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OPTICAL–GEOMETRIC ANALYSIS OF A LINEAR FRESNEL CONCENTRATOR WITH A TUBULAR CYLINDRICAL RECEIVER

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Annotation. In this paper, linear Fresnel concentrators (LFCs) will be considered as promising equipment used for solar power generation. In particular, such concentrators have a rather simple design, relatively cheap installation procedure, and provide efficient usage of the ground area for their placement. The purpose of this study was to conduct an optical-geometric analysis of linear Fresnel concentrator, which is used with a tubular cylindrical receiver. In general, the goal of the study was to determine the effect of geometrical parameters and position of mirrors on the distribution of concentrated sunlight at the receiver surface. To achieve the stated objectives, a geometric model of concentrator system will be developed based on the theory of sunlight reflection and relative position of the sun, mirror strips, and tubular receiver. As part of this model, several optical parameters will be used, including incidence angles of sunlight, angle between each mirror strip and sunlight ray, receiver height, as well as shading/blocking effect by adjacent mirrors. Based on these parameters, the geometry of sunlight reflection from the mirror field will be estimated along with trajectories of reflected rays towards the cylindrical receiver. As follows from the conducted research, the efficiency of optical processes occurring within linear Fresnel concentrator depends significantly on precise position of individual mirrors and appropriate location of a tubular receiver. In this case, geometric optimization of mirror positioning may result in considerable improvement of radiation interception at the receiver surface and decrease in optical losses.

Key words: Linear Fresnel concentrator; optical–geometric analysis; solar radiation concentration; tubular cylindrical receiver; solar thermal energy.

Аннотация. В данной работе линейные концентраторы Френеля (ЛКФ) рассматриваются как перспективное оборудование для выработки солнечной энергии. В частности, такие концентраторы имеют достаточно простую конструкцию, относительно недорогую процедуру установки и обеспечивают эффективное использование площади земли для их размещения. Целью данного исследования был оптико-геометрический анализ линейного концентратора Френеля, используемого с трубчатым цилиндрическим приемником. В целом, целью исследования было определение влияния геометрических параметров и положения зеркал на распределение концентрированного солнечного света на поверхности

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приемника. Для достижения поставленных целей будет разработана геометрическая модель системы концентратора на основе теории отражения солнечного света и относительного положения солнца, зеркальных полос и трубчатого приемника. В рамках этой модели будут использованы несколько оптических параметров, включая углы падения солнечного света, угол между каждой зеркальной полосой и солнечным лучом, высоту приемника, а также эффект затенения/блокировки соседними зеркалами. На основе этих параметров будет оценена геометрия отражения солнечного света от зеркального поля, а также траектории отраженных лучей к цилиндрическому приемнику. Как следует из проведенных исследований, эффективность оптических процессов, происходящих внутри линейного концентратора Френеля, в значительной степени зависит от точного положения отдельных зеркал и соответствующего расположения трубчатого приемника. В этом случае геометрическая оптимизация расположения зеркал может привести к значительному улучшению перехвата излучения на поверхности приемника и снижению оптических потерь.

Ключевые слова: линейный концентратор Френеля; оптико-геометрический анализ; концентрация солнечного излучения; трубчатый цилиндрический приемник; солнечная тепловая энергия.

Annotatsiya. Ushbu maqolada chiziqli Frenel kontsentratorlari (ChFC) quyosh energiyasini ishlab chiqarishda ishlatiladigan istiqbolli uskunalar sifatida ko'rib chiqiladi. Xususan, bunday kontsentratorlar juda oddiy dizaynga, nisbatan arzon o‘rnatish tartibiga ega va ularni joylashtirish uchun yer maydonidan samarali foydalanishni ta’minlaydi. Ushbu tadqiqotning maqsadi naychali silindrsimon qabul qilgich bilan ishlatiladigan chiziqli Frenel kontsentratorining optik-geometrik tahlilini o‘tkazish edi. Umuman olganda, tadqiqotning maqsadi geometrik parametrlar va oynalarning joylashuvining qabul qilgich yuzasida konsentrlangan quyosh nurining tarqalishiga ta’sirini aniqlash edi. Belgilangan maqsadlarga erishish uchun quyosh nuri aks etishi nazariyasi va quyosh, oyna chiziqlari va naychali qabul qilgichning nisbiy joylashuvi asosida kontsentrator tizimining geometrik modeli ishlab chiqiladi. Ushbu modelning bir qismi sifatida quyosh nurining tushish burchaklari, har bir oyna chizig‘i va quyosh nuri orasidagi burchak, qabul qilgich balandligi, shuningdek, qo‘shni oynalar tomonidan soyalash/blokirovka effekti kabi bir nechta optik parametrlardan foydalaniladi. Ushbu parametrlarga asoslanib, oyna maydonidan quyosh nuri aks etishi geometriyasi silindrsimon qabul qilgichga qarab aks ettirilgan nurlarning traektoriyalari bilan birga baholanadi. Olib borilgan tadqiqotlardan ko‘rinib turibdiki, chiziqli Frenel konsentratorida sodir bo‘ladigan optik jarayonlarning

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samaradorligi alohida oynalarning aniq joylashuviga va naychali qabul qilgichning to‘g‘ri joylashishiga sezilarli darajada bog‘liq. Bu holda, oyna joylashuvini geometrik optimallashtirish qabul qilgich yuzasida nurlanishni ushlab turishni sezilarli darajada yaxshilaydi va optik yo‘qotishlarni kamaytiradi.

Kalit so‘zlar: Chiziqli Frenel konsentratori; optik-geometrik tahlil; quyosh nurlanishining konsentratsiyasi; naychali silindrsimon qabul qilgich; quyosh issiqlik energiyasi.

INTRODUCTION.

Linear Fresnel concentrators (LFCs) use arrays of narrow flat or slightly curved mirrors to focus sunlight onto an elevated linear receiver [1, 2]. Pioneered by Francia in the 1960s [1], LFCs promise simpler, cheaper CSP fields than parabolic troughs due to low-profile flat mirrors and fixed receivers [3]. They require less structural support and land area than parabolic designs [4], and can achieve relatively uniform flux on the absorber [6]. However, their optical efficiency is inherently lower: typical peak optical efficiency is only about 18–20%, with annual averages around 13–18% [4]. This deficit arises from several loss mechanisms (e.g. incidence angle cosine effects, mirror blocking/shading, and flux spillage) and from practical limits (mirror alignment and tracking).

Linear Fresnel concentrators (LFCs, also called linear Fresnel reflectors, LFRs) are line-focus solar collectors composed of many long, narrow reflector strips arranged in parallel rows on the ground [1, 2]. Each mirror rotates about its long axis (one-axis tracking) to follow the sun, reflecting direct solar rays onto a fixed receiver tube positioned above the mirror field [1, 7]. This geometry is similar in principle to parabolic troughs but uses discrete flat (or slightly curved) facets instead of a continuous parabola [1, 5]. Because the mirrors are flat and closer to the ground, LFC systems have lower structural and fabrication costs than parabolic trough fields [3, 4]. They also have low wind loads and can be roof-mounted [3, 4]. Typical LFC plants aim for medium-to-high operating temperatures (≈150–550 °C [5]) by using heat-transfer fluids such as thermal oil, molten salt, or steam. The absorber tube is often enclosed in a glass sleeve under vacuum (as in parabolic troughs) or placed inside a secondary concentrator (e.g. a trapezoidal cavity or CPC) to reduce convective losses [8, 9]. For example, Memme and Fossa note that the LFC absorber “is usually fixed and housed within a secondary concentrator, which can take the form of a trapezoidal cavity or a compound parabolic collector (CPC)” [8]. High-temperature applications (>400 °C) typically use evacuated tubular receivers due to their low heat loss [9, 10].

Despite these advantages, LFC optical performance lags behind more mature CSP technologies. Global LFC market share remains small [11]. Comparative data

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show LFC peak optical efficiencies around 18–20% (annual 13–18%), versus ≈20–25% (annual 14–22%) for parabolic troughs [5]. LFC concentration ratios are generally modest (≈30–80) compared to ~80–90 for troughs [4, 5]. This is partly due to unavoidable optical losses: (1) Cosine/inclination losses, since each mirror sees the sun at an oblique angle (incidence factor $\cos\theta$); (2) Shading/blocking, where mirrors cast shadows on neighbors or reflected beams hit other mirrors rather than the receiver [12]; (3) Spillage or intercept losses, where reflected rays miss the tube (especially at extreme sun angles); and (4) Reflectance losses, due to finite mirror reflectivity (typically 90–96%) and any glass cover transmittance [13]. Many studies explicitly identify blocking, shading, and missed rays as the primary geometric loss mechanisms [12]. Cosine effects are usually treated either within the ray-trace or as a separate. Combined, these losses reduce the fraction of incident DNI that is captured. For design and analysis, it is common to define an intercept factor or optical efficiency equal to (effective power on receiver)/(available power on aperture) [14]. In fact, as Santos et al. (2021) note, following Rabl (1985) one can decompose optical efficiency into material terms (mirror reflectance × glass transmittance) times a geometric intercept factor [13]. Under idealized assumptions (specular reflection, point sun, perfect tracking, etc.), analytical models compute shading, blocking, and end-loss effects using geometry [12, 15]. These analytical or quasi-analytical methods are valuable for rapid design exploration. However, accurate assessment often requires detailed ray-tracing: Monte Carlo or deterministic ray-trace codes (FresnelSim, SolTrace, Tonatiuh, etc.) can simulate each sunray's path, accounting for tracking error, mirror slope error, Sun's angular width, and complex secondary optics [16]. Ray-tracing yields flux distributions on the absorber as well as overall efficiency.

Despite extensive study, challenges remain. There is a need for more accurate combined optical-thermal models: many analyses still treat optics and heat transfer separately. Particularly for advanced cavities or multi-tube receivers, coupling ray-based flux maps with temperature-dependent emissivity and convection is complex and not fully solved. Models that include real-world effects (mirror misalignment, diffuse light, soiling) would improve reliability. Large-scale experimental validation is also sparse, as only a few demonstration LFC plants exist. Control strategies (dynamic aiming lines, heliostat-like adjustment) are relatively unexplored for LFCs. New geometries (e.g. non-flat facets, deformable mirrors, or building-integrated Fresnels) have been proposed but need further optical evaluation. In summary, while fundamental optical–geometric principles of LFCs are established, optimizing a practical system requires addressing these

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remaining uncertainties. The citations above provide both the seminal foundations and the state-of-art, but future work is needed to bridge the gaps identified.

MATERIALS AND METHODS.

When designing a linear Fresnel concentrator (LFC) with a tubular (cylindrical) receiver, the receiver creates a certain amount of shadow on the concentrator aperture. Therefore, it is not possible to place mirror elements under the receiver. As a result, the first mirror element on both sides of the concentrator must be placed at a certain minimum distance from the center of the aperture. This minimum distance is determined by the following relationship:

$$W_1 = R + f\tan(\gamma_0) \quad (1)$$

where, R - tubular receiver radius, f - vertical distance between the center of the receiver and the aperture plane, γ_0 - The semi-angular diameter of the Sun's disk.

The geometrical scheme of the LFC with a tubular receiver is presented in figure 1.

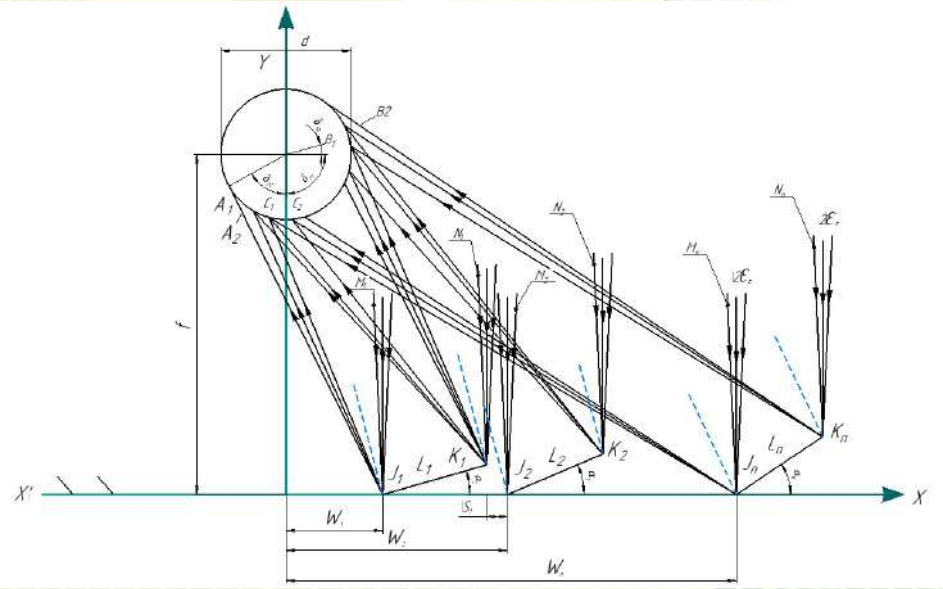


Figure 1. Linear Fresnel concentrator with tubular receiver.

During the geometric design process, the angle of inclination α_1 of the first mirror element is chosen so that the outer ray of the cone of rays M_1J_1 should be tangentially incident on the point A_1 of the receiver circle. At the same time, the ray of the inner part of the cone of rays M'_1J_1 should be directed to the point C_1 of the receiver.

Using simplified geometric relations, the deviation angle of the first mirror element is determined as follows:

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$$\alpha_1 = \frac{1}{2}\tan^{-1}\left(\frac{x_{1a}^2 - R^2}{W_1 f - R\sqrt{(x_{1a}^2 - R^2) + (y_{1a} - f)^2}}\right) - \gamma_0 \quad (2)$$

where, (x_{1a}, y_{1a}) - coordinates of point A_1 on the receiver surface.

The width of the first mirror element is found by the following relation:

$$L_1 = \sqrt{(x_{1c} - x_{1b})^2 + (y_{1b} - y_{1c})^2}\,\frac{\cos(2\alpha_1 - \gamma_0 - \psi_1)}{\cos(\alpha_1 - \gamma_0)} \quad (3)$$

where, (x_{1b}, y_{1b}) and (x_{1c}, y_{1c}) — the coordinates of points B_1 and C_1, respectively.

The angle of the line connecting points B_1 and C_1 with respect to the horizontal is:

$$\psi_1 = \tan^{-1}\left(\frac{y_{1b} - y_{1c}}{x_{1b} - x_{1c}}\right) \quad (4)$$

The amount of displacement along the Y axis for the second mirror is determined as follows:

$$Z_2 = \frac{(W_1 + L_1\cos\alpha_1)L_1\sin\alpha_1}{f - L_1\sin\alpha_1} \quad (5)$$

The position coordinate of the second mirror with respect to the aperture:

$$W_2 = W_1 + L_1\cos\alpha_1 + Z_2 \quad (5)$$

The angle of deviation of the second mirror:

$$\alpha_2 = \frac{1}{2}\arctan\left(\frac{x_{2c}^2 - R^2}{W_2 f - R\sqrt{(x_{2c}^2 - R^2) + (y_{2c} - f)^2}}\right) - \gamma_0 \quad (6)$$

The width of the second mirror:

$$L_2 = \sqrt{(x_{2c} - x_{2b})^2 + (y_{2b} - y_{2c})^2}\,\frac{\cos(2\alpha_2 - \gamma_0 - \psi_2)}{\cos(\alpha_2 - \gamma_0)} \quad (7)$$

Mirror displacement:

$$Z_n = \frac{(W_{n-1} + L_{n-1}\cos\alpha_{n-1} + x_{na})L_{n-1}\sin\alpha_{n-1}}{y_{na} - L_{n-1}\sin\alpha_{n-1}} \quad (8)$$

Mirror coordinate:

$$W_n = W_{n-1} + L_{n-1}\cos(\alpha_{n-1}) + Z_n \quad (9)$$

Tilt angle:

$$\alpha_n = \frac{1}{2}\tan^{-1}\left(\frac{x_{nc}^2 - R^2}{W_n f - R\sqrt{(x_{nc}^2 - R^2) + (y_{nc} - f)^2}}\right) - \gamma_0 \quad (10)$$

Mirror width:

$$L_n = \sqrt{(x_{nc} - x_{nb})^2 + (y_{nb} - y_{nc})^2}\,\frac{\cos(2\alpha_n - \gamma_0 - \psi_n)}{\cos(\alpha_n - \gamma_0)} \quad (11)$$

where,

$$\psi_n = \tan^{-1}\left(\frac{y_{nb} - y_{nc}}{x_{nb} - x_{nc}}\right).$$

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Initial values:

$$L_0 = 0, Z_1 = 0, \alpha_0 = 0. \quad W_1 = W_0 = R + f\tan(\gamma_0).$$

Where, (x_{na}, y_{na}), (x_nb, y_nb) ва (x_nc, y_nc) — are the coordinates of points A_n, B_n, and C_n, respectively, which are determined by simple geometric methods for each nth mirror element [17, 19].

Since the tube-shaped receiver has a circular geometry, the coordinates of the points A_n, B_n, and C_n located on the receiver surface are determined based on the equation of the circle. With the coordinates of the receiver center at $(0, f)$ and its radius R, the coordinates of an arbitrary point on the receiver surface are expressed by the following parametric relations:

$$x_{na} = R\cos\ \theta_n$$
$$y_{na} = f + R\sin\ \theta_n$$

where, θ_n — is the angular coordinate of a point on the receiver's circle, which determines the point where the light hits the receiver. The coordinates of points B_n and C_n are determined in the same way.

The aperture diameter D of the concentrator is determined by the following expression [131–132]:

$$D = 2X = 2\sum_{n=1}^{k}(L_n\cos(\alpha_n) + Z_n) + 2W_1 \qquad (12)$$

Where, k — the number of mirror elements in the half of the concentrator.

The following geometric condition must be met in order to prevent the beam path from being blocked between the panels in the LFC:

$$f - L_n\sin\ \alpha_n > 0 \qquad (13)$$

where, (f) — distance between the center of the receiver and the aperture plane, (L_n) — nth facet width, (α_n) — its angle of deviation.

Projection loss coefficient:

$$\eta_{gt,n} = 1 - \frac{L_n,|\sin\ \alpha_n|}{f}, 0 \le \eta_{gt,n} \le 1 \qquad (14)$$

α_n decreases with an increase in the facet angle, which leads to a decrease in the real reflection coefficient.

RESULTS AND DISCUSSIONS.

In a faceted concentrator, the spatial orientation of the facets varies depending on the receiver geometry. Therefore, the facet deflection angle for different receiver configurations was analyzed in comparison. The variation of the facet deflection angle α_n with the facet index n is shown in Figure 2. The mutual arrangement of the facets and the receiver geometry create a geometric obstruction effect in the concentrator. The variation of the geometric obstruction coefficient for different receiver configurations is shown in Figure 3.

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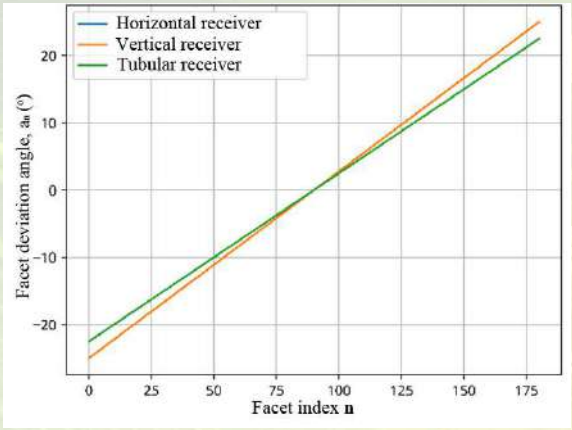


Figure 2. Facet Angle Comparison Chart

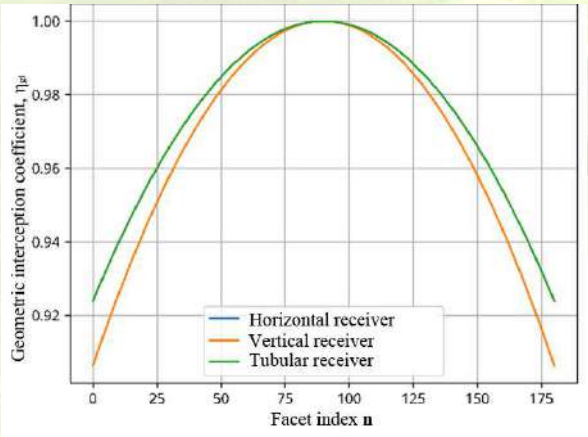


Figure 3. Graph of the geometric barrier coefficient

Figure 2 shows the variation of the facet deflection angle α_n with the facet index n for horizontal, vertical, and tubular receivers. According to the results, with increasing n, the angle α_n changes almost linearly. In the case of the vertical receiver, the range of angle changes is wider, since $\alpha_{max} = 22.5°$, while in the case of the horizontal and tubular receivers, the changes are similar, since . This indicates that the receiver geometry plays an important role in determining the optimal orientation of the facets.

Figure 3 shows the variation of the geometric obstruction coefficient η_{gt} with facet index n for various receiver configurations. The value of η_{gt} is larger around the central facets and decreases towards the periphery as the geometric obstruction effect increases. Due to the wide range of angles in the vertical receiver, the variation of η_{gt} is also observed in a relatively wide interval. In the horizontal and tubular receivers, the coefficient distribution has a similar pattern.

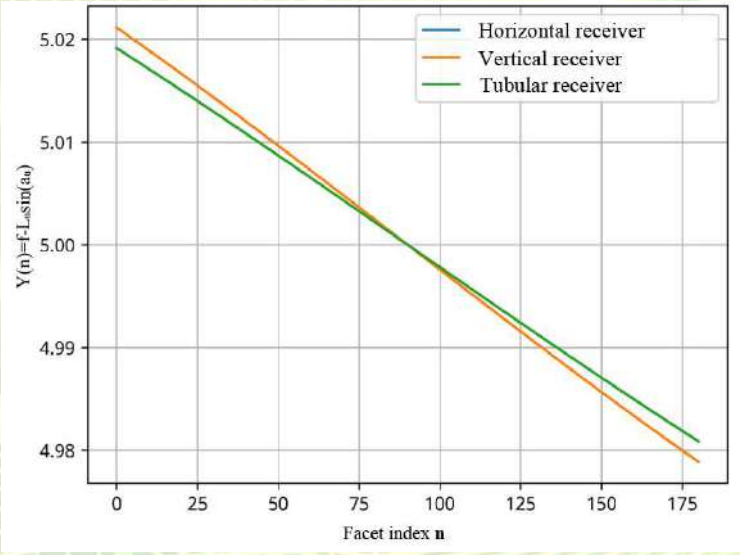


Figure 4. Variation of the functio $Y(n) = f - L_n \sin(\alpha_n)$n by facet index n.

Figure 4 shows the variation of the function $Y(n) = f - L_n \sin(\alpha_n)$ with the facet index n, which represents the geometric position of the concentrator facets

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relative to the focus. The analysis results show that with increasing n, the function *Y(n)* changes according to a symmetrical law and approaches maximum values around the central facets. The difference in the facet deflection angles depending on the type of receiver also causes certain changes in the amplitude of the function *Y(n)*. This indicates the need for a comprehensive analysis of the relationship between the concentrator geometry, facet angles, and receiver location. The results obtained are of important practical importance in the optimal design of faceted concentrators and increasing optical efficiency.

CONCLUSION.

From the results obtained in the optical–geometric analysis of a linear Fresnel concentrator with a tubular cylindrical receiver, one can conclude about the strong impact of geometric parameters on the effectiveness of solar energy concentration. The correct location and angle of mirror strips, as well as the position of the receiver, play an important role in the solar concentrating system effectiveness.

The presented geometric model can be used to calculate the required mirror tilt angles, which enable reflection and focusing of solar beams onto the receiver during all positions of the sun. It can be concluded from the obtained data that increasing the precision of mirror adjustment and appropriate selection of the height at which the receiver will be installed can greatly reduce the loss of concentrated light due to shading, blocking, and radiation scattering.

As was found in the performed analysis, the tubular receiver with a cylindrical cross-section can provide even distribution of concentrated radiation over the receiver's surface, ensuring good heat transmission through it. However, taking into account the geometry of mirrors, proper location of the receiver can increase the interception of reflected rays by the concentrator.

The results of the performed analysis can be used as a basis for designing solar power plants based on linear Fresnel concentrators. Further research should include computer simulation and experimental testing of the device in action and installation of secondary concentrators.

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