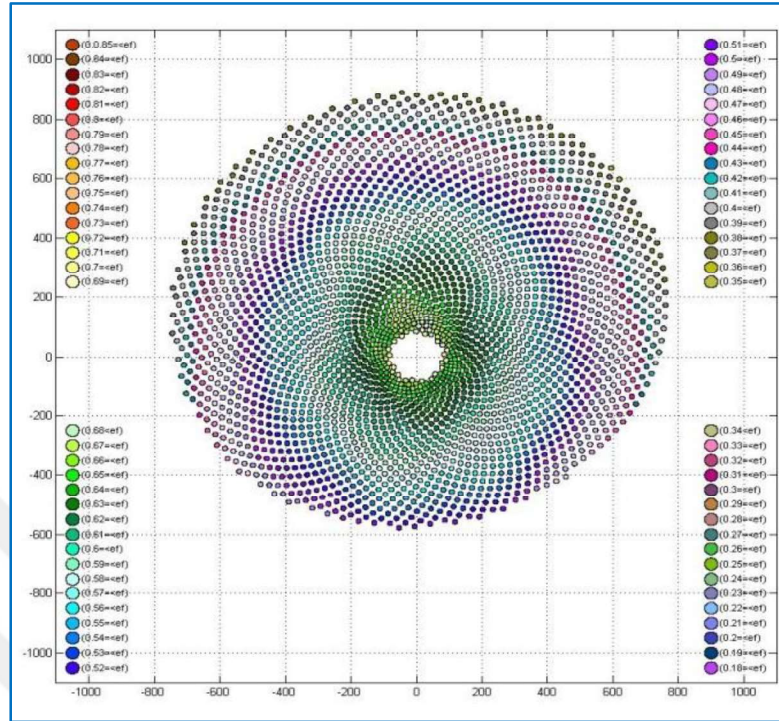


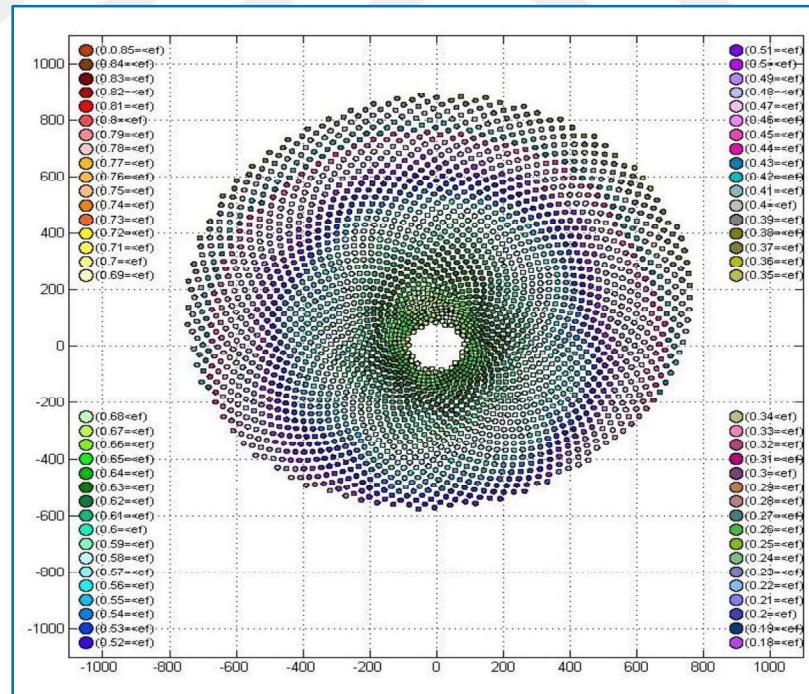
Figure 5.2 Different between ANNs and the discretization model, for computing the field efficiency (eft) and shadow efficiency (efs) and block efficiency (efb), for day 180 and every 4 minutes

Further, Table 5.2 shows the total values of efficiencies and all for field, for ANNs and the discretization model, throughout the day, while for the overall efficiency for each heliostat, for the same day is shown in Figure 5.3.

Table 5.2 The values of efficiencies during the day 180			
	Field Efficiency	Shadow Efficiency	Block Efficiency
ANNs	0.539321	0.97353	0.984169
Discretization Model with Parallel	0.539909	0.97457	0.984228



by discretization model



by ANNs

Figure 5.3 Field efficiency by discretization model and by ANNs

Two heliostats from the field (2640, 3006) are chosen and used to study ANNs performance, as seen in Figure 5.4, which presents their position as a red circle inside the figures

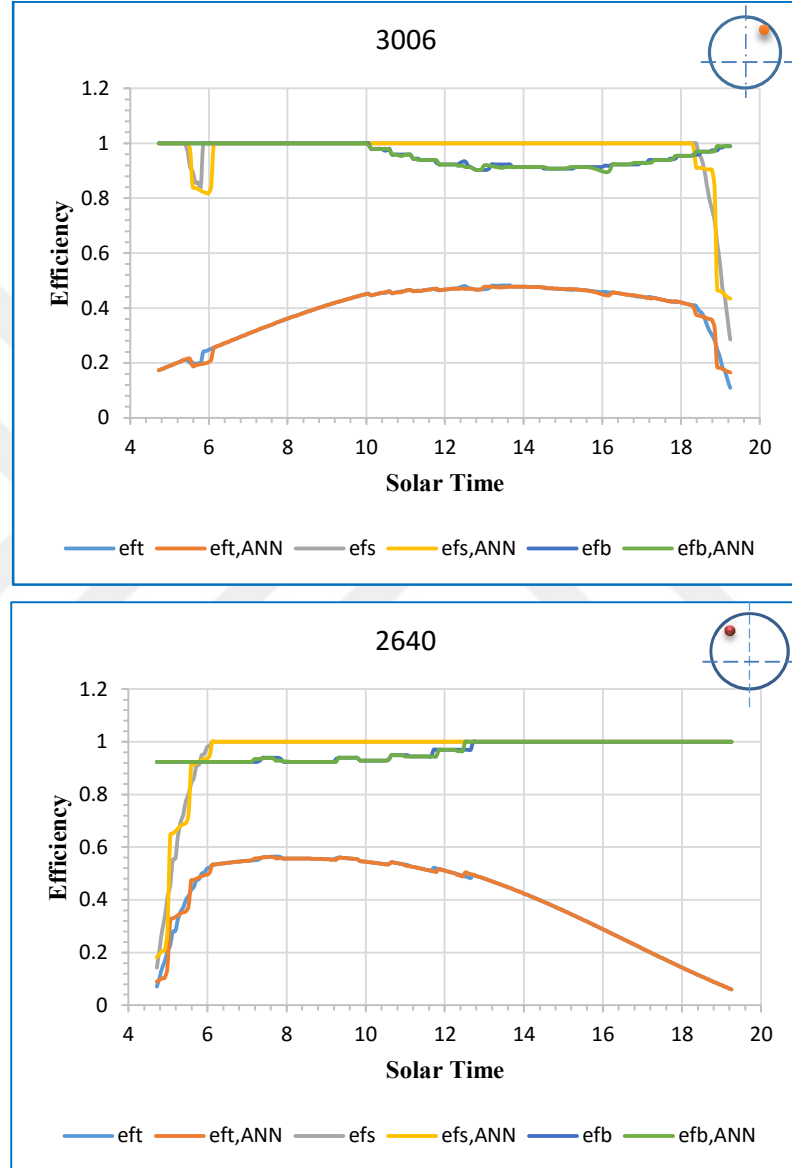


Figure 5.4 Different between ANNs and discretization model for computing efficiencies for heliostats (2640,3006)

Additionally, the implementation time for one- step has been reduced to 191.79 sec as shown in Table 5.3, which present The values of the implementation time (sec) for one- step for the different technique.

Table 5.3 The values of the implementation time (Sec) for one step with different techniques			
Discretization Model without Parallel	Discretization Model with Parallel	ANNs without Parallel	ANNs with Parallel
16750.045	2640.2844	573.909	191.79

5.1.3. Analysis of Increased Height for Certain Groups of Heliostats

As previously mentioned, the other objectives for this thesis is to study the increased height of specified strips of heliostats that are located farthest from the tower and exhibit the highest optical losses in the heliostat field. The main objective of this analysis is to determine the optimal number of strips with increased height. Figure 5.5 shows $\eta_{year,Eb}$ results for gradually and sequentially increasing the heights of different numbers of strips, where the first strip is farthest from the tower. Eight is shown to be the optimal number of strips in this heliostat field; after that, the value of ($\eta_{year,Eb}$) becomes approximately constant.

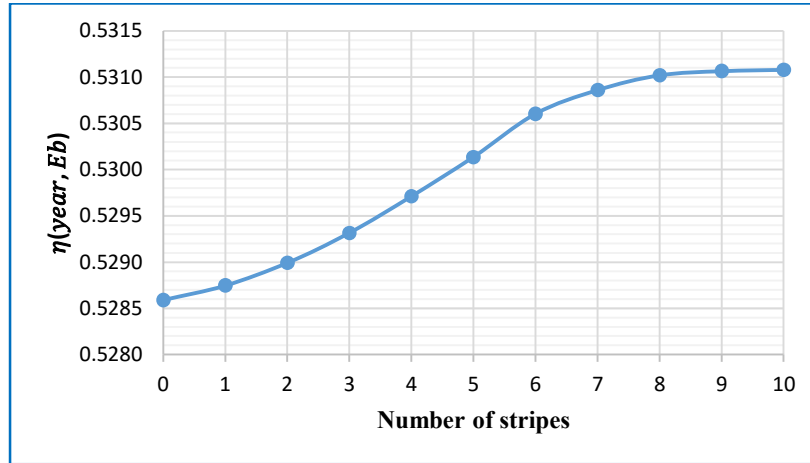


Figure 5.5 Mean yearly heliostat field efficiency $\eta_{year,Eb}$ with increasing the heights of different numbers of strips.

The reason for fixing $\eta_{year,Eb}$ is shown in Figure 5.6, which illustrates that the heliostat strips are formed of different lengths. In addition, strips in the farthest regions become similar to straight line, and a few circumvent the line because of the small number of heliostats they contain. As a result, the shadow losses in successive strips are very

small or nonexistent; as they get closer to the tower, the length of the strips begins to increase and assumes a horseshoe shape, as shown in Figure 5.6. These horseshoe-shaped strips begin to rotate around the field, and shadow losses increase as the strips get closer to the tower, until plateauing at eight strips.

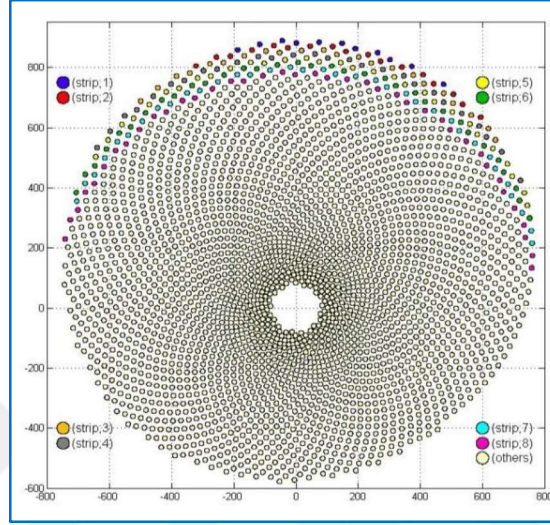


Figure 5.6 Eight heliostat strips encircling the center of the tower.

After increasing the heights of the eight strips based on Eq. (3.55), we noted an increase in the blocking efficiency of the eight strips, offset by increased shadow losses for heliostats placed in front of the strips, as well as a slight decrease in η_{cos} appear with increasing numbers of strips.

As a result of the increased heights of the eight strips, $\eta_{year,Eb}$ increased from 0.5286 to 0.5310, and the average increase in $\eta_{year,Eb}$ for each strip with increased height was in the range from 8.5% to 9.1%, as Table 5.4 shows. The overall efficiency of the proposed heliostat field is presented in Figure 5.7.

Table 5.4 Average increase in annual efficiency $\eta_{year,Eb}$ with increasing heights for successive strips								
Number of strips	1	2	3	4	5	6	7	8
Height difference (m)*	60.49	52.74	45.07	37.41	29.80	22.26	14.78	7.35
Number of heliostats in each strip	11	17	22	27	30	33	35	39
Average net increase in $\eta_{year,Eb}$	9.1%	9%	8.91%	8.85%	8.8%	8.7%	8.6%	8.5%
* Height difference (m) = increased height – height without increasing								

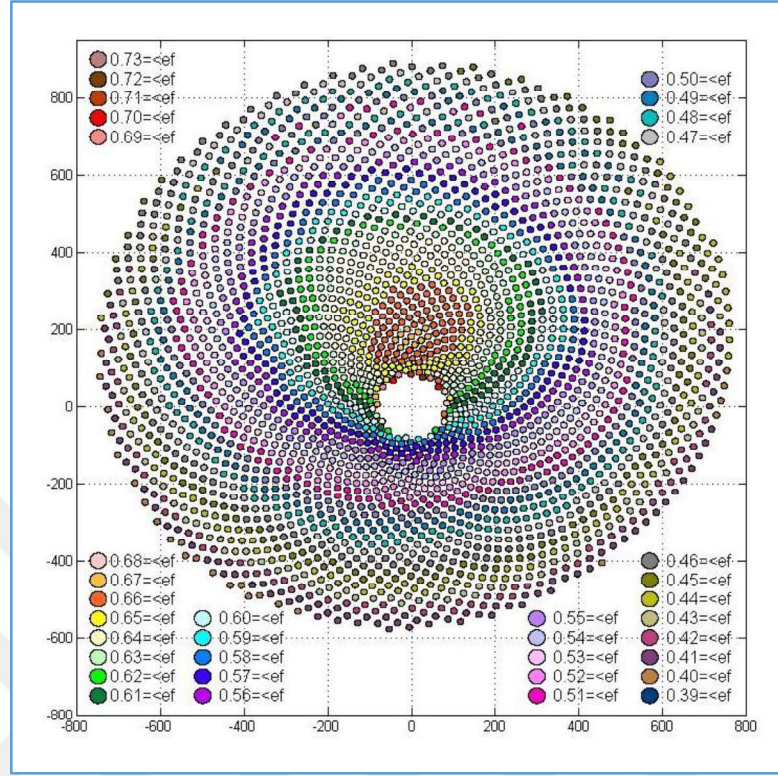


Figure 5.7 $\eta_{year, Eb}$ for the full heliostat field after increasing heights for eight strips.

5.1.4. A Thermo Economic Optimization Analysis.

For a typical solar heliostat field sizing problem using the cost data [50, 51], it is assumed that $i = 0.1$, $d = 0.1$, $C_N = 22500$ \$/m², $C_E = 0.01$ \$/(kW.hr), $M_S = 0$, $R_V = 0$, and $M=10$ years. The values of total net life cycle savings for this specific example are depicted in Figure 5.8. There exist specific local maximum saving points in this figure. The optimum number of heliostats is calculated as 803.5 and this value is close to heliostat field number for specific plants like Noone et al. [5] which about 624 for this sample problem, which is close to the optimum but not equal. This difference is normal since design of the system is generally not optimized. The optimum number of heliostats may change due to the optical efficiency of the field which strongly depends on tower height and the occupied area of heliostats exactly together with the distribution of the heliostats. The values of net life cycle savings with corresponding optimum number of heliostats, and solar thermal energy values are presented in Table 5.5. Payback period is calculated as 3.92 years by means of Eqn. (3.72) for this sample problem. On the other hand, critical number of heliostats is calculated as 1608 by using Eqn. (3.74) through Eqn. (3.76). There exist so many design tools such as computer

codes for designing the solar heliostats. These codes are not helpful for speedy estimation of optimum number of heliostats and they are used in industry. These computer codes select the standardized solar heliostats due to pre designed operating conditions by using solar thermal data without considering economics.

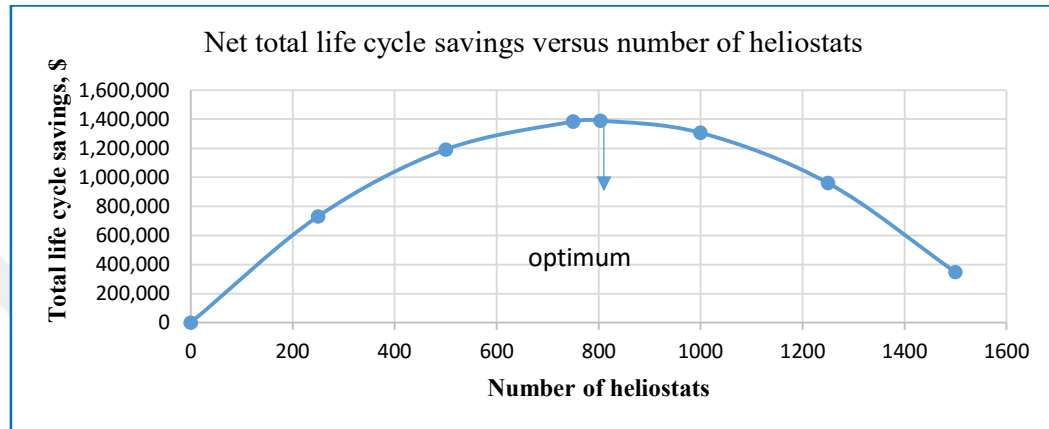


Figure 5.8 Total life cycle savings versus number of heliostats.

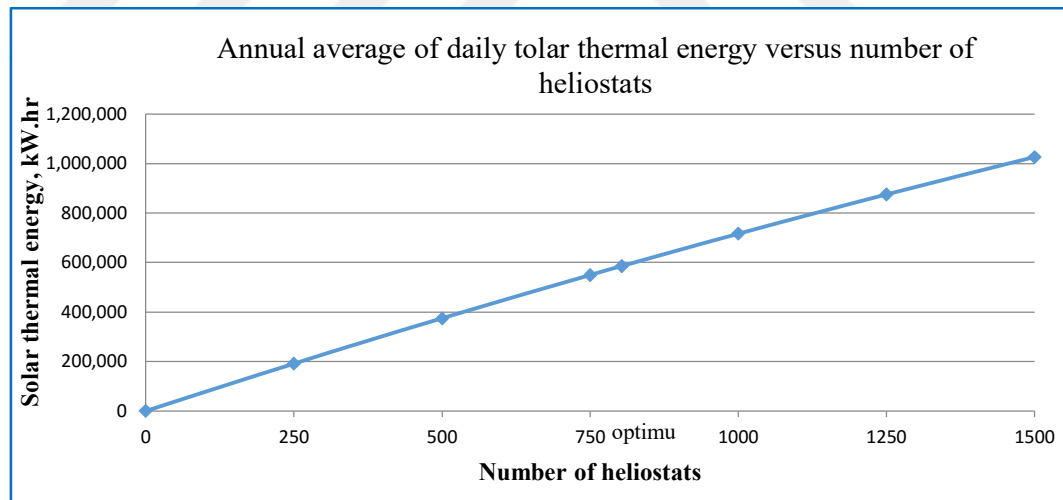


Figure 5.9 Annual average of daily total solar thermal energy versus number of heliostats.

N	250	500	750	803.5	1000	1250	1500
E(kW.hr)	191449	374715	549894	586332	716985	875989	1026905
S (\$)	731969	1192241	1383972	1390119	1307161	961808	347914

5.2. Solar Receiver.

5.2.1. Computational Benchmarking for Solar Receiver Efficiency and Performance

To validate a thermal model for the solar receiver, we compare the efficiency value at spring equinox-solar noon in Seville, Spain, with the experimental result of Ref. [41], considering the same condition and selecting the highest wind speed in the reference 6.4 m/s. The reference result is 85.6%, and the result in the present model result is 87.904%. By using another validation, the result shows the convergence with one of the results of Ref. [52] for different models of the receiver, who show an efficiency range of different model (77.4%–87.6%) and the last validation by estimate the distribution of the temperatures $T_{HTF}(i, j)$, and $T_{s,i,j}$ along the path flow of HTF which presented in Figure 5.10 That appears close to result of Ref. [62].

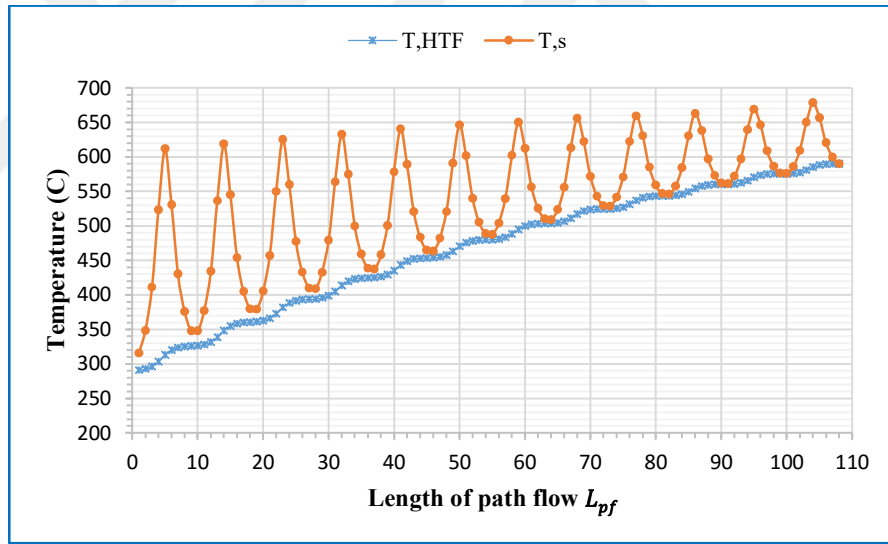


Figure 5.10 Temperatures of $T_{HTF}(i, j)$ and $T_{s,i,j}$ along length of path flow L_{pf}
(Analytic solution)

5.2.2. Numerical Simulation Result

In order to increase the reliability for a thermal model for solar receiver, we estimate the efficiency value at spring equinox-solar noon in seville at wind speed equal zero, with CFD model which clarified in chapter four, and the outcome of the numerical simulation record (84.8%) . It close to the theoretical solution with the same condition which equal (88.51%). At the same time comparison for Temperatures of T_{HTF} at output of each panel for path flow (north - west - south) and for (Analytic solution and

Numerical solution) presented in Figure 5.11 which shows strong convergence between the results

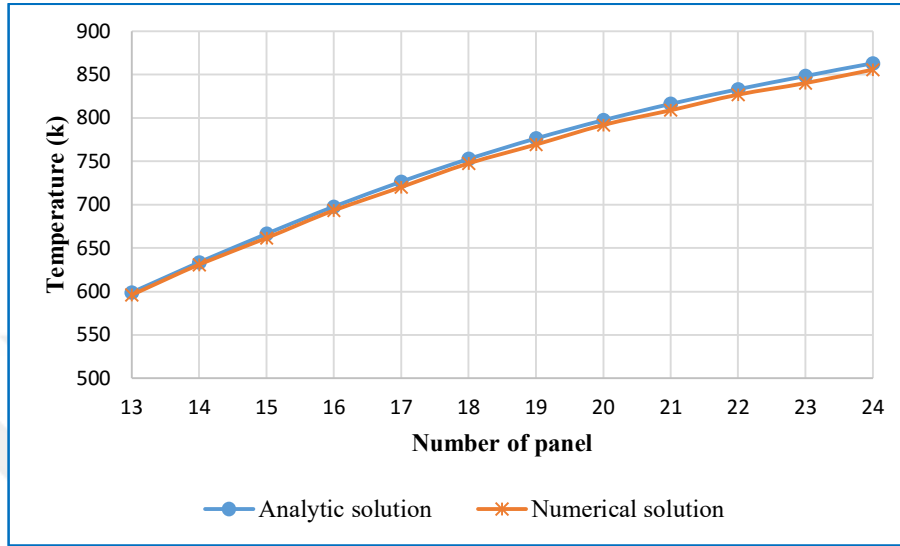


Figure 5.11 Temperature of T_{HTF} at output of each panel for path flow (north - west - south) and for (Analytic solution and Numerical solution)

5.3 Analysis of Simulating the (CRS) Behavior in Different Locations

Another main objective was to study the potential of concentrating solar power by (CRS) in new areas such as the south of Turkey (Gaziantep, Sanliurfa, and Finike), in addition to existing locations such as Gemasolar in Seville, Spain. The analysis focused on three energy conditions: the SPTPs input solar radiation $E_b(t)$, the output energy from the heliostat field $\dot{Q}_{inc}(t)$, and the output energy from the solar receiver $\dot{Q}_{abs}(t)$. A dynamic simulation developed in MATLAB was structured to focus on the performance of the heliostat field and solar receiver because these units are the parts of the plant that are most affected by the location conditions, including solar radiation, ambient temperature, latitude and longitude angles, and wind speed. In addition, the daily accumulated energy results for the 21st day of each month, from sunrise to sunset, were determined for each unit to clearly understand the SPTP unit's performance at each hypothetical location. The first location represents the original location of Gemasolar in Seville, Spain (Lat. 37.42N), which was considered as the reference in this study. Figure 5.12 presents the accumulated input and output energies for the heliostat field and receiver for 12 average days.

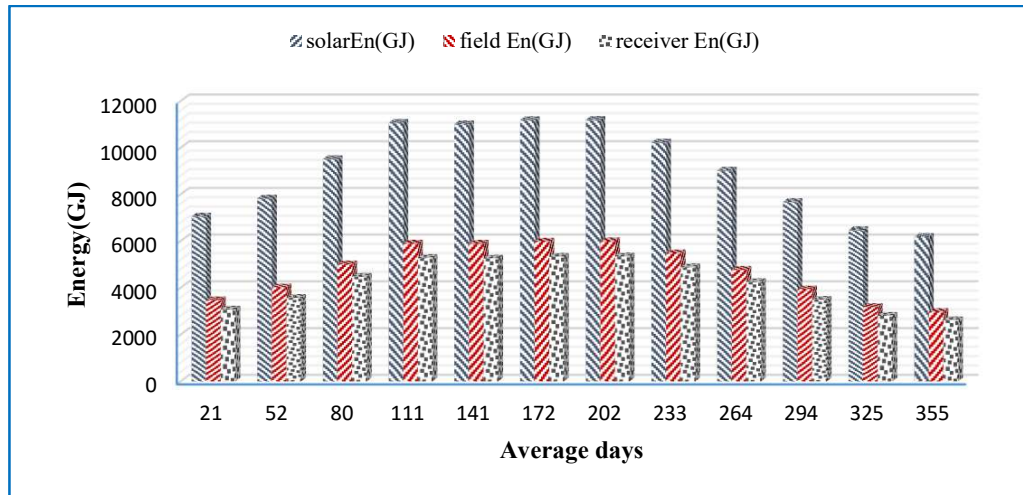


Figure 5.12 Accumulated solar energies transformed from the heliostat field and receiver for 12 average days in Seville, Spain.

The maximum value for the accumulated solar energies that; hit the heliostat field (11,199.098 G J) and that provided by heliostat field (5,994.431 GJ) and that provided by the receiver (5,346.6098 GJ) that transformed later into the electrical energy by Rankin cycle occurs at day 202, and the minimum occur on day 355, and the value of energies equal (6,183.71 GJ), (2,974.772 GJ), (2620.951 GJ) respectively.

Then, the rate of energy that is transformed during the same days for every (20 minutes), represented in Figure 5.13 and Figure 5.14

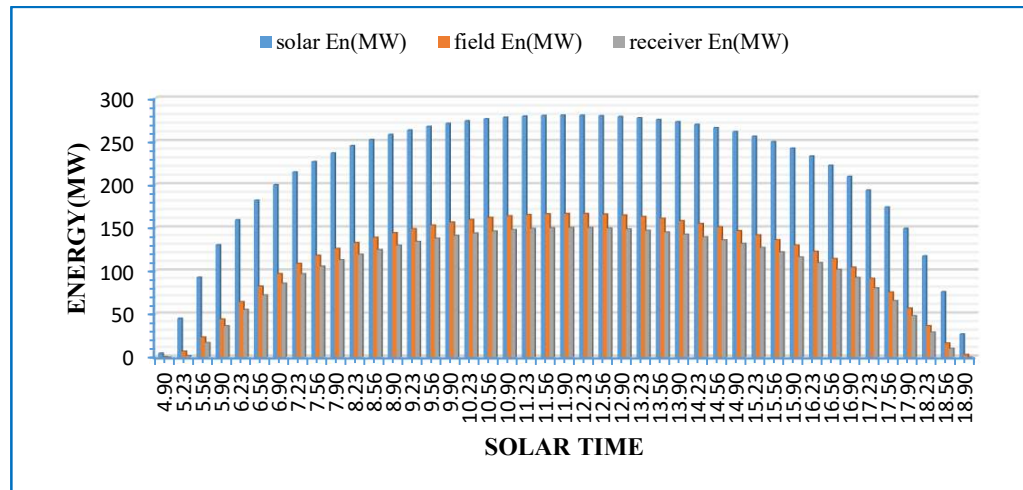


Figure 5.13 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 202 and for Seville –Spain.

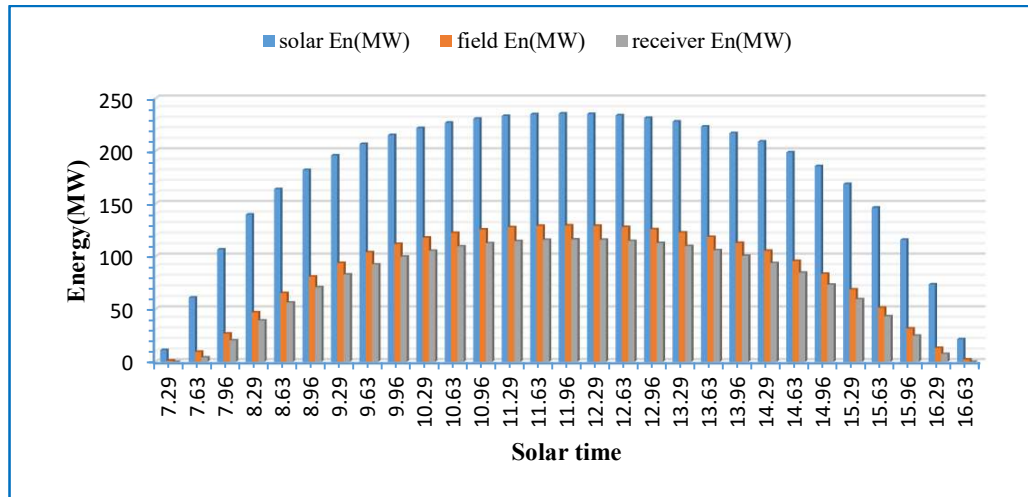


Figure 5.14 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Seville –Spain.

The maximum range for the rate of solar energies that; hit heliostat field (280.558 MW) and that provided by heliostat field (166.826 MW) and that provided by receiver (150.608MW)

The second location which targeting by this study to analysis the relocation of (CRS) represent (Gaziantep, Turkey) and as shown in Figure 5.15 which present the input and output accumulated energies for heliostat field and receiver for 12 average days.

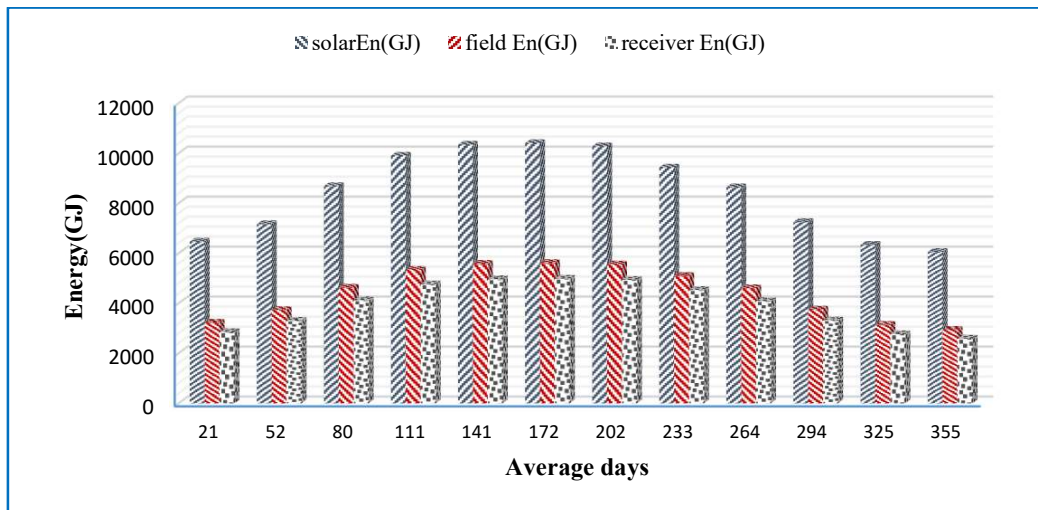


Figure 5.15 Accumulated energies for Gaziantep, Turkey

The maximum value for the accumulated solar energies that; hit the heliostat field (10,404.477 GJ) and that provided by heliostat field (5,608.469731 GJ) and that

provided by the receiver (4,986.824 GJ) that transformed later into the electrical energy by Rankin cycle occurs at day 172, and the minimum occur on day 355, and the value of energies equal (6,048.386 GJ), (2,936.521 GJ), (2,588.862 GJ) respectively.

Then, the rate of energy that is transformed during the same days for every (20 minutes), represented in Figure 5.16 and Figure 5.17

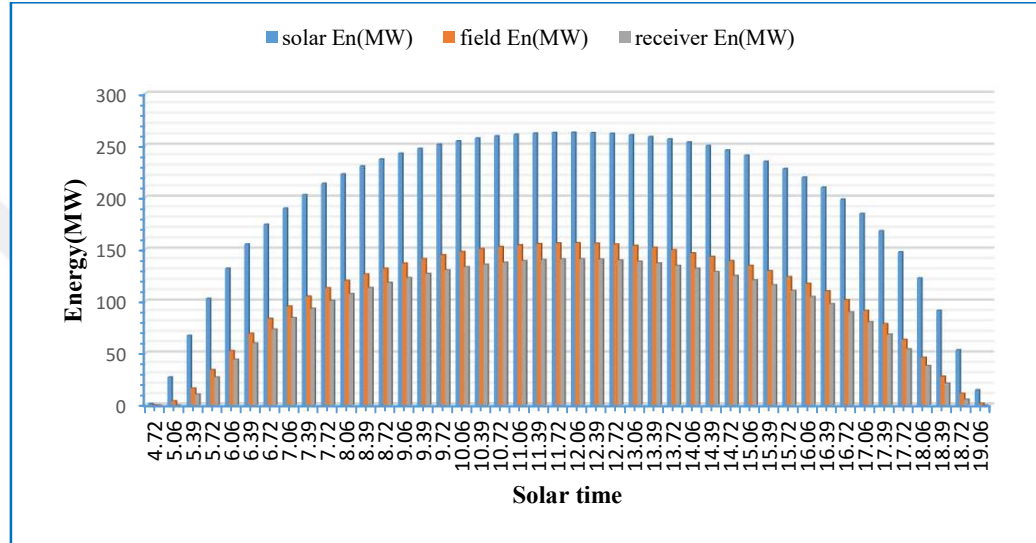


Figure 5.16 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 172 and for Gaziantep, Turkey.

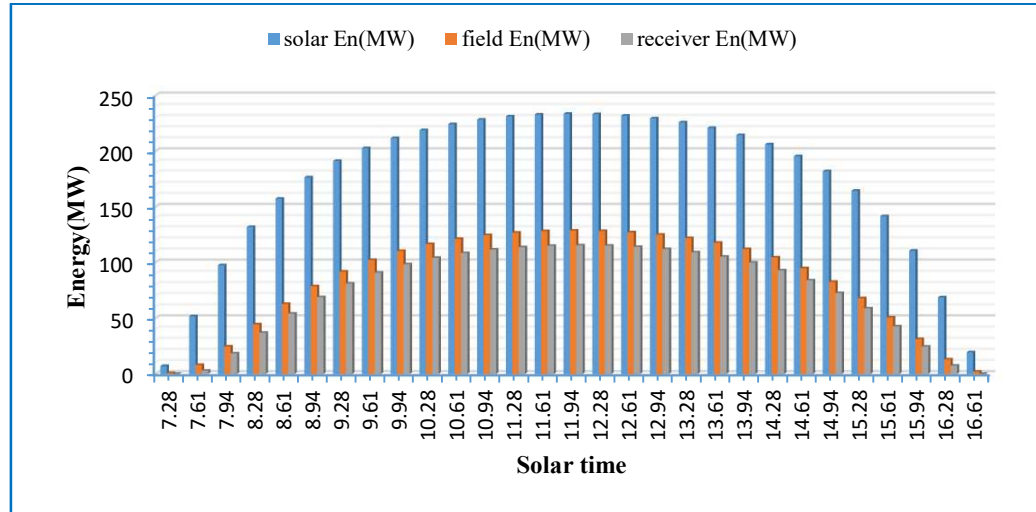


Figure 5.17 the power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Gaziantep, Turkey.

The maximum range for the rate of solar energies that; hit heliostat field (262.577 MW) and that provided by heliostat field (156.193 MW) and that provided by receiver (140.774MW).

The third location which targeting by this study to analysis the relocation of (CRS) represent (Sanliurfa, Turkey) and as shown in Figure 5.18 which present the input and output accumulated energies for heliostat field and receiver for 12 average days.

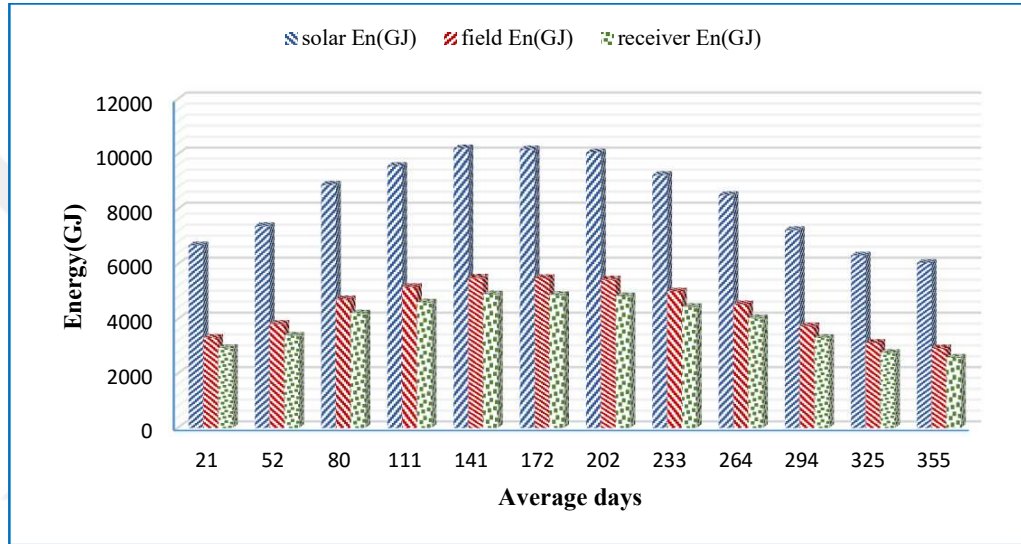


Figure 5.18 Accumulated energies for Sanliurfa, Turkey

The maximum value for the accumulated solar energies that; hit the heliostat field (10,215.199 GJ) and that provided by heliostat field (5,513.522 GJ) and that provided by the receiver (4,906.939 GJ) that transformed later into the electrical energy by Rankin cycle occurs at day 141, and the minimum occur on day 355, and the value of energies equal (6,048.048 GJ), (2,935.146 GJ), (2,587.289 GJ) respectively.

Then, the rate of energy that is transformed during the same days for every (20 minutes), represented in Figure 5.19 and Figure 5.20.

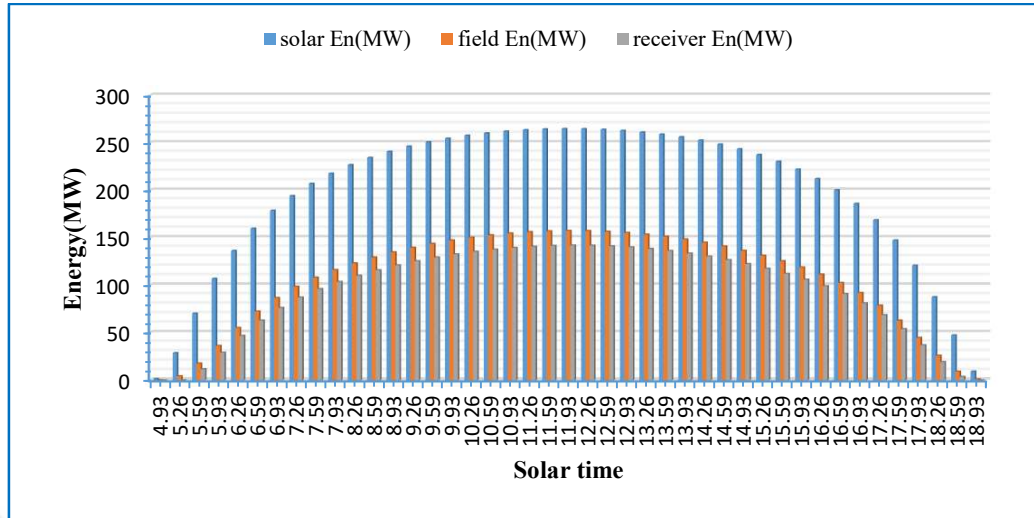


Figure 5.19 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 141 and for Sanliurfa, Turkey.

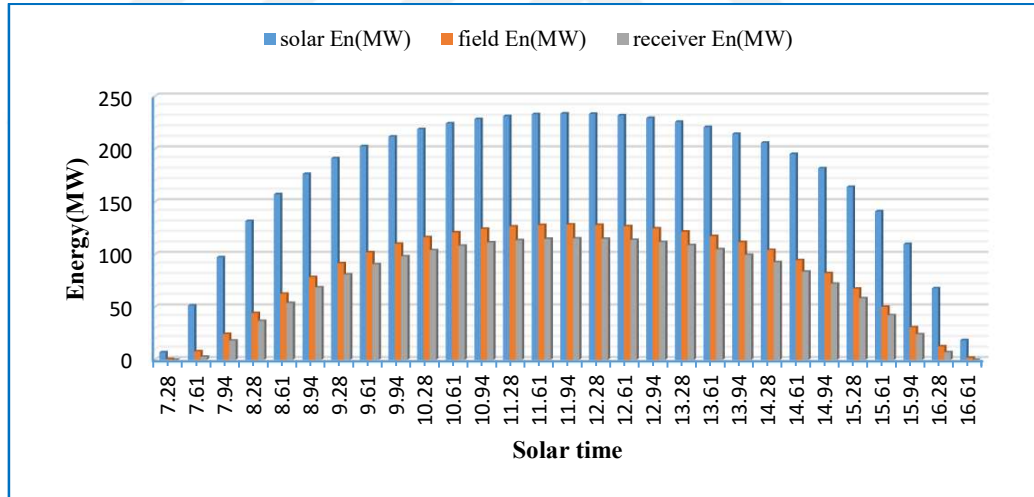


Figure 5.20 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Sanliurfa, Turkey.

The maximum range for the rate of solar energies that; hit heliostat field (264.84 MW) and that provided by heliostat field (157.47 MW) and that provided by receiver (142.04MW).

The fourth location which targeting by this study to analysis the relocation of (CRS) represent (Finike, Turkey) and as shown in Figure 5.21 which present the input and output accumulated energies for heliostat field and receiver for 12 average days.

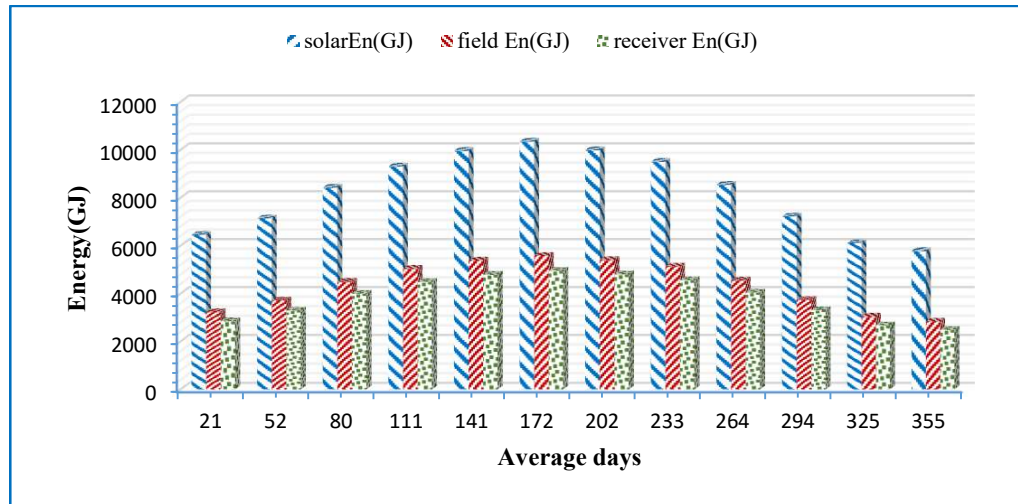


Figure 5.21 Accumulated energies for Finike, Turkey

The maximum value for the accumulated solar energies that; hit the heliostat field (10348.10 GJ) and that provided by heliostat field (5568.34 GJ) and that provided by the receiver (4950.83 GJ) that transformed later into the electrical energy by Rankine cycle occurs at day 172, and the minimum occur on day 355, and the value of energies is equal to (5777.92 GJ), (2828.83 GJ), (2484.93 GJ) respectively.

Then, the rate of energy that is transformed during the same days for every (20 minutes), represented in Figure 5.22 and Figure 5.23.

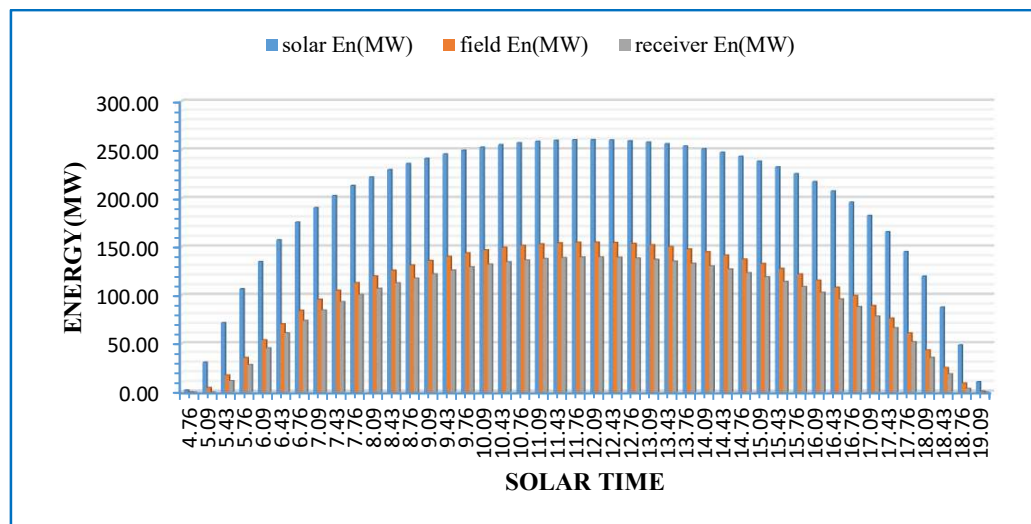


Figure 5.22 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 172 and for Finike, Turkey.

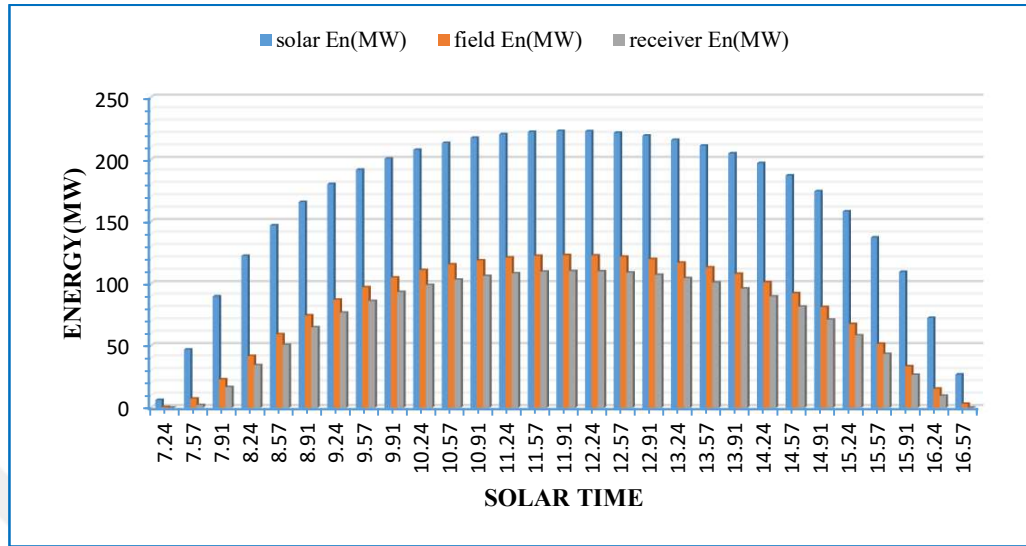


Figure 5.23 The power; that is applied on the heliostat field, and that transformed from heliostat field and the receiver every 20 minutes and for day number 355 and for Finike, Turkey.

The maximum range for the rate of solar energies that hit heliostat field is (260.50 MW), and that provided by heliostat field is (154.96 MW), and that provided by receiver is (139.67MW).

At the same time Tables 5.6, 5.7, 5.8, 5.9 presented The Accumulated mass of HTF during the day (kg) in the storage, thermal, the Mass flow rate of HTF during the day (kg/s) to the heat exchanger of power block, The Power transferred (kW), The Mass flow rate of the steam during the day (kg/s), and Power generated (MW).

Table 5.6 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Seville –Spain

Day Number	Accumulated mass of HTF during the day (kg)	Mass flow rate of HTF during the day (kg/s)	The Power transferred (kW)	Mass flow rate of the steam during the day (kg/s)	Power generated (MW)
21	6636909.02	76.816	35590.847	14.610	12.165
52	7706889.23	89.200	41328.684	16.965	14.127
80	9660394.46	111.810	51804.480	21.265	17.708
111	11394300.5	131.878	61102.662	25.082	20.886
141	11347618.6	131.338	60852.327	24.979	20.800
172	11505888.1	133.170	61701.058	25.327	21.090
202	11539640.6	133.561	61882.057	25.402	21.152
233	10540897.5	122.001	56526.234	23.203	19.321
264	9173406.4	106.174	49192.976	20.193	16.815
294	7531031.18	87.165	40385.634	16.578	13.804
325	6059210.14	70.130	32492.900	13.338	11.107
355	5656823.1	65.472	30335.074	12.452	10.369

Table 5.7 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Gaziantep, Turkey.

Day Number	Accumulated mass of HTF during the day (kg)	Mass flow rate of HTF during the day (kg/s)	The energy transferred (kW)	Mass flow rate of the steam during the day (kg/s)	Power generated (MW)
21	6153063.239	71.216	32996.193	13.544	11.279
52	7128226.452	82.503	38225.568	15.691	13.066
80	8892660.827	102.924	47687.460	19.575	16.300
111	10275614.04	118.931	55103.634	22.619	18.835
141	10714895.99	124.015	57459.312	23.586	19.640
172	10763110.48	124.573	57717.865	23.692	19.729
202	10658396.54	123.361	57156.330	23.462	19.537
233	9777316.09	113.163	52431.480	21.522	17.922
264	8826199.02	102.155	47331.054	19.429	16.178
294	7161289.786	82.885	38402.872	15.764	13.127
325	5972656.362	69.128	32028.750	13.147	10.948
355	5587565.249	64.671	29963.674	12.300	10.242

Table 5.8 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Sanliurfa, Turkey

Day Number	Accumulated mass of HTF during the day (kg)	Mass flow rate of HTF during the day (kg/s)	The energy transferred (kW)	Mass flow rate of the steam during the day (kg/s)	Power generated (MW)
21	6349596.98	73.491	34050.118	13.977	11.639
52	7339244.62	84.945	39357.166	16.156	13.453
80	9096167.47	105.280	48778.777	20.023	16.673
111	9952321.28	115.189	53369.956	21.908	18.243
141	10590694.5	122.577	56793.273	23.313	19.413
172	10538723.6	121.976	56514.576	23.198	19.318
202	10445367.7	120.895	56013.949	22.993	19.146
233	9600525.37	111.117	51483.428	21.133	17.598
264	8710825.34	100.820	46712.355	19.175	15.967
294	7159187.79	82.861	38391.600	15.759	13.123
325	5960389.47	68.986	31962.968	13.120	10.925
355	5584170.62	64.632	29945.470	12.292	10.236

Table 5.9 Accumulated mass of HTF in the thermal storage and flow rate of HTF transferred to the power block with power generated in Finike, Turkey					
Day Number	Accumulated mass of HTF during the day (kg)	Mass flow rate of HTF during the day (kg/s)	The energy transferred (kW)	Mass flow rate of the steam during the day (kg/s)	Power generated (MW)
21	6143996.24	71.111	32947.57	13.52	11.26
52	7093185.29	82.097	38037.66	15.61	13.00
80	8620585.57	99.775	46228.44	18.98	15.80
111	9673741.33	111.965	51876.05	21.29	17.73
141	10324218.37	119.493	55364.28	22.73	18.92
172	10685426.10	123.674	57301.28	23.52	19.59
202	10353447.74	119.832	55521.02	22.79	18.98
233	9836297.41	113.846	52747.77	21.65	18.03
264	8723188.70	100.963	46778.65	19.20	15.99
294	7130818.18	82.533	38239.47	15.70	13.07
325	5769458.91	66.776	30939.09	12.70	10.58
355	5363254.76	62.075	28760.8	11.81	9.83

For all locations, the total field and receiver efficiencies for total duration of the accumulated solar energies are as shown in Tables 5.10.

Table 5.10 Field and receiver efficiencies for each city				
Location	Seville, Spain	Gaziantep, Turkey	Sanliurfa, Turkey	Finike, Turkey
Field efficiency	0.529	0.534	0.534	0.534
Receiver efficiency	0.890	0.888	0.888	0.887

Finally, as we have already noted, the main reference Gemasolar in Seville, Spain, exhibits the best SPTP potential energies. With regard to the other selected cities in Turkey, the results show that the SPTP will exhibit the best performance in Gaziantep, as shown in the previous figures and in Figure 5.24, which presents the total

accumulated solar energies for all 12 days for each different location. For all the cities in Turkey, the results are close in terms of field efficiency the lowest field efficiency value was exhibited in Seville, Spain, and the lowest receiver efficiency was exhibited in Finike ; however, this SPTP in Seville exhibits the highest receiver efficiency value with the highest solar radiation, and Seville is therefore the best SPTP location investigated in this study.

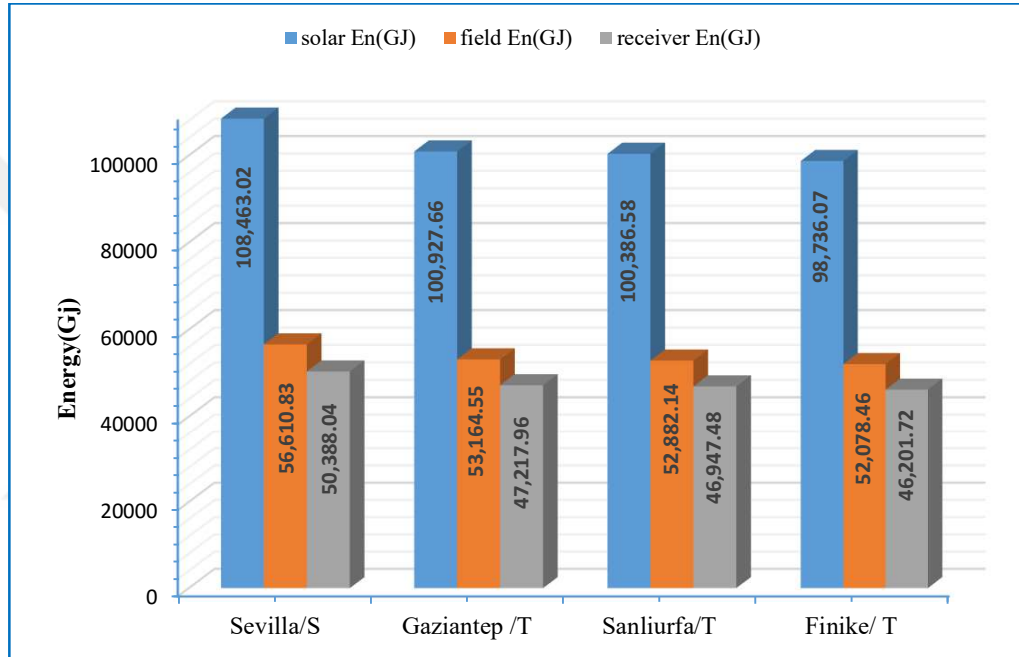


Figure 5.24 Total accumulated solar energies for all 12 days at different locations

CHAPTER 6

CONCLUSION

6.1. Findings

In this study, an accurate model of computing ($\eta_{s\&b}$) was first developed, known as “the discretization model.” At the same time, using this model, we cut out superfluous computations for heliostats that are not considered in shading or blocking causes and that lead to improving the computational time. However, the model is still considered the slowest model. Therefore, the operations have been speeded up by maintaining a high accuracy in calculations on three levels. First, by using the parallel computing with a workstation computer; second, by using the artificial neural networks; third, by using the artificial neural networks with parallel computing with a workstation computer. This scheme leads to reduced implementation time on the same workstation computer. With this methodology and accuracy, processing times for this estimate that usually take several hours can be reduced to a matter of minutes by using this technique (from 4.6528 hours to 3.197 minutes). Two factors are responsible for the scheme of the layout of the field, and these factors are handled as the forming variables, where the best values are estimated by using an optimization algorithm while improving the annual efficiency ($\eta_{year,Eb}$) when chosen as a target. Benchmarking with the previous study, a clarified higher efficiency than that estimated by others, and displaying the new model can estimate the ($\eta_{s\&b}$) precisely with a low implementation time.

On the other hand, it can be deduced that there exists always a local maximum number of heliostats in solar field applications. Excessive number of heliostats will not be cost effective beyond the optimum values in spite of a greater solar thermal energy production potential. The number of heliostats of solar fields has dominant effect on the amount of total life cycle earnings of such systems. It is clear that there exist good thermal and economic performances all together at the optimum point for solar heliostat systems. These systems must be designed close to this optimum point.

The present formula may seem to be helpful for solar heliostat system designers and manufacturers. Furthermore, a novel geometrical equation presented for the purpose of optimizing the heliostat field layout by increasing the height of specified heliostats exhibiting the lowest optical.

Changes in heliostat levels with no blocking consideration are investigated, and heliostat located farthest from the tower's central receiver is considered. The results showed that the proposed layout increases the overall $\eta_{year, Eb}$ from 52.86% to 53.10%, and selected heliostat strips increased in the range between 8.5% and 9.1%.

After that, the performance was compared based on the cumulative energies of the units under investigation, using Gemasolar as a reference. A comparison of these results showed that among the accumulated energies of the heliostat field and receiver for areas in the south of Turkey (Gaziantep, Sanliurfa, and Finike), the highest accumulated energy was exhibited in Gaziantep, after the reference location in Seville, Spain, and the minimum accumulated energy was exhibited in Finike, Turkey. On the other hand, the field efficiency for all locations tested in Turkey is equal or higher than the reference location. Further, the highest value for receiver performance occurred in Seville, Spain, compared to the values in Gaziantep and Sanliurfa, and the minimum value occurred in Finike, Turkey. Further, the result shows that the highest net output energy in Gaziantep city in Turkey was less than the reference case by about 6.71%.

6.2. Recommendations for Future Work

This section describes suggestions for further work that could be done in this field of research should it be continued. Further work can be done on both the field analysis model, for heliostat field and solar central receiver. A useful addition to the analysis model would be the consideration of different shapes of heliostats with the spiral patterns which used in the distribution of the heliostats. This could include circular or rhombus shapes for heliostats, which may reduce the extent of blocking and shading and allow for a more densely packed field.

The other Research points which recommended to study, is the study of the effect of a tilt angle of the solar recipient panels toward the solar field, on the solar field and central receiver performance, because the improvement may be achieved in the field efficiently, but the opposite may occur in the central receiver because of the increased surface area for heat transfer, then this variable could be added to the optimization by making the analysis model a function of this variable.

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APPENDIX (A)

Climatic design conditions [ASHRAE Handbook (2013)]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Day of year	21	52	80	111	141	172	202	233	264	294	325	355
SEVILLA, Spain			Lat:37.42N		Long:5.9W		Elev:31		Extreme Annual WS: 6.9 m/s			
τ_h	0.347	0.369	0.371	0.362	0.388	0.387	0.392	0.410	0.406	0.376	0.365	0.366
τ_d	2.556	2.462	2.434	2.401	2.303	2.293	2.294	2.259	2.324	2.476	2.532	2.538
DB	17	19.8	24	26.1	30.8	35	38.3	37.7	34	28.1	22.1	18
MCDBR	12	13	15.6	15.8	17	17.3	18.3	17.7	16.2	13.4	11.6	9.1
GAZIANTEP, Turkey			Lat:37.08N		Long:37.37E		Elev:701		Extreme Annual WS: 6.3 m/s			
τ_h	0.375	0.401	0.413	0.424	0.421	0.426	0.439	0.453	0.423	0.397	0.367	0.365
τ_d	2.292	2.163	2.136	2.095	2.099	2.064	2.037	2.021	2.146	2.276	2.401	2.392
DB	10.6	12.8	18.1	23.8	29.9	34.7	37.9	37.8	33.8	28	19.8	12.7
MCDBR	11.3	11.9	13.8	15.2	16.4	15.2	15.1	15.3	16.3	15.9	15.1	12.3
SANLIURFA, Turkey			Lat:37.13N		Long:38.77E		Elev:549		Extreme Annual WS: 4.5 m/s			
τ_h	0.362	0.387	0.4	0.444	0.428	0.439	0.451	0.463	0.429	0.395	0.366	0.364
τ_d	2.366	2.234	2.189	2.029	2.065	2.005	1.978	1.966	2.105	2.26	2.389	2.39
DB	12.4	14.8	20.7	25.2	32	37	40.9	39.8	35.2	29.9	22.2	14.4
MCDBR	9	10.1	11.5	12.3	13.2	13.3	14.1	13.4	13.5	12.4	11.5	9.3
FINIKE, Turkey			Lat:36.30N		Long:30.15E		Elev:2		Extreme Annual WS: 3.9 m/s			
τ_h	0.398	0.422	0.444	0.469	0.450	0.435	0.464	0.458	0.443	0.417	0.405	0.406
τ_d	2.377	2.262	2.180	2.050	2.111	2.154	2.085	2.140	2.224	2.360	2.420	2.389
DB	17	17.6	20.2	23.1	27.4	33.7	35.5	35.9	31.7	27.6	22.5	19
MCDBR	8.7	8.6	9.4	10.8	11	12.9	12.7	12.4	11.4	10.3	9.5	8.9

Table 4 fraction of daily temperature range[ASHRAE handbook (2013)]

Time, h	fraction	Time, h	fraction	Time, h	fraction
1	0.88	9	0.55	17	0.14
2	0.92	10	0.38	18	0.24
3	0.95	11	0.23	19	0.39
4	0.98	12	0.13	20	0.50
5	1	13	0.05	21	0.59
6	0.98	14	0	22	0.68
7	0.91	15	0	23	0.75
8	0.74	16	0.06	24	0.82

APPENDIX (B).

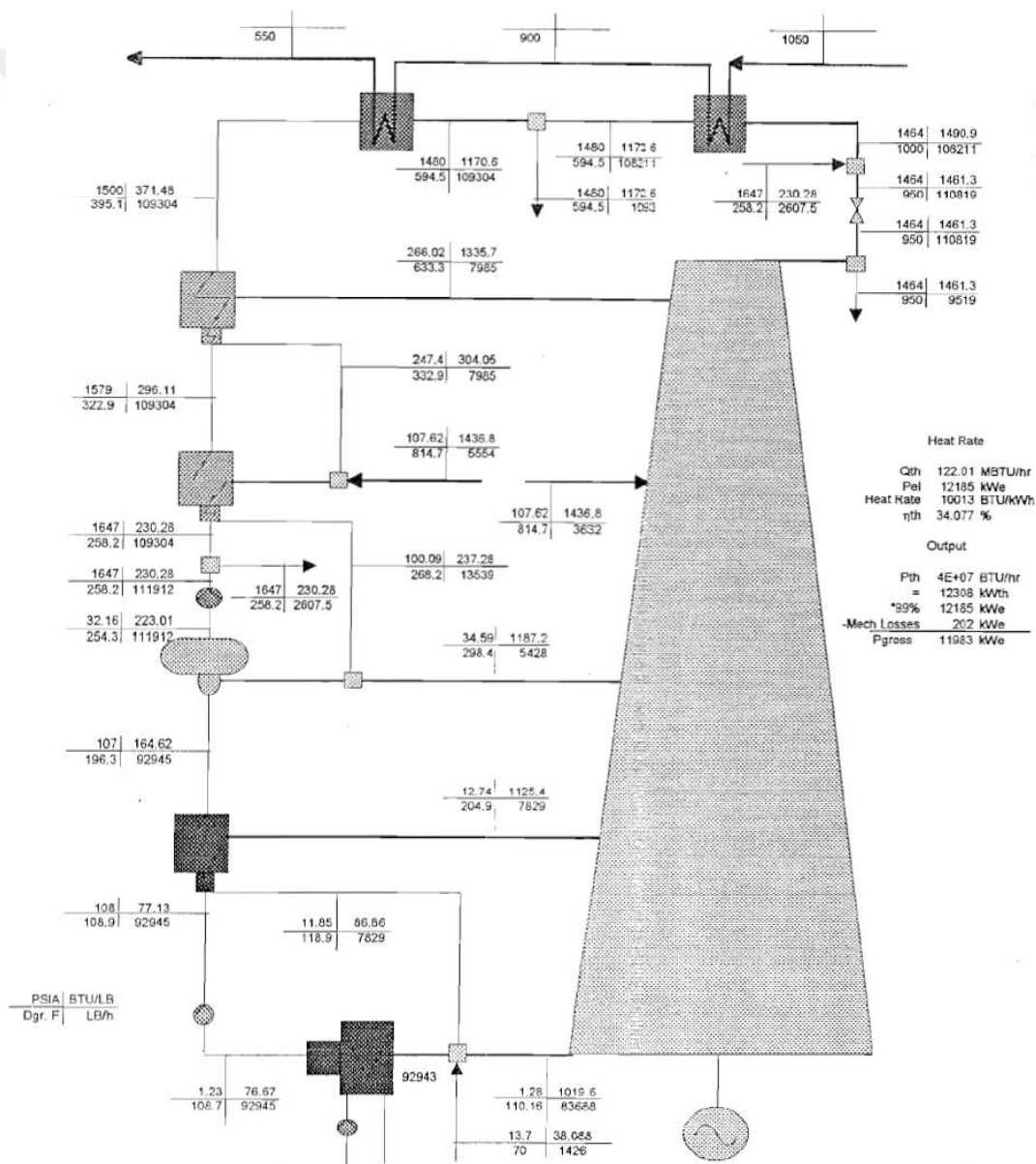
Thermal Properties for pipe material

Temperature	Electrical Resistivity	Thermal Conductivity	Coefficient of Expansion ^a
°F	ohm•circ mil/ft	Btu•in/ft ² •h°F	10 ⁻⁶ in/in°F
70	595	80	-
100	600	83	-
200	620	89	7.9
400	657	103	8.8
600	682	115	9.0
800	704	127	9.2
1000	722	139	9.4
1200	746	152	9.6
1400	758	166	9.9
1600	770	181	10.2
1800	776	214	-
2000	788	-	-
°C	μΩ•m	W/m°C	μm/m/°C
20	0.989	11.5	-
100	1.035	13.0	14.4
200	1.089	14.7	15.9
300	1.127	16.3	16.2
400	1.157	17.9	16.5
500	1.191	19.5	16.8
600	1.223	21.1	17.1
700	1.251	22.8	17.5
800	1.266	24.7	18.0
900	1.283	27.1	-
1000	1.291	31.9	-

^aBetween 70°F (21°C) and temperature shown.

APPENDIX (C).

Solar II Rankine Cycle Diagram



APPENDIX (D).

MATLAB Codes

%% the main code to estimate the performance of the heliostat field and solar central receiver

clear all

close all

clc

tic

nh3

nh4=zeros(1,5100); %% nh4 : logic vector for specifying max heliostat number

nh=5100; %% number of heliostats test

eln=10; %% eln=number of an element on each side of the heliostat

w=12.305; %% width of heliostat

we=w/eln; %% discrete width

h=9.752; %% height of heliostat

he=h/eln; %% discrete height

*A=w*h; %% area of the heliostat*

de=((we)^2)+(he)^2)^0.5; %% the diameter of diagonal of the element

r2=((w^2)+(h^2))^0.5)/2; %% the radius of the diagonal of the heliostat

*d=r2*2;*

lt=d; %% test length

tm=0; %% time counter

%% Tower height

ht=140;

%% Latitude Angle

tld=37.42;

tl=(tld)(pi/180);*

%% fix logic value for selected max heliostat ef

for lp10=1:2650

va=nh3(lp10);

nh4(1,va)=1;

end

ef81=zeros(1,2650); %% cos ef for all duration of running

ef82=zeros(1,2650); %% sh ef for all duration of running

ef83=zeros(1,2650); %% bl ef for all duration of running

ef84=zeros(1,2650); %% atm ef for all duration of running

ef85=zeros(1,2650); %% int ef for all duration of running

ef87=zeros(1,2650); %% tot ef for all duration of running

tp1=zeros(1,5100); %% tp1: polar position Angle for heliostat as a vector

```

tp2=zeros(1,5100); %% tp2:angle position for heliostat as vector
to = zeros(1,5100); %% to : orientation angle of heliostat
k = zeros(1,5100); %% k : distance between heliostat centre and receiver
rp=zeros(1,5100); %% rp:radius position for heliostat as row vector
rt = zeros(1,5100);
y1=zeros(1,5100); %% y1 & z1 cartesian coordinate for heliostat position
z1=zeros(1,5100); %% y1 & z1 cartesian coordinate for heliostat position
x1 = ones(1,5100)*10;
hd=zeros(1,5100); %% difference between tower height and heliostat height
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
flr=zeros(9,24); %% flux destrubution matrix on receiver
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
T=cell(1,5100); %% T:Vector for incident beam from tower
fid=fopen('solarplant1','a');
fprintf(fid,'HelNu      PolarRad  PolarAng  PolarDirAng  OrientedAng  XAxis
YAxis  ZAxis\n');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for lp1=100:5100 %% heliostat looping
    %% compute polar position for heliostat
    tp=2*pi*(((1+sqrt(5))/2)^-2)*(lp1);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    while tp>=(2*pi)
        tp=tp-(2*pi);
    end
    tp1(lp1)=tp;
    %% compute the polar position for heliostat
    if (tp>=0)&&(tp<=(3*pi/2));
        tp2(lp1)=(3*pi/2)-tp;
    elseif (tp>(3*pi/2))&&(tp<=2*pi);
        tp2(lp1)=(7*pi/2)-tp;
    end
    %% distribution position computing for heliostat
    r1 =3.55*(lp1)^0.675;
    rp(lp1)=r1;
    [y1(lp1),z1(lp1)] = pol2cart(tp,r1);
    %%difference between tower height and heliostat height
    hd(lp1)=ht-x1(lp1);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    to(lp1)=atan((hd(lp1))/r1); %% the orientation angle of the heliostat
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    T{lp1}=[(hd(lp1))/((((hd(lp1))^2)+(y1(lp1)^2)+(z1(lp1)^2))^0.5) ; (-
        y1(lp1))/((((hd(lp1))^2)+(y1(lp1)^2)+(z1(lp1)^2))^0.5) ; (-z1(lp1))/((((
        hd(lp1))^2)+(y1(lp1)^2)+(z1(lp1)^2))^0.5)] ;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    k(lp1)=((r1^2)+(hd(lp1)^2))^0.5; %% distance between the heliostat and receiver

```

```

fprintf(fid,'%+f %+f %+f %+f %+f %+f %+f %+f
        \n',lp1,r1,tp*(180/pi),tp2(lp1)*(180/pi),to(lp1)*(180/pi),x1(lp1),y1(lp1),z1(l
        p1));

end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fclose(fid);
G=cell(1,5100);
%% summation for heliostat energy for deferent efficiency for all duration as a vector
sr1=zeros(1,2650); %% the vector of summation energy after multiplying by cos ef for
    all duration of running
sr2=zeros(1,2650); %% the vector of summation energy after multiply by sh ef for all
    duration of running
sr3=zeros(1,2650); %% the vector of summation energy after multiplying by bl ef for
    all duration of running
sr4=zeros(1,2650); %% the vector of summation energy after multiplying by atm ef for
    all duration of running
sr5=zeros(1,2650); %% the vector of summation energy after multiplying by int ef for
    all duration of running
sr7=zeros(1,2650); %% the vector of summation energy after multiplying by tot ef for
    all duration of running
sd=zeros(1,2650);
%% summation for field efficiency
srt1=0;
srt2=0;
srt3=0;
srt4=0;
srt5=0;
srt7=0;
sdt=0;
Qabst=0;
fid=fopen('solarplant2','a');
fprintf(fid,'nd    time    helef    solEn(w)    helEn(w)    deshelEn(w)    desrecEn(w)\n');
matlabpool('open',8)
%% looping for number of days
%for nd=1:365
%% looping for specified number of days
% nnd=[21, 52, 80, 111, 141, 172, 202, 233, 264, 294, 325, 355];
% L2=length(nnd);
% for lp7=1:L2
% nd=nnd(lp7)
    nd=111;

mft=0;
srt8d=0; %% daily summation of energy after multiplying by total eff
sdt2d=0; %% daily sumation of solar Energy
ef87td=0; %% daily field efficiency

```

```

Qabstd=0; %% daily sumation of reciever Energy
%% Declination angle calculation
t2=(23.45*(pi/180))*sin(2*pi*((284+nd)/365));

%% sunrise then sunset in radiant
%% t3=acos(tan(t1)*tan(t2))-pi;
%% ts1=12+(t3/(15*pi/180));
%% t4=-1*t3;
%% t4=acos((-1)*tan(t1)*tan(t2));
%% ts2=12+(t4/(15*pi/180));

%% sunset then sunrise
% t4=acos((-1)*tan(t1)*tan(t2));
% t3=-1*t4;
% ts1=12+(t3/(15*pi/180));
% ts2=12+(t4/(15*pi/180));
%% sunrise & sunset looping

%% while ts1<=ts2 imp loop for sunrise to sunset
ts1=12.065396;
srt8 =0; %% instantly summation of energy after multiplying by total eff
sdt2=0; %% instantly summation of solar Energy
ef87t=0; %% instantly field efficiency
sr7t=zeros(1,2650); %%% vector for instantly summation of energy after
multiplying by total eff
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
t9= zeros(1,5100);
t10p=zeros(1,5100);
t13=zeros(1,5100);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ef1v=zeros(1,2650); %% cos ef for all duration of running
ef2v=zeros(1,2650); %% sh ef for all duration of running
ef3v=zeros(1,2650); %% bl ef for all duration of running
ef4v=zeros(1,2650); %% atm ef for all duration of running
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
G=cell(1,5100);
t5=(15*pi/180)*(ts1-12);
%% solar altitude angle
t6=asin(cos(t1)*cos(t2)*cos(t5)+sin(t1)*sin(t2));
%% solar radiation beam
[Ic] = fc( nd,t6 );
Id=Ic*((5/15)*60*60)*115.7;
%% solar azimuth angle (general)
t7=acos((sin(t2)*cos(t1)-cos(t2)*cos(t5)*sin(t1))/cos(t6));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% solar azimuth angle
if sin(t5)<=0
t8=t7;

```

```

else
    t8=(2*pi)-t7;
end
%%% sun vector
S=[sin(t6);cos(t6)*sin(t8);cos(t6)*cos(t8)];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
parfor lp2=100:5100

    %%% incident angle
    t9(1,lp2)=0.5*acos(((( hd(lp2))*sin(t6))-(y1(lp2)*cos(t6)*sin(t8))-
        (z1(lp2)*cos(t6)*cos(t8)))/(((( hd(lp2))^2+(y1(lp2))^2+(z1(lp2))^2)^0.5)));
    %%% elevation angle
    t10=asin((( hd(lp2))/(((
        hd(lp2))^2+(y1(lp2))^2+(z1(lp2))^2)^0.5)+sin(t6)))/(2*cos(t9(1,lp2))));
    t10p(lp2)=t10;
    tt10=[cos(t10),0,sin(t10),0;0,1,0,0;-sin(t10),0,cos(t10),0;0,0,0,1];
    %%% azimuth angle
    t11a=((( -1*z1(lp2))/(((
        hd(lp2))^2+(y1(lp2))^2+(z1(lp2))^2)^0.5)+(cos(t6)*cos(t8)))/(2*cos(t9(1,
        lp2))*cos(t10)));
    t11b=((( -1*y1(lp2))/(((
        hd(lp2))^2+(y1(lp2))^2+(z1(lp2))^2)^0.5)+(cos(t6)*sin(t8)))/(2*cos(t9(1,
        lp2))*cos(t10)));
    if t11a>0
        t11=asin(t11b);
    else
        t11=pi-asin(t11b);
    end
    tt11=[1,0,0,0;0,cos(t11),sin(t11),0;0,-sin(t11),cos(t11),0;0,0,0,1];
    t13(lp2)=atan(tan(t6)/cos(abs(t8- t11)));

    G{lp2}=[1,0,0,(x1(lp2));0,1,0,y1(lp2);0,0,1,z1(lp2);0,0,0,1]*(tt11*tt10);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ir1=0;
Ir2=0;
Ir3=0;
Ir4=0;
Ir5=0;
Ir7=0;
% parfor lp3=100:nh
parfor lp11=1:2650
    % lp11=100
    % for lp11=1:2650
    lp3=nh3(lp11);
    %%% shadow efficiency cells
    %%% shadow & block logic condition

```

```

ms=zeros(eln,elN);
mb=zeros(eln,elN);
%% number of element
ns=elN*elN;
nb=elN*elN;
%% shadow & block logic condition
switch lp3
    %%%%%%%%%%%
    case 100
        %%%% Number of heliostat test
        sb=[155, 189, 134, 168, 147, 113, 126, 108, 142, 121, 176];
[ns,nb]=fa(sb,elN,nh4,ms,mb,ns,nb,lp3,x1,y1,z1,d,de,S,T,tp2,t8,t10p,t13,lt,G,h,he,w,we);
        %%%%%%%%%%%
        .↓
        .↓
        .↓
    case 5100
        %%%% Number of heliostat test
        sb=[5045, 4901, 4956, 4812, 4579, 4723, 4490, 4634, 4867, 4545, 4778,
4689, 5011, 4922, 5066];
[ns,nb]=fa(sb,elN,nh4,ms,mb,ns,nb,lp3,x1,y1,z1,d,de,S,T,tp2,t8,t10p,t13,lt,G,h,he,w,we);
        %%%%%%%%%%%
    otherwise
        disp('other value');
end

[ ef1, ef2,ef3, ef4, ef5,ef7]=fe(lp3,t9,ns,nb,A,h,w,we,he,k,to );

ef1v(lp11)=ef1; %%% cos efficiency for each heliostat for each step time
ef2v(lp11)=ef2; %%% shadow efficiency for each heliostat for each step time
ef3v(lp11)=ef3; %%% block efficiency for each heliostat for each step time
ef4v(lp11)=ef4; %%% atmospheric efficiency for each heliostat for each step time

Ir7=Id*ef7;
Ir1=Id*ef1;
Ir2=Id*ef2;
Ir3=Id*ef3;
Ir4=Id*ef4;
Ir5=Id*ef5;
%%%%%%%%%%
sr7(lp11)= sr7(lp11)+Ir7;
sr1(lp11)= sr1(lp11)+Ir1;
sr2(lp11)= sr2(lp11)+Ir2;
sr3(lp11)= sr3(lp11)+Ir3;
sr4(lp11)= sr4(lp11)+Ir4;
sr5(lp11)= sr5(lp11)+Ir2;
sd(lp11)=sd(lp11)+Id;

```



```

% shading interp
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
srt8d=srt8d+(srt8*((5/15)*60*60)); %%% daily summation of energy(joul) after
multiplying by total eff
sdt2d=sdt2d+(sdt2*((5/15)*60*60)); %%% daily summation of solar Energy(joul)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[Qabs2,mf,Qabse,Qrade,Qconve,Tfs,Tss,Tfsq,tamb] = frt( nd,ts1,srt8,flr );

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Qabst=Qabst+(Qabs2*((5/15)*60*60)); %%% total summation energy for all
duration for receiver(joul)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mft=mft+(mf*((5/15)*60*60));
Qabstd=Qabstd+(Qabs2*((5/15)*60*60));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% increasing step time
% tm=tm+(5/15)*60;
% ts1=ts1+(5/15)
% fprintf(fid,' %f\n',Qabs2);
% fprintf(fid,' %f\n',ReQ);
% Tamb
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% end imp loop for sunrise to sunsit
ef87td=srt8d/sdt2d; %%% daily field efficiency
fprintf(fid,'dailysolarEnJ=%f daily fieldEnJ=%f dailyrecEnJ=%f
dailySumMass=%f dailyfield efficiency=%f\n',sdt2d,srt8d,Qabstd,mft,ef87td);
%% end loop for day number
fclose(fid);
matlabpool('close')
toc

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% subroutine code to estimate the number of elements that is not effected by
%% shadowing and blocking, then to estimate the shadowing and blocking efficiency
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function[ns,nb]=fa(sb,eln,nh4,ms,mb,ns,nb,lp3,x1,y1,z1,d,de,S,T,tp2,t8,t10p,t13,lt,G,h,h
e,w,we)
L=length(sb);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%% heliostat test looping
for lp6=1:L
    q=sb(lp6);
    %%%%%%%%% angle calculation for heliostat shadow relative to the main heliostat
    df1=[(x1(q));(y1(q));(z1(q))]-[(x1(lp3));(y1(lp3));(z1(lp3))];
    df2= df1';
    df3=[ df2(1) df2(2) df2(3)];

    [t12,rt] = cart2pol(df2(2),df2(3));
    %%%%%%%%%%
    %%%%%%%%% intersection condition
    if d >= rt
        fprintf('There intersection between heliostat test %f and main heliostat %f\n',q,lp3)
        break
    end
    %%%%%%%%%%
    while sign(t12)=-1
        t12=(2*pi)-abs(t12);
    end
    %%%%%%%%% rotation angle
    %%%%%%%%%%
    if (t12 >=0)&&(t12 <=(pi/2));
        t12 =(pi/2)-t12;
    elseif(t12 >(pi/2))&&(t12 <=2*pi);
        t12 =(5*pi/2)-t12;
    end
    %%%%%%%%%%
    ds2=norm(cross(S,df3'))/norm(S);
    db2=norm(cross((T{lp3}),df3'))/norm(T{lp3});
    t14= atan((1.5*(h+(x1(q)-10))*cos(t10p(q)))/(rt-((h+(x1(q)-10))*sin(t10p(q)))));
    %%%%%%%%%%
    if (((t12>(t8+(pi/3))) || (t12<(t8-(pi/3)))) || (t13(lp3)>t14)|| (ds2
>lt))&&((t12>(tp2(lp3)+(pi/3))) || ( t12<(tp2(lp3)-(pi/3)))||(db2 >lt))) || (nh4(1,q)==0)
;
        continue;
    end
    %%%%%%%%%%

```

```

for lz1=1:eln
    for le1=1:eln
        %%%%%%%%%%
        ct1=[1,0,0,((h/2)-(((2*lz1)-1)/2)*he));0,1,0,((-w/2)+(((2*le1)-
1)/2)*we));0,0,1,0;0,0,0,1];
        pt1=G{q}* (ct1*[0;0;0;1]);
        %%%%%%%%%%
        for lz2=1:eln
            for le2=1:eln
                ct2=[1,0,0,((h/2)-(((2*lz2)-1)/2)*he));0,1,0,((-w/2)+(((2*le2)-
1)/2)*we));0,0,1,0;0,0,0,1];
                pt2=G{lp3}* (ct2*[0;0;0;1]);
                %%%%%%%%%%
                df4 = (pt1-pt2);
                df5=df4';
                df6=[df5(1) df5(2) df5(3)];
                %%%%%%%%%%
                bb=((((140-pt2(1))^2)+(pt2(2)^2)+(pt2(3)^2))^0.5;
                TT=[(140-pt2(1))/bb;-pt2(2)/bb;-pt2(3)/bb];
                db=norm(cross((TT),df6'))/norm(TT);
                %%%%%%%%%%
                ds=norm(cross(S,df6'))/norm(S);
                %%%%%%%%%%
                if (ds <=(de)) && (ms(lz2,le2)==0) && (t12<(t8+(pi/3))) && (t12>(t8-
(pi/3)));
                    ns=ns-1;
                    ms(lz2,le2)=ms(lz2,le2)+1;
                    end
                    %%%%%%%%%%
                    if (db <=(de)) && (mb(lz2,le2)==0) && (t12<((tp2(lp3))+(pi/3))) &&
(t12>((tp2(lp3))-(pi/3)));
                        nb=nb-1;
                        mb(lz2,le2)=mb(lz2,le2)+1;
                        end
                        %%%%%%%%%%
                    end
                end
            end
        end
    end
    %%%%%%%%%%
end
%%%%%%%%%

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% subroutine code to estimate the optical efficiencies
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [ ef1, ef2, ef3, ef4, ef5, ef7 ] = fe( lp3, t9, ns, nb, A, h, w, we, he, k, to )

r3=4; %% receiver radius
h2=9; %% receiver height
Ae=we*he; %% area of element
d2=(w*h)^0.5; %% square root of the whole heliostat area
sg2=2.51*(1/1000); %% standard deviation of sun shape
sg4=0.94*(1/1000); %% standard deviation surface error
sg6=0.63*(1/1000); %% standard deviation tracking error

%% Cosine efficiency
ef1=cos(t9(lp3));
%% shadow efficiency
As=ns*Ae;
ef2=As/A;
%% block efficiency
Ab=nb*Ae;
ef3=Ab/A;
%% atmospheric attenuation efficiency
if k(lp3) <=1000
    ef4=0.99321-(0.0001176*k(lp3))+(1.97*10^-8*k(lp3)^2);
elseif k(lp3) >1000
    ef4=exp(-0.0001106*k(lp3));
end
%% Interception efficiency
h3=d2*abs(1-ef1);
w3=d2*abs(ef1-1);
sg3=2*sg4;
sg5=((0.5*((h3^2)+(w3^2)))^0.5)/(4*k(lp3));
sg1=((k(lp3)^2)*(sg2^2)+(sg3^2)+(sg5^2)+(sg6^2))^0.5;
fd=@(x4,y4)exp(-1*((x4.^2)+(y4.^2))/(2*(sg1^2)));
k3=dblquad(fd,-(h2*cos(to(lp3)))/2,(h2*cos(to(lp3)))/2,-r3,r3);
ef5=(1/(2*pi*(sg1^2)))*k3;
%% effective reflectivity
ef6=0.88*0.95;
%% total efficiency
ef7=ef1*ef2*ef3*ef4*ef5*ef6;

end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% subroutine code to estimate the distribution power on the receiver
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

function[f1r]=fr(lp13,lr4,tp1,k,to,h,w,Id,ef1v,ef2v,ef3v,ef4v,f1r )
f1p=zeros(9,11);
Id=Id/((5/15)*60*60); %% change input energy to watt
sg2=2.51*(1/1000); %%standard deviation of sun shape
sg4=0.94*(1/1000); %%standard deviation surface error
sg6=0.63*(1/1000); %%standard deviation tracking error
d2=(w*h)^0.5; %%square root of the whol heliosta area
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h3=d2*abs(1-ef1v(lp13));
w3=d2*abs(ef1v(lp13)-1);
sg3=2*sg4;
sg5=((0.5*((h3^2)+(w3^2)))^0.5)/(4*k(lr4));
sg1=((k(lr4)^2)*((sg2^2)+(sg3^2)+(sg5^2)+(sg6^2)))^0.5/(cos(to(lr4)))^0.5;
rx=[-3.86, -3.46, -2.83, -2, -1.04, 0, 1.04, 2, 2.83, 3.46, 3.86];
Lrx=length(rx);
for lr1=1:Lrx
    qrx=rx(lr1);
    ry=[4:-1:-4];
    Lry=length(ry);
    for lr2=1:Lry;
        qry=ry(lr2);
        f1p(lr2,lr1)=Id*ef1v(lp13)*ef2v(lp13)*ef3v(lp13)*ef4v(lp13)*
0.88*0.95*(1/(2*pi*(sg1^2)))*exp(-1*((qrx.^2)+(qry.^2))/(2*(sg1^2)));
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% column 7 in receiver
if (tp1(lr4)>0)&&(tp1(lr4)<=15*(pi/180));
    pc=1;
    rc=2;
    for lr3=1:9
        f1r(lr3,rc)=f1r(lr3,rc)+f1p(lr3,pc);
    end
    pc=2;
    rc=3;
    for lr3=1:9
        f1r(lr3,rc)=f1r(lr3,rc)+f1p(lr3,pc);
    end
    pc=3;
    rc=4;
    for lr3=1:9
        f1r(lr3,rc)=f1r(lr3,rc)+f1p(lr3,pc);
    end
end

```

```

pc=4;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 8 in receiver
elseif (tp1(lr4)>15*(pi/180))&&(tp1(lr4)<=30*(pi/180));
pc=1;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end

```

```

pc=2;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=13;

```

```

for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 9 in receiver
elseif (tp1(lr4)>30*(pi/180))&&(tp1(lr4)<=45*(pi/180));
pc=1;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=12;

```

```

for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 10 in receiver
elseif (tp1(lr4)>45*(pi/180))&&(tp1(lr4)<=60*(pi/180));
pc=1;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=11;

```

```

for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 11 in receiver
elseif (tp1(lr4)>60*(pi/180))&&(tp1(lr4)<=75*(pi/180));
pc=1;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=10;

```

```

for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 12 in receiver
elseif (tp1(lr4)>75*(pi/180))&&(tp1(lr4)<=90*(pi/180));
pc=1;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=9;

```

```

for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 13 in receiver
elseif (tp1(lr4)>90*(pi/180))&&(tp1(lr4)<=105*(pi/180));
pc=1;
rc=8;

```

```

for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end

```

```

end
pc=11;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 14 in receiver
elseif (tp1(lr4)>105*(pi/180))&&(tp1(lr4)<=120*(pi/180));
pc=1;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end

```

```

end
pc=9;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 15 in receiver
elseif (tp1(lr4)>120*(pi/180))&&(tp1(lr4)<=135*(pi/180));
pc=1;
rc=10;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end

```

```

end
pc=7;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 16 in receiver
elseif (tp1(lr4)>135*(pi/180))&&(tp1(lr4)<=150*(pi/180));
pc=1;
rc=11;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);

```

```

end
pc=5;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 17 in receiver
elseif (tp1(lr4)>150*(pi/180))&&(tp1(lr4)<=165*(pi/180));
pc=1;
rc=12;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);

```

```

end
pc=3;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
end
%% column 18 in receiver

```

```

elseif (tp1(lr4)>165*(pi/180))&&(tp1(lr4)<=180*(pi/180));
pc=1;
rc=13;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;

```

```

rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 19 in receiver
elseif (tp1(lr4)>180*(pi/180))&&(tp1(lr4)<=195*(pi/180));
pc=1;
rc=14;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;

```

```

rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 20 in receiver
elseif (tp1(lr4)>195*(pi/180))&&(tp1(lr4)<=210*(pi/180));
pc=1;
rc=15;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;

```

```

rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 21 in receiver
elseif (tp1(lr4)>210*(pi/180))&&(tp1(lr4)<=225*(pi/180));
pc=1;
rc=16;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;

```

```

rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 22 in receiver
elseif (tp1(lr4)>225*(pi/180))&&(tp1(lr4)<=240*(pi/180));
pc=1;
rc=17;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;

```

```

rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=3;
for lr3=1:9

```

```

    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 23 in receiver
elseif (tp1(lr4)>240*(pi/180))&&(tp1(lr4)<=255*(pi/180));
pc=1;
rc=18;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=19;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=2;
for lr3=1:9

```

```

    flr(lr3,rc)=flr(lr3,rc)+ flp(lr3,pc);
end
pc=10;
rc=3;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=11;
rc=4;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
%% column 24 in receiver
elseif (tp1(lr4)>255*(pi/180))&&(tp1(lr4)<=270*(pi/180));
pc=1;
rc=19;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=2;
rc=20;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=3;
rc=21;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=4;
rc=22;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=5;
rc=23;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=6;
rc=24;
for lr3=1:9
    flr(lr3,rc)= flr(lr3,rc)+ flp(lr3,pc);
end
pc=7;
rc=1;
for lr3=1:9

```

```

    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 1 in receiver
elseif (tp1(lr4)>270*(pi/180))&&(tp1(lr4)<=285*(pi/180));
pc=1;
rc=20;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=24;
for lr3=1:9

```

```

    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 2 in receiver
elseif (tp1(lr4)>285*(pi/180))&&(tp1(lr4)<=300*(pi/180));
pc=1;
rc=21;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=22;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=23;
for lr3=1:9

```

```

    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 3 in receiver
elseif (tp1(lr4)>300*(pi/180))&&(tp1(lr4)<=315*(pi/180));
pc=1;
rc=22;
for lr3=1:9

```

```

    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=9;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
end

```

```

pc=11;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 4 in receiver
elseif (tp1(lr4)>315*(pi/180))&&(tp1(lr4)<=330*(pi/180));
pc=1;
rc=23;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=7;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=8;
rc=6;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end

```

```

pc=9;
rc=7;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=10;
rc=8;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=11;
rc=9;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
%% column 5 in receiver
elseif (tp1(lr4)>330*(pi/180))&&(tp1(lr4)<=345*(pi/180));
pc=1;
rc=24;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=2;
rc=1;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=3;
rc=2;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=4;
rc=3;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=5;
rc=4;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
pc=6;
rc=5;
for lr3=1:9
    flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
end
end

```

```

    pc=7;
    rc=6;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=8;
    rc=7;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=9;
    rc=8;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=10;
    rc=9;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=11;
    rc=10;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    %% column 6 in receiver
else (tp1(lr4)>345*(pi/180))&&(tp1(lr4)<=360*(pi/180));
    pc=1;
    rc=1;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=2;
    rc=2;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=3;
    rc=3;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=4;
    rc=4;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
end

```

```

    pc=5;
    rc=5;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=6;
    rc=6;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=7;
    rc=7;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=8;
    rc=8;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=9;
    rc=9;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=10;
    rc=10;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
    pc=11;
    rc=11;
    for lr3=1:9
        flr(lr3,rc)=flr(lr3,rc)+flp(lr3,pc);
    end
end
end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% the subroutine- code to estimate the performance of the solar central receiver
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Qabs2,mf,Qabse,Qrade,Qconve,Tfs,Tss,Tfsq,tamb] = frt(nd,ts1,srt8,flr )
%% lr5
%% lr5
%% Tfs: temperature of the fluid as matrix
%% Tss: temperature of the surface as matrix
%% Tdif: deference temperature between surface anf inlet
%% Qinc: total incident heat
%% Qabse1: absorber heat for element
Asu=38*(pi*0.025/2)*1;

%% salt fluid property
Tinc=290; %%temperatute of the inlet fluid
Tink=Tinc+273.15;
Touc=595;
Touk=Touc+273.15;
Ws=6.9; % wind speed
%%ambient temperature calculation
if (nd>=1) && (nd<=31);
    Tdb=17;
    mdtr=12;
elseif(nd>=32) && (nd<=59);
    Tdb=19.8;
    mdtr=13;
elseif(nd>=60) && (nd<=90);
    Tdb=24;
    mdtr=15.6;
elseif(nd>=91) && (nd<=120);
    Tdb=26.1;
    mdtr=15.8;
elseif(nd>=121) && (nd<=151);
    Tdb=30.8;
    mdtr=17;
elseif(nd>=152) && (nd<=181);
    Tdb=35;
    mdtr=17.3;
elseif(nd>=182) && (nd<=212);
    Tdb=38.3;
    mdtr=18.3;
elseif(nd>=213) && (nd<=243);
    Tdb=37.7;
    mdtr=17.7;
elseif(nd>=244) && (nd<=273);

```

```

    Tdb=34;
    mdr=16.2;
elseif(nd>=274) && (nd<=304);
    Tdb=28.1;
    mdr=13.4;
elseif(nd>=305) && (nd<=334);
    Tdb=22.1;
    mdr=11.6;

else(nd>=335) && (nd<=365);
    Tdb=18;
    mdr=9.1;

end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

cfr = (tsl-12.5)/7.0711;
fr = (0.04116)*cfr^9 + (-0.0094566)*cfr^8 + (-0.24691)*cfr^7 + (0.14578)*cfr^6
+ (0.42214)*cfr^5 + (-0.64772)*cfr^4 + (0.048419)*cfr^3 + (1.1653)*cfr^2 + (-
0.54494)*cfr + (0.067108);

tamb=Tdb-(fr*mdr); %% ambient temperature(c)
Tamb=tamb+273.15; %% ambient temperature (k)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tskyk=0.0552*Tamb^1.5; %% sky temperature (k)
%% surface temperature calculation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Qabse=zeros(9,24);
Qrade=zeros(9,24);
Qconve=zeros(9,24);

Qabs1=0; %% initial value for absorber heat
Qabs2=0; %% initial value for absorber heat
Qinc=0; %% initial value for incident heat
mf=0; %% initial value for mass transfer in receiver
mfp=0; %% initial value for mass transfer in panel
Tfs=zeros(9,24); %% Tfs: temperature of the fluid as matrix
Tss=zeros(9,24); %% Tss: temperature of the surface as matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for lr5=1:24;
    for lr6=1:9
        Qinc=Qinc+flr(lr6,lr5);
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% *assumptions*
Qabs1=Qinc; %% give the value of the total energy incident on the receiver

```

```

mf=Qabs1/((1.5191e+03)*(Touk-Tink)); %% total mass flowrate through receiver
mfp=mf/2;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tfsq= zeros(1,110); %% Tfsq: temperature of the fluid as sequence of the fluid flow
sq=1;
Tfsk=Tink; %% initial value for fluid temperature at block which equal 290+273.15
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Qrae=0;
Qce=0;
Qrfe=0;
Qtbl=0; %%%% initial value for tube block energy
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for lr5=12:-1:1;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if mod(lr5,2) ==0
        bls=[1, 2, 3, 4, 5, 6, 7, 8, 9];
    else
        bls=[9, 8, 7, 6, 5, 4, 3, 2, 1];
    end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    for lr6=1:1:9;
        lr6=bls(lr6);
        sq=sq+1;
        %% *assumptions*
        Qabse1=f1r(lr6,lr5);
        Qtbl=Qtbl+Qabse1; %% summation heat from entrance to specified element
        cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
        Tfsk=Tink+(Qtbl/(mfp* cpL));
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        if (Tfsk>=Touk);
            Tfsk=Touk;
        end
        Tfsq(sq)=Tfsk;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        Tp=(Tfsk-273.15); %% temperature of the material pipe(c)
        %% pipe thermal conductivity (w/(m.k))
        ckp = (Tp-501.82)/328.69;
        kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
            +0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %% characteristic of the fluid
        spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
        cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
        kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity (w/(m.k))
        dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
            ((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
    end
end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vf=(mfp/38)/((1/spv)*(3.976*10^(-4))); %%%% fluid velocity
Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
      transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% surface temperature equation
Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp)))+(1/(hl*pi*0.02252*1)))+(Tfsk-273.15);
Tsk1=Tsc1+273.15;
%%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %%% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %%%air specific heat
      (j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %%% air thermal conductivity
      (w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %%% dynamic viscosity for air
      (pa.s)
Pra=(dyva*cpa)/ka; %%% prantle number of air
kiv=dyva/dea; %%% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %%% grashof number
Ra=Gr*Pra; %%% ralih number
Rea=(Ws*8)/kiv; %%% Renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3))*((Tsk1/Tamb)^(-0.14)));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while abs(Qabse1-Qabse2)>0.001
    Qtb1=Qtb1-Qabse1;
    Qabse1=Qabse2;
    Qtb1=Qtb1+Qabse1;
    cpL=1443+0.172*(Tfsk-273.15); %%% liquid specific heat (j/(kg.k))
    Tfsk=Tink+(Qtb1/(mfp*cpL));
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if (Tfsk>=Touk);

```

```

Tfsk=Touk;
end
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tp=((Tfsk-273)+Tsc1)/2; %% temperature of the material pipe(c)
%% pipe thermal conductivity (w/(m.k))
ckp = (Tp-501.82)/328.69;
kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
+0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% characteristic of the fluid
spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity
(w/(m.k))
dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vf= (mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity
Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% surface temberature equation

Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp))+(1/(hl*pi*0.02252*1)))+(Tfsk-
273.15);
Tsk1=Tsc1+273.15;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%
%
%% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
(j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
(w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for air
(pa.s)
Pra=(dyva*cpa)/ka; %% prantle number of air
kiv=dyva/dea; %% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %% grashof number

```

```

Ra=Gr*Pra; %% ralih number
Rea=(Ws*8)/kiv; %% Renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3))*((Tsk1/Tamb)^(-0.14)));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if Qabse2>0
    Qabs2= Qabs2+Qabse2;
else
    Qabse2=0;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tfsq= zeros(1,110); %% Tfsq: temperature of the fluid as sequence of the fluid flow
sq=1;
Tfsk=Tink; %% initial value for fluid temperature at block which equal 290+273.15
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Qabse1=0;
Qabse2=0;
Qtb2=0;
for lr5=13:1:24;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if mod(lr5,2) ==0
        bls=[9, 8, 7, 6, 5, 4, 3, 2, 1];
    else
        bls=[1, 2, 3, 4, 5, 6, 7, 8, 9];
    end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    for lr66=1:1:9;
        lr6=bls(lr66);
        sq=sq+1;
        %% *assumptions*
        Qabse1=flr(lr6,lr5);
        Qtb2=Qtb2+Qabse1;
        cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
        Tfsk=Tink+(Qtb2/(mfp* cpL));
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    end
end

```

```

if (Tfsk>=Touk);
    Tfsk=Touk;
end
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tp=(Tfsk-273.15); %% temperature of the material pipe(c)
%% pipe thermal conductivity (w/(m.k))
ckp = (Tp-501.82)/328.69;
kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
    +0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% surface temperature equation
%% characteristic of the fluid
spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity (w/(m.k))
dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
    ((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vf= (mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity
Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
    transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp)))+(1/(hl*pi*0.02252*1)))+(Tfsk-273.15);
Tsk1=Tsc1+273.15;
%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%
% %% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
    (j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
    (w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for air
    (pa.s)
Pra=(dyva*cpa)/ka; %%% prantle number of air
kiv=dyva/dea; %%% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %%% grashof number
Ra=Gr*Pra; %%% ralih number
Rea=(Ws*8)/kiv; %%% renold number for force convection in air

```

```

hnat=(ka/9)*(0.098*(Gr^(1/3))*((Tsk1/Tamb)^(-0.14)));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from reciever
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while abs(Qabse1-Qabse2)>0.001
    Qtb2=Qtb2-Qabse1;
    Qabse1=Qabse2;
    Qtb2=Qtb2+Qabse1;
    cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
    Tfsk=Tink+(Qtb2/(mfp*cpL));
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if (Tfsk>=Touk);
        Tfsk=Touk;
    end
    Tfsq(sq)=Tfsk;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    Tp=((Tfsk-273.15)+Tsc1)/2; %% temperature of the material pipe(c)
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %% pipe thermal conductivity (w/(m.k))
    ckp = (Tp-501.82)/328.69;
    kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
    +0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %% characteristic of the fluid
    spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
    cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
    kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity
    (w/(m.k))
    dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
    ((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    Vf= (mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity
    Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
    Pr=(dyv*cpL)/kL; %% prantle number
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
    transfer w/m^2.k
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %% surface temperature equation

Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp))+(1/(hl*pi*0.02252*1)))+(Tfsk-
273.15);

```

```

Tsk1=Tsc1+273.15;
%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
(j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
(w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for air
(pa.s)
Pra=(dyva*cpa)/ka; %% prantle number of air
kiv=dyva/dea; %% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %% grashof number
Ra=Gr*Pra; %% ralih number
Rea=(Ws*8)/kiv; %% renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3)))*((Tsk1/Tamb)^(-0.14));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if Qabse2>0
    Qabs2= Qabs2+Qabse2;
else
    Qabse2=0;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while abs(Qabs1-Qabs2)>0.001
    Qabs1=Qabs2; %%%% give the new value of the total energy absorbed in the
receiver
    Qabs2=0;
    mf=Qabs1/((1.5191e+03)*(Touk-Tink)); %% total mass flowrate through receiver
    mfp=mf/2;

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tfsq= zeros(1,110); %% Tfsq: temperature of the fluid as sequence of the fluid flow
sq=1;
Tfsk=Tink; %% initial value for fluid temperature at block which equal 290+273.15
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Qrae=0;
Qce=0;
Qrfe=0;
Qtb1=0; %% initial value for tube block energy
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for lr5=12:-1:1;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if mod(lr5,2) ==0
        bls=[1, 2, 3, 4, 5, 6, 7, 8, 9];
    else
        bls=[9, 8, 7, 6, 5, 4, 3, 2, 1];
    end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    for lr66=1:1:9;
        lr6=bls(lr66);
        sq=sq+1;
        %% *assumptions*
        Qabse1=flr(lr6,lr5);
        Qtb1=Qtb1+Qabse1;
        cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
        Tfsk=Tink+(Qtb1/(mfp* cpL));
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        if (Tfsk>=Touk);
            Tfsk=Touk;
        end
        Tfsq(sq)=Tfsk;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        Tp=(Tfsk-273.15); %% temperature of the material pipe(c)
        %% pipe thermal conductivity (w/(m.k))
        ckp = (Tp-501.82)/328.69;
        kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
            +0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %% characteristic of the fluid
        spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific vlume (m^3/kg)
        cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
        kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity
            (w/(m.k))
        dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
            ((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

Vf=(mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity
Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%surface temperature equation

Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp))+(1/(hl*pi*0.02252*1)))+(Tfsk-
273.15);
Tsk1=Tsc1+273.15;
%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
(j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
(w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for air
(pa.s)
Pra=(dyva*cpa)/ka; %% prantle number of air
kiv=dyva/dea; %% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %% grashof number
Ra=Gr*Pra; %% ralih number
Rea=(Ws*8)/kiv; %% renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3)))*((Tsk1/Tamb)^(-0.14));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while abs(Qabse1-Qabse2)>0.001
Qtb1=Qtb1-Qabse1; %% subtract the old value for energy element in energy
storage
Qabse1=Qabse2; %% take the new value for energy element
Qtb1=Qtb1+Qabse1;
cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
Tfsk=Tink+(Qtb1/(mfp*cpL));

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if (Tfsk>=Touk);
    Tfsk=Touk;
end
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tp=((Tfsk-273.15)+Tsc1)/2; %% temperature of the material pipe(c)
%% pipe thermal conductivity (w/(m.k))
ckp = (Tp-501.82)/328.69;
kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
+0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% characteristic of the fluid
spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity
(w/(m.k))
dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vf= (mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity
Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% surface temperature equation

Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp))+(1/(hl*pi*0.02252*1)))+(Tfsk-
273.15);
Tsk1=Tsc1+273.15;
%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
(j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
(w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for
air (pa.s)
Pra=(dyva*cpa)/ka; %% prantle number of air

```

```

kiv=dyva/dea; %% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %% grashof number
Ra=Gr*Pra; %% ralih number
Rea=(Ws*8)/kiv; %% renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3))*((Tsk1/Tamb)^(-0.14)));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if Qabse2>0
    Qabs2= Qabs2+Qabse2;
    Qabse(lr6,lr5)=Qabse2;
    Qrade(lr6,lr5)=Qrae;
    Qconve(lr6,lr5)=Qce;
    Tfs(lr6,lr5)=Tfsk;
    Tss(lr6,lr5)=Tsk1;
else
    Qabse2=0;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tfsq= zeros(1,110); %% Tfsq: temperature of the fluid as sequence of the fluid flow
sq=1;
Tfsk=Tink; %% initial value for fluid temperature at block which equal 290+273.15
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Qabse1=0;
Qabse2=0;
Qtb2=0;
for lr5=13:1:24;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if mod(lr5,2) ==0
        bls=[9, 8, 7, 6, 5, 4, 3, 2, 1];
    else
        bls=[1, 2, 3, 4, 5, 6, 7, 8, 9];
    end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    for lr66=1:1:9;
        lr6=bls(lr66);
        sq=sq+1;
    end
end

```

```

%% *assumptions*
Qabse1=flr(lr6,lr5);
Qtb2=Qtb2+Qabse1;
cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
Tfsk=Tink+(Qtb2/(mfp* cpL));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if (Tfsk>=Touk);
    Tfsk=Touk;
end
Tfsq(sq)=Tfsk;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tp=(Tfsk-273.15); %% temperature of the material pipe(c)

%% pipe thermal conductivity (w/(m.k))
ckp = (Tp-501.82)/328.69;
kp = 0.15166*ckp^8 + 0.17318*ckp^7 +(-0.42419)*ckp^6 + (-0.28009)*ckp^5
+0.56529*ckp^4 + 0.43014*ckp^3 +(-0.016959)*ckp^2 + 5.2173*ckp +19.528;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% characteristic of the fluid
spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
    kL=0.443+(1.9*(10^-4)*(Tfsk-273.15)); %% liquid thermal conductivity
(w/(m.k))
dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^-4)*(Tfsk-273.15)^2))/1000)-
((1.474*(10^-7)*(Tfsk-273.15)^3)/1000);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vf= (mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity
Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% surface temperature equation

Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp))+(1/(hl*pi*0.02252*1)))+(Tfsk-
273.15);
Tsk1=Tsc1+273.15;
%% radiation losses
    hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
    hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
    Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)

```

```

cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
(j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
(w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for air
(pa.s)
Pra=(dyva*cpa)/ka; %% prantle number of air
kiv=dyva/dea; %% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %% grashof number
Ra=Gr*Pra; %% ralih number
Rea=(Ws*8)/kiv; %% renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3))*((Tsk1/Tamb)^(-0.14)));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while abs(Qabse1-Qabse2)>0.001
    Qtb2=Qtb2-Qabse1;
    Qabse1=Qabse2;
    Qtb2=Qtb2+Qabse1;
    cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
    Tfsk=Tink+(Qtb2/(mfp*cpL));
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if (Tfsk>=Touk);
        Tfsk=Touk;
    end
    Tfsg(sq)=Tfsk;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    Tp=((Tfsk-273.15)+Tsc1)/2; %% temperature of the material pipe(c)
    %% pipe thermal conductivity (w/(m.k))
    ckp = (Tp-501.82)/328.69;
    kp = 0.15166*ckp^8 + 0.17318*ckp^7 + (-0.42419)*ckp^6 + (-0.28009)*ckp^5
+0.56529*ckp^4 + 0.43014*ckp^3 + (-0.016959)*ckp^2 + 5.2173*ckp +19.528;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %% characteristic of the fluid
    spv=1/(2090-(0.636*(Tfsk-273.15))); %% liquid specific volume (m^3/kg)
    cpL=1443+0.172*(Tfsk-273.15); %% liquid specific heat (j/(kg.k))
    kL=0.443+(1.9*(10^(-4))*(Tfsk-273.15)); %% liquid thermal conductivity
(w/(m.k))
    dyv=((22.714-(0.12*(Tfsk-273.15)))+(2.281*(10^(-4))*(Tfsk-273.15)^2))/1000)-
((1.474*(10^(-7))*(Tfsk-273.15)^3))/1000;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    Vf= (mfp/38)/((1/spv)*(3.976*10^(-4))); %% fluid velocity

```

```

Re=((1/spv)*Vf*0.02252)/dyv; %% renold number
Pr=(dyv*cpL)/kL; %% prantle number
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
hl=(kL/0.02252)*0.023*(Re^0.8)*(Pr^0.4); %% molten salt convective heat
transfer w/m^2.k
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% surface temperature equation

Tsc1=(Qabse1/38)*((0.1045/(2*pi*1*kp))+(1/(hl*pi*0.02252*1)))+(Tfsk-
273.15);
Tsk1=Tsc1+273.15;
%% radiation losses
hra=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tamb^2)*(Tsk1+Tamb);
hrs=(5.67*10^(-8))*0.88*0.5*(Tsk1^2+Tskyk^2)*(Tsk1+Tskyk);
Qrae=hra*Asu*(Tsk1-Tamb)+hrs*Asu*(Tsk1+Tskyk);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %% convective losses
Tfi=(Tsk1+Tamb)/2;
dea=(351.99/Tfi)+(344.84/Tfi^2); %% density of air (kg/m^3)
cpa=1030.5-(0.19975*Tfi)+(3.9734*(10^(-4))*Tfi^2); %% air specific heat
(j/(kg.k))
ka=(2.334*(10^(-3))*(Tfi^(3/2)))/(164.54+Tfi); %% air thermal conductivity
(w/(m.k))
dyva=((1.4592*(Tfi^(3/2)))/(109.1+Tfi))*10^(-6); %% dynamic viscosity for
air (pa.s)
Pra=(dyva*cpa)/ka; %% prantle number of air
kiv=dyva/dea; %% kinematic viscosity (m^2/s)
Gr=(9.81*(1/Tfi)*(Tsk1-Tamb)*9)/kiv^2; %% grashof number
Ra=Gr*Pra; %% ralih number
Rea=(Ws*8)/kiv; %% renold number for force convection in air
hnat=(ka/9)*(0.098*(Gr^(1/3))*((Tsk1/Tamb)^(-0.14)));
hfor=(ka/8)*(0.3+0.488*(Rea^0.5)*(1+(Rea/282000)^0.625)^0.8);
hm=((hnat^3.2)+(hfor^3.2))^(1/3.2);
Qce=hm*Asu*(Tsc1-tamb);
%% reflected losses
Qrfe=(1-0.95)*flr(lr6,lr5);
%% absorber energy from receiver
Qabse2=flr(lr6,lr5)-(Qrae+Qce+Qrfe);

end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if Qabse2>0
Qabs2= Qabs2+Qabse2;
Qabse(lr6,lr5)=Qabse2;
Qgrade(lr6,lr5)=Qrae;
Qconve(lr6,lr5)=Qce;
Tfs(lr6,lr5)=Tfsk;

```

```

        Tss(lr6,lr5)=Tsk1;
    else
        Qabse2=0;
    end
    %%%%%%%%%%%%%%
end
end
%%%%%%%%%%%%%
end
end

```

