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Design optimization of a new cavity receiver for a parabolic trough solar collector

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Anahtar Kelimeler

Kaviteli Güneş Alıcısı
Optik Verim
Optimizasyon
Yanıt Yüzey Metodu
Parabolik Oluk Kollektör

Graphical/Tabular Abstract (Grafik Özet)

This study aims to propose and optimize a new cavity receiver for use in parabolic trough collectors to increase optical efficiency. Three geometries (triangle, rectangle, and polygon), along with various aperture widths, heights, and positions of the cavity receiver, are considered as optimization parameters. / Bu çalışma, optik verimliliği artırmak için parabolik oluk kollektörlerde kullanılmak üzere yeni bir kaviteli alıcı önermeyi ve optimize etmeyi amaçlamaktadır. Çeşitli kavite açıklık genişlikleri, yükseklikleri ve kavite alıcısının konumlarıyla birlikte üç geometri (üçgen, dikdörtgen ve çokgen) optimizasyon parametreleri olarak ele alınmıştır.

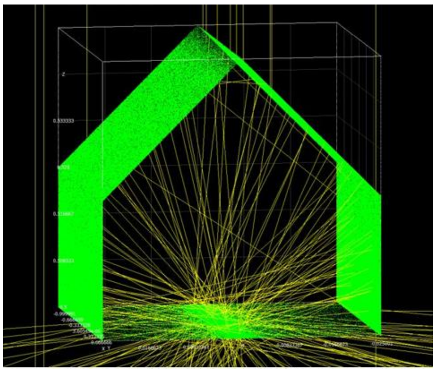

***Figure A**: Perspective view of SolTrace analysis result of optimum cavity receiver / **Şekil A:** Optimum kaviteli alıcının SolTrace analiz sonucunun perspektif görünümü*

Highlights (Önemli noktalar)

- *Development of a new cavity receiver for parabolic trough collector with high optical efficiency / Yüksek optik verimliliğe sahip parabolik oluk kollektör için yeni bir boşluklu alıcının geliştirilmesi*
- *Design of an experimental plan by response surface method and analysis of results / Yanıt yüzey metodu ile deneysel bir planın tasarlanması ve sonuçların analizi*
- *Determination of the most effective parameters for the cavity receivers of parabolic trough collector / Parabolik oluk kollektörün kaviteli alıcıları için en etkili parametrelerin belirlenmesi*

Aim (Amaç): *This study aims to propose and optimize a new cavity receiver for use in PTCs to increase optical efficiency. / Bu çalışma, optik verimliliği artırmak için parabolik oluk kollektörlerde kullanılmak üzere yeni bir kaviteli alıcı önermeyi ve optimize etmeyi amaçlamaktadır.*

Originality (Özgünlük): *The originality of this work is the evaluation of the effects of parameters on optical efficiency of cavity receivers, i.e. geometry, dimensions, and position by design of experiments approach and inspection of the effects on the absorbed thermal radiation heat rate by the cavity receiver. / Bu çalışmanın özgünlüğü, kaviteli alıcılarda, geometri, boyutlar ve konum gibi parametrelerin optik verimlilik üzerine etkilerinin deney tasarımı yaklaşımıyla değerlendirilmesi ve kaviteli alıcı tarafından absorbe edilen ısıl ışınım gücü üzerindeki etkilerinin incelenmesidir.*

Results (Bulgular): *The results indicate that the optimum cavity geometry is polygonal, with the cavity depth and aperture equal to 0.05 m. Moreover, it is found that the most effective parameter is the position of the cavity receiver. / Sonuçlar, optimum kavite yüksekliği ve açıklığının 0,05 m olarak eşit ve optimum geometrinin ise çokgen olduğunu göstermektedir. Ayrıca, en etkili parametrenin kavite alıcısının konumu olduğu bulunmuştur.*

Conclusion (Sonuç): *The highest absorbed thermal radiation rate by the cavity receiver and the optical efficiency of the system are 3241.99 W and 81.05%, respectively, for the optimum cavity receiver design. / Optimum kaviteli alıcı tasarımı için kavite alıcısı tarafından absorbe edilen en yüksek ısıl ışınım gücü ve sistemin optik verimliliği sırasıyla 3241,99 W ve %81,05 değerindedir.*

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Design Optimization of a New Cavity Receiver for a Parabolic Trough Solar Collector

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Abstract

The most critical parameter affecting the optical efficiency, the upper limit for the overall efficiency of a parabolic trough solar collector (PTC), is the net absorbed heat rate by the receiver on which solar beam radiation is concentrated. This study aims to propose and optimize a new cavity receiver for use in PTCs to increase optical efficiency. Three geometries (triangle, rectangle, and polygon), along with various aperture widths, heights, and positions of the cavity receiver, are considered optimization parameters. A design of experiments (DoE) approach is used to evaluate the effects of these parameters on the absorbed radiation heat rate by the receiver. SolTrace is utilized to investigate these effects through optical analysis. The results indicate that the optimum cavity geometry is polygonal, with the cavity depth and aperture equal to 0.05 m. Moreover, it is found that the most influential parameter is the position of the cavity receiver, with the optimum position being at the focal line of the parabolic concentrator. The highest absorbed radiation rate by the cavity receiver and the optical efficiency of the PTC are 3241.99 W and 81.05%, respectively, for the optimum cavity receiver design.

Parabolik Oluk Güneş Kollektörü için Yeni Bir Kaviteli Alıcının Tasarım Optimizasyonu

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Öz

Bir parabolik oluk güneş kollektörünün (PTC) toplam veriminin üst sınırı olan optik verimini etkileyen en kritik parametre, direkt güneş ışınımının üzerine yoğunlaştırıldığı alıcı tarafından absorbe edilen net ısıl güç değeridir. Bu çalışma, optik verimliliği artırmak için PTC'lerde kullanılmak üzere yeni bir kaviteli alıcı önermeyi ve optimize etmeyi amaçlamaktadır. Çeşitli kavite açıklık genişlikleri, yükseklikleri ve kavite alıcısının konumuyla birlikte üç farklı geometri (üçgen, dikdörtgen ve çokgen) optimizasyon parametreleri olarak ele alınmıştır. Bu parametrelerin alıcı tarafından absorbe edilen ısıl ışınım gücü üzerindeki etkilerini değerlendirmek için bir deney tasarımı (DoE) yaklaşımı kullanılmıştır. Bu etkileri optik analiz yoluyla araştırmak için SolTrace kullanılmıştır. Sonuçlar, optimum kavite yüksekliği ve açıklığının 0,05 m olarak eşit ve optimum geometrinin ise çokgen olduğunu göstermektedir. Ayrıca, en etkili parametrenin kavite alıcısının konumu olduğu ve optimum konumun parabolik yoğunlaştırıcının odak çizgisi olduğu bulunmuştur. Optimum kaviteli alıcı tasarımı için, kavite alıcısı tarafından absorbe edilen en yüksek ısıl ışınım gücü ve en yüksek parabolik oluk kollektör optik verimi sırasıyla 3241,99 W ve %81,05 değeri olarak bulunmuştur.

1. INTRODUCTION (GİRİŞ)

One of the most promising, accessible, and clean forms of renewable energy for various applications is solar energy [1]. Parabolic trough collector (PTC) applications represent the industry's most mature solar thermal technologies. PTC systems have two main components: a receiver and a parabolic-shaped reflector. The parabolic reflector concentrates the solar beam onto the solar absorber. The concentrated radiation on the receiver is then converted into heat, with a heat transfer fluid flowing inside the receiver to carry away the heat [2]. This radiation-to-heat conversion is a complex process. It is crucial to obtain the heat flux distribution on the receiver surface as a result of this conversion process, as the heat flux on the absorber serves as a boundary condition for thermal calculations.

Optical efficiency is the theoretical upper limit of collector efficiency and depends on material properties and design factors. These design factors include tracking accuracy, surface quality, and

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receiver geometry. Therefore, optical efficiency dramatically influences the overall efficiency of the PTC [3].

Since photo-thermal conversion occurs in the solar receiver, the receiver's shape is crucial for overall collector efficiency. Cavity receivers have the potential to perform better than cylindrical receivers because concentrated sun rays can be reflected multiple times between cavity surfaces [4]. Daabo et al. [5] investigated the effects of cavity geometry on optical efficiency using the ray tracing method. They found that optical efficiency changes with the flux distribution on the cavity's inner surfaces. Kalidasan et al. [4] reported that efficiency varied considerably with different receiver configurations. Slootweg et al. [6] studied a novel cavity solar receiver regarding heat transfer and indicated that it was promising but still needed improvements. Kasaeian et al. [7] reviewed different geometries for cavity receivers and their optimization methodologies, showing that the optimum geometry is crucial for system efficiency.

The radiation flux concentrated on the receiver is crucial for optimal efficiency. Various methods are used to construct the radiation map on the receiver surface. The Monte Carlo Ray Tracing (MCRT), a flexible and highly efficient method, is commonly employed to analyze the optical properties of concentrated solar collectors [3]. Zou et al. [3] provided a reference for designing and optimizing PTCs. Loni et al. [8] investigated different dimensions of solar cavity geometry to achieve maximum thermal efficiency, using sensitivity analysis that included the aperture, tube diameter, height, and cavity position. Natraj et al. [9] proposed a methodology for designing and optimizing parabolic trough collectors based on the finite element method and MCRT.

The geometric design of the receiver directly affects the collector's overall optical efficiency. Sensitivity analyses provide limited results, as all parameters and configurations must be considered. The combined effect of parameters on the response variables offers valuable insights into solar receiver design. Gorji and Ranjbar [10] performed an optimization based on the response surface model to determine the optimum collector geometry dimensions. Moghimi et al. [11] studied the optimization of a trapezoidal cavity receiver and identified the most sensitive parameters. Afzal et al. [12] recommended using algorithms to optimize the thermal efficiency of devices used in solar energy systems, describing several challenges and issues in the optimization process. Ghazouani et al. [13] presented comprehensive optimization analyses to examine the effect of design parameters and operating conditions on a small PTC. Moghadam and Samimi [14] investigated the geometrical features of evacuated solar tube collectors using the Box-Behnken design model based on response surface methodology (RSM). Sharifzadeh and Loni [15] studied a V-shaped cavity receiver for use in parabolic trough collectors. They showed that thermal efficiency increased due to decreased thermal losses compared to conventional solar receivers. They also found that cavity dimensions affect thermal efficiency. Ferrer et al. [16] discussed design approaches for a receiver enclosed in an opaque cavity using parameter optimization. They proposed three different focal plane positions relative to the receiver and showed that the position of the cavity on the focal line impacted the receiver's temperature and efficiency. Taher et al. [17] introduced a novel design to optimize the optical performance of parabolic trough collectors using an optimization method. They employed the MCRT method to predict the solar flux distribution on the absorber tube surface and analyzed the variance to show the effect of solar flux on the receiver surface. Loni and Sharifzadeh [18] conducted a numerical investigation of a solar PTC with various linear cavity receivers. They highlighted the significance of cavity shape and aperture width on the optical, thermal, and energetic performance of solar PTC systems. Facão and Oliveira [19] investigated a new trapezoidal cavity receiver, optimized it via ray-tracing, and studied the inclination of the cavity walls. Tariq et al. [20] explored a humidifier using multi-objective optimization to achieve the highest overall energy performance. They conducted a sensitivity analysis to evaluate system performance under different parameters.

This study investigated the effects and importance of the dimension, position, and geometry parameters of a cavity solar receiver used in PTCs on the heat flux absorbed on the cavity surfaces. To achieve this, a design of experiments (DoE) approach is used to evaluate the effects of multiple parameters (or factors) simultaneously and to examine their impact on the output parameter (or response). The concentrated heat flux falling on the cavity receiver surface was obtained using SolTrace software and the MCRT methodology. An experimental setup was created using the Box-Behnken design method (BBD), and the concentrated heat flux collected on the receiver surfaces, which serves as the response parameter, was obtained with SolTrace software using the MCRT. Solving the regression equation with the Minitab Response Optimizer determined the parameter values that maximize the response parameter. The optimal geometry and corresponding dimensions that provide the highest optical efficiency for the investigated system are also evaluated.

2. METHODOLOGY (METODOLOJİ)

2.1. The Cavity Solar Receiver Concept (Kaviteli Güneş Alıcısı Konsepti)

Cavity receivers, compared to conventional cylindrical receivers, offer several advantages. Higher concentration ratios, geometric benefits, and extended working temperature ranges give them higher optical and thermal efficiencies at elevated temperatures [4]. In this study, the cavity receiver is analyzed as the absorber in a PTC system using an optimization methodology. The schematic of the collector is shown in Figure 1. As illustrated, incoming direct solar radiation on the parabolic reflective surface is concentrated on the cavity receiver aperture. The concentrated beam radiation passes through the low-iron glass plate at the cavity entrance. Low-iron glass, a key component in reducing radiation losses, allows low-wavelength rays from the sun to pass through while blocking high-wavelength rays emitted from the receiver surface. The cavity's internal surfaces absorb the radiation that passes through the low-iron glass plate, heating the working fluid that flows through the cavity absorber. The outer surface of the receiver is insulated to minimize heat losses to the environment. The advantages of the investigated cavity receiver are as follows:

• reducing optical losses from the solar receiver because the cavity and glass plate prevent most of the radiation losses

• increasing radiative concentration through multiple reflections between the internal surfaces of the cavity receiver.

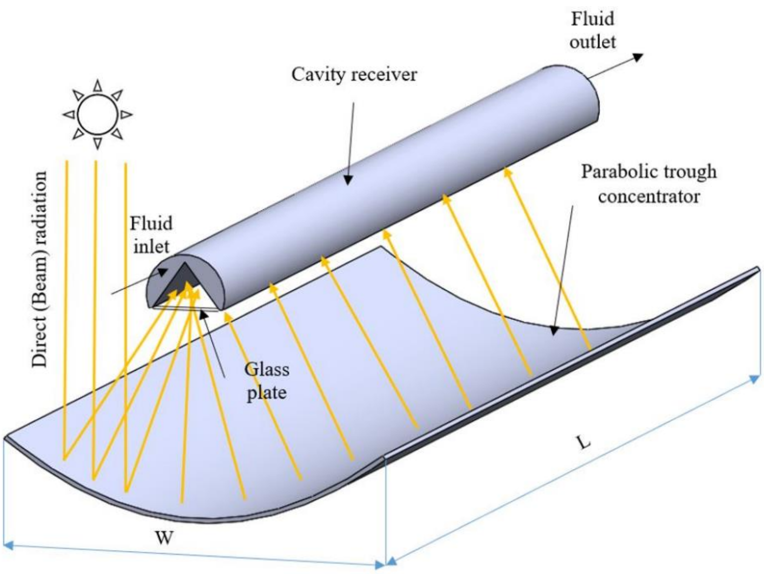


Figure 1. Schematic of the collector with solar cavity absorber (Kaviteli güneş alıcılı kollektörün şeması)

Table 1. Dimensions of the parabolic trough collector (Parabolik oluk kollektörün boyutları)

Description	Value
Parabolic collector length (L)	2 m
Parabolic collector aperture (W)	2 m
Focal length (f)	0.5 m
Parabolic collector rim angle	90°

Table 1 summarizes the dimensions of the PTC studied in this research. The cavity length is assumed to be constant, equal to the parabolic collector length (L). However, cavity geometry (triangle, rectangle, and polygon), cavity aperture width (a), cavity height (b), and the position of the cavity receiver (h) are varied within specified ranges using optimization methods.

2.2. Optical Model (Optik Model)

An optical model of the investigated parabolic trough solar collector with the cavity receiver was developed based on optical equations for the sample absorber geometry. The optical model of the investigated cavity receiver is illustrated in Figure

2. The equations [21] describing the optical model were presented in this section.

Optical efficiency of the collector is expressed by:

$$\eta_{opt} = 100 \cdot \frac{\dot{Q}_{abs}}{I_d \cdot A_C} \quad (1)$$

$\dot{Q}_{abs}$ represents the net heat rate absorbed by the inner surfaces of the cavity, while I_d denotes the beam solar radiation. The total area of the parabola concentrator surface is A_C and its dimensions were given in Table 1.

$$A_C = W \cdot L \quad (2)$$

where

$$\dot{Q}_{abs} = Q_{abs} \cdot A_{PTC} \quad (3)$$

A_{PTC} is the unshaded aperture area of the parabolic reflective surface as given:

$$A_{PTC} = (W - a) \cdot L \quad (4)$$

a represents the width of the receiver cavity. An equation for Q_{abs} (W/m^2) [21], the absorbed radiation flux of the unshaded area is:

$$Q_{abs} = I_d \cdot \rho \cdot \tau \cdot \alpha \cdot \gamma \cdot K \quad (5)$$

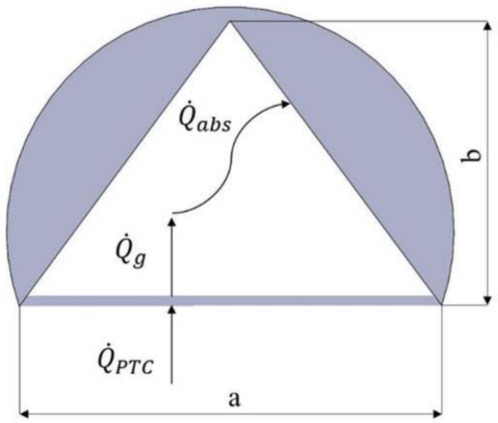


Figure 2. Optical model of the cavity solar absorber (sample geometry) (Kaviteli güneş alıcısının optik modeli (örnek geometri))

ρ denotes the reflectivity efficiency of the parabolic collector, α indicates the absorptivity of the receiver surface, and τ represents the transmittance of the glass. γ, the intercept factor, represents the fraction of reflected radiation incident on the absorbing receiver surface. γ values are commonly greater than 0.9. In this study, γ was set to 1.0. K is a modifier that adjusts for deviations from the average angle of incidence of radiation on the aperture. In this study, K was also set to 1.0, as deviations from the incidence angle were neglected.

The incident solar energy on the parabolic concentrator depends on the solar beam radiation (I_d) and the unshaded area of the parabolic collector (A_{PTC}) where the unshaded aperture is directly related to the cavity width, (a). Solar irradiation ($\dot{Q}_s$) can be calculated as:

$$\dot{Q}_s = I_d \cdot A_{PTC} \quad (6)$$

$\dot{Q}_s$ (W) refers to the total solar heat rate received by the unshaded area of a parabolic trough reflector. The total concentrated heat rate reflected from PTC is expressed by:

$$\dot{Q}_{PTC} = \rho \cdot I_d \cdot A_{PTC} \quad (7)$$

The radiation through the glass plate depends on the transmittance (τ) of the glass. It is given by the following equation:

$$\dot{Q}_g = \tau \cdot \dot{Q}_{PTC} \quad (8)$$

The net heat flux absorbed by cavity's inner surfaces is given as:

$$\dot{Q}_{abs} = \alpha \cdot \dot{Q}_g \quad (9)$$

In this modeling approach, I_d is assumed to be 1000 W/m^2. The reflectivity ρ is assumed to be 95%, based on the optical properties of the parabolic reflective surfaces. $\dot{Q}_g$ represents the radiation that passes through the glass plate at the cavity receiver entrance. According to Eq. (8), the transmittance of the low-iron glass plate at the receiver entrance is 0.95. The absorbed net heat rate by the cavity's inner surfaces ($\dot{Q}_{abs}$) also depends on the receiver absorptivity properties of the receiver surface, denoted by α. The receiver cavity surface is coated with solar-selective paint with a high absorption rate of 0.94. As shown in Eq. (1), the optical efficiency, η_{opt} (%) of the PTC system depends on the heat rate absorbed by the cavity receiver's inner surfaces

($\dot{Q}_{abs}$), given that the dimensions of the concentrator and its optical properties are constant in this modeling approach.

2.3. Optimization Method (Optimizasyon Metodu)

The main challenge in optimizing the geometric features of cavity receivers lies in the synergistic relationship between thermal and optical approaches [4]. Consequently, the geometry and dimensions of cavity receivers significantly affect the efficiency of the PTC and must be examined simultaneously. The most effective way to achieve this is by using an optimization method to investigate all parameters. To this end, the DoE (Design of Experiments) optimization method was employed to determine the factor settings that optimize the results. DoE encompasses a collection of mathematical and statistical techniques to assess the impact of parameters within a system [22], intending to reduce the number of experiments, time, and cost [23].

In this study, the entire experimental design and optimization solutions were analyzed in detail using Minitab V.19. The flowchart for the optimization procedure is presented in Figure 3. The first step in the Response Surface Methodology (RSM) was defining variables and their levels. Using statistical and mathematical tools, RSM designs and analyzes response surfaces [24]. Different variable parameters influence response surfaces. This optimization method employs experiment plans to find an optimal response. RSM establishes a relationship between factors and responses. It achieves good results with a small number of experimental plans and introduces different experimental designs. The Box-Behnken design (BBD) is used to evaluate factors with three levels and the relationships, running with minor experimental plans [25]. After defining parameters and levels, an experimental design setup was created using the Box-Behnken design. All model geometries were modeled and analyzed in SolTrace. A regression equation was obtained using Minitab software, and the optimum geometry was determined by solving the equation equation with the Minitab Response Optimizer.

Y is the predicted response equation [26]:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon \qquad (10)$$

β_0 the offset term, β_i the linear effect, β_{ij} the squared effect and β_{ii} is the interaction effect In Eq. (10). cavity receiver.

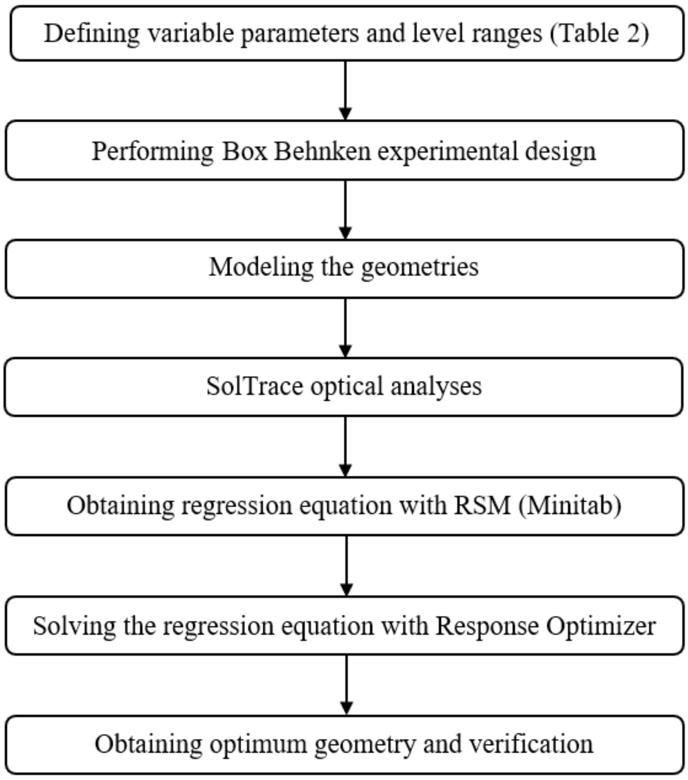


Figure 3. Flowchart for the optimization procedure (Optimizasyon prosedürü için akış şeması)

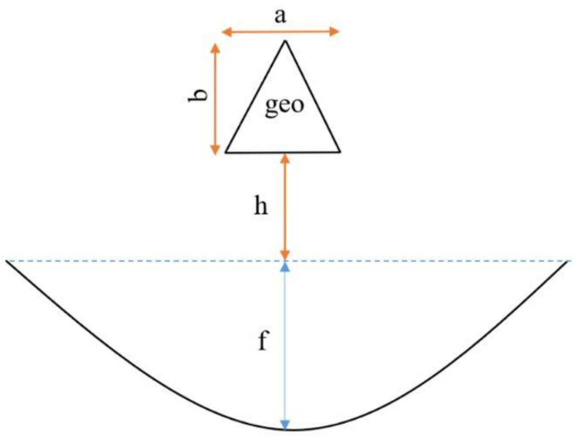


Figure 4. Optimization parameters (Optimizasyon parametreleri)

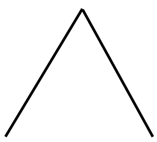
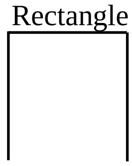
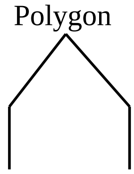
The parameters (factors) of the investigated system are shown in Figure 4. There are four parameters: h (distance from the cavity receiver to the focal length), a (cavity width), b (cavity height), and geo (geometry of the cavity receiver).

The total efficiency of a PTC is the product of the optical efficiency and the thermal efficiency. Optical efficiency is the ratio of the heat rate absorbed in the receiver to the radiation falling on the parabolic collector, as defined by Eq. (1). In this study, the dimensions of the parabolic concentrator were constant, with their values provided in Table 1. Consequently, the total radiation collected on the parabolic mirror ($I_d \cdot A_C$) was constant as 4000 W. Therefore, the radiation ($\dot{Q}_{abs}$) absorbed in the receiver inner walls, which affects the optical efficiency, was selected as the response parameter, Y. Eq. (10) was rearranged with the independent variables geo, h, a, b and to obtain a second-order polynomial equation, as shown below. Eq. (11) clearly illustrates the effect of each parameter's linear, second order, and interaction terms on the response parameter.

$$\begin{aligned} Y\ (\dot{Q}_{abs}) = \beta_0 &+ \beta_1(geo) + \beta_2(h) \\ &+ \beta_3(a) + \beta_4(b) \\ &+ \beta_{11}(geo^2) \\ &+ \beta_{22}(h^2) + \beta_{33}(a^2) \\ &+ \beta_{44}(b^2) \\ &+ \beta_{12}(geo)(h) \\ &+ \beta_{13}(geo)(a) \\ &+ \beta_{14}(geo)(b) \\ &+ \beta_{23}(h)(a) \\ &+ \beta_{24}(h)(b) \\ &+ \beta_{34}(a)(b) \end{aligned} \tag{11}$$

The levels and expressions of factors are given in Table 2. Three different geometries were created for the cavity shape parameter 'geo': triangle, rectangle, and a four-sided polygon formed by combining triangle and rectangle. In the polygon geometry, the length of the perpendicular plates is half the cavity height (b/2). Using the glass plate at the entrance of the cavity receiver as a reference datum, the distance from this glass plate to the focal point (h=0.0 m) of the parabolic collector is the h parameter (see Figure 4). The values of the levels for the geo, h, a, and b are shown in Table 2. The Box-Behnken experimental design method generated 27 experimental plans for four parameters at three levels.

Table 2. The levels of factors and level values (Faktörlerin seviyeleri ve seviye değerleri)

Factors	First level (-1)	Second level (0)	Third level (1)
geo	Triangle 	Rectangle 	Polygon 
h	0.00 m (at focal point)	0.05 m	0.10 m
a	0.025 m	0.0375 m	0.050 m
b	0.025 m	0.0375 m	0.050 m

2.4. Optical Model Validation (Optik Model Doğrulama)

The LS-2 PTC system tested at Sandia was used to validate the optical model. The receiver surface radiation distribution was obtained using SolTrace. The system parameters of the LS-2 PTC system are provided in Table 3.

Table 3. Properties of the LS-2 parabolic collector [27] (LS-2 parabolik kollektörün özellikleri)

Properties	Value
Receiver length (L)	7.8 m
Collector aperture (W)	5.0 m
Focal distance (f)	1.84 m
Absorber internal diameter	0.066 m
Absorber external diameter	0.070 m
Glass internal diameter	0.109 m
Glass external diameter	0.115 m
Receiver absorptance (α)	0.96
Glass transmittance (τ)	0.95
Parabolic collector reflectance (ρ)	0.93
Solar incident angle (θ)	0.0^{o}
Direct normal irradiation (I_d)	933.7 W/m^2

A Pillbox sun shape was selected, assuming a uniform sunray distribution. The reflectance value of the receiver surface was 0.04, and the optical properties were assumed to be independent of temperature and angle. These values were considered constant in the analysis, and optical errors were neglected. The direct normal radiation was taken as 933.7 W/m², which was the measured value in the tests.

The thickness of the glass tube was so small that the change in the direction of the rays, as described by Snell's law, was neglected [28]. Consequently, the refractive index of the glass was not considered. The effect of the glass was evaluated by reducing the radiation, taking into account the transmittance ratio of the solar radiation to the absorber tube. Since the refractive index of the glass was not considered, only the outer diameter of the glass was modeled in the system.

Results from SolTrace were compared with two different studies from the literature (Figure 5). Since the problem was symmetrical, the results were defined for one-half of the receiver. In Figure 5, the curves show a similar trend in the comparative results. The maximum and minimum values were also very close, confirming the reliability of the currrent model.

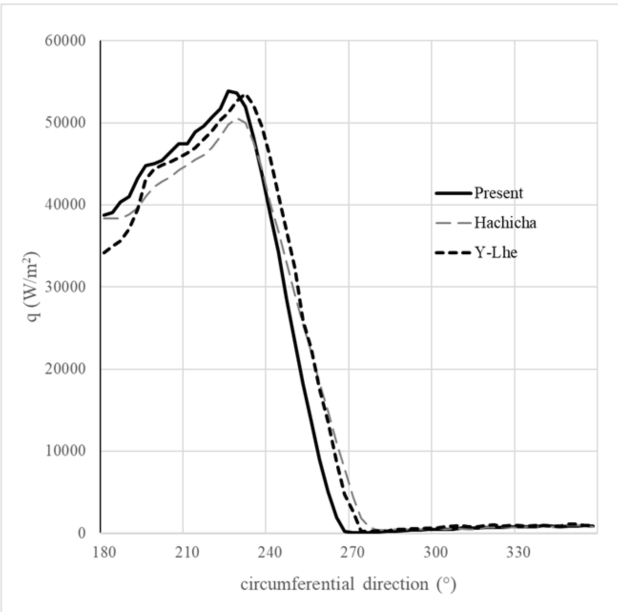


Figure 5. Comparison with the heat flux distribution results of the LS-2 absorber tube [28] (LS-2 alıcı tüpün ısı akısı dağılım sonuçlarıyla karşılaştırma)

2.5. Optical Analyses (Optik Analizler)

Optical analyses of concentrating collectors are extensively performed using the ray-tracing process. Many incident radiation rays travel through the optical system's surfaces, including those with reflective and refractive properties, and are tracked using this method [21]. The Monte Carlo Ray Tracing (MCRT) methodology is the most commonly used, particularly for structured geometries [29]. This study used SolTrace, an open-source numerical ray-tracing software, to investigate the optical system. This optical simulation tool is commonly utilized in concentrating solar power (CSP) applications [30].

In this study, the geometry and dimensions that maximize the solar radiation absorbed in the cavity receiver interior surfaces were investigated. The dimension of the section through which the heat transfer fluid flows was not the subject of this study. The radiation, which passes through the glass plate at the cavity entrance and absorbed on the inner surfaces of the cavity, was investigated. All interactions, including re-radiation between the receiver walls and between the receiver and collector, were taken into account. For this reason, the entire solar-parabolic collector-receiver system was considered as a single environment and SolTrace analyzes were run in 'one stage'.

Optical analyses were performed using SolTrace version 2012.7.9. The direct solar radiation value was set at 1000 W/m². Optical errors, including slope and specularity errors, were neglected. The sun shape was modeled as a Pillbox with an angle range of 4.65 mrad. Since the SolTrace analyses were conducted in 'one stage,' all interactions, including shaded areas and re-reflections between the receiver and collector, were taken into account. All optical parameters of the PTC system are presented in Table 4.

Table 4. Optical parameters of investigating collector system (Araştırılan kollektör sisteminin optik parametreleri)

Parameter	Value
Parabolic collector reflectance (ρ)	0.95
Cavity inner surface absorptance (α)	0.94
Cavity inner outer absorptance	1.00
Glass transmittance (τ)	0.95

3. RESULTS AND DISCUSSION (BULGULAR VE TARTIŞMA)

A comprehensive analysis was conducted to investigate the combined effects of all input factors (geo, h, a, b) on the output factor ($\dot{Q}_{abs}$) simultaneously. To achieve this, cavity geometry (triangle, rectangle, and polygon), cavity aperture width (a), cavity height (b), and the position of the cavity receiver (h) were investigated using RSM optimization based on the DoE approach. An experimental design was created using the Box-Behnken method, as presented in Table 5. The results for absorbed radiation, $\dot{Q}_{abs}$, (output from the SolTrace software), are clearly shown in the Table 5.

The regression equation, Y, for $\dot{Q}_{abs}$ obtained using Minitab was given below.

$$\begin{aligned}\dot{Q}_{abs}(W) = 572.7 + 4.08geo &- 1455.62h(m) \\ &+ 142.31a(m) \\ &+ 4.65b(m) \\ &+ 1.80geo^2 \\ &+ 1144.68h^2(m^2) \\ &- 5.62a^2(m^2) \\ &+ 5.63b^2(m^2) \\ &- 14.9geo * h(m) \\ &+ 0.8geo * a(m) \\ &+ 2.8geo * b(m) \\ &+ 7.8h * a(m^2) \\ &- 4.6h * b(m^2) \\ &+ +0.9a * b(m^2)\end{aligned} \tag{12}$$

By examining each coefficient of the parameters, it can be concluded that the larger the coefficient, the greater its effect on the response parameter's equation. Another way to assess the effects of the parameters is by examining the p-value. The p-values for all factors, including linear, square, and two-way interactions, are presented in Table 6.

Table 5. Factor levels and absorbed radiation values (Faktör seviyeleri ve absorbe edilen ışınım değerleri)

geo	h	a	b	$\dot{Q}_{abs}$ (W)
0	1	0	1	261.69
0	-1	1	0	3235.36
0	-1	0	1	3202.28
0	0	0	0	573.52
-1	0	0	1	585.97
1	0	1	0	746.26
0	1	1	0	342.20
1	0	0	1	584.24
0	0	-1	-1	388.40
1	0	0	-1	570.32
0	0	1	-1	738.32
-1	0	0	-1	583.20
1	1	0	0	266.57
0	0	-1	1	391.74
0	1	0	-1	257.06
-1	0	1	0	745.14
0	-1	0	-1	3181.85
0	-1	-1	0	3098.94
1	-1	0	0	3185.66
-1	0	-1	0	399.51
0	0	0	0	570.64
-1	-1	0	0	3136.21
0	0	0	0	571.13
-1	1	0	0	266.82
0	0	1	1	747.16

Table 6. Variance analysis (Varyans analizi)

Source	P-Value	Source	P-Value	Source	P-Value
Linear	**0.000**	**Square**	**0.000**	**2-Way Interaction**	**0.819**
geo	0.498	geo*geo	0.842	geo*h	0.157
h	0.000	h*h	0.000	geo*a	0.942
a	0.000	a*a	0.534	geo*b	0.786
b	0.441	b*b	0.533	h*a	0.457
				h*b	0.659
				a*b	0.929

The p-value is the significance level used to assess the null hypothesis. It indicates whether the association between the response and each term in the model is statistically significant. A significance level of 0.05 or less is typically considered acceptable. As shown in Table 6, the response $\dot{Q}_{abs}$ was significantly affected by the position of the cavity receiver (h), with a p-value of 0.000. The response was also significantly influenced by the linear term of cavity aperture width (a), with a p-value of 0.000, and by the quadratic term of the position of the cavity receiver (h), with a p-value of 0.000. It was observed that the parameter that had the least effect on the response equation was geo. This is due to the low-iron glass used at the cavity entrance and the selective surface paint on the inner cavity walls, which minimized the probability of re-radiation from the cavity's inner walls and losses from the glass plate.

The parameters that maximize the response function and their values were obtained by solving Eq. (11) using the Minitab Response Optimizer, a powerful tool for such analyses, the results are presented in Table 7. The optimum model's levels and their values are shown in Table 7. The Response

Optimizer tool estimated that $\dot{Q}_{abs}$ would be 3341.6 W with the optimum model.

Based on the parameter values in Table 7, the receiver geometry was modeled and an optical analysis was conducted using SolTrace. This analysis was performed for the optimal model, with the results summarized in Table 8.

Table 7. Parameter levels and values that maximize the response value (Yanıt değerini en üst düzeye çıkaran parametre düzeyleri ve değerleri)

Factor	Level	Level value
geo	1	Polygon
h	-1	0.00 m
a	1	0.05 m
b	1	0.05 m

Table 8. Results for optimum model (Optimum model için sonuçlar)

geo	h	a	b	$\dot{Q}_{abs}$	η_{opt}
1	-1	1	1	3241.99	81.05

Table 9. Comparison of Minitab and SolTrace analysis results for optimum model (Optimum model için Minitab ve SolTrace analiz sonuçlarının karşılaştırılması)

	Minitab	SolTrace	Error (%)
$\dot{Q}_{abs}$	3341.60	3241.99	2.98

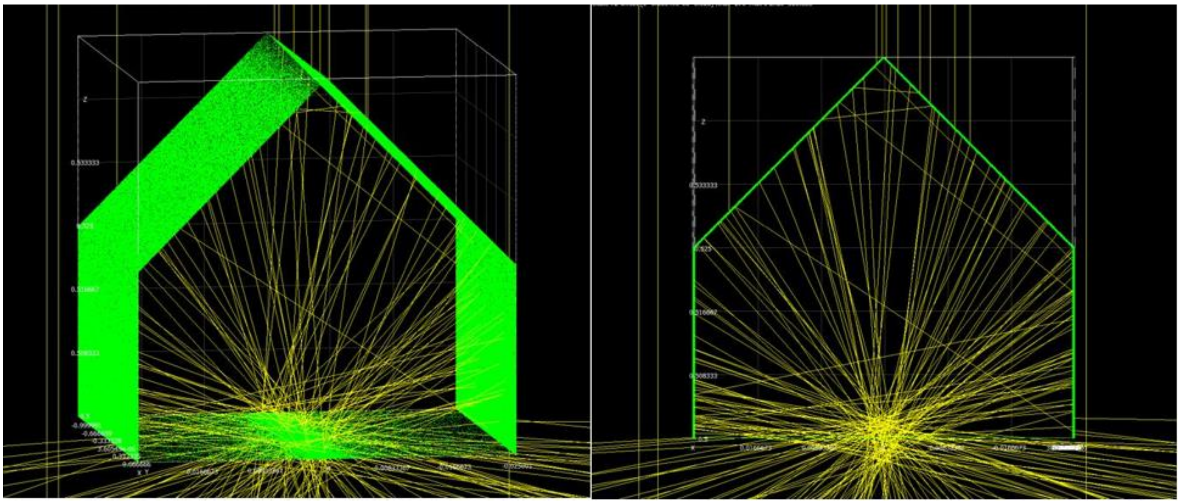


Figure 6. Perspective and front view of SolTrace analysis result of optimum cavity receiver (Optimum kaviteli alıcının SolTrace analiz sonucunun perspektif ve ön görünümü)

The results obtained from Minitab and SolTrace are compared in Table 9. According to the analysis, the difference between the Minitab and SolTrace results was less than 3%, which is considered acceptable. Figure 6 shows the heat flux distribution on the optimal cavity solar receiver model. The distribution of radiation intensity on the glass plate is visible in the figure. While the radiation is concentrated in a narrow area on the glass plate, radiation from the side areas also passes into the cavity area. The area where the angled plates of the polygon geometry merge is the least irradiated region. Figure 6 shows the distribution of radiation passing through the glass more clearly. Perpendicular plates receive more radiation, while angled plates receive less. This phenomenon, related to the angle of incidence of the radiation from the collector, is due to the scattering of the radiation beam at larger angles. The radiation passing through the glass is scattered over a large area, causing the angled plates on top to be exposed to less radiation.

4. CONCLUSIONS (SONUÇLAR)

In this study, the shape, position, and dimension optimization of a cavity geometry for a parabolic trough solar concentrator were performed to achieve the highest possible radiative heat rate absorbed by the cavity receiver, thereby enhancing optical efficiency. The effects of various parameters, including cavity geometry, cavity aperture width, cavity height, and cavity position, on the PTC optical performance were extensively studied using SolTrace modeling, accompanied by an optimization procedure. An optimization model for the cavity receiver was created using Response Surface Methodology. An analysis setup was developed for the determined factors (geometry, height, aperture width, and position) using the Box-Behnken design method. The parabolic trough collector (PTC) with the cavity receiver was optically modeled using SolTrace. The significant results of this study are summarized below:

- When examining the effect of each parameter on the response function ($\dot{Q}_{abs}$ it was found that geometry (geo) had the least impact. This is attributed to the use of a low-iron glass plate at the entrance of the cavity, which has high transmittance for radiation from the parabolic collector but low transmittance for re-reflected rays within the cavity. Additionally, the inner surfaces of the cavity were coated with a selective surface paint with very low reflectivity (0.04) in the model designed and investigated in this study.

- Since the receiver had a shading effect on the parabolic collector, a smaller cavity aperture width (a) reduced the shading area. However, a larger cavity aperture was crucial for capturing the entirety of the radiation beam concentrated by the parabolic collector.

- Although the effect of cavity height (b) on the response function was minimal, it was observed that increasing both the cavity width and cavity height positively influenced the optical efficiency.

- The most effective parameter of the system was the position of the cavity receiver relative to the parabolic collector (h). Positioning the receiver at the focal point maximized the response function, while deviations from the focal point significantly reduced both $\dot{Q}_{abs}$ and optical efficiency, η_{opt}. Furthermore, when evaluating the interactions of the h parameter with other parameters, it was evident that the h parameter was always dominant in binary interactions.

- The optimal model which maximized the net heat flux absorbed by the inner surfaces of the cavity receiver ($\dot{Q}_{abs}$) and the optical efficiency (η_{opt}), was determined through optimization methodology. This model featured a polygonal receiver geometry, positioning at the focal point, and equal cavity height and width of 0.05 meters.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The authors' of this article declare that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarları çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Gülden ADIYAMAN*:** She conducted the optimization and optical analysis, evaluated the results, and performed the writing process.

Optimizasyon ve optik analizleri yapmış, sonuçları değerlendirmiş ve yazım sürecini gerçekleştirmiştir.

***Levent ÇOLAK*:** He created the optical mathematical model of the system, directed the study, commented about results and also contributed to the writing process.

Sistemin optik matematiksel modelini oluşturmuş, çalışmayı yönetmiş, sonuçlar hakkında yorum yapmış ve yazım sürecine de katkı sağlamıştır.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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