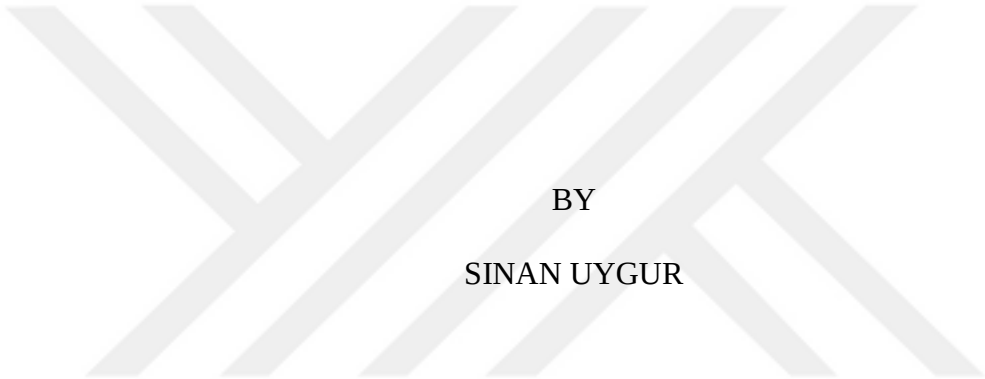


DETAILED SIMULATIONS OF PARABOLIC TROUGH COLLECTOR FOR
INVESTIGATING ENHANCEMENT OF HEAT TRANSFER TO ABSORBER
TUBE FLOW

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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SINAN UYGUR

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Approval of the thesis:

**DETAILED SIMULATIONS OF PARABOLIC TROUGH COLLECTOR
FOR INVESTIGATING ENHANCEMENT OF HEAT TRANSFER TO
ABSORBER TUBE FLOW**

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ABSTRACT

DETAILED SIMULATIONS OF PARABOLIC TROUGH COLLECTOR FOR INVESTIGATING ENHANCEMENT OF HEAT TRANSFER TO ABSORBER TUBE FLOW

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In this thesis, a detailed method to simulate heat transfer and fluid flow of parabolic trough solar collectors is presented. An optical model of the considered collector is created with Tonatiuh ray tracing program. The data of ray tracing analysis is exported to MATLAB as a binary file for post-processing. Curve fitting and surface fitting to the data are performed to obtain the heat flux distribution on the absorber tube's outer surface. User-defined functions (UDFs) for ANSYS Fluent Computational Fluid Dynamics (CFD) code are created with the fit relations. The UDFs are used as boundary conditions in ANSYS Fluent to solve the tube fluid flow and the heat transfer to the heat transfer fluid. The results of the CFD analyses are compared with the existing experimental data for validation of the collector numerical model. The maximum error between the CFD and experimental results is observed to be 3.58%.

Moreover, heat flux distribution on the absorber tube is analyzed for six different incidence angles. Total solar energy on the tube surface and ineffective lengths of the absorber tube are calculated for these six different sun positions. Furthermore, four different enhanced inner tube geometries are investigated to increase the heat transfer inside the absorber tube. The investigated geometry is a plus-shaped insert fin. This geometry leads to heat transfer improvement due to increased heat transfer surface areas and improved flow characteristics. Among the investigated

enhancement options, the plus-shaped fin insert with 30° rotation deemed to be the best option.

Keywords: Parabolic Trough Collector, Ray Tracing, Heat Flux Distribution, Heat Transfer Enhancement, Variable Incidence Angle



ÖZ

SOĞURUCU BORU AKIŞINA ISI AKTARIMININ ARTTIRILMASININ İNCELENMESİ İÇİN DETAYLI PARABOLİK OLUKLU KOLLEKTÖR SİMÜLASYONLARI

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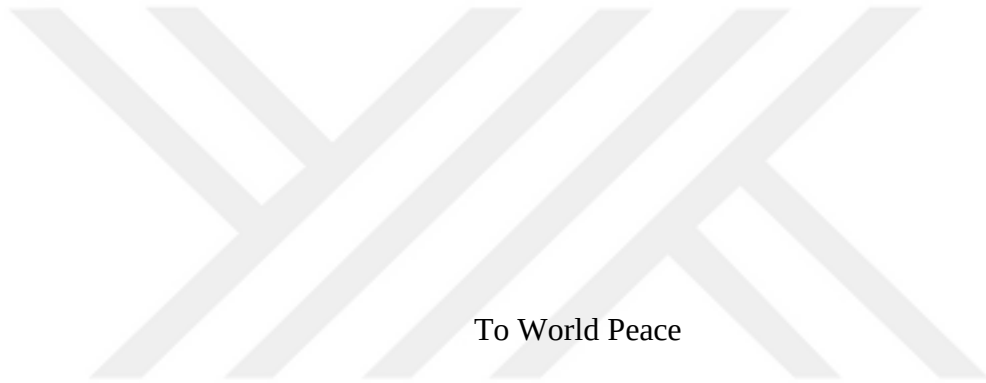
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Bu tezde, parabolik oluklu kollektörlerdeki ısı transferinin ve akışın simülasyonu için detaylı bir yöntem sunulmuştur. Parabolik oluklu kollektörün optik modeli bir ışın izleme programı olan Tonatiuh ile oluşturuldu. Işın izleme analiz sonuçları ileri işleme için MATLAB programına biner dosya olarak aktarıldı. Soğurucu tübün dış yüzeyindeki ısı akısı dağılımını elde etmek için eğri uydurma ve yüzey uydurma işlemleri yapıldı. Eğri uydurma ve yüzey uydurma işlemlerinden elde edilen denklemler ile Fluent programı için kullanıcı tanımlı fonksiyonlar oluşturuldu. Kullanıcı tanımlı fonksiyonlar tüp akışını ve ısı transferini çözmek için Fluent programında sınır koşulları olarak kullanıldı. Modeli doğrulamak için hesaplamalı akışkanlar dinamiği (HAD) sonuçları deneysel sonuçlarla karşılaştırıldı. HAD ve deneysel sonuçlar arasındaki maksimum hata %3.58.

Buna ek olarak, soğurucu tüp üzerindeki ısı akısı dağılımı altı farklı gelme açısı için analiz edildi. Soğurucu tübün yüzeyindeki toplam güneş enerjisi ve tüp etkisiz uzunlukları Güneş'in bu altı konumu için hesaplandı. Dahası, tübün içindeki ısı transferini artırmak için dört farklı tüp geometrisi incelendi. İncelenen geometri artı şeklinde bir fin. Bu geometri ısı transferi yüzey alanını arttırdığı ve akış özelliklerini iyileştirdiği için, daha iyi ısı transferi sağlar. İncelenen geometriler arasında 30° döndürülmüş artı şeklindeki fin en iyi seçenek oldu.

Anahtar Kelimeler: Parabolik Oluklu Kollektör, Işın İzleme, Isı Akısı Dağılımı,
Soğurucu Tübün İçindeki Isı Transferini Artırmak, Değişken Gelme Açısı





To World Peace

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LIST OF ABBREVIATIONS

ABBREVIATIONS

CFD	Computational Fluid Dynamics
CR	Central Receiver
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
EW	East-West
HTF	Heat Transfer Fluid
IAM	Incidence Angle Modifier
LCR	Local Concentration Ratio
LFC	Linear Fresnel Collector
LFCs	Linear Fresnel Collectors
MCRT	Monte Carlo Ray Tracing
NREL	National Renewable Energy Laboratory
NS	North-South
PSA	Plataforma Solar De Almeria
PTC	Parabolic Trough Collector
PTCs	Parabolic Trough Collectors
S2S	Surface-to-Surface
UDF	User Defined Function
UDFs	User Defined Functions

LIST OF SYMBOLS

SYMBOLS

c_p	Specific Heat
$G_{glass\ outer}$	Outer Diameter of the Glass Cover
G_{beam}	Incident Beam Irradiance
h_{wind}	Wind Heat Transfer Coefficient
I	Turbulence Intensity
k	Thermal Conductivity
$K_{\tau\alpha}$	Incidence Angle Modifier
q	Local Energy Flux
V_{wind}	Wind Speed
θ	Incidence Angle
ρ	Density
μ	Dynamic Viscosity
ε_{cermet}	Emissivity of The Cermet Coating

CHAPTER 1

INTRODUCTION

Concentrated Solar Power (CSP) is one of the most promising renewable energy technologies to satisfy the energy demand of the world by decarbonizing the electricity generation. In CSP systems, sunlight is concentrated on an area with the help of mirrors. Then, this focused energy can be used for electricity generation and heating. There are four different relatively mature CSP technologies: the central tower, parabolic trough collector, parabolic dish, and linear fresnel collector. The central tower and the parabolic dish are point focus systems, whereas the parabolic trough and the linear fresnel collectors are line focus systems. Among these four systems, the Parabolic Trough Collector (PTC) is one of the most advanced and mature CSP technology.

PTCs are widely used both for electricity generation and heating. Many CSP plants use parabolic troughs because their annual optical performance is superior[1] to other CSP technologies.

1.1 Components of a PTC

A parabolic trough collector has four main components: the parabolic mirror, the absorber tube, the synthetic oil, and the glass cover.

1.1.1 Parabolic Mirror

Sheet metal is bent into a parabola shape so that incoming Sunlight is concentrated on to the focal line of the parabolic mirror where the absorber tube is located. The surface of the parabolic mirror reflectivity is generally greater than 0.9. Three

parameters define the parabolic mirror. These are its length, its aperture width, and the focal length of the reflector surface.

The parabolic mirror stands on a strong structure. This structure follows the Sun with a one-axis tracker. It is found that the best orientation of a PTC for maximum efficiency is the North-South (NS) orientation[2] with East-West tracking of the sun. Higher temperatures can be achieved by using larger mirrors. On the other hand, the larger parabolic mirror surface area results in more wind load and vibration. Therefore, larger mirrors require stronger structures to handle the increasing wind load.

Moreover, the parabolic mirrors in a PTC power plant can shadow each other. Therefore, the distance between them should be arranged accordingly. An image from Noor 1 CSP plant is given in Figure 1.1 to show the importance of the distance between PTC lines.



Figure 1.1. An image from Noor 1 CSP plant [3]

1.1.2 Absorber Tube

An absorber tube is placed at the focal line of the parabolic mirror. The tube material is generally stainless steel. A selective coating with high absorptivity and low emissivity is applied to the outer surface of the tube. The absorber tube with a glass cover is shown in Figure 1.2.



Figure 1.2. The absorber tube with the glass cover [4]

1.1.3 Synthetic Oil

Synthetic oil flows inside the absorber tube. The main objective of a PTC system is to heat synthetic oil as much as possible. The oil temperature can reach up to 400°C. In this thesis, Syltherm 800 oil is considered for the analyses.

1.1.4 Glass Cover

The glass cover is used to reduce convective and long-wavelength radiative heat losses from the absorber tube. The region between the glass cover and the absorber tube is vacuumed to minimize the natural convection heat losses. The glass cover has a very high transmissivity value, generally about 0.95 in visible and ultraviolet spectrum. It selectively reflects some of the infrared radiation emitted by the absorber tube by creating greenhouse effect.

1.2 Organization of The Thesis

In CHAPTER 1, brief information is given about the PTC and its advantages. In Section 1.1, the components of a PTC are explained.

In CHAPTER 2, the literature review is given. In Section 2.1, the studies about optical and thermal modeling of PTCs are summarized. In Section 2.2, the most

recent studies investigating increasing the heat transfer inside absorber tube are presented. In Section 2.3, the objective of this thesis is explained.

In CHAPTER 3, the optical and thermal model used in this thesis are explained. The optical model is presented in Section 3.1, and the thermal model is presented in Section 3.4.

In CHAPTER 4, the results are presented. The optical and thermal model validations are given in Section 4.1. Free convection and radiative heat losses for the LS-2 PTC absorber tube are shown in Section 4.2. Heat flux distribution around the LS-2 absorber tube for six different Sun positions are given in Section 4.3. The ineffective lengths of an absorber tube due to variable incidence angle are presented in Section 4.3.7. Finally, the new tube geometry with a plus-shape insert is compared with a standard absorber tube in Section 4.5.

The conclusions of the thesis and recommendations for future work are given in CHAPTER 5.

CHAPTER 2

LITERATURE REVIEW

In this part, a literature review about optical and thermal modeling of parabolic trough collectors (PTCs) is given. Moreover, the recent studies that investigate to increase the heat transfer inside the absorber tube are summarized. Finally, the gaps in the literature that this thesis fills are explained.

2.1 Optical and Thermal Modeling of PTC

An optical modeling study is performed by Abbas et al. [2]. The study compares the optical performance of PTCs and linear fresnel collectors (LFCs). The authors developed their codes with MATLAB to perform the Monte-Carlo Ray Tracing (MCRT) analysis. The results of developed codes are compared with the results of SolTrace, and they are in good agreement with each other. It is stated that the North-South orientation gives the maximum efficiency for PTCs. It is concluded that the optical efficiency of PTCs is superior to that of LFCs since the parabolic mirror can focus almost all of the incoming sunlight on the absorber tube.

Another optical modeling study is performed by Kincaid et al.[1]. This study compares the optical performance of a PTC, an LFC, and a Central Receiver (CR) using SolTrace. It is concluded that the PTC (EuroTrough model ET150) has the highest annual optical efficiency with 60%. The CR (SAM model) has the second-highest annual optical efficiency with 52%, and the LFC (Hyperlight) has the least annual optical efficiency with 40%. The monthly DNI weighted average efficiency for the three technologies with two different collector orientations for the PTC and the LFC is presented in Figure 2.1.

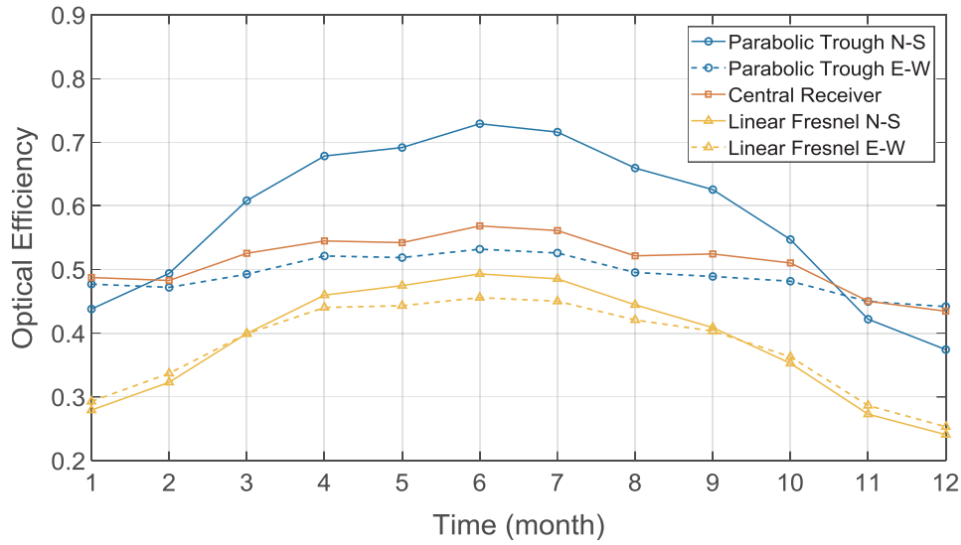


Figure 2.1. The monthly DNI weighted average efficiency for the three technologies with collector orientation for PTC and LFC [1]

From Figure 2.1, it can be seen that the N-S orientation of the PTC gives higher annual optical efficiency compared to the E-W orientation.

Zou et al. [5] studied the optical performance of a PTC by developing an MCRT code. The effects of geometrical parameters such as the mirror aperture width, the focal length, and the absorber tube diameter on the optical performance are investigated. It is concluded that the absorber tube diameter must be larger than the reflected light cone's size. Otherwise, there will be a significant optical loss due to escaping rays.

Cheng et al. [6] presented a method to simulate the LS-2 PTC by combining a developed MCRT code and ANSYS Fluent. The S2S (surface to surface) radiation model of ANSYS Fluent is used to calculate radiative heat loss from the tube's outer surface. The $k - \varepsilon$ turbulence modeling is chosen to solve the tube flow. It is explained that eddies are observed in the tube due to non-uniform solar heat flux conditions. Two different synthetic oils (Syltherm 800 and Therminol VPI) and two molten salts (Nitrate Salt and Hitec XL) are compared. It is concluded that the two synthetic oils' heat transfer performances are better than the two salts. Moreover, the pressure drop values are lower for the synthetic oils compared to the two molten salts.

Wu et al. [7] developed a method to simulate PTCs by using an MCRT code and ANSYS Fluent. The heat transfer mechanisms for the PTC are presented in Figure 2.2.

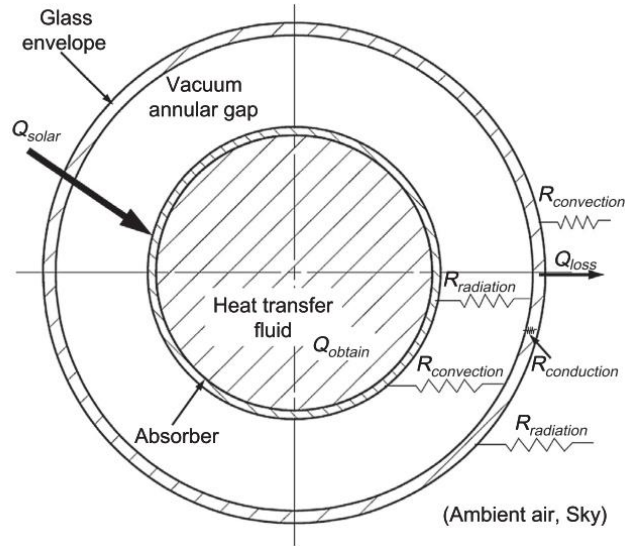


Figure 2.2. The heat transfer mechanism for a PTC [7]

The S2S (surface to surface) radiation model is used to calculate radiative heat loss from the tube's outer surface. The $k - \varepsilon$ turbulence modeling is chosen to solve the tube flow. It is stated that obtaining the non-uniform temperature distribution around the tube's outer surface is essential to optimize the absorber tube's structure.

Another optical and thermal analysis of a PTC is performed by Wang et al.[8]. SolTrace is used to find the non-uniform solar heat flux distribution. The $k - w$ turbulence model is preferred to solve the tube flow. It is stated that absorber tube's thermal stress and deformations are greater than the glass cover. The Von Mises effective stress of the absorber tube and the glass cover are shown in Figure 2.3.

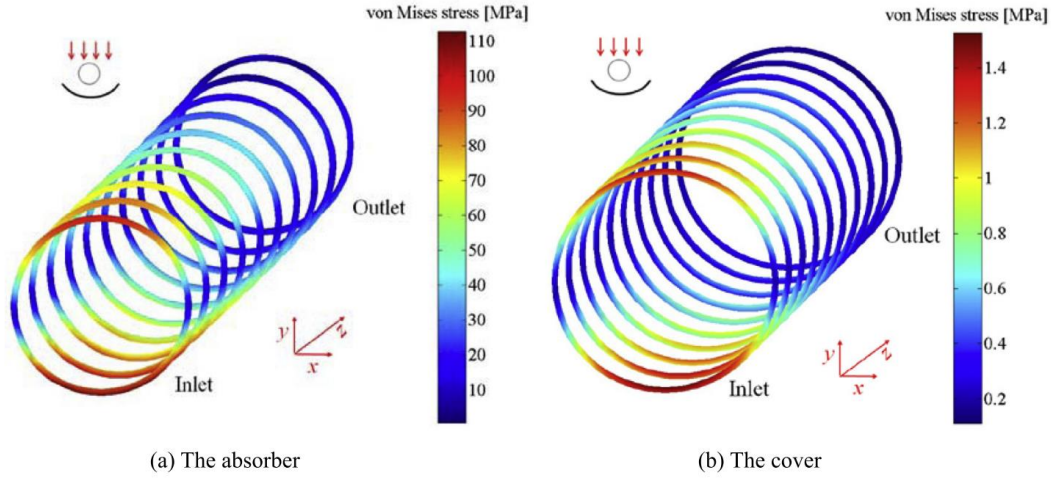


Figure 2.3. The Von Mises effective stress of the absorber tube (a) and the glass cover (b) (from [8])

It is concluded that the circumferential temperature difference of the absorber tube increases as the DNI increases and decreases as the heat transfer fluid's (HTF's) temperature and velocity at the inlet increase. It is also concluded that the HTF temperature difference at a cross-section increases as DNI increases and decreases as the inlet velocity of HTF increases.

Ghomrassi et al. [9] performed a numerical study to optimize the PTC absorber tube geometry. The solar heat flux distribution is calculated using SolTrace. Then the tube flow is solved with ANSYS Fluent using $k - \varepsilon$ RNG turbulence model. The effect of changing the absorber tube diameter on the thermal performance is investigated. It is concluded that as the tube diameter increases, the solar heat flux on the absorber tube's bottom periphery increases. It is also concluded that the PTC thermal performance increases with increasing tube metallic thickness.

2.2 Increasing Heat Transfer Inside the Absorber Tube

Munoz and Abanades [10] studied the internally finned tubes using ANSYS Fluent. The RNG $k - \varepsilon$ turbulence model is used to solve the tube flow. The surface model for the finned tube and the geometrical variables of the helical fin are given in Figure 2.4 and Figure 2.5, respectively.

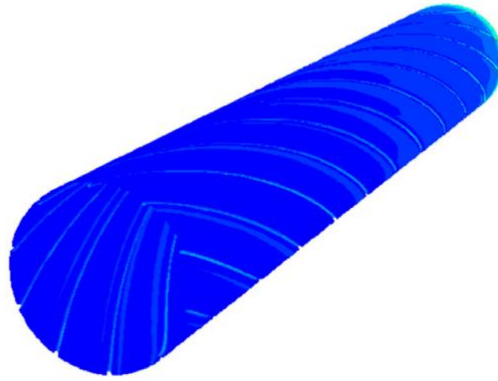


Figure 2.4. Surface model for the finned tube [10]

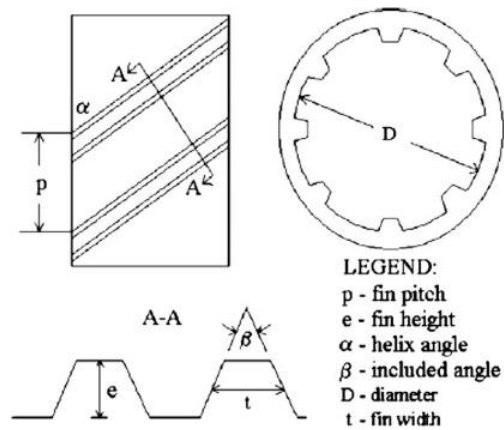


Figure 2.5. Geometric variables of the helical fin [10]

It is concluded that although the pressure drop increases between 10% and 50% depending on the finned tube design, the plant performance can only be increased by 2%.

Cheng et al.[11] studied the unilateral longitudinal vortex generators inside the PTC absorber tube. ANSYS Fluent is used to solve the tube flow. The periodic computational model is given in Figure 2.6.



Figure 2.6. The periodic computational model [11]

The temperature distribution on the smooth absorber tube's inner surface and the tube with longitudinal vortex generators are shown in Figure 2.7.

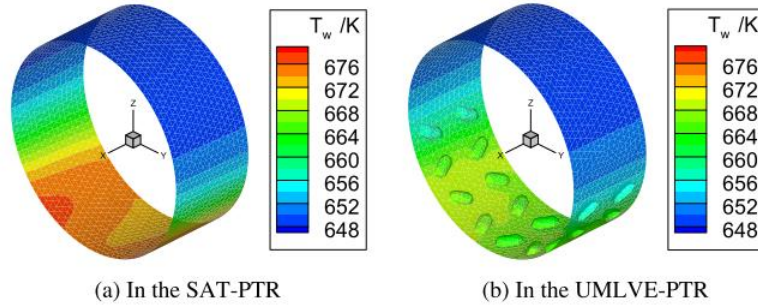


Figure 2.7. The temperature distribution on the smooth absorber tube's inner surface (a) and the tube with longitudinal vortex generators (b) [11]

It is concluded that the average tube wall temperature and the thermal loss of tube with longitudinal vortex generators are less compared to the smooth absorber tube.

Song et al. [12] studied helical screw-tape inserts to enhance thermal efficiency and homogenize the absorber tube temperature distribution. ANSYS Fluent with $k - w SST$ turbulence model is used to solve the tube flow. The schematic of the absorber tube with a helical screw-tape is given in Figure 2.8.

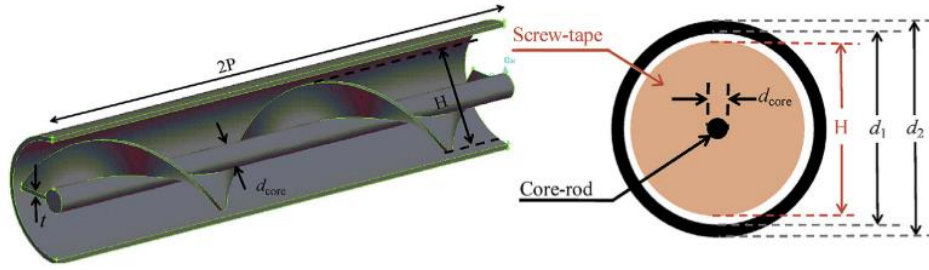


Figure 2.8. The schematic of the absorber tube with helical screw-tape insert [12]

The temperature distribution of the smooth absorber tube and the tube with helical screw-tape insert is given in Figure 2.9.

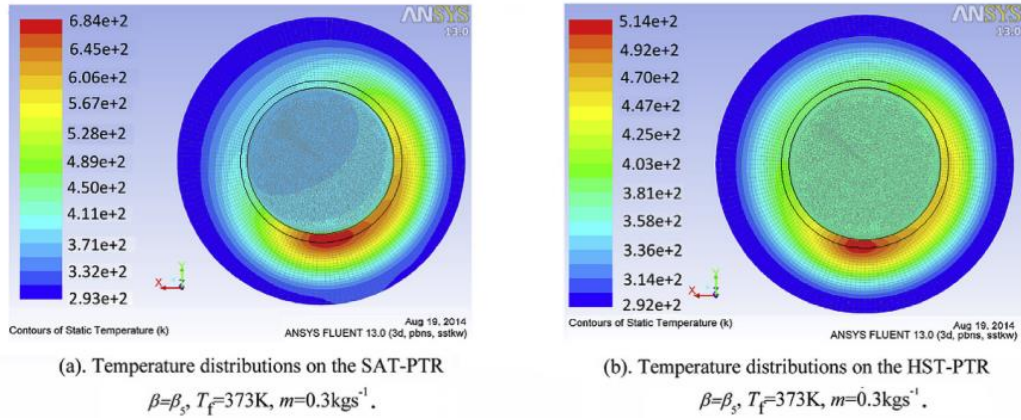


Figure 2.9. The temperature distribution of the smooth absorber tube (a) and the tube with helical screw-tape insert (b) [12]

It is concluded that the helical screw-tape inserts reduce the maximum temperature and temperature difference. The heat loss in a tube with helical screw-tape inserts is almost one-sixth of the smooth absorber tube for inlet temperature $373K$ and flow rate of $0.11 \frac{kg}{s}$.

Huang et al. [13] performed a numerical study on increasing the heat transfer in a PTC absorber tube using dimples, protrusions, and helical fins. The absorber tubes with dimples, protrusions, and helical fins are given in Figure 2.10.

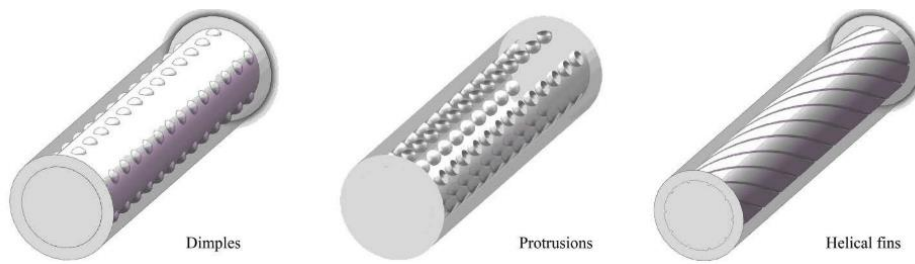


Figure 2.10. The absorber tubes with dimples, protrusions, and helical fins [13]

It is concluded that the absorber tube with dimples has the highest heat transfer increase compared to protrusions and helical fins. The heat transfer increases with increasing dimple depth and increasing dimple number in the circumferential direction. The heat transfer decreases as the dimple pitch increases.

Mwesigye et al. [14] studied the performance of a PTC absorber tube with perforated plate inserts. ANSYS Fluent with the $k - \varepsilon$ realizable turbulence model is used to solve the tube flow. The physical model of the receiver with perforated plates is given in Figure 2.11.

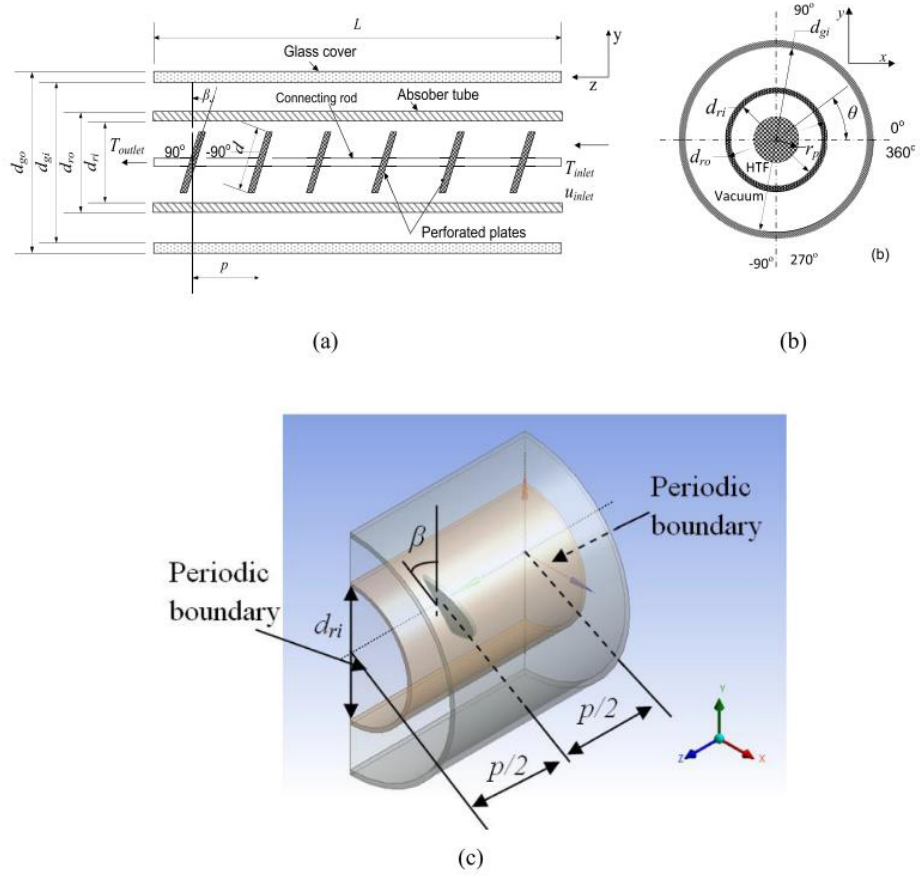


Figure 2.11. The physical model of the receiver, longitudinal section of the receiver with perforated plate inserts (a), the cross-section of the receiver with perforated plates (b), the periodic computational domain (c) [14]

The NSGA-II algorithm is used for multi-objective optimization to obtain Pareto optimal solutions for the Nusselt number and pressure drop. It is concluded that the entropy generation decreases as the angle of orientation increases. It is also concluded that the optimum Reynolds number decreases as plate spacing decreases and plate size increases.

Gong et al. [15] studied the PTC absorber tube with inserted pin fin arrays. The schematic of the absorber tube with inserted pin fin arrays is given in Figure 2.12.

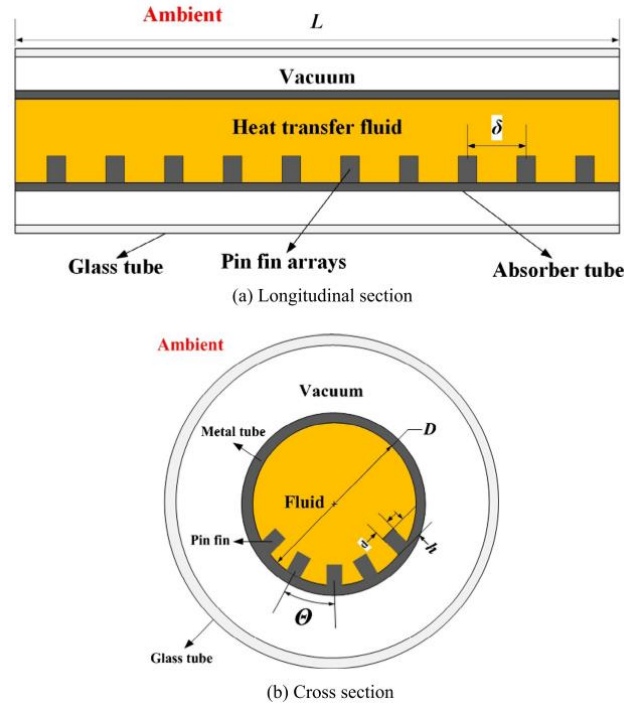


Figure 2.12. The schematic of the absorber tube with inserted pin fin arrays [15]

The absorber tubes with different numbers of pin fin inserts are shown in Figure 2.13.

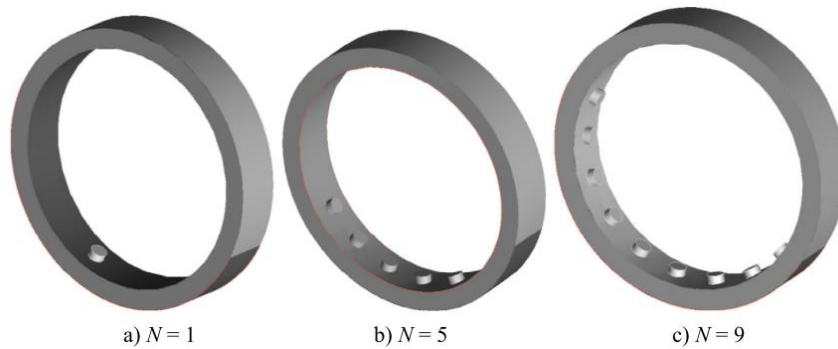


Figure 2.13. The absorber tubes with different number of pin fin inserts [15]

It is concluded that the average Nusselt number can be enhanced up to 9%, and the overall heat transfer performance factor can be increased up to 12%.

Huang et al. [16] performed a numerical analysis on the dimpled PTC absorber tube. ANSYS Fluent is used to solve the tube flow. Six dimples are placed uniformly in the circumferential direction, shown in Figure 2.14.

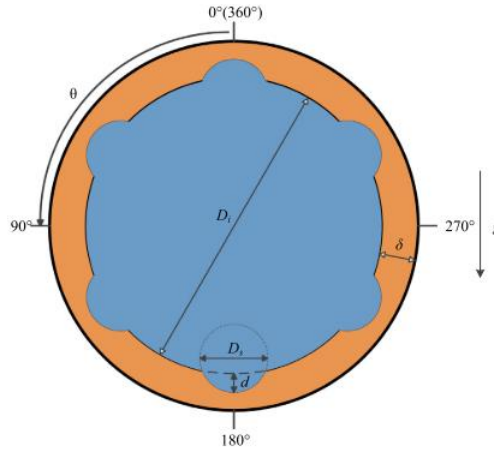


Figure 2.14. Six dimples are placed uniformly in the circumferential direction [16]

It is concluded that deep dimples are much better compared to shallow dimples at the same Grashof number.

2.3 The Objective of the Thesis

Recent studies in the literature [5], [17], [18] obtained the non-uniform heat flux distribution around the absorber tube using a zero-degree incidence angle. However, most of the time, a PTC module cannot get the solar rays with a zero-degree incidence angle because it only has a one-axis tracker. The incidence angle is very important for PTC performance. An LS2 collector performance, with $DNI = 950 \frac{W}{m^2}$, is reduced by approximately 15% for 30° incidence angle and 65% for 60° incidence angle[19].

The first gap that this thesis fills is that the method used in this thesis can simulate PTCs for any incidence angle, i.e., for any position of the sun. A new method is presented to simulate PTCs both optically and thermally by combining Tonatiuh, MATLAB, and ANSYS Fluent. Moreover, ineffective tube lengths are calculated for six different incidence angles. Note that many developed in-house MCRT codes are not publicly available, whereas Tonatiuh is a free package program and can be used by everyone.

The second gap that this thesis fills is that a new absorber tube geometry with four different configurations is investigated to increase the heat transfer inside the absorber tube.



CHAPTER 3

MODEL DESCRIPTION

In this chapter, an LS-2 parabolic trough collector's optical and thermal modeling is explained in detail. Firstly, the LS2 PTC module is created with Tonatiuh. Secondly, data from the Tonatiuh simulation is exported to MATLAB for post-processing. Thirdly, using the post-processed data in MATLAB, user-defined functions (UDFs) are written for ANSYS Fluent to obtain the non-uniform heat flux distribution around the absorber tube. Finally, the LS2 PTC module is created in ANSYS Fluent, and UDFs are inserted into the Fluent model.

The model in this thesis can simulate all PTC systems for any incidence angle.

3.1 Optical Model

Tonatiuh v2.2.4 is used to model the LS2 PTC module optically. It is developed by the National Renewable Energy Center of Spain (CENER) in collaboration with the University of Texas at Brownsville (UTB), with the support of the National Renewable Energy Laboratory (NREL) [20]. Tonatiuh uses the MCRT method to perform simulations, and it can model all the systems which use the sun as the source.

At first, SolTrace was planned to be used for optical modeling. Then, Tonatiuh is chosen due to its ease of use and user-friendly interface.

Note that one can enter the parameters (reflectivity, diameter, aperture width, absorptivity, azimuth, etc.) of the components (parabolic mirror, absorber tube, glass cover, sun, etc.) and also see the 3D model of the object at the same time. However, this is not possible with SolTrace. Moreover, Tonaiuh uses a tree structure (see Figure 3.2) similar to CAD programs, making the model very organized and easy to work with.

LS2 PTC is chosen for this thesis because many experimental and numerical studies exist in the literature. Properties of LS2 PTC module tested at Sandia National Laboratories[21] are given in Table 3-1.

Table 3-1 Properties of LS2 PTC tested at Sandia National Laboratories[21]

Variable	Value	Unit
Aperture Width	5	m
Aperture Length	7.8	m
Focal Length	1.84	m
Rim Angle	70	°
Concentration Ratio	71	-
Mirror Reflectivity	0.93	-
Absorber tube Inner Diameter	66	mm
Absorber tube Outer Diameter	70	mm
Absorber tube Coating Absorptivity	0.96	-
Absorber tube Coating Emissivity	$0.000327(T)[K] + 0.023349$	-
Diameter of the solid plug in the absorber tube	50.8	mm
Glass Cover Inner Diameter	109	mm
Glass Cover Outer Diameter	115	mm
Glass Cover Transmissivity	0.95	-

The critical points about creating the optical model of LS2 PTC are given from Section 3.1.1 to Section 3.1.8. The details of Tonatiuh usage are presented in APPENDIX A, APPENDIX B, and APPENDIX C.

3.1.1 General Outlook of Tonatiuh

The interface of Tonatiuh is similar to CAD programs, which makes it very easy to use. In Figure 3.1, the general outlook of Tonatiuh with an LS2 PTC module is shown.

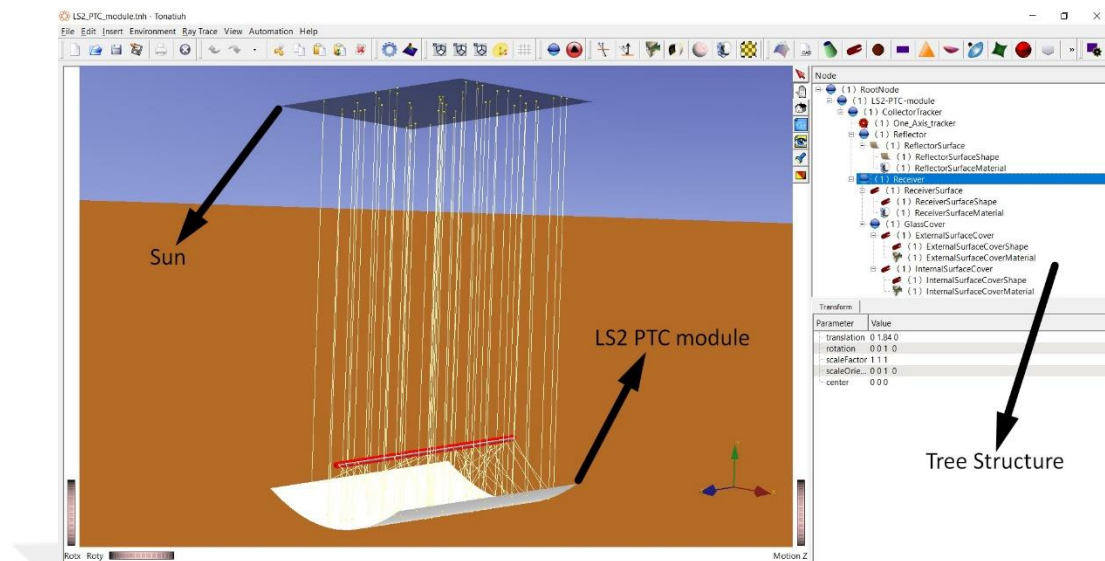


Figure 3.1. General Outlook of Tonatiuh with an LS2 PTC module

The whole PTC system is created with Tonatiuh.

In Figure 3.2, a detailed tree structure of the LS2 PTC module is presented.

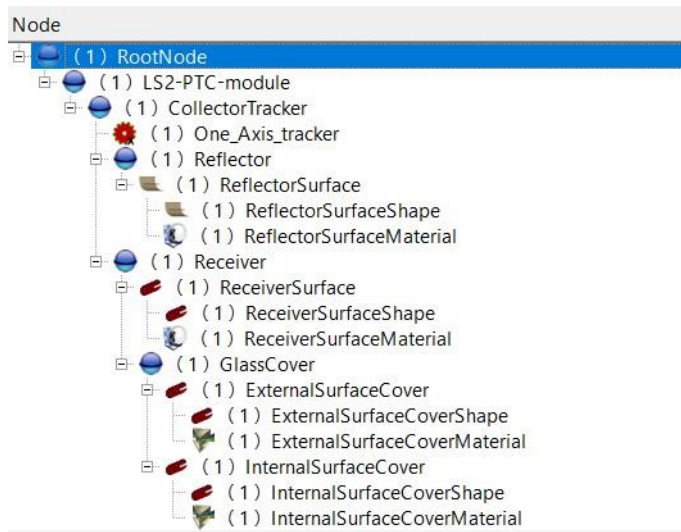


Figure 3.2. The detailed tree structure of the LS2 PTC module

In Figure 3.2, it can be seen that one axis tracker is placed above both the reflector and receiver so that they track the sun together. PTC system with one axis tracker follows the sun in the east-west direction.

3.1.2 Orientation of the PTC and the One Axis Tracker

PTC system extends along the North-South (N-S) axis. In other words, the z-axis in Tonatiuh is the N-S axis. The N-S orientation is chosen for this thesis because it gives the maximum efficiency for a PTC system [2]. The coordinate system of Tonatiuh is defined in Table 3-2. See Figure 3.3 for the PTC system orientation.

Table 3-2 Coordinate system of Tonatiuh

Coordinate in Tonatiuh	Direction
-z	North
+z	South
+x	East
-x	West

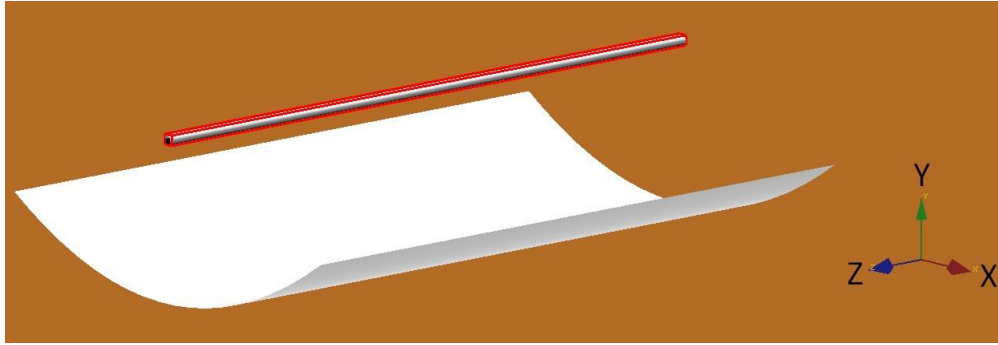


Figure 3.3. Orientation of the PTC system

First, the parabolic mirror, the absorber tube, and the glass cover geometries are created.

3.1.3 Parabolic Reflector

First, a group node, called “Reflector,” is created for the parabolic mirror. Then, a surface node, called “ReflectorSurface” is defined under the group node. Finally, the shape and the material for the surface node are implemented. See APPENDIX A for details.

The parabolic mirror starts from $z = 0$ and extends up to $z = 7.8m$.

3.1.4 Absorber Tube

First, a group node, called “Receiver,” is created for both the absorber tube and the glass cover. Then, a surface node, called “ReceiverSurface” is defined under the group node. Finally, the shape and the material for the surface node are implemented. See APPENDIX B for details.

The absorber tube starts from $z = 0$ and extends up to $z = 7.8m$.

3.1.5 Glass Cover

First, a group node, called “GlassCover,” is created for the glass cover. Then, two surface nodes are defined under the group node. One surface node is for the glass cover’s outer surface, and the other surface node is for the inner surface of the glass cover. Finally, the shape and material for the surface nodes are implemented. See APPENDIX C for details.

The refraction index is chosen as 1 for air and 1.5 for glass cover. Glass cover starts from $z = 0$ and extends up to $z = 7.8m$.

3.1.6 Sun Definition

After defining the PTC geometry, the Sun definition must be introduced.

The section in Tonatiuh to insert the Sun is shown in Figure 3.4.

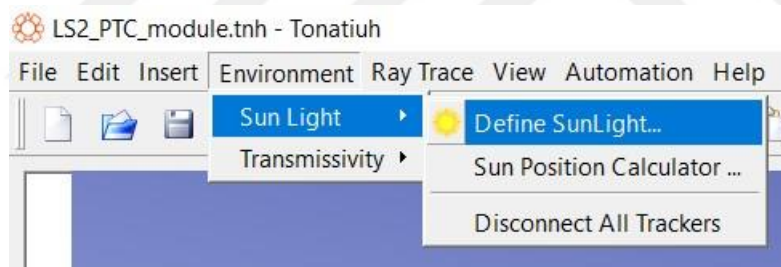


Figure 3.4. The section in Tonatiuh to insert Sun

The “Define SunLight” option allows users to manually enter the parameters (Sun shape, DNI, azimuth angle, angle of incidence, etc.). Therefore, it is used for the Sun definition. Note that the “Sun Position Calculator” in Figure 3.4 is also quite useful since it allows users to select the location and time on Earth directly.

Details of the Sun definition are shown in Figure 3.5.

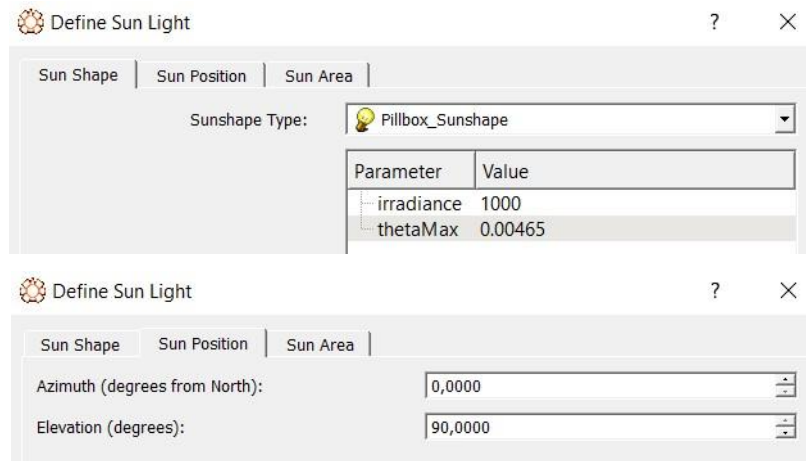


Figure 3.5. Details of the Sun definition

In Figure 3.5, The “Elevation (degrees)” (under the “Sun Position” tab) can be changed to obtain a variable incidence angle.

$$Incidence\ angle(degrees) = 90 - Elevation(degrees) \quad (3.1)$$

After the Sun is defined, the PTC module is placed in the East-West axis due to the already inserted one-axis tracker. Therefore, the system is rotated $\frac{3\pi}{2}$ (or $\frac{\pi}{2}$) radians to place the PTC module back in the North-South axis. The details of the process are shown in Figure 3.6.

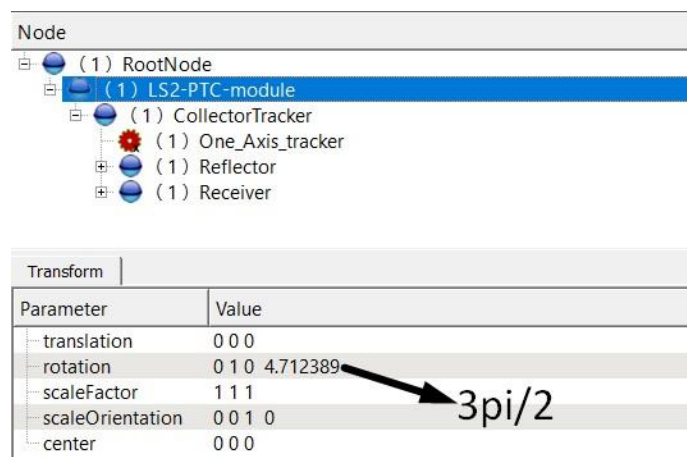


Figure 3.6. Rotation of the system after defining the Sun

Note that in Figure 3.6, “0 1 0” at the “rotation” part stands for the x-axis, y-axis, and z-axis, respectively. The x-axis and y-axis have the “0” value so that they are not used for rotation. The y-axis has the “1” value so that it is used for rotation. In other words, the PTC system is rotated $\frac{3\pi}{2}$ radians around the y-axis.

3.1.7 Number of Rays

After the PTC geometry is defined and the Sun definition is introduced, the number of rays must be determined to start the ray-tracing simulation.

Tonatiuh uses the MCRT method, which is a stochastic approach. Therefore, one has to make sure that the number of rays used is sufficient enough so that the total solar irradiation on the absorber tube’s surface can be accurately calculated. The SEGS LS-2 PTC with a 7.8 m length is used to determine the number of rays. The total power on the tube for different ray numbers is given in Table 3-3.

Table 3-3 The total power on the tube for different ray numbers

Ray Number	Total Power on the Tube [W]
1000000	32597.7
2500000	32597.0
5000000	32587.9
7500000	32591.2
10000000	32591.4
20000000	32590.3
35000000	32590.6

From Table 3-3, it is decided that using 10 million rays is good enough for the optical analyses.

3.1.8 Exporting the Absorber Tube Tonatiuh Data for Post-Processing

The PTC geometry is created, the Sun definition is introduced, and the number of rays has been determined. Now, ray-tracing simulation can be performed.

First, the number of rays and the random number generation algorithm is chosen. Details are shown in Figure 3.7 and Figure 3.8.

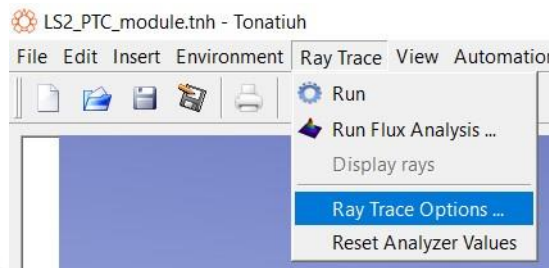


Figure 3.7. The section in Tonatiuh to choose ray-trace settings

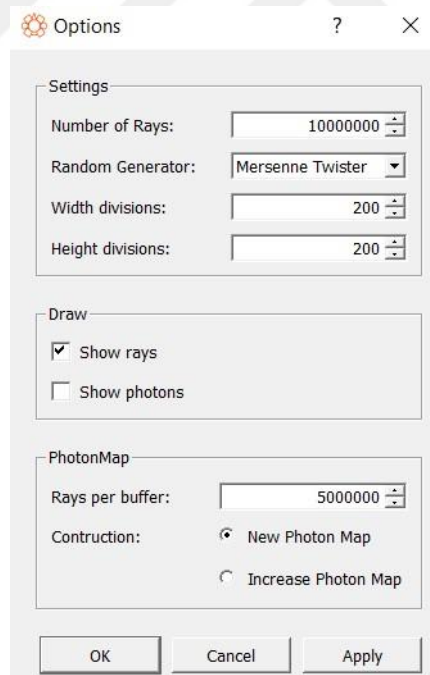


Figure 3.8. Details of the ray-trace settings

In Figure 3.8, Mersenne Twister is chosen for “Random Generator”. Ten million, which can be changed by the user, is entered for “Number of Rays”.

Secondly, Tonatiuh ray-tracing data is exported as a binary file. Details are explained in Figure 3.9 and Figure 3.10.

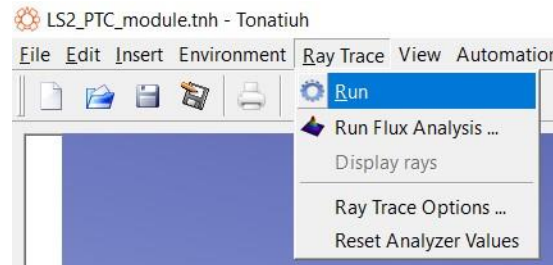


Figure 3.9. The section in Tonatiuh to export ray-tracing data of the absorber tube

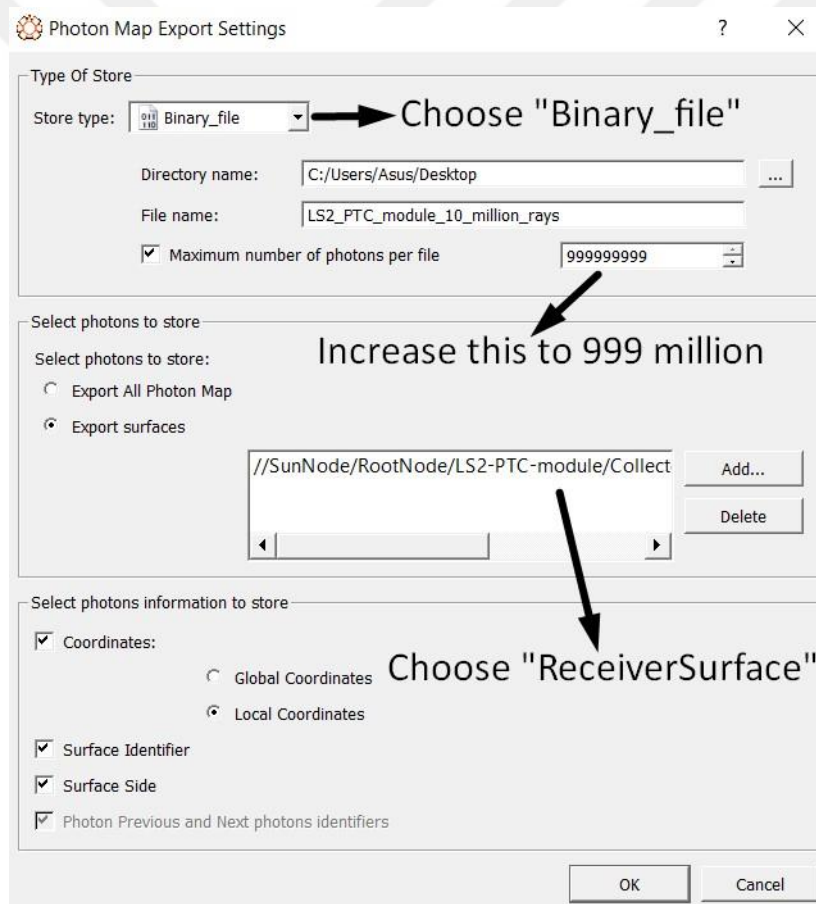


Figure 3.10. Details of exporting ray tracing data of the absorber tube

In Figure 3.10, “Maximum number of photons per file” is increased to 999 million so that all ray-tracing data is written in one file only, which is easier to work with

compared to having multiple binary files. There is no need to export all the simulation data. The photon information on the surface of the absorber tube is extracted only. Therefore, using the “Add...” button, choose “ReceiverSurface” from the tree structure.

In the end, it gives one .dat file and one .txt file. The binary file is read with MATLAB. The general outlook of the .txt file is shown in Figure 3.11.

```

START PARAMETERS
id
x → x-coordinates
y → y-coordinates
z → z-coordinates
side
surface ID
END PARAMETERS
START SURFACES
1 //SunNode/RootNode/LS2-PTC-module/CollectorTracker/Receiver/ReceiverSurface
END SURFACES
0.00404286 → Power of one photon

```

Figure 3.11. General Outlook of the .txt file

In Figure 3.11, the coordinates of rays and one photon's power will be the inputs for the developed MATLAB code.

3.2 Post-processing Tonatiuh Data with MATLAB

One of the most challenging parts of this thesis is post-processing the Tonatiuh simulation data and using them in ANSYS Fluent as boundary conditions. Since the ray-tracing data is saved in a binary file, it is impossible to see this content without using another program. MATLAB R2018b is used to read the binary file coming from the Tonatiuh simulation. The exact location of each photon is extracted from the binary file.

First, a 2D code is developed. The spatial discretization of the absorber tube is performed in the radial direction only.

Finally, a 3D code is developed. The spatial discretization of the absorber tube is performed both in radial and axial directions.

In the end, user-defined functions (UDFs) are written using the developed 3D code for the ANSYS Fluent model.

3.2.1 2D Discretization of the Absorber Tube's Outer Surface

The absorber tube's outer surface is discretized only in the radial direction, similar to all other studies in the literature. In other words, this discretization can be used for zero incidence angle only. In Figure 3.3, x-direction is the radial direction, and z-direction is the axial direction.

In the MATLAB code, the absorber tube's outer surface is divided into four parts. See Figure 3.12 for details.

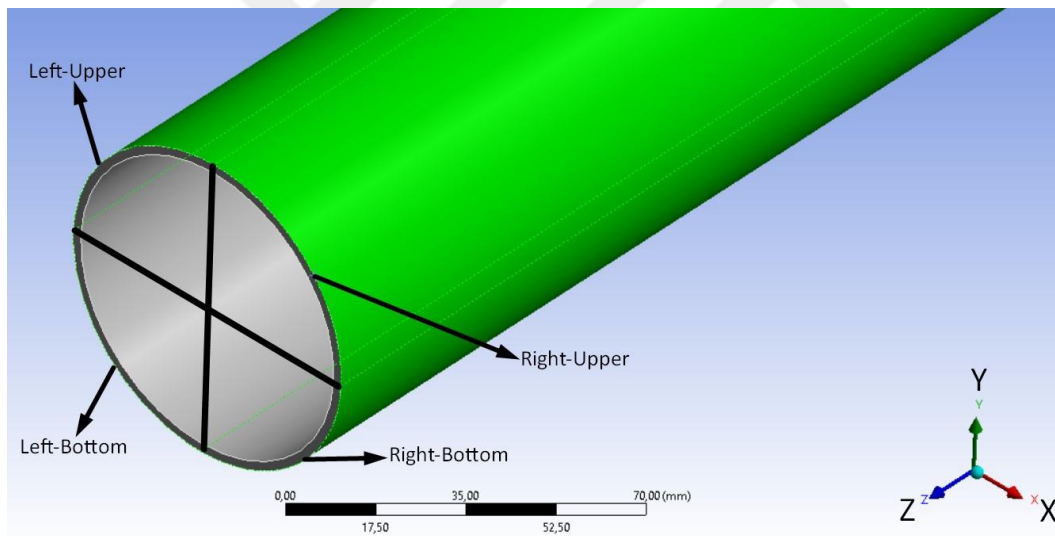


Figure 3.12. The absorber tube outer surface is divided into four parts

“Left-Bottom” and “Right-Bottom” surfaces, which are the surfaces of the absorber tube closer to the parabolic mirror, get significantly higher heat flux compared to “Left-Upper” and “Right-Upper” surfaces. See Figure 3.3 for the orientation of the PTC.

The absorber tube's outer surface is divided into 360 (0 to 360 degrees with 1-degree increment) strips in angular (circumferential) direction. The power of one photon and the exact location of each photon is known. The energy of each strip is calculated. See APPENDIX D for MATLAB code of the 2D discretization approach. Then, MATLAB's curve fitting tool is used. Piecewise curve fitting is performed. The interval from 0 to 0.035 m in angular direction is divided into three sub-intervals for the absorber tube's outer surfaces (Left-Bottom, Right-Bottom, Left-Upper Right-Upper). Piecewise curve-fitting for the "Left-Upper" surface of LS2 PTC module with zero-degree incidence angle is explained in APPENDIX E.

3.2.2 3D Discretization of the Absorber Tube's Outer Surface

The absorber tube's outer surface is discretized in both radial and axial directions. In other words, this discretization can be used for any incidence angle (for any position of Sun).

In the MATLAB code, the absorber tube outer surface is divided into four parts. See Figure 3.12 for details.

The absorber tube's outer surface is divided into 360 (0 to 360 degrees with 1-degree increment) pieces in radial (circumferential) direction and 39 (0 to 7.8 m with 0.2 m increment) pieces in axial direction. The power of one photon and the exact location of each photon are known. The energy of each element is calculated. See APPENDIX F for MATLAB code of the 3D discretization approach. Then, MATLAB's curve fitting tool is used. Piecewise surface fitting is performed. The interval from 0 to 7.8 m in axial direction is divided into three sub-intervals for absorber tube outer surfaces (Left-Bottom, Right-Bottom, Left-Upper, and Right-Upper). Piecewise surface-fitting for the "Left-Bottom" surface of LS2 PTC module with 45 degrees incidence angle is explained in APPENDIX G.

3.2.3 Creating User-Defined Functions (UDFs) for the Absorber Tube

For 2D discretization, piecewise curve fitting is performed. UDFs contain polynomial equations that define the heat flux distribution on absorber tube outer surfaces (Left-Bottom, Right-Bottom, Left-Upper, and Right-Upper). These are 3rd or 4th order polynomial equations, and they have only one independent variable, which is “x”.

For 3D discretization, piecewise surface fitting is performed. UDFs contain polynomial equations that define the heat flux distribution on absorber tube outer surfaces (Left-Bottom, Right-Bottom, Left-Upper, and Right-Upper). These are 4th or 5th order polynomial equations, and they have two independent variables, which are “x” and “z”.

“DEFINE_PROFILE”, which is a function of ANSYS Fluent, is used for the UDFs.

The UDFs are written with “Notepad”. After preparing the UDFs, the Notepad files should be saved with the “.c” extension so that ANSYS Fluent can see them as C files.

UDFs of the 2D discretization approach for the LS2 PTC module with zero-degree incidence angle are given in APPENDIX H.

UDFs of 3D discretization approach for LS2 PTC module with 45 degrees incidence angle are given APPENDIX I.

3.3 Thermal Model for Obtaining the Heat Flux Distribution Around the Absorber Tube

After preparing the UDFs, one has to check whether these UDFs can be used for both the amount of heat flux and the heat flux distribution or not. Therefore, only the heat flux distribution around the LS2 PTC absorber tube is visualized using ANSYS Fluent in this part. No tube flow is solved.

3.3.1 Geometry

The absorber tube starts from $z = 0$ and ends at $z = 7.8 \text{ m}$, similar to the Tonatiuh model. Like the MATLAB code model, the absorber tube outer surface is divided into four parts (Left-Bottom, Right-Bottom, Left-Upper, and Right-Upper). See Figure 3.12 for details.

3.3.2 Mesh

In the mesh, edge sizing is applied to the tube outer surface's circles. Sizing with 30 divisions is applied to each edge. In Figure 3.13, edge sizing is shown. Edge sizing is used to obtain the non-uniform heat flux distribution around the absorber tube accurately.

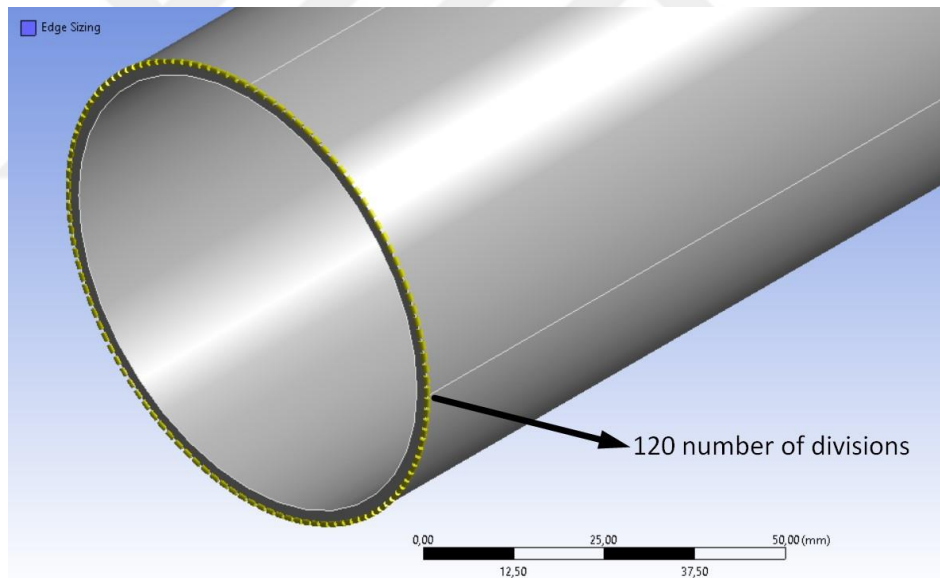


Figure 3.13. Edge Sizing

3.3.3 Boundary Conditions

Under the “Models” tab, “Energy Equation” is checked.

Then, UDFs are introduced to the Fluent model. The below procedure is followed.

User Defined → Functions → Compiled

Note that Visual Studio (2017) is used to compile the UDFs.

In the “Boundary Conditions”, choose the UDFs for the outer surfaces of the absorber tube.

After defining boundary conditions, hybrid initialization is performed. The solution is converged in 2 or 3 iterations since there is no tube flow in the model yet.

3.4 Thermal Model of SEGS LS-2 Solar Collector

In this part, the CFD model of SEGS LS-2 Solar Collector[21] is explained. Note that the test loop could not provide the flow rate of a real SEGS power plant. Therefore, a 2-inch diameter solid plug (a flow restriction device) is inserted inside the absorber tube to obtain similarity between the test and the real case. Oil flow is confined in the region between the absorber tube and the solid plug (flow restriction device). See Figure 3.14 for details.

3.4.1 Geometry

The whole domain starts from $z = 0$ and ends at $z = 7.8\text{ m}$. There are two fluid domains and seven solid domains. Four very thin sheets (volumes) are created outside the tube. These four sections have 0.02 mm in thickness. Data obtained from Tonatiuh is defined as variable heat generation in these four sections. Oil and vacuum regions are the fluid domains. Flow restriction device, absorber tube, four thin heat generation volumes, and glass cover are the solid domains. Geometry from the +z direction is given in Figure 3.14.

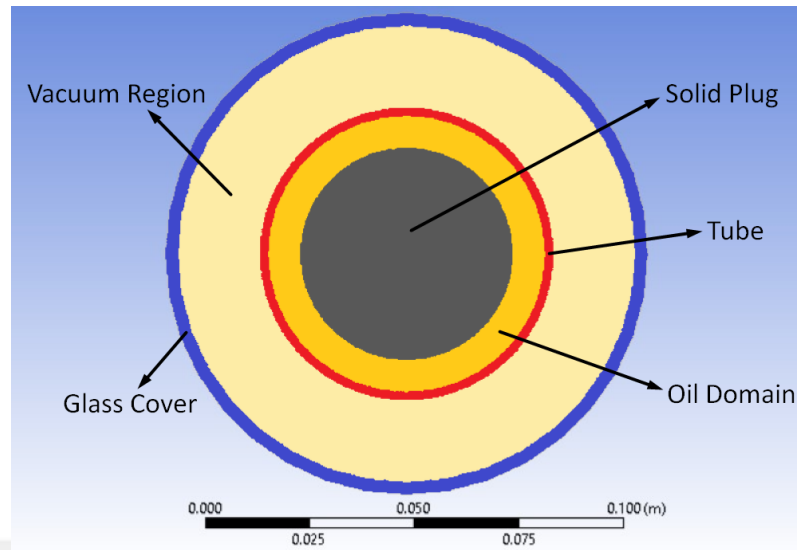


Figure 3.14. Geometry from +z direction

3.4.2 Mesh

The geometry is clean and has a large volume with its 7.8 m length. Therefore, the multizone method is used to decrease the node and element number and decrease the computation time. Inflation layers are added to the tube's inner surface and the flow restriction device surfaces. A cross-section of the mesh is given in Figure 3.15. The skewness of the mesh is shown in Figure 3.16. The Orthogonal quality of the mesh is given in Figure 3.17.

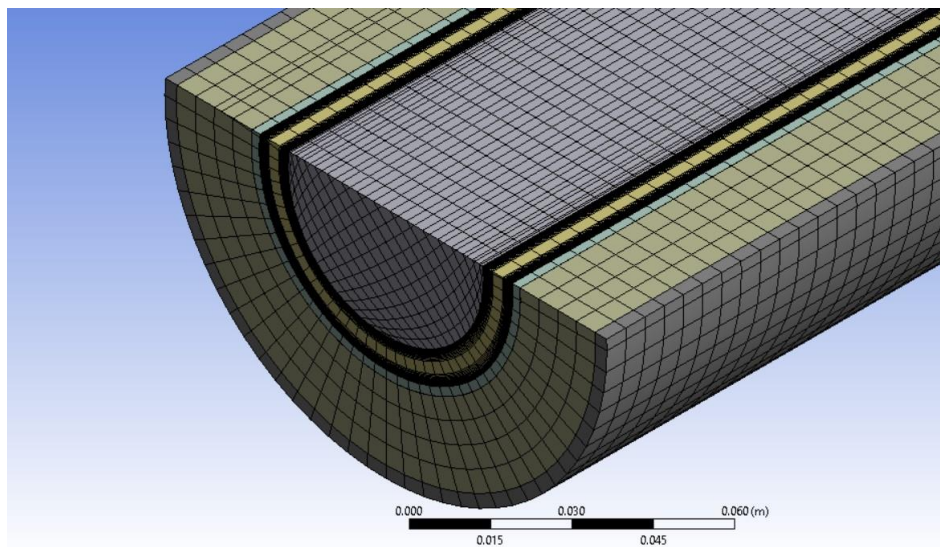


Figure 3.15. Cross-section of the mesh

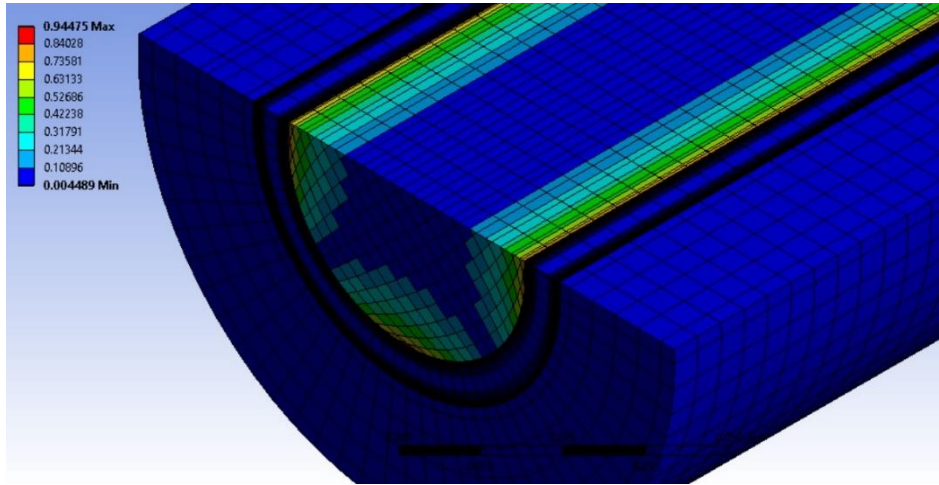


Figure 3.16. The skewness of the mesh

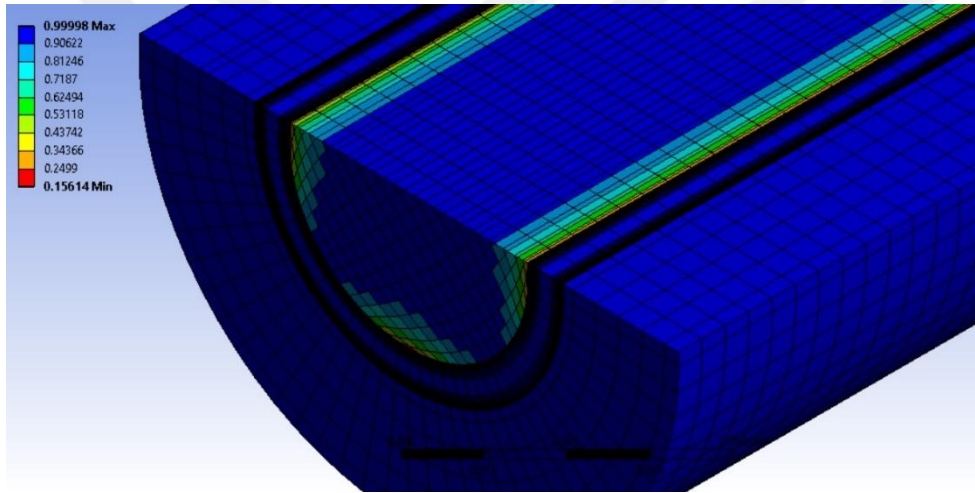


Figure 3.17. Orthogonal quality of the mesh

3.4.3 Boundary Conditions

The energy equation is activated.

The $k - w$ SST turbulence model is used for the tube flow. The $k - w$ SST is a hybrid model that has been designed [22] to avoid freestream sensitivity of the standard $k - w$ model, by combining elements of the w -equation and the ε -equation.

The region between the tube and glass cover is vacuumed. Therefore, the primary mode of heat transfer is radiation. The Surface to Surface (S2S) radiation model is used to calculate radiative heat transfer between the absorber tube's outer surface and the glass cover's inner surface. The S2S radiation model assumes that any emission, absorption, and scattering of radiation in the medium are ignored. The "medium" here is the tiny amount of air in the vacuumed region. Therefore, the S2S radiation model is very suitable for solar collectors to calculate the radiative heat losses.

The density of the air in the vacuum region is defined using the ideal gas relation,

$$P = \rho RT \quad (3.2)$$

where $P[Pa]$ is the pressure of the vacuumed region, $\rho \left[\frac{kg}{m^3} \right]$ is the density of air, $R \left[\frac{J}{kg.K} \right]$ is the gas constant of air and $T[K]$ is the temperature of the air in the vacuumed region. First, an average temperature is assumed for the air in the vacuumed area, and a simulation is performed. Second, the average temperature result of air in the vacuum region is compared with the initial assumption. One or two more iterations are performed until the air's average temperature in the vacuum region converges.

Syltherm-800 oil properties[23] are defined as temperature-dependent. The "Polynomial" function is used for specific heat, density, and thermal conductivity. The "Power Law" function is used for viscosity. Equations of the oil properties are given below. Note that the unit of temperature is Kelvin.

$$c_p = 1.7073(T[K]) + 1107.9 \left[\frac{J}{kg.K} \right] \quad (3.3)$$

$$\rho = -0.9841(T[K]) + 1228.9 \left[\frac{kg}{m^3} \right] \quad (3.4)$$

$$k = -0.0002(T[K]) + 0.1901 \left[\frac{W}{m.K} \right] \quad (3.5)$$

$$\mu = 8e^9(T[K])^{-4.805} [Pa.s] \quad (3.6)$$

The wind convection coefficient[6] around the glass cover is calculated as

$$h_{wind} = 4V_{wind}^{0.58}D_{glass\ outer}^{-0.42} \quad (3.7)$$

The sky temperature [19] is assumed 8K lower than the ambient air temperature. Ambient air temperature values are given in Table 4-3.

The glass cover [24] emissivity is taken as 0.9, and the glass cover absorbtivity is taken as 0.023. Absorbtivity of the glass cover is taken as constant, i.e., the glass cover's absorbtivity does not depend on the incidence angle.

The turbulence intensity [22] is determined using

$$I = 0.16(Re_{D_H})^{-1/8} \quad (3.8)$$

The sky emissivity [25] is assumed as 0.8.

The absorber tube material properties [26] are,

$$c_p = 502.4 \left[\frac{J}{kg.K} \right] \quad (3.9)$$

$$\rho = 8027.17 \left[\frac{kg}{m^3} \right] \quad (3.10)$$

$$k = 0.0151(T[^\circ C]) + 14.5837 \left[\frac{W}{m.K} \right] \quad (3.11)$$

The emissivity of the Cermet coating [19] on the tube surface is,

$$\varepsilon_{cermet} = 0.000327(T[K] + 273.15) - 0.065971 \quad (3.12)$$

The heat absorbed by the glass cover is also taken into account. Constant heat generation is defined inside the glass cover domain. The MATLAB code used to determine the absorbed energy by the glass cover is given in APPENDIX K.

The pyrex glass cover properties [27] are,

$$c_p = 835 \left[\frac{J}{kg.K} \right] \quad (3.13)$$

$$\rho = 2225 \left[\frac{kg}{m^3} \right] \quad (3.14)$$

$$k = 1.4 \left[\frac{W}{m.K} \right] \quad (3.15)$$

Four very thin volumes are created on the outer surface of the absorber tube. These sections have 0.02 mm in thickness (the absorber tube thickness is 2 mm). Heat flux on the tube surface is defined as variable volumetric heat generation inside these four volumes. UDFs are used for heat generation.

The end surfaces of the glass cover, vacuum domain, and the absorber tube at $z = 0$ and $z = 7.8 \text{ m}$ are assumed as insulated.

The “SIMPLE” scheme is used for pressure-velocity coupling. The “Least Squares Cell-Based” option is chosen for Gradient. The “Second Order” is selected for pressure. The “Second Order Upwind” is chosen for momentum, turbulent kinetic energy, specific dissipation rate, and energy.

Hybrid initialization is used.

3.5 Thermal Model of Normal Absorber Tube and Absorber Tube with Plus-Shaped Fin Insert

The standard receiver (normal absorber tube and glass cover) is compared with the receiver (absorber tube with plus-shaped fin insert and glass cover) with a plus-shaped fin insert for zero-degree incidence angle. The absorber tube's oil flow with a plus-shaped fin insert is divided into four equal regions to increase the heat transfer area.

The plus-shaped fin insert is investigated for increasing the heat transfer because other heat transfer enhancement methods such as helical screw tape insert, dimpled tube, and corrugated tube have some disadvantages.

The helical-screw tape with a core rod introduces extra manufacturing costs due to the complexity of the geometry. Moreover, Song et al. [12] concluded that for an inlet temperature of 100°C , if the flow rate increases from 0.1 kg/s to 0.6 kg/s the pressure drop of a normal absorber tube increases 4 times while the pressure drop of an absorber tube with helical screw-tape insert increases 23 times.

Therefore, the absorber tube with a helical screw-tape insert is not suitable for high flow rates.

Although a corrugated absorber tube can be easily manufactured, it has two main disadvantages. First, the absorber tube's outer surface area increases significantly, leading to extra heat loss from the tube's outer surface. Second, the corrugation pattern at the tube's outer surface can decrease absorptivity and increase reflectivity. This change in optical properties leads to lower HTF outlet temperatures.

The manufacturing of dimpled absorber tubes is also easy. However, dimples also increase the absorber tube's outer surface area, similar to corrugated tubes.

Although the increase in the tube's outer surface area is not as much as a corrugated tube, the more the tube's outer surface area, the more the heat loss from the absorber tube. Moreover, the dimple pattern at the tube's outer surface can decrease absorptivity and increase reflectivity. This change in optical properties leads to lower HTF outlet temperatures.

3.5.1 Geometry

The whole domain starts from $z = 0$ and ends at $z = 1\text{ m}$, for the normal absorber tube. There are two fluid domains and six solid domains. Four very thin sheets (volumes) are created outside the tube. These four sections have 0.02 mm in thickness. Data obtained from Tonatiuh is defined as variable heat generation in

these four sections. Oil and vacuum regions are the fluid domains. Absorber tube, four thin heat generation volumes, and glass cover are the solid domains. Geometry of the normal absorber tube from the +z direction is given in Figure 3.18.

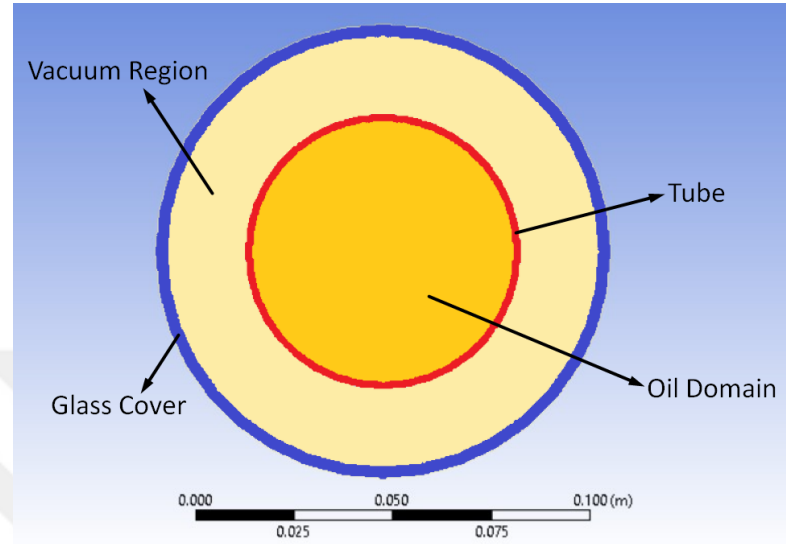


Figure 3.18. Geometry of the normal absorber tube from +z direction

The whole domain starts from $z = 0$ and ends at $z = 1 \text{ m}$, for the absorber tube with a plus-shaped fin insert. There are five fluid domains and six solid domains. Four very thin sheets (volumes) are created outside the tube. These four sections have 0.02 mm in thickness. Data obtained from Tonatiuh is defined as variable heat generation in these four sections. Oil and vacuum regions are the fluid domains. Absorber tube with a plus-shaped fin insert, four thin heat generation volumes, and glass cover are the solid domains. Geometry of the absorber tube with a plus-shaped fin insert from the +z direction is given in Figure 3.19.

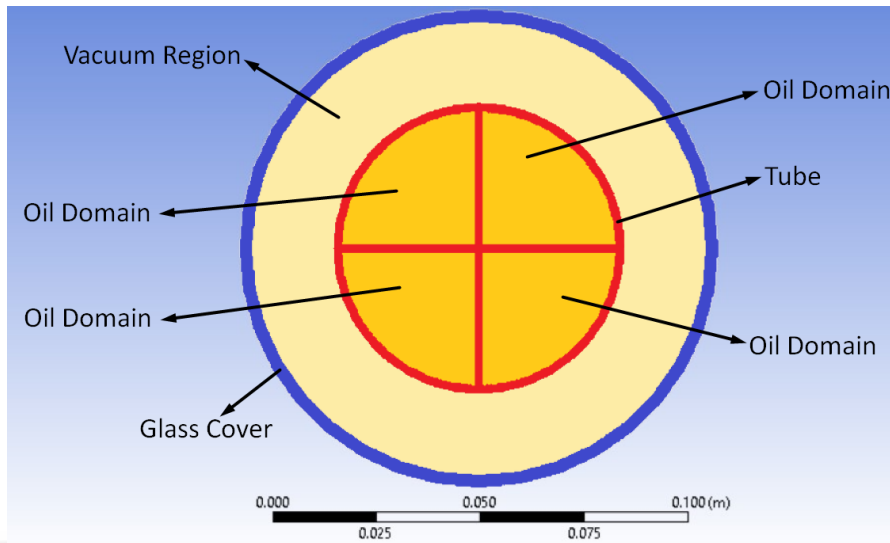


Figure 3.19. Geometry of the absorber tube with a plus-shaped fin insert from +z direction

Four different configurations of plus-shaped fin insert are investigated, which are 0° , 30° , 40° and 45° rotated configurations. The geometries of the plus-shaped fin insert with 0° and 45° rotated versions are given in Figure 3.20 and Figure 3.21 for demonstration, respectively. Note that there are four oil domains in all configurations. All have a length of $1m$. In the end, these configurations are compared with a $1m$ normal absorber tube. The plus-shaped fin insert touches the tube's inner surface, and it is stationary. The thickness of the plus-shaped fin insert is the same as the absorber tube's thickness.

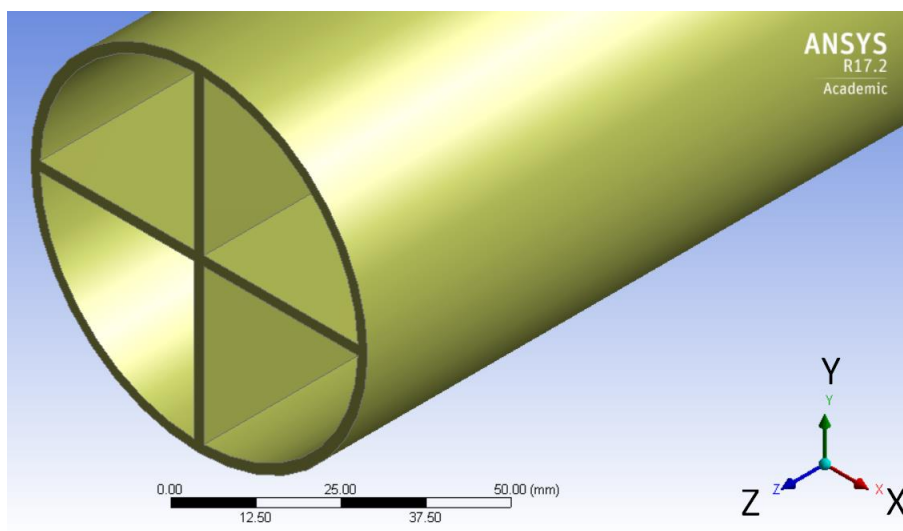


Figure 3.20. The absorber tube with a plus-shaped fin insert with 0° rotation

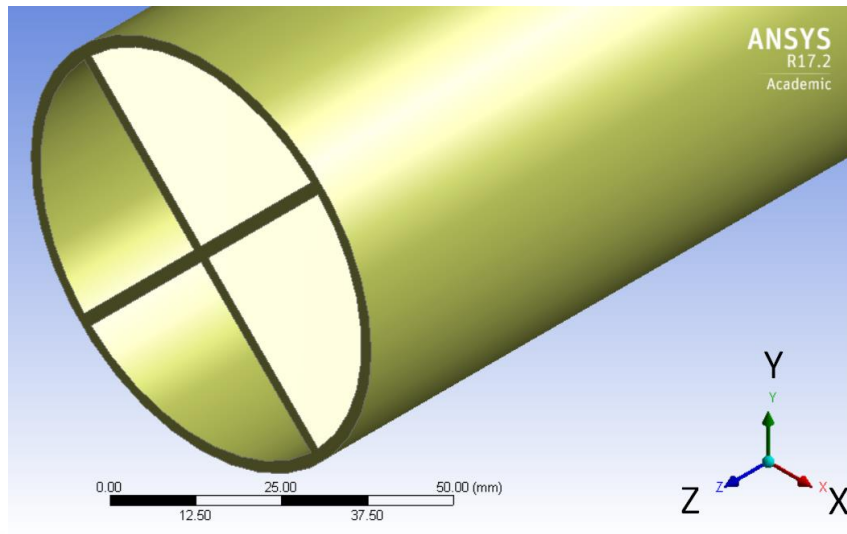


Figure 3.21. The absorber tube with a plus-shaped insert with 45° rotation

3.5.2 Mesh

The multizone method is used to decrease the node and element number and decrease the computation time. Inflation layers are added to the absorber tube's inner surface, and the plus-shaped fin insert surfaces. The mesh of a receiver with a plus-shaped fin insert with 0-degree rotation and a plus-shaped fin insert with 45 degrees rotation are given in Figure 3.22 and Figure 3.23, respectively.

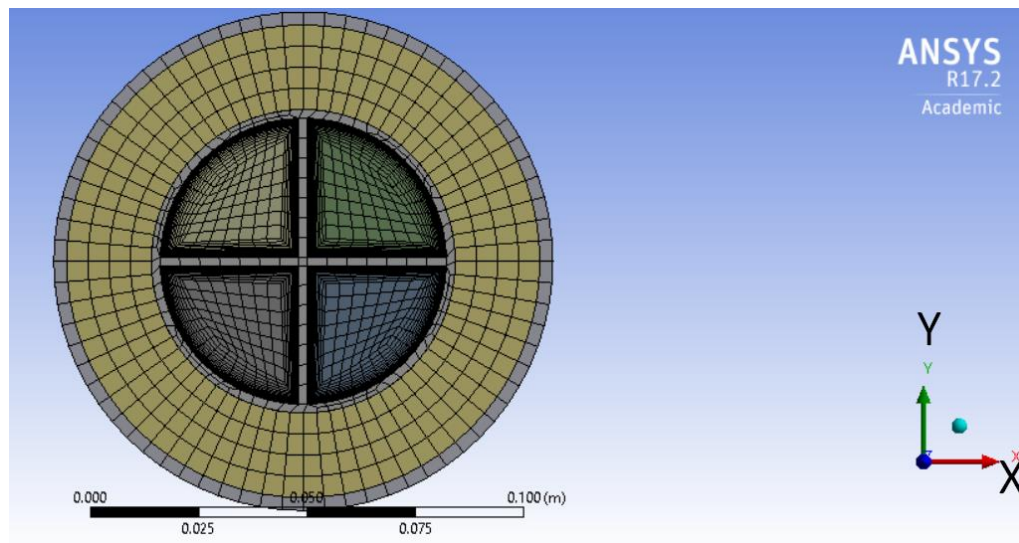


Figure 3.22. The mesh of a receiver with plus-shaped fin insert with 0° rotation

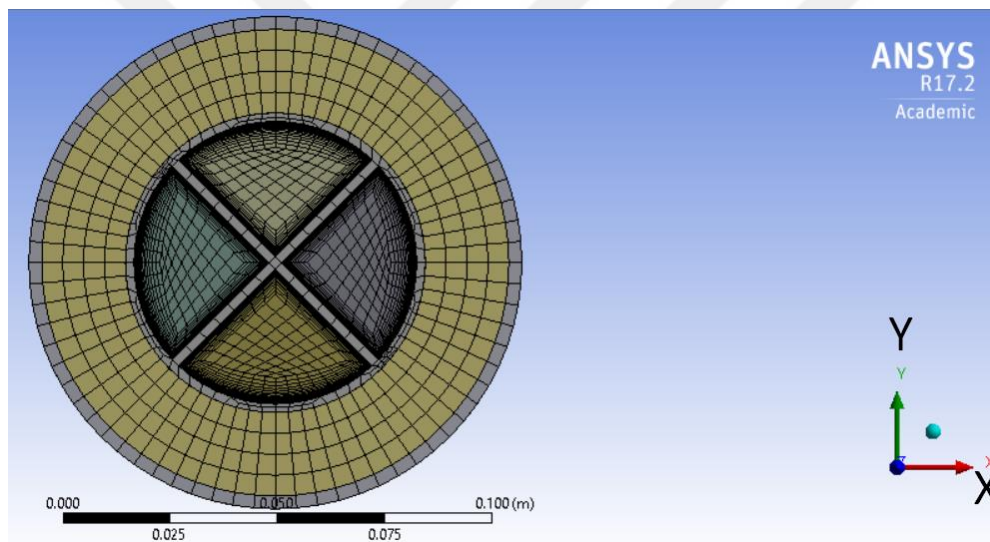


Figure 3.23. The mesh of a receiver with plus-shaped fin insert with 45° rotation

The skewness distribution of plus-shaped fin insert with no rotation and plus-shaped fin insert with 45 degrees rotation are given in Figure 3.24 and Figure 3.25, respectively.

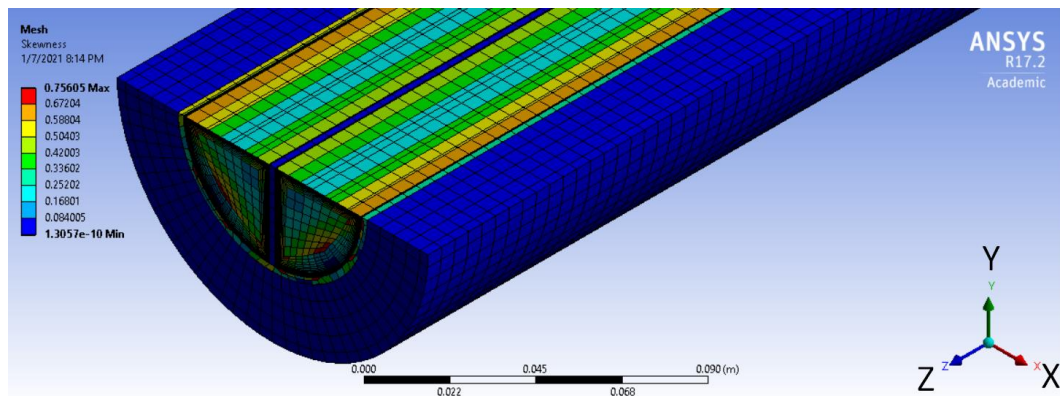


Figure 3.24. The skewness distribution of a receiver with plus-shaped fin insert with 0° rotation

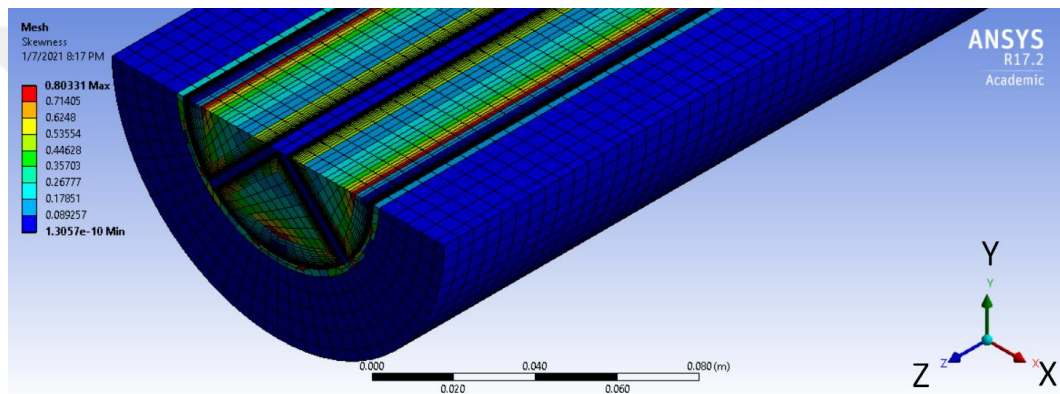


Figure 3.25. The skewness distribution of a receiver with plus-shaped fin insert with 45 degrees rotation

The mesh of a normal receiver (absorber tube and glass cover) is given in Figure 3.26.

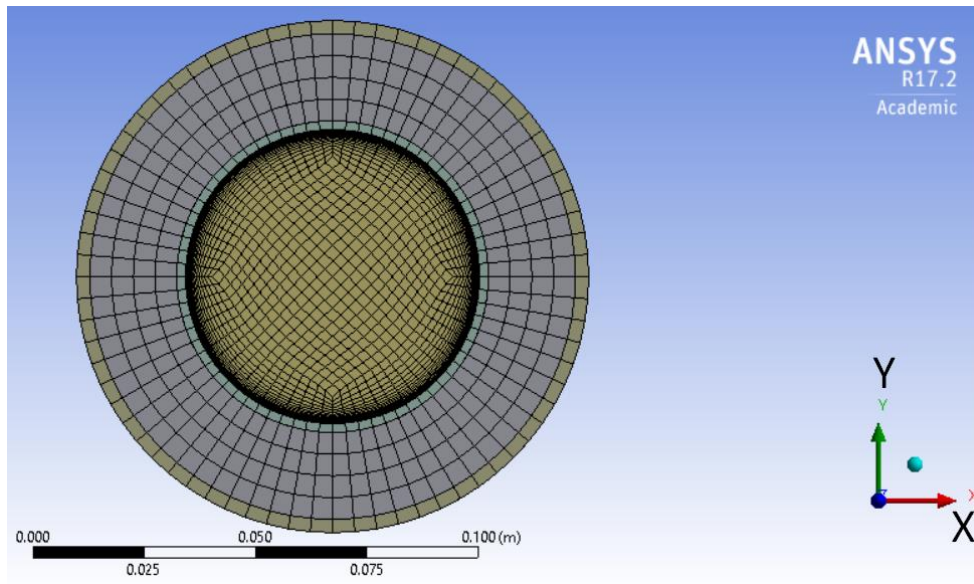


Figure 3.26. The mesh of a normal receiver

The skewness distribution of a normal receiver (absorber tube and glass cover) is given in Figure 3.27.

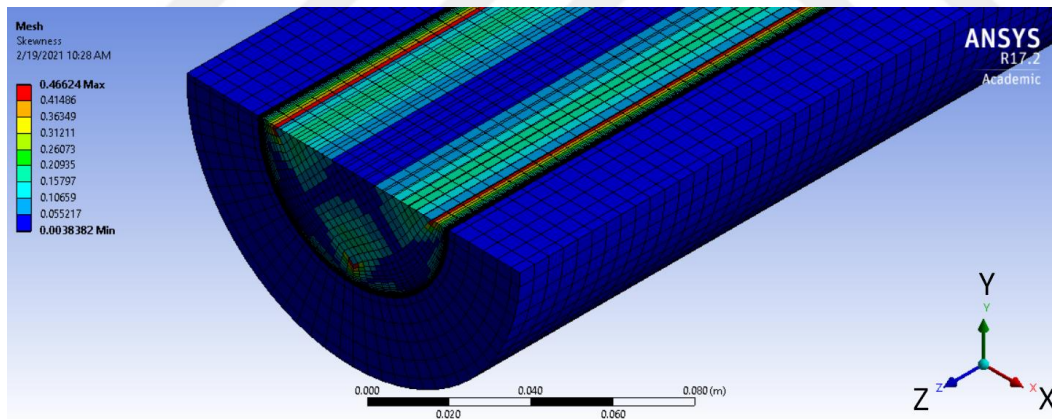


Figure 3.27. The skewness distribution of a normal receiver

3.5.3 Boundary Conditions

The plus shape insert's material is the same as the absorber tube's material. The other boundary conditions are the same as Section 3.4.3.

3.5.4 Inlet Velocity and Temperature Profiles

We are interested in the region with high oil temperatures where oil is transferred from one PTC line to another. When the oil is transferred from one PTC line to another, oil has fully developed velocity and temperature profiles. Therefore, different tube geometries are compared using fully developed velocity and temperature profiles. The case 7 data in Table 4-3 is used to obtain the profiles since it has the least error between the CFD model and the experimental data. It is found that a normal absorber tube with a 2 m length is enough to obtain fully developed velocity and temperature profiles. Absorber tube is subjected to non-uniform constant heat flux boundary condition. Therefore, if the flow is thermally fully developed, the local heat transfer coefficient along a line should become constant after a point. Velocity profiles at different z -locations are given in Figure 3.28. The local convection heat transfer coefficient along the right side of the tube's inner surface is given in Figure 3.29. The line along the right side of the tube's inner surface is shown in Figure 3.30.

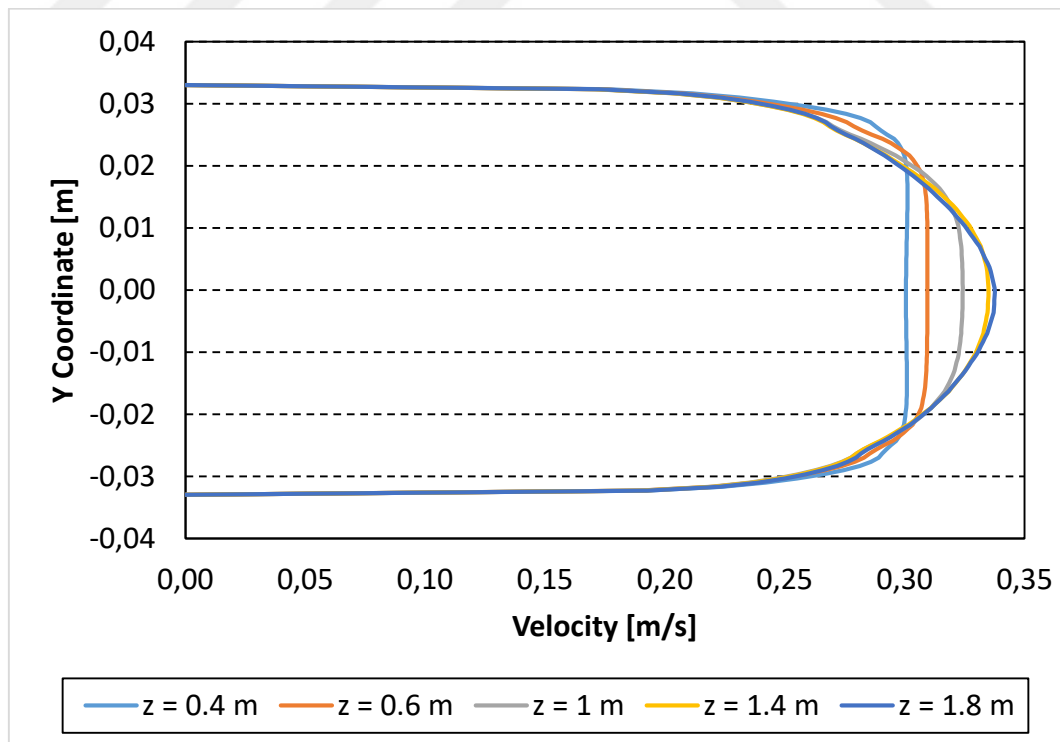


Figure 3.28. Velocity profiles at different z -locations

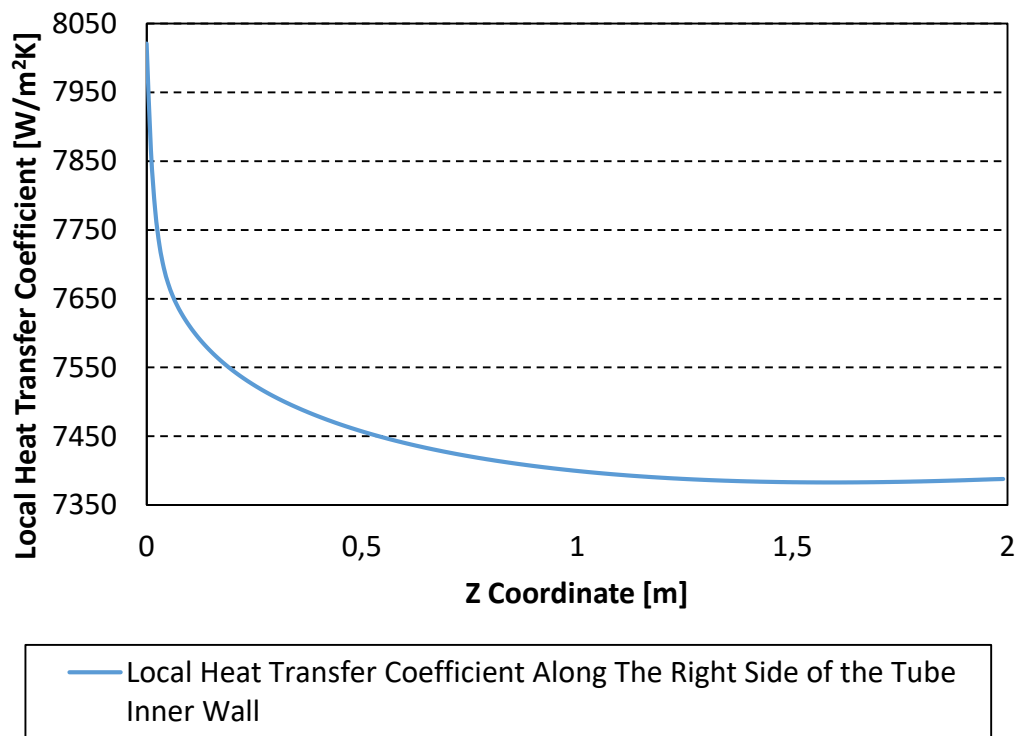


Figure 3.29. Local convection heat transfer coefficient along the right side of inner tube surface

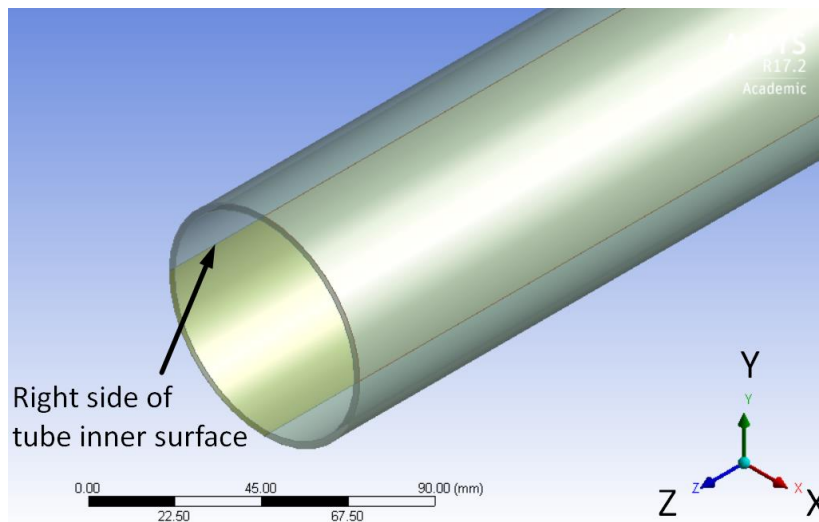


Figure 3.30. The line along the right side of the tube inner surface

From Figure 3.28 and Figure 3.29, it can be concluded that after 2 meters, the flow is both hydrodynamically and thermally fully developed. When different tube

geometries with 1m length are compared, the oil outlet profile (both velocity and temperature) from a 2 m normal tube will be their oil inlet profiles. The methodology for comparing different absorber tube geometries is explained in Figure 3.31.

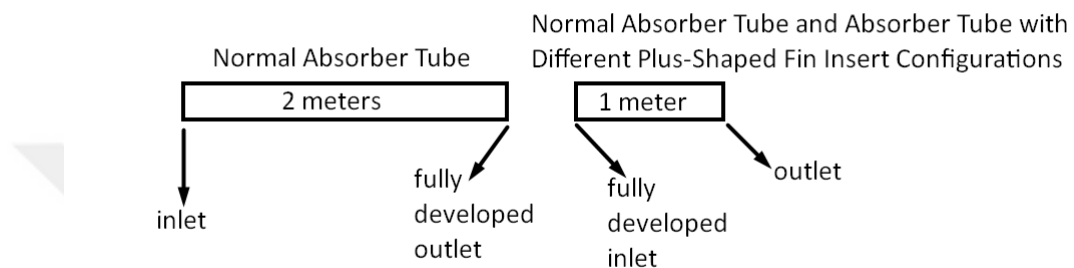


Figure 3.31. The methodology for comparing different absorber tube geometries

From Figure 3.31, a 2-meter normal absorber tube is solved to obtain fully-developed velocity and temperature profiles. These fully developed velocity and temperature profiles are used as oil inlets for a 1-meter normal absorber tube and 1-meter absorber tube with a plus-shaped fin insert for comparison.



CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, model validation is performed. Moreover, the results of Tonatiuh, MATLAB codes, and ANSYS Fluent are presented.

4.1 Model Validation

Model validation is performed in three steps. First, the reliability of Tonatiuh is shown in Section 4.1.1. Secondly, the non-uniform heat flux distribution around the absorber tube is validated in Section 4.1.3. The combined optical and thermal model is validated against the experimental data in Section 4.1.5.

4.1.1 Validation of Tonatiuh

Obtaining the non-uniform heat flux distribution around the absorber tube is all about ray-tracing. Tonatiuh is a validated Monte-Carlo ray tracing (MCRT) package program.

Numerical validation of Tonatiuh is done with SolTrace[20], another ray-tracing package program developed by NREL (National Renewable Energy Laboratory), by comparing the two programs' results. The results of Tonatiuh and SolTrace are in good agreement with each other.

Experimental validation of Tonatiuh is performed using the Plataforma Solar de Almeria (PSA) secondary concentrator test campaign data[28]. Another experimental validation of Tonatiuh is performed at Mini-Pegase CNRS-PROMES facility[29].

In conclusion, Tonatiuh is a reliable MCRT package program and can be used for optical analysis of PTC systems.

4.1.2 Amount of Heat Flux Around the LS2 PTC Module Absorber Tube

The average heat flux values on the LS2 PTC module absorber tube for different incidence angles are presented in this part.

Piecewise surface fit is performed with MATLAB for Tonatiuh simulation data. Therefore, one has to check the amount of heat flux on the absorber tube's outer surface.

The comparison of absorber tube average heat flux results of Tonatiuh and CFD-Post is presented in Table 4-1.

Table 4-1 The comparison of absorber tube average heat flux results of Tonatiuh and CFD-Post

Incidence Angle	CFD-Post Average Heat Flux [W/m ²]	Tonatiuh Average Heat Flux [W/m ²]	%Error
0	19013.320	19005.600	0.04%
15	17094.268	17090.300	0.02%
30	13960.605	13991.000	0.22%
45	9954.160	9933.890	0.20%
60	5170.060	5164.900	0.10%
75	321.190	318.632	0.80%

In Table 4-1, the maximum error between Tonatiuh and CFD-Post results is 0.8%.

In conclusion, the amount of heat flux is transferred to ANSYS Fluent as a boundary condition accurately.

4.1.3 Non-Uniform Heat Flux Distribution Around the Absorber Tube

In this part, both the amount of heat flux and the heat flux distribution are validated against the numerical studies in the literature.

A comparison is performed with Jeter [30], in which an ideal PTC with 0-degree incidence angle, 20x geometrical concentration, 90° rim angle for a uniform Sun of 7.5 mrad angular radius is investigated. This ideal PTC is analyzed using

Tonatiuh and 2D-discretization MATLAB code (which can be used for 0-degree incidence angle), both explained in detail in the previous chapter. The optical and geometrical properties of this ideal PTC is given in Table 4-2.

Table 4-2 Properties of an ideal PTC with 20x geometrical concentration and 90° rim angle

Variable	Value	Unit
Aperture Width	7.36	m
Aperture Length	7.8	m
Focal Length	1.84	m
Rim Angle	90	°
Mirror Reflectivity	1	-
Absorber tube Inner Diameter	113.14	mm
Absorber tube Outer Diameter	117.14	mm
Absorber tube Coating Absorptivity	1	-
Glass Cover Inner Diameter	156.14	mm
Glass Cover Outer Diameter	162.14	mm
Glass Cover Transmissivity	1	-

Note that all “m_sigmaSlope” and “sigmaSlope” values, which are optical errors of the surfaces, in Tonatiuh are set to zero to have a perfect PTC model.

LCR (local concentration ratio) can be defined as

$$LCR = \frac{q}{G_{beam}} \quad (4.1)$$

where “q” is local energy flux [30], [31] and “ G_{beam} ” is the incident beam irradiance. “ G_{beam} ” is taken as $1000 \frac{W}{m^2}$ for the validation.

The comparison of Jeter’s [30] and this thesis’ LCR distributions are presented in Figure 4.1. See APPENDIX J to create a cross-section on the absorber tube and obtain the heat flux distribution.

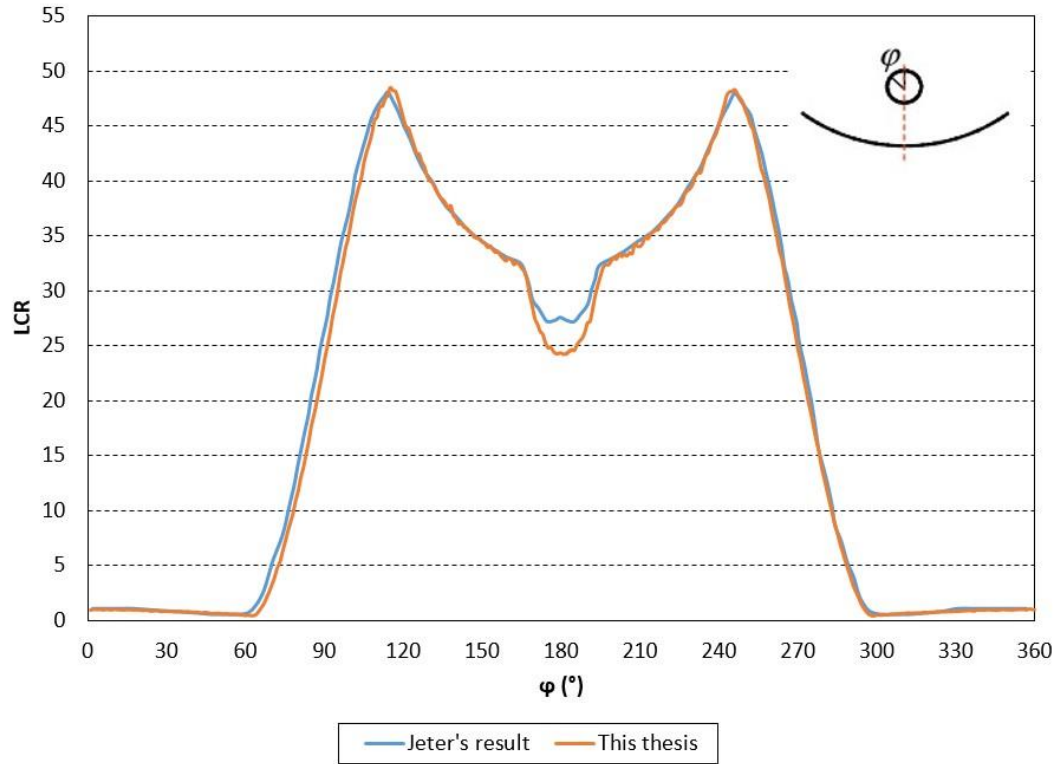


Figure 4.1. Comparison of Jeter's [30] and this thesis' LCR (local concentration ratio) distribution results for an ideal PTC with 0-degree incidence angle, 20x geometrical concentration, 90° rim angle for a uniform Sun of 7.5 mrad angular radius

Figure 4.1 shows that the LCR (local concentration ratio) distribution of this thesis is in good agreement with Jeter [30].

Another comparison is performed with Cheng [32], in which an ideal PTC with 0-degree incidence angle, 20x geometrical concentration, 90° rim angle for a uniform Sun of 4.65 mrad angular radius is investigated. Optical and geometrical properties of the PTC are given in Table 4-2. In other words, all properties are same with the ideal PTC explained in Jeter [30] except the angular radius of the Sun. The comparison of Cheng's [32] and this thesis' LCR distributions are presented in Figure 4.2.

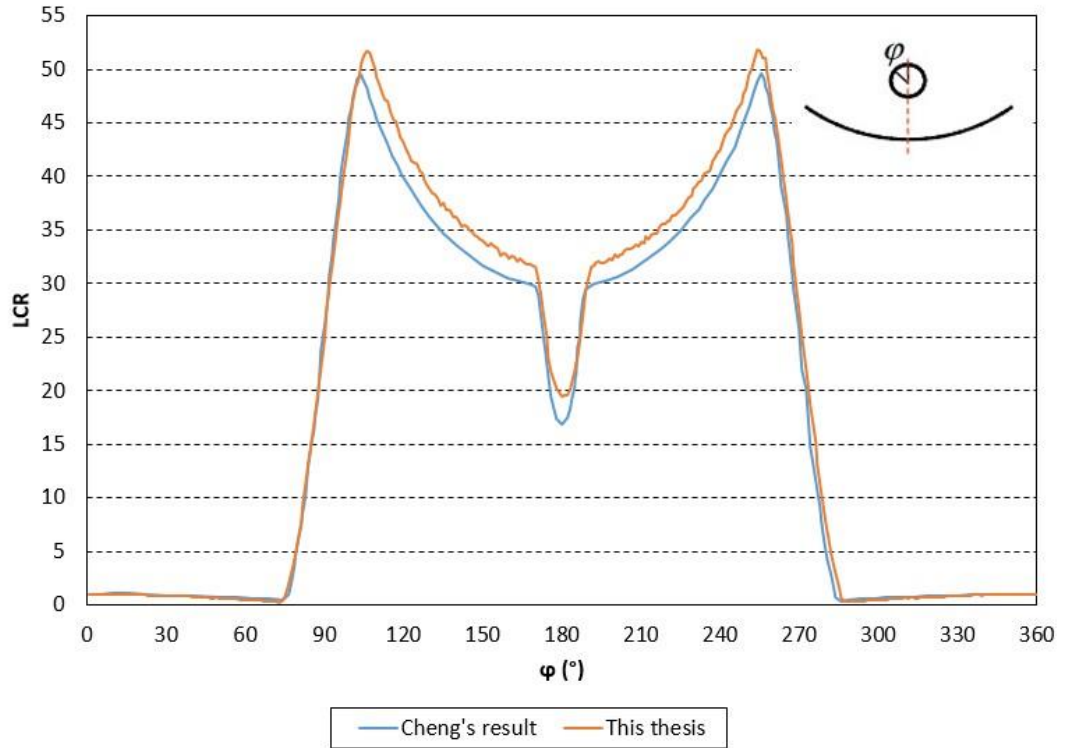


Figure 4.2. Comparison of Cheng's [32] and this thesis' LCR (local concentration ratio) distribution results for an ideal PTC with 0-degree incidence angle, 20x geometrical concentration, 90° rim angle for a uniform Sun of 4.65 mrad angular radius

From Figure 4.2, it can be seen that the LCR (local concentration ratio) distribution of this thesis is in good agreement with Cheng [32].

In conclusion, UDFs are created using piecewise surface fits, and Tonatiuh simulation data (both the heat flux distribution and the amount of heat flux around the absorber tube) is transferred to ANSYS Fluent as a boundary condition accurately.

Thus, the non-uniform heat flux distribution around the absorber tube can be obtained correctly using the optical method (creating the PTC with Tonatiuh and post-processing Tonatiuh data with MATLAB) in this thesis.

4.1.4 Comparison of 2D and 3D Discretization MATLAB Codes

As mentioned before, the absorber tube's outer surface's spatial discretization is performed both in 2D and 3D. The 2D discretization (in radial direction only) can be used for zero-degree incidence angle only, whereas 3D discretization (both in radial and axial direction) can be used for any incidence angle. Therefore, 2D and 3D discretization approaches should give the same heat flux distribution for zero-degree incidence angle.

Incident beam irradiance, “ G_{beam} ”, is taken as $1000 \frac{W}{m^2}$. A cross-section is created at $z = 7.7 \text{ m}$ with ANSYS Fluent. The comparison of heat flux distributions at $z = 7.7 \text{ m}$ cross-section for LS2 PTC module with 0-degree incidence angle using both 2D and 3D discretization approaches is presented in Figure 4.3.

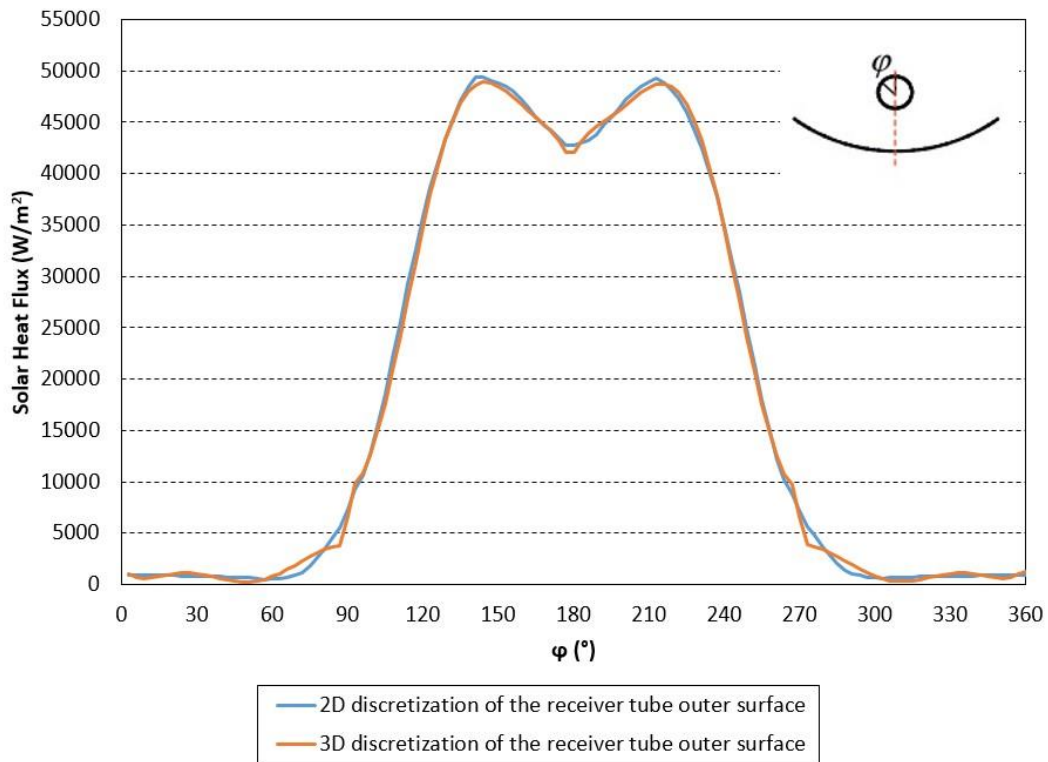


Figure 4.3. Comparison of heat flux distributions at $z = 7.7 \text{ m}$ cross-section for LS2 PTC module with 0-degree incidence angle using both 2D and 3D discretization approaches

Figure 4.3 shows that 2D and 3D discretization approaches give almost the same heat flux distribution for zero-degree incidence angle, as expected. The small

differences between them are due to the performed curve-fitting and surface-fitting. To conclude, the results of 2D and 3D discretization approaches are consistent with each other, as expected.

4.1.5 Validation of the CFD Model with SEGS LS-2 Experimental Data

After validating the heat flux boundary condition and the MATLAB code of 3D discretization, the CFD analyses can be performed.

In this part, the CFD model results in this thesis are validated using the SEGS LS-2 experimental data. Eight different cases are simulated. Note that the DNI, wind speed, ambient temperature, oil inlet temperature, and flow rate values are different for each case. The experimental conditions of the SEGS LS-2 collector are presented in Table 4-3.

Table 4-3 Experimental conditions of SEGS LS-2 collector

Case	DNI [W/m ²]	Wind Speed [m/s]	Ambient Air Temperature [Celcius]	Oil Inlet Temperature [Celcius]	Oil Flow Rate [L/min]
1	933.7	2.6	21.2	102.2	47.7
2	968.2	3.7	22.4	151	47.8
3	982.3	2.5	24.3	197.5	49.1
4	909.5	3.3	26.2	250.7	54.7
5	937.9	1	28.8	297.8	55.5
6	880.6	2.9	27.5	299	55.6
7	920.9	2.6	29.5	379.5	56.8
8	903.2	4.2	31.1	355.9	56.3

Before analyzing these cases in Table 4-3, one has to ensure that the results should be mesh independent. Therefore, a mesh refinement study is performed for Case 1, and the final mesh is used for other cases. Mesh refinement results for Case 1 are presented in Table 4-4.

Table 4-4 Mesh refinement results for Case 1

Case	Mesh Nodes	Mesh Elements	Oil Outlet Temperature [Celcius]	Pressure Drop [Pa]
1	1014112	998865	128.75	4087.16
1	1166418	1149120	128.50	4090.64
1	1354672	1335285	128.68	4073.88
1	2024745	1996800	128.45	4076.65
1	4834417	4773600	128.43	4077.14
1	8123964	8028150	128.49	4070.07

The mesh independence is achieved by checking both the oil outlet temperature and the pressure drop. The final mesh has 4834417 nodes and 4773600 elements.

The comparison of the CFD model and the SEGS LS-2 collector's experimental results are presented in Table 4-5.

Table 4-5 The comparison of the CFD model and experimental results of SEGS LS-2 collector

Case	Experiment Oil Outlet Temperature [Celcius]	CFD Oil Outlet Temperature [Celcius]	Temperature Difference [Celcius]	Error
1	124.00	128.43	4.43	3.58%
2	173.30	177.92	4.62	2.67%
3	219.50	224.10	4.60	2.10%
4	269.40	272.87	3.47	1.29%
5	316.90	320.34	3.44	1.09%
6	317.20	320.06	2.86	0.90%
7	398.00	400.99	2.99	0.75%
8	374.00	377.19	3.19	0.85%

In Table 4-5, the percentage error values are calculated using the degrees Celcius unit. If the degrees Kelvin unit were used, then the percentage error values would be smaller since the percentage error equation's denominator becomes larger. It can be seen that the CFD results are in good agreement with the experimental data. The

difference between CFD and experimental results depends on four main reasons. Firstly, the heat losses from metal bellows are not considered in the model. Wu et al. [7] stated that 7% of the total heat loss occurs from metal bellows for a 4.1 meters long PTC if a convection heat coefficient of $10 \frac{W}{m^2}$ is defined on the bellows. Although the length of the PTC in SEGS LS-2 experiments is 7.8 meters, the convection coefficient outside the glass cover varies between $9.9 \frac{W}{m^2}$ and $22.8 \frac{W}{m^2}$ in the CFD model. This could be one reason why the CFD model's oil outlet temperatures are always higher than the experiment's. Secondly, a correlation is used to predict the convection heat transfer coefficient outside the glass cover. The sky temperature is assumed as 8 K lower than the ambient temperature. The sky and glass cover emissivity values are taken as constant. The ideal gas model is used to model the vacuumed region between the absorber tube and the glass cover. These correlations and assumptions also introduce some errors for the solution. Thirdly, the reflectivity of the parabolic mirror is taken as 0.93 in the Tonatiuh model. In the SEGS LS-2 experiment, the reflectivity may not be 0.93 at every point of the mirror due to the dirt formation on the surface and slight manufacturing errors. This could be another reason why the CFD model's oil outlet temperatures are always higher than the experiment's. Finally, the DNI, wind speed, ambient air temperature, oil inlet, and outlet temperatures, and oil flow rate values are measured in these experiments. There could also be measurement errors. Overall, considering the receiver's 7.8 meters length of the receiver, the difference between the CFD and experimental results is quite acceptable.

Moreover, the maximum error between the CFD and experimental results is 3.58%. Thus, it can be concluded that the method (combining Tonatiuh, MATLAB, and Fluent) used in this thesis is reliable to simulate parabolic trough collectors.

4.2 Heat Losses for SEGS LS-2 PTC

Heat losses are also calculated in the CFD model. Free convection and radiative heat losses from the absorber tube of SEGS LS-2 PTC are given in Table 4-6 for all eight cases, which are mentioned in Section 4.1.5.

Table 4-6 Free convection and radiative heat losses from the absorber tube of SEGS LS-2 PTC

Case	Oil Inlet Temperature [Celcius]	Free Convection Heat Loss From The Absorber Tube [W]	Radiative Heat Loss From The Absorber Tube [W]
1	102.2	349.8	271.0
2	151	458.6	455.9
3	197.5	556.5	721.4
4	250.7	669.3	1117.0
5	297.8	771.4	1741.0
6	299	783.4	1717.0
7	379.5	980.6	3359.3
8	355.9	922.7	2779.5

Table 4-5 shows that, as the oil temperature increases, radiative heat losses exceed the free convection heat losses, as expected. The free convection heat loss is greater than the radiative heat loss for cases 1 and 2. The free convection heat loss is smaller than the radiative heat loss for cases 3, 4, 5, 6, 7, and 8, but it still has the same order of magnitude with radiative heat losses. In conclusion, the heat losses with free convection in the vacuum region should not be neglected.

4.3 Heat Flux Distribution Around the LS2 PTC Module Absorber Tube

The heat flux distribution results around the LS2 PTC module absorber tube for six different incidence angles are presented in this part. All results are found using Tonatiuh, MATLAB 3D discretization approach, and ANSYS Fluent. Incident beam

irradiance, “ G_{beam} ”, is taken as $1000 \frac{W}{m^2}$. All “m_sigmaSlope” and “sigmaSlope” values, which are optical errors of the surfaces, in Tonatiuh are set to 2 for the analysis.

4.3.1 Heat Flux Distribution for 0 Degree Incidence Angle

An isometric view of heat flux distribution around the LS2 PTC module absorber tube for 0-degree incidence angle is presented in Figure 4.4.

In Figure 4.5, heat flux distribution around the LS2 PTC module absorber tube for 0-degree incidence angle is presented for the view from +x direction.

101 number of contours are used for Figure 4.4 and Figure 4.5.

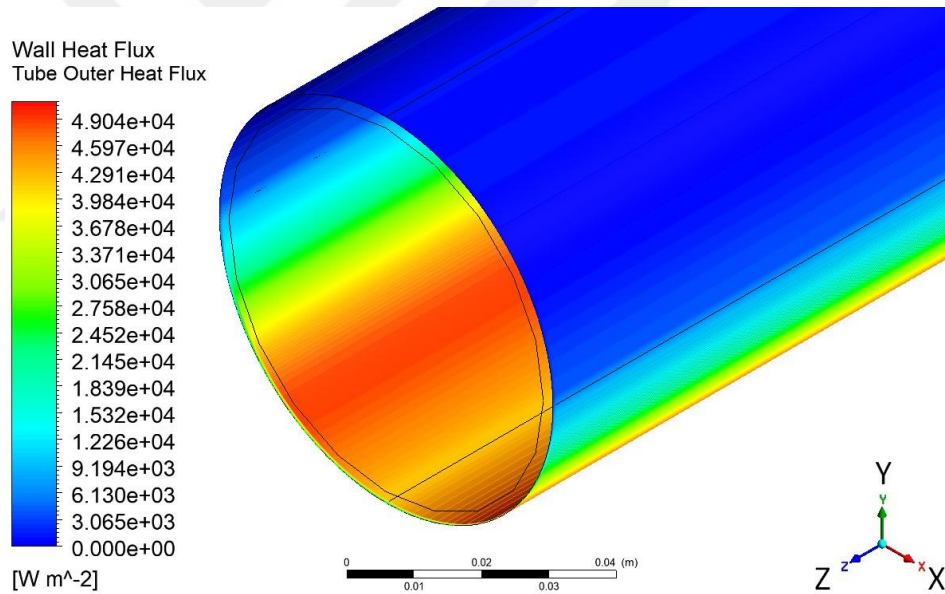


Figure 4.4. Isometric view of heat flux distribution around the LS2 PTC module absorber tube for 0-degree incidence angle

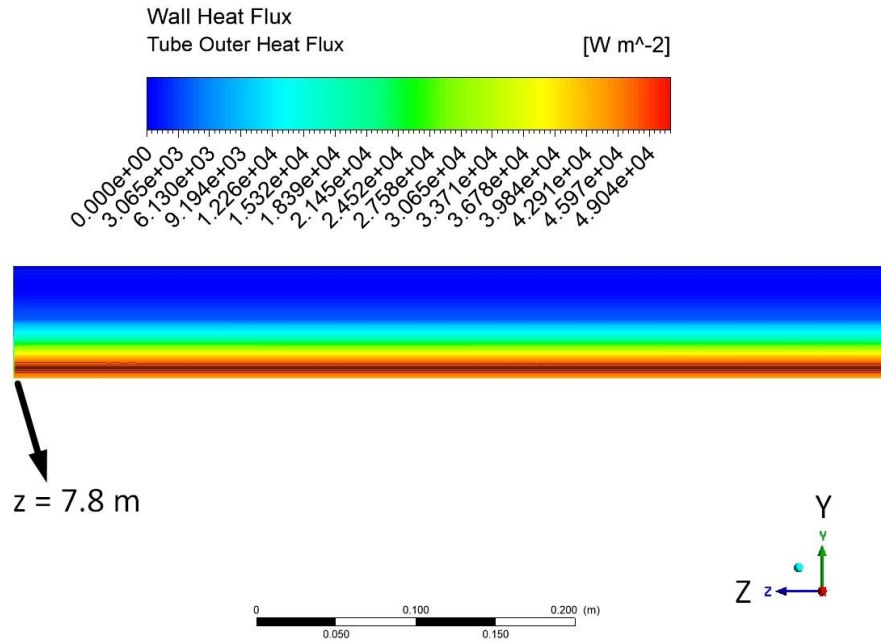


Figure 4.5. Heat flux distribution around the LS2 PTC module absorber tube for 0-degree incidence angle, view from +x direction

One can say that the heat flux profile almost does not change in the axial direction (z-direction). There are very small changes due to included optical errors in the analysis.

Heat flux distribution at $z = 7.7 \text{ m}$ cross-section around the LS2 PTC module absorber tube with 0-degree incidence angle is shown in Figure 4.6.

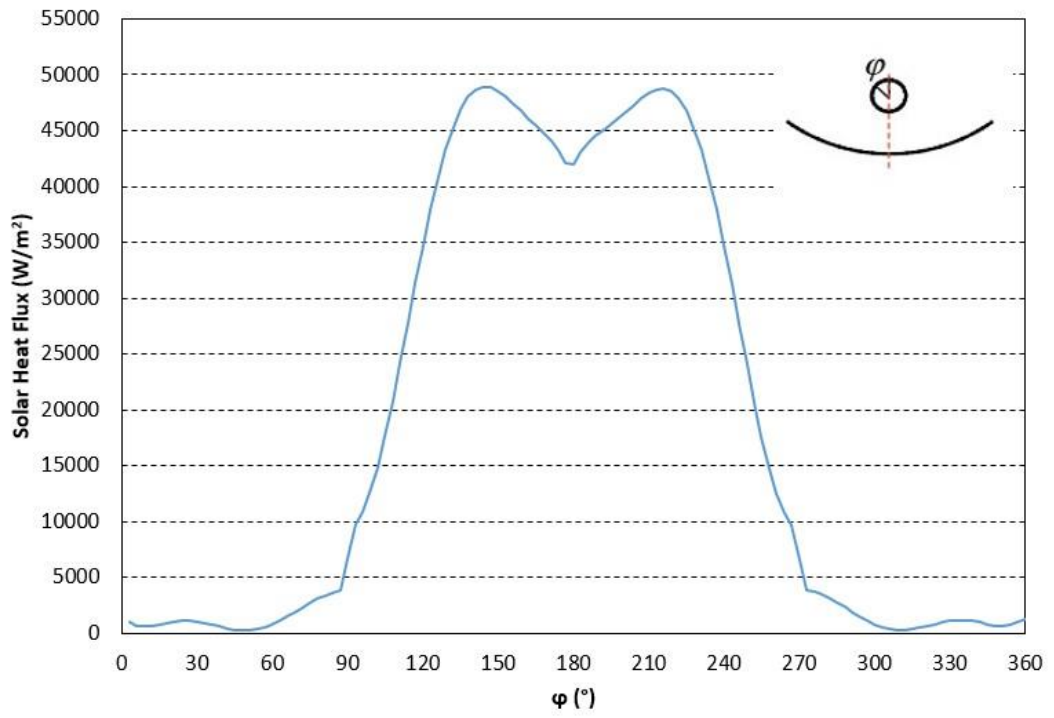


Figure 4.6. Heat flux distribution at $z = 7.7 \text{ m}$ cross-section around the LS2 PTC module absorber tube with 0-degree incidence angle

Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 0-degree incidence angle is presented in Figure 4.7.

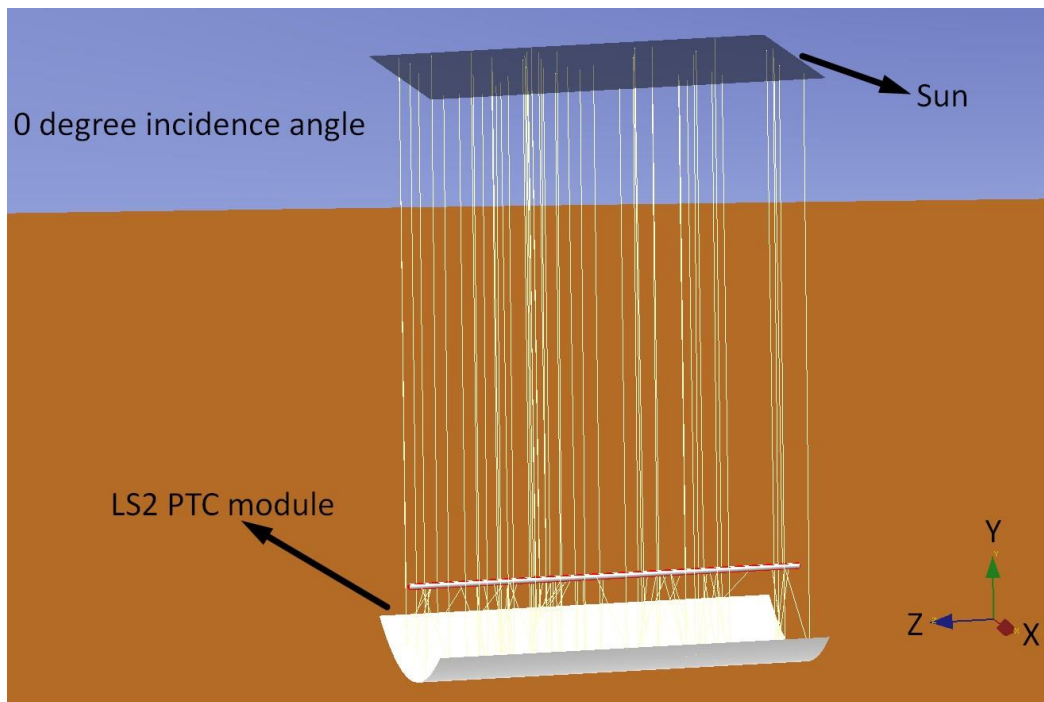


Figure 4.7. Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 0-degree incidence angle

4.3.2 Heat Flux Distribution for 15 Degrees Incidence Angle

An isometric view of heat flux distribution around the LS2 PTC module absorber tube for 15 degrees incidence angle is presented in Figure 4.8.

In Figure 4.9, heat flux distribution around the LS2 PTC module absorber tube for 15 degrees incidence angle is presented for the view from the +x direction.

101 number of contours are used for Figure 4.8 and Figure 4.9.

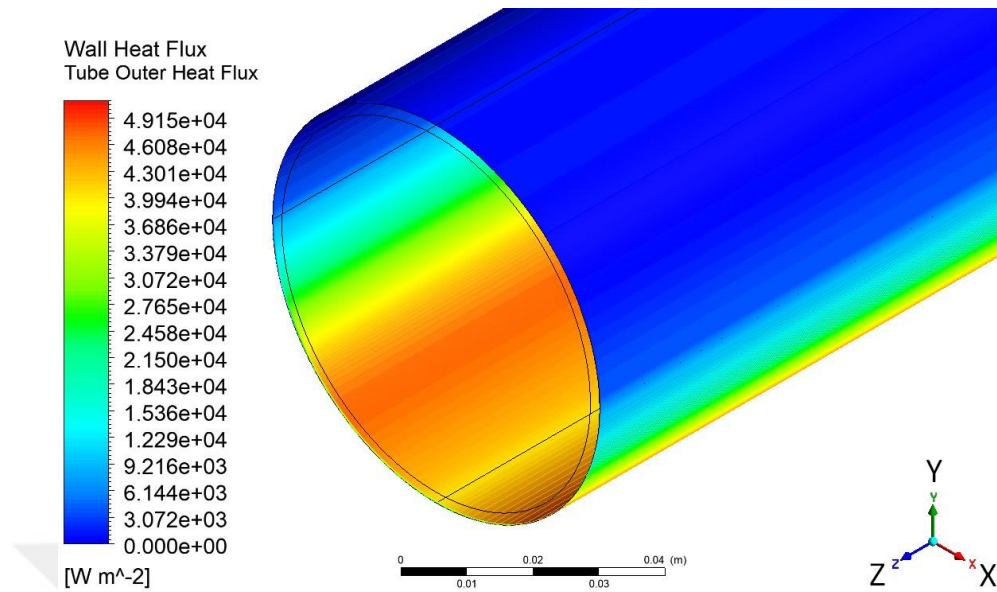


Figure 4.8. Isometric view of heat flux distribution around the LS2 PTC module absorber tube for 15 degrees incidence angle

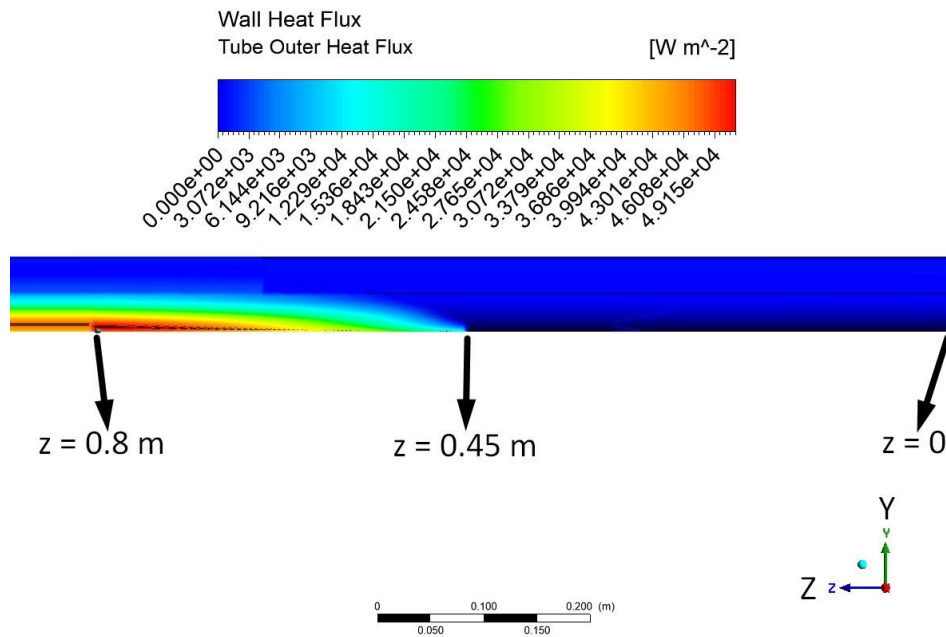


Figure 4.9. Heat flux distribution around the LS2 PTC module absorber tube for 15 degrees incidence angle, view from +x direction

Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 15 degrees incidence angle is presented in Figure 4.10.

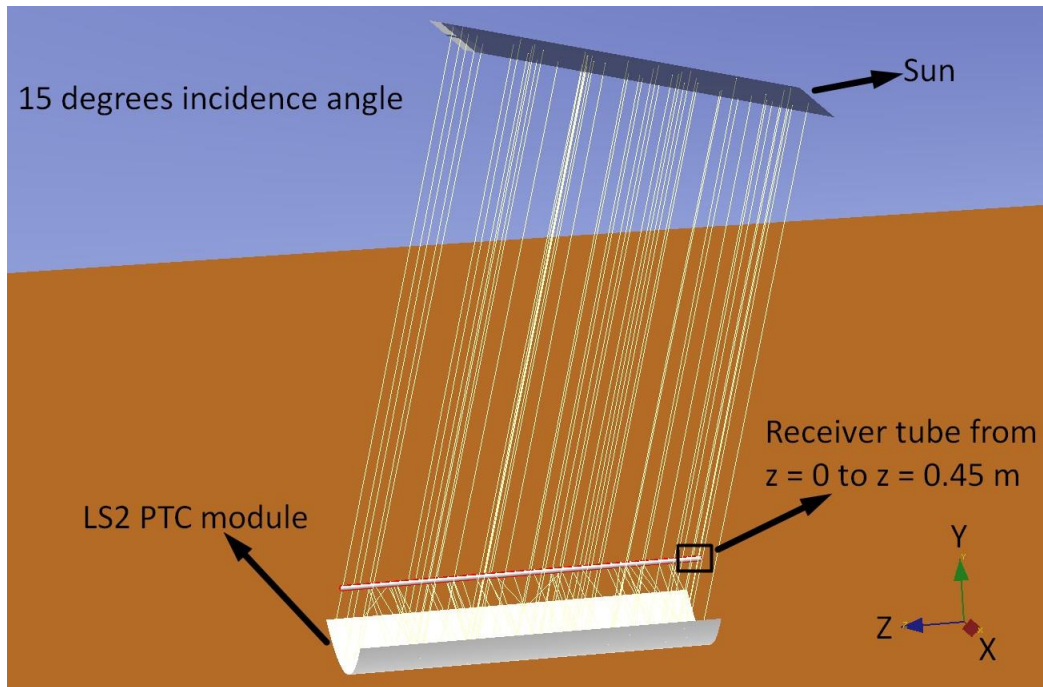


Figure 4.10. Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 15 degrees incidence angle

From Figure 4.9 and Figure 4.10, it can be seen that the bottom part of the absorber tube from $z = 0$ to $z = 0.45$ m does not get hit by many rays. In other words, first 0.45 m of the absorber tube is not effectively used for 15 degrees incidence angle.

4.3.3 Heat Flux Distribution for 30 Degrees Incidence Angle

An isometric view of heat flux distribution around the LS2 PTC module absorber tube for 30 degrees incidence angle is presented in Figure 4.11.

In Figure 4.12, heat flux distribution around the LS2 PTC module absorber tube for 30 degrees incidence angle is presented for the view from +x direction.

101 number of contours are used for Figure 4.11 and Figure 4.12.

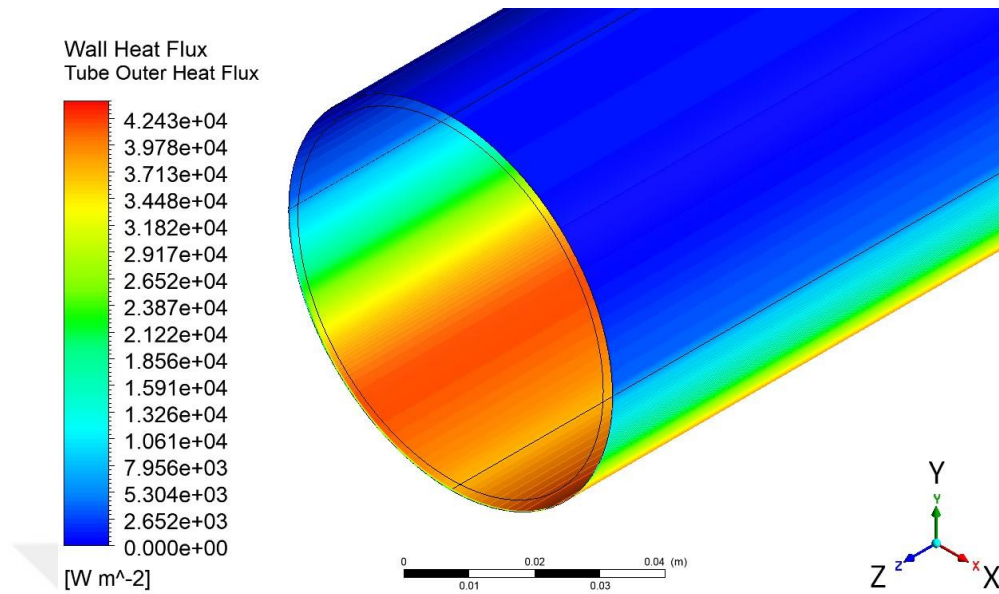


Figure 4.11. Isometric view of heat flux distribution around the LS2 PTC module absorber tube for 30 degrees incidence angle

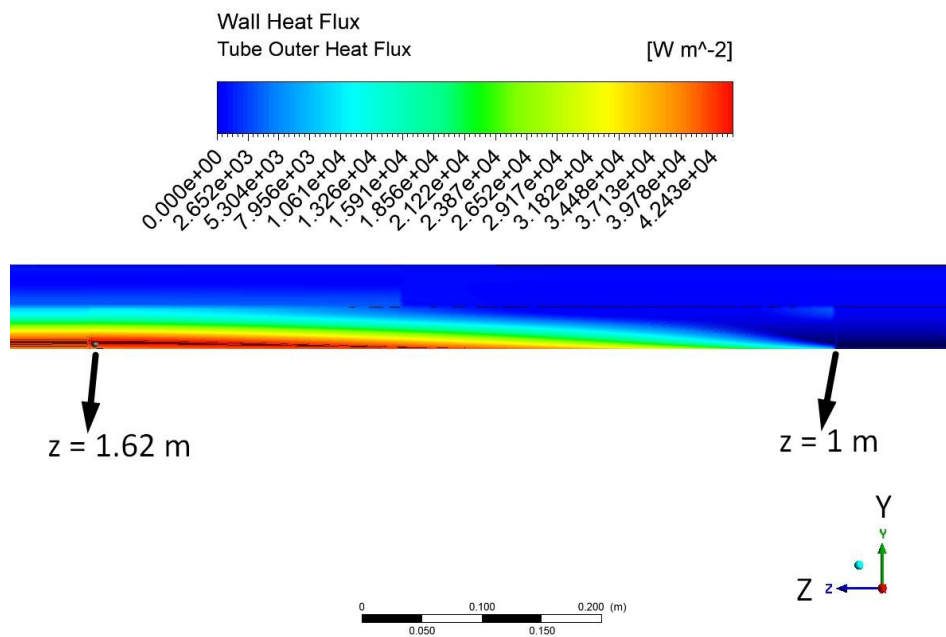


Figure 4.12. Heat flux distribution around the LS2 PTC module absorber tube for 30 degrees incidence angle, view from +x direction

Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 30 degrees incidence angle is presented in Figure 4.13.

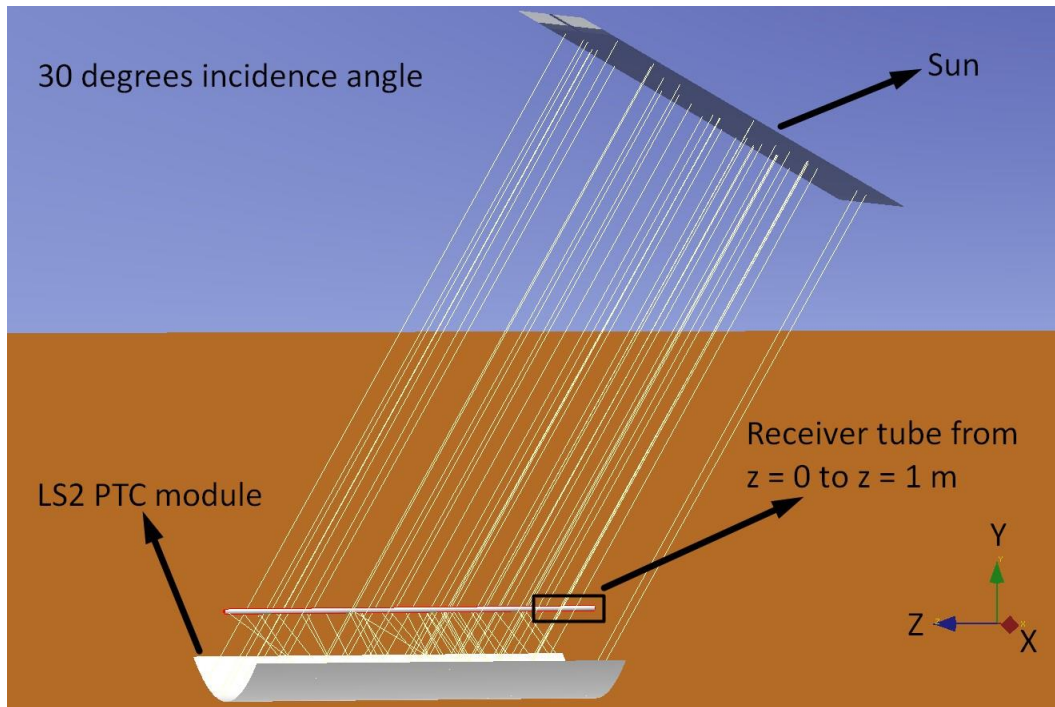


Figure 4.13. Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 30 degrees incidence angle

From Figure 4.12 and Figure 4.13, it can be seen that the bottom part of the absorber tube from $z = 0$ to $z = 1$ m does not get hit by many rays. In other words, first 1 m of the absorber tube is not effectively used for 30 degrees incidence angle.

4.3.4 Heat Flux Distribution for 45 Degrees Incidence Angle

An isometric view of heat flux distribution around the LS2 PTC module absorber tube for 45 degrees incidence angle is presented in Figure 4.14.

In Figure 4.15, heat flux distribution around the LS2 PTC module absorber tube for 45 degrees incidence angle is presented for the view from +x direction.

101 number of contours are used for Figure 4.14 and Figure 4.15.

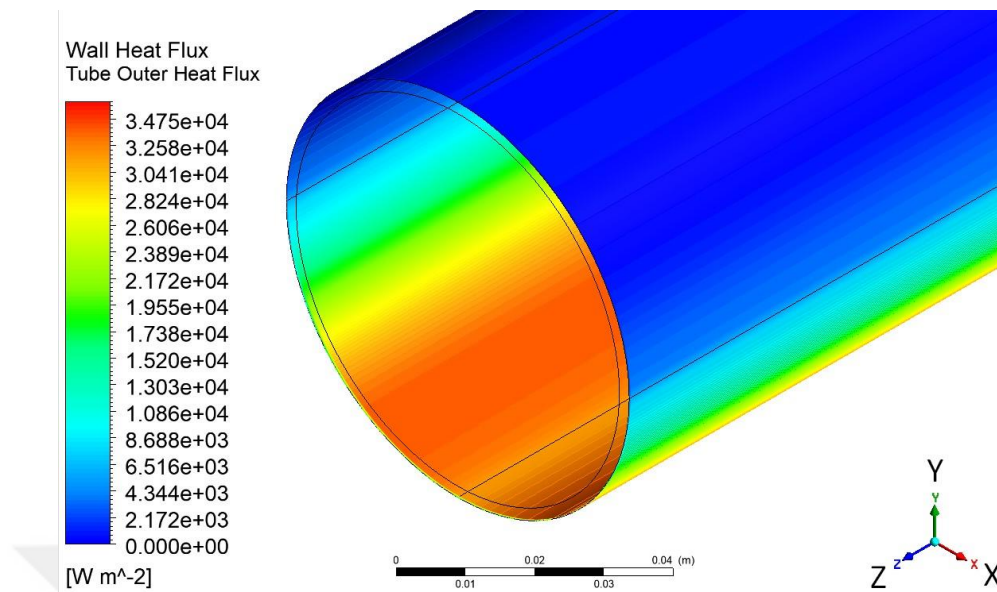


Figure 4.14. Isometric view of heat flux distribution around the LS2 PTC module absorber tube for 45 degrees incidence angle

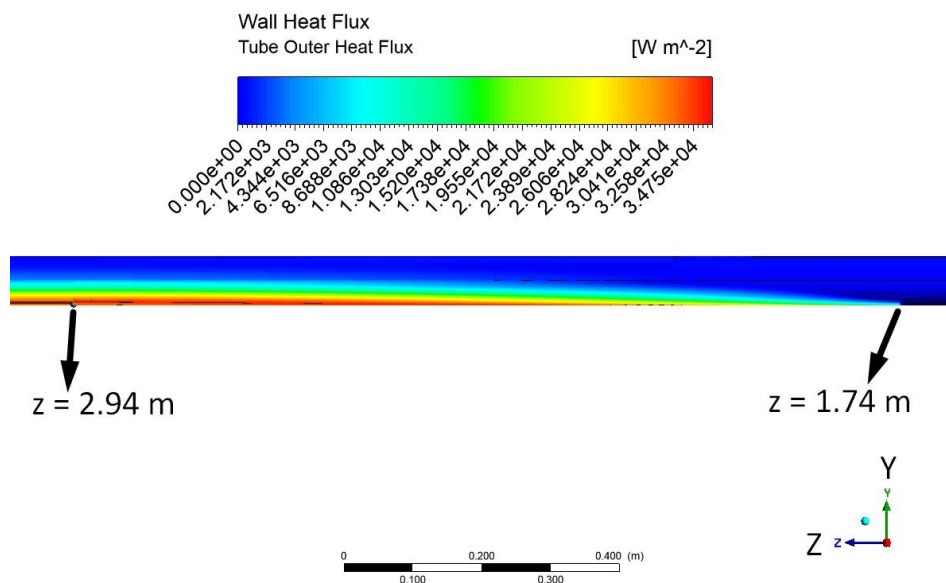


Figure 4.15. Heat flux distribution around the LS2 PTC module absorber tube for 45 degrees incidence angle, view from +x direction

Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 45 degrees incidence angle is presented in Figure 4.16.

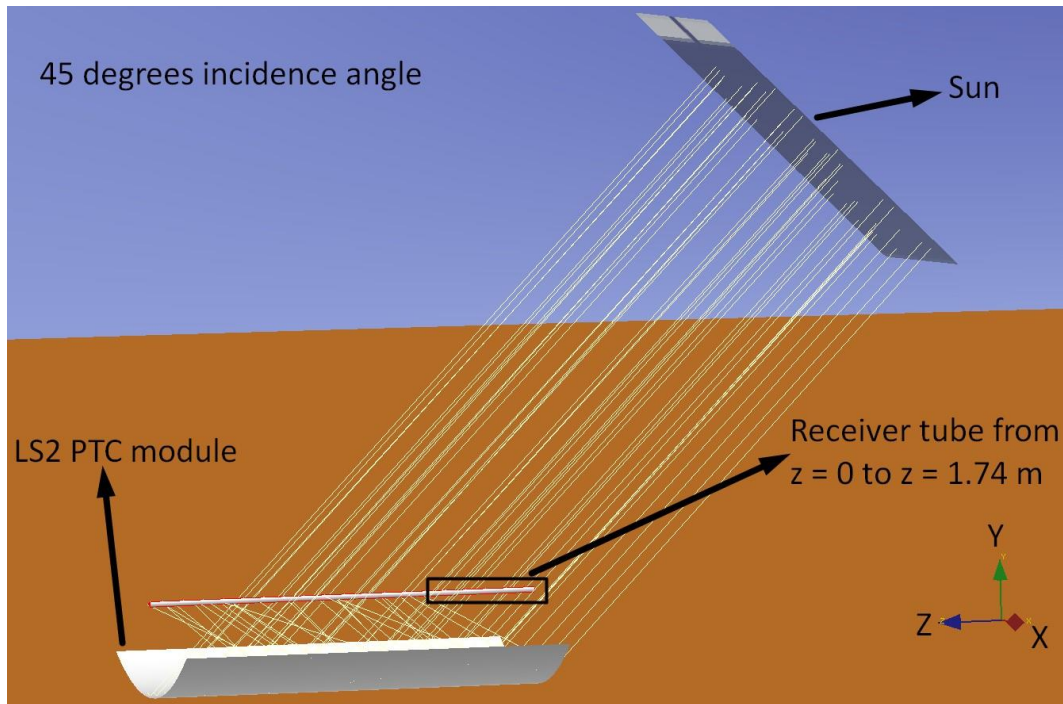


Figure 4.16. Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 45 degrees incidence angle

From Figure 4.15 and Figure 4.16, it can be seen that the bottom part of the absorber tube from $z = 0$ to $z = 1.74\text{ m}$ does not get hit by many rays. In other words, first 1.74 m of the absorber tube is not effectively used for 45 degrees incidence angle.

4.3.5 Heat Flux Distribution for 60 Degrees Incidence Angle

An isometric view of heat flux distribution around the LS2 PTC module absorber tube for 60 degrees incidence angle is presented in Figure 4.17.

In Figure 4.18, heat flux distribution around the LS2 PTC module absorber tube for 60 degrees incidence angle is presented for the view from +x direction.

101 number of contours are used for Figure 4.17 and Figure 4.18.

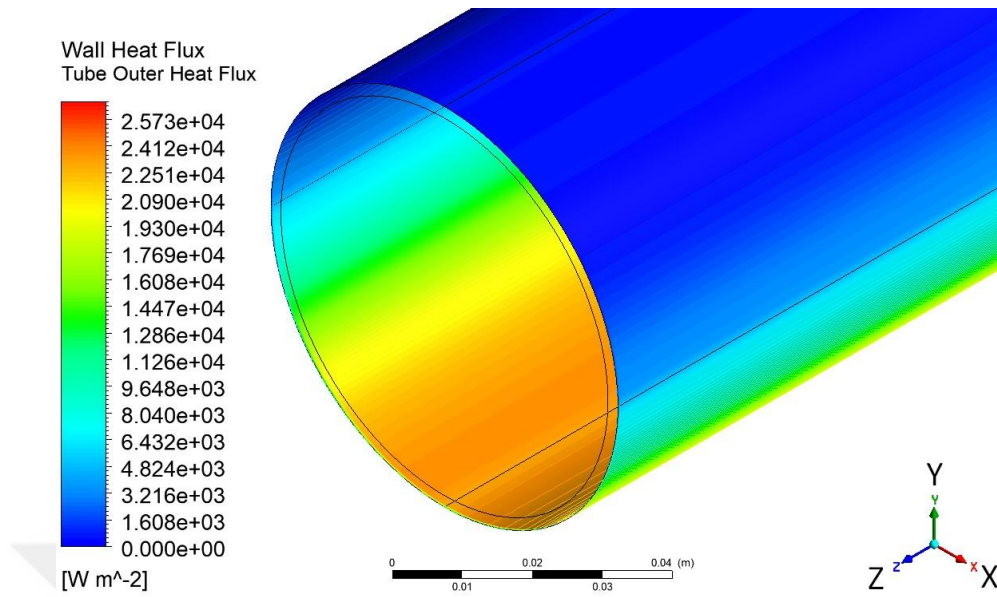


Figure 4.17. Isometric view of heat flux distribution around the LS2 PTC module absorber tube for 60 degrees incidence angle

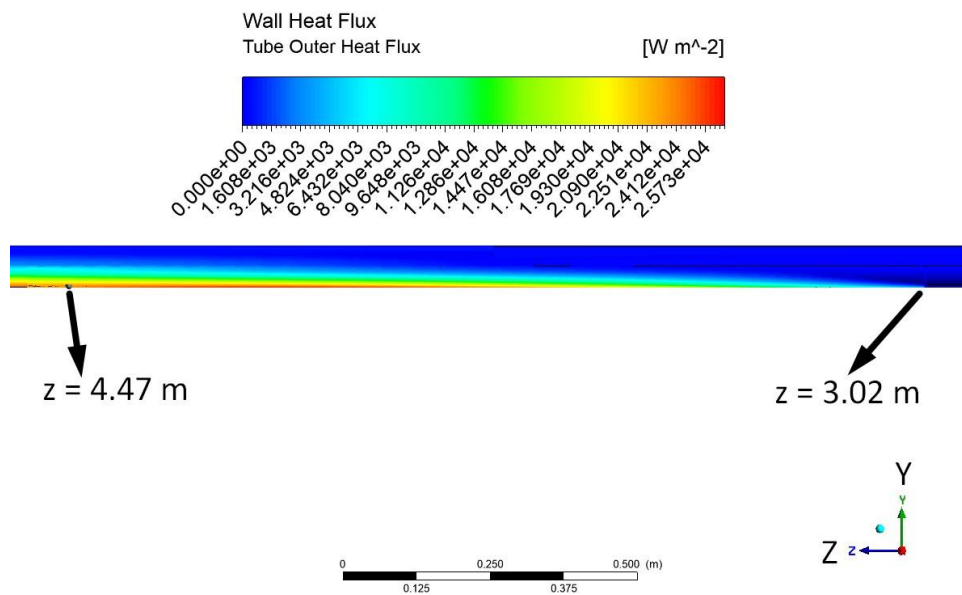


Figure 4.18. Heat flux distribution around the LS2 PTC module absorber tube for 60 degrees incidence angle, view from +x direction

Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 60 degrees incidence angle is presented in Figure 4.19.

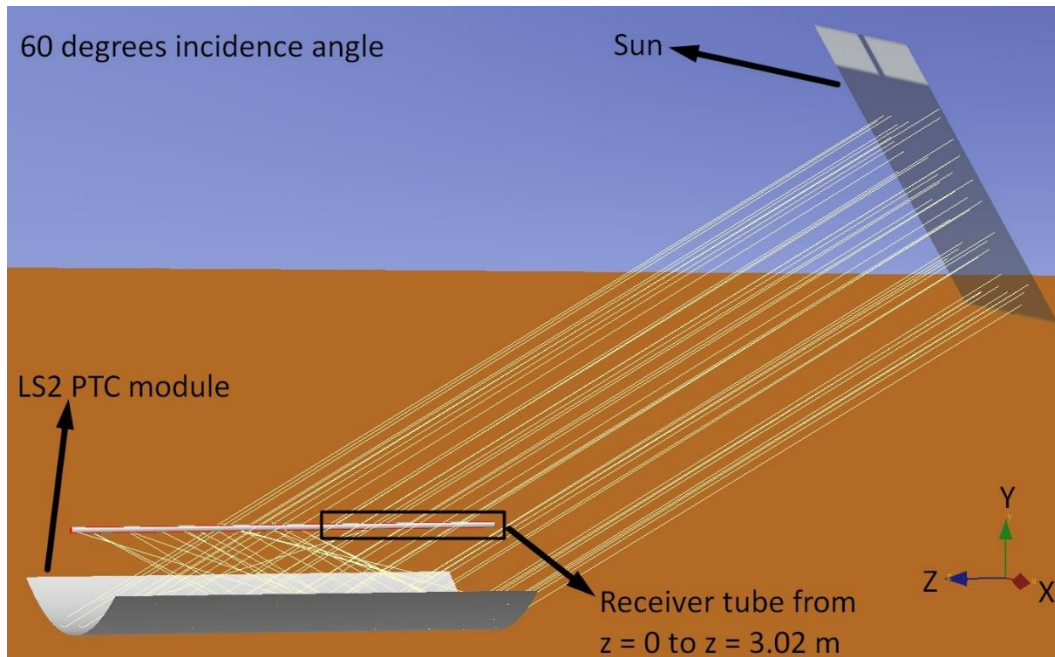


Figure 4.19. Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 60 degrees incidence angle

From Figure 4.18 and Figure 4.19, it can be seen that the bottom part of the absorber tube from $z = 0$ to $z = 3.02\text{ m}$ does not get hit by many rays. In other words, first 3.02 m of the absorber tube is not effectively used for 60 degrees incidence angle.

4.3.6 Heat Flux Distribution for 75 Degrees Incidence Angle

An isometric view of heat flux distribution around the LS2 PTC module absorber tube for 75 degrees incidence angle is presented in Figure 4.20.

In Figure 4.21, heat flux distribution around the LS2 PTC module absorber tube for 75 degrees incidence angle is presented for the view from +x direction.

101 number of contours are used for Figure 4.20 and Figure 4.21.

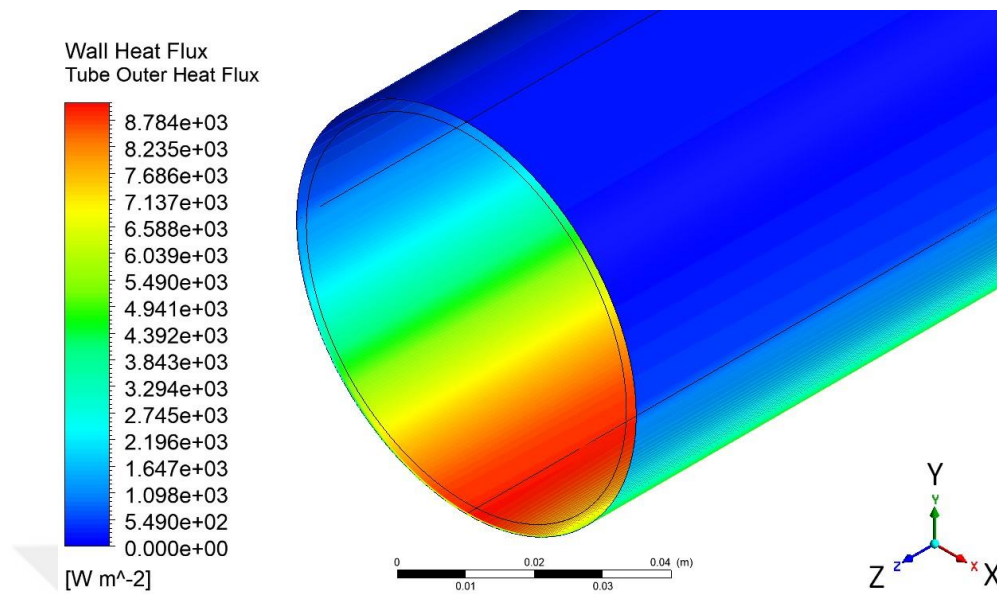


Figure 4.20. Isometric view of heat flux distribution around the LS2 PTC module absorber tube for 75 degrees incidence angle

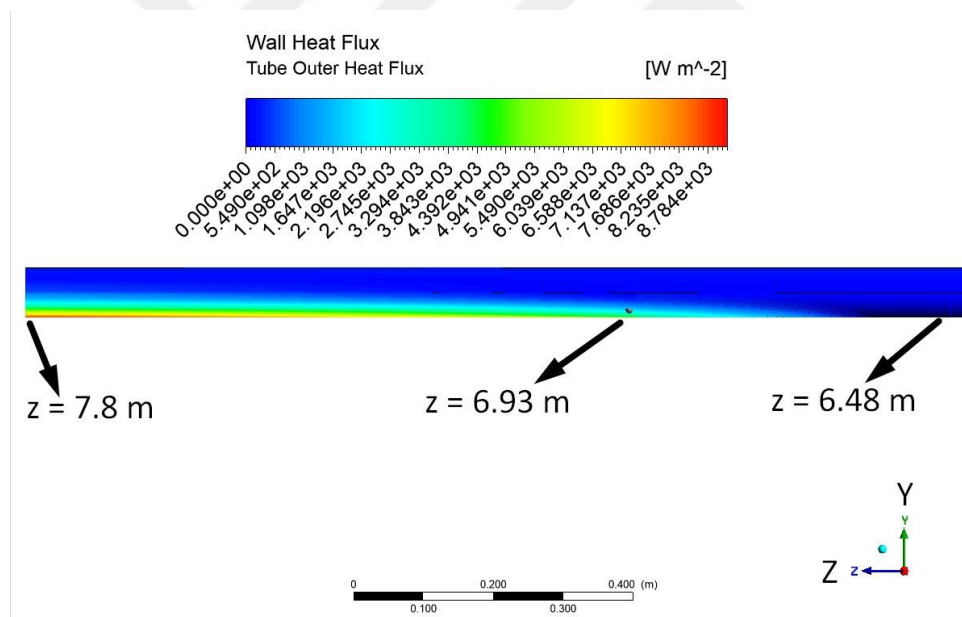


Figure 4.21. Heat flux distribution around the LS2 PTC module absorber tube for 75 degrees incidence angle, view from +x direction

Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 75 degrees incidence angle is presented in Figure 4.22.

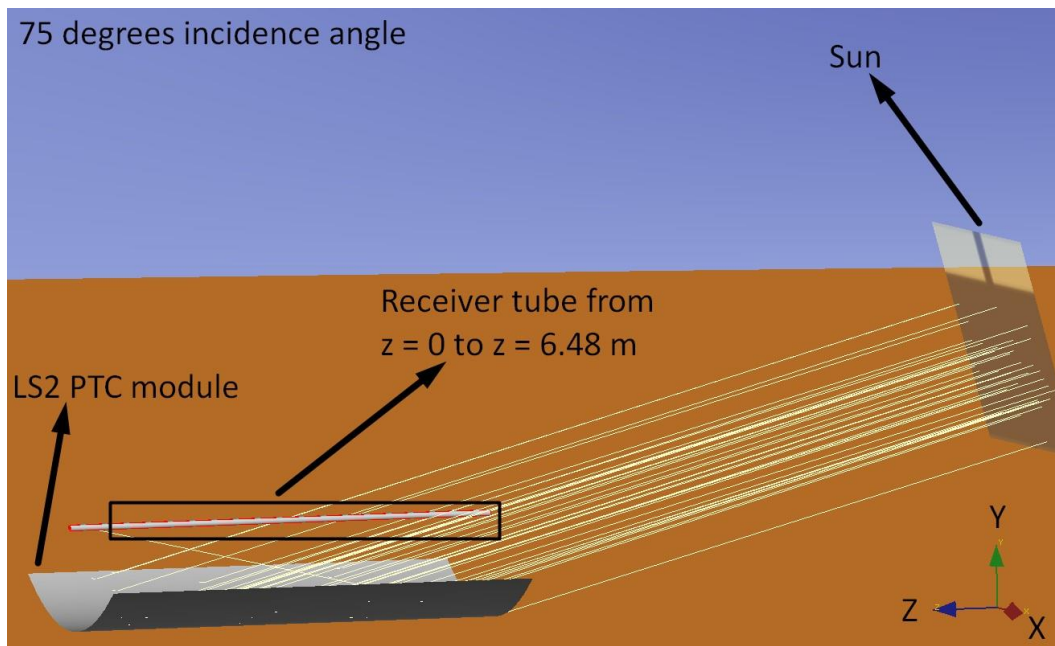


Figure 4.22. Ray-tracing visual of LS2 PTC module (with 50 rays) using Tonatiuh for 75 degrees incidence angle

From Figure 4.21 and Figure 4.22, it can be seen that the bottom part of the absorber tube from $z = 0$ to $z = 6.48 \text{ m}$ does not get hit by many rays. In other words, first 6.48 m of the absorber tube is not effectively used for 75 degrees incidence angle.

4.3.7 Ineffective Length of the Absorber Tube for Variable Incidence Angle

The effect of incidence angle on the PTC module is presented from Section 4.3.1 to Section 4.3.6. It is clear that as the incidence angle increases, the absorber tube's length, which is not effectively used, also increases.

In this section, the effect of incidence angle on the ineffective tube length and the total solar radiation on the absorber tube are tabulated.

In Table 4-7, total power on the absorber tube and the absorber tube's ineffective length are presented for six different incidence angles.

Table 4-7. Ineffective length of the absorber tube for six different incidence angles

Incidence Angle[°]	CFD-Post Total Power [W]	Ineffective Length of the Absorber tube [m]
0	32610.028	0.00
15	29318.618	0.45
30	23944.051	1.00
45	17072.508	1.74
60	8867.247	3.02
75	550.876	6.48

Table 4-7 shows that the incidence angle significantly affects the PTC performance.

In conclusion, the performance loss due to ineffective tube length can be neglected for very long PTC lines. Therefore, a long PTC line should be preferred if possible instead of multiple and short PTC lines.

4.4 IAM (Incidence Angle Modifier) Curve of LS2 PTC Module

In this section, the IAM curve of LS-2 PTC is obtained.

Incidence angle is the angle between the beam radiation on a surface and the plane that is normal to that surface [33]. The angle of incidence for a PTC is shown in Figure 4.23.

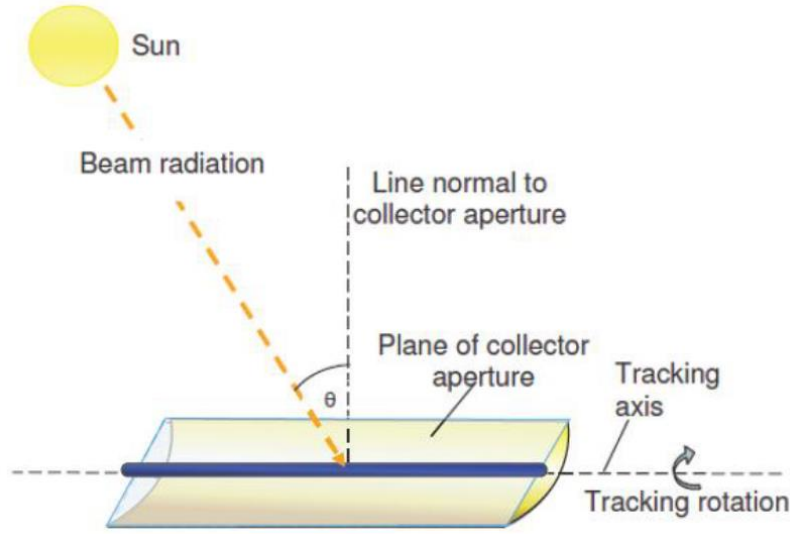


Figure 4.23. The angle of incidence for a parabolic trough collector [33]

In Figure 4.23, θ stands for the incidence angle.

Most of the time, parabolic trough collectors do not get the sunlight with a zero-degree incidence angle for two main reasons. Firstly, the PTC has a one-axis tracking system. It can follow the Sun in one direction only. Secondly, the incidence angle depends on the latitude of the location of the PTC module. For example, Turkey is located between the latitudes of $36^\circ N - 42^\circ N$. A PTC module cannot get the Sunlight with zero-degree incidence angle in Turkey unless it has a two-axis tracking system. Therefore, knowing the IAM (Incidence Angle Modifier) curve of a PTC module is essential.

Total solar power on the absorber tube decreases as the incidence angle increases. The x-axis of the IAM curve is the incidence angle values from 0 to 90 degrees. The y-axis values of the IAM curve are between 0 and 1 and found below

$$y - axis = \frac{\text{Total power on receiver tube for any incidence angle}}{\text{Total power on receiver tube for 0 degree incidence angle}} \quad (4.2)$$

Total solar power on the absorber tube is maximum for 0-degree incidence angle. Therefore, $IAM = 1$ for the 0-degree incidence angle. IAM value goes to 0 as the incidence angle goes to 90 degrees.

Incident beam irradiance, “ G_{beam} ”, is taken as $1000 \frac{W}{m^2}$ And all “m_sigmaSlope” and “sigmaSlope” values, which are optical errors of the surfaces, in Tonatiuh are set to 2 for the analysis. See APPENDIX L for details.

IAM curve of the LS-2 PTC module is presented in Figure 4.24.

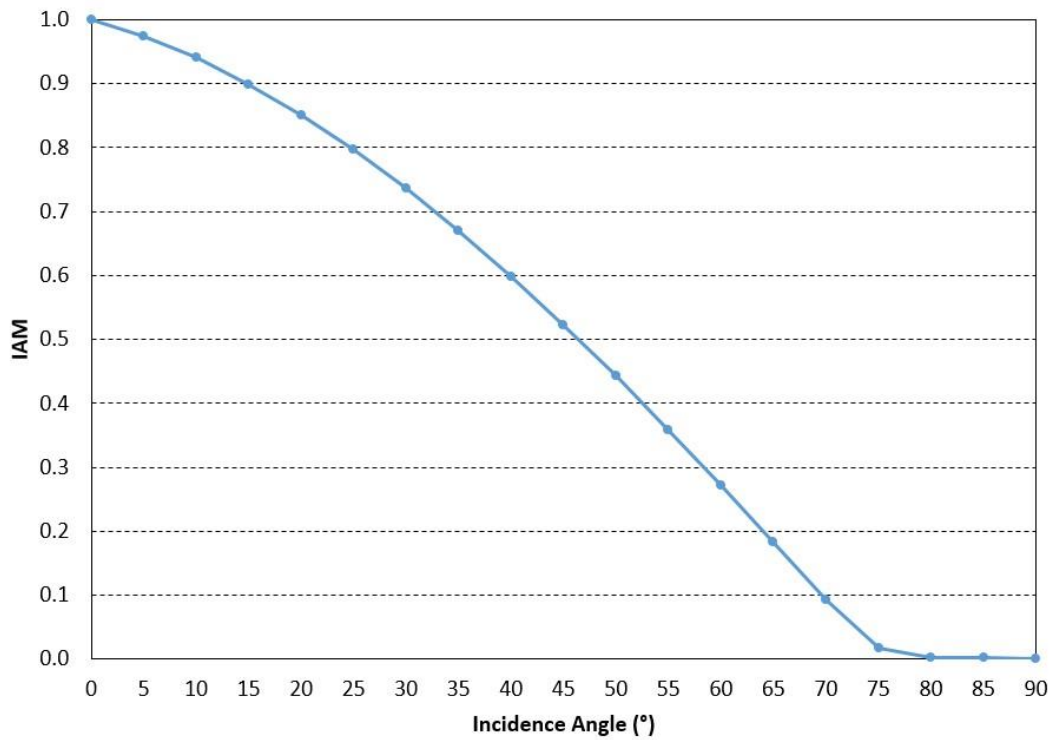


Figure 4.24. IAM curve of LS2 PTC module

The IAM for LS2 PTC is found as

For $0^\circ \leq \theta \leq 75^\circ$,

$$K_{\tau\alpha} = 1 - 4.93 \times 10^{-3} \theta - 1.17 \times 10^{-4} \theta^2 - 6.85 \times 10^{-7} \theta^3 + 1.05 \times 10^{-8} \theta^4 \quad (4.3)$$

For $80^\circ \leq \theta \leq 90^\circ$,

$$K_{\tau\alpha} = 0 \quad (4.4)$$

where θ is incidence angle and $K_{\tau\alpha}$ is the IAM (incidence angle modifier). For Turkey, if the incidence angle is 40° , then the IAM becomes 0.6.

In the SEGS LS-2 test report [21], the IAM curve is obtained from 0 to 60 degrees incidence angle.

The comparison of the IAM curve obtained in this thesis and the one in the SEGS LS-2 test report is given in Figure 4.25.

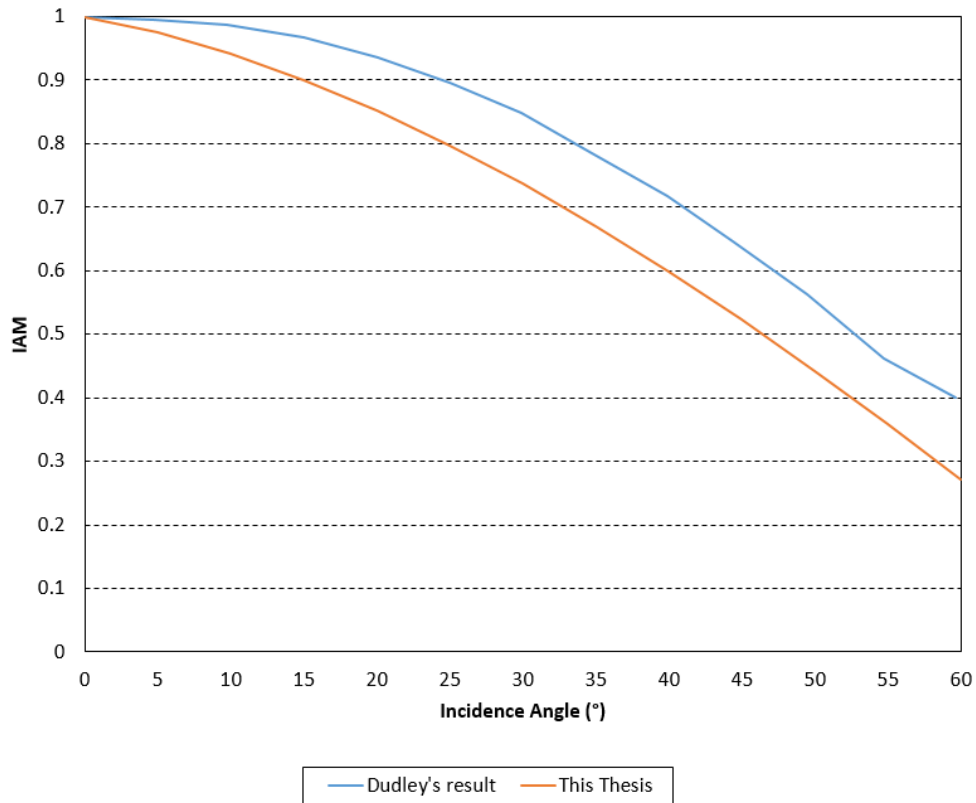


Figure 4.25. The comparison of the IAM curve obtained in this thesis and the one in the SEGS LS-2 [21] test report

In Figure 4.25, the reason for the difference between the two curves is that in this thesis, the IAM curve is obtained only for one LS-2 PTC module with a length of 7.8 meters. However, in the SEGS LS-2 experiment report[21], it is stated that end losses due to the finite length of the collector are neglected in IAM calculations. In other words, in the SEGS LS-2 experiment report, IAM results are calculated assuming a collector with infinite length. The end losses become negligible for a

collector with infinite length. On the other hand, the end losses due to incidence angle become important as the PTC length becomes shorter. The end losses due to incidence angle are explained in detail in Section 4.3.

In conclusion, since the collector's finite length is not taken into account in the SEGS LS-2 test report, the IAM values of Dudley et al. [21] are always greater than the IAM values obtained in this thesis as expected.

4.5 Comparison of Absorber Tube with Plus-Shaped Fin Insert and Normal Absorber Tube

In this part, different tube geometries with a length of 1 meter are compared. The temperature increase and the pressure drop per meter are calculated. The oil velocity and temperature profiles are fully developed, as mentioned in Section 3.5.4.

First, the mesh refinement test is performed for the tube with plus shape insert. The mesh refinement test for 45° rotated insert is presented in Table 4-8.

Table 4-8 The mesh refinement test for 45° rotated plus shape insert

Mesh Nodes	Mesh Elements	Oil Inlet Temperature [Celcius]	Oil Outlet Temperature [Celcius]	Pressure Drop [Pa]
207950	201984	392.99	396.85	25.72
343445	335322	392.99	396.57	24.75
737621	724296	392.99	396.33	24.70
956981	941305	392.99	396.28	24.64

The mesh with 737621 nodes and 724296 elements is selected as the final mesh, and the same mesh is used in 0°, 30°, 40° and 45° configurations.

The temperature increase and pressure drop per meter for the absorber tube with four different plus-shaped fin insert configurations and the normal absorber tube are given in Table 4-9.

Table 4-9 The temperature increase and pressure drop per meter for the absorber tube with four different plus-shaped fin insert configurations and the normal absorber tube

Tube Geometry	Oil Inlet Temperature [Celcius]	Oil Outlet Temperature [Celcius]	Pressure Drop [Pa]	Temperature Increase [Celcius]
Normal Tube	392.99	395.14	6.36	2.14
Plus Shape 0 degree rotation	392.99	396.20	24.15	3.20
Plus Shape 30 degree rotation	392.99	396.51	24.28	3.51
Plus Shape 40 degree rotation	392.99	396.30	24.12	3.30
Plus Shape 45 degree rotation	392.99	396.34	24.70	3.34

Table 4-9 shows that the absorber tube with 30° rotated plus shape insert gives the maximum temperature increase for the LS-2 absorber tube. The plus-shaped fin insert with 30° rotation are shown in Figure 4.26.

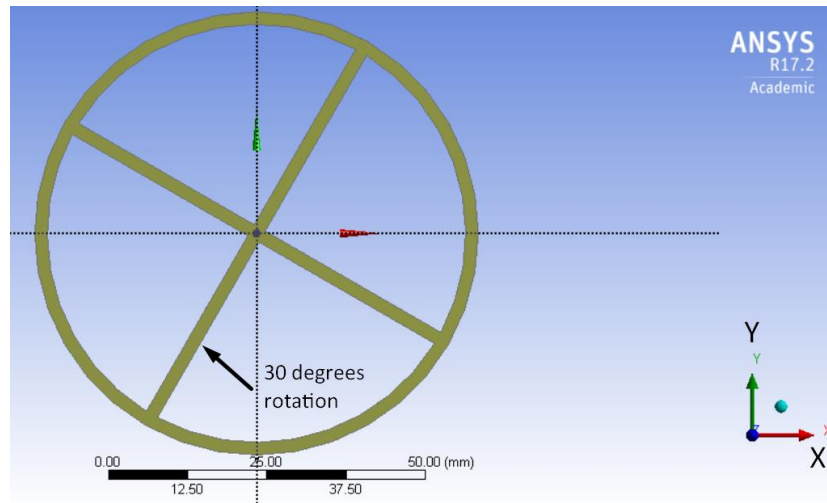


Figure 4.26. Plus-shaped fin insert with 30° rotation

In Figure 4.27, the heat flux distribution on a cross-section of an LS-2 PTC module is presented for zero-degree incidence angle.

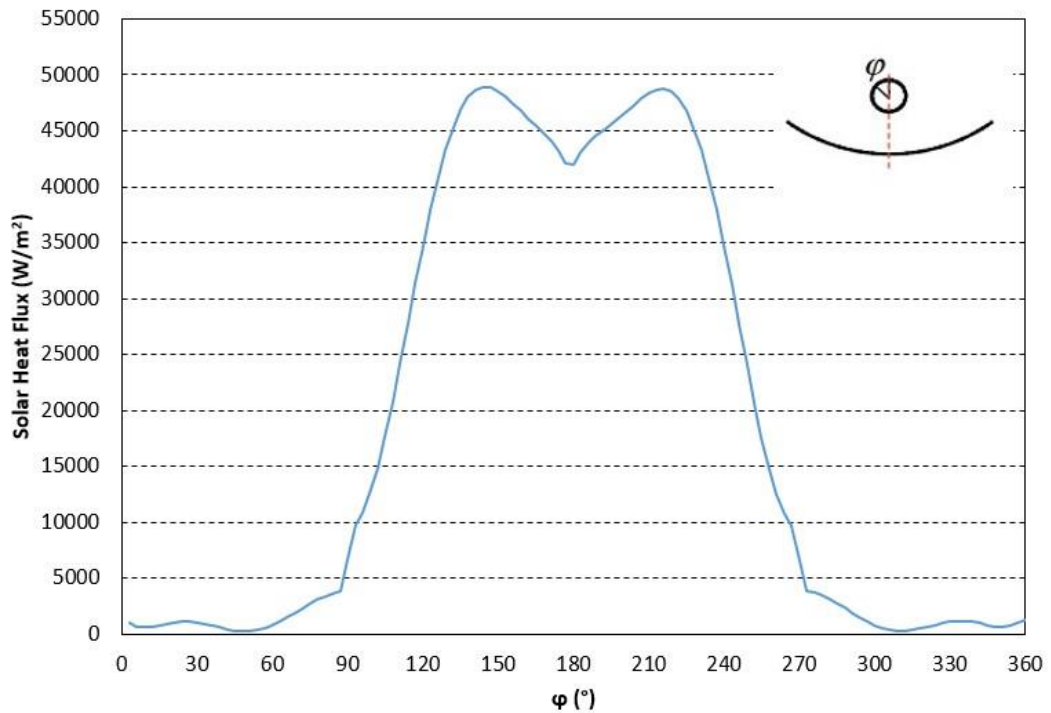


Figure 4.27. Heat flux distribution at $z = 7.7\text{ m}$ cross-section around the LS2 PTC module absorber tube with 0-degree incidence angle

In Figure 4.27, the maximum heat flux on the absorber tube surface occurs between the angles of $144^\circ - 147^\circ$ and $213^\circ - 216^\circ$.

When the plus-shaped fin insert is rotated 30°, one of its legs becomes very close to the maximum heat flux region, and the other leg comes closer to the other maximum heat flux region. More heat is transferred to the plus-shaped fin insert, and the heat losses from the absorber tube become less than other configurations.

Heat losses from normal absorber tube and the absorber tubes with plus-shaped fin insert with 0°, 30°, 40°, and 45° degrees rotation are presented in Table 4-10.

Table 4-10 Heat losses from normal absorber tube and the absorber tubes with plus-shaped fin insert with 0°, 30°, 40°, and 45° degrees rotation

Tube Geometry	Total Heat Loss [W]	Radiative Heat Loss [W]	The decrease in Heat Loss Compared to Normal Absorber Tube
Normal Tube	689.95	557.00	-
Plus Shape 0 degree rotation	650.51	518.13	5.72%
Plus Shape 30 degree rotation	634.46	504.70	8.04%
Plus Shape 40 degree rotation	643.79	511.79	6.69%
Plus Shape 45 degree rotation	639.15	508.25	7.36%

The absorber tube's heat loss is decreased by 8.04% using an absorber tube with a 30° rotated plus-shaped fin insert. Heat loss decrease results from the absorber tube of other studies are given below.

Muno et al. [10] investigated four different internally finned tubes. The heat losses for the internally finned tubes decreased between 7% – 18.6% compared to the normal absorber tube. Cheng et al. [11] studied the heat transfer enhancement using unilateral longitudinal vortex generators inside the absorber tube. The authors

concluded that the absorber tube's thermal losses with vortex generators decrease between 0.11% – 13.39% compared to the normal absorber tube for different incident solar radiation values. Song et al. [12] performed a numerical study about absorber tubes with helical screw-tape inserts. The authors concluded that the heat loss in a tube with helical screw-tape insert is almost one-sixth of the smooth absorber tube for inlet temperature $373K$ and flow rate of $0.11 \frac{kg}{s}$. If the flow rate is increased to $0.6 \frac{kg}{s}$, the heat loss in a tube with helical screw-tape insert is almost one-third of the smooth absorber tube. On the other hand, the pressure loss increases 4 times for the normal absorber tube, whereas it increases 23 times for the absorber tube with helical screw-tape insert, for the flow rate of $0.6 \frac{kg}{s}$.

The temperature contours of normal absorber tube and the absorber tubes with plus-shaped fin insert with 0° , 30° , 40° , and 45° degrees rotation at $z = 3m$ are given in Figure 4.28, Figure 4.29, Figure 4.30, Figure 4.31, and Figure 4.32 respectively.

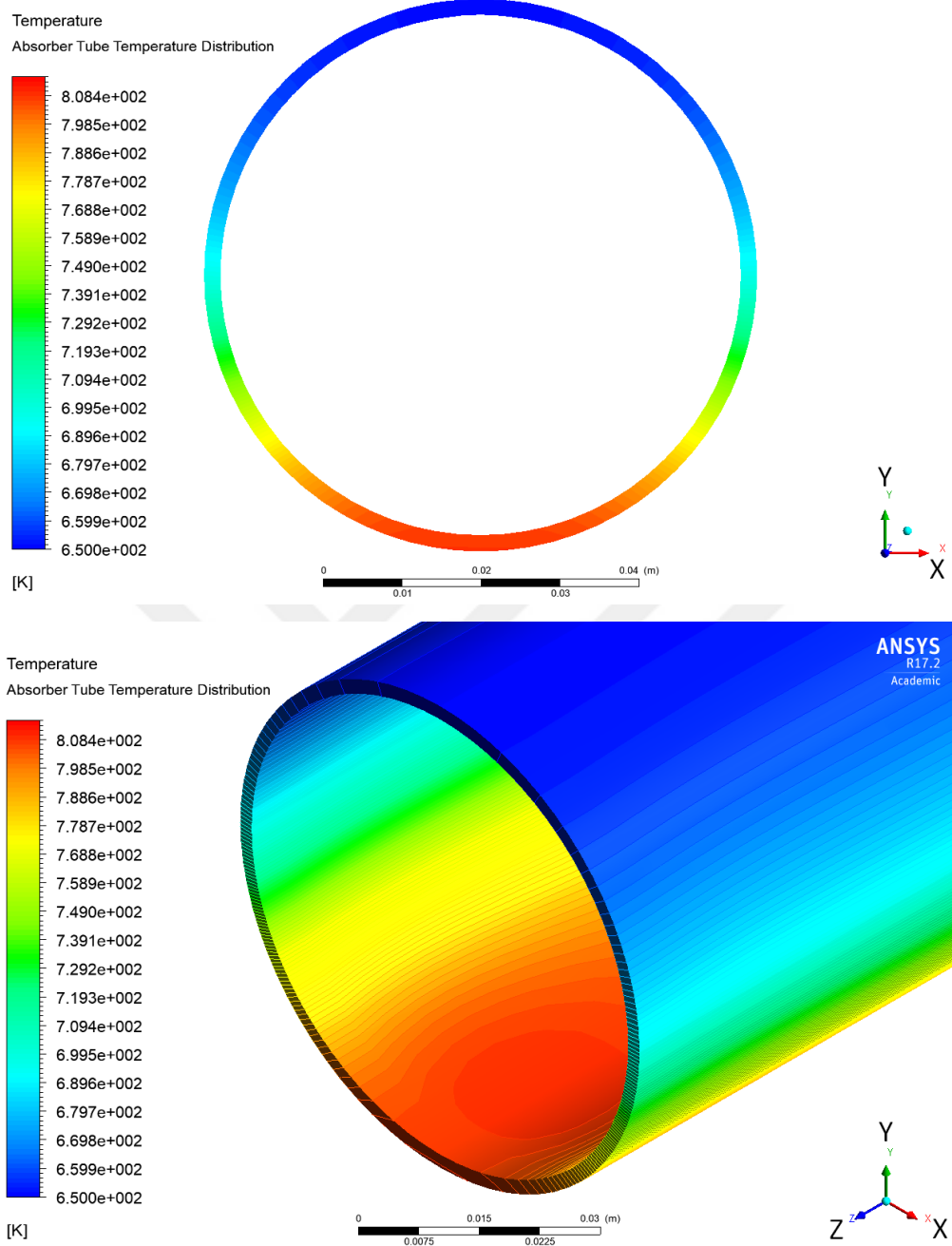


Figure 4.28. The temperature contours of normal absorber tube at $z = 3m$

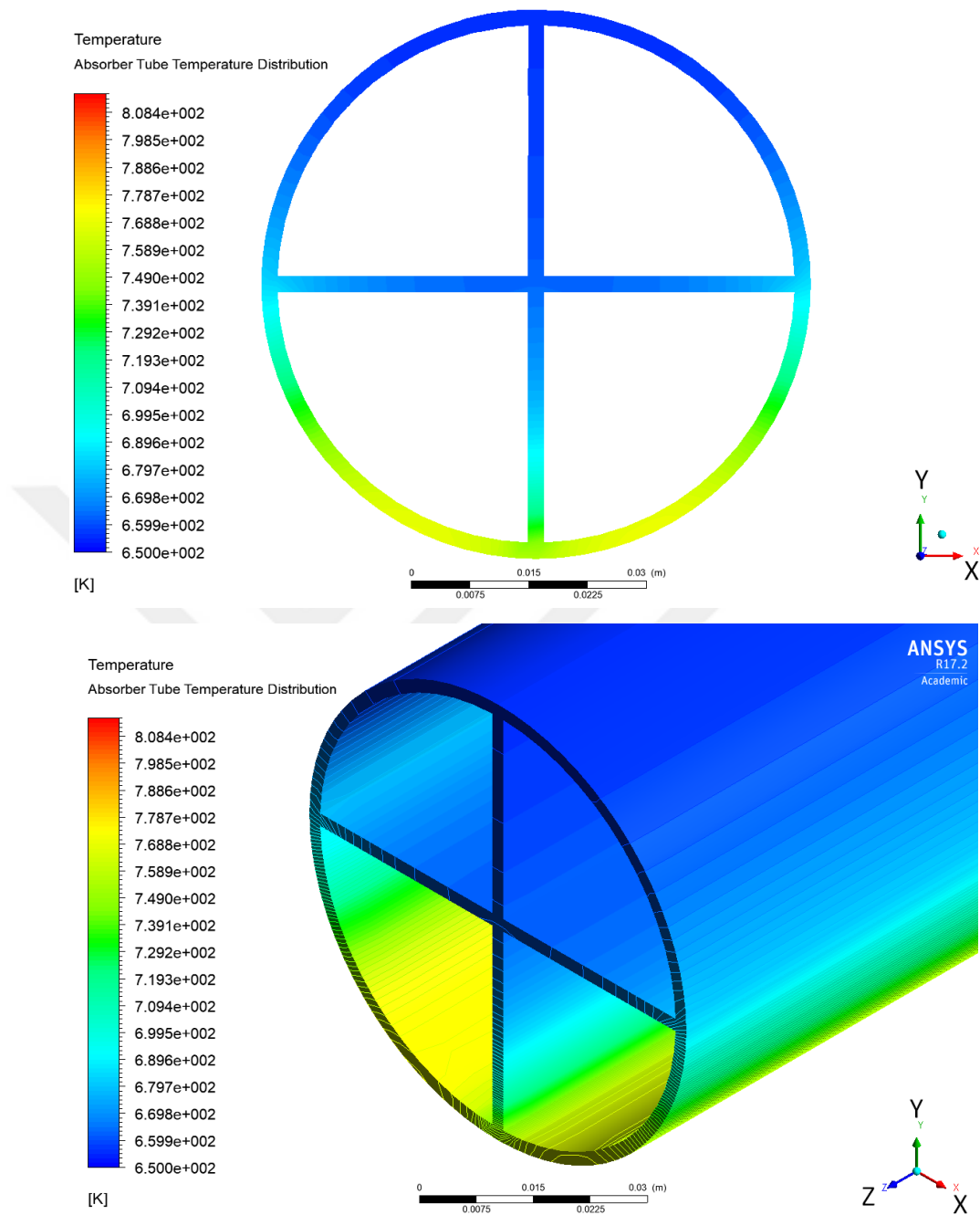


Figure 4.29. The temperature contours of absorber tube with plus-shaped fin insert with 0° rotation at $z = 3m$

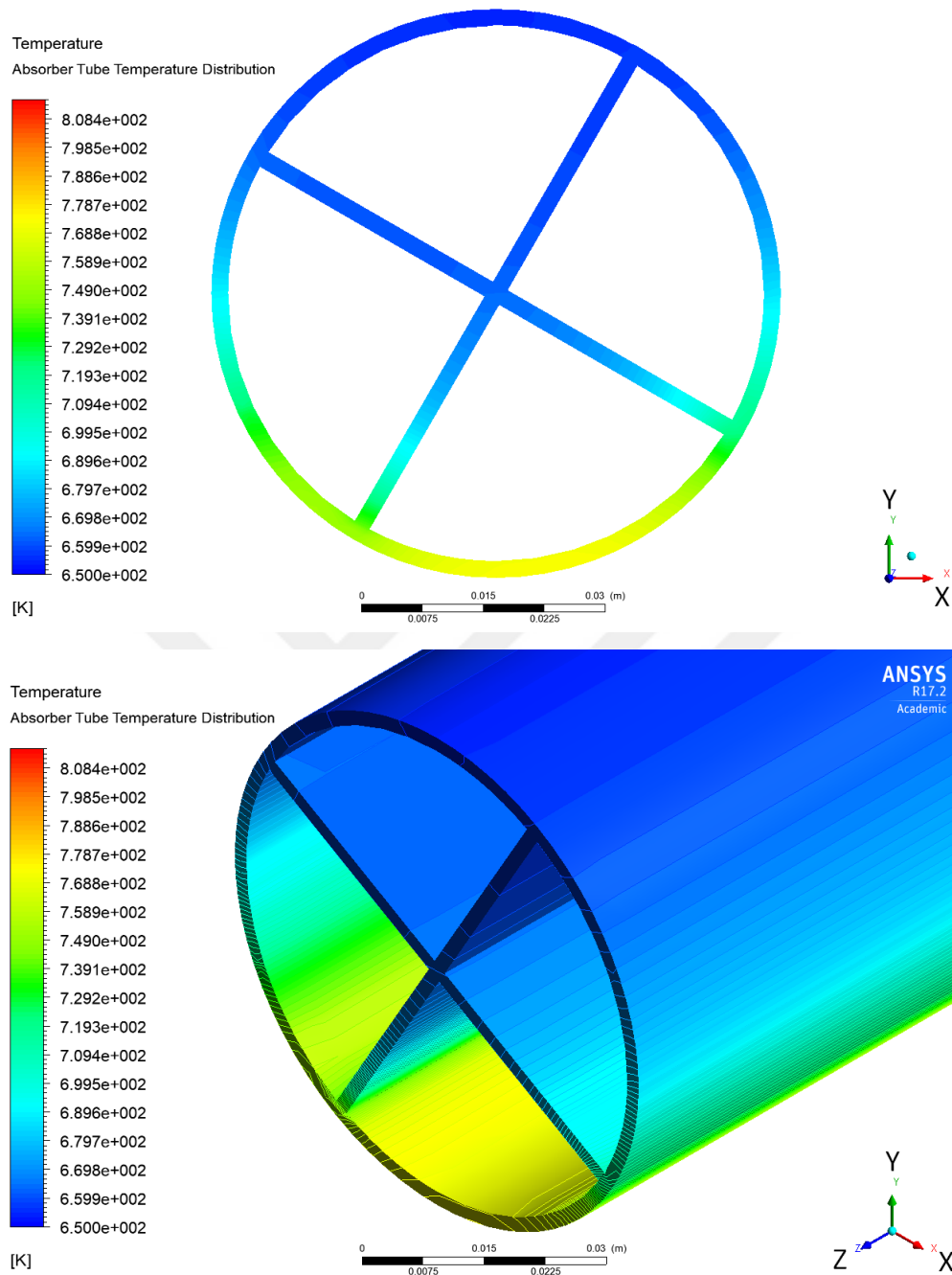


Figure 4.30. The temperature contours of absorber tube with plus-shaped fin insert with 30° rotation at $z = 3m$

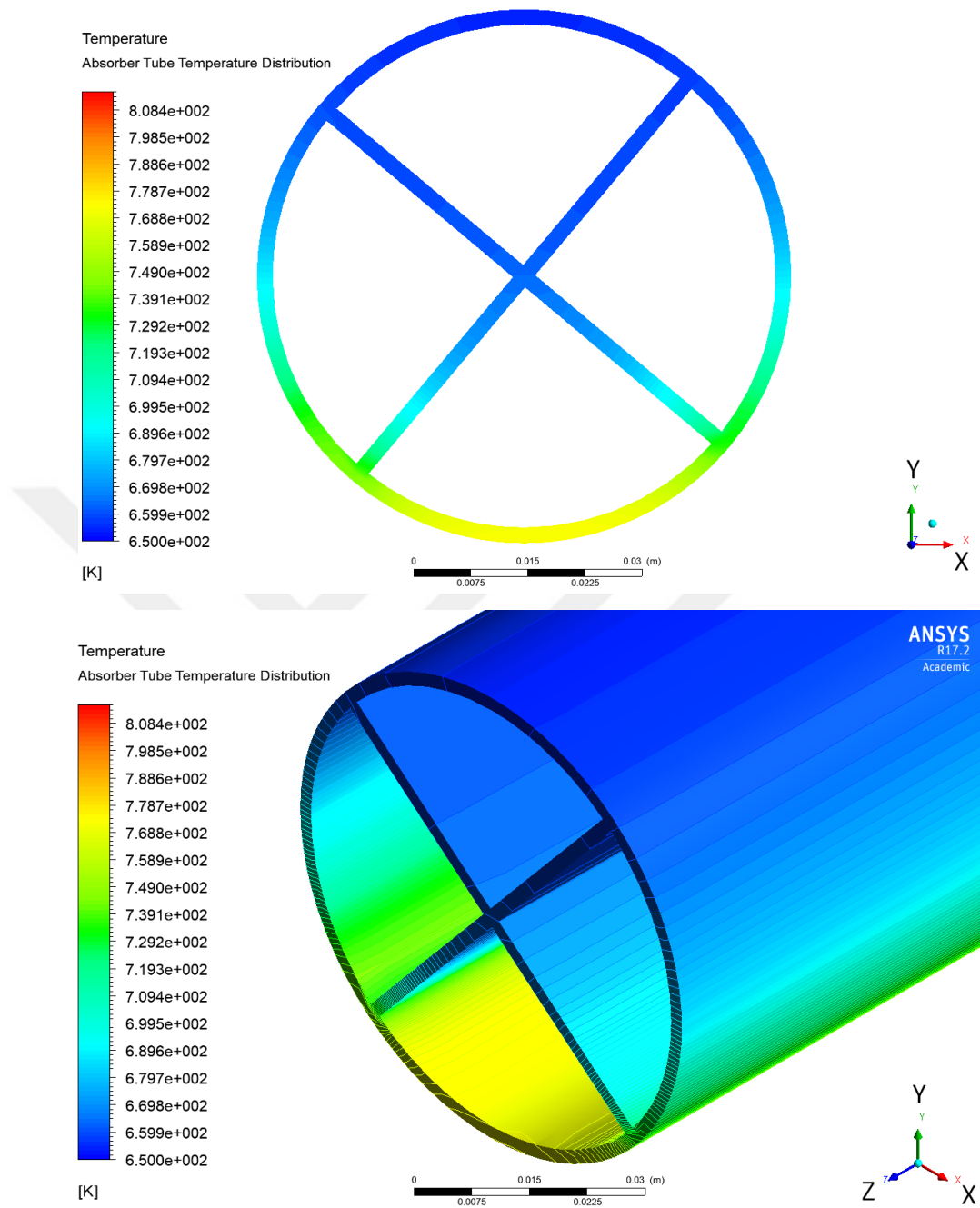


Figure 4.31. The temperature contours of absorber tube with plus-shaped fin insert with 40° rotation at $z = 3m$

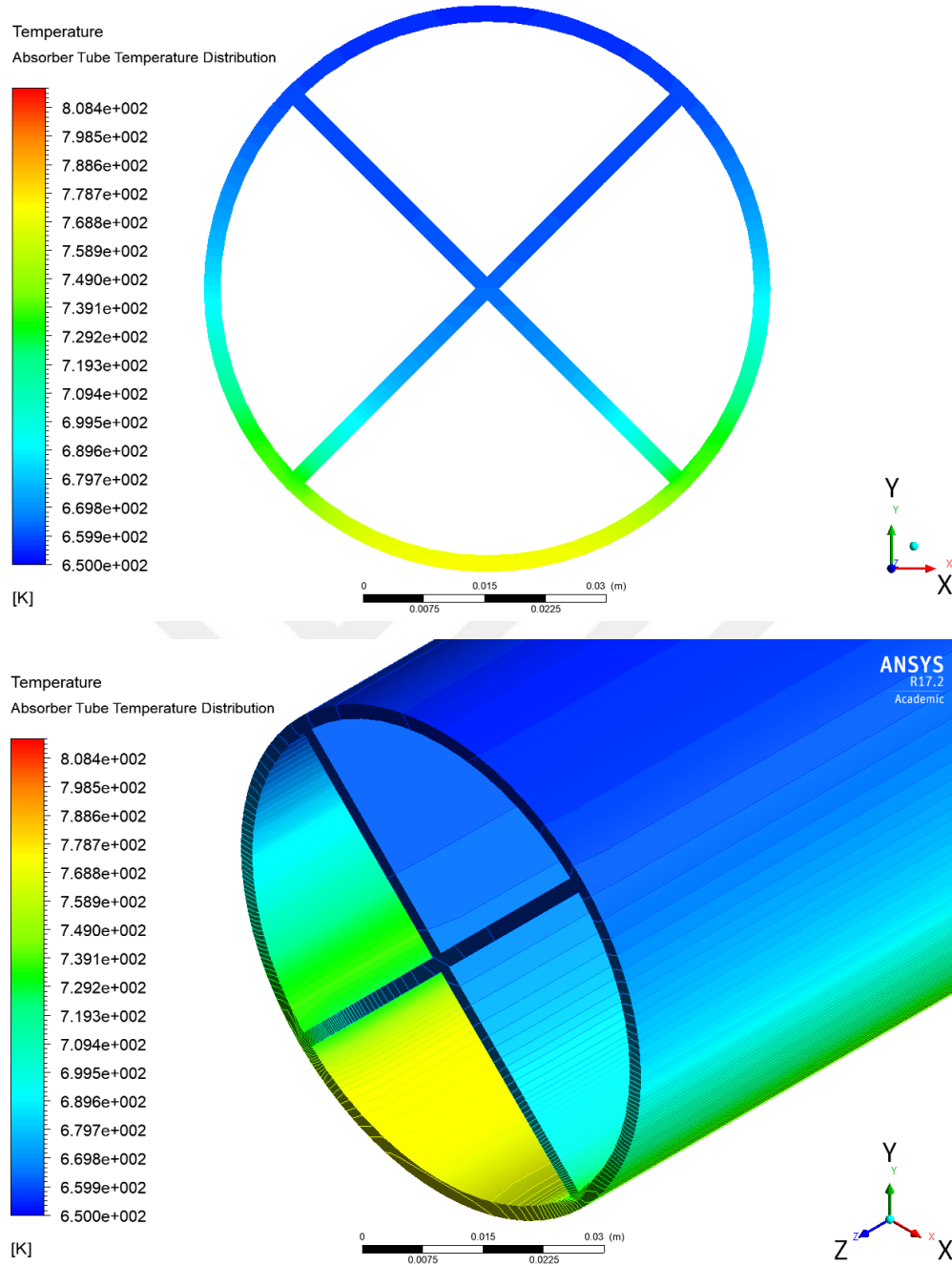


Figure 4.32. The temperature contours of absorber tube with plus-shaped fin insert with 45° rotation at $z = 3m$

The same temperature legend is used for comparison from Figure 4.28 to Figure 4.32.

The plus-shaped fin insert not only increases the heat transfer area but also reduces the maximum temperature on the absorber tube's outer surface. It can be seen that the maximum temperature on the absorber tube's outer surface with any configuration of plus-shaped fin insert is less than the normal absorber tube. Reducing the maximum temperature on the absorber tube's outer surface reduces the heat losses with radiation and free convection.

The 30° rotated plus-shaped fin insert provide the maximum temperature increase. The reason is when the plus-shaped fin insert is rotated 30°, one of its legs becomes very close to the maximum heat flux region, and the other leg comes closer to the other maximum heat flux region as much as possible. More heat is transferred to the plus-shaped fin insert, and the heat losses from the absorber tube become less than other configurations. This phenomenon can be seen by comparing Figure 4.29 and Figure 4.30. In Figure 4.30, the absorbed solar energy diffuses into the 30° degrees rotated plus-shaped fin insert better than the 0° rotated plus-shape fin insert in Figure 4.29.

Moreover, if Figure 4.30 is compared with Figure 4.28, it can be seen that the absorber tube with 30° rotated plus-shaped fin insert has more homogenized temperature distribution than the normal absorber tube. More homogenized temperature distribution also reduces the thermal stresses inside the absorber tube and increases the absorber tube's lifetime.

In conclusion, the 30° rotated plus-shaped fin insert provides the maximum temperature increase with a homogenized temperature distribution.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

In this section, the conclusions of this thesis and recommendations for future work are explained.

5.1 Conclusion

A new method is presented to simulate PTCs by using Tonatiuh, MATLAB, and ANSYS Fluent. This method can be used for any incidence angle. First, the optical model is validated with numerical studies in the literature by comparing the heat flux distribution and the amount of heat flux on the absorber tube. Second, the results of the CFD model are validated using the SEGS LS-2 experimental data.

Ineffective lengths of the absorber tube are found for six different incidence angles. It is concluded that the ineffective length of the absorber tube increases with increasing incidence angle.

The performance loss due to ineffective tube length can be neglected for very long PTC lines. Therefore, a long PTC line should be preferred if possible instead of multiple and short PTC lines.

The free convection and radiative heat losses are calculated with Fluent. As the oil temperature increases, radiative heat losses exceed the free convection heat losses, as expected. The free convection heat loss is greater than the radiative heat loss for low oil temperatures. The free convection heat loss is smaller than the radiative heat loss for high oil temperatures, but it still has the same order of magnitude as radiative heat losses. Thus, it is concluded that the heat loss with free convection in the vacuum region should not be neglected.

New tube geometry with four different configurations is investigated to increase the heat transfer inside the absorber tube. It is concluded that the 30° rotated plus-

shaped fin insert gives the best results compared to other configurations. The 30° rotated plus-shaped fin insert provides a 1.37°C extra temperature increase per meter than a normal absorber tube for an oil inlet temperature of 393°C. On the other hand, it introduces an additional pressure drop of 17.93 *Pa* per meter. The heat loss from the absorber tube with a 30° rotated plus-shaped fin insert is 8.04% less than the normal absorber tube.

The absorber tube with a plus-shaped fin insert can be manufactured by drawing operation. Therefore, the only extra cost is the initial material cost of the fin structure.

Using hexahedral elements for meshing decreased the number of nodes and elements significantly. Thus, the computation time is reduced. Therefore, hexahedral elements are strongly recommended for clean geometries and large volumes.

5.2 Recommendations For Future Work

Other absorber tube geometries such as the absorber tube of 1 m length with twisted tape insert, the 1 m long dimpled tube, and 1 m long corrugated tubes can be compared with the new tube geometry presented in this thesis in terms of oil outlet temperature increase and the pressure drop.

Economic analysis can be performed considering the extra pressure drop and manufacturing cost that the plus-shaped fin insert introduces.

The method presented in this thesis can also be used to simulate LFCs. After the LFC is created with Tonatiuh, the MATLAB code for post-processing the binary file of Tonatiuh data and the absorber tube's discretization is available in APPENDIX F.

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APPENDICES

A. Creating the Parabolic Mirror of LS2 PTC Module using Tonatiuh

This APPENDIX explains how to create the parabolic mirror of the LS2 PTC module using Tonatiuh.

In Figure A 1, the group node and surface node are shown in the tree structure of the parabolic mirror.

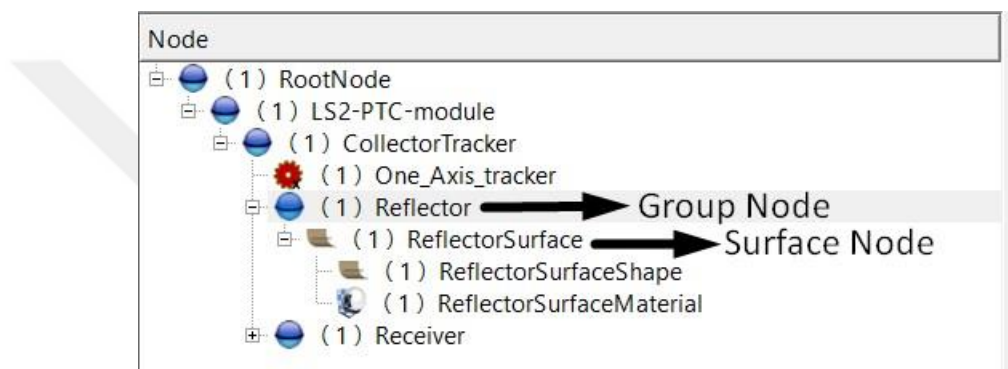


Figure A 1. Group node and surface node in the tree structure of the parabolic reflector

Figure A 2 shows how to create a group and surface node.

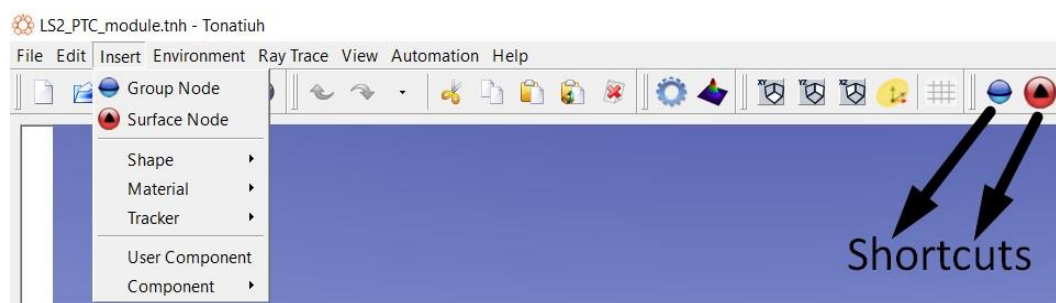


Figure A 2. The section in Tonatiuh to insert Group and Surface node

“Trough_Parabola” is chosen for the shape. “Specular_Standard_Material” is chosen for the material.

The sections in Tonatiuh to insert shape and material are shown in Figure A 3 and Figure A 4, respectively.

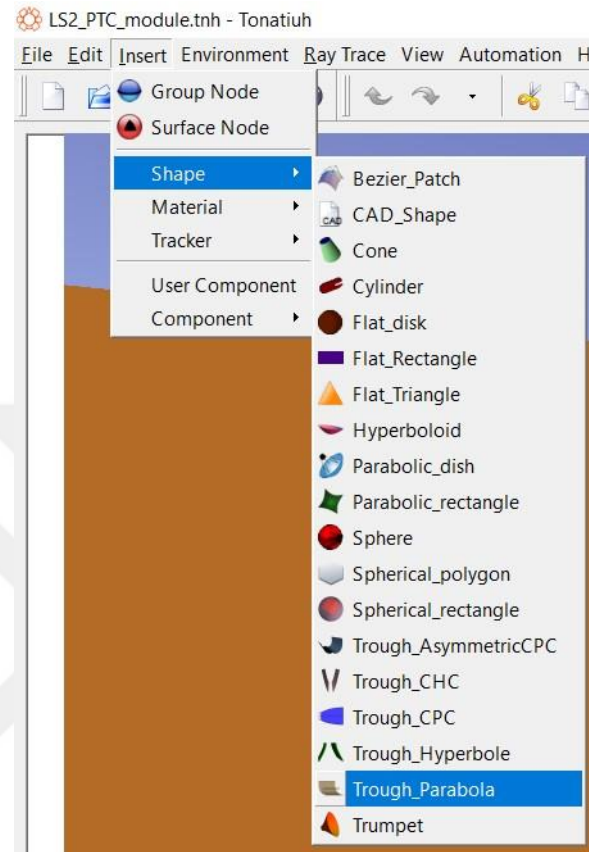


Figure A 3. The section in Tonatiuh to insert surface shape of the parabolic mirror

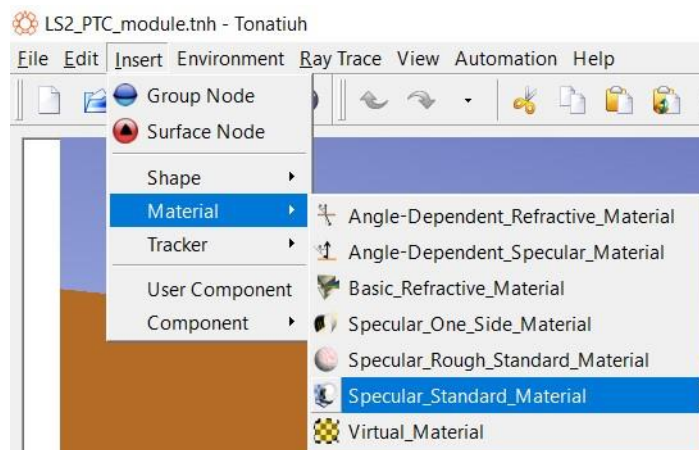
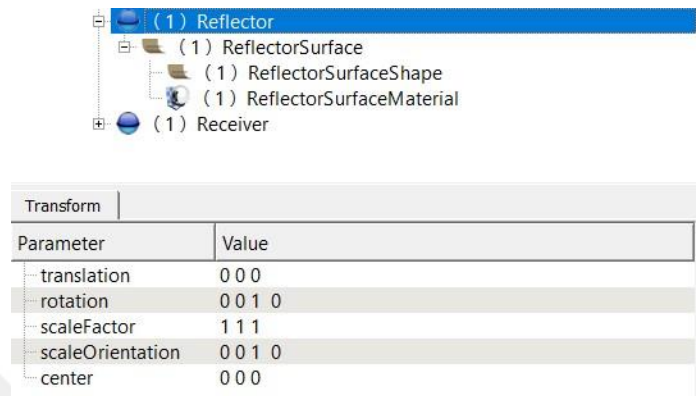


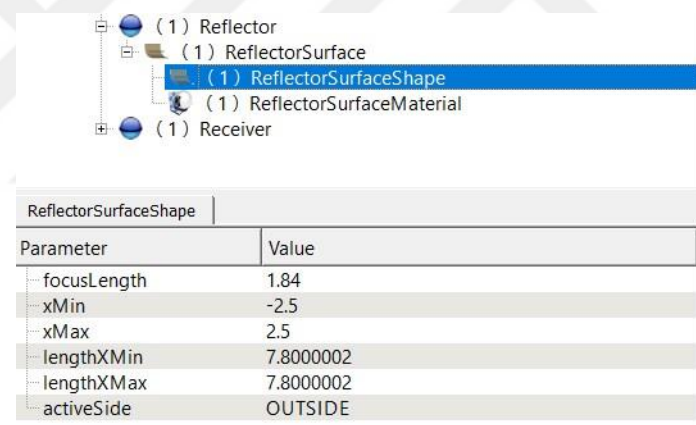
Figure A 4. The section in Tonatiuh to insert surface material of the parabolic mirror

Geometrical and optical property data are entered to define the parabolic mirror completely. Reflector group node, geometrical and optical data are shown in Figure A 5, Figure A 6, and Figure A 7, respectively.



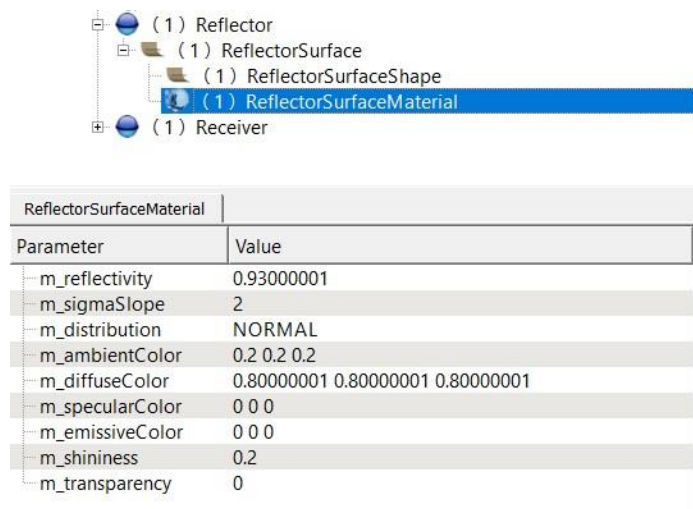
Parameter	Value
translation	0 0 0
rotation	0 0 1 0
scaleFactor	1 1 1
scaleOrientation	0 0 1 0
center	0 0 0

Figure A 5. Reflector group node data



Parameter	Value
focusLength	1.84
xMin	-2.5
xMax	2.5
lengthXMin	7.8000002
lengthXMax	7.8000002
activeSide	OUTSIDE

Figure A 6. Geometrical data of the parabolic mirror



ReflectorSurfaceMaterial	
Parameter	Value
m_reflectivity	0.93000001
m_sigmaSlope	2
m_distribution	NORMAL
m_ambientColor	0.2 0.2 0.2
m_diffuseColor	0.80000001 0.80000001 0.80000001
m_specularColor	0 0 0
m_emissiveColor	0 0 0
m_shininess	0.2
m_transparency	0

Figure A 7. Optical data of the parabolic mirror

B. Creating the Absorber tube of LS2 PTC Module using Tonatiuh

This APPENDIX explains how to create the receiver of the LS2 PTC module using Tonatiuh.

In Figure B 1, the group node and surface node are shown in the tree structure of the absorber tube.

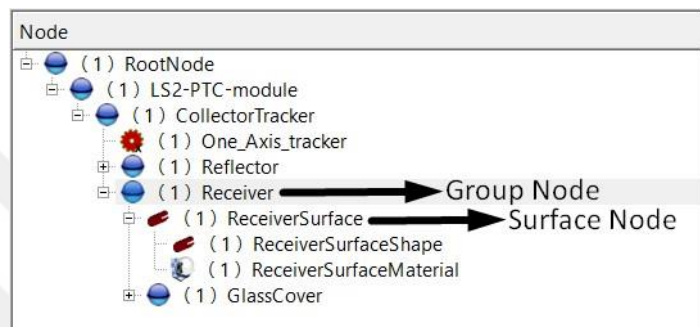


Figure B 1. Group node and surface node in the tree structure of the absorber tube

“Cylinder” is chosen for the shape. “Specular_Standard_Material” is selected for the material.

The sections in Tonatiuh to insert shape and material are shown in Figure B 2 and Figure B 3, respectively.

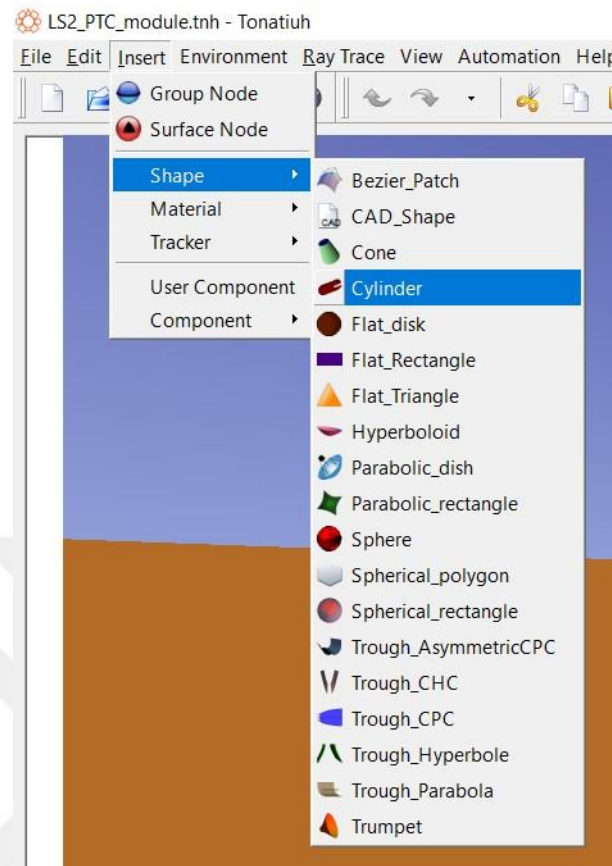


Figure B 2. The section in Tonatiuh to insert surface shape of the absorber tube

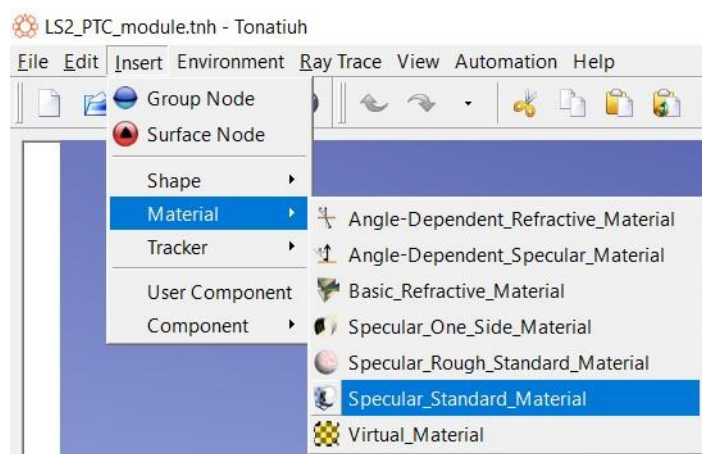


Figure B 3. The section in Tonatiuh to insert surface material of the absorber tube

Geometrical and optical property data are entered to define the absorber tube completely. The receiver group node, geometrical and optical data are shown in Figure B 4, Figure B 5, and Figure B 6, respectively.

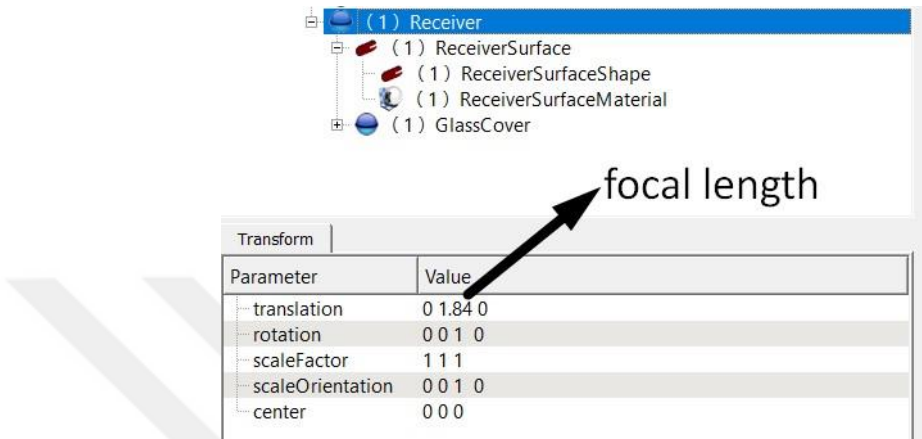


Figure B 4. Receiver group node data

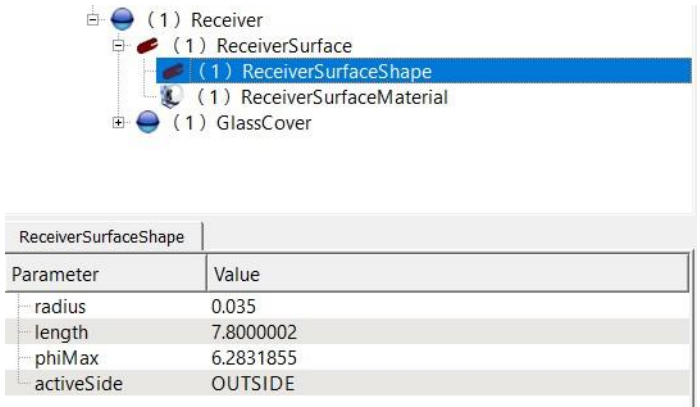


Figure B 5. Geometrical data of the absorber tube

(1) Receiver
(1) ReceiverSurface
(1) ReceiverSurfaceShape
(1) ReceiverSurfaceMaterial
(1) GlassCover

ReceiverSurfaceMaterial	
Parameter	Value
m_reflectivity	0.039999999
m_sigmaSlope	2
m_distribution	NORMAL
m_ambientColor	0.2 0.2 0.2
m_diffuseColor	0.80000001 0.80000001 0.80000001
m_specularColor	0 0 0
m_emissiveColor	0 0 0
m_shininess	0.2
m_transparency	0

Figure B 6. Optical data of the absorber tube

C. Creating the Glass Cover of LS2 PTC Module using Tonatiuh

This APPENDIX explains how to create the glass cover of the LS2 PTC module using Tonatiuh.

In Figure C 1, the group node and two surface nodes are shown in the tree structure of the glass cover.

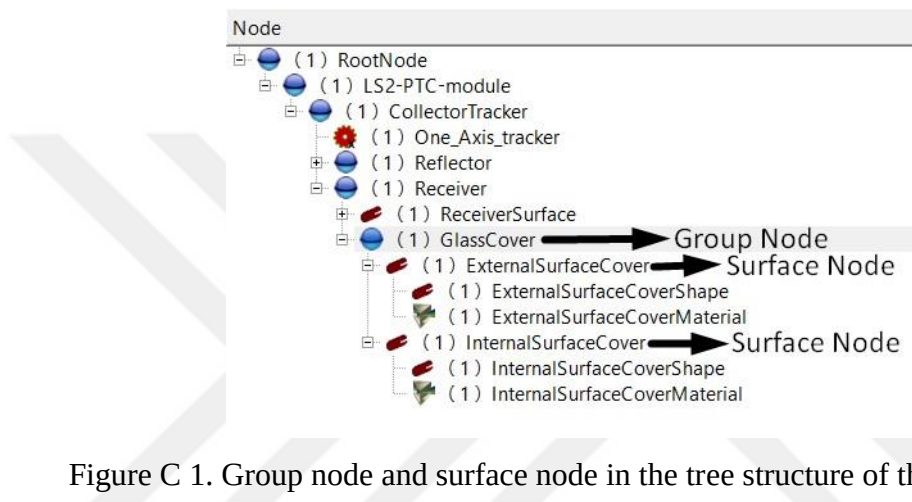


Figure C 1. Group node and surface node in the tree structure of the glass cover

“Cylinder” is chosen for the shape. “Basic_Refractive_Material” is chosen for the material.

The sections in Tonatiuh to insert shape and material are shown in Figure C 2 and Figure C 3, respectively.

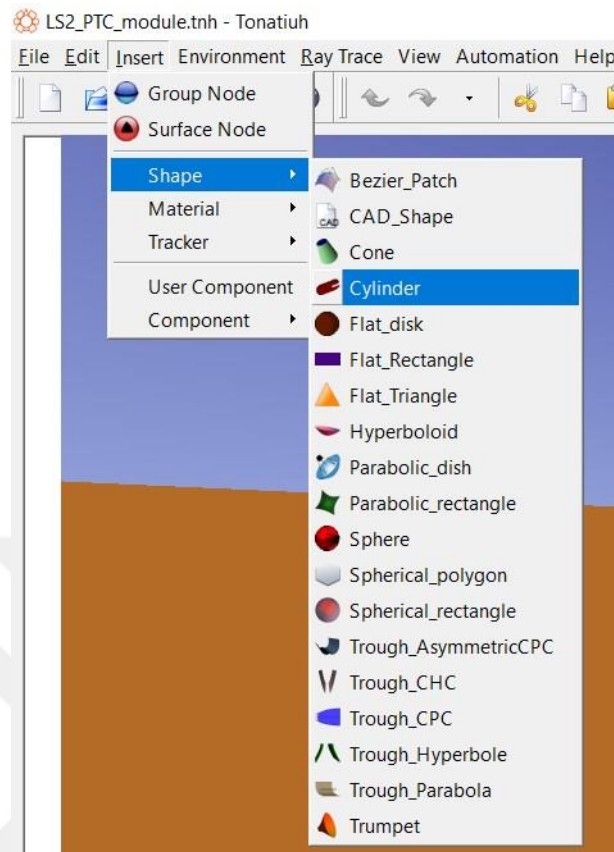


Figure C 2. The section in Tonatiuh to insert surface shape of the glass cover

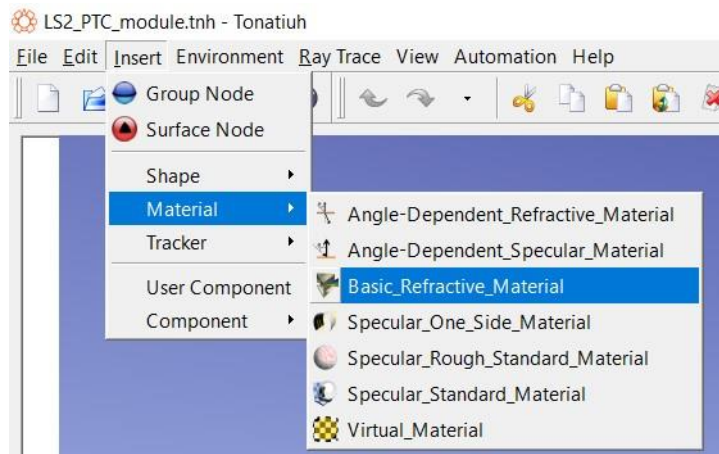


Figure C 3. The section in Tonatiuh to insert surface material of the glass cover

Geometrical and optical property data are entered to define the glass cover completely. Glass cover group node, geometrical and optical data of glass cover outer surface, geometrical and optical data of glass cover inner surface are shown in Figure C 4, Figure C 5, Figure C 6, Figure C 7 and Figure C 8, respectively.

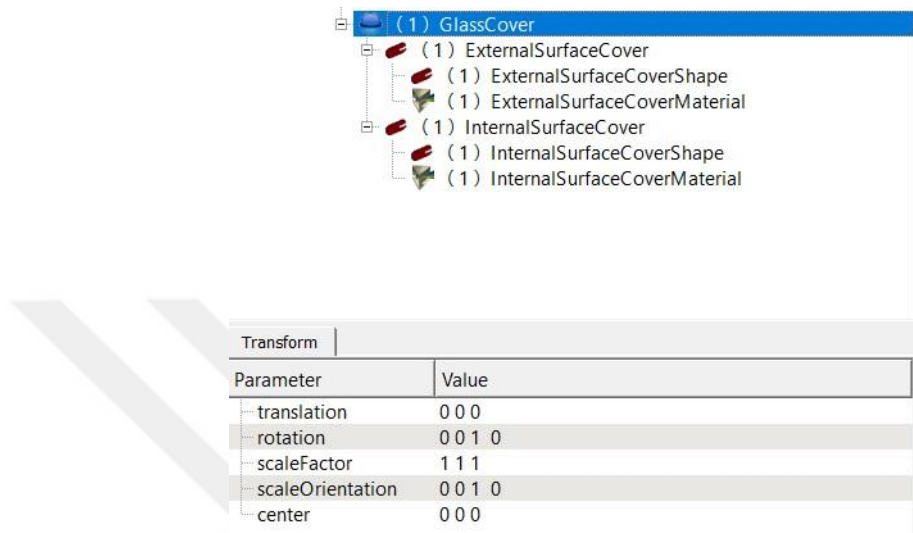


Figure C 4. Glass Cover group node data

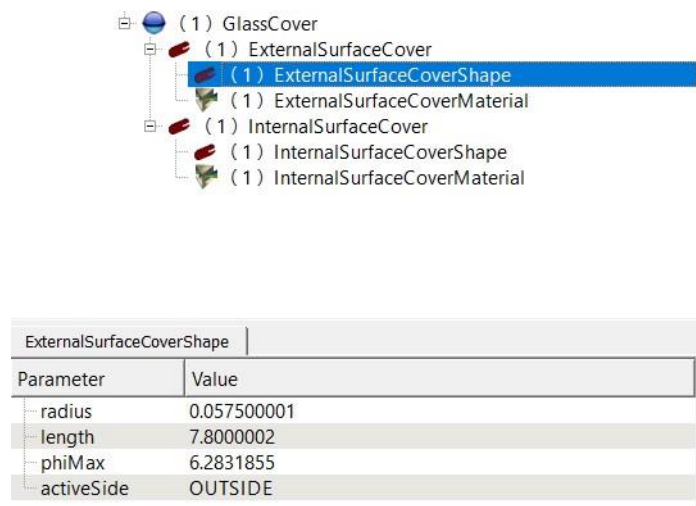
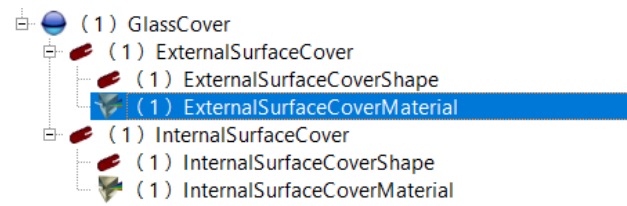
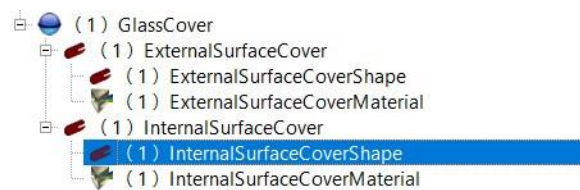


Figure C 5. Geometrical data of the glass cover outer surface



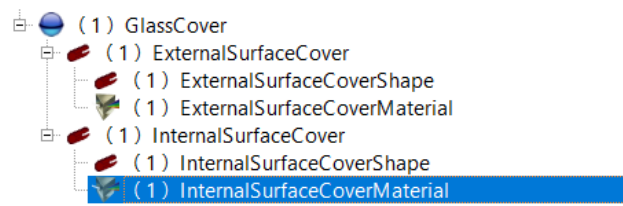
ExternalSurfaceCoverMaterial	
Parameter	Value
reflectivityFront	0.035
reflectivityBack	0.035
transmissivityFront	0.94999999
transmissivityBack	0.94999999
nFront	1
nBack	1.5
sigmaSlope	2
distribution	NORMAL
m_ambientColor	0.2 0.2 0.2
m_diffuseColor	0.80000001 0.80000001 0.80000001
m_specularColor	0 0 0
m_emissiveColor	0 0 0
m_shininess	0.2
m_transparency	0

Figure C 6. Optical data of the glass cover outer surface



InternalSurfaceCoverShape	
Parameter	Value
radius	0.054499999
length	7.8000002
phiMax	6.2831855
activeSide	OUTSIDE

Figure C 7. Geometrical data of the glass cover inner surface



InternalSurfaceCoverMaterial	
Parameter	Value
reflectivityFront	0.035
reflectivityBack	0.035
transmissivityFront	0.94999999
transmissivityBack	0.94999999
nFront	1.5
nBack	1
sigmaSlope	2
distribution	NORMAL
m_ambientColor	0.2 0.2 0.2
m_diffuseColor	0.80000001 0.80000001 0.80000001
m_specularColor	0 0 0
m_emissiveColor	0 0 0
m_shininess	0.2
m_transparency	0

Figure C 8. Optical data of the glass cover inner surface



D. MATLAB Code of 2D Discretization Approach

In this part, the 2D discretization MATLAB code is given. The absorber tube's outer surface is divided into finite strips in the radial direction. Discretization of the cylinder surface with finite strips is shown in Figure D 1.

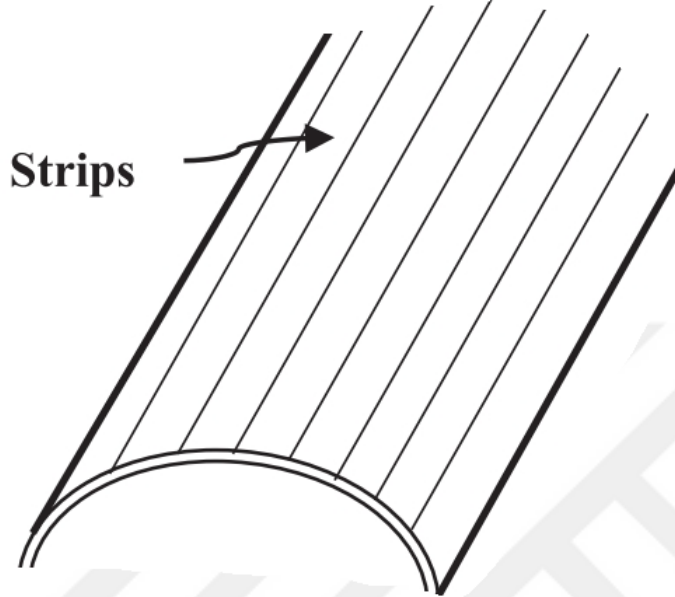


Figure D 1. Discretization of the cylinder surface with finite strips[34]

This discretization assumes that the solar radiation on the tube surface does not change in the axial direction. Thus, this type of spatial discretization is suitable for 0-degree incidence angle.

Some explanations are also provided in the code.

```
clear all
clc
format long

%% Rays absorbed by the Absorber tube
% Extracting Tonatiuh Absorber tube data to MATLAB
fileID =
fopen('LS2_PTC_module_10millionRays_receiver_tube_data_1.dat');
Tube_Raw_Data = fread(fileID, 'double', 'b'); % b is for Big-endian
ordering
Tube_Processed_Data = reshape(Tube_Raw_Data, [6,
length(Tube_Raw_Data)/6]);
Tube_Data = Tube_Processed_Data';
Tube_Data_x = Tube_Data(:,2);
Tube_Data_y = Tube_Data(:,3);
Tube_Data_z = Tube_Data(:,4);
```

```

% Data for right-bottom part (1/4) of the circle
j = 1; k = 1; % Used for the below for loop, dummies
for i = 1:1:length(Tube_Data_x)
    if Tube_Data_x(i,1) >= 0
        if Tube_Data_y(i,1) <= 0
            Tube_data_y_RightBottom(j,1) = Tube_Data_y(i,1);
            Tube_data_x_RightBottom(k,1) = Tube_Data_x(i,1);
            j = j + 1;
            k = k + 1;
        end
    end
end

% Data for left-bottom part (1/4) of the circle
j = 1; k = 1; % Used for the below for loop, dummies
for i = 1:1:length(Tube_Data_x)
    if Tube_Data_x(i,1) <= 0
        if Tube_Data_y(i,1) <= 0
            Tube_data_y_LeftBottom(j,1) = Tube_Data_y(i,1);
            Tube_data_x_LeftBottom(k,1) = Tube_Data_x(i,1);
            j = j + 1;
            k = k + 1;
        end
    end
end

% Data for right-upper part (1/4) of the circle
j = 1; k = 1; % Used for the below for loop, dummies
for i = 1:1:length(Tube_Data_x)
    if Tube_Data_x(i,1) >= 0
        if Tube_Data_y(i,1) >= 0
            Tube_data_y_RightUpper(j,1) = Tube_Data_y(i,1);
            Tube_data_x_RightUpper(k,1) = Tube_Data_x(i,1);
            j = j + 1;
            k = k + 1;
        end
    end
end

% Data for left-upper part (1/4) of the circle
j = 1; k = 1; % Used for the below for loop, dummies
for i = 1:1:length(Tube_Data_x)
    if Tube_Data_x(i,1) <= 0
        if Tube_Data_y(i,1) >= 0
            Tube_data_y_LeftUpper(j,1) = Tube_Data_y(i,1);
            Tube_data_x_LeftUpper(k,1) = Tube_Data_x(i,1);
            j = j + 1;
            k = k + 1;
        end
    end
end

% Obtaining Heat Flux Profile
OneRayPower = 0.00404286; % [W] Data from Tonatiuh, for 10 million
rays, 7.8 m tube length
r = 0.035; % [m] radius of the absorber tube
L = 7.8; % length of the receiver tube in z-direction

```

```

teta = 0:1:90; % This is "Width" in Tonatiuh. (Height is the
division in z-direction.)
n = length(teta) - 1; % Number of strips (cells)
Surface_RightBottom_coordinates = r .* sind(teta); % Array storing
coordinates of strip borders
Surface_LeftBottom_coordinates = -r .* cosd(teta); % Array storing
coordinates of strip borders
Surface_RightUpper_coordinates = r .* sind(teta); % Array storing
coordinates of strip borders
Surface_LeftUpper_coordinates = -r .* cosd(teta); % Array storing
coordinates of strip borders
Eb_RightBottom_strip_array_count = zeros(n, 1);
Eb_LeftBottom_strip_array_count = zeros(n, 1);
Eb_RightUpper_strip_array_count = zeros(n, 1);
Eb_LeftUpper_strip_array_count = zeros(n, 1);

% Right Bottom, Energy calculations
for i = 1:length(Tube_data_x_RightBottom)
    j = 1;
    if Surface_RightBottom_coordinates(1,
length(Surface_RightBottom_coordinates) - 1) <
Tube_data_x_RightBottom(i,1)
        j = n + 1;
    elseif Tube_data_x_RightBottom(i,1) <
Surface_RightBottom_coordinates(1,2)
        j = 2;
    else
        while Surface_RightBottom_coordinates(1,j) <
Tube_data_x_RightBottom(i,1)
            j = j + 1;
        end
    end
    Eb_RightBottom_strip_array_count(j-1,1) =
Eb_RightBottom_strip_array_count(j-1,1) + 1;
end
% Energy of each strip, "Incident Flux Distribution" in Tonatiuh
for i = 1:length(Eb_RightBottom_strip_array_count)
Eb_RightBottom_strip_array_energy(i,1) =
(Eb_RightBottom_strip_array_count(i,1) *
OneRayPower)/(0.5*pi*r*L/(length(Eb_RightBottom_strip_array_count))
);
end

% Left Bottom, Energy calculations
for i = 1:length(Tube_data_x_LeftBottom)
    j = 1;
    if Surface_LeftBottom_coordinates(1,
length(Surface_LeftBottom_coordinates) - 1) <
Tube_data_x_LeftBottom(i,1)
        j = n + 1;
    elseif Tube_data_x_LeftBottom(i,1) <
Surface_LeftBottom_coordinates(1,2)
        j = 2;
    else
        while Surface_LeftBottom_coordinates(1,j) <
Tube_data_x_LeftBottom(i,1)

```

```

        j = j + 1;
    end
    end
    Eb_LeftBottom_strip_array_count(j-1,1) =
Eb_LeftBottom_strip_array_count(j-1,1) + 1;
end
% Energy of each strip, "Incident Flux Distribution" in Tonatiuh
for i = 1:1:length(Eb_LeftBottom_strip_array_count)
Eb_LeftBottom_strip_array_energy(i,1) =
(Eb_LeftBottom_strip_array_count(i,1) *
OneRayPower)/(0.5*pi*r*L/(length(Eb_LeftBottom_strip_array_count)))
;
end

% Right Upper, Energy calculations
for i = 1:1:length(Tube_data_x_RightUpper)
    j = 1;
    if Surface_RightUpper_coordinates(1,
length(Surface_RightUpper_coordinates) - 1) <
Tube_data_x_RightUpper(i,1)
        j = n + 1;
    elseif Tube_data_x_RightUpper(i,1) <
Surface_RightUpper_coordinates(1,2)
        j = 2;
    else
        while Surface_RightUpper_coordinates(1,j) <
Tube_data_x_RightUpper(i,1)
            j = j + 1;
        end
    end
    Eb_RightUpper_strip_array_count(j-1,1) =
Eb_RightUpper_strip_array_count(j-1,1) + 1;
end
% Energy of each strip, "Incident Flux Distribution" in Tonatiuh
for i = 1:1:length(Eb_RightUpper_strip_array_count)
Eb_RightUpper_strip_array_energy(i,1) =
(Eb_RightUpper_strip_array_count(i,1) *
OneRayPower)/(0.5*pi*r*L/(length(Eb_RightUpper_strip_array_count)))
;
end

% Left Upper, Energy calculations
for i = 1:1:length(Tube_data_x_LeftUpper)
    j = 1;
    if Surface_LeftUpper_coordinates(1,
length(Surface_LeftUpper_coordinates) - 1) <
Tube_data_x_LeftUpper(i,1)
        j = n + 1;
    elseif Tube_data_x_LeftUpper(i,1) <
Surface_LeftUpper_coordinates(1,2)
        j = 2;
    else
        while Surface_LeftUpper_coordinates(1,j) <
Tube_data_x_LeftUpper(i,1)

```

```

        j = j + 1;
    end
    end
    Eb_LeftUpper_strip_array_count(j-1,1) =
Eb_LeftUpper_strip_array_count(j-1,1) + 1;
end
% Energy of each strip, "Incident Flux Distribution" in Tonatiuh
for i = 1:1:length(Eb_RightUpper_strip_array_count)
Eb_LeftUpper_strip_array_energy(i,1) =
(Eb_LeftUpper_strip_array_count(i,1) *
OneRayPower)/(0.5*pi*r*L/(length(Eb_LeftUpper_strip_array_count)));
end

% x_plot = linspace(Surface1_coordinates(1,1),
Surface1_coordinates(1,end), length(Eb_1_strip_array_count));
for i = 1:1:length(Surface_RightBottom_coordinates) - 1
    x_RightBottom(i,1) = (Surface_RightBottom_coordinates(1,i) +
Surface_RightBottom_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_LeftBottom_coordinates) - 1
    x_LeftBottom(i,1) = (Surface_LeftBottom_coordinates(1,i) +
Surface_LeftBottom_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_RightUpper_coordinates) - 1
    x_RightUpper(i,1) = (Surface_RightUpper_coordinates(1,i) +
Surface_RightUpper_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_LeftUpper_coordinates) - 1
    x_LeftUpper(i,1) = (Surface_LeftUpper_coordinates(1,i) +
Surface_LeftUpper_coordinates(1,i+1)) / 2;
end

% Piecewise, Right Bottom
j = 1; k = 1; m = 1;
for i = 1:1:length(x_RightBottom)
    if x_RightBottom(i,1) <= 0.005
        x_RightBottom_upto5mm(j,1) = x_RightBottom(i,1);
        Eb_RightBottom_strip_array_energy_upto5mm(j,1) =
Eb_RightBottom_strip_array_energy(i,1);
        j = j + 1;
    elseif (0.005 < x_RightBottom(i,1)) && (x_RightBottom(i,1) <=
0.02)
        x_RightBottom_5_20mm(k,1) = x_RightBottom(i,1);
        Eb_RightBottom_strip_array_energy_5_20mm(k,1) =
Eb_RightBottom_strip_array_energy(i,1);
        k = k + 1;
    else
        x_RightBottom_after20mm(m,1) = x_RightBottom(i,1);

```

```

        Eb_RightBottom_strip_array_energy_after20mm(m,1) =
Eb_RightBottom_strip_array_energy(i,1);
        m = m + 1;
    end
end

% Piecewise, Left Bottom
j = 1; k = 1; m = 1;
for i = 1:1:length(x_LeftBottom)
    if x_LeftBottom(i,1) >= -0.005
        x_LeftBottom_upto5mm(j,1) = x_LeftBottom(i,1);
        Eb_LeftBottom_strip_array_energy_upto5mm(j,1) =
Eb_LeftBottom_strip_array_energy(i,1);
        j = j + 1;
    elseif (-0.005 > x_LeftBottom(i,1)) && (x_LeftBottom(i,1) >= -
0.02)
        x_LeftBottom_5_20mm(k,1) = x_LeftBottom(i,1);
        Eb_LeftBottom_strip_array_energy_5_20mm(k,1) =
Eb_LeftBottom_strip_array_energy(i,1);
        k = k + 1;
    else
        x_LeftBottom_after20mm(m,1) = x_LeftBottom(i,1);
        Eb_LeftBottom_strip_array_energy_after20mm(m,1) =
Eb_LeftBottom_strip_array_energy(i,1);
        m = m + 1;
    end
end

% Piecewise, Right Upper
j = 1; k = 1; m = 1;
for i = 1:1:length(x_RightUpper)
    if x_RightUpper(i,1) <= 0.02813
        x_RightUpper_upto28mm(j,1) = x_RightUpper(i,1);
        Eb_RightUpper_strip_array_energy_upto28mm(j,1) =
Eb_RightUpper_strip_array_energy(i,1);
        j = j + 1;
    elseif (0.02813 < x_RightUpper(i,1)) && (x_RightUpper(i,1) <=
0.03373)
        x_RightUpper_28_33mm(k,1) = x_RightUpper(i,1);
        Eb_RightUpper_strip_array_energy_28_33mm(k,1) =
Eb_RightUpper_strip_array_energy(i,1);
        k = k + 1;
    else
        x_RightUpper_after33mm(m,1) = x_RightUpper(i,1);
        Eb_RightUpper_strip_array_energy_after33mm(m,1) =
Eb_RightUpper_strip_array_energy(i,1);
        m = m + 1;
    end
end

% Piecewise, Left Upper
j = 1; k = 1; m = 1;
for i = 1:1:length(x_LeftUpper)
    if x_LeftUpper(i,1) >= -0.02849
        x_LeftUpper_upto28mm(j,1) = x_LeftUpper(i,1);
        Eb_LeftUpper_strip_array_energy_upto28mm(j,1) =
Eb_LeftUpper_strip_array_energy(i,1);
        j = j + 1;

```

```

elseif (-0.02849 > x_LeftUpper(i,1)) && (x_LeftUpper(i,1) >= -
0.03373)
    x_LeftUpper_28_33mm(k,1) = x_LeftUpper(i,1);
    Eb_LeftUpper_strip_array_energy_28_33mm(k,1) =
Eb_LeftUpper_strip_array_energy(i,1);
    k = k + 1;
else
    x_LeftUpper_after33mm(m,1) = x_LeftUpper(i,1);
    Eb_LeftUpper_strip_array_energy_after33mm(m,1) =
Eb_LeftUpper_strip_array_energy(i,1);
    m = m + 1;
end
end

% Plot, Right Bottom
figure(1)
plot(x_RightBottom,Eb_RightBottom_strip_array_energy)
set(gca, 'FontSize', 18)
xlabel('x-coordinate', 'FontSize', 20)
ylabel('Incident Flux Distribution', 'FontSize', 20)
title('Non-uniform distribution of rays on the x-z cross section of
the absorber tube (Rigth-bottom part)', 'FontSize', 20)

% Plot, Left Bottom
figure(2)
plot(x_LeftBottom,Eb_LeftBottom_strip_array_energy)
set(gca, 'FontSize', 18)
xlabel('x-coordinate', 'FontSize', 20)
ylabel('Incident Flux Distribution', 'FontSize', 20)
title('Non-uniform distribution of rays on the x-z cross section of
the absorber tube (Left-bottom part)', 'FontSize', 20)

% Plot, Right Upper
figure(3)
plot(x_RightUpper,Eb_RightUpper_strip_array_energy)
set(gca, 'FontSize', 18)
xlabel('x-coordinate', 'FontSize', 20)
ylabel('Incident Flux Distribution', 'FontSize', 20)
title('Non-uniform distribution of rays on the x-z cross section of
the absorber tube (Rigth-upper part)', 'FontSize', 20)

% Plot, Left Upper
figure(4)
plot(x_LeftUpper,Eb_LeftUpper_strip_array_energy)
set(gca, 'FontSize', 18)
xlabel('x-coordinate', 'FontSize', 20)
ylabel('Incident Flux Distribution', 'FontSize', 20)
title('Non-uniform distribution of rays on the x-z cross section of
the absorber tube (Left-upper part)', 'FontSize', 20)

% Verification of Tonatiuh results
Total_Power = length(Tube_Data_x)*OneRayPower
Average_Flux = Total_Power / (2*pi*r*L)

if max(Eb_RightBottom_strip_array_count) >=
max(Eb_LeftBottom_strip_array_count)

```

```

        Eb_max_strip_array_count = Eb_RightBottom_strip_array_count;
else
    Eb_max_strip_array_count = Eb_LeftBottom_strip_array_count;
end
Maximum_Flux =
    (max(Eb_max_strip_array_count)*OneRayPower)/(0.5*pi*r*L/(length(Eb_
max_strip_array_count)))

```



E. Piecewise Curve-Fitting for “Left-Upper” Surface of LS2 PTC Module with Zero-Degree Incidence Angle

In this APPENDIX, piecewise curve-fitting for the “Left-Upper” surface is explained in detail.

First, heat flux distribution on the “Left-Upper” surface is plotted, and the highest order polynomial is fitted to it. In this case, the highest order of the polynomial curve is 4. Fitted 4th order polynomial for the whole “Left-Upper” surface is given in Figure E 1.

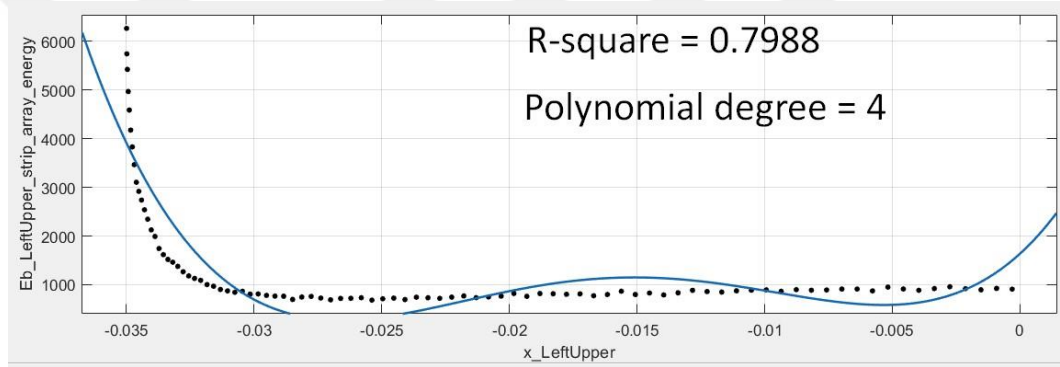


Figure E 1. Fitted 4th order polynomial for the whole “Left-Upper” surface

Note that if polynomial order is higher than 4, MATLAB gives “Equation is badly conditioned. Remove repeated data points or try centering and scaling” error.

After investigating Figure E 1, 35 mm distance in x-direction is divided into three sub-intervals as,

$$x \geq -0.02849 \text{ m}$$

$$-0.02849 \text{ m} > x \geq -0.03373 \text{ m}$$

$$x < -0.03373 \text{ m}$$

Then, a polynomial curve with the highest order is fitted to each of these sub-intervals.

Curve fit for $x \geq -0.02849 \text{ m}$ is given in Figure E 2.

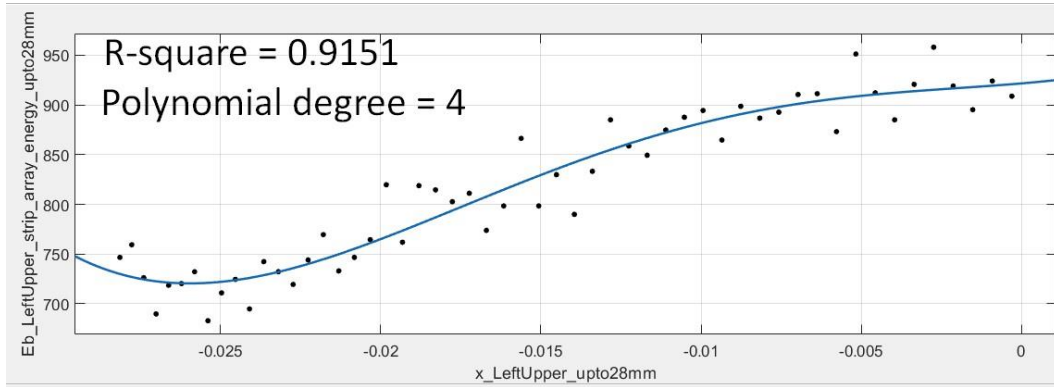


Figure E 2. Curve fit for $x \geq -0.02849 \text{ m}$

Curve fit for $-0.02849 \text{ m} > x \geq -0.03373 \text{ m}$ is given in Figure E 3.

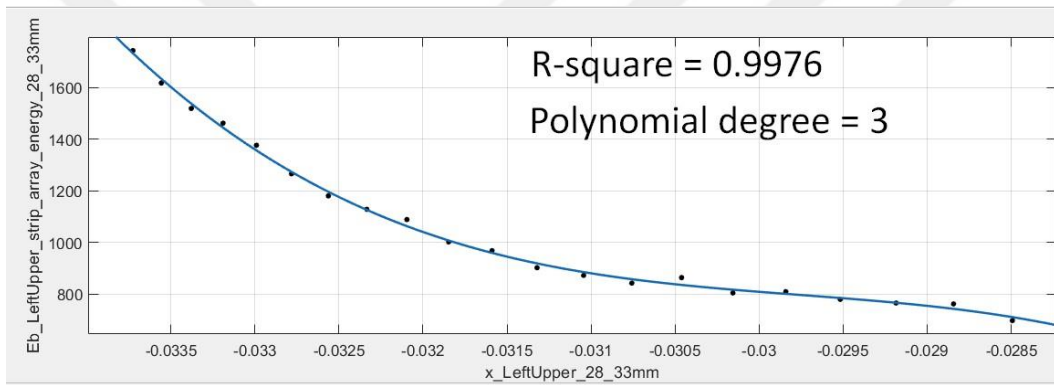


Figure E 3. Curve fit for $-0.02849 \text{ m} > x \geq -0.03373 \text{ m}$

Curve fit for $x < -0.03373 \text{ m}$ is given in Figure E 4.

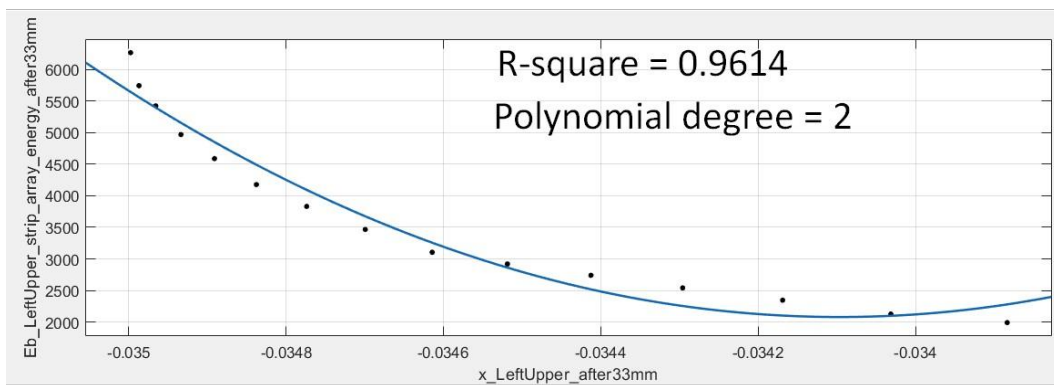


Figure E 4. Curve fit for $x < -0.03373 \text{ m}$

The purpose of using piecewise curve-fitting is to resolve heat flux distribution around the absorber tube as accurately as possible.

In conclusion, the 35 mm distance (outer radius of the absorber tube) in x-direction is divided into three sub-intervals and a polynomial curve with the highest order is fitted to each of these sub-intervals instead of fitting a one polynomial curve for the whole region.





F. MATLAB Code of 3D Discretization Approach

In this part, the 3D discretization MATLAB code is given. The absorber tube's outer surface is divided into finite elements both in the radial and axial directions. Discretization of the cylinder surface with finite elements is shown in Figure F 1.

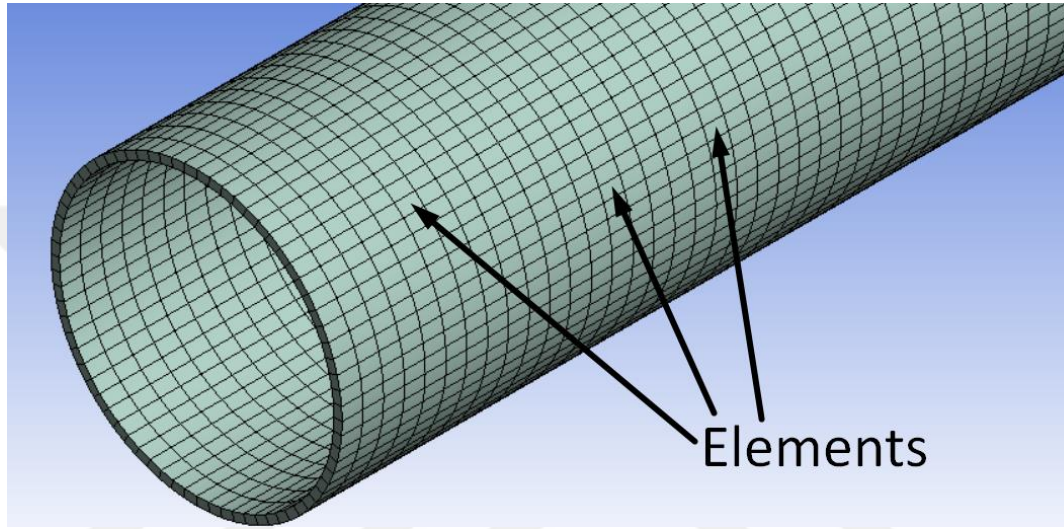


Figure F 1. Discretization of the cylinder surface with finite elements

This discretization assumes that the solar radiation on the tube surface can change not only in the radial direction but also in the axial direction. Thus, this type of spatial discretization is suitable for any incidence angle.

Some explanations are also provided in the code.

```
clear all
clc
format long

%% Rays absorbed by the Absorber tube
% Extracting Tonatiuh Absorber tube data to MATLAB
fileID =
fopen('LS2_PTC_module_10millionRays_90_degrees_elevation_receiver_t
ube_data_1.dat');
Tube_Raw_Data = fread(fileID,'double','b'); % b is for Big-endian
ordering
Tube_Processed_Data = reshape(Tube_Raw_Data, [6,
length(Tube_Raw_Data)/6]);
Tube_Data = Tube_Processed_Data';
Tube_Data_x = Tube_Data(:,2);
Tube_Data_y = Tube_Data(:,3);
Tube_Data_z = Tube_Data(:,4);
```

```

% Data for right-bottom part (1/4) of the circle
j = 1; k = 1; m = 1; % Used for the below for loop, dummies
for i = 1:length(Tube_Data_x)
    if Tube_Data_x(i,1) >= 0
        if Tube_Data_y(i,1) <= 0
            Tube_data_y_RightBottom(j,1) = Tube_Data_y(i,1);
            Tube_data_x_RightBottom(k,1) = Tube_Data_x(i,1);
            Tube_data_z_RightBottom(m,1) = Tube_Data_z(i,1);
            j = j + 1;
            k = k + 1;
            m = m + 1;
        end
    end
end

% Data for left-bottom part (1/4) of the circle
j = 1; k = 1; m = 1; % Used for the below for loop, dummies
for i = 1:length(Tube_Data_x)
    if Tube_Data_x(i,1) <= 0
        if Tube_Data_y(i,1) <= 0
            Tube_data_y_LeftBottom(j,1) = Tube_Data_y(i,1);
            Tube_data_x_LeftBottom(k,1) = Tube_Data_x(i,1);
            Tube_data_z_LeftBottom(k,1) = Tube_Data_z(i,1);
            j = j + 1;
            k = k + 1;
            m = m + 1;
        end
    end
end

% Data for right-upper part (1/4) of the circle
j = 1; k = 1; m = 1; % Used for the below for loop, dummies
for i = 1:length(Tube_Data_x)
    if Tube_Data_x(i,1) >= 0
        if Tube_Data_y(i,1) >= 0
            Tube_data_y_RightUpper(j,1) = Tube_Data_y(i,1);
            Tube_data_x_RightUpper(k,1) = Tube_Data_x(i,1);
            Tube_data_z_RightUpper(k,1) = Tube_Data_z(i,1);
            j = j + 1;
            k = k + 1;
            m = m + 1;
        end
    end
end

% Data for left-upper part (1/4) of the circle
j = 1; k = 1; m = 1; % Used for the below for loop, dummies
for i = 1:length(Tube_Data_x)
    if Tube_Data_x(i,1) <= 0
        if Tube_Data_y(i,1) >= 0
            Tube_data_y_LeftUpper(j,1) = Tube_Data_y(i,1);
            Tube_data_x_LeftUpper(k,1) = Tube_Data_x(i,1);
            Tube_data_z_LeftUpper(k,1) = Tube_Data_z(i,1);
            j = j + 1;
            k = k + 1;
            m = m + 1;
        end
    end
end

```

```

        end
    end
end

% Obtaining Heat Flux Profile
OneRayPower = 0.00404286; % [W] Data from Tonatiuh, for 10 million
rays, 90 degrees elevation, 7.8 m tube length
r = 0.035; % [m] radius of the absorber tube
L = 7.8; % length of the receiver tube in z-direction
teta = 0:1:90; % This is "Width" in Tonatiuh. (Height is the
division in z-direction.)
n = length(teta) - 1; % Number of strips (cells)
% z-discretization
Surface_RightBottom_z_coordinates = 0:0.2:L; % Array storing
coordinates of strip borders
Surface_LeftBottom_z_coordinates = 0:0.2:L; % Array storing
coordinates of strip borders
Surface_RightUpper_z_coordinates = 0:0.2:L; % Array storing
coordinates of strip borders
Surface_LeftUpper_z_coordinates = 0:0.2:L; % Array storing
coordinates of strip borders
n_z = length(Surface_RightBottom_z_coordinates) - 1; % Number of
strips (cells)

Surface_RightBottom_x_coordinates = r .* sind(teta); % Array
storing coordinates of strip borders
Surface_LeftBottom_x_coordinates = -r .* cosd(teta); % Array
storing coordinates of strip borders
Surface_RightUpper_x_coordinates = r .* sind(teta); % Array storing
coordinates of strip borders
Surface_LeftUpper_x_coordinates = -r .* cosd(teta); % Array storing
coordinates of strip borders

Eb_RightBottom_strip_array_count = zeros(n, n_z);
Eb_LeftBottom_strip_array_count = zeros(n, n_z);
Eb_RightUpper_strip_array_count = zeros(n, n_z);
Eb_LeftUpper_strip_array_count = zeros(n, n_z);

% Right Bottom, Energy calculations

for i = 1:length(Tube_data_x_RightBottom)
    j = 1; k = 1;
    if Surface_RightBottom_x_coordinates(1,
length(Surface_RightBottom_x_coordinates) - 1) <
Tube_data_x_RightBottom(i,1)
        j = n + 1;
    elseif Tube_data_x_RightBottom(i,1) <
Surface_RightBottom_x_coordinates(1,2)
        j = 2;
    else
        while Surface_RightBottom_x_coordinates(1,j) <
Tube_data_x_RightBottom(i,1)
            j = j + 1;
        end
    end
end
end

```

```

        if Surface_RightBottom_z_coordinates(1,
length(Surface_RightBottom_z_coordinates) - 1) <
Tube_data_z_RightBottom(i,1)
            k = n_z + 1;
        elseif Tube_data_z_RightBottom(i,1) <
Surface_RightBottom_z_coordinates(1,2)
            k = 2;
        else
            while Surface_RightBottom_z_coordinates(1,k) <
Tube_data_z_RightBottom(i,1)
                k = k + 1;
            end
        end
        Eb_RightBottom_strip_array_count(j-1,k-1) =
Eb_RightBottom_strip_array_count(j-1,k-1) + 1;
    end
    % Energy of each element, "Incident Flux Distribution" in Tonatiuh
    for i = 1:1:n
        for j = 1:1:n_z
            Eb_RightBottom_strip_array_energy(i,j) =
(Eb_RightBottom_strip_array_count(i,j) *
OneRayPower)/(0.5*pi*r*L/(n*n_z));
        end
    end

    % Left Bottom, Energy calculations
    for i = 1:1:length(Tube_data_x_LeftBottom)
        j = 1; k = 1;
        if Surface_LeftBottom_x_coordinates(1,
length(Surface_LeftBottom_x_coordinates) - 1) <
Tube_data_x_LeftBottom(i,1)
            j = n + 1;
        elseif Tube_data_x_LeftBottom(i,1) <
Surface_LeftBottom_x_coordinates(1,2)
            j = 2;
        else
            while Surface_LeftBottom_x_coordinates(1,j) <
Tube_data_x_LeftBottom(i,1)
                j = j + 1;
            end
        end
        if Surface_LeftBottom_z_coordinates(1,
length(Surface_LeftBottom_z_coordinates) - 1) <
Tube_data_z_LeftBottom(i,1)
            k = n_z + 1;
        elseif Tube_data_z_LeftBottom(i,1) <
Surface_LeftBottom_z_coordinates(1,2)
            k = 2;
        else
            while Surface_LeftBottom_z_coordinates(1,k) <
Tube_data_z_LeftBottom(i,1)
                k = k + 1;
            end
        end
    end
end

```

```

Eb_LeftBottom_strip_array_count(j-1,k-1) =
Eb_LeftBottom_strip_array_count(j-1,k-1) + 1;
end
% Energy of each element, "Incident Flux Distribution" in Tonatiuh
for i = 1:1:n
    for j = 1:1:n_z
        Eb_LeftBottom_strip_array_energy(i,j) =
(Eb_LeftBottom_strip_array_count(i,j) *
OneRayPower)/((0.5*pi*r*L)/(n*n_z));
    end
end

% Right Upper, Energy calculations
for i = 1:length(Tube_data_x_RightUpper)
    j = 1; k = 1;
    if Surface_RightUpper_x_coordinates(1,
length(Surface_RightUpper_x_coordinates) - 1) <
Tube_data_x_RightUpper(i,1)
        j = n + 1;
    elseif Tube_data_x_RightUpper(i,1) <
Surface_RightUpper_x_coordinates(1,2)
        j = 2;
    else
        while Surface_RightUpper_x_coordinates(1,j) <
Tube_data_x_RightUpper(i,1)
            j = j + 1;
        end
    end
    if Surface_RightUpper_z_coordinates(1,
length(Surface_RightUpper_z_coordinates) - 1) <
Tube_data_z_RightUpper(i,1)
        k = n_z + 1;
    elseif Tube_data_z_RightUpper(i,1) <
Surface_RightUpper_z_coordinates(1,2)
        k = 2;
    else
        while Surface_RightUpper_z_coordinates(1,k) <
Tube_data_z_RightUpper(i,1)
            k = k + 1;
        end
    end
    Eb_RightUpper_strip_array_count(j-1,k-1) =
Eb_RightUpper_strip_array_count(j-1,k-1) + 1;
end
% Energy of each element, "Incident Flux Distribution" in Tonatiuh
for i = 1:1:n
    for j = 1:1:n_z
        Eb_RightUpper_strip_array_energy(i,j) =
(Eb_RightUpper_strip_array_count(i,j) *
OneRayPower)/((0.5*pi*r*L)/(n*n_z));
    end
end

```

```

% Left Upper, Energy calculations
for i = 1:1:length(Tube_data_x_LeftUpper)
    j = 1; k = 1;
    if Surface_LeftUpper_x_coordinates(1,
length(Surface_LeftUpper_x_coordinates) - 1) <
Tube_data_x_LeftUpper(i,1)
        j = n + 1;
    elseif Tube_data_x_LeftUpper(i,1) <
Surface_LeftUpper_x_coordinates(1,2)
        j = 2;
    else
        while Surface_LeftUpper_x_coordinates(1,j) <
Tube_data_x_LeftUpper(i,1)
            j = j + 1;
        end
    end

    if Surface_LeftUpper_z_coordinates(1,
length(Surface_LeftUpper_z_coordinates) - 1) <
Tube_data_z_LeftUpper(i,1)
        k = n_z + 1;
    elseif Tube_data_z_LeftUpper(i,1) <
Surface_LeftUpper_z_coordinates(1,2)
        k = 2;
    else
        while Surface_LeftUpper_z_coordinates(1,k) <
Tube_data_z_LeftUpper(i,1)
            k = k + 1;
        end
    end

    Eb_LeftUpper_strip_array_count(j-1,k-1) =
Eb_LeftUpper_strip_array_count(j-1,k-1) + 1;
end
% Energy of each element, "Incident Flux Distribution" in Tonatiuh
for i = 1:1:n
    for j = 1:1:n_z
        Eb_LeftUpper_strip_array_energy(i,j) =
(Eb_LeftUpper_strip_array_count(i,j) *
OneRayPower)/((0.5*pi*r*L)/(n*n_z));
    end
end

% x_plot
for i = 1:1:length(Surface_RightBottom_x_coordinates) - 1
    x_RightBottom(i,1) = (Surface_RightBottom_x_coordinates(1,i) +
Surface_RightBottom_x_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_LeftBottom_x_coordinates) - 1
    x_LeftBottom(i,1) = (Surface_LeftBottom_x_coordinates(1,i) +
Surface_LeftBottom_x_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_RightUpper_x_coordinates) - 1
    x_RightUpper(i,1) = (Surface_RightUpper_x_coordinates(1,i) +
Surface_RightUpper_x_coordinates(1,i+1)) / 2;

```

```

end

for i = 1:1:length(Surface_LeftUpper_x_coordinates) - 1
    x_LeftUpper(i,1) = (Surface_LeftUpper_x_coordinates(1,i) +
    Surface_LeftUpper_x_coordinates(1,i+1)) / 2;
end

% z_plot
for i = 1:1:length(Surface_RightBottom_z_coordinates) - 1
    z_RightBottom(i,1) = (Surface_RightBottom_z_coordinates(1,i) +
    Surface_RightBottom_z_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_LeftBottom_z_coordinates) - 1
    z_LeftBottom(i,1) = (Surface_LeftBottom_z_coordinates(1,i) +
    Surface_LeftBottom_z_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_RightUpper_z_coordinates) - 1
    z_RightUpper(i,1) = (Surface_RightUpper_z_coordinates(1,i) +
    Surface_RightUpper_z_coordinates(1,i+1)) / 2;
end

for i = 1:1:length(Surface_LeftUpper_z_coordinates) - 1
    z_LeftUpper(i,1) = (Surface_LeftUpper_z_coordinates(1,i) +
    Surface_LeftUpper_z_coordinates(1,i+1)) / 2;
end

% Piecewise, Right Bottom
j = 1; k = 1; m = 1;

for i = 1:1:length(z_RightBottom)
    if z_RightBottom(i,1) <= 1.7
        z_RightBottom_upto_1dot7_m(j,1) = z_RightBottom(i,1);
        for ii = 1:1:length(x_RightBottom)
            Eb_RightBottom_strip_array_energy_upto_1dot7_m(ii,j) =
            Eb_RightBottom_strip_array_energy(ii,i);
        end
        j = j + 1;
    elseif (1.7 < z_RightBottom(i,1)) && (z_RightBottom(i,1) <=
    3.1)
        z_RightBottom_1dot7_3dot1_m(k,1) = z_RightBottom(i,1);
        for ii = 1:1:length(x_RightBottom)
            Eb_RightBottom_strip_array_energy_1dot7_3dot1_m(ii,k) =
            Eb_RightBottom_strip_array_energy(ii,i);
        end
        k = k + 1;
    else
        z_RightBottom_after_3dot1_m(m,1) = z_RightBottom(i,1);
        for ii = 1:1:length(x_RightBottom)
            Eb_RightBottom_strip_array_energy_after_3dot1_m(ii,m) =
            Eb_RightBottom_strip_array_energy(ii,i);
        end
        m = m + 1;
    end
end

```

end

% Piecewise, Left Bottom

j = 1; k = 1; m = 1;

```
for i = 1:1:length(z_LeftBottom)
    if z_LeftBottom(i,1) <= 1.7
        z_LeftBottom_upto_1dot7_m(j,1) = z_LeftBottom(i,1);
        for ii = 1:1:length(x_LeftBottom)
            Eb_LeftBottom_strip_array_energy_upto_1dot7_m(ii,j) =
Eb_LeftBottom_strip_array_energy(ii,i);
        end
        j = j + 1;
    elseif (1.7 < z_LeftBottom(i,1)) && (z_LeftBottom(i,1) <= 3.1)
        z_LeftBottom_1dot7_3dot1_m(k,1) = z_LeftBottom(i,1);
        for ii = 1:1:length(x_LeftBottom)
            Eb_LeftBottom_strip_array_energy_1dot7_3dot1_m(ii,k) =
Eb_LeftBottom_strip_array_energy(ii,i);
        end
        k = k + 1;
    else
        z_LeftBottom_after_3dot1_m(m,1) = z_LeftBottom(i,1);
        for ii = 1:1:length(x_LeftBottom)
            Eb_LeftBottom_strip_array_energy_after_3dot1_m(ii,m) =
Eb_LeftBottom_strip_array_energy(ii,i);
        end
        m = m + 1;
    end
end
end
```

% Piecewise, Right Upper

j = 1; k = 1; m = 1;

```
for i = 1:1:length(z_RightUpper)
    if z_RightUpper(i,1) <= 1.9
        z_RightUpper_upto_1dot9_m(j,1) = z_RightUpper(i,1);
        for ii = 1:1:length(x_RightUpper)
            Eb_RightUpper_strip_array_energy_upto_1dot9_m(ii,j) =
Eb_RightUpper_strip_array_energy(ii,i);
        end
        j = j + 1;
    elseif (1.9 < z_RightUpper(i,1)) && (z_RightUpper(i,1) <= 4.1)
        z_RightUpper_1dot9_4dot1_m(k,1) = z_RightUpper(i,1);
        for ii = 1:1:length(x_RightUpper)
            Eb_RightUpper_strip_array_energy_1dot9_4dot1_m(ii,k) =
Eb_RightUpper_strip_array_energy(ii,i);
        end
        k = k + 1;
    else
        z_RightUpper_after_4dot1_m(m,1) = z_RightUpper(i,1);
        for ii = 1:1:length(x_RightUpper)
            Eb_RightUpper_strip_array_energy_after_4dot1_m(ii,m) =
Eb_RightUpper_strip_array_energy(ii,i);
        end
        m = m + 1;
    end
end
end
```

```

% Piecewise, Left Upper
j = 1; k = 1; m = 1;

for i = 1:1:length(z_LeftUpper)
    if z_LeftUpper(i,1) <= 1.9
        z_LeftUpper_upto_1dot9_m(j,1) = z_LeftUpper(i,1);
        for ii = 1:1:length(x_LeftUpper)
            Eb_LeftUpper_strip_array_energy_upto_1dot9_m(ii,j) =
Eb_LeftUpper_strip_array_energy(ii,i);
        end
        j = j + 1;
    elseif (1.9 < z_LeftUpper(i,1)) && (z_LeftUpper(i,1) <= 4.1)
        z_LeftUpper_1dot9_4dot1_m(k,1) = z_LeftUpper(i,1);
        for ii = 1:1:length(x_LeftUpper)
            Eb_LeftUpper_strip_array_energy_1dot9_4dot1_m(ii,k) =
Eb_LeftUpper_strip_array_energy(ii,i);
        end
        k = k + 1;
    else
        z_LeftUpper_after_4dot1_m(m,1) = z_LeftUpper(i,1);
        for ii = 1:1:length(x_LeftUpper)
            Eb_LeftUpper_strip_array_energy_after_4dot1_m(ii,m) =
Eb_LeftUpper_strip_array_energy(ii,i);
        end
        m = m + 1;
    end
end
end

```



G. Piecewise Surface-Fitting for “Left-Bottom” Surface of LS2 PTC Module with 45 Degrees Incidence Angle

In this APPENDIX, piecewise surface-fitting for the “Left-Bottom” surface is explained in detail.

First, heat flux distribution on the “Left-Bottom” surface is plotted, and the surface with the highest R-square value is fitted to it. Note that the surface equation has two independent variables, i.e., “x” and “z”. Fitted surface with 2nd order in “z” and 4th order in “x” for the whole “Left-Bottom” surface is given in Figure G 1.

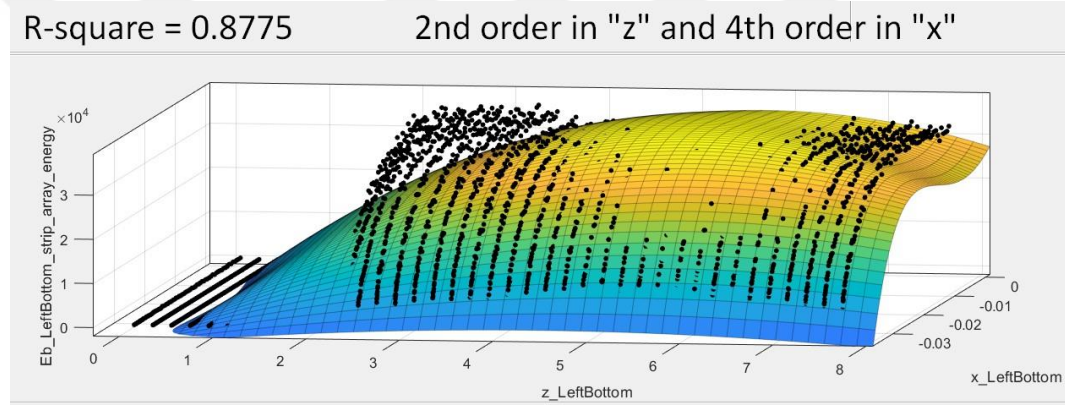


Figure G 1. Fitted surface with 2nd order in “z” and 4th order in “x” for the whole “Left-Bottom” surface

Note that if the order is higher than 2 in “z” or higher than 4 in “x”, MATLAB gives “Equation is badly conditioned. Remove repeated data points or try centering and scaling” error.

After investigating Figure G 1, 7.8 m distance in z-direction is divided into three sub-intervals as,

$$z \leq 1.7 \text{ m}$$

$$1.7 \text{ m} < z \leq 3.1 \text{ m}$$

$$z > 3.1 \text{ m}$$

Then, a surface with the highest R-square value is fitted to each of these sub-intervals.

The surface fit for $z \leq 1.7 \text{ m}$ is given in Figure G 2.

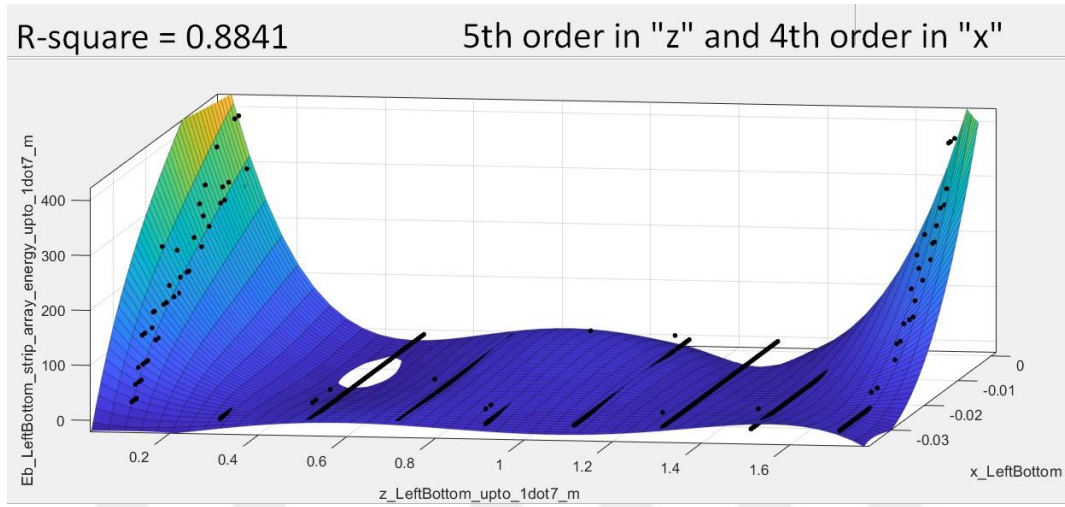


Figure G 2. The surface fit for $z \leq 1.7 \text{ m}$

Surface fit for $1.7 \text{ m} < z \leq 3.1 \text{ m}$ is given in Figure G 3.

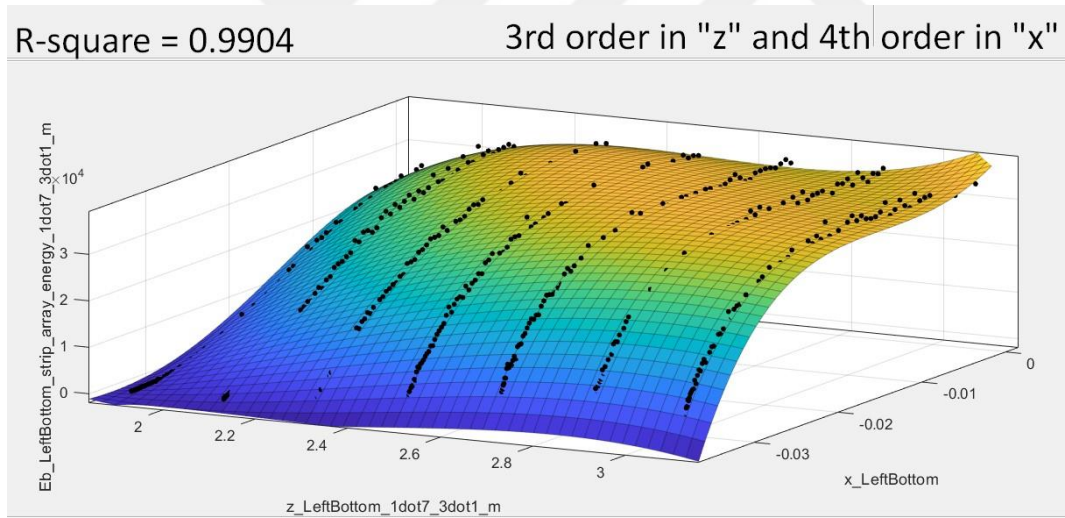


Figure G 3. Surface fit for $1.7 \text{ m} < z \leq 3.1 \text{ m}$

Surface fit for $z > 3.1 \text{ m}$ is given in Figure G 4.

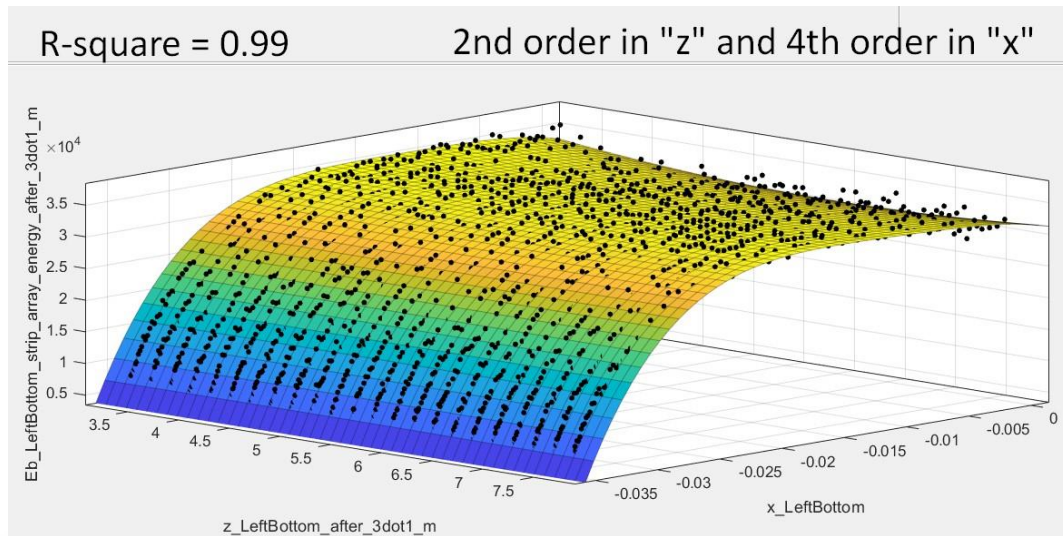


Figure G 4. Surface fit for $z > 3.1 \text{ m}$

The purpose of using piecewise surface-fitting is to resolve heat flux distribution around the absorber tube as accurately as possible.

In conclusion, the 7.8 m distance (length of the absorber tube) in z-direction is divided into three sub-intervals and a surface with the highest R-square value is fitted to each of these sub-intervals instead of fitting one surface for the whole region.



H. UDFs (User Defined Functions) of 2D Discretization Approach for LS2 PTC Module with Zero-Degree Incidence Angle

UDF of “Left-Bottom” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(leftbottom_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
if (y>=-0.005)
```

```
    F_PROFILE(f, t, i) = -5.146e10*y*y*y*y - 2.765e8*y*y - 5.858e5*y +  
    4.228e4;
```

```
else if (y<-0.005 && y>=-0.02)
```

```
    F_PROFILE(f, t, i) = 8.34e10*y*y*y*y*y + 6.256e9*y*y*y*y + 1.379e8*y*y*y +  
    7.051e5*y + 4.472e4;
```

```
else
```

```
    F_PROFILE(f, t, i) = -1.625e12*y*y*y*y*y - 1.651e11*y*y*y*y - 6.404e9*y*y*y  
    - 1.109e8*y - 6.681e5;
```

```
}
```

```
end_f_loop(f, t)
```

```
}
```

UDF of “Left-Upper” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(leftupper_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
if (y>=-0.02849)
```

```
    F_PROFILE(f, t, i) = 1.451e9*y*y*y*y + 5.636e7*y*y*y + 2.922e5*y*y +  
    2738*y + 921.6;
```

```
else if (y<-0.02849 && y>=-0.03373)
```

```
    F_PROFILE(f, t, i) = -1.186e10*y*y*y*y - 1.059e9*y*y - 3.155e7*y -  
    3.131e5;
```

```
else
```

```
    F_PROFILE(f, t, i) = 4.398e9*y*y + 2.999e8*y + 5.115e6;
```

```
}
```

```
end_f_loop(f, t)
```

```
}
```

UDF of “Right-Bottom” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(rightbottom_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
if (y<=0.005)
```

```
    F_PROFILE(f, t, i) = -5.393e10*y*y*y*y + 4.17e8*y*y - 7.774e5*y +  
    4.328e4;
```

```
else if (y>0.005 && y<=0.02)
```

```
    F_PROFILE(f, t, i) = -1.337e10*y*y*y*y*y - 8.585e8*y*y*y*y + 3.397e7*y*y  
    + 1.175e5*y + 4.24e4;
```

```
else
```

```
    F_PROFILE(f, t, i) = -1.61e12*y*y*y*y*y + 1.638e11*y*y*y*y - 6.365e9*y*y  
    + 1.105e8*y - 6.691e5;
```

```
}
```

```
end_f_loop(f, t)
```

```
}
```

UDF of “Right-Upper” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(rightupper_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
if (y<=0.02813)
```

```
    F_PROFILE(f, t, i) = 1.829e9*y*y*y*y - 1.001e8*y*y*y + 1.636e6*y*y -  
    1.538e4*y + 938.4;
```

```
else if (y>0.02813 && y<=0.03373)
```

```
    F_PROFILE(f, t, i) = 1.032e10*y*y*y*y - 9.078e8*y*y + 2.664e7*y -  
    2.602e5;
```

```
else
```

```
    F_PROFILE(f, t, i) = 4.243e9*y*y - 2.893e8*y + 4.934e6;
```

```
}
```

```
end_f_loop(f, t)
```

```
}
```





I. UDFs (User Defined Functions) of 3D Discretization Approach for LS2 PTC Module with 45 Degrees Incidence Angle

The absorber tube is divided into 780 pieces in the axial direction (z-direction) in order to determine the boundaries of the piecewise surface fits accurately.

UDF of “Left-Bottom” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(leftbottom_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
real z;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
z = x[2];
```

```
if (z<=1.755)
```

```
    F_PROFILE(f, t, i) = 8.391e7*z*y*y*y*y + 7.782e6*z*z*y*y*y +  
    8.244e5*z*z*z*y*y + 4.262e4*z*z*z*z*y - 288.9*z*z*z*z*z - 1.635e8*y*y*y*y -  
    9.763e6*z*y*y*y - 1.562e6*z*z*y*y - 1.214e5*z*z*z*y + 2746*z*z*z*z -  
    4.978e6*y*y*y + 6.457e5*z*y*y + 1.207e5*z*z*y - 7204*z*z*z - 1.507e5*y*y -  
    5.471e4*z*y + 7766*z*z + 9545*y - 3598*z + 577.3;
```

else if (z>1.755 && z<=2.975)

```
F_PROFILE(f, t, i) = -2.743e10*y*y*y*y + 3.289e9*z*y*y*y +  
7.728e7*z*z*y*y + 1.794e6*z*z*z*y - 9.268e9*y*y*y - 2.428e8*z*y*y -  
1.07e7*z*z*y + 4.624e4*z*z*z + 8.151e7*y*y + 2.032e7*z*y - 3.51e5*z*z -  
1.255e7*y + 8.83e5*z - 7.026e5;
```

else

```
F_PROFILE(f, t, i) = -7.195e10*y*y*y*y + 1.413e7*z*y*y*y +  
1.82e5*z*z*y*y - 3.101e9*y*y*y - 1.497e6*z*y*y + 1.636e4*z*z*y -  
4.865e7*y*y - 1.854e5*z*y + 328.3*z*z - 821.7*y - 3853*z + 4.194e4;
```

```
}
```

```
end_f_loop(f, t)
```

```
}
```

UDF of “Left-Upper” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(leftupper_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
real z;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
z = x[2];
```

```
if (z<=2.065)
```

```
    F_PROFILE(f, t, i) = -1.973e8*z*y*y*y*y - 1.994e7*z*z*y*y*y +  
3.745e5*z*z*z*y*y - 831.8*z*z*z*z*y - 128*z*z*z*z*z - 2.612e9*y*y*y*y +  
2.94e7*z*y*y*y - 2.448e6*z*z*y*y + 1.97e4*z*z*z*y + 617.7*z*z*z*z -  
1.783e8*y*y*y + 3.414e6*z*y*y - 8.006e4*z*z*y - 962.7*z*z*z - 4.769e6*y*y +  
9.334e4*z*y + 322.3*z*z - 4.764e4*y + 297*z + 527.1;
```

```
else if (z>2.065 && z<=4.175)
```

```
    F_PROFILE(f, t, i) = 3.605e10*y*y*y*y - 2.453e8*z*y*y*y -  
4.035e6*z*z*y*y - 2.924e4*z*z*z*y + 2.975e9*y*y*y + 1.44e7*z*y*y +  
1.592e5*z*z*y - 332*z*z*z + 3.917e7*y*y - 2.434e5*z*y + 2579*z*z +  
4.365e5*y - 6452*z + 6399;
```

```
else
```

```
    F_PROFILE(f, t, i) = 4.589e10*y*y*y*y + 4.166e6*z*y*y*y +  
5796*z*z*y*y + 2.803e9*y*y*y + 1.627e5*z*y*y + 299.1*z*z*y + 5.456e7*y*y  
+ 1055*z*y + 2.21*z*z + 3.619e5*y + 4.045*z + 1113;
```

```
}
```

```
end_f_loop(f, t)
```

```
}
```

UDF of “Right-Bottom” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(rightbottom_profile, t, i)
```

```
{
```

```

real x[ND_ND]; /* this will hold the position vector */

real y;

real z;

face_t f;

begin_f_loop(f, t)

{

F_CENTROID(x,f,t);

y = x[0];

z = x[2];

if (z<=1.745)

    F_PROFILE(f, t, i) = -2.898e8*z*y*y*y*y + 2.648e6*z*z*y*y*y +
6.866e5*z*z*z*y*y - 4.292e4*z*z*z*z*y - 361.1*z*z*z*z*z - 4.56e7*y*y*y*y +
1.72e7*z*y*y*y - 1.808e6*z*z*y*y + 1.323e5*z*z*z*y + 3065*z*z*z*z +
4.405e6*y*y*y + 8.755e5*z*y*y - 1.383e5*z*z*y - 7867*z*z*z - 3.502e5*y*y +
6.288e4*z*y + 8498*z*z - 8713*y - 3975*z + 640.9;

else if (z>1.745 && z<=2.945)

    F_PROFILE(f, t, i) = -3.033e10*y*y*y*y - 3.28e9*z*y*y*y +
7.977e7*z*z*y*y - 1.714e6*z*z*z*y + 9.489e9*y*y*y - 2.547e8*z*y*y +
1e7*z*z*y + 4.504e4*z*z*z + 8.807e7*y*y - 1.839e7*z*y - 3.413e5*z*z +
1.095e7*y + 8.574e5*z - 6.814e5;

else

    F_PROFILE(f, t, i) = -6.901e10*y*y*y*y - 1.404e7*z*y*y*y +
2.853e9*y*y*y + 1.908e5*z*y*y - 4.516e7*y*y + 1.723e4*z*y + 3.273e5*y -
283.3*z + 3.309e4;

}

```

```
end_f_loop(f, t)
```

```
}
```

UDF of “Right-Upper” surface is,

```
#include "udf.h"
```

```
DEFINE_PROFILE(rightupper_profile, t, i)
```

```
{
```

```
real x[ND_ND]; /* this will hold the position vector */
```

```
real y;
```

```
real z;
```

```
face_t f;
```

```
begin_f_loop(f, t)
```

```
{
```

```
F_CENTROID(x,f,t);
```

```
y = x[0];
```

```
z = x[2];
```

```
if (z<=2.075)
```

```
    F_PROFILE(f, t, i) = -1.182e9*z*y*y*y*y - 2.558e7*z*z*y*y*y +  
    3.578e5*z*z*z*y*y + 1445*z*z*z*z*y + 31.07*z*z*z*z*z - 1.289e9*y*y*y*y +  
    1.495e8*z*y*y*y + 7.039e5*z*z*y*y - 2.24e4*z*z*z*y - 47.56*z*z*z*z +  
    4.73e7*y*y*y - 5.461e6*z*y*y + 2.234e4*z*z*y - 25.86*z*z*z - 2.65e5*y*y +  
    5.587e4*z*y + 113.5*z*z - 1.118e4*y - 256.5*z + 719.6;
```

```
else if (z>2.075 && z<=3.975)
```

```

        F_PROFILE(f, t, i) = 3.756e10*y*y*y*y + 2.43e8*z*y*y*y -
4.047e6*z*z*y*y + 2.994e4*z*z*z*y - 3.077e9*y*y*y + 1.442e7*z*y*y -
1.667e5*z*z*y - 400.7*z*z*z + 4.171e7*y*y + 2.747e5*z*y + 3225*z*z -
4.991e5*y - 8465*z + 8502;

```

```

else

```

```

        F_PROFILE(f, t, i) = 4.72e10*y*y*y*y + 2.599e6*z*y*y*y -
6.029e4*z*z*y*y - 2.944e9*y*y*y + 5.383e5*z*y*y + 1801*z*z*y + 5.73e7*y*y
- 1.731e4*z*y - 2.323*z*z - 3.664e5*y - 7.339*z + 1412;

```

```

}

```

```

end_f_loop(f, t)

```

```

}

```

J. Creating a Cross-Section on the Absorber tube and Obtaining the Heat Flux Distribution on It

In this part, creating a cross-section on the absorber tube and obtaining heat flux distribution on it are explained.

Firstly, an “Isosurface” is created. In Figure J 1, the section in Results to insert “Isosurface” is shown.

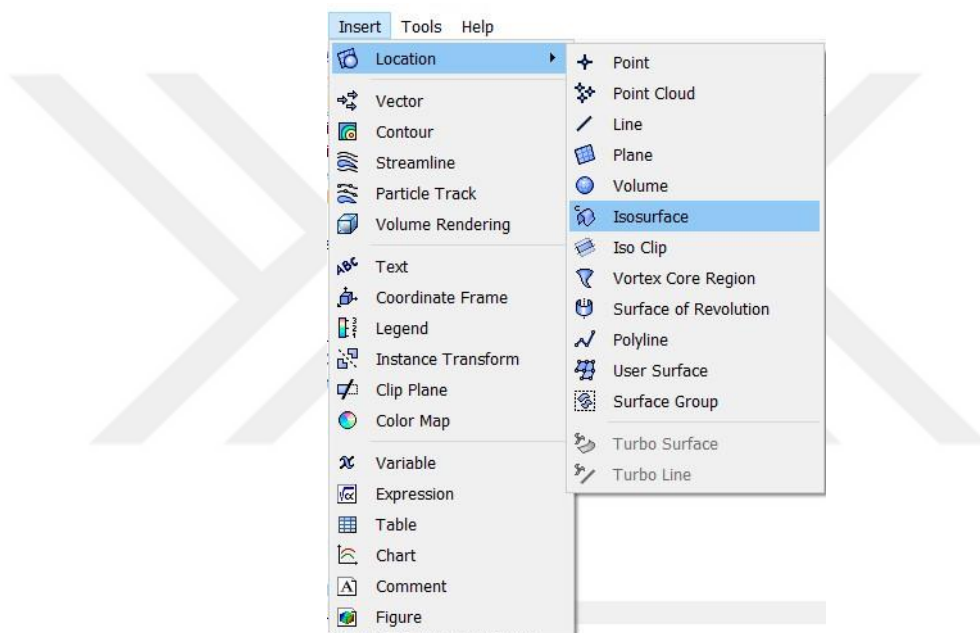


Figure J 1. The section in Results to insert an “Isosurface”

Choose “Z” for the variable and enter the location of the cross-section plane for the value. Details of the “Isosurface” function are given in Figure J 2.

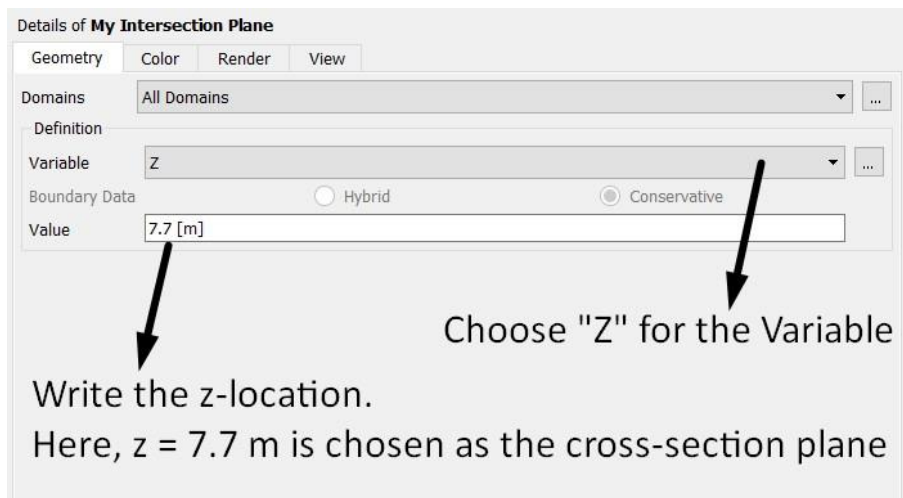


Figure J 2. Details of “Isosurface” function

In Figure J 3, the created “Isosurface” at $z = 7.7$ m is shown.

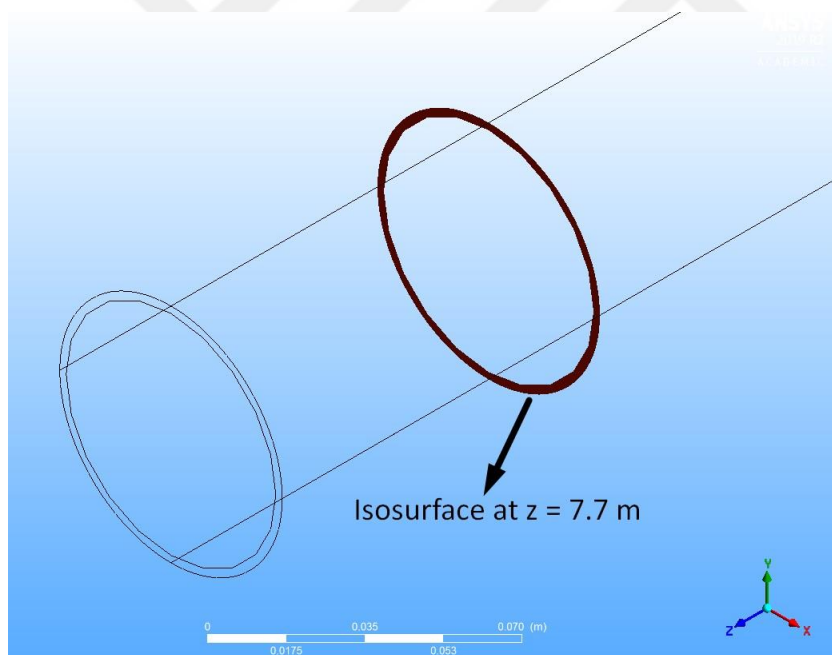


Figure J 3. “Isosurface” at $z = 7.7$ m

Secondly, “Polyline” is created. In Figure J 4, the section in Results to insert “Polyline” is shown.

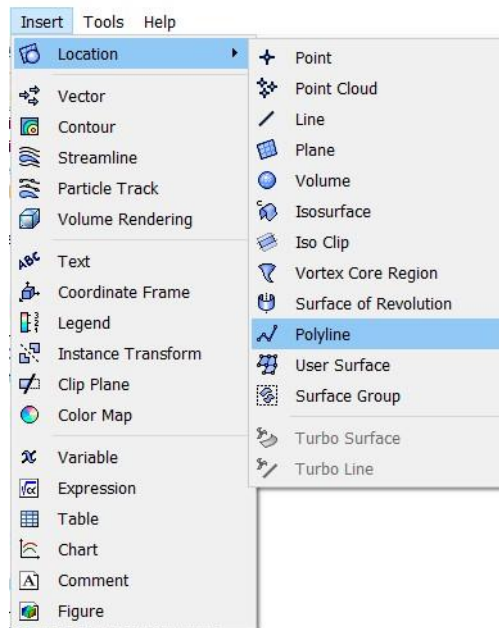


Figure J 4. The section in Results to insert a “Polyline”

Choose “Boundary Intersection” for the Method. Choose four outer surfaces of the absorber tube for the Boundary List. Choose “My Intersection Plane”, which is the name of the created Isosurface at the previous step, for the Intersect with. Details of the “Polyline” function are given in Figure J 5.

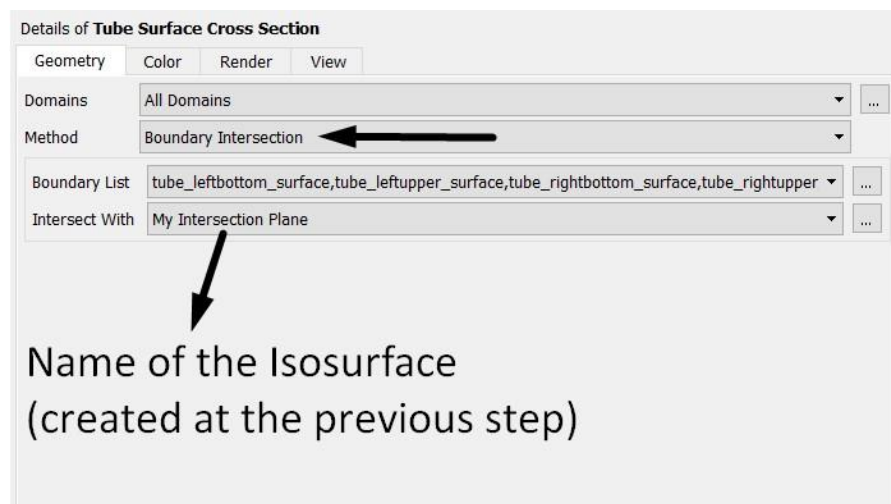


Figure J 5. Details of “Polyline” function

Note that only the bottom surfaces (surfaces of the tube closer to the parabolic mirror) can be selected to find the heat flux distribution on bottom surfaces.

In Figure J 6, the created Polyline is shown with the Isosurface. The green circular line is the Polyline, and it is used as a cross-section of the absorber tube outer surface.

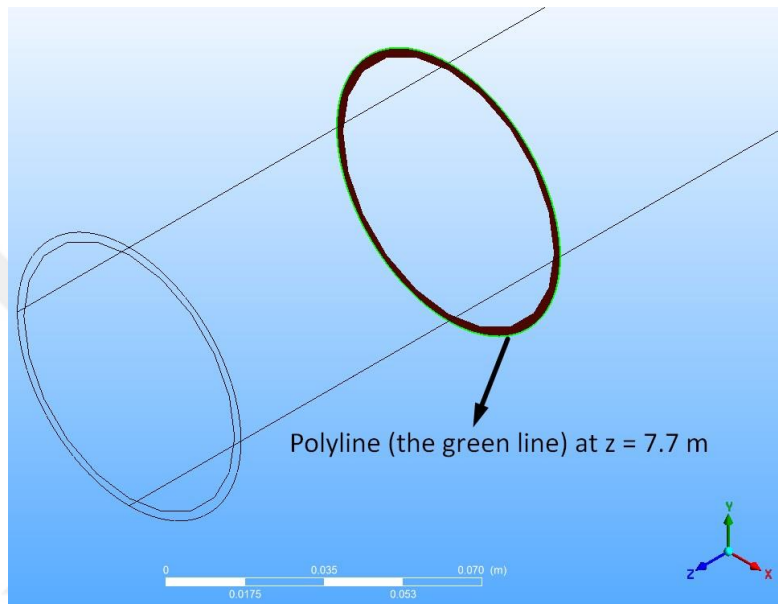


Figure J 6. “Polyline” at $z = 7.7 \text{ m}$

Finally, heat flux distribution at a particular cross-section can be found by plotting the heat flux values on the Polyline using the “Chart” function. The section of “Chart” in Results are shown in Figure J 7.

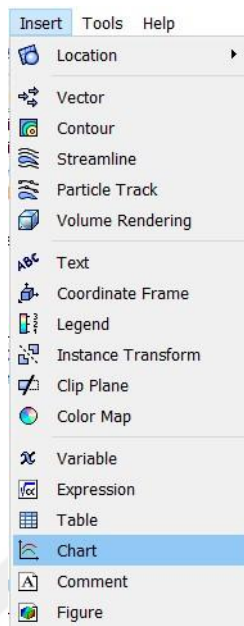


Figure J 7. The section in Results to insert a “Chart”

Select “XY-Line” for the Type. See Figure J 8.

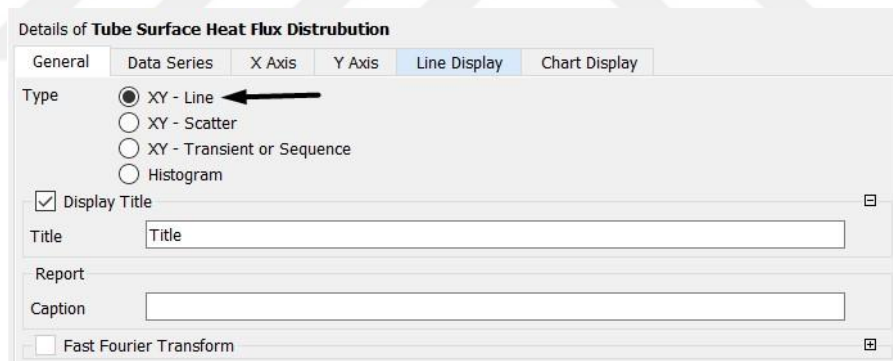


Figure J 8. Chart General tab

Select the Polyline, which is created at the previous step, for Location. See Figure J 9.

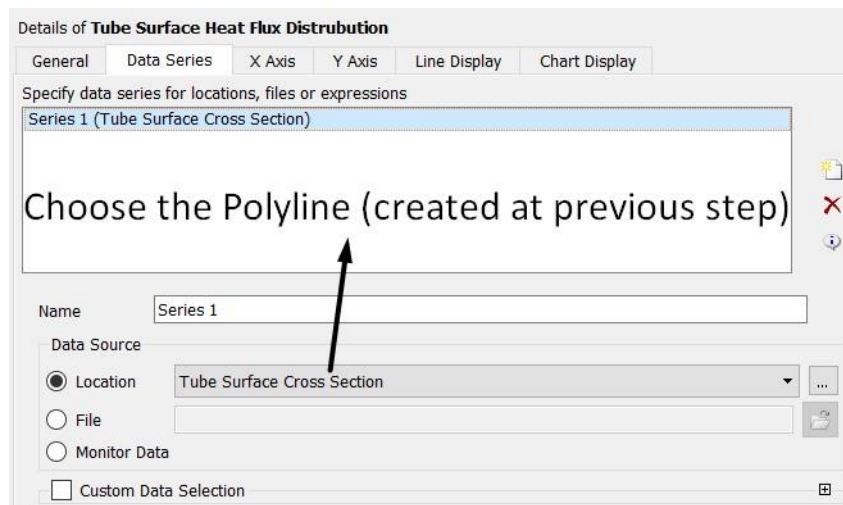


Figure J 9. Chart Data Series tab

Choose “X” for the first variable. See Figure J 10.



Figure J 10. Chart X-Axis tab

Choose “Wall Heat Flux” for the second variable. See Figure J 11.



Figure J 11. Chart Y-Axis tab

After obtaining the graph, the general pattern is checked. The general pattern is correct. Then, the data is exported as a .csv file to make a more professional-looking plot.

K. MATLAB Code to Determine the Absorbed Energy by Glass Cover

In this APPENDIX, the MATLAB code to determine the absorbed energy by glass cover is given.

```
clear all
clc
format long

%% Glass Cover Outer Surface
% Extracting Tonatiuh Glass Cover data to MATLAB
fileID =
fopen('LS2_PTC_module_10millionRays_90_degrees_elevation_glass_cove
r_outer_data_1.dat');
Glass_Outer_Raw_Data = fread(fileID,'double','b'); % b is for Big-
endian ordering
Glass_Outer_Processed_Data = reshape(Glass_Outer_Raw_Data, [6,
length(Glass_Outer_Raw_Data)/6]);
Glass_Outer_Data = Glass_Outer_Processed_Data';
Glass_Outer_Data_x = Glass_Outer_Data(:,2);
Glass_Outer_Data_y = Glass_Outer_Data(:,3);
Glass_Outer_Data_z = Glass_Outer_Data(:,4);

%% Absorbed solar energy by glass cover
OneRayPower = 0.00404286; % [Watt]
Ray_Count = length(Glass_Outer_Data_x);
Glass_Cover_Absorbtivity = 0.023;
Glass_cover_absorbed_energy = Ray_Count * OneRayPower *
Glass_Cover_Absorbtivity;
```



L. Obtaining the IAM Curve by Using Tonatiuh

In this part, obtaining the IAM curve by using Tonatiuh is explained.

Detailed Sun definition for the IAM curve analysis is given in Figure L 1.

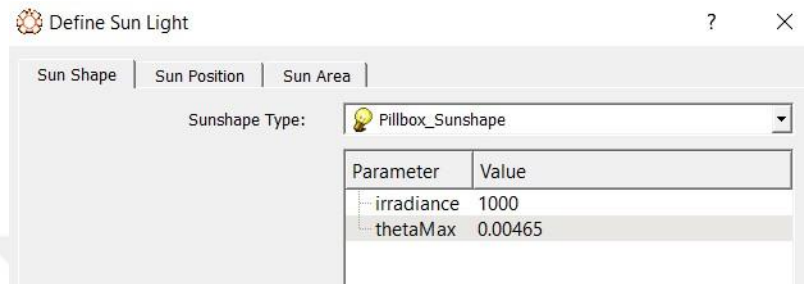


Figure L 1. Detailed Sun definition for IAM curve analysis

Tonatiuh's "Run Flux Analysis" function is used, shown in Figure L 2, to obtain the LS2 PTC module's IAM curve.

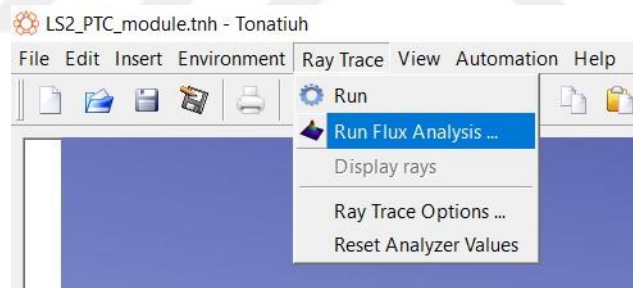


Figure L 2. The section of "Run Flux Analysis" function in Tonatiuh

"Run Flux Analysis" function is used for each incidence angle from 0 to 90 degrees with 5 degrees increment.

Below, the procedure is explained for a 0-degree incidence angle for demonstration.

"ReceiverSurface" is selected for the "Surface URL" from the tree structure. "OUTSIDE" is chosen for the "Active side". In the "Grid divisions" section, "Width" stands for division in the radial direction (x-direction), and "Height"

stands for division in the axial direction (z-direction). Flux analysis is first performed with 5×10^5 rays. Then, “Append to previous simulation” option is checked, and the number of rays is increased step by step until the “Horizontal Sector” and “Vertical Sector” plots become smooth, i.e., fluctuations in the graphs disappear. This procedure is explained for 10^6 rays in Figure L 3.

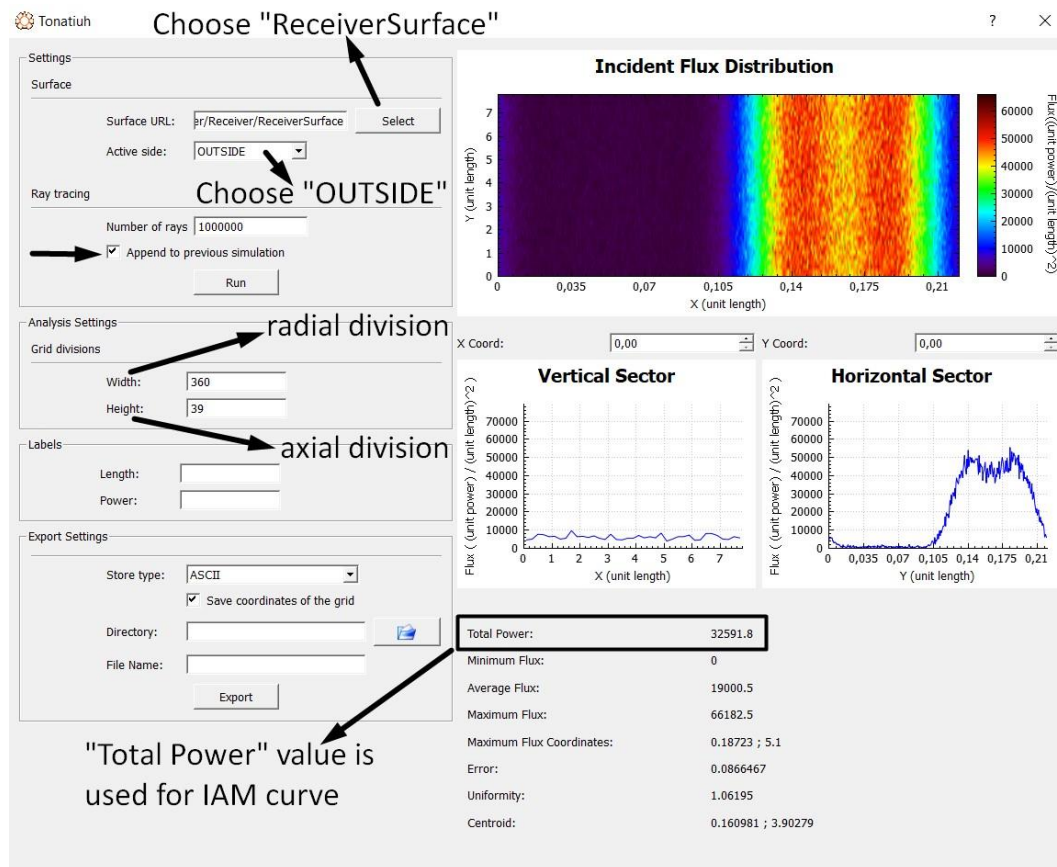


Figure L 3. “Run Flux Analysis” function for 10^6 rays, LS2 PTC module

The heat flux distribution along axial direction can be seen using the “Vertical Sector” plot by arranging the “X Coord” value, and heat flux distribution in the radial direction can be seen using the “Horizontal Sector” plot by setting “Y Coord” value.

Detailed view of heat flux map and plots for 10^6 rays are given in Figure L 4.

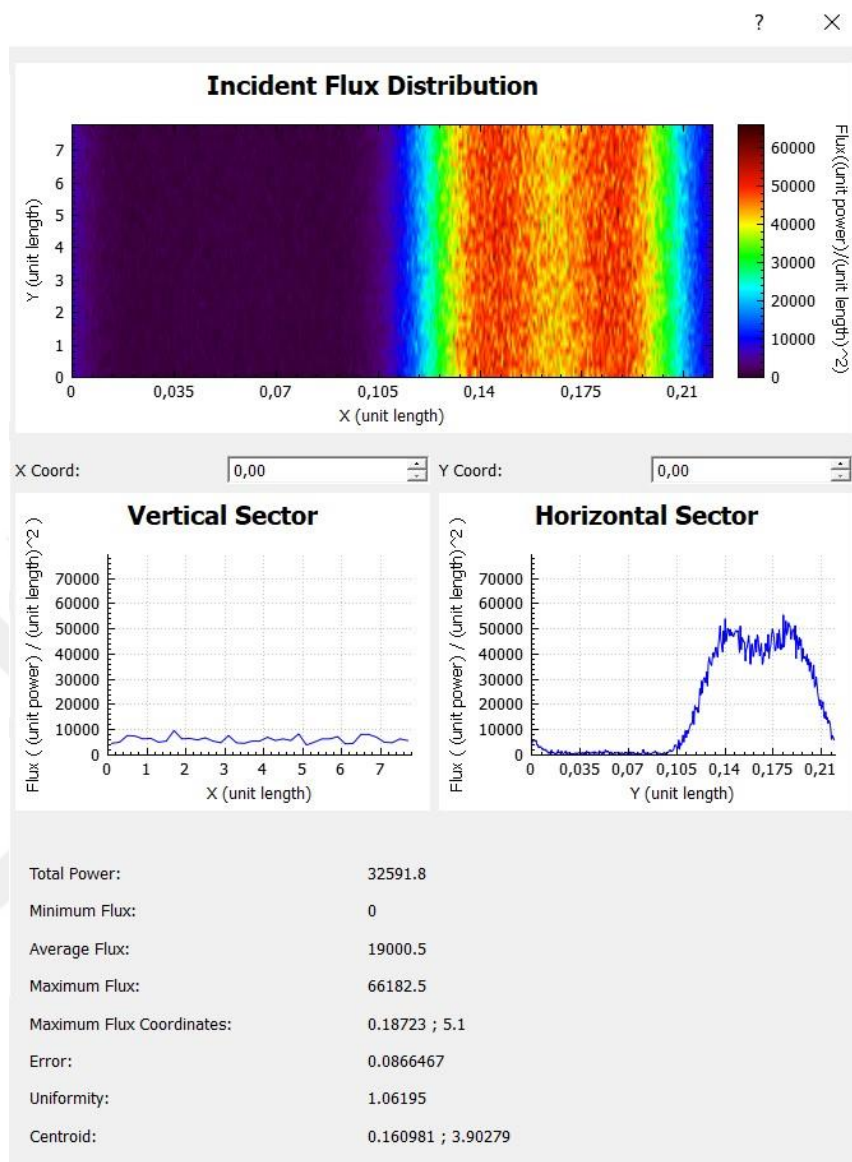


Figure L 4. “Run Flux Analysis” function, detailed view of heat flux map and plots for 10^6 rays, LS2 PTC module

The number of rays is increased from 10^6 to 10^7 with a 1 million increment. Detailed view of heat flux map and plots for 10^7 rays are given in Figure L 5.

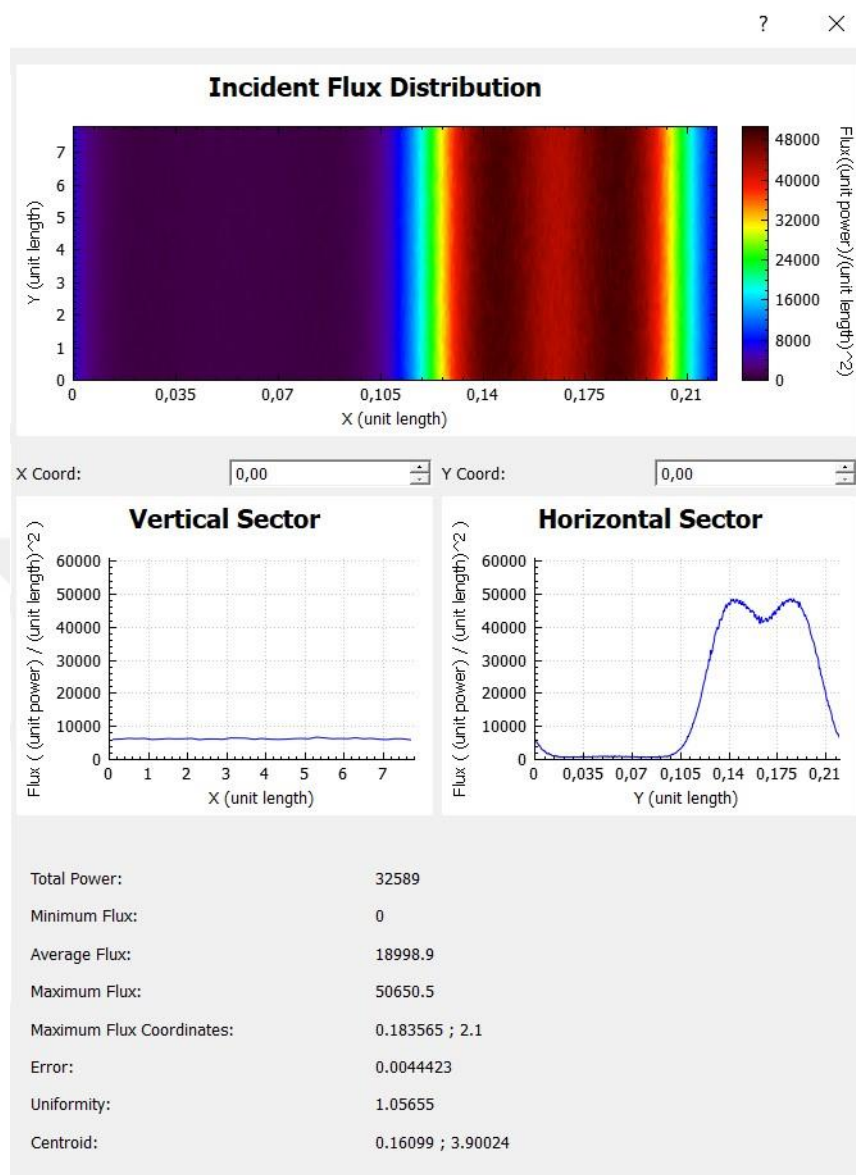


Figure L 5. “Run Flux Analysis” function, detailed view of heat flux map and plots for 10^7 rays, LS2 PTC module

Comparing Figure L 4 and Figure L 5, the effect of increasing the number of rays with “Append to previous simulation” option checked can be seen clearly. The “Vertical Sector” and “Horizontal Sector” plots are smooth for 10^7 rays, whereas this not the case for 10^6 number of rays. In other words, the heat flux map is more accurate for 10^7 number of rays than 10^6 .